

Virtual Surgery and Orthopaedic Surgery: Towards Training using Haptic Technology

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Crazy. Crazy. Crazy. Obvious.

— Harvard Professor Lant Pritchett on the process of adapting new game-changing ideas.

Abstract

Medical education and practical training in surgery is changing, by shifting from an on the job learning paradigm, which possesses problems such as that it is unpredictable, dependent on clinical needs and that patient safety may be jeopardised, to an evidence-based surgical skills training driven by curricular needs, and acquiring basic surgical skills prior to assisting in the operating theatre and thus reducing operation duration. Towards achieving this goal, virtual reality (VR) simulators are used in minimally invasive surgery for technical skills training at the beginning of the learning curve, but have not yet been adapted for open surgery due to its complexity for simulation. This thesis investigated the potential of using a VR simulator for training in orthopaedic hand surgery, with an emphasis on providing a meaningful, effective and motivating addition to current training methods for surgical procedures.

A review of literature, preliminary research projects and currently available surgical systems revealed limited results on whether a VR simulation of orthopaedic hand surgery could be created, fulfilling the needs of medical experts. Therefore, a study investigating the current state of medical education and to understand the expectations on such a simulator was carried out, which resulted in the identification of promising medical scenarios for simulation (such as carpal tunnel release, distal radius fracture treatment or surgical incision) and in requirements for its development. Different software frameworks have been evaluated for their ability for use by analysing five developed demonstrators, with the result that a custom implementation of a six-degrees-of-freedom haptic algorithm was required. By following a human-centred design approach, a VR surgical simulator with inbuilt objective measures of assessment has been developed, allowing applying a plate, drilling holes, measuring their lengths, inserting screws and taking virtual X-rays, supported by haptic feedback for increased realism and teaching aspects not possible by common computer-based simulators, such as feeling the resistance when drilling through the cortical bone. By close collaboration with medical experts and following user interface design principles, a carried out medical evaluation of the simulator showed that the simulator was well-received by the targeted young doctors and

medical students, that relevant aspects of the implemented medical scenario are taught and that the users' performance can be assessed.

The findings of this work showed that it is possible to create an interactive VR simulator aimed at early stages to learn basic orthopaedic principles of open surgery using the example of the treatment of distal radius fractures in a meaningful manner. It addresses issues in the current medical education and enables learning educational objectives repeatedly in reusable medical scenarios and in a safe and controlled environment, without the risk of harming patients, and thus contributing to improved quality and patient safety when proceeding to the operating theatre.

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Glossary

The following terms are used throughout this thesis. They are explained in greater detail in the chapters, but are also noted here for quick reference.

AO Foundation. *Arbeitsgemeinschaft für Osteosynthesefragen* (Association for the study of internal fixation); a medical non-profit organisation with international research, development, quality assurance and educational activities led by surgeons specialised in trauma, spinal, craniomaxillofacial and veterinary surgery.

Cancellous bone. One of the two bone tissue types; spongy trabecular bone, which is porous and has a mesh-like structure; found mostly at the proximal and distal bone ends.

Collision filtering. A technique to define how a pair of potentially colliding objects should be processed.

Cortical bone. One of the two bone tissue types; the dense bone forming the tubular element of the shaft (middle part) and the metaphysis (between shaft and rounded end of bone) of a long bone, covering the cancellous bone.

CT. Computed tomography; the use of many X-ray images to create a three-dimensional image.

Degree of freedom (**DoF**). A direction (or rotation) an independent motion can occur. Three-DoF allows to change position in all three perpendicular axes; six-DoF adds changes in orientation about three perpendicular axes.

Distal/proximal. Away from the centre of the body, more peripheral (distal); as opposed to proximal, which is closest to the centre of the body.

Dorsal/volar. The back of the body (dorsal), as opposed to volar, which is the front of the body. In humans, dorsal and volar are mostly the same as posterior and anterior.

Fixation. An orthopaedic procedure; the application of an implant (such as screws, plates or pins) to a broken bone (internal fixation) or of a cast (external fixation) to support healing in a controlled position and (usually) to facilitate early mobility and functional rehabilitation.

Haptic texture/effect. Simulating haptic surface properties (texture) such as smooth-shaped, friction or sticking, or simulating force effects such as magnetic fields or springs by modifying the force applied by a haptic device to the user.

Haptics. Receive feedback from computer systems in the form of "feeling" virtual objects using haptic devices (also referred to as haptic interfaces); concerns the sense of touch.

HIP and IHIP. Terms used in haptic rendering to describe the current position of the end effector of the haptic device (haptic interface point) and the corresponding surface point (ideal haptic interface point, also known as god-object or proxy point).

Kirschner wires. Also referred to as K-wires or pins. A sharpened steel wire widely used in orthopaedics and surgery for temporary fixation of bone fragments or to provide skeletal traction.

Minimally invasive surgery (**MIS**). Any surgical procedures undertaken that limit the size of incisions needed. Typically, arthroscopic or laparoscopic devices are used with an endoscope for indirect observation of the surgical field.

MRI. Magnetic resonance imaging; the use of a magnetic field and pulses of radio wave energy to create a three-dimensional image.

Open surgery. Any surgical procedure undertaken using incisions large enough to insert the surgical instruments, to visualise the surgical field and to perform the surgery.

Orthopaedic hand surgery. Deals with the diagnosis and treatment of problems of the hand, wrist and upper extremity, such as complex fractures or injuries to the carpal bones.

Osteosynthesis. A surgical procedure using reduction and internal fixation with implants, aiming to stabilise and immobilise the bone fracture.

Reduction. An orthopaedic procedure; restoring a fracture to its normal bone morphology by realigning the bone fragments (anatomical reduction), or restoring the length, alignment and rotation of the main fragments (functional reduction). Can be either with open surgery (open reduction) or by pushing or pulling the bone (called traction) without surgery (closed reduction).

Scene graph. Representing the virtual world as a graph of nodes. These nodes (i.e. the elements of the scene graph) typically represent objects of the scene or transformations that apply to the attached children.

(**Software**) **framework**. A reusable software environment providing foundation functionality which can be used for application development.

Surgical simulation. A system which represents aspects of the real world, often in an immersive and interactive environment.

Surgical simulator. A device which is used to teach particular surgical skills, techniques or procedures.

Virtual surgery. A computer-based system to simulate surgical procedures for medical training using virtual reality technology (without the use of anatomical specimens or patients).

X-ray. An image produced by X-rays (ionising electromagnetic radiation) passing through parts of the body and being absorbed to different degrees depending on the material. Typically used to identify bone structures, which contain much calcium and therefore absorb X-rays efficiently.

Chapter 1

Introduction

1.1 Chapter Summary

This chapter introduces the background to the research project presented in this thesis. A brief introduction to medical training and simulation in surgery is presented and the need for research into virtual reality-based surgical simulators for open surgery is highlighted. This is followed by the aims and objectives of the PhD specifying the purpose of this research.

The organisation of the thesis shows the overall process and development of the understanding of the usefulness of the developed simulator in a future competency-based surgical skills curriculum. The chapter concludes with an overview of the contributions of this work.

1.2 Background

Medical education and practical training of surgeons has considerably changed in the last decades for certain medical fields. In the past, young surgeons were trained on the job under the guidance of more experienced surgeons on the patient to prepare them for the operating theatre. Pellegrini (2006, p.338) summarised the set of problems using this paradigm as follows:

> "Learning on the job, particularly surgery, is relatively disorganized, it is unpredictable, it is time-consuming, and it is costly. Learning is not driven by curricular needs; it is instead dependent on clinical needs and subject to available opportunity. Assessment and validation are difficult, and more importantly, patient safety may be jeopardized."

With the introduction of working hour restrictions, increased regulations and the decline in the number of operations a young doctor assists, new strategies are needed to modernise the surgical training system. According to Aggarwal, et al. (2006), a transition from the traditional, experience-

based training to a structured, evidence-based surgical skills training program with built-in assessment functionality is required to reduce operation duration and to acquire basic surgical skills prior assisting in the operating theatre. Virtual reality simulators have shown to be effective and appropriate for technical skills training in minimally invasive surgery at an earlier stage of the surgeon's education. However, they are used hardly if at all for open surgery due to the complexity of the simulation, as minimally invasive instruments have reduced degrees of freedom of movements and limited haptic feedback.

The research detailed in this thesis aims to investigate the effectiveness, usefulness and practicability of using a virtual reality-based surgical simulator in the field of orthopaedic hand surgery. About a third of all occupational and non-occupational incidents affect wrist, hand and fingers (Koordinationsgruppe für die Statistik der Unfallversicherung UVG (KSUV), 2015, pp.43) and different surgical skills are used to treat them, which are also applicable to different surgical procedures. Through recent advances in technology, virtual reality-based surgical simulators can form a key element in the future medical education for open surgery by allowing training of basic surgical skills outside of the operating theatre and thus increase patient safety. In addition, the recent developments of virtual reality surgical simulators are more technology-driven, but the progress should be accompanied by medical experts to support integration of such simulators into a structured medical curriculum, similar to the training of pilots, where it is standard for over two decades (Allerton, 2009, p.7).

Attention should be turned to performance assessment, which is a significant advantage of computer-based surgical simulators, as the objective assessment of the surgeons' performance can be automatically and immediately shown after the training session and can also be used as a motivational factor (Hammoud, 2008). By this, performance scores can be defined which have to be achieved prior continuing with the next training stage. However, in open surgery, no standards exist yet for assessing the surgeon's performance and no consensus exists about the assessment of practical skills or defining such scores; therefore, outcome measures, which would optimally control the training, do not exist (Shaharan and Neary, 2014).

Several research projects demonstrated that the particular technologies required for the development of a virtual reality-based open surgery simulator exist to a certain extent, but there is a need to investigate if current technology, if used according to medical experts' needs using a human factors-led development approach, is applicable and can form the prerequisites for a similar paradigm shift as it is currently discussed for minimally invasive surgery, which is in the process of integrating virtual reality-based simulations into the surgical training curriculum.

This work is the result of a part-time PhD research project carried out by the author, which is based in Switzerland. The motivation of combining virtual reality and haptics with human factors in a medical context, which make this PhD particularly of value, resulted from the outcome of prior projects (see section 3.3), and the connection between the University of Nottingham and the Bern University of Applied Sciences was established during a European research project (A configurable virtual reality system for multi-purpose industrial manufacturing application (IRMA)[1], 2000-2004).

1.3 Aims and Objectives

The overall goal of this PhD research project is to improve training and education in osteosynthesis in orthopaedic hand surgery. In this research, a prototype was developed by using an innovative approach to adapt recent technical achievements in surgical simulation, which are partially already used for minimally invasive surgery, such as for laparoscopy or endoscopy, to open surgery. Therefore, the result of the prototype aims to answer the question, if this novel approach of using virtual reality and haptics for simulating both soft and bone tissue will lead to improved quality and patient safety in surgery through the training with this surgical simulator.

The biomechanical complexity of the hand and wrist currently limits wider adoption of surgical simulators to hand surgery. The aim is to show how (patient-specific) data from CT (computed tomography) and MRI (magnetic resonance imaging) scans or textured 3D models, in conjunction with biomechanical parameters can be used to generate interactive virtual models that react in response to the surgeon's actions. This data is an important step to formulate an accurate learning environment for surgical procedures and techniques. The use of patient-specific data would enable a better diagnosis as well as assessment of the risks and prognosis of individual patients, taking into account the clinical variability of patients. In addition, using patient-specific data would allow using this simulator for planning an operation, but this research focused on training. By taking into account patient-specific data, a more realistic medical scenario can be created and the decision making process can be supported, as the treatment plan not only depends on the fracture itself, but also upon patient factors such as age or general health status. The virtual model includes soft and hard tissue visualisation and haptic feedback with a focus on simulating surgical procedures or surgical techniques in orthopaedic hand surgery. The medical scenario the simulator addresses, in particular

1. Publications Office of the European Union (2005) *European Commission : CORDIS : Projects & Results Service : A configurable virtual reality system for multi-purpose industrial manufacturing application (IRMA).* [Online]. 2005. Available from: http://cordis.europa.eu/project/rcn/51633_en.html [Accessed: 21 December 2015].

the treatment of distal radius fractures, is based on the needs of hand surgeons, which were identified in a user requirements gathering study.

Virtual reality provides the surgeon the possibility to visualise and interact with the relevant anatomical structure of the patient, supporting a better three dimensional understanding of anatomy. This interactivity consists in the ability to view the required elements of the data and utilise virtual surgical instruments, controlled by a haptic device, to perform the necessary surgical task. The dynamic model and the generic system design can also enable surgeons to investigate a number of alternative surgical interventions and to assess the implications of these.

Overall aim:

- To use a human factors-led approach to create an immersive, haptic environment to simulate surgical procedures or techniques and understand the effectiveness of this tool with the aim to provide an effective addition to the current training and education concept of orthopaedic hand surgeons.

This research project is related to both the human factors and the computer science research areas. Including user experience in the development process by following a human-centred design approach has the advantage of for example increased ease of use and user satisfaction, as well as lower error rates or decreased need for redesign and subsequent development cost (Bias and Mayhew, 2005, pp.17). In addition, involving medical experts in the design and the decision-making process enables the development of the surgical simulator according to their needs and allows the refinement of the simulator functionality in early stages and thus saving development time.

The use of on the job training for surgical interventions is no longer a feasible method for a variety of reasons, including the increased patient safety requirements, increased use of new technologies, new complex surgical procedures and the aim to reduce costs. This requires a paradigm shift from "see one, do one, teach one" to "simulate many, do one, teach one" and the use of virtual reality and high-fidelity simulators (Vozenilek, Huff, Reznek and Gordon, 2004). However, current simulators do not adequately compare to the real operating procedures or real patient, or there are simply none as in the area of hand surgery; therefore, they are restricted in what they can train.

Objectives:

- To gather user requirements to create a specification for a surgical simulator in hand surgery based on the current needs of hand surgeons.
- To develop a virtual environment to simulate surgical procedures, techniques or tasks.
- To evaluate the benefit of using this prototype in addition to the current training and education concept in hand surgery.

The particular surgical procedure for which the simulator is developed is defined based on the analysis of the interviews and internet surveys. The chosen scenario further defines the visual requirements on the anatomical structures and the use of haptic technology.

1.4 Organisation of Thesis

To achieve the aim of this PhD research project, a literature review was conducted to get an overview of the current state of the field of study, including analysing the outcome of projects that led to this research project and the commercially available state-of-the-art surgical systems and haptic devices. Then, a user requirements study was carried out to form the specification on the surgical simulator. These requirements and the identified use cases were then analysed for feasibility and the surgical simulator was developed based on this specification using a human-centred design approach. This simulator was then technically validated and a medical evaluation was carried out to find out whether it would be medical relevant and appeal to the targeted medical students and young doctors.

The work carried out in the scope of this thesis can be divided into three phases, see figure 1-1. To build a surgical simulator that fulfils the surgeons' needs, preliminary work had to be done, which is detailed in the chapters of the preparation phase. The main aim of this project, the design and development of the surgical simulator (development phase) and to understand its effectiveness and its potential integration into the medical curriculum (evaluation phase), was supported by a human factors-led approach through understanding the tasks, equipment and interaction between the simulator and its users. The increased understanding is indicated by the arrows as the research progressed.

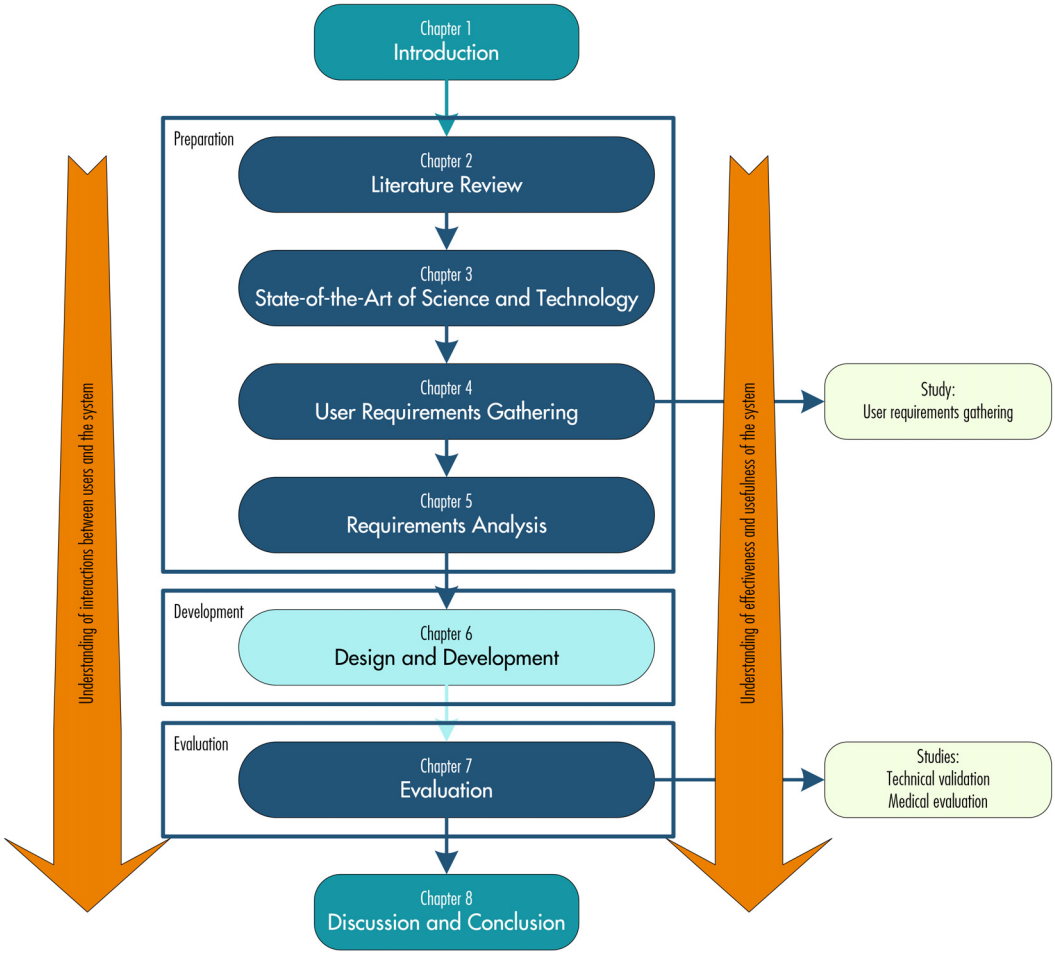


Figure 1-1: Structure of the thesis with human factors-led approach and carried out studies at the relevant stages.

Chapter 2 reviews the medical and technical literature relevant to the work in this thesis. The medical literature covers surgical simulation and virtual surgery, current training possibilities for orthopaedic surgeons and training effectiveness of virtual reality-based surgical simulators. Technical aspects are discussed that are needed to develop a surgical simulator, with focus on software frameworks to render haptic feedback.

Chapter 3 presents preliminary work that was completed by the author or where he performed a significant role within and led to this PhD research project, as well as the state-of-the-art of currently commercially available surgical systems and haptic devices.

Chapter 4 describes the process undertaken to gather user requirements and the methodological approach used, and the results of the interviews and the internet survey with hand surgeons are presented.

Chapter 5 gives an overview of the chosen medical scenario and the developed user requirements specification. The technical feasibility of the different steps of the medical scenario are discussed, with a final decision for the further development of the surgical simulator.

Chapter 6 describes the software framework evaluation process, the developed demonstrators and the development of the resulting surgical simulator. It contains technical information and therefore includes an additional brief glossary containing terms and concepts used for the design and development.

Chapter 7 describes the medical evaluation which examined usability, user experience and medical relevance of the developed surgical simulator with three user groups: medical experts, young doctors and medical students.

Chapter 8 presents the discussion and conclusion of the complete research project and highlights the contributions to knowledge and its implications.

A glossary at the beginning of this thesis presents terms and their definitions used in this PhD.

Appendix A contains the description of the intended behaviour of the surgical simulator in the form of use cases and user requirements.

Appendix B contains the technical description of implementation aspects relevant to the development of a similar surgical simulator.

Appendix C contains the data which was collected during the medical evaluation study for the medical students hands-on with the surgical simulator.

Appendix D contains the interview and internet survey questions from the studies carried out during this research project.

1.4.1 Contributions and Studies Program

The following are the technical contributions and the studies that were carried out:

- *Technical development:* To enable medical students and young doctors training relevant medical aspects in orthopaedic surgery by using six-degrees-of-freedom haptic feedback in a real-time virtual environment.
- *Performance assessment:* To enable medical experts assessing and comparing the users' performance based on recorded metrics data.

- *User requirements gathering:* To understand the need of the surgeons and build a requirements specification on which the development is based on. Thirteen hand surgeons from Switzerland, United Kingdom and Germany participated (chapter 4).
- *Technical validation:* To ensure the surgical simulator is ready for the medical evaluation by using dynamic testing. One software engineer from Switzerland participated (chapter 7).
- *Medical evaluation:* To find out whether the surgical simulator is medically relevant and appeals to the targeted user group, focusing on both the usability of the simulator and on the users' experience. Forty-five participants, in particular medical experts (10), young doctors (21) and medical students (14) from Germany and Switzerland, attended (chapter 7).

During this research project, one hand surgeon from Switzerland participated from beginning on and provided feedback at all relevant stages of the work. An additional hand surgeon joined during the iteration of the development of the prototype and provided feedback in all following stages, beginning from version 2 of the prototype (see section 6.8.4, *Version 2: Refinements of the Interaction Paradigms*).

Chapter 2

Literature Review

2.1 Chapter Summary

This chapter contains a review of past and current literature relevant to this thesis. First, surgical simulation in general focused on computer-based simulators, its effectiveness and the transfer of skills to the operating theatre are reviewed. Then, a high-level overview of technical aspects for developing a computer-based surgical simulator such as haptic feedback, previously used software frameworks and requirements and components of such simulators in general are presented. The chapter concludes with the identification of research questions and areas which are to be examined.

2.2 Introduction

Virtual reality (VR) is a term relatively unknown until 1968, when the first head-mounted display system was created by Sutherland (1968), and gained popularity in the following virtual reality research boom in the 1990s. It is defined by the Oxford Dictionaries as:

> "The computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors."

The aviation industry, military and commercial airlines adopted the use of VR technology in their flight simulators for the training of pilots over two decades ago (Allerton, 2009, p.7). In medicine, it has not yet made the same progress. Virtual reality-based surgical simulators are part of the emerging market of healthcare and medical simulation, which is expected to reach $2.07 billion by 2019. (MarketsandMarkets, 2015). However, only a few medical domains are already using them in training and education, mainly for endoscopic, laparoscopic and arthroscopic surgery (Balcombe, 2004,

pp.554). These simulators allow for example to train basic skills such as camera and instrument navigation, object manipulation, needle control/driving or suturing skills.

When speaking about simulation in healthcare, a distinction is drawn between surgical simulators and surgical simulation. A simulator is "*a device that presents a simulated patient (or part of a patient) and interacts appropriately with the actions taken by the simulation participant*", as opposed to a simulation, which aims "*to replace or amplify real experiences with guided experiences, often immersive in nature, that evoke or replicate substantial aspects of the real world in a fully interactive fashion*" (Gaba, 2004, p.i2). For example, a manikin/patient simulator can be used as a task trainer to teach surgical skills, however, incorporated into an elaborate medical scenario and an immersive hospital environment, this simulator can be part of a simulation.

It has now become more and more generally accepted that surgical simulators are not meant to replace the current training with supervised work on real patients or in the actual operating theatre. Instead, it should be considered as an addition, to reduce the time required to develop basic skills in a safe, controlled environment without the training directly on patients (for example Gaba, 2004, Burden, Oestergaard and Larsen, 2011). However, simple factors can prevent simulators being used, such as that they are kept under lock and key, are inadequately maintained or the trainees are not motivated to use them (Walker, 2009).

This literature review gives an overview of the current state of surgical simulation as well as technical aspects relevant for developing surgical simulators.

2.3 Review of Medical Literature

2.3.1 Surgical Simulation and Virtual Surgery

Surgical simulation is well known and has been used for centuries and dates back to the ancient Mesopotamia, when simple models created from sheep lungs and liver were used for instructing principles, which evolved to diagnostic tools for demonstration of clinical features. In the 1980s, the first human body simulators were developed which replicate accurately the functionality of the human body (Kunkler, 2006, pp.203), or more recently, non-cadaveric bone models made of artificial materials were developed. But in the age of virtual reality technology, interactive computer-based simulators are now more and more common. One of the earliest surgical simulators using virtual reality technology was presented by Delp, et al. (1990) to analyse and later also to practise tendon transfer operations by simulating the musculotendinous system of the lower extremities. In 1993, Satava (1993) proposed early adaption of virtual reality to train surgical skills as it has been successfully used in the aviation on flight simulation for the training of pilots (Allerton, 2009, p.9).

But until 1998, the use of virtual reality in the surgical field was limited until Marescaux, et al. (1998) published a study describing their work and application of virtual reality to hepatic surgery simulation. They discuss the use of virtual reality in surgical training, preoperative planning and robot-assisted surgery. Furthermore, they stated that virtual reality requires three concepts to represent an environment that gives the impression of actually being present: immersion, navigation and interaction. Immersion, either by immersing in the world, for example using three-dimensional images, or physical with the aid of stereoscopic glasses and datagloves; navigation, the ability to move around and interaction, the ability to interact in real time with objects.

Most of the earliest commercially available surgical simulators are for the training of minimally invasive surgery and endoscopic work since the movements are restricted in the degrees of freedom when operating with endoscopic instruments and the visual image that presents during endoscopy lends itself to simulation, which reduces the technical requirements on its development. Such a simulator is for example MIST VR for laparoscopic surgery (Wilson, et al., 1997). It is able to train fundamental surgical skills, including picking, placing and transferring, and has been used by Seymour, et al. (2002) to demonstrate the value of using surgical simulation and showed a reduction of operating time on gallbladder dissection.

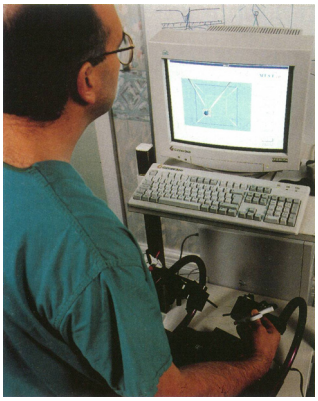


Figure 2-1: MIST VR, providing six levels of basic manoeuvres for laparoscopic cholecystectomy (Wilson, et al., 1997).

A 2007 review of virtual reality-based simulators for training in minimally invasive surgery lists 31 commercially available part-task simulators and includes procedural simulators, basic-skills simulators and hardware interfaces with and without haptic feedback (Basdogan, Sedef, Harders and Wesarg, 2007). They cover the following surgical procedures: general laparoendoscopic surgery, laparoscopy (cholecystectomy, colectomy, anastomosis, gastric bypass, ventral hernia), cardiovascular and endovascular interventions, arthroscopy, gynaecology and hysteroscopy, bronchoscopy, upper and lower GI, endourology, percutaneous access and endoscopic sinus surgery. These simulators

offer training possibilities for basic minimally invasive surgery skills such as palpation, grasping or stretching, as well as for incision, dissection or clamping.

Training on human corpses and animals has several advantages such as that human corpses have the correct anatomy and relations or that animal tissue is relatively cheap. However, the drawbacks of this approach are that there is a short supply of human corpses, ethical issues and the use of live animal tissue is not permitted in the UK and several European and North American countries. Furthermore, human tissue cannot reproduce bleeding and does not behave like live human tissue (Sarker and Patel, 2007).

Besides the simulation on human corpses or animals, surgical simulators can be divided depending on the technology they use into mechanical, hybrid and virtual reality simulators (Halvorsen, Elle and Fosse, 2005). Mechanical simulators can be used to train minimally invasive procedure techniques such as the manipulation on organs or other objects, which are placed in a training box, using surgical instruments (known as tower trainers or video box trainers, see figure 2-2, left), or to train open surgical procedures, such as dissection or suturing for example (known as bench or benchtop models, see figure 2-2, second illustration).

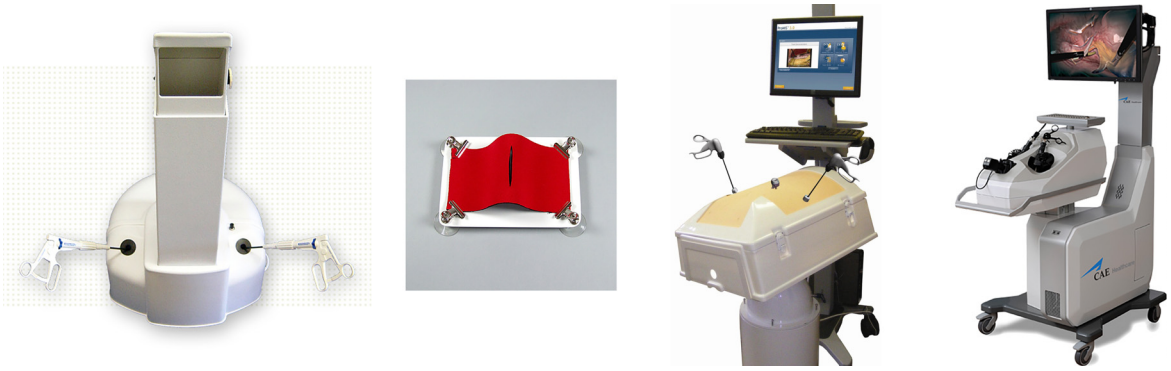


Figure 2-2: Surgical simulator categories: basic laparoscopic skills tower trainer[1] (left), suturing base benchtop model[2] (second), ProMIS hybrid simulator for basic skills and a range of surgical procedures training[3] (third), LapVR virtual reality simulator for basic skills, procedural skills and full procedures[4] (right).

Tower trainers use a camera inside the box to provide the visualisation of the laparoscopic instruments, which are typically inserted through two slits into the box, on a display. Their main advantage is the sensory feedback of the real surgical instruments on the tissue surface and the pressure of opening and closing these instruments (Hammoud, et al., 2008). Mechanical simulators require ob-

1. Photo courtesy of Simulab USA.
2. Photo courtesy of Limbs & Things.
3. Photo courtesy of CAE Healthcare.
4. Photo courtesy of CAE Healthcare.

servation by an experienced trainee for feedback as there is no computer-based guidance or evaluation.

Hybrid simulators use a box, similar to tower trainers, but are extended with a computer-based guidance on how to perform the task and evaluation based on programmed parameters (see figure 2-2, third illustration). This has the advantage that they reproduce the feeling of tissue and the instruments, and can benefit from a computer-based simulation (Halvorsen, Elle and Fosse, 2005, pp.214-215).

Virtual reality simulators are computer-based environments which use conventional 2D or stereoscopic displays, and more and more, haptic devices to provide force feedback (see figure 2-2, right). Their main advantages are the safe environment, the possibility to repeat tasks and objective measurements and feedback (Halvorsen, Elle and Fosse, 2005). Simulators that can teach an entire surgical procedure are often called procedural simulators (Basdogan, Sedef, Harders and Wesarg, 2007). They not only train basic surgical skills, but also enhance the understanding of anatomy and the sequence of the surgical procedure (Kunkler, 2006).

According to the American College of Surgeons (2011), commercially available virtual reality-based surgical simulators or simulators that have undergone testing in the literature are available for the training of the following surgical procedures (non-exhaustive enumeration): laparoscopic surgical simulators (basic laparoscopic skills or complex procedures), endoscopic simulators (bronchoscopy, colonoscopy and sigmoidoscopy, upper GI endoscopy, endourological procedures, hysteroscopy, sinusoscopy), anastomosis simulators (bowel or vascular), orthopaedic and arthroscopic simulators, ophthalmologic simulators and intravenous catheter insertion simulators.

Another commonly used differentiation between surgical simulators is low and high fidelity (Hammoud, et al., 2008). Low-fidelity surgical simulators are for example benchtop models that teach a particular surgical technique, but are made of simple materials and do not correspond with the actual anatomy or reality. High-fidelity surgical simulators are for example human corpses or highly realistic visual and haptic virtual reality-based simulations. Hammoud, et al. (2008, p.339) published a comparison of the low and high-fidelity surgical simulators described in this section with the respective advantages and disadvantages of each group. They list the limited feedback in general as a disadvantage of all simulator types (besides animal models), that low-fidelity simulators are moderately inexpensive or that high-fidelity simulators are aimed at practising at the trainees own pace, can be more attractive but may not be optimal to teach more than basic skills.

MarketsandMarkets (2013, 2015) report that the global healthcare/medical simulation market was estimated to be worth $863.5 million in 2014 and is expected to grow at a CAGR (compound annual growth rate) of 19.1% to reach $2.07 billion by 2019. As seen in figure 2-3, patient simulators and simulation training services, with being the largest market segment, are expected to grow at the highest CAGRs. This healthcare/medical simulation market has grown significantly in the past decade (despite the impact of the global recession in 2008-09) with key factors being technological advancements, increasing health costs and rising demand for minimally invasive treatment. They also state that the high cost of simulators, economic slowdown in the developed region and limited availability of funds prevent the growth of the market.

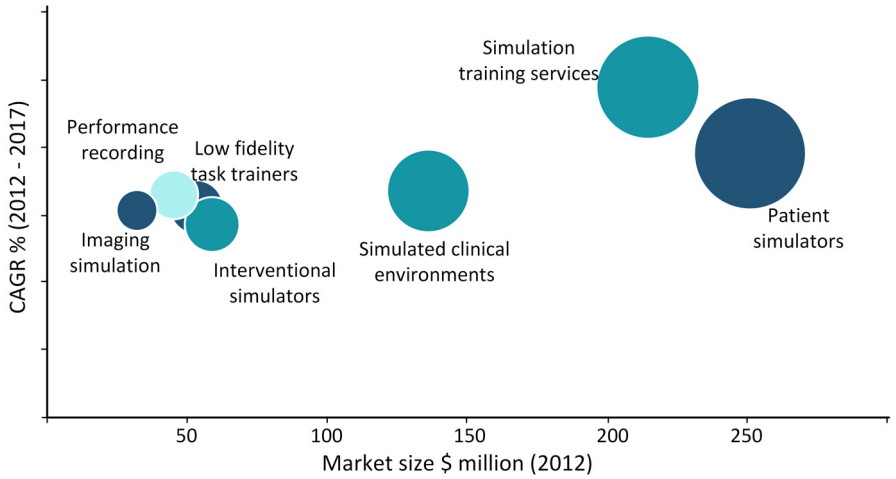


Figure 2-3: Relative healthcare/medical simulation market growth per segment (MarketsandMarkets, 2013).

The largest market for healthcare/medical simulation in 2013 is North America, followed by Europe and Asia-Pacific, as North American and European companies expanded through acquisition and therefore improved accessibility of such products and services. However, Asia-Pacific and Latin American regions are expected to grow at a higher CAGR compared to North America and Europe due to the continuous efforts towards the development of the healthcare sector, the economic slowdown in North America and Europe and the eurozone debt crisis, but not to a great extent (MarketsandMarkets, 2013, 2015).

The market for augmented reality and virtual reality systems is expected to grow at a CAGR of 15.18% from 2013 to 2018 to reach $1.06 billion in 2018, excluding mobile based AR and non-immersive VR (MarketsandMarkets, 2014). The immersive virtual reality market is expected to reach $407.51 million by 2018, with the major driving forces behind AR and VR technology being advancements in computer technology and internet connectivity, followed by consumer demand in

the m-commerce industry. The largest market is North America and Europe, followed by the Asia-Pacific economic area.

2.3.2 Training and Surgical Simulators in Hand and Wrist Surgery

Commonly used in the training of hand surgery, and also for orthopaedic surgery, are benchtop models. These synthetic plastic bones are used for the training of different surgical techniques, such as reduction and fixation using implants and surgical instruments. The trainees normally stand in the same position as they would typically during a real operation, but they can access the bones as it is most suitable for them, often ignoring anatomical structures which would prevent performing particular tasks from an arbitrary position, see figure 2-4. The drawback of these synthetic bones is that there is no blood, and soft tissue is simulated with a foam coating surrounding the plastic bone; however they enable the trainees to use real surgical instruments and implants and concentrate on a particular, isolated step of an entire procedure.



Figure 2-4: Using artificial bone models in a basic principles of fracture management course from the AO Foundation.

Another commonly used type of training is using human anatomical specimens of hands. They are used to teach core skills in hand surgery, for example by the Royal College of Surgeons of England. Training on human corpses provides the opportunity to understand the anatomy and technical as-

pects of surgical procedures, combined with working without the pressure of time but having a feedback of experienced surgeons (Holland, et al., 2011).

However, virtual reality-based surgical simulators are not used for the training of hand and wrist surgery. Although there are several surgical simulators available for different medical fields, no commercially available virtual reality-based surgical simulators for open surgery of the hand or wrist exist that the author is aware of. There is a virtual reality-based surgical simulator for shoulder (and knee) arthroscopy commercially available (InsightArthroVR; Bayonat, Garcia, Mendoza and Fernandez, 2006; now sold by Simbionix as Arthro Mentor), which has also been evaluated for example by Gomoll, Pappas, Forsythe and Warner (2008), who showed improvements in the performance on simulator retesting. According to the manufacturer, Arthro Mentor uses two haptic devices (Geomagic Touch, see section 3.4.2.2) with custom camera and grasper end effectors (and the standard stylus to simulate virtual tools) for training of arthroscopic basic skills and surgical procedure cases. A software system allows proficiency-based hands-on trainings, assessment and performance reports. Another shoulder arthroscopy simulator was the Procedicus MIST shoulder arthroscopy simulator from Mentice, Sweden, but due to recent changes on the software platform, the shoulder module is not available anymore.

In the field of simulating endoscopic carpal tunnel release (ECTR), a project was carried out at the Department of Biomedical Engineering at the University of Wisconsin-Madison that dealt with the design and construction of a low-cost hybrid simulator for ECTR (Johnson, Switalski and Jellings, 2011). They used a plastic hand model, including the carpal tunnel and transverse carpal ligament, an endoscope with an attached blade cap for haptic feedback and a LED circuit which is tracked by an IR receiver (see figure 2-5).



Figure 2-5: Endoscopic carpal tunnel release prototype; hand model, endoscope with attached blade and LED circuit, IR receiver (Johnson, Switalski and Jellings, 2011).

Kempton, Israel, Mandel and Salyapongse (2015) used this simulator for beta testing on 22 participants (12 simulation-trained, 10 non-simulation) and found that the simulation-trained group performed significantly better on operative steps. In addition, the simulation-trained participants without prior ECTR experience performed also better than non-simulation-trained participants who have performed at least one case. They concluded that early implementation of such a simulator can improve knowledge and operative performance in inexperienced ECTR subjects.

But research was carried out in several hand and wrist-related medical projects. In 2001, an orthopaedic virtual reality surgical simulator was developed without haptic feedback to simulate rigid anatomical structures (Tsai, Hsieh and Jou, 2001) for different surgical procedures such as arthroplasty, osteotomy or open reduction. It uses volume data and a very basic visualisation; the participants particularly liked the stereographic image and that the models could be examined from an arbitrary perspective, in contrast to the paper approach, which it was compared with. But they complained that the response time of the system was insufficient and that they had expected haptic feedback.

Using a much more realistic visualisation, a research project currently still under development aims at creating a virtual hand model that can be dissected (Needham, Wilkinson and Soames, 2011). They use CT scans of bones, data from The Visible Human Project[1] for the muscles and skin and self-provided data for other anatomical structures to create a model which can imitate realistic cutting, possibly using a dual haptic interface.

With surgical simulators using more and more haptic feedback in research, a study assessed in 2013 whether a surgical simulator with haptic feedback for the fixation of an ulna bone has comparable levels of fidelity as training with artificial plastic bones (LeBlanc, Hutchison, Hu and Donnon, 2013). A questionnaire was used to assess the environmental, equipment and psychological fidelity, and it was reported that most of the participants favoured the plastic bones over the surgical simulator. They concluded that the simulator was of lower fidelity (only the ulna bone and the required surgical instruments were visualised), as the user experience, interaction and the realism of the visualisation were not convincing, which all affected the psychological fidelity. In addition, they remarked that the participants missed the ability to use both hands and sound effects. They also reported that the development time and the experience of the developers was insufficient, which had an impact on achieving a more realistic simulator. Additionally, the participants practised on

1. U.S. National Library of Medicine (2003) *The National Library of Medicine's Visible Human Project.* [Online]. 2003. Available from: https://www.nlm.nih.gov/research/visible/visible_human.html [Accessed: 22 November 2011].

the simulator for only 10 minutes, which can be too short to get a more favourable rating as simulators typically have a learning curve.

In the field of open surgery, a virtual reality-surgical simulator suite (SurgSim Trainers) for open incision simulation is being developed by SimQuest (SimQuest, 2011). They use haptic devices with custom end effectors to recreate an operating theatre environment, including the correct standing position (see figure 2-6). However, information is limited about the current state of the product and no use cases are available.

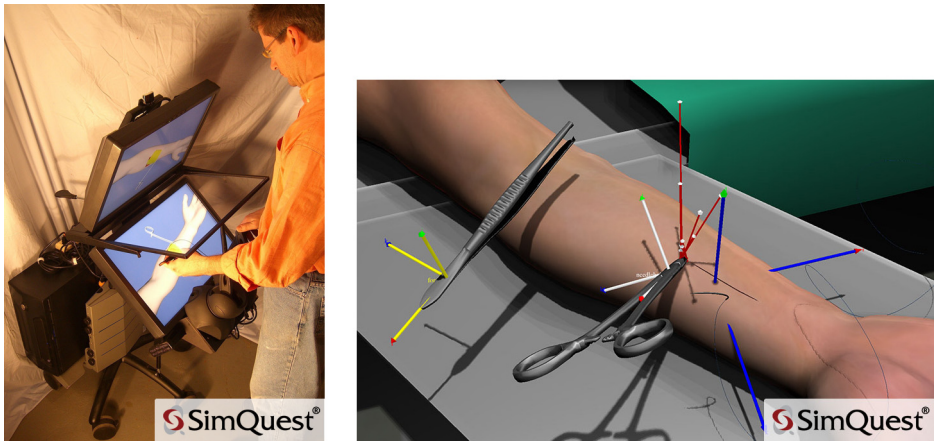


Figure 2-6: Virtual reality-based open-incision simulator SurgSim Trainers from SimQuest.[1]

Based on the work by SimQuest, a new medical simulation software development platform has been created in 2013. This OpenSurgSim project (SimQuest Solutions, 2014) aims to build an open-source surgical simulator with haptic capability, including features such as:

- High-fidelity tissue interactions
- Lifelike haptic feedback
- Actual surgical tool usage and manipulation
- Minimally invasive and open surgical capabilities
- FEM and mass-spring systems

According to the development roadmap as of January 2014, the basic framework has been developed with limited support for physics and haptics, but no interaction (grasping, clamping, stapling) is yet available. A short code review showed that for example the haptic implementation

1. Photo courtesy of SimQuest.

follows a naïve approach based on virtual coupling, but no prediction on the new object state is included.

Based on the review of literature, building a simulator for open surgery of the hand and wrist requires current software frameworks to be advanced in terms of technical developments to improve interactiveness, quality of the graphics rendering (in real time), haptic algorithms and modelling of anatomical structures (such as material properties and biomechanical data), see also section 2.6, *Requirements and Components of Surgical Simulators*. These research directions are not limited to hand and wrist surgery, but also apply to open surgery and to surgical simulations in the field of orthopaedics and traumatology in general.

2.3.3 Training Effectiveness of Virtual Reality Surgical Simulators

Using simulators to train surgical skills is appealing, because surgeons can learn in a safe environment which does not involve the use of patients. However, the question remains, is the use of (virtual reality-based) surgical simulators an effective form of training skills and is there a measurable transfer of skills to the operating theatre?

One of the first studies which analysed if virtual reality-based training of technical skills can be transferred to the operating theatre was carried out by Seymour, et al. (2002). They analysed 16 surgical residents performing laparoscopic cholecystectomy using videotapes (eight virtual reality-trained, eight non-virtual reality-trained; randomised and double blinded). They could demonstrate that the virtual reality-trained group was 29% faster and that the other group was nine times more likely to transiently fail to make progress and five times more likely to injure the gallbladder or unintentionally burn tissue. Another study by Grantcharov, et al. (2004), carried out in a similar way with 16 participants performing laparoscopic cholecystectomy (eight virtual reality-trained, eight without training), revealed consistent results with the study of Seymour, et al., and according to Grantcharov, et al., the virtual reality-trained surgeons performed significantly faster and showed greater improvements in error and economy of movement scores.

A 2006 study investigated the attitude of orthopaedic surgeons and advanced trainees towards virtual reality surgical simulators in orthopaedics. Blyth, Anderson and Stott (2006) used a postal survey to analyse the responses for two groups, those who qualified before 1990 and those after 1989 or which are still in training. Two findings were highlighted: that the most important task was angulation/spatial orientation and that a realistic visualisation of the surgical site was the most important requirement on virtual reality surgical simulators. Interestingly, earlier qualifying surgeons saw

a greater benefit of using virtual reality simulators than those who qualified recently. However, of the 142 participants, only four had practical experience with a surgical simulator.

Two studies have reviewed 30 and 16 studies in 2006 for the training effectiveness of virtual reality simulators. Sutherland, et al. (2006) reviewed 30 studies until April 2005 of randomised controlled trials to compare the effectiveness of surgical simulations to other surgical training methods, for example video simulation, anatomical specimens, physical models or no training at all. First, they noted that in many cases the randomised controlled studies were of poor quality. They reported amongst other things that computer simulation was generally better than no training, but was not convincingly superior than standard training (such as surgical drills) or video simulation (in particular when assessed by operative performance). In a comment on this study, Dutta, Gaba and Krummel (2006) published an editorial to put the findings into perspective and wrote about asking the correct research question when determining the effectiveness of surgical simulators. They state that "*the question is not whether simulators are better than other training tools, but rather if simulation as part of a competency-based curriculum is an effective pedagogical strategy compared with the existing approach*". Furthermore, they state that it is not the intention to replace standard surgical training with surgical simulators, as Sutherland, et al. asked, but rather as complementary tools in the training of surgeons.

In the second study, Haque and Srinivasan (2006) report a meta-analysis of the effectiveness of virtual reality surgical simulators and analysed 16 studies between 1996 and 2004. Their aim was to analyse if there is a measurable transfer of surgical skills into the operating theatre and if it is possible to discriminate between the experienced and less experienced surgeons. They concluded that there is evidence that using virtual reality-based surgical simulators decreases the time surgeons use for the surgical procedure and that it also decreases the errors during the performance. Furthermore, it was possible to clearly differentiate between the surgical experience, as the more experienced performed better than the less experienced. This implies that the skill measurement criteria such as task completion time or error scores and the surgical realism were appropriate and sufficient, as otherwise the performance would not be clearly differentiable.

The outcome of a third meta-analysis reviewing 23 trials about laparoscopy until March 2008 (Gurusamy, Aggarwal, Palanivelu and Davidson, 2008) also reported a decrease in time to complete a surgical task, increased accuracy and a decrease in errors compared to no training, and virtual reality training was more accurate than video simulation training. The conclusion was that virtual reality-based training "*is at least as effective as video training in supplementing standard laparoscopic training*".

In a comment to the meta-analysis of Gurusamy, Aggarwal, Palanivelu and Davidson (2008), Walker (2009), after visiting several clinical labs using laparoscopic surgical simulators, pointed out that despite of the benefit, simple factors prevented the use of these simulators, such as that the access to the simulators was limited or they were kept under lock and key, or that they were inadequately maintained. In other cases, the trainees were not motivated to use the simulator for more than once or twice.

In recent years, several studies demonstrated skills transfer after virtual reality simulation training. For example, Araujo, et al. (2014) found that a two-hour pre-procedural VR training in a sigmoidectomy procedure module on LAP Mentor positively impacted the performance of surgeons conducting a laparoscopic colectomy in a swine model. Although the study did not show transfer into a real clinical setting, it was the first showing impact for minimally invasive colorectal surgery. Previous studies analysing pre-procedural training verified skills in simulator tasks.

Lehmann, et al. (2012) analysed the suitability and acceptance of virtual surgery simulators in an existing surgical training course. One third of the course participants were trained for five days on two standardised training tasks on LapSim and using questionnaires, the laparoscopic experience, training situation and acceptance of the training was assessed. They found that the learning curve measured on the simulator followed the typical progress in laparoscopy. This simulator was also suitable for course assessment, as the different experience levels could be clearly distinguished. Acceptance amongst the participants was high, however, current high cost of such simulators prevent the practical use in large courses.

Dawe, et al. (2014) conducted a systematic review of 17 trials and three comparative studies to determine skills transfer to the operating theatre for laparoscopic cholecystectomy (removal of gall bladder) and endoscopy, where in most cases simulation-based training was in addition to patient-based training, whereas two studies directly compared those trainings in isolation. Participants, which reached a certain level of proficiency on the simulator performed better in the operating theatre with higher assessment scores and fewer errors, compared to patient-based training. Although the studies varied such as in the simulators used, the research design or the population, they concluded that it seems that simulation-based training, as part of a program, results in skills for the investigated procedures that are transferable to the operating theatre. They also deduce that "*simulation-based training provides a safe, effective, and ethical way for trainees to acquire surgical skills before entering the operating room*".

Similarly, Aim, Lonjon, Hannouche and Nizard (2015) conducted a systematic review of 10 relevant trials on training in arthroscopic surgery to determine the effectiveness of virtual reality-based simulators in orthopaedic surgery. Most of the outcomes were about skills assessment and three studies reported significant improvement in technical skills. However, no statements could be made about the transfer of virtual reality training to the operating theatre.

In contrast to a positive transfer of skills which occurs when learned skills in one context improve performance in a different context, a negative transfer of skills occurs when learned skills have a negative impact on the performance in a different context. According to Perkins and Salomon (1992), such a negative transfer is real can often be a problematic effect in learning, but it is much less a problem as it mainly presents only a problem in the early stages of learning and with experience, this effect of negative transfer is corrected by learners.

To conclude, more and more studies are demonstrating transfer of skills acquired from simulation-based and virtual reality-based training to an actual surgery, and that the simulation-trained group performs significantly better than control groups in different areas, but not generally, and depending on the measured metrics. Therefore, further studies are needed to verify these findings and strengthen the evidence base, and also to establish metrics for the skills measured during the virtual reality-based simulation training. In addition, these studies largely focused on assessing technical skills, but decision-making skills are required as well in the operating theatre. Typical metrics that are assessed in these studies include performance time, damage of anatomical structures, intraoperative errors and accuracy.

2.3.4 Serious Games

Another field of medical education are serious games, digital games aimed to train medical professionals. Zyda (2005), who participated in the development of America's Army (one of the first successful serious game), proposed the following definition of serious games:

> "Serious game: a mental contest, played with a computer in accordance with specific rules, that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives."

Serious games provide a challenging simulated environment to learn knowledge or skills, motivation to play is achieved by a chance to win the game and often by a high score system. They combine the excitement of playing digital games while ensuring that the purposed knowledge is still taught. A recent systematic review (Graafland, Schraagen and Schijven, 2012) analysed 17 of 30 serious games for training medical professionals (the remaining were not specifically developed for educa-

tional purposes) and showed, that none of these games have completed a full validation process yet. Most of these games are aimed for training critical care or triage, some also provide multiplayer functionality for team training. One game is aimed to train the particular decision steps for a total knee arthroplasty (Sabri, et al., 2010) with a scoring system for measuring trainee's performance and based on the choices made.

Although there is a lack of empirical studies investigating training effectiveness of serious games, Girard, Ecalle and Magnan (2013) indicate in a meta-analysis that they might be powerful tools for learning and that they could provide techniques to keep trainees engaged and motivated when traditional methods fail.

2.4 State-of-the-Art of Virtual Reality Techniques

This section gives an overview about the current research of techniques used for software-based surgical simulators and focuses on the basic principles of haptic and soft tissue rendering, as well as available software frameworks to render haptic effects.

2.4.1 Haptics

Surgical simulators highly depend on haptics, since surgeons not only utilise the visual sense for a surgical procedure, but also the haptic sense, for example, to check the pulse, to find the pulsating arteries during open surgery, to diagnose pathologies or to manipulate tissue. Therefore, the use of haptic technology is not only suitable for medical training (of procedures and anatomy), but also for clinical practice applications (Fager and von Wowern, 2004).

Haptic rendering, which is the process of making virtual objects tactile manipulatable, is described by Basdogan and Srinivasan (2002, p.117) as:

> "Just as computer graphics is concerned with synthesizing and rendering visual images, computer haptics is the art and science of developing software algorithms that synthesize computer generated forces to be displayed to the user for perception and manipulation of virtual objects through touch."

Before the 1990s, haptic feedback was already used for example in master-slave robotic teleoperation, which used a mechanical linkage between the master and the slave (an operator manipulates a master arm and the slave arm performs the task exactly as instructed and feeds back force and position information). One of the first projects which computed forces based on the interaction of objects with geometries was the Sandpaper project (Minsky, et al., 1990), which used a 2D force-feedback joystick to haptically render 2D textures. In the early 1990s, the first algorithms (for example Zilles and Salisbury, 1995) and the PHANToM haptic device (Massie and Salisbury, 1994) were developed, which can be seen as the start of three-DoF haptics with polygonal models, how-

ever limited to point-to-object interaction. Starting in the late 1990s until today, research focuses on six-DoF haptics, which allows to grasp a virtual object and simulate object-to-object interaction.

Using visual-only surgical simulators – without haptics – factors out the influence of the haptic sense on the performance. However, compared with investigating training effectiveness and transfer of skills, little research has been conducted on the benefits of haptics. In a meta-analysis of literature regarding the current status and value of haptics in virtual reality-based surgical simulators, van der Meijden and Schijven (2009) concluded that "*no firm consensus exists in the importance of haptic feedback in performing minimally invasive surgery*". As to virtual reality-based simulators, they note that there is an indication that "*haptic feedback is important during the early phase of psychomotor skill acquisition*". They state that some results suggest that adding haptic feedback may improve the performance of trainees' in early training phases, as the trainee's sensoric perception capabilities can be enhanced and thus facilitating transfer of skills to the operating theatre. But they also emphasise that a negative learning effect may occur when tasks involving haptic feedback play a major role on the surgical task outcome with unrealistic haptics.

Regarding three dimensional understanding, Jones, et al. (2002, 2005) showed in two studies that if haptic feedback is available, the students' attitudes towards investigating objects were more positive when they could manipulate the object and receive tactile feedback. In addition, Jones, et al. (2005) concluded that using haptic devices tends to support the development of three dimensional understanding of objects.

Haptic feedback has been well researched for minimally invasive surgery, for example by Basdogan, et al. (2004). They explored areas such as haptic devices, haptic rendering, measurement of organ properties with haptic devices and using force feedback for guidance. They concluded for example that it may be necessary to have different haptic devices for different medical procedures due to the different requirements in forces and motions, that visual cues can significantly affect the haptic perception of the softness of a material, that the development of a meaningful force model for the interactions between the sharp edge of a tool and the soft tissue is an active research issue or that the number of computations required for real-time visual and haptic rendering of organ-force models is a bottleneck.

In contrast to the research being undertaken in minimally invasive surgery, surgical simulators for open surgery are still rare due to the complexity to simulate direct haptic contact with anatomical structures and the numerous interaction possibilities. Using two haptic devices which have surgical instruments attached and a mirror set-up that places the visualisation from the display in front of

the surgeon, Playter and Raibert (1997) built a surgical simulator providing a realistic sense of touch to practice end-to-end anastomosis procedures. It has been used by O'Toole, et al. (1999) to compare the performance of a suturing task between experienced surgeons and medical students and concluded that the data indicated differences in performance between these two groups and in improvement in performance with training (measured with eight parameters: tissue damage, surface damage, accuracy error, excess time, angle error and peak force, overall error score (average of previous six parameters) and excess tool motion).

In contrast to surgical simulators using haptic devices with attached surgical instruments or custom built effectors, Hu, et al. (2006) designed a magnetic haptic feedback system which tracks the surgical instrument using a camera, magnetic and optical sensors and uses multiple electromagnets in a movable magnetic actuator to apply force to the magnetised surgical instruments. This system is in particular suitable for open surgery, since the surgical instruments are not restricted to the range of motion of the haptic devices, on which they were mounted.

There are mainly three types of haptic devices: mechanical arm devices, cable-driven and magnetic levitation devices (see figure 2-7). Mechanical arm devices are the most common and built based on a linkage system. An end effector, such as a stylus for example, is attached at the end of the arm and force feedback is provided by motors that apply torque at each joint of the arm.



Figure 2-7: Haptic devices: magnetic levitation device[1] (left), mechanical arm device[2] (middle), cable-driven device in a CAVE.

Cable-driven (or tension-driven) devices use cables to apply the force feedback to a contact point (actuator) and are often used in a CAVE (cave automatic virtual environment: an immersive virtual reality environment with three or more walls of a room-sized cube on which the virtual world is projected to), where cables with very small diameter do not occlude the visualisation on the screens (see Sato, 2002). Magnetic levitation devices use a handle that is levitated by a strong magnetic field and

1. Photo courtesy of Butterfly Haptics.
2. Photo courtesy of Geomagic.

is tracked by optical sensors. For an overview of currently commercially available haptic devices, see section 3.4, *Current Surgical Systems and Haptic Devices*.

A further distinction is made between two types of controlling haptic devices: impedance-controlled devices and admittance-controlled devices. Impedance-controlled devices sense a position and produce a force, whereas admittance-controlled devices sense a force and produce a position. The advantage of impedance-controlled haptic devices is that they do not need force sensors, are cheaper to build and can be back drivable, but are limited in the range of force and joint stiffness they can produce compared to admittance-controlled devices. The commonly used haptic devices (such as from Geomagic and Force Dimension) are impedance-controlled devices.

Haptic devices can be further divided based on the number of degrees of freedom (DoF) they support. A three-DoF device allows movement in all three directions, whereas six-DoF devices combine translation with rotation. Higher degrees of freedom may include for example grasping. Furthermore, a distinction is drawn between sensing (passive) and force feedback (active). For example, the Geomagic Touch device provides six-DoFs positional sensing but only three-DoFs force feedback.

The high haptic rendering update rate of 1 kHz or more, which is widely accepted and typically used (Lin and Otaduy, 2008), is required to maintain the effect of smooth and realistic forces and torques and system stability, but results in high computational cost. Too low update rates can lead to undesired effects, for example when rendering haptic textures, resulting in so-called perceived instabilities, described by Choi and Tan (2004):

- *Buzzing:* High-frequency vibrations that can occur when touching virtual surfaces (Seungmoon and Tan, 2004).
- *Aliveness:* Discontinuities of the collision detection calculations result in large force variations on small movements of the end effector; feels like a low frequency artefact (Seungmoon and Tan, 2003).
- *Ridge instability:* Refers to an effect of being gravitated towards the valleys of a haptic texture (simulating surface properties of virtual objects to feel micro surface details) when the end effector is placed on the ridges of the texture.

A general haptic rendering algorithm for impedance haptic devices uses three components, as shown in figure 2-8. The tool solver computes the configuration of the tool, whereas the collision detection module detects potentially violated environment constraints for a given tool configura-

tion. The device controller reads the device configuration and renders the force and torque computed by the haptic rendering algorithm.

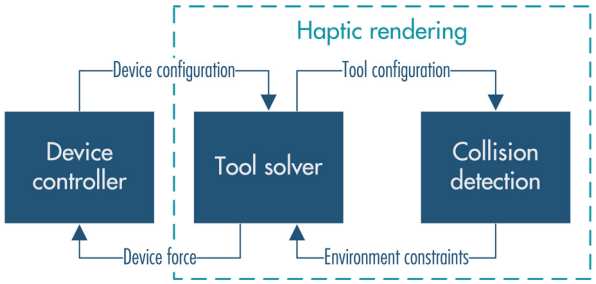


Figure 2-8: Main components of a general impedance-type haptic rendering algorithm (Lin and Otaduy, 2008, p.163).

A distinction between three-DoF and six-DoF haptic rendering can be drawn. Three-DoF haptic rendering involves point-to-object collision detection, which can be efficiently computed, for example by the god-object method described by Zilles and Salisbury (1995). However, six-DoF haptic rendering involves object-to-object interaction, which leads to high computational requirements. Most methods for the implementation of such a haptic rendering pipeline can be categorised into two groups:

- *Direct rendering methods:* The position and orientation of the virtual tool is defined directly by the haptic device configuration. Collision detection is computed between the virtual tool and the other objects and collision response is computed based on a function of object separation or penetration depth. The resulting force and torque is applied directly to the haptic device, generating the haptic feedback to the user, see figure 2-9. This method is relatively easy to implement since no state of the previous configuration is retained, but several limitations arise such as force discontinuities, pop-through or instabilities during low collision detection rate (see Gregory, et al., 2000; Johnson and Willemsen, 2003).

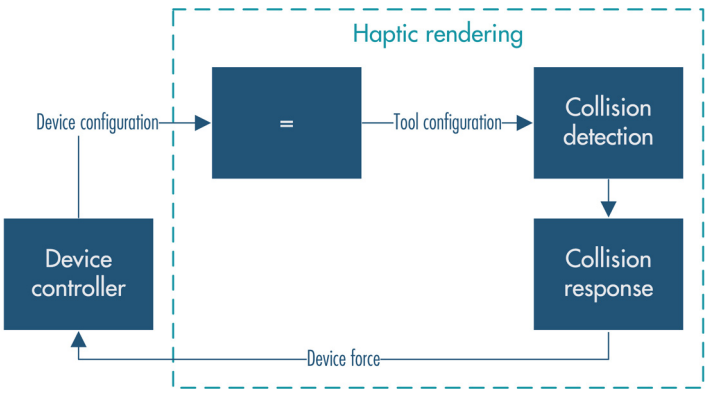


Figure 2-9: Main components of a direct rendering algorithm (Lin and Otaduy, 2008, p.166).

- *Simulation-based (or virtual coupling) methods:* The haptic device configuration produces force and torque that controls the virtual tool, named as the ideal haptic interface point (IHIP). The position and orientation of this IHIP are virtually coupled with the position and orientation of the haptic device, for example implemented as a virtual spring-damper (Mark, et al., 1996). Collision detection is performed between the IHIP and the other objects. The haptic feedback is generated based on the coupling force and torque combined with the collision response, see figure 2-10. This method is more complex to compute, but avoids for example the effect of pop-through. It is used in most recent six-DoF methods, for example by McNeely, Puterbaugh and Troy, 1999 or Otaduy and Lin, 2006. Virtual coupling has also been used to simulate interaction with fluids of variable viscosity (Cirio, Marchal, Otaduy and Lecuyer, 2013).

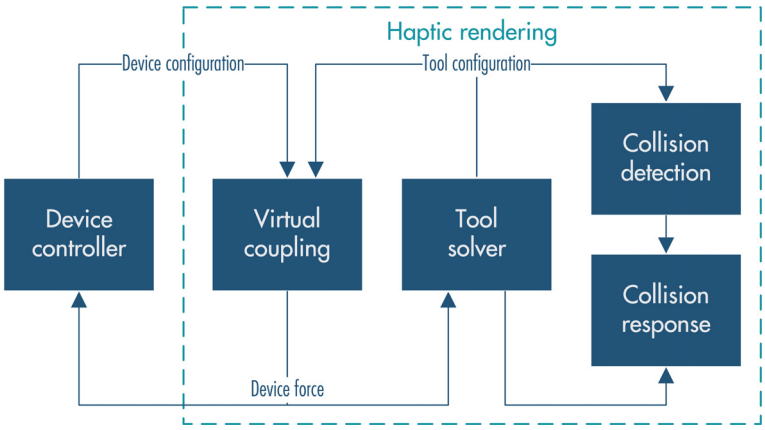


Figure 2-10: Main components of a rendering algorithm using virtual coupling (Lin and Otaduy, 2008, p.168).

In contrast to impedance-controlled haptic rendering, a rendering algorithm for admittance control measures the user's interaction force and computes the position, velocity and acceleration (PVA) an object would obtain as a result of this interaction force (see figure 2-11). For complex scenes, a local mass model is rendered on the haptic server and the resulting forces acting on this mass from the virtual world are computed by a host computer. The PVA vector is then used as a reference signal for the haptic device (van der Linde and Lammertse, 2003).

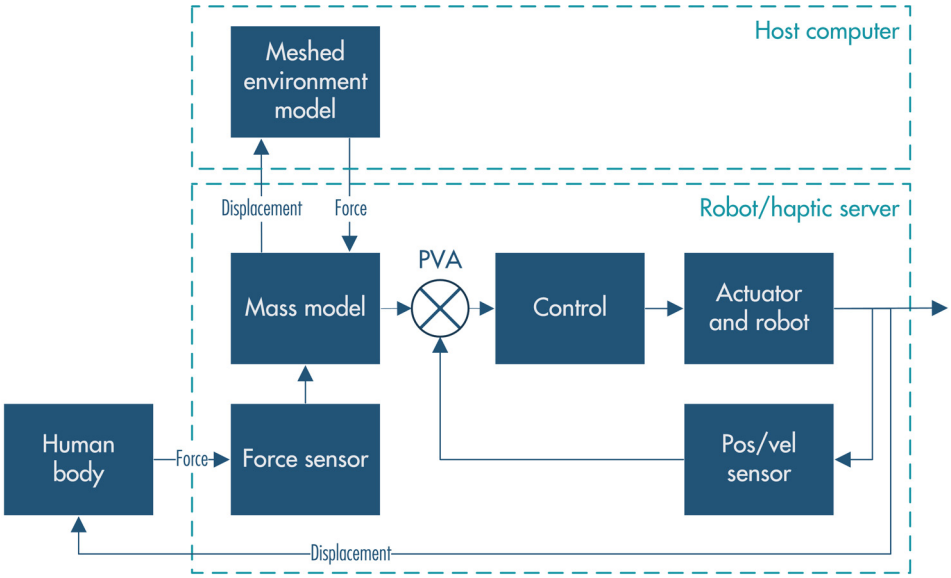


Figure 2-11: Admittance-controlled haptic rendering using the example of the Moog FCS HapticMaster (van der Linde and Lammertse, 2003).

Currently, haptic rendering of solid objects, i.e. the simulation of the tool state, is efficiently feasible with commodity computing; the challenge lies in the complexity of the virtual environment and thus the computational complexity of the collision detection determines the overall performance of the haptic rendering algorithm. Simulation between rigid and deformable bodies (such as bone and soft tissue) creates additional difficulties, as these bodies have large areas where they collide. Recently, algorithms are presented to overcome parts of these difficulties (for example Miguel and Otaduy, 2011). However, simulation of complex deformable objects at high rendering rates still deserves further research.

2.4.2 Software Frameworks to Render Haptic Effects

Several haptic software libraries are available, which allow adding haptic functionality to software applications. Low-level haptic libraries mainly allow reading the haptic device configuration and applying force and torque. High-level haptic libraries simplify the process of interacting with 3D models, and a few also provide scene graph functionality and other such as dynamics or a graphics rendering engine. Most haptic libraries use the C++ programming language, and in rare cases the Python scripting language. It must be pointed out that some haptic libraries are developed to work with haptic devices from a particular manufacturer, whereas others support a broader range of devices.

A non-exhaustive enumeration of the most common haptic toolkits includes:

- *CHAI3D (Conti, et al., 2003):* An open-source toolkit for scene graph-based haptic rendering, graphic visualisation and interaction. It supports different haptic devices, for example from Geomagic, Force Dimension and Novint, and is easily extendible through an interface for custom device integration. CHAI3D offers extensions for physics, deformable models and audio. It is heavily used in teaching haptics and in research projects.
- *Force Dimension SDK*[1]*, Force Dimension:* Haptic rendering engine which can be integrated into different visualisation packages such as CHAI3D or H3D. It allows high-level software development as well as full low-level device control of Force Dimension haptic devices.
- *HaptX*[2]*, Reachin Technologies:* A pure haptic rendering engine that is designed to be integrated into existing graphics and physics engines. HaptX provides a haptic toolbox which simplifies the integration of haptic effects, mainly aimed at game developers. It supports devices from Novint and Geomagic (seems outdated as of 2009).
- *H3DAPI*[3]*, SenseGraphics, part of Geomagic:* High-level open-source haptic software development kit that includes a scene graph and uses the open standard X3D for 3D objects. H3DAPI provides a graphics and a haptic rendering engine and supports using different haptic renderers besides the default H3D point and sphere-based haptic renderer. Additional features include physics simulation, built-in haptic textures/effects and scripting possibilities using Python. A broad range of haptic devices such as from Geomagic, Force Dimension, Novint and others are supported.
- *Novint HDAL*[4]*, Novint Technologies:* HDAL is a high-level interface which abstracts the actual device initialisation and the data handling. It is aimed at game developers; add-ons for several computer games to add three-dimensional force feedback are available. Currently, only the Novint Falcon is supported (not updated since 2008).

1. FORCE DIMENSION (2011) *Force Dimension - products - sdk - overview.* [Online]. 2011. Available from: http://www.forcedimension.com/products/sdk/overview [Accessed: 25 November 2011].
2. REACHIN TECHNOLOGIES (2010) *Reachin - Products - HaptX (the leading haptic software solution company)*. [Online]. 2010. Available from: http://www.reachin.se/products/HaptX [Accessed: 25 November 2011].
3. SENSEGRAPHICS (2004) *Open Source Haptics - H3D.org.* [Online]. 2004. Available from: http://www.h3dapi.org [Accessed: 25 November 2011].
4. NOVINT TECHNOLOGIES (2011) *Downloads*. [Online]. 2011. Available from: http://www.novint.com/index.php/support/downloads [Accessed: 25 November 2011].

- *OpenHaptics*[1]*, Geomagic:* A toolkit that includes several libraries, such as a low-level API (HDAPI), which allows access to read the device configuration and to apply forces and torques, a high-level API (HLAPI), which is responsible for haptic rendering, and an API encapsulating basic programming steps which are common to many haptic applications. OpenHaptics only supports Geomagic Touch devices.
- *Reachin API*[2]*, Reachin Technologies:* A commercial development platform for haptic rendering, graphics visualisation, interaction and audio aspects. It supports the development using the C++, VRML and Python programming languages and is suitable for both high-level application development and low-level device control. Reachin API is hardware independent and supports devices from Geomagic, Force Dimension, Haption and Quanser (not updated since 2007).
- *Virtuose API, IPSI SDK, IPP Core and IPP Human*[3]*, Haption:* The software development kit for Haption haptic devices provides three different integration possibilities: a low-level driver provides access to the haptic devices, rigid body physics simulation with haptic feedback using a voxel-based representation of objects is provided by a physics simulation interface, and high-level libraries for graphics programming and real-time motion of characters with collision detection.

An overview of selected features of each haptic software toolkit is given in table 2-1.

Table 2-1: Comparison of haptic software toolkits.

	CHAI3D	*Force Dimension SDK*	*HaptX*	*H3DAPI*	*Novint HDAL*	*OpenHaptics*	*Reachin API*	*Haption SDK*
Supported devices	Omega, Delta, Falcon, Freedom, Touch and custom	Force Dimension devices	Falcon, Touch	Omega, Delta, Touch, Falcon, others	Falcon	Touch	Geomagic and Force Dimension devices	Haption devices
Programming language	C++	C/C++	C++	C++, Python, X3D	C++	C++	C++, Python, VRML	C++

1. GEOMAGIC (2013) *OpenHaptics Toolkit Overview*. [Online]. 2013. Available from: http://geomagic.com/en/products/open-haptics/overview [Accessed: 17 March 2014].
2. REACHIN TECHNOLOGIES (2010) *Reachin - Products - ReachinAPI - (The leading haptic software solution company)*. [Online]. 2010. Available from: http://www.reachin.se/products/ReachinAPI/index.asp [Accessed: 25 November 2011].
3. HAPTION (2011) *Haption SA - Software*. [Online]. 2011. Available from: http://www.haption.com/site/index.php/en/products-menu-en/software-menu-en [Accessed: 25 November 2011].

	CHAI3D	*Force Dimension SDK*	*HaptX*	*H3DAPI*	*Novint HDAL*	*OpenHaptics*	*Reachin API*	*Haption SDK*
DoF	3	n/a	3	3, own renderer	n/a	3	3	n/a
Abstraction layer	High	Low	High	High/ low	Low	High/ low	High	Low
License	Open-source (GPL), commercial	n/a	n/a	Open-source (GPL), commercial	Commercial, non-commercial	Commercial, academic	Commercial	Closed source
Portability	Windows, Linux, Apple	Windows, Linux, Apple, QNX, VxWorks	Windows	Windows, Linux, Apple	Windows (32-bit)	Windows, Linux, Apple	Windows	Windows, Linux
Scene graph-based	X	—	—	X	—	—	X	—
Integrated physics	ODE	—	ODE, Newton	ODE, PhysX*, Bullet*	—	—	—	X
Primary market	Research and industrial	Research and industrial	Game industry	Research, (medical) simulations	Game industry	Research	Research	Research
Community	Medium	Support by manufacturer	Small, probably inactive	Large	Inactive	Forum, but almost no support	Small, probably inactive	Support by manufacturer

Key: *: partially supported, Omega: Force Dimension omega.x, Delta: Force Dimension delta.x, Freedom: MPB Technologies Freedom 6S, Touch: Geomagic Touch devices, Falcon: Novint Falcon.

Not a haptic library in the classical meaning, the Haptik Library (De Pascale and Prattichizzo, 2007) is a hardware abstraction layer providing unified access to different haptic devices. No haptic or physics algorithms are provided, it is aimed to be integrated into existing applications replacing manufacturer depending haptic libraries.

Several software frameworks use these haptic software toolkits to provide a simulation framework for a wide range of simulators, including medical simulation with haptic feedback, see 6.4.3.1, *3D Graphics Toolkits*.

2.4.3 Soft Tissue Rendering

A second key aspect of surgical simulators is the visualisation of anatomical structures and in particular soft tissue. In consideration of real-time surgical simulators, modelling the biomechanical complexity of real soft tissue is not (yet) possible. Therefore, algorithms are needed that simplify

the computational cost of rendering soft tissue in real time. Several constraints have to be taken into account for modelling soft tissue (according to Delingette, 1998):

- *Biomechanical model:* One of the most important aspects of soft tissue modelling is the accurate representation of deformation. However, the level of accuracy depends on the surgical procedure. Computation of deformation is based on studies of the behaviour and properties of real soft tissue and affects the underlying mathematical model which is used for soft tissue simulation (Fung, 1993).
- *Interaction with rigid or soft bodies:* Detecting collisions between soft tissue, virtual surgical instruments and other anatomical structures requires that the soft tissue is considered as deformable moving meshes and surgical instruments as rigid bodies. Several methods have been proposed, for example by Cotin, Delingette and Ayache (1999) and by Courtecuisse, et al. (2010), to render deformable meshes with haptic feedback.
- *Real-time deformation:* The user experience depends highly on the responsiveness of the system, mainly on the latency and computation time. Latency describes the time between the sensor registering motion and the resulting visual or haptic feedback; computation time is the time required to update the 3D models.
- *Tissue cutting and suturing:* Cutting or suturing tissue requires real-time modifications to the topology of the 3D model. When using volumetric or surface models, cutting can lead to self-intersections in the new geometry, whose detection can be computationally expensive. A method for multi-contact skin manipulation and cutting has been published by Lindblad and Turkiyyah (2007) or a hybrid elastic model simulating deformations and cutting by Cotin, Delingette and Ayache (2000).
- *Force feedback computation:* Surgeons can benefit by haptic feedback and are able to test mechanical properties of anatomical structures to distinguish between them. However, computing the forces and torques for the haptic feedback is computationally expensive and requires synchronisation between haptic and visual rendering, see also section 2.4.1, *Haptics* (Delingette, 1998).
- *Visualisation:* The visual representation of anatomical structures has a significant effect on the user experience. Soft tissue visualisation depends not only on the polygon count, but also on the adaptation of modifications on the topology of 3D models after cutting, which requires modification of texture coordinates when using surface models, or additionally, bleeding when cutting tissues (Delingette, 1998).

Combining soft tissue visual rendering with haptic interaction requires a dynamic physics model that allows real-time deformation. Using a massive parallel algorithm to solve a volumetric mass-spring model on high-end NVIDIA Tesla GPU computing processors, Etheredge, Kunst and Sanders (2013) showed that they are able to simulate a model with over 100,000 masses at 1 kHz, and are also able to use multi-device configurations.

In the field of surgical cutting, Wu, Westermann and Dick (2014) showed a physically accurate real-time soft tissue cutting simulation of a high-resolution deformable body with 170,000 finite elements, representing a liver. Instead of using a physically simplified model (such as a mass-spring model), they used a semi-regular hexahedral finite element grid and a linked octree discretisation of the deformable body, which allows to update the finite element model in a fast and robust way.

2.5 Learning and Teaching in Medical Education

Medical students need to acquire a large amount of knowledge within a limited period of time. Furthermore, they need to adopt this knowledge to new problems by effectively interpreting it and continuously educate themselves. To support the students in achieving this, teaching has shifted from didactic teacher-centred and subject-based to the use of interactive, problem-based and student-centred learning methods (Samarakoon, Fernando and Rodrigo, 2013). This section presents learning styles and approaches with regard to medical education. A comprehensive introduction into general principles and theories of learning is given by Ormrod (2012), who presents research and pedagogical concepts of learning theories with teaching implications.

2.5.1 Learning Theories

Learning theories are concepts which describe the sequence of learning from a psychological point of view and how information is obtained and retained. Different influences such as cognitive or emotional, but also prior experience play a part in learning, but three basic types of learning theories can be distinguished: behaviourism, social cognitive theory and constructivism (Schunk, 2012, pp.71, pp.117, pp.228). Behaviourism explains learning in terms of the process of forming associations between stimuli and responses, assuming that the learner passively absorbs by repetition the body of knowledge (conditioning). It dominated learning for the first half of the twentieth century and many principles of it are still evident in current learning theories (Schunk, 2012, p.114). Social cognitive learning theories focus on how people learn from observing one another, i.e. from the social environment. However, observing a model does not guarantee learning or be able to perform the behaviour, they rather show consequences and motivate the learner to act accordingly (Schunk, 2012, p.160). Constructivism explains learning by discovery and verification. It assumes that

knowledge is not imposed from other people but rather developed from the inside. Therefore, constructivism requires structured training which challenges learners so that they will construct knew knowledge (Schunk, 2012, p.274).

In medical training, several learning theories are used side by side depending on their application and to create appropriate learning environments to optimise learning. Torre, Daley, Sebastian and Elnicki (2006) describe key learning theories in medical education and how specific methodologies are linked to these. They found five commonly used learning theories: behaviourism, cognitivism (focuses on the individual learner and the thought processes), humanism (relates to the needs of the learner and finally self-actualisation and self-fulfilment), social learning (similar to social cognitive, but based on a sociological perspective) and constructivism; and described typical applications of them, such as (Torre, Daley, Sebastian and Elnicki, 2006, p.907):

- Behaviourism: preferably to learn how to perform a new skill.
- Cognitivism: preferably to develop critical thinking and clinical problem-solving skills.
- Humanism: preferably to assume responsibility for the professional development.
- Social learning: preferably to learn best practices in a clinical setting.
- Constructivism: preferably to understand physician-patient relationships or the meaning of family dynamics.

In contrast, Kaufman (2003) found three educational learning theories that can be applied to practice: social constructivism (similar to constructivism but with activating learners prior experience with group interaction), experiential learning (four steps: prior experience, observation, forming abstract concepts and applying them to new situations) and communities of practice (integrating individuals within a professional community). He developed seven principles which should guide educational practice from these three learning theories (Kaufman, 2003, p.215):

1. The learner should be an active contributor to the educational process.
2. Learning should closely relate to understanding and solving real-life problems.
3. Learners' current knowledge and experience are critical in new learning situations and need to be taken into account.
4. Learners should be given the opportunity and support to use self-direction in their learning.
5. Learners should be given opportunities and support for practice, accompanied by self-assessment and constructive feedback from teachers and peers.

6. Learners should be given opportunities to reflect on their practice; this involves analysing and assessing their own performance and developing new perspectives and options.
7. Use of role models by medical educators has a major impact on learners. As people often teach the way they were taught, medical educators should model these educational principles with their students and junior doctors. This will help the next generation of teachers and learners to become more effective and should lead to better care for patients.

Kaufman concludes that by following these seven principles, medical educators will become more effective teachers and therefore enhance and develop knowledge, skills and positive attitudes in their students, which will become the next generation of teachers and therefore result in better trained surgeons with providing a higher level of patient care and improved patient outcomes.

2.5.2 Unimodal versus Multimodal Learning Styles

New information is learned differently by each individual in terms of how they think and prefer to learn and by which method. This is known as learning styles, which describes the method of processing certain types of information or of processing information in certain ways, which can be distinguished in different ways such as between visual, auditory and kinaesthetic, between intuitive and analytic thinkers or between activist, reflecting and pragmatic thinkers, depending on the definition of learning styles. However, reviews evaluating the literature on learning styles draw the conclusion that there is still no viable evidence to support these theories. But they offer a compromise between treating all students the same way and treating every student uniquely (Willingham, Hughes and Dobolyi, 2015, p.266-267).

In medical education, different learning styles are usually combined during medical school, such as teaching methodologies vary in lectures, tutorials, practicals and dissection courses. Kharb, Samanta, Jindal and Singh (2013) investigated the preferred learning styles and teaching-learning methods of first semester medical students. By using a questionnaire, the learning preference was assessed with regard to the visual, auditory, read and write and kinaesthetic sensory modalities (known as the VARK model; Fleming and Mills, 1992) and with regard to unimodal versus multimodal preference. They found that 61% of the students preferred a multimodal learning style, indicating that they prefer different modes of information representation. In addition, they list the correlation between the learning style and teaching-learning methods, such as that the students preferred the kinaesthetic mode for practical exercises and dissection courses, the visual mode for lecturers, the auditory mode for tutorials and the read and write mode for self-study. These findings are consist-

ent with literature, such as Lujan and DiCarlo (2006), which also found that medical students prefer multiple learning styles instead of unimodal training.

In addition to the different learning style preferences amongst medical students, Engels and de Gara (2010) found that medical students also have a significantly different learning style than general surgical trainees and general surgeons. They found that medical students prefer a cognitive approach, i.e. they prefer lectures with demonstrators and like organised and structured understanding. In contrast, surgical trainees and general surgeons prefer practical hands-ons and applications of theories. This has implications on the medical education, such as that educational techniques used for medical students should not be applied in continuing education, instead, practical workshops will more likely meet the learning style, similar to the courses that are offered for example by the AO Foundation for training basic skills.

While investigating knowledge decay of first year medical students on three basic science courses in Canada, D'Eon (2006) found that there was a significant knowledge loss of 13.1% to 46.5%, depending on the course, and in addition, he found a difference between the courses. These results were consistent with other publications, and as there were differences between the courses, he concluded that it is not only the students forgetting knowledge, but that to some extent the variance is also found in the courses. D'Eon reviewed publications regarding different learning styles, which found that in a longer term, there was no difference between visually presented material (which was initially better learned) and verbally presented material. He also stated that factors facilitating long-term retention of information are initial learning, taking successive courses and the way the material is presented. In addition, focusing on meaning and understanding instead of memorising, granting time to learn and practice can help initial learning. These results support the multimodal training approach and also meet the preference of the learning style of medical students and in continuing education, as Engels and de Gara (2010) found.

2.5.3 Teaching Using Instructional Resources in Virtual Environments

To support trainees in acquiring new concepts or tasks, existing knowledge and supporting structures which are gradually removed once the trainees become more proficient (which is known as scaffolding (Sawyer, 2014, pp.14)) can be used during the learning process. Using principles from learning sciences and the access to technology for learning can replace traditional passive learning methods with ones that encourage medical students to interact with the virtual environment, however, the availability of a formal training with educational methods and principles is limited (Sweeney, 2012). In a response to an article investigating the applicability of the use of self-determi-

nation in postgraduate medical education, which implies a negative effect on motivation and clinical performance due to the diverging perception of the level of autonomy residents receive and the faculty provides, Kusurkar and Croiset (2015) suggest scaffolding should be applied throughout undergraduate and postgraduate medical education. For more information about the key features of learning sciences, see Sawyer (2014).

2.5.4 Gamification

Modern students (known as digital natives) entering medical school already have a high level of digital technology literacy, which also changed radically how they receive information, and are also open to new training methodologies (Prensky, 2001). They are also familiar with computer games, social media and mobile applications, and as a result, medical education has adapted game principles and game-design elements into technology-enhanced learning, which is known as gamification. In contrast to serious games (see section 2.3.4), which consist of a complete game for non-entertainment purposes, gamification only uses elements of games (Deterding, Dixon, Khaled and Nacke, 2011, p.11). In 2016, a study reviewed literature and 27 electronic games, mobile applications and virtual patient simulations for clinical education (amongst others) for the benefits of using gamification (McCoy, Lewis and Dalton, 2016). It showed significantly improved learning outcomes with virtual patient simulations in eight studies (they evaluated one intervention performed on a virtual patient simulator, but without a control group) and conclude that games have the potential to promote learning and that there are many potential advantages of using games in medical education such as increased engagement, enhanced collaboration or clinical decision making. However, there is still no clear evidence showing that using gamification is superior to other learning technologies, as studies that reviewed the impact of using gaming techniques mostly only analysed single interventions or medical knowledge and therefore state that more research is needed.

2.6 Requirements and Components of Surgical Simulators

Depending on the application area, for example minimally invasive or open surgery, surgical simulators have different requirements. But in general, a surgical simulator consists of four main components, as depicted in figure 2-12.

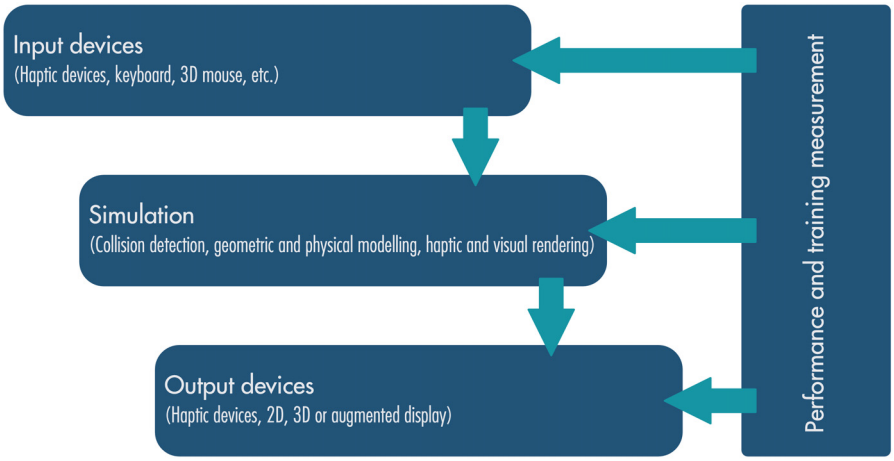


Figure 2-12: Main components of a software-based surgical simulator.

Input devices are used to simulate the surgical instruments, to change the perspective or to modify the settings of the simulation. Typically, one or two haptic devices are used to control the virtual surgical instruments. The simulation consists of several core components. Collision detection is used to compute contact forces and torques, geometric and physical modelling involves creating 3D models from medical images, deforming models due to interaction between virtual surgical instruments and anatomical structures, bleeding or realistic modelling of tissue and organ properties. Output devices are used to provide an immersive user interface with visual and haptic feedback. Throughout the entire simulation of a surgical procedure or technique, performance and training measurement is needed to assess the training effect of surgical skills and progress. Liu, Tendick, Cleary and Kaufmann (2003) discussed the simulation component in more detail, as well as key issues requiring further research.

In a 2007 review of virtual reality-based simulators for training in minimally invasive surgery, Basdogan, Sedef, Harders and Wesarg (2007) point out next-generation medical training and highlight the following research directions that require further attention:

- *Variations in anatomical models:* Effective surgical training simulators require different anatomies and pathologies to present realistic situations as no two patients are the same. Current simulators mostly use only one static model.

- *Material properties of organs:* Still little is known about the material properties of organs and furthermore, great variation between two patients can occur, depending on age, weight and gender.
- *Integrating material properties into deformable models:* There are a number of methods on how to set deformation model parameters, but it is still a complicated task.
- *Physics-based tissue models:* What level of physical correctness for realistic feedback is needed between organs and surgical instruments for effective training to preserve fidelity.
- *Graphical rendering and visual realism:* Realistic, high-fidelity 3D geometric models and complex scenes lead to high rendering cost and can require a level of detail approach or other rendering methods, for example, image-based rendering.
- *Human factors studies:* Validation of surgical simulators requires detailed human factor studies, which are missing. A better understanding and measurement of human perceptual and cognitive abilities is important for more effective training and training transfer. The development of surgical simulators can benefit from guidelines for visual, auditory and haptic design.
- *Integrating virtual reality-based simulators into the medical curriculum:* Surgical simulators will likely become part of the medical education program and therefore, the development process should involve medical experts at the right stage. The (technical) requirements for an effective virtual reality-based training are partially still unknown.

2.7 Development Guidelines and System Integration

Usability and user experience are both essential to the success of an application. To make a task not only easy and intuitive, but also meaningful and valuable requires to identify the needs and establish requirements by understanding the target users group, what their motivation is and what they should accomplish. Millo, et al. (2014) proposed a set of recommendations to ensure that the surgical simulator development and integration meet surgically relevant educational and curricular goals. They include considering what the simulator is aimed for, technical aspects such as performance metrics and internationalisation and localisation, or validation.

Gallagher, et al. (2005) reviewed literature from surgical education, human factors and psychology to analyse how virtual reality surgical simulators can be successfully integrated into a surgical training curriculum. They state that it can only be successful if the curriculum is adapted to the use of these simulators, skills improvements is assessed and that the training is performed over a long period of time instead of a short, extensive practice. They also propose eight steps to develop a curric-

ulum, which first teaches the relevant knowledge, instructs the steps and common errors of the task or procedure, and then introduces the training on the simulator with immediate feedback on errors and a summative feedback at the end, with the last step being the iteration of the skills training and providing evidence of progress.

Burden, Oestergaard and Larsen (2011) describe the implementation of a competency-based laparoscopic surgical skills training in gynaecology for the UK, also emphasizing the issues that needed to be considered for the implementation into training programmes. They noted that the differently equipped facilities, the motivation of the internal trainees and finally the maintenance cost and staff training pose a challenge, which could be addressed by sharing organisation, equipment and development of it and make the use of simulators mandatory.

2.8 Identification of Research Area

This literature review gives an overview of the current research in the area of the current medical education with regard to computer-based surgical simulation in orthopaedics and the development of a simulator using haptic feedback technology for open surgery. As the main aim of this research project was to develop a computer-based surgical simulator for educational research, the acceptance of the target medical user group was essential. Therefore, a human-centred development approach was used to actively involve medical experts in the development process in order to design a simulator that is medical relevant and to meet, or even better exceed the users' expectations. However, opinions the medical experts have and decisions regarding functionality and relevant aspects they took, change (as they could change their mind based on the impressions they get from new developed software prototypes), which has a significant effect on the software engineering method to develop the surgical simulator, in that it has to be flexible enough to support such changes. From different software development processes (Pressman, 2009), an agile approach was chosen, as it allows integrating medical experts' suggestions for improvements and changes on requirements during each iteration, and focuses on implementing required functionality and on user feedback, rather than specifying the requirements on the surgical simulator at the beginning of the project without iterations, as in traditional development processes. However, due to the scope of the project, several methods are not applicable, such as pair programming or giving weekly demonstrations to the medical experts. But the principle of iterations consisting of planing, analysis, design, coding and testing with a working software prototype at the end of each iteration (Pressman, 2009, pp.73) ensures that the surgical simulator meets the expectations of the medical experts and targeted users. Limitations of this approach are that it greatly depends on the medical experts, which define the direction the

development of the surgical simulator will take and the required commitment for the duration of the project.

Liu, Tendick, Cleary and Kaufmann (2003, p.602) stated about a decade ago, which is still applicable:

> "Open surgery remains the holy grail of surgical simulation. Considerable advances in haptics, real-time deformation, organ and tissue modelling and visual rendering must be made before open surgery can be simulated realistically."

As there are almost no research results in the area of orthopaedic hand and wrist surgery for computer-based simulation, focusing on the users and understanding who the users are, their tasks and the context of use, i.e. identifying the needs, is an important step. In addition, advances in the stated topics have been made, but it is still undetermined if it is possible to develop such a system based on conventional, possibly consumer hardware, without using highly specialised equipment that could prevent adapting it by a large user group. It is of importance to understand what the simulator should do and to elicit and establish requirements by interviewing medical experts. This also includes determining if all software components are required for the particular medical scenario, for which a simulator will be developed, or if for example volume rendering or deformable models can be omitted.

During the medical education of orthopaedic surgeons, different training materials are used, mainly conventional books, dissection courses and training on patients. How, when and in what stage of the medical education computer-based simulators can be supportive is an additional research question which cannot be answered by the literature. In addition, a further research question is, how visually and haptically realistic a simulator needs to be for communication or acquisition of knowledge or information and to have a measurable transfer of skills to the operating theatre.

These are research questions and areas that address usability and user experience such as efficiency, effectiveness and satisfaction, which eventually will determine if the surgical simulator gets accepted by the target medical user group.

The literature has no answers for these aforementioned areas and therefore were identified as appropriate research areas. To summarise, meeting users' expectations with a currently feasible computer-based surgical simulator, training acceptance and effectiveness of learning new procedures and medical relevance in the field of orthopaedic hand surgery are the areas to be examined.

Chapter 3

State-of-the-Art of Science and Technology

3.1 Chapter Summary

This chapter builds on the literature review of the previous chapter and focuses on the technological aspects of surgical simulators. First, the preliminary work is presented, which was carried out prior to this PhD research where the author has performed a significant role within, and is included as its results had a substantial influence on the design and development of the surgical simulator of this PhD research project. Then, an overview is given about commercially available surgical systems ranging from general purpose haptic devices used for developing (medical) applications with support for haptic feedback, to entire surgical simulators used to simulate complete procedures, including medical instruments. The chapter concludes with a review of the research gap identified in the literature review and examines this gap from a technical point of view.

3.2 Introduction

The literature review conveyed what knowledge and research have been established on medical simulation with regard to orthopaedic hand and wrist surgery and virtual reality-based (VR) simulation. As medical simulation is well known and already integrated in the medical education in certain medical fields, this chapter examines the current use of commercially available surgical simulators in related fields, after highlighting research projects which led or had a significant impact to this research project. In contrast to the literature review, which focused on published current knowledge from a theoretical point of view, this chapter approaches the identified area of study from an applied and more practical point of view, investigating the market of available systems both for medical education and for suitability of use in research of virtual surgery.

3.3 Preliminary Work and Research Projects

The following research projects represent work that the author has performed a significant role within or have been conducted at the CPVR (Computer Perception and Virtual Reality) research group at the Bern University of Applied Sciences (BUAS) prior to this PhD. For each project a short description is given with relevant outcomes and implications for the work of the PhD.

3.3.1 Haptic Osteosynthesis Planning

The goal of the Haptic Osteosynthesis Planning research project was to improve the current state of the art 2D/3D visual-only osteosynthesis (surgical procedure of reduction and fixation of a bone fracture using implants such as plates, screws or nails) planning tools. This included the modelling of haptic feedback during osteosynthesis and implant application (2006–2008).

Results

Based on a software requirements specification which has been elaborated in the project, a prototype for an osteosynthesis planning tool has been developed to assess the feasibility and application of using virtual reality and haptic feedback technologies. The application provides advanced stereoscopic visualisation through the use of an active stereo system. Bone fragments and different implant models can be loaded and a haptic device can be used for reduction and fixation with haptic feedback for object surfaces and collisions, see figure 3-1.



Figure 3-1: Stereoscopic reduction and fixation with haptic feedback.

Torque feedback in the three rotational degrees of freedom has not been implemented since the haptic devices used only supported force feedback in three translational degrees of freedom. See Künzler, et al. (2009) for further information.

Relevant Outcomes and Decisions

The calculation of the haptic feedback has to be highly efficient so that objects cannot drop into the inner volume of the colliding object. This was achieved by an iterative approach, which, moves the object that is controlled by the end effector during collisions only half of the effective distance so that it always visually remains outside. Thus, the resulting force is much lower, which has an adverse effect on the stiffness. This approach slightly enlarges the objects on large movements but prevents glancing off the objects surface. The disadvantage is that the end effector can vibrate on the surface due to the rapidly varying forces. By using hysteresis (using past and present input values to calculate the output value) to filter the force and take recent history into account, this could be eliminated.

H3DAPI[1], the software framework that was used did not provide any collision detection algorithms between objects at that time, therefore, a point-to-face collision detection has been implemented. To provide torque feedback, a face-to-face collision detection algorithm would be needed, which is computationally much more intensive.

H3DAPI has already been used in various research projects and has been adopted for specific use cases, such as Palmerius (2011) combined kinaesthetic with tactile feedback by overlaying the individual forces by a vector sum to haptically explore volumetric data and to simultaneously add additional features and information such as roughness to generate the sense of a surface in 3D or to sense transitions between regions in the volume. In an evaluation, Palmerius found that the participants (eight experienced with scientific visualisation) were able to identify the combined features.

3.3.2 AR Intraoperative Planning Data Information System

The goal of this research project, partially carried out by the author, was to develop an intraoperative augmented reality information system for in situ access of surgery planning data. This included the development of a framework for unified display and access to 2D/3D pre- and intraoperative information (data and images) and the elaboration of algorithms for intraoperative update of precomputed 3D fracture models. Intraoperative usability required novel, non-hand-operated (such as eye tracking) multimodal human-machine interaction techniques (2007–2008).

1. H3DAPI is an open-source haptics software development platform, see section 2.4.2, *Software Frameworks to Render Haptic Effects*.

Results

A novel paradigm for controlling 3D models using eye tracking (eye motion and eye dwell time) has been established. The system continuously rotates the 3D model in such a way that a point of interest, which is on the rear side of the object (such as a fracture gap, which extends to the rear side of a bone), is rotated to the centre on the front side by fixating the border of the object. Zooming to an area on the object and selecting eye trackable buttons are realised by dwelling for a period of time.

Additionally, using a head-mounted augmented reality display and a tracking system, a software prototype has been developed that projects simplified precomputed 3D fracture models on the exact location on the patient's leg. See Künzler, et al. (2009) for further information.

Relevant Outcomes and Decisions

Rotating a 3D model by looking up, down or sidewards, as with a keyboard, is not suitable, because intuitively we look immediately back at the object to see progress so far. Furthermore, indicating the calculated gaze point is not recommended, because the exact position of this point cannot be determined due the accumulation of the tracker errors (eye tracking and head tracking) and in addition, the user then tends to follow this point.

3.3.3 Operating Room Interactive Surgery Workflow Simulation

The goal of this project, carried out by the author, was to improve the currently very limited planning task for the operating theatre instrumentation and setup. At best, a 2D map is drawn on which the layout of the patient, the equipment and the surgical tools are roughly outlined. But this completely neglects the intraoperative 3D handling of these devices. The simulation of such intraoperative surgery workflows within a CAVE environment has the advantage that not only complex inter-person and human-machine-interaction procedures, but also the medical equipment placement and device operation can be optimised within the virtual operating theatre (2006–2009).

Results

A software prototype has been developed which can simulate a surgical workflow and has been evaluated using the example of the treatment of a femur bone fracture with a proximal femur nail (PFNA) in a CAVE environment. The setup of the equipment in the operating theatre can interactively be modified to investigate for example the influence of display visibility at different placements. See Künzler, et al. (2009) and Hauck, et al. (2011) for further information.

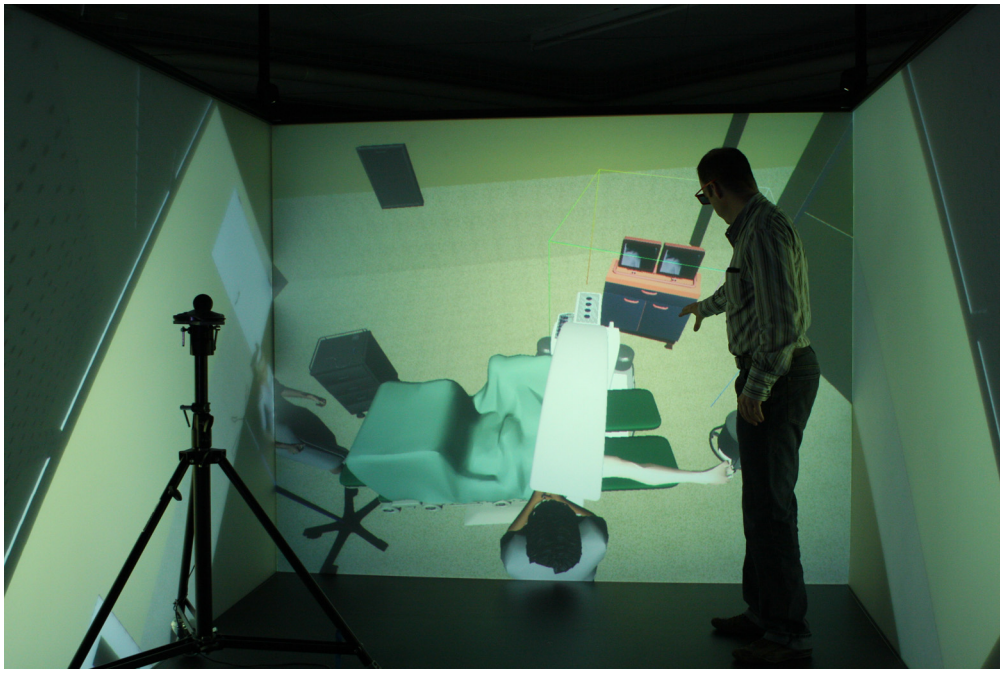


Figure 3-2: Evaluating the arrangement of medical equipment in a virtual operating theatre.

Relevant Outcomes and Decisions

This project showed that the optimisation done in a stereoscopic environment offers a considerable advantage compared with a traditional two-dimensional simulation. Medical experts become immersed in the virtual operating theatre due to the third dimension, which becomes more realistic and allows easier identification of conflicting operating theatre arrangements. The library that was used to synchronise the nine workstations which render the operating theatre simulation in a CAVE turned out to be strongly network bandwidth limited. This lead to the development of I3D, the new software framework (see section 3.3.6, *Virtual Reality Rendering Framework I3D*) which uses the Equalizer multi-pipe rendering framework[1] to increase rendering-fidelity and interactive response.

3.3.4 Virtual Morphometric Instruments

In the context of a diploma thesis (Günel, 2007) at the BUAS, appropriate methods and algorithms have been developed to create virtual morphometric instruments which can be used to test and classify surfaces of virtual 3D bone models. This is done thus far on anatomical specimens, but with the use of medical imaging systems (such as MRI and CT for example), visualisation and processing of 3D bone models is now technically feasible. Several instruments have been developed for example

1. Equalizer is a middleware to create and deploy parallel OpenGL-based applications, see http://www.equalizergraphics.com.

to identify anatomical landmarks, to measure curves and angles on the bone surface and distances between landmarks or to calculate the area and perimeter of a sectional plane.

3.3.5 BoneVis — Processing CT Data for Visualisation

In the context of a diploma thesis (Mürner, Weber and Zesiger, 2007) at the BUAS, a software prototype has been developed to simulate and visualise structural-mechanical properties of bones. By calculating the elasticity based on the intensity of the pixels of the CT scan and by creating a 3D volume from the CT scan, a 3D bone model, coloured accordingly to the elasticity can be generated. To create the 3D volume, two methods have been implemented: firstly, by creating a 3D texture for volume rendering and secondly, by creating a mesh using the marching cube algorithm to create a surface rendering. The elasticity has been calculated by computing the Young's modulus (a material constant defining the correlation between tension and extension during deformation when a force is applied) from the levels of grey of the CT scan and then by calculating the biomechanical properties using the finite element method.

3.3.6 Virtual Reality Rendering Framework I3D

I3D (Immersive 3D) is a software framework developed by the author, that is used at the CPVR research group of the BUAS for projects using virtual reality, high-performance 3D graphics visualisation and new interaction paradigms. The development started in 2010 and uses free software to create a generic framework providing basic functionality such as a scene graph, physics, haptic technology, animations and the handling of different input devices. It can be easily configured to run on different system configurations such as a conventional 2D or a stereoscopic workstation, a powerwall or in a CAVE. It replaced the previous framework with which the Haptic Osteosynthesis Planning, the Operating Room Interactive Surgery Workflow Simulation and the AR Intraoperative Planning Data Information System projects (see previous sections) have been developed.

Results

Various projects and technology demonstrators have already been realised with I3D in student projects such as an improved version of the operating theatre simulation, games using 3D audio, physics and haptics, different VR devices such as eye tracking or motion sensing, as well as the medical demonstrator application used for the interviews to gather user requirements for a surgical simulator, see section 4.4, *Methodology*.

Relevant Outcomes and Decisions

This software framework was used for the development of the surgical simulator. New and enhanced functionalities were integrated directly into I3D so that other projects can benefit from them.

3.4 Current Surgical Systems and Haptic Devices

Medical training equipment can be roughly divided into two categories, complete surgical systems and haptic devices. Surgical systems are widely-used in the training of medical students and personnel, ranging from simple models to train specific skills, to complete immersive environments to simulate complete procedures. In contrast, haptic devices are (mostly) general purpose devices used mainly in research and specific application areas. They are used to develop applications or prototypes, which eventually may become a surgical system, where haptic devices can be replaced by custom built haptic devices representing the simulated medical instruments.

3.4.1 Surgical Systems

The market for surgical systems is served by different companies selling specialised systems for specific medical fields and surgical areas. The following non-exhaustive overview categorises the different system types relevant for the scope of this thesis. Task trainers and surgical systems are well known and can be classified into (see also 2.3.1, *Surgical Simulation and Virtual Surgery*):

- *Manikin/patient simulators:* Computerised manikins recreate the real physical patient in a realistic physical environment and simulate actual functions such as breathing. Real-time display of electronically monitored information have become common in different fields, such as in an operating theatre, in intensive care and emergency departments or in delivery rooms.

  Examples of full-body patient simulators include the SimMan 3G from Laerdal, featuring for example airway, circulation, blood pressure/pulse, catheterisation and breathing, or the NOELLE birthing simulator from Gaumard (see figure 3-3).



Figure 3-3: SimMan 3G full-body patient simulator[1] (left) and NOELLE S575.100 birthing simulator[2].

- *Simulated clinical environments:* Reproduce parts or all of a clinical encounter in a safe, protected environment. Enables the practitioners to learn non-technical skills including decision-making and communication, either in live environments or in high-fidelity virtual reality environments (see figure 3-4). This also may extend to serious games. Standardised rooms are commonly used to simulate clinical conditions, controlled by instructors, where individuals or teams have to recognise and treat these situations.





Figure 3-4: Trent Simulation and Clinical Skills Centre at the QMC[1] (left), serious game HumanSim to train teamwork, communication and collaboration skills (Taekman and Shelley, 2010).

- *Interventional simulation:* Recreate surgical procedures in different medical fields, such as cardiovascular disease, intravenous or endovascular surgery, or in general, minimally invasive surgery, or ultrasound imaging for example for echocardiography training. Such simulators often use VR technology and haptics to produce a highly realistic simulation of the particular tasks or procedure.

  One of the most used surgical simulator for laparoscopic surgery is the da Vinci Surgical System from Intuitive Surgical (see figure 3-5), using interactive robotic arms on a patient-side cart, which are controlled by a surgeon's console. Other commonly used laparoscopic surgical simulators are the Simbionix LAP Mentor[2] or the Surgical Science LapSim systems[3].

  Such surgical systems are expensive, a da Vinci system costs 1.5 to 2.5 million dollars per station[4] (in addition to annual maintenance fees), LapSim 40-45,000 pounds (plus value-added tax) for a basic station (according to Limbs & Things in 2012).

1. Photo courtesy of Laerdal.
2. Photo courtesy of Gaumard Scientific.
1. Photo courtesy of Nottingham University Hospitals NHS Trust.
2. SIMBIONIX (2014) *Lap Mentor | Simbionix.* [Online]. 2014. Available from: http://simbionix.com/simulators/lap-mentor [Accessed: 20 March 2014].
3. SURGICAL SCIENCE (2014) *LapSim The Proven laparoscopic Training System, simulation.* [Online]. 2014. Available from: http://www.surgical-science.com/lapsim-the-proven-training-system [Accessed: 20 March 2014].
4. BARBASH, G.I. & GLIED, S.A. (2010) New Technology and Health Care Costs — The Case of Robot-Assisted Surgery. *New England Journal of Medicine.* [Online] 363 (8), 701–704. Available from: doi:10.1056/NEJMp1006602.



Figure 3-5: da Vinci Surgical System with console (left), patient-side cart (middle) and vision system (right)[1]. The surgeon operates seated at a console while viewing a 3D image of the patient's surgical site. The patient is positioned during surgery at the patient-side cart which carries out the surgeon's commands by robotic arms. The vision system provides true-to-life 3D images of the patient's anatomy.

- *Task trainers:* Simulate specific parts of procedures or basic skills. They normally recreate only the key elements of a procedure and allow acquiring basic skills. Different kinds of task trainers are used, ranging from food (such as for learning epidural anaesthesia for pain relief using watermelons for example) to special soft plastic materials for suturing.

  Numerous task trainers for different medical fields exist, such as from Laerdal for blood pressure or central venous and vital signs training, from Gaumard for auscultation, birthing and nursing skills, or from Limbs & Things for suturing, general procedural or physical examination skills (see figure 3-6).



Figure 3-6: Skills trainers: auscultation (Gaumard[2], left), blood pressure (Laerdal[3]), basic surgical skills (Limbs & Things[4]).

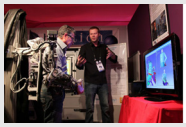
1. Photo courtesy of Intuitive Surgical.
2. Photo courtesy of Gaumard Scientific.
3. Photo courtesy of Laerdal.
4. Photo courtesy of Limbs & Things.

The largest part of the market consists of high-fidelity manikin/patient simulators, as recent technology advances allow for the creation of highly realistic simulators.

3.4.2 Haptic Devices

One of the first successful commercially sold haptic device was the PHANToM (Massie and Salisbury, 1994, now Geomagic Touch). Haptic devices can be categorised by the degrees of freedom they can provide force feedback, and by the targeted customer segment. Typically, one-DoF and two-DoF devices are aimed at the consumer market, three+-DoF devices are commonly used in R&D and in specific application areas, with the exception of the Novint Falcon, a three-DoF device which was targeted at the gaming industry, but is often used in education at universities. Table 3-1 shows the different devices which are discussed in this section, and their intended area of application. In addition, medical systems supporting haptic feedback are also included within the context of haptic devices and systems.

Table 3-1: Overview of haptic devices and systems and their typical areas of application.

	Consumer devices	Professional devices	Medical systems
Entertainment	Two-DoF: 		
Research/ education	Three-DoF: 	Three-DoF:   Six-DoF:    Seven-DoF:  	
Medical use		 	

3.4.2.1 Consumer Devices

One-DoF devices, such as steering wheels, and two-DoF devices such as force feedback joysticks (see figure 3-7) are well established in the consumer market, mainly for driving and flight simulations.



Figure 3-7: Consumer haptic devices: one-DoF steering wheel[1] (left), two-DoF joystick[2].

However, no force feedback joysticks are currently sold for the consumer market; probably that they have not succeeded in the market yet (only applicable for flight simulators) or due to a patent infringement lawsuit about the use of haptic technology in game controllers[3].

3.4.2.2 General-Purpose Haptic Devices

Different approaches have been taken to provide haptic feedback to three+-DoF devices. Most common are single point devices such as the Geomagic Touch, which simulate touching at a single point, often by using a kinematic structure with motors. Another category form exoskeletons, which fit over the entire hand and can provide force feedback to each finger.

Haptic devices differ in the degrees of freedom they can provide active force feedback, workspace, force, stiffness, resolution, and whether they can compensate for gravity (see table 3-2). Most haptic devices are built on either a serial or parallel kinematic structure (a mechanical system using joints and links constrained by their connection). Parallel structures, such as Force Dimension uses, can generate higher continuous forces and torques than serial structures. Three-DoF devices are the most widely-used devices, such as for teaching haptics for example, by reason of the affordable price, starting at $250 for a Novint Falcon. Six-DoF devices are much more expensive.

1. Photo courtesy of Logitech International.
2. Photo courtesy of Logitech International.
3. IMMERSION CORPORATION (2002) *Immersion Corporation — Immersion Files Suit Against Microsoft and Sony Computer Entertainment for Patent Infringement.* [Online]. 2002. Available from: http://immr.client.shareholder.com/releasedetail.cfm?ReleaseID=111788 [Accessed: 20 October 2015].

Examples of three-DoF devices include Geomagic Touch, Force Dimension omega and delta families and Novint Falcon (see figure 3-8).



Figure 3-8: Three-DoF haptic devices: Geomagic Touch[1] (left), Force Dimension omega.6[2], Novint Falcon[3].

Examples of six-DoF devices include Geomagic Phantom Premium, Force Dimension delta and Haption Virtuose 6D (see figure 3-9).



Figure 3-9: Six-DoF haptic devices: Geomagic Phantom Premium 3.0 6DOF[4] (left), Force Dimension delta.6[5], Haption Virtuose 6D[6].

Seven-DoF devices are often built on three/six-DoF devices, providing an additional degree of freedom with a different handle for example for grasping capability. Examples include Force Dimension omega.7, sigma.7 and MPB Freedom 7S (see figure 3-10).



Figure 3-10: Seven-DoF haptic devices: Force Dimension sigma.7[7] (left), MPB Freedom 7S[8].

1. Photo courtesy of Geomagic.
2. Photo courtesy of Force Dimension.
3. Photo courtesy of Novint Technologies.
4. Photo courtesy of Geomagic.
5. Photo courtesy of Force Dimension.
6. Photo courtesy of Haption.
7. Photo courtesy of Force Dimension.

The following tables 3-2 and 3-3 give a non-exhaustive overview of different haptic devices and their specifications. Certain manufacturers offer different versions of the same haptic device, such as Force Dimension with the omega family, which is basically a three-DoF device, available with position sensing in only three-DoFs for the omega.3, six-DoFs sensing for the omega.6 and with an additional grasping handle providing active feedback with the omega.7.

Table 3-2: Specifications of selected three-DoF haptic devices, provided by the manufacturers.

	Geomagic Touch	*Geomagic Touch X*	*Force Dimension omega.6*	*Haption Virtuose 3D Dekstop*	*Moog FCS HapticMaster*
DoF	3	3	3	3	3
Structure	Serial	Serial	Parallel	Serial	Serial
Workspace translation [mm]	> 160 x 120 x 70	> 160 x 120 x 120	Ø 160 x 110	Ø 200	~0.08 m^3
Workspace rotation [°]	-	-	240 x 140 x 320	145 x 115 x 148	-
Force translation [N]	3.3	7.9	12.0	10.0	250.0
Stiffness [N/mm, Nm/rad]	1.02-2.31	1.48-2.35	14.5	1.0	10.0-50.0
Resolution translation [mm]	~0.055	~0.023	< 0.01	0.02	0.004-0.012
Resolution rotation [°]	-	-	0.09	-	-
Gravity compensation	-	-	X	X	X
Control: admittance or impedance [A/I]	I	I	I	A/I	A

Table 3-3: Specifications of selected six/seven-DoF haptic devices, provided by the manufacturers.

	Geomagic PHANTOM Premium 3.0 6DOF	*Force Dimension delta.6*	*Haption Virtuose 6D Dekstop*	*Haption Virtuose 6D*	*MPB Freedom 6S*	*MPB Freedom 7S*	*Force Dimension sigma.7*
DoF	6	6	6	6	6	7	7
Structure	Serial	Parallel	Serial	Serial	Serial	Serial	Parallel
Workspace translation [mm]	838 x 584 x 406	Ø 400 x 260	Ø 200	1300 x 658 x 1080	170 x 220 x 330	170 x 220 x 330	Ø 190 x 130
Workspace rotation [°]	297 x 260 x 335	±22	200 x 90 x 200	300 x 100 x 250	130 x 170 x 340	130 x 170 x 340	235 x 140 x 200
Workspace grasping	-	-	-	-	-	40 deg	25 mm
Force translation [N]	22.0	20.0	10.0	31.0	2.5	2.5	20.0
Force rotation [mNm]	515, 170	150	400	3100	150-370	150-370	400
Force grasping	-	-	-	-	-	0.45 Nm	±8.0 N
Stiffness [N/mm, Nm/rad]	1.0	14.5	2.0	2.0, 30.0	2.0, 0.2-4.0	2.0, 4.0-20.0	-
Resolution translation [mm]	~0.02	0.02	<0.03	0.02	0.002	0.002	0.0015

8. Photo courtesy of MPB Technologies.

	Geomagic PHANTOM Premium 3.0 6DOF	*Force Dimension delta.6*	*Haption Virtuose 6D Dekstop*	*Haption Virtuose 6D*	*MPB Freedom 6S*	*MPB Freedom 7S*	*Force Dimension sigma.7*
Resolution rotation [°]	0.0023, 0.008	< 0.04	0.004	-	0.0011	0.00074-0.00097	0.013
Resolution grasping	-	-	-	-	-	14 µrad	0.006 mm
Gravity compensation	-	X	X	X	unknown	unknown	X
Control: admittance or impedance [A/I]	I	I	A/I	A/I	I	I	I

Other technical approaches for haptic devices exist, for example the Haption Inca6D, a cable-driven device based on the Spidar (Sato, 2002), providing a large workspace which depends on the position of the motors and cables. In contrast to devices built on a kinematic structure, the Butterfly Maglev 200 is a six-DoF device built on the magnetic levitation principle, eliminating the drawbacks of using mechanical elements. However, the workspace is limited with a diameter sphere of 24 mm.

3.4.2.3 Exoskeletons

Exoskeletons can provide force feedback to the hand and fingers, shoulder and elbow, depending on the device. They are mainly used in teleoperation and rehabilitation. Examples are the Haption Able and the CyberGlove Systems CyberGrasp (see figure 3-11).

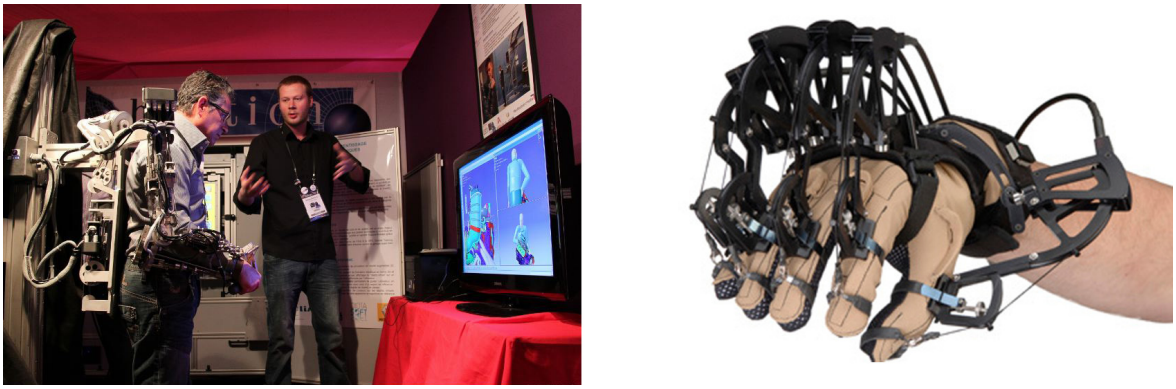


Figure 3-11: Exoskeletons: Haption Able[1] (left), CyberGlove Systems CyberGrasp[2].

1. Photo courtesy of Haption.
2. Photo courtesy of CyberGlove Systems.

3.5 Review of Identification of Gap

As identified in the literature review, computer-based surgical simulators for open surgery, and in particular for orthopaedic hand surgery, are still in an early state of subject of research, but have potential, as for example the training effectiveness of virtual reality-based surgical simulators is more and more demonstrated (see section 2.3.3, *Training Effectiveness of Virtual Reality Surgical Simulators*). With different isolated components required for their development, such as haptic rendering or deformable models for example, being researched, the review of technology confirmed that there is a gap in the current list of available surgical simulators, as none of them allows training basic skills or procedures with regard to orthopaedic surgery. First steps towards developing orthopaedic simulators have been undertaken, but with limited success (Tsai, Hsieh and Jou, 2001), as for example the required technology was not yet available or the users' expectations were not met. But with recent technology advances, there is a possibility to move beyond simulating minimally invasive surgery and apply similar concepts to simulating open surgery. However, particular challenges are still faced, such as with simulating soft tissue, or more generally, what the requirements are with regard to open surgery.

The approach of adapting commercially available surgical systems and extend their capabilities to support open surgery is only feasible with great difficulties, if at all, as such systems are closed systems (no custom development possible) or due to the required high initial cost, or that they are highly specialised for minimally invasive surgery by using belonging medical instruments. Therefore, using general purpose haptic devices and appropriate software frameworks allows to investigate the identified research areas.

To summarise from a technical point of view, the research questions and areas identified in the literature review are confirmed and the research question, whether it is possible to use current technology and general purpose haptic devices for the development of a virtual reality-based surgical simulator, is added to be examined.

Chapter 4

User Requirements Gathering

4.1 Chapter Summary

This chapter describes the user requirements gathering process which was undertaken to create the requirements specification in the following chapter. A study was carried out with hand surgeons and technical experts to investigate the training of surgeons, surgical simulators and the usability and visualisation techniques involved. The results of the user requirements gathering study are discussed and six surgical procedures or techniques have been proposed for implementation. Then, they are evaluated for implementation feasibility and the medical scenario is defined.

4.2 Motivation

The success of a newly developed surgical simulator depends largely upon the acceptance amongst surgeons, as they are responsible for teaching learners and of employing not only traditional technique methods (passive learning), but also of employing new modalities such as medical simulation where appropriate (Sweeney, 2012, p.127). Therefore, the aim was to actively involve them and let them take part in decision-making. In the field of software development, this process is called human-centred design (HCD, also known as user-centred design). As currently no computer-based surgical simulator for hand surgery is available (see 2.3.2, *Training and Surgical Simulators in Hand and Wrist Surgery*), this medical area has been chosen. The development of surgical simulators relies on opinions from the involved surgeons. Experience from previous research projects (see chapter 3, *State-of-the-Art of Science and Technology*) has shown that often several iterations in the development cycle are needed to reach the eventual aim. During those projects, using workflows to describe the problem and the scope of the simulation has turned out to be an effective tool to define the requirements on a simulation. A similar approach has been described by Burgert, et al. (2007),

who were also using images and videos to illustrate the different steps of a surgical procedure. They record interventions and surgeries, with the number of the required recorded interventions depending on the complexity and variability of the procedure, and take intraoperative videos (such as from an endoscope) and pictures to document situations of high importance. Such surgical workflows can then be used for interdisciplinary discussions between surgeons and developers and can help identifying relevant steps of the intervention. Burgert, et al. used this method to develop a surgical simulator for pituitary gland surgeries and recorded seven endoscopic surgeries of pituitary adenomas to specify a surgical workflow. However, no information on the outcome are available.

Based on the literature review and the insights gained from interviews with hand surgeons from Switzerland, the United Kingdom and Germany, the medical context has been determined and requirements on visualisation and interactiveness are gathered to create a user requirements specification, on which the surgical simulator is based on.

4.2.1 Human-Centred Design (HCD)

Software development not only concerns about meeting technical and functional requirements, but also about creating usable software. This needs to follow a user-oriented development approach instead of a technology-oriented development approach. Users will benefit from usable systems as they are able to achieve their tasks more efficiently, resulting in increased productivity. The International Organization for Standardization (2010b) outlines in ISO 9241-210 a framework for human-centred design to incorporate usability requirements into the development process (see figure 4-1).

This HCD approach extends the development process by six key principles:

- The design is based upon an explicit understanding of users, tasks and environments.
- Users are involved throughout the design and development.
- The design is driven and refined by user-centred evaluation.
- The process is iterative.
- The design addresses the whole user experience.
- The design team includes multidisciplinary skills and perspectives.

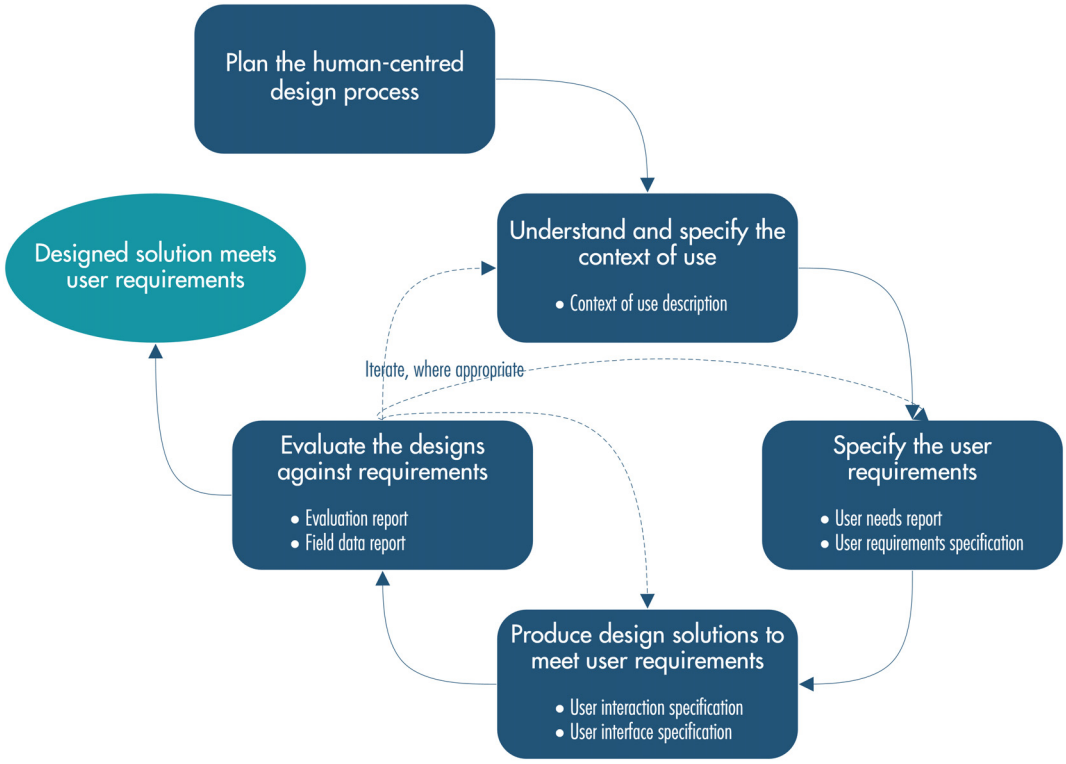


Figure 4-1: Key activities of the usability engineering process according to ISO 9241-210:2010 (International Organization for Standardization, 2010b).

One of the key aspects of HCD is the iterative design. Depending on the achieved level of knowledge, specific iterations of user-orientated activities come into focus instead of following a rigorous waterfall model (sequential design process (Royce, 1970, p.329)). As it is typically difficult for users to explain what they want from a system, several iterations can be needed to build design solutions that meet the users expectations and design criteria.

Following a HCD approach results in usability-related information documents, which are needed to get the usability of the to be developed product under control. These documents are described in the ISO/IEC TR 25060 standard (International Organization for Standardization, 2010a) and are as follows:

- *Context of use description:* Describes user tasks and how the user handles them, working conditions and regulations which need to be considered during the development process.
- *User needs report:* Describes what is mandatory in the context of use from a user point of view and which requirements must be fulfilled (or created) in order to reach the work results and organisational goals.

- *User requirements specification:* Describes the functionality the system really has to provide from a user point of view, what the user can input, choose and which information must be available at a glance.
- *User interaction specification:* Describes how the user can interact with the system, in which order and which information must be available at a particular step.
- *User interface specification:* Describes the interaction possibilities the user has and the interface of the system.
- *Evaluation report:* Describes where the system differs from the user requirements and the problems user have using the system.
- *Field data report:* Describes findings after the system has been used for a longer period of time, unknown problems in utilisation of the system or requirements that emerge after the roll-out.

Applying the HCD approach requires using different methods to support a human-centred software development process. Although these methods are well known, they are often used independently and not focused on the usability. Maguire (2001) gives an overview of usability methods to support HCD, based on the previous standard of ISO 9241-210 (which was ISO 13407:1999), but can also be applied to the revised standard. These methods to perform the HCD activities address specific problems of requirements engineering and are widely adapted for software development, such as by IBM (Vredenburg, 1999). The HCD process is used for the development of the surgical simulator prototype and selected usability methods described by Maguire were used for the HCD activities (see in figure 4-1), such as (hierarchical) task analysis, user observation, user requirements interviews, brainstorming, software prototyping and assisted evaluation.

4.2.2 Early Medical Scenario Considerations

In a first step, two brainstorming sessions with medical and technical experts were used to get an initial idea of which medical domains could be addressed with a surgical simulator, and in particular which surgical interventions. Additionally, a common understanding of how the surgical simulator should be used has been developed. This included discussions about the targeted user group and technical aspects such as how to use virtual reality and haptic technologies. Two medical training areas resulted from these sessions: osteosynthesis in general and scaphoid fractures as a particular bone fracture. These medical conditions are quite common today and represent surgical procedures which are, for the most part, standardised. Technical experts in the field of virtual reality and medical simulations (n = 4, mean average experience in years 6.7, standard deviation 2.9), as well as medical experts (n = 2, more than 10 years experience in orthopaedics), participated in these

brainstorming sessions. As a result, it was identified that interviews with more hand surgeons were required to elaborate a scenario and to define user requirements.

4.2.3 Process of Gathering User Requirements

Understanding the users' needs is an integral part to design and develop a training system and for its success. The overall process for user requirements gathering and analysis that was followed in this PhD project is shown in figure 4-2:

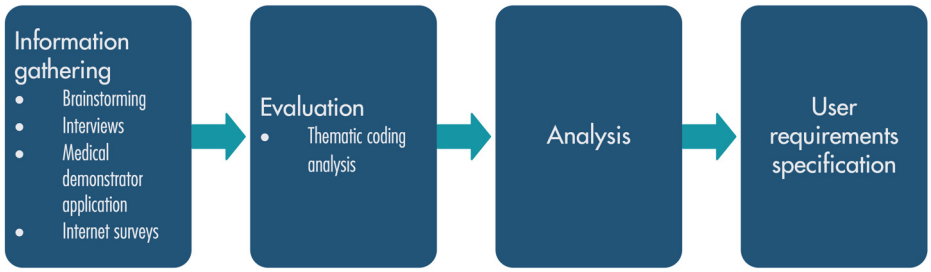


Figure 4-2: Stages taken in this PhD project to define the user requirements specification.

4.3 User Requirements Specification

The outcome of the interviews forms the specification of a surgical simulator. A user requirements specification includes details about end user operability, functionality, performance considerations, as well as regulatory requirements. It details a common understanding about the simulator between medical experts, software developers and end users, which are in this case the medical students or surgeons, which use the simulator for training reference. The specification is also used as a basis for cost estimation and can provide a baseline for the validation and verification of the product.

This section gives an overview of methods used in this study. Section 4.4, *Methodology* details the participant group, procedure and the how these methods were applied to the interviews and internet surveys.

4.3.1 Gathering Data

The surgical simulator should meet the current needs of surgeons for training and should also be adaptable for future requirements. This was achieved by involving the surgeons in the design phase and iteratively evaluate the software development process with the expertise of the surgeons. Gathering background information about the target group of this system is an important part, and additionally, gathering information about potential customers and markets that such a surgical simulator will address.

Most of the gathered data was qualitative, such as interviews or drawings, which the participants could create to illustrate a statement or topic. To identify the user needs and to specify the user requirements, use cases were used to specify the interaction between user roles and the system, requirements were specified and the scenario was further analysed using task analysis.

4.3.1.1 Scenarios and Use Cases

The medical scenario is defined based on the AO Surgery Reference (AO Foundation, 2012), an open access, comprehensive online reference of surgical knowledge about surgical procedures and approaches for daily clinical life. It describes the surgical process of the treatment of fractures from diagnosis to aftercare, and collects relevant medical information the AO Foundation has published, which is linked to the particular fractures. Based on the results of the user requirements gathering study and in collaboration with surgeons, a prototype scenario was chosen, which emerged to be the most promising for computer-based simulation.

Fractures can be classified according to different schemes. Commonly used is the system known as the "AO/OTA Classification of Fractures and Dislocations" (Association for Osteosynthesis/American Orthopaedic Trauma Association; previously known as the Müller/AO Classification; AO Foundation, 2014). It is composed of the localisation of the bone (the bone and the affected segment) and the fracture morphology, i.e. the type (extra-articular, partial articular and complete articular) and its corresponding fracture group and subgroup, based on the fracture pattern. For example, a medical scenario for an ulnar shaft fracture could be defined by forearm shaft 22-A1.1 with a lag screw and plate fixation, implying that it is a simple isolated (radius intact) fracture of the ulna bone with an oblique fracture line, which is treated by an open compression plating in association with a lag screw (a screw providing compression to the fracture). The number 22-A1.1 indicates that the radius/ulna (2) is affected, the bone segment location is diaphyseal (22, concerning the shaft), a simple fracture type (22-A) with the ulna fractured and the radius intact (22-A1) and an oblique fracture pattern (22-A1.1). Using this classification system and the recommended treatment methods from the AO Surgery Reference, the medical scenario can be clearly defined.

The surgical simulator has been implemented using a generic approach. This allows a follow-up project to easily adapt new scenarios and training possibilities. New scenarios could be described as a workflow (based on the AO/OTA classification), which allows users to create their own scenarios or to change parameters of existing ones, and based on the recommended treatment methods from the AO Surgery Reference, use cases can be identified, which need to be implemented.

4.3.1.2 Context of Use

The design of the surgical simulator involved understanding where, how and by whom it will be used. These characteristics can be defined by functional requirements that define specific functionality:

- *Functional requirements:* The functionality of the surgical simulator was specified by evaluating the images taken during the surgical intervention and in close collaboration with surgeons.

In addition, non-functional requirements describe what the constraints are on the simulator (Sharp, Rogers and Preece, 2007, pp.477), such as:

- *Data requirements:* All data, such as 3D models of bones, soft tissue, amongst others, need to be processed in order to be visualised in real time.
- *Environmental requirements:* The surgical simulator will be used for training purposes. It will not be used in an operating theatre, therefore, it should reflect the surgical environment as realistically as possible, for example by simulating the correct sounds of the medical instruments or ambient noises.
- *User characteristics:* The main user group will be surgeons and medical students. It has to be decided which level of surgical training the simulator will address.
- *Usability requirements*: The surgical simulator should provide an intuitive interface.

To collect this information, brainstorming meetings (see section 4.2.2, *Early Medical Scenario Considerations*) have been organised which brought together medical experts as user representatives, technical experts and a software engineer. The final requirements were specified based on the responses of the participants (non-functional requirements) and on the use cases (functional requirements). Additional non-functional requirements are defined by software and engineering considerations (such as the programming language). Functional requirements, which represent learning objectives, can best be described by medical experts, which defined those for their training courses.

4.3.1.3 Task Analysis

Surgical procedures can be analysed and structured using task analysis, for example hierarchical task analysis (HTA), described through diagrams which show the different user tasks to perform this procedure. In a HTA, tasks that a user performs are broken down into multiple levels, which represent subtasks and with each level, elaborate the task in more details. These subtasks can be grouped together as a plan to specify in which order the tasks are performed (Sharp, Rogers and Preece,

2007, pp.516). HTA can help for example software engineers understanding how a surgical procedure is performed, as it reduces the complexity of the entire procedure to single, relevant tasks with arbitrary detail. However, creating such a diagram can be time and resource intensive, as for complex procedures, a significant amount of tasks are created and not all tasks may be required in the same granularity. HTA has been used to define the implemented medical scenario to analyse and describe the interactions between the user and the surgical simulator, see figure 5-6 on page 112.

4.3.1.4 Video Recording

The entire surgical intervention can be recorded for a better understanding of the surgical process. During post-processing, surgeons can add remarks to the video and explain important aspects of the surgical intervention. This will develop a common understanding in order to guard against misinterpretations during the final user requirements stage and the design process.

For a better evaluation of the video recordings, the stages of the surgical procedure can be mapped to positions in the video recording, resulting in an index which maps user events from the task analysis to images or sequences in the video recordings. This can be used as a basis of decision-making for the analysis of the performed surgical procedure, since it allows comparison between the actual training sequence of the surgeon and the proposed method.

4.3.2 Evaluation Method: Thematic Coding Analysis

Virtual environments can be experienced in different manners, often controllable in up to six degrees of freedom (DoF) and with a wide variety of virtual reality input devices. Therefore, it can be difficult to control the users' experience of virtual environments and to gather requirements with structured methods. Robson (2011, pp.474) describes thematic coding analysis, a generic approach to analyse qualitative data. Two methods can be used, either summarising or reducing the data, such as experiences, meanings and the reality of the participants (realist method), or examining the data, and determining the effect of a range of discourses operating within sociality (constructionist method). It is a flexible method that can be used for virtually all types of qualitative data (Robson, 2011, p.477), such as for the evaluation of user requirements when designing virtual environments. Thematic coding analysis consists of five stages:

1. *Familiarising with data:* The data is transcribed if necessary, repeatedly read and first ideas are noted down.
2. *Generating initial codes:* Initial codes can be prepared before the interaction with the data or during. Pieces of data that can be assessed in a meaningful way are systematically given codes (coded), similar data pieces are being coded likewise.

3. *Identifying themes:* The codes are grouped according to potential themes, gathering all relevant codes to each potential theme. These potential themes are checked if they work in relation to the data pieces and the entire data set, while revising the themes or codes if necessary.
4. *Constructing thematic networks:* The analysed data is developed into a thematic map or network to show how themes can be put together.
5. *Integration and interpretation:* Different aspects of the data are compared using, for example, tables and networks to explore, describe and summarise or interpret patterns. The results can then be used to present the analysis of the participants answers to the development team of the virtual environment and for decision-making.

The use of thematic coding analysis aims to classify the different statements made during the interviews, such as the training of surgeons and the usability of input devices. Parts of the interview can be evaluated using simple tables, but the interviewees also gave valuable input for the design of the virtual environment throughout the entire interview, therefore, the thematic coding analysis approach was chosen as it also allows to identify themes out of the data instead of concrete statements from the participants.

4.4 Methodology

During the creation of the questionnaire for the interviews, a medical demonstrator application has been developed (see figure 4-3) which is based on the same software framework that was used for the surgical simulator prototype. Instead of using images or describing a virtual environment or the behaviour of the surgical simulator, it can be easier for surgeons if they are able to try it out themselves and see what a virtual reality-based simulator is capable of.

The application shows only the most important 3D objects for a specific task so that the attention is not drawn off the topic to be investigated, and allowed the interviewee the following actions:

- Visualise different combinations of anatomical structures.
- Interact with the virtual objects by using three different navigation paradigms.
- Use different (virtual reality) input devices to change the perspective of the simulator.
- Verbally comment on the visual representation of medical instruments.



Figure 4-3: Medical demonstrator application used during the interviews.

The interview process has been evaluated by a participant with technical knowledge but relatively little medical background. Based on the result of this interview, some changes have been made such as the integration of an additional navigation paradigm, the improvement of existing ones and questions about integrating a surgical simulator into an existing training concept. To reach more surgeons, especially in the UK, an internet survey has been set up with almost identical questions as in the interviews, excluding the parts involving the medical demonstrator application.

All participants have been invited by email with an invitation letter and a description about the study. After the interviews have been conducted, they have been transcribed and the German interviews have been translated into English. The interviews and internet surveys have been analysed using thematic coding analysis, resulting in the user requirements specification.

Once the user requirements for a surgical simulator have been defined, a simple software prototype can be made to illustrate how the simulator could look. This allows an early verification of the previously defined functionality and eventually shows some usability issues.

4.4.1 Participants

There were two types of participants; orthopaedic surgeons and technical experts in the fields of virtual reality simulations, graphics programming and user interface design. The reasoning behind interviewing both participant types was to understand the different views and ideas surgeons and technical experts may have. This is particularly important for the design of the interaction because

surgeons have a different understanding or practical knowledge of using virtual reality input devices, if any.

The medical participants were orthopaedic surgeons specialised in disorders of the hand and wrist. There are also plastic surgeons with specialisation in hand surgery, their field is mainly traumatic hand and digit amputations that require a replant operation (surgically reattach), whereas orthopaedic surgeons are trained to handle complex fractures of the hand. However, operative interventions can also include plastic surgery, for example in skin grafting.

In Switzerland, four orthopaedic surgeons with a specialisation in hand surgery were selected, based on the medical database of the FMH Swiss Medical Association (2012), and invited to participate in the interview. The participants of the internet survey have also been selected based on the same database, but only one participant has finished the online survey. One participant refused the invitation with the reason that he is unconvinced of surgical simulators and that in times when money is spent restrainedly for medical science/training, simulators were an unnecessary waste of resources. All participants have experience in orthopaedic surgery for an average of 15.5 years (7.5 to 26 years, n = 5, mean average = 15.5, standard deviation = 6.7) and four are currently working in the field of hand surgery.

In England, the surgeons have been selected based on the member directory of the BSSH — British Society for Surgery of the Hand (2010b). Two participants agreed to take the interview, one consultant and one in his specialty training, and two participated in the internet survey (orthopaedic experience: 4 to 32 years, n = 4, mean average = 15, standard deviation = 10.4).

In Germany, one surgeon has been selected based on a current research project in the field of medical education (8 years of experience in orthopaedic surgery).

The technical experts have been chosen based on previous research projects in the field of virtual reality simulations and on the recommendation of those in Switzerland and the UK. They have experience in medical simulation (such as in brain surgery), preoperative planning and medical image registration (n = 3, mean average = 7.3, standard deviation = 2.1).

Overall, 13 participants from Switzerland, the United Kingdom and Germany participated (see figure 4-4) in this study, 10 surgeons with an average of 14.6 years of experience in orthopaedic surgery (standard deviation = 8.4) and three technical experts with an average of 7.3 years of experience in medical simulation, see figure 4-5.



Figure 4-4: Overall number and country of origin of participants.

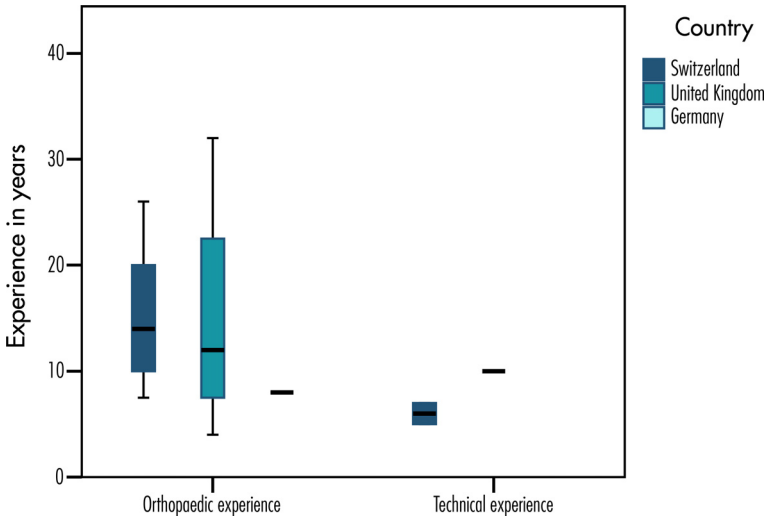


Figure 4-5: Experience of orthopaedic surgeons and technical experts.

4.4.2 Procedure of the Interview and Internet Survey

The one-to-one interviews were carried out according to Robson (2011, pp.285). All medical interviewees had the same questions to ensure consistency. First, a short introduction was given, including the research topic and the purpose of the interview as well as the assurance of confidentiality and the permission to tape-record the interview. Second, according to the University of Nottingham ethics guidelines, the participant consent form was handed out to the interviewee, providing information about their rights and confidentiality issues.

The interview questions were structured as follows:

1. *Demographic questions:* Information about the participants' experience in orthopaedic and hand surgery.
2. *General questions:* The current methods of training surgeons, questions about surgical simulators and its impact on patient-safety as well as questions about the most promising procedure to simulate in a surgical simulator.
3. *Functionality:* Questions about the visual representation of anatomical structures and medical instruments, navigation and interaction paradigms and the need of displaying information relating to the current state of the simulation. This part involves short tasks with the medical demonstrator application.
4. *Patient-specific data:* What is the difference between generic and patient-specific data and is there any benefit in using patient-specific data?
5. *Evaluation:* How to measure the performance of surgeons.
6. *Environment:* The placement of the surgical simulator.

The closure of the interview included the invitation to participate in the research project or in the final evaluation of the surgical simulator.

The interview for technical experts is based on the same questions, however, questions regarding medical training or surgical procedures have been omitted and the term of surgical simulators has been widened to virtual reality-based simulators in general where necessary.

The website-based internet survey was carried out in a similar manner, also according to Robson (2011, pp.247). The participants received an invitation email with a short description and explanations about the study, as with the interviews, and the hyperlink to take part in the survey. First, they had to accept the participant consent form, then the internet survey started with the same questions as in the interviews, excluding the tasks involving the medical demonstrator application.

At the end, the participants could state if they would participate in the research project or that they should be contacted for further information.

4.4.3 Interviews

Since the surgeons which have been interviewed may have gotten their training in foreign countries, and additionally, the specialisation in hand surgery is a continuing education (after the medical studies), the answers to the questions may vary and the interview may evolve into a different direc-

tion as it was originally thought in advance. Therefore, the one-to-one semi-structured interview type was chosen. All interviews had the same question, but depending on the answers, specific topics could be investigated in more detail or be omitted.

4.4.3.1 Medical Participants

The interviews for medical participants included the following questions:

Table 4-1: Demographic questions.

	Interview questions	*Rationale*
MQ1	Name, title, age and nationality	Verify personal details; used for statistical data.
MQ2	Position / Job title	Verify the correct writing of the title.
MQ3	Experience and training	How many years of experience in orthopaedics and hand surgery does the surgeon have?
MQ4	Surgeons in the same medical field	Information about the hospital, other hand surgeons, orthopaedic and plastic surgery in general.

Table 4-2: General questions.

	Interview questions	*Rationale*
MQ5	Current methods of training	Get an overview of the current methods of the training of surgeons. Depending on the country they can get a diverse training.
MQ6	Already used surgical simulators	Experience in the use of surgical simulators for training purposes.
MQ7	Acceptance of surgical simulators	How is the acceptance by surgeons? Is there a difference between younger and older surgeons?
MQ8	Does the use of surgical simulators lead to higher patient-safety	In their opinion, are there an increased patient-safety or less complications when using surgical simulators for the training of surgical treatments?
MQ9	Usefulness today and in long-term	What they would do if they had a surgical simulator now and in four years.
MQ10	Integration into existing training concept	What steps are required to integrate a new surgical simulator into an existing training concept.
MQ11	Regulations	What are the regulations for the use of surgical simulators.
MQ12	AO Surgery Reference	Knowledge about the AO Surgery Reference from the AO Foundation
MQ13	Most common surgical procedures	What procedures are the most common in the professional routine of surgeons.
MQ14	First scenario to implement	Which procedure they propose to build a surgical simulator for.
MQ15	Also important scenarios	Additional procedures that are worth considering.
MQ16	Different stages of scenario	The different stages of the selected procedure.
MQ17	Most valuable stage	The stages which would benefit most having a training possibility.
MQ18	Required medical instruments	The required medical instruments for the selected procedure.

Table 4-3: Functionality questions.

	Interview questions	*Rationale*
MQ19	Prefer 2D or 3D	If they already have experienced 3D, what is their opinion?
MQ20	Required anatomical structures	Which anatomical structures are essential, desirable or not important for the selected procedure. Most likely they will say all of them are essential.
MQ21	Anatomical Structures that can be omitted	Based on the previous question, which anatomical structures could be omitted if they had to choose three?
MQ22	Level of detail (LOD)	What is the minimal level of detail for the anatomical structures in general?
MQ23	Different LODs for each stage	Can the anatomical structures be visualised in different levels of detail depending on the current stage of the procedure?
MQ24	Visualisation of medical instruments	Do they prefer an abstract representation, a simplified representation with geometrical objects or a realistic visualisation of the input devices (see figure 4-6)?
MQ25	Movement of objects in scene	Should the view be modifiable and how: • Head tracking, optical motion tracking • Auto-rotate • Manually controllable
MQ26	Navigation paradigm	Which navigation paradigm is the easiest to rotate and zoom in and out.
MQ27	Input devices	What input device they prefer for changing the view.
MQ28	Benefit from information shown in surgical simulator	Is there a demand to have information shown in the surgical simulator?
MQ29	What information to be shown	What kind of information would they like to have.
MQ30	Value of real-time information	Is there an additional benefit if the information is updated in real time?

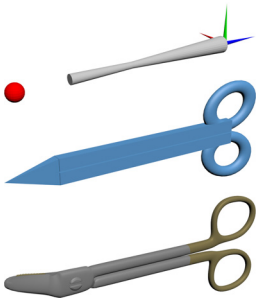


Figure 4-6: Visualisation of medical instruments: abstract (top), simplified (middle) and realistic (bottom).

Table 4-4: Patient-specific data questions.

	Interview questions	*Rationale*
MQ31	Benefit for surgical simulator	Is there a benefit in using patient-specific data instead of generic models in surgical simulators?
MQ32	Value for training	Does training with patient-specific data improve the skills of surgeons more than training with generic data?
MQ33	Difference between generic and patient-specific data	What is the difference between patient-specific and generic data; can they be combined?

Table 4-5: Evaluation question.

	Interview questions	*Rationale*
MQ34	Evaluation functionality	Should the surgical simulator provide evaluation functionality to measure the progress or performance of surgeons?
MQ35	Performance measurement	Are there any standards in measuring performance of surgical procedures? How can this be evaluated?
MQ36	Evaluation parameters	Which parameters provide information about the performance of surgeons?

Table 4-6: Environment questions.

	Interview questions	*Rationale*
MQ37	Placement of surgical simulator	Where would the surgeon place the surgical simulator? Does it have to be sterile to be usable in an operating theatre? Should it be available on Internet to be usable whenever and wherever they want?

4.4.3.2 Participants with Technical Background

The interviews for technical participants were based on the same questions as for medical participants. The changes are as follows:

- The following questions were the same: MQ1-2, MQ19, MQ22, MQ24-30, MQ31 and MQ34-36.
- The following questions were modified: MQ3 and MQ6:

Table 4-7: Modified questions for technical participants.

	Interview questions	*Rationale*
TQ3	Experience and training	Experience in developing graphics and virtual reality applications. Technical participants may have experience in other simulations, not only surgical simulations.
TQ4	Already used VR simulators	Experience in the use of (virtual reality) simulators.

- The following questions have been omitted: MQ4-5, MQ7-18, MQ20-21, MQ23, MQ32-33 and MQ37.

4.4.4 Internet Survey

Getting surgeons to participate in the interviews was a difficult task. Therefore, to get more responses, a self-completion website-based internet survey was used which took the participants only 10 to 20 minutes for completion. The questions were the same as those in the interviews with the following changes:

- The following questions were the same: MQ1-3, MQ5-9, MQ11-12, MQ14-19, MQ21-22, MQ25 and MQ29-38.

- The following questions were omitted: MQ4, MQ10, MQ13, MQ20, MQ23-24 and MQ26-28.
- The following question was added:

Table 4-8: Question added for internet survey.

	Interview questions	*Rationale*
SQ13	Importance of chosen procedure	Reasons for the chosen surgical procedure.

The questions were presented to the participant in groups according to the structure as in the interviews.

4.4.5 Thematic Coding Applied to Interviews and Internet Surveys

The interview evaluation has been carried out according to the thematic coding analysis evaluation method, consisting of the following procedure:

1. *Familiarising with data:* The information from the surgeons has been gathered using one-to-one interviews. They have been tape-recorded, transcribed and the German interviews have been translated into English, resulting in about 130 pages of qualitative data.
2. *Generating initial codes:* The transcribed interviews have been imported into the qualitative data analysis software NVivo[1]. The transcripts have been 'coded' to get the information of the interviews and grouped accordingly into first potential themes, partially based on the initial questions of the interviews (see figure 4-7). These themes are data-driven, i.e. themes arise during the coding process, as well as theory-driven, meaning themes are based on the specific questions of the interviews.
3. *Identifying themes:* Based on the initial coding, the codes have been grouped into different themes and sub-themes. Existing themes from the initial coding have been tested against the meanings of the codes and, if necessary, refined. The entire data has been reread to check if the themes represent the content of the interviews and surveys and some data pieces have been additionally coded or recoded to reflect the refined themes.
4. *Constructing thematic networks:* Themes which are related to each other have been put together, forming a thematic network with a main theme and sub-themes, which further describe in detail the main theme (see figures 4-8 and 4-9). The data set has once again been reviewed to

1. QSR INTERNATIONAL (2011) *QSR - NVivo Products | QSR International.* [Online]. 2011. Available from: http://www.qsrinternational.com/product [Accessed: 25 May 2012].

ensure the thematic network represents the meanings of the data, the particular important aspects of virtual reality-based surgical simulators.

5. *Integration and interpretation:* The thematic networks were used to interpret the interviews and extract important aspects to create a requirements specification for the development of the surgical simulator, see section 5.3, *Requirements Specification*.

4.4.6 Analysis Structure of Results

The transcribed interviews have been imported into NVivo as internal sources. Then, nodes have been created as initial codes, based on the interview questions and additionally for general themes that emerged during the interview, such as statements about preoperative planning or what surgeons are interested in (see figure 4-7). The coding of the sources resulted in up to 470 references per interview and in a total of over 800 unique codes.

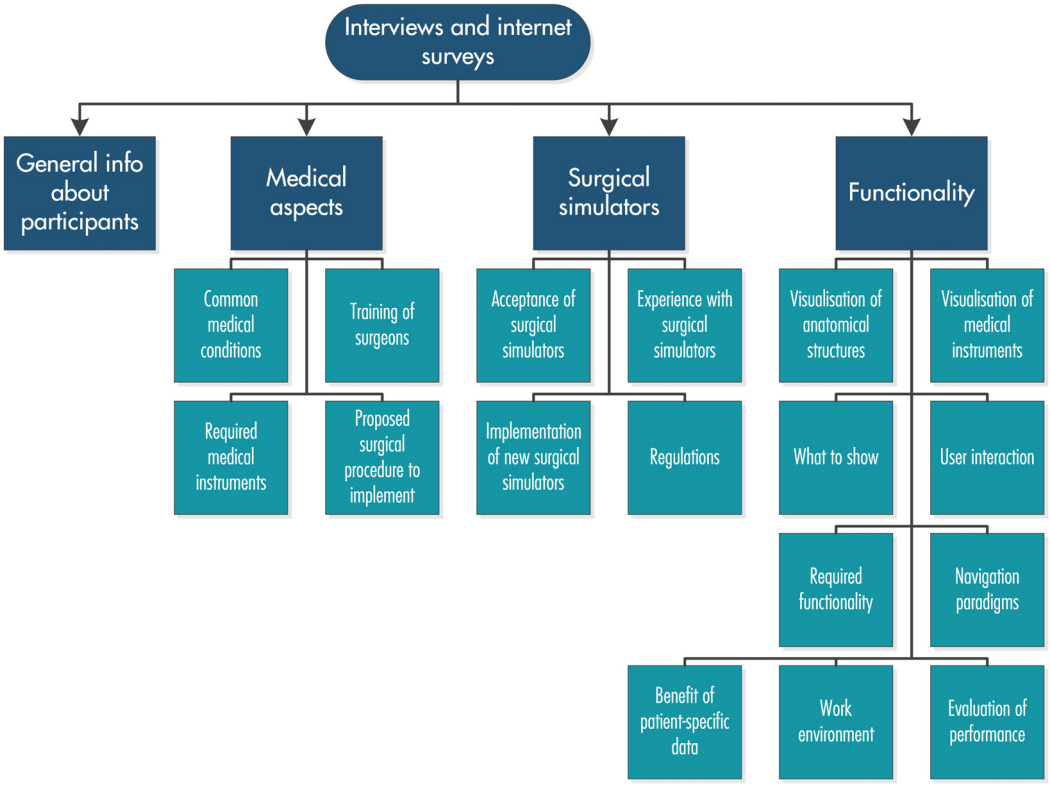


Figure 4-7: Initial codes for the thematic coding analysis.

For the process of coding the sources and identifying themes, additional nodes representing these new themes have been created, or existing ones redefined. The data has been reviewed and if necessary recoded to match these themes. The list of themes was then grouped together into thematic groups, again using NVivo nodes to represent these thematic groups.

Primarily, three main thematic groups have been investigated: medical applications of surgical simulators, training of surgeons and functionality requirements of surgical simulators (see figures 4-8 and 4-9).



Figure 4-8: Thematic networks about medical and general information.

The following themes have been investigated belonging to the medical applications of surgical simulators thematic group:

- *Surgery:* Information about the work of hand surgeons and illustrative examples.
- *Surgical simulators:* All information connected with the use, pros and cons of surgical simulators and surgeons' personal experiences.
- *Medical conditions:* Investigates common injuries of the hand and wrist and which surgical procedures or techniques are promising to simulate.

- *Other application areas:* Medical topics that arose during the interviews that are worth considering but are not directly connected to hand and wrist surgery.

The thematic group for the training of surgeons consists of one core theme:

- *Training:* How surgeons are currently trained in Switzerland and the United Kingdom.

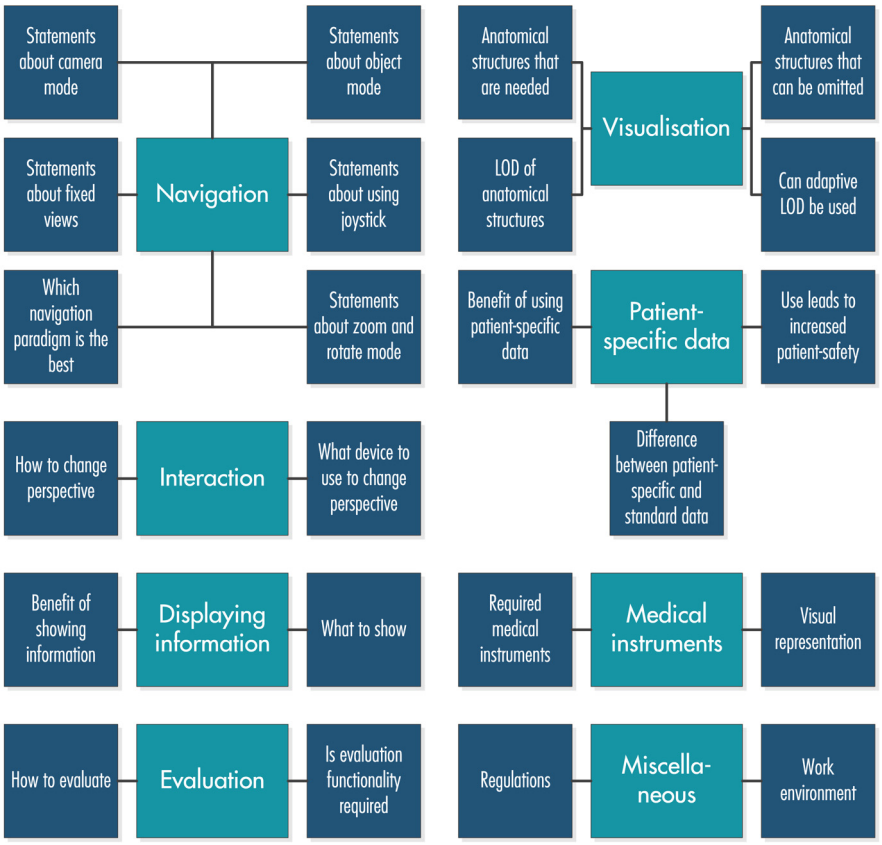


Figure 4-9: Thematic networks about the functionality of surgical simulators.

Themes belonging to the functionality requirements thematic group were as follows:

- *Displaying information:* What surgeons expect to see or experience when using a surgical simulator.
- *Evaluation:* Ideas on how to evaluate surgeons' performance.
- *Interaction:* Statements of the surgeons when interacting with the surgical simulator, such as changing the perspective for example.
- *Medical instruments:* Overview of the required medical instruments for a particular surgical procedure and how to visualise them.

- *Navigation:* Statements of the surgeons when they used the medical demonstrator application and performed simple navigation tasks.
- *Patient-specific data:* Investigates the benefit of using patient-specific data models instead of generic 3D models.
- *Visualisation:* How surgeons expect to see the different anatomical structures.

Furthermore, some miscellaneous information about participants and other topics have been gathered.

The results from the internet surveys were analysed in the same manner as the results from the one-to-one interviews, coded and integrated into the same themes (nodes). They contributed mainly to the medical training methods, surgical simulators, medical conditions and the particular medical scenario for which a simulator should be developed. As these answers were brief and as it was not possible to clarify or discuss the answers, these results could lead to less reliable data as the results from the one-to-one interviews. However, by comparing them with the interview results, they corresponded with these results in topics which were comparable, such as the medical training or justifications such as for the benefit of patient-specific data. The results presented in the following sections which reflect opinions or elaborate topics in depth are mainly based on the one-to-one interviews, but are supported by the answers from the internet survey. Sections are marked where a differentiation between interview and internet survey results contributes to the understanding of the results or conclusions.

The coding of the sources is given in table 4-9, broken down by each theme, whereas one particular data piece can be coded more than once if it fits into different themes.

Table 4-9: Coding of interviews and internet surveys.

Thematic networks	*Themes*	*Number of sources*	*Number of codes*
About surgery	What hand surgery does	4	20
	Real-life examples	2	30
	What orthopaedics do	2	5
	What plastic surgeons do	2	2
	Why skin is important; landmarks	2	2
	What wrist arthroscopy is	1	4
About surgical simulators	Already used surgical simulators	9	27
	Implementation in hospitals	8	39
	Acceptance amongst surgeons	8	10
	What it should have	5	42

Thematic networks	*Themes*	*Number of sources*	*Number of codes*
	Disadvantages and problems	5	28
	Like or do not like surgical simulators	5	8
	Previous experience with 3D or 3D simulators	5	5
	Advantage of surgical simulators	4	10
	What they would do with it	3	11
Displaying information	What to show	9	24
	Benefit of showing information	8	13
Evaluation	How to evaluate	7	29
	Is evaluation functionality required	7	7
General info about participants	Job title	9	12
	Age	8	9
	Professional experience in hand surgery	7	8
	Professional experience in orthopaedics	7	8
	Knows the AO Surgery Reference	5	9
	Education country	4	4
Interaction	How to change perspective	5	16
	What device to use to change the view	5	15
Medical conditions	Proposed surgical procedure to simulate	9	32
	Common medical conditions	9	24
	Important topics about selected procedure	7	28
	Different phases of selected procedure	7	13
Medical instruments	Visual representation of medical instruments	8	20
	Required medical instruments	8	8
Miscellaneous	Work environment	9	16
	Regulations	5	11
Navigation	Which navigation paradigm is the best	4	9
	Zoom and rotate mode	3	6
	Camera mode	3	4
	Object mode	3	3
	Fixed views	2	3
	Joystick	1	2
Other application areas	Surgeons are interested in	3	8
	Good ideas	3	6
	Preoperative planning	2	6
Patient-specific data	Benefit of using patient-specific data	8	25
	Use leads to increased patient-safety	8	9
	Difference patient-specific and standard data	6	6
Training	How surgeons currently get trained	9	76
	Problems of current training of surgeons	4	13
Visualisation	Anatomical structures that are needed	8	46
	Anatomical structures that can be omitted	6	11

Thematic networks	*Themes*	*Number of sources*	*Number of codes*
	Can adaptive LOD be used	5	9
	LOD of anatomical structures	4	30

As seen in figure 4-10, the most statements for a single topic have been given about the training of surgeons. Overall, the most statements have been recorded about surgical simulators.

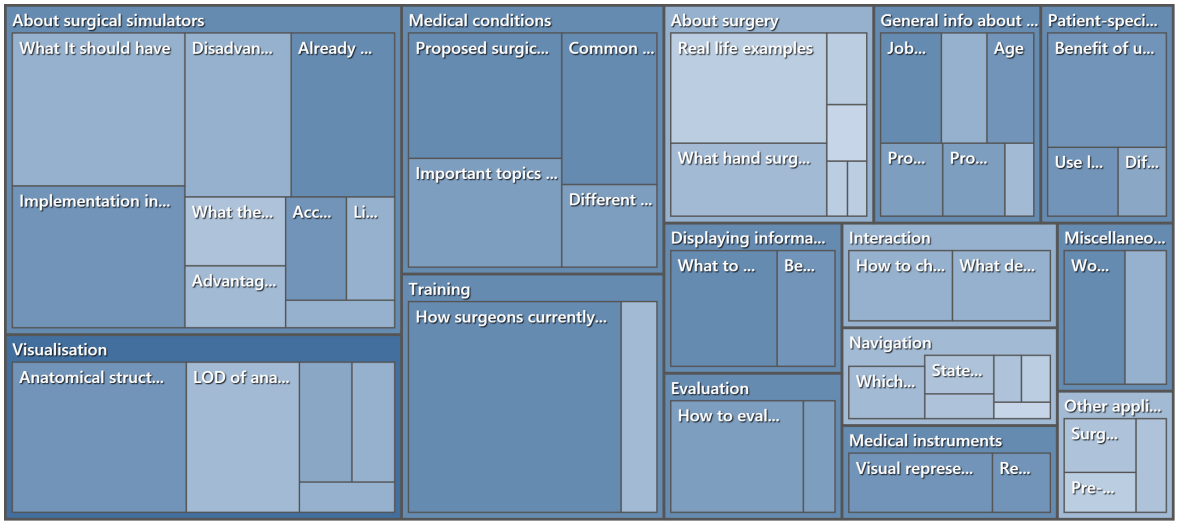


Figure 4-10: Visual representation of the coding: the size of the rectangles reflects the number of coding references, a darker colour indicates more items coded (see table 4-9 for truncated topic descriptions).

4.5 Interview and Internet Survey Results

4.5.1 Training of Surgeons

The interviews of the surgeons showed that the structure of the academic studies in (human) medicine can vary quite largely and depends on the university. One of the most important basic requirements of surgeons is three-dimensional awareness, which is used to transfer an image onto an anatomical situation. This is taught in the high school or in general in the school system. In the secondary school (before higher education), the awareness of ethical and cultural principles are taught. Beginning with the university studies, the training in medicine varies between Switzerland and the UK and is not directly comparable. Switzerland and the UK were particularly suitable, as this PhD project was carried out mainly in these two countries and therefore visiting participants and conducting studies was limited to these countries in the scope of this PhD project.

4.5.1.1 Switzerland

The medical education in the universities is divided into the preclinical (2 years) and clinical (4 years) stage. One of the first topics that is taught at universities which is of special importance for

hand surgery is anatomy, as fine structures such as nerves, sinews and vessels, are close to each other and therefore can require minimally invasive procedure techniques. Anatomy also includes the entire issue of infections, healing and so on. After six years, the university studies end with the state examination and the degree of an *eidgenössisch diplomierter Arzt* (UK: Bachelor of Medicine, Bachelor of Surgery), which authorises to work as an *Assistenzarzt* (UK: Foundation Doctor, FY1 and FY2) in hospitals and private practices as an employee. Since 2007 with the introduction of the Bologna process, students complete their studies with Bachelor in Medicine and Master of Medicine each in three years. After a further year, the doctorate can be completed.

In the surgical disciplines, the first two years working as an *Assistenzarzt* are basically attending and seeing what happens in the hospital. This is completed with a basic exam, similar to the state examination. After that, they work as a doctor, are drafted into military service and then go back to the hospital and work as an *Assistenzarzt in Facharztausbildung* (UK: Specialty Registrar, 1st year). First, they learn traumatology, where they will learn by assisting and start with small things like incised wounds in the emergency department, supervised by experienced surgeons, and later with wound care, which may have already been taught in the senior year during the university studies. The professionals give advice and if it is a more complex problem, take it into the operating theatre themselves where the young assistants can follow them, but that depends on the hospital. They also learn to refine the different examination methods, limits, policies and standards. Basically, it is learning on the job by definition. During the entire time as an *Assistenzarzt*, graduates are expected to familiarise themselves with the literature, writing publications and attending conferences. The training to get the *Facharzt* (UK: Specialty Registrar) can take up to eight years after the final degree and is completed with the *Facharztprüfung* (specialist examinations). After three years of learning hand surgery at an advanced training educational facility, a *Facharzt* is entitled to bear the title *Facharzt (FMH) Handchirurgie* (Schweizer Gesellschaft für Handchirurgie, 2011).

During the university studies, students become more familiar with human anatomy via dissection courses as well as with orthopaedic and surgical procedures. Realistic artificial anatomical models also exist, but they are used mainly only in special courses, offered for example by the AO Foundation. These plastic bone models are typically without soft tissue, although there are models surrounded with foam to simulate soft tissue, but without the associated nerves.

The training on corpses and body parts is becoming more and more difficult due to Switzerland becoming more and more restrictive in these areas. It was common practice that human material, for example surgical specimens, biopsy samples or amputated parts, were used for research without further information or approval of the person concerned (Swiss Academy of Medical Sciences SAMW,

2008). This is not done anymore and it is particularly difficult to get hands or faces. There is a shortage of cadavers, therefore, several institutes import body parts for their courses, which involves the approval of an ethics commission.

4.5.1.2 United Kingdom

The medical education system in the UK changed in 2007 with the introduction of the Modernising Medical Careers (MMC) program, a postgraduate medical training program. First, medical students complete five or six years of medical school, where they learn theoretical basics in areas such as anatomy, physiology and ethics. The admission and course structure depends on the University. Medical students typically get preclinical training in an academic environment for two years and clinical training at a teaching hospital and community settings for three years. After medical school, they undertake two years in a foundation training program, where they learn different specialities, including general medicine and general surgery. During these years, they rotate in different hospital specialities and depending on the region, they also spend six months in a hand surgery department. Then they specialise in one field during a speciality registrar training which lasts a minimum of six years and varies in the different surgical specialities. The curricular scheme of the specialty training is defined by a medical body, the Royal College of Surgeons of England in the case of surgeons. These specialities are offered in two types: run-through trainings, where they automatically progress to the next level as long as they satisfy the requirements, and the uncoupled training program, which is split into a two-year core training and higher specialty training, such as orthopaedics for example. Hand Surgery is also a core component of the higher specialty training in orthopaedic and plastic surgery and includes skills in hand and wrist surgery and techniques in arthroscopic surgery. During the specialty training (between years 5 to 8), advanced training posts are offered to surgeons who want to receive training in both plastic surgery as well as trauma and orthopaedic surgery and take six or 12 months.

Completing the specialty training program with a Certificate of Completion of Training (CCT) qualifies the individual to be entered in the Specialist Register (or GP Register for general practitioners) and is a requirement to get a consultant post in orthopaedic and plastic surgery.

After finishing the training, hand surgery can further be deepened with a Diploma in Hand Surgery program (minimum nine months) or with a fellowship which allows the trainee to visit centres of excellence in the UK and overseas.

4.5.1.3 Stages of Medical Education in Switzerland and United Kingdom

The structure of the medical education is not directly comparable between Switzerland and the United Kingdom. Figure 4-11 outlines the medical career a surgeon pursues until he is a trained hand surgeon.

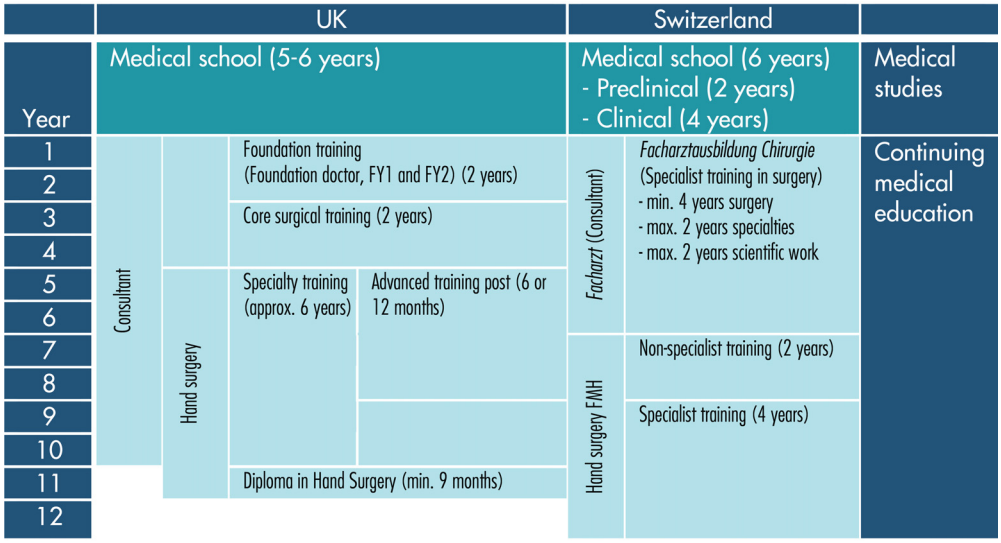


Figure 4-11: Medical education in the United Kingdom and in Switzerland.

The main difference between the training in Switzerland and the United Kingdom is that in Switzerland, training in hand surgery starts after completion of the consultant training, whereas in the UK, parts of the hand surgery training are integrated into the consultant training and continue after becoming a consultant.

4.5.1.4 Medical Education Costs in Switzerland

Although not a topic directly investigated, but raised several times during the interviews is the cost of the medical studies and continuing medical education. Cost estimation is difficult, as the training is organised by both Universities and hospitals. In 2006, the Federal Office of Public Health FOPH (Bundesamt für Gesundheit BAG, 2006) in Switzerland calculated the cost of the medical studies in human medicine to CHF 120,000 per year, summing up to CHF 720,000 for the six-year medical studies. The continuing medical education is estimated to cost CHF 60,000 per year, with a typical length of 8 to 10 years (minimum length five years), summing up to CHF 300,000 to 500,000 (which was roughly 126.000 to 210.000 pounds in 2006 with a relative value of 167.000 to 279.000 pounds in 2015 by respecting UK inflation rates). The overall cost in medicine for surgeons who acquire a Swiss federal certificate of continuing medical education (such as in orthopaedic surgery, internal medicine or anaesthesiology) is estimated to be CHF 1-1.2 million, funded by the cantons with Universities, indirectly by tax money and by insurance rates.

4.5.2 Current Issues with the Training of Surgeons

Three topics have been mentioned which restrict the training of surgeons. First, especially in Switzerland, the use of body parts is becoming more restrictive in medical research or training. Second, in the UK, with the introduction of the Working Time Directive (European Parliament, Council of the European Union, 2003), surgeons are only permitted to work a maximum number of hours, culminating in working 3500 hours instead of 10,000 hours, as it was before, and they will receive their training in a shorter period of time. Thirdly, surgeons in the foundation training would benefit if they had a series of the same operations to gain experience in a particular operation. They may not experience similar operations for two months or more.

4.5.3 Surgery and Surgical Simulators

4.5.3.1 Hand Surgery

Principally, hand surgery is concerned with the diagnosis and treatment of bone and soft tissue injuries of the upper extremities, i.e. fingers, hand, wrist, forearm, upper arm and shoulder. It is usually practiced by an orthopaedic or a plastic hand surgeon. These specialities may overlap, for example for reconstructive surgery.

4.5.3.2 Hand Conditions

According to the surgeons, the most common diseases and surgical procedures in hand surgery are (followed by indicating the number of mentions):

- Nerve entrapment syndrome, such as the carpal tunnel syndrome (5)
- Fractures (4)
- Accidents that are connected with tendons, blood vessels or nerve injuries (3)
- Osteosynthesis, removal of osteosynthetic material (3)
- Stenosing tenosynovitis, such as trigger finger (3)
- Tumour, such as a ganglion cyst (2)
- Corrective osteotomy and arthrodesis (1)
- Infections (on the emergency treatment) (1)
- Other soft tissue disorders such as Dupuytren's contracture (1)
- Pains (1)
- Traumatology and cold hand surgery (1)

- Wrist and elbow arthroscopy (1)

This corresponds with the BSSH — The British Society for Surgery of the Hand (2010a), which lists most of the mentioned medical conditions as common hand conditions, and also with the Schweizer Gesellschaft für Handchirurgie (2011), which lists carpal tunnel syndrome, Dupuytren's contracture and trigger finger as common hand conditions. No differences could be found between the answers from the interviews and the internet surveys, both participant groups noted common hand conditions which are found in the literature.

4.5.3.3 Recommended Surgical Procedures for Training Purposes

The responses to the question "*Which surgical procedure would be the most valuable to practice on a surgical simulator?*" can be divided into two categories: firstly, surgical procedures which are complex or often encountered on a daily basis, and secondly, procedures which include basic operation steps and/or are used in each surgery such as creating the approach to the surgical site with an incision. One participant from the internet surveys responded that simulators are vastly inferior to using living human tissue and that *"there is no substitute for training a surgeon by supervision on the living hand."* Furthermore, he did not suggest a surgical procedure to be used in simulators because *"any time taken is time that could have been used for teaching in vivo"*. However, this way of thinking seems short-sighted, as the point is to investigate if simulators can be a meaningful addition to the current medical training, instead of replacing it, and whether they may one day provide a similar experience as when teaching in vivo.

The following surgical procedures have been primarily suggested:

- *Carpal tunnel release:* Release of the transverse carpal ligament by dividing it into two; the nerve is damaged as a result of a narrowing of the carpal tunnel.
- *Distal radius fracture:* Fracture of the radius bone, can surgically be reduced either by Kirschner wire osteosynthesis (using a wire to reposition the bone fragments) or by open surgery using plates (see also 5.2.3.1, *Operative Treatment Methods*); caused typically by a fall on the outstretched upward wrist.
- *Surgical incision:* The surgical approach on anatomical preparations to be used in each surgery; deciding the right type is based on such factors as the surgical site, related anatomical structures and quicker healing for example.
- *Trapeziectomy:* Removal of the trapezium, a small bone at the base of the thumb; as a result of thumb base osteoarthritis.

- *Treatment of scaphoid fracture:* Reposition of the bones and fixation using metal implants such as screws and wires; caused usually by direct traumatic force, for example by a fall or athletic injuries.
- *Wrist arthroscopy:* Minimally invasive technique to visualise the inside of the wrist; used to assess the integrity of anatomical structures, to aid in the reduction of fractures of the bone and also to remove some types of ganglion cysts.

In addition, the following surgical procedures have been mentioned to be important as well:

- *Arthrodesis:* Artificial induction of joint ossification between two bones, for example interphalangeal joint fusion.
- *Corrective osteotomy:* One or more bones are cut specifically to correct deformities such as malunion of the scaphoid.
- *Elbow arthroscopy:* Treating certain elbow conditions such as small loose fragments of cartilage, bone or elbow joint spurs using arthroscopic surgery.
- *Osteosynthesis:* Reduction and fixation of a bone fracture using implants, mostly made of metal.
- *Other nerve decompressions, for example ulnar nerve decompressions:* Relieving pressure on a nerve trunk by excision of constricting ligaments or widening of the bony canal.
- *Tendon sutures and tendon transplantation:* Sewing a tendon directly to one other or transplantation of a tendon if not enough healthy tissue is available.

Based on the feedback and the variety of the procedures proposed for simulation, orthopaedic surgeons can conceive using simulators in medical education, similarly as in minimally invasive surgery, to teach open surgery basic skills and procedures in a meaningful manner and safe environment. The six procedures, which were additionally mentioned, represent either general approaches (osteosynthesis, corrective osteotomy), specific surgeries (arthrodesis, tendon sutures/transplantation, nerve decompression) or minimally invasive surgery (arthroscopy), which are less suitable for simulation due to the smaller impact in medical education or are already being simulated and researched, such as arthroscopy. Therefore, the following overview focuses on the procedures which were primarily suggested for simulation. Data for epidemiology is stated based on the latest available publications; many authors report similar data in older publications.

Carpal Tunnel Release

This procedure is particularly suitable for practicing basic steps according to a relatively simple scheme and involves mainly only an incision for the approach to the transverse carpal ligament. The pressure from the nerve is relieved by cutting the ligament and thus releasing tension in the carpal tunnel. Carpal tunnel syndrome is one of the most common upper limb compression neuropathies and accounts for approximately 90% of all entrapment neuropathies (Aroori and Spence, 2008). However, the orthopaedic surgery for the carpal tunnel syndrome may be learnt more quickly by observing an experienced surgeon for a certain number of times. The prevalence rate is 3.8% and it is more common in women (Atroshi, et al., 1999).

Distal Radius Fracture

Fractures of the radius bone are the most common fractures. The prevalence is estimated to be 2-3% and about every sixth fracture is a distal radius fracture; about 200,000 people in Germany suffer such a fracture each year (Raschke and Stange, 2009). The treatment depends, amongst other factors, on the displacement and the instability of the fracture fragments. Fractures with no displacement can be immobilised (retention) with an orthopaedic cast; simple displacements are first repositioned and afterwards immobilised with an orthopaedic cast. Surgical treatment involves fixation with Kirschner wires or operative open reduction and internal fixation with plates. There is a large variation in fracture types and there are several approaches to get to the surgical site, but the procedures are standardised.

Surgical Incision

To access the surgical site, incisions are used and usually made with a scalpel, but recent technical innovations led to the usage of high-frequency diathermy devices, such as laser or ultrasonic scalpels. The type of incision depends on the situation and to allow the best possible healing. Incisions made along relaxed skin tension lines may heal better and achieve better cosmetic results, which can be important in sensitive areas and is therefore used especially in aesthetic surgery. The incision is crucial to get a good exposure to the anatomical structures and simulating the approach would therefore be useful for various surgical procedures. A comprehensive standard work about surgical incisions is published by Hoppenfeld, deBoer and Buckley (2009).

Trapeziectomy

The most common procedure for thumb osteoarthritis, which is also the most common osteoarthritis of the hand. For example, it is assumed that about 10% of the German population is affected (Wagenhäuser, 1969). The surgery involves the complete removal of the trapezium and thereby provides more space for the thumb to move, and the pain, caused by the arthritic bone surfaces rub-

bing together, is in most cases eliminated. The treatment modality of suspension arthroplasty for first carpometacarpal joint arthritis contains different surgical techniques and it is rare that assistants perform this operation themselves, especially in large departments where the main focus is on traumatology.

Scaphoid Fracture

The fracture of the scaphoid bone, one of the eight carpal bones of the wrist, occurs most often to young, active people, frequently during sporting events and is the most common type of wrist fracture (Phillips, Reibach and Slomiany, 2004). Each scaphoid fracture is different and requires different operational methods. If the fracture is displaced, the treatment involves using a screw to stabilise the fracture. Although a scaphoid fracture is the most common wrist fracture type, it is much rarer than a carpal tunnel syndrome, and the treatment is only performed by experienced surgeons. Furthermore, simulation can be difficult because the mechanical behaviour of the ligaments on the bones is complex, as many of the adjacent carpal ligaments play a role as secondary stabilisers of the scaphoid and lunate bone complex and also have different tensile strengths such as 150 N for the scapholunate interosseous ligament, which exceeds the maximum force most haptic devices can provide (Pappou, Basel and Deal, 2013, pp.146-147). The annual incidence rate of true scaphoid fractures in the United States is described as 0.029% by Duckworth, et al. (2012).

Wrist Arthroscopy

A minimally invasive surgical procedure used to examine and diagnose such conditions as ongoing pains, the removal of a ganglion cyst or injuries of cartilage, ligaments or articular disk. Under anaesthetic, a fiber-optic tube with a camera attached is inserted into the wrist joint through small incisions in the skin. Introducing small instruments in these incisions, a surgeon can remove portions of tissue or operate on a ganglion cyst (American Academy of Orthopaedic Surgeons, 2013).

4.5.3.4 Previous Experience with Surgical Simulators

Some of the participants have already seen or used surgical simulators for various medical domains, mainly for minimally invasive surgical techniques with endoscopes, for example for shoulder arthroscopy or laparoscopy. Other application fields of simulators the participants have noted are orthopaedics, osteosynthesis and resuscitation. In particular for the training of hand surgery, all participants replied that no surgical simulators do exist, but there are training possibilities for surgical techniques such as enzyme injection (collagenase) into simulated Dupuytren's cord or using animal tendons for repairing. Although not a computer-based simulator, plastic bones are commonly used at courses from the AO Foundation and at universities.

The practical experience of the participants in stereoscopy is mostly limited to three-dimensional films. Except one, none of the participants has ever used a stereoscopic 3D software application.

4.5.3.5 Acceptance of Surgical Simulators

In general, it appears that surgeons are open-minded about surgical simulators, but it can depend on the interest of the surgeon, less on the age group. However, one participant concluded that the acceptance is higher amongst younger surgeons, as they grow up with digital technologies (digital natives). One participant said he knows of certain cases where older surgeons started using laparoscopy, although they always performed it open. They also raised concerns over using surgical simulators as the only method of teaching surgery, but it can be a reasonable addition to for example the dissection of human anatomical specimens.

4.5.3.6 Advantages and Limitations of Surgical Simulators

One of the major advantages of using surgical simulators the participants came up with is that trainees can exceed the limit of what is permitted and see what happens, which is not possible otherwise. The learning process should include occasions where they can make mistakes — to have permission to fail — to realise where the boundaries are and to learn how to avoid them. But then, not every simulator can react to unexpected actions, for example, if a blood vessel is cut, it has to bleed.

One participant came up with another application area where surgical simulators have an advantage over traditional education techniques: the learning of anatomy. Computer-based 3D simulators are ideally suited for training and improving visual-spatial ability and the three-dimensional perspective, which is difficult to get from a book or from interactive learning programs with traditional photographic and illustrated two-dimensional images.

Almost all participant mentioned several times during the interviews that another key aspect is that a surgical simulator should be as realistic as possible and that it represents what a surgeon is expecting in the operating theatre. Otherwise, it could convey the wrong sense. And, as one participant said, *"in the end, it still has to be better than simply send people to a course and let them make it on anatomical specimens"*, meaning considered under economical, usability or flexibility aspects, it has to provide considerable advantages than training people on anatomical specimens, as it is currently practised.

But they also noted that the overall responsiveness of the system could be a drawback. If the visualisation is highly realistic, but each modification of the perspective or the display modes takes some time, the system is not intuitively usable anymore. Therefore, surgical simulators should be designed to run in real time.

The participants also raised concerns about the cost of the system and that it is difficult to find time to use these simulators if it is not part of a medical curriculum.

The following topics are a summary of the salient features, advantages or considerations that have been mentioned:

- Go beyond the limit, see what happens and be able to make mistakes in a controlled environment.
- Be aware of the differences between surgical simulators and real patients.
- Little benefit for procedures which are learnt by observing experts for a couple of times.
- Meaningful to learn anatomy by using 3D visualisation and to gain an understanding of spatial relation.
- The required realism, responsiveness and interactiveness of the visualisation.
- Cost of the system.
- Understand the limitations of simulations.
- Little time available during working hours (and limited willingness to do it after work).

4.5.4 Functional Aspects

The functional aspects were mainly discussed using the developed demonstrator application (see section 4.4) in the one-to-one interviews, as it is easier for surgeons to understand technical aspects if they can try it out themselves. However, as the framework which was used to develop this demonstrator did not yet support haptic feedback at the time the interviews were conducted, haptics was not discussed in depth. It was noted that during using the demonstrator (and in the final surgical simulator), there would be haptic feedback. During preliminary projects (see section 3.3), the value of haptic feedback has already been evaluated and therefore the focus was more on medical aspects and on the current state of medical training, in particular orthopaedic hand surgery. In addition, during the evaluation of the surgical simulator prototypes (see section 6.8), haptic feedback has been discussed during the evaluation of the interaction paradigms.

4.5.4.1 Visualisation

Medical simulations typically have three main elements: medical instruments, anatomical structures of the surgical site and the environment such as the surgical table. All participants generally agreed that the medical instruments (as well as the implants) should be visualised as realistic as possible. One participant, who had previous experience with virtual reality-based simulators, suggested

an additional mode which can be switched on showing overlay trajectories for a better aiming with the wire.

Regarding the visualisation of the anatomical structures, two aspects have been investigated. First, which level of detail is required for each anatomical structure and second, if it is possible to use an adaptive level of detail, which is not distance or frame rate dependent (described by Funkhouser and Séquin, 1993), but time or stage dependent.

Each participant had to choose a surgical procedure and define, which anatomical structures are needed and at what level of geometric detail. This has been done by showing two images for each anatomical structure, one in a higher and one in a lower resolution, as shown in figure 4-12.

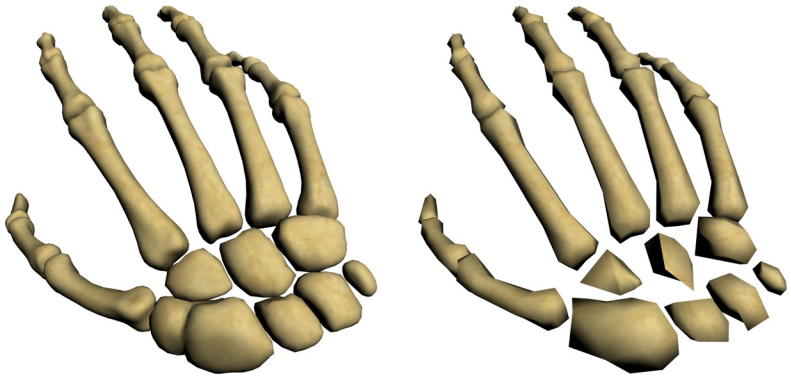


Figure 4-12: Visualisation of anatomical structures, high (left) and low resolution.

The required anatomical structures and their level of detail for the proposed surgical procedures are shown in table 4-10. Although these requirements cannot be directly compared to each other, it emerges that the most important structures for osteosynthesis are bones, bone fragments and nerves. This is not actually surprising, because bones are needed for reduction and fixation and all participants replied that they need the bones to be as realistic as possible, and damaging nerves can lead to severe problems. Additionally, skin is important for the simulation of the access, especially the skin landmarks, from which the position of the osseous anatomy can be deduced (Bugbee and Botte, 1993).

Table 4-10: Required anatomical structures for chosen surgical procedure.

	Carpal tunnel release (2)	*Distal radius fracture (3)*	*Scaphoid fracture*	*Surgical incision*	*Trapezi-ectomy*	*Wrist arthroscopy*
Arteries	1L, 1	–, 1, –	1L	1	–L	1L
Bones	1H, 1	1H, –, 1H	1H	1	1H	1H
Bone fragments	1H, 1	1H, –, 1H	1H	1	1H	1H
Cartilage and ligaments	3L* (carti-lage), 2	–, 1, –	2L	2*	–H* (liga-ments)	1L
Fatty tissue	2*, 2*	1L, 3, –	2*	2*	2*	–*
Muscles	1L, 2	1L,H, 1	1L	1	1H	1L*
Nerves	1L, 1	1L, 1, –	1L	1	1L	1L
Skin	1H, 2*	1L, –, –	1H	2	1	2*
Veins	2*, 3	1L, 1, –	2*	2*	3L*	1L

Key: 1: essential, 2: desirable but not essential, 3: not important, –: not answered. H: high level of detail, L: low level of detail. *: can be omitted if had to.

Numbers in parenthesis indicate the number of participants who chose this particular surgical procedure. Results for each participant are separated by a comma.

Keys consisting only of numbers result from internet survey answers.

As most of the participants started answering this question with something like *"actually, everything"* or by enumerating more or less each anatomical structure, additionally, they had to name those structures they would omit if they had to (marked with a '*' in table 4-10). Most mentioned was fatty tissue (6), followed by veins (4). But from the interview answers, it can be concluded that all anatomical structures should be visualised, as the participants repeatedly mentioned, the simulator should be as realistic as possible and replicate what they will see in an operating theatre, or because *"all structures interact together in creating the conditions which a surgeon has to face"*.

The second aspect of visualising anatomical structures that was investigated was if it is possible to choose from different visualisation levels depending on the stage of the surgical procedure. All participants agreed, that anatomical structures that are not important anymore for a particular stage can either be visualised in a lower level of detail, made translucent or be omitted. So for example during placing the plate, the highest resolution bone is required, but veins and muscles can be shown in lower resolution.

From the interviews, it can be concluded that the environment should be somehow visualised. The minimum would be to visualise the surgical table, as it is an important reference object for the spatial sense. Without any reference for the spatial arrangement, it can be difficult to deduce the position and orientation of the hand model.

4.5.4.2 Interaction

Three topics have been investigated: if and how should the hand be moveable, by which navigation paradigm this should be achievable and which input devices they would use for navigation.

In hand surgery, the hand can be fixed during most of the operation or it can be moved and flipped, depending on the particular type of surgical procedure. For example, for percutaneous osteosynthesis of scaphoid fractures, the hand is not fixed, whereas for a carpal tunnel release, the hand is fixed during the entire operation. The participants were given four choices on how they can move the hand in the simulator or how they can change their view onto the surgical site:

- Not movable at all, only one fixed view.
- Precomputed rotation, the simulator rotates automatically to a predefined view.
- Manual rotation, the user can change the view as he wants to.
- Any other method.

In addition, head tracking was explained and proposed as an option for increased realism, so that the view is changed according to the head position.

The participants liked the idea of having the head position tracked, however, two were not sure if it is really necessary and one makes it dependent on the surgical procedure. No participant favoured the precomputed rotation, but all participants suggested having the possibility to manually rotate the hand. They could also imagine having some predefined views, such as anteroposterior or lateral, which then can be redefined by manually modifying the axes with a 3D mouse.

One participant suggested having a (plastic) model of a hand lying on the table which they can move and turn and the virtual hand model in the simulation is aligned accordingly. The other participants found this also a valuable idea.

The second part of the interaction questions dealt with different navigation paradigms on altering the perspective on the surgical site. The medical demonstrator was used to investigate the acceptance of these paradigms amongst the participants. Four different paradigms were investigated:

- *Fixed views:* Several predefined perspectives such as anteroposterior or lateral which surgeons know from X-ray images.
- *Camera mode:* The camera is manipulated similar to the navigation in first-person shooter games. Pushing the 3D mouse cap forwards, i.e. moving the camera forwards, brings the object nearer.

- *Object mode:* The object is directly manipulated. Pushing the 3D mouse cap forwards also moves the object further away, just as holding the object in the hand.
- *Zoom and rotate:* The manipulation is restricted to four degrees of freedom, namely zooming and rotating.

The fixed views got some acceptance, but the participants criticised that they were obviously less free and that they would need a possibility for further refinements. The camera mode seemed rather difficult to the participants and they showed difficulty with keeping the object in the centre of the screen. The participants showed similar behaviour during the object mode as with the camera mode, but the manipulated object was slightly more centred (possibly due to a learning effect). Both camera and object mode had no restrictions on the movement, whereas the zoom and rotate mode was limited not only to one axis when moving the model, but also the amount of movement was restricted so that the model could not go out of sight. Because during surgery, surgeons cannot move the hand freely in all directions, they liked the idea of just being able to have a closer look at it and rotate it. When asked which one they prefer, they favoured the fixed mode as a starting point and then having the possibility to modify it a little bit. Two points seemed important, first, to have a fixed view as a starting point, which is what they know from X-ray images, and second, being able to have a look at the hand from a slightly different angle is of importance at a later point in the procedure.

The last question was about which input device they would use for changing the view. They used the 3D mouse for three of the navigation paradigms, but they chose to use mouse and keyboard to switch between fixed views and to change the viewing angle. Rotation of the model could be done by mapping different axes to the 2D mouse, changeable with the keyboard. They also mentioned that they are comfortable with what they already know, i.e. mouse and keyboard. If at a later date, 3D mice are common amongst radiologists for example, then, they will also use a 3D mouse, and younger surgeons will probably utilise new input devices. But at the moment, mouse and keyboard are what they expect.

4.5.4.3 Information and Visual Feedback

Most of the participants agreed that showing information during the simulation about the currently selected medical instrument or implant would be helpful. Only one participant was of the opinion that information in not substantially needed, because there is no information displayed in an operating theatre. But when asked, what information to show, the opinions differed. Only a third of the participants suggested showing additional information such as which plate or instrument is cur-

rently selected or the inserting angle of screws. The others preferred having a simulation which is as realistic as possible, with the same information that is available in an operating theatre. One participant preferred to have audio feedback instead of visual feedback, which would not distract that much from the surgical procedure than having to look at information shown near the view field of the simulation.

4.5.4.4 Using Patient-Specific Data

The participants have been asked if patient-specific 3D bone models would provide a benefit. First, three currently available techniques for creating 3D models have been explained:

- *Generic, non-patient-specific model:* The bone model is modelled in common 3D computer graphics software or obtained from a volume model for example.
- *Statistical bone model:* An existing bone model can be adjusted by modifying several components to approximate the patient's bone (Albrecht, 2011).
- *Patient-specific 3D bone model:* A bone model is obtained from a CT scan by converting the volume data into a surface model.

At first, some of the participants supported the idea of using patient-specific bones in the surgical simulator, but when asked about the benefit of it, especially in the case of training, they qualified their statements and noted that it does not matter how the bone model is generated as long as it is realistic, the proportions are correct and it simulates the particular fracture they want to train. However, had the focus of this thesis been on the development of a planning tool, then it would absolutely be necessary to use patient-specific bone models.

4.5.5 Evaluation Methods

All participants agreed that a surgical simulator should provide evaluation functionality. However, how to measure the performance of surgeons is difficult and there are no standards. The first comments of the participants were typically similar to *"you know that usually a few weeks later, when the patient comes back"* or *"you do well if you do it the way the boss wants it"*. Then, stated more precisely, the following approaches on how to evaluate the performance have been mentioned:

- Indication of accidentally injured important anatomical structures such as nerves and arteries.
- Time spent for the procedure.
- Observation by experts and discussion after the task is completed.

- Counting the number of for example instrument changes, rearrangements or position changes of the hand and changes of position or viewing direction.

Although they mentioned the time spent for a surgical procedure, they also said that it is not that important. More important is the patient-safety and that the procedure is executed according to the supervisor.

It gets even more difficult the performance between the trainees should be compared. The participants suggest it is very difficult, almost infeasible. Different techniques exist for the treatment of a specific disease. What is being done to compare different techniques is that final results from clinical studies for a particular disease and the various treatment methods are compared, based on for example the flexibility of the finger joint or if the pains have disappeared after the treatment.

In addition, measuring performance using scores can be a disadvantage for people who have difficulties using computers, but have good clinical motor skills. Instead of using absolute performance ratings, it could be better to measure the improvements from one exercise to another.

4.5.6 Working Environment

The responses of the participants showed that there are two possible locations where they would use a surgical simulator: in their own office or in an open-plan office/dedicated laboratory (skills lab), if one exists. They prefer to have one in their office so they could use it whenever they have some time.

One participant suggested to have the surgical simulator as a web-based application, to offer it as a module or an education course. Then, the surgeons would be able to use it whenever and wherever they want. However, in consideration of the fact that they have little time anyway and that they would need a haptic device attached to the computer, resulting in the installation of additional drivers when they want to train, this is almost infeasible. And, another participant noted that he most likely will not use such a simulator at home.

4.5.7 Additional Topics

In the conversations during the interviews, several considerable topics have been raised. Several participants mentioned that an interesting additional application area for the surgical simulator would be preoperative planning. There, it is mandatory to have patient-specific bone models and anatomical structures and that the surgeons are able to make the planning as they know it from using X-ray images of the fracture and uninjured side and tracing paper (see figure 4-13), as it is still done.

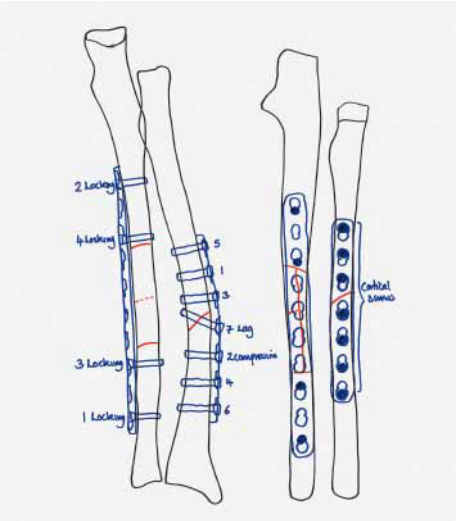


Figure 4-13: Preoperative planning: using tracing paper and X-rays of the fracture and the uninjured side, the fractures are drawn into the intact bone and further details such as the screw sequence is added, leading to the final preoperative plan.[1]

Additionally, it is required that they can save their different steps (including repositioning of the bone fragments, placing the implant and screwing angles) and use it during the operation. Furthermore, a useful addition would be that the screws could then be virtually stressed, to see if it can sustain the load and ensure it is still inside specification.

4.6 Results Summary

This section summarises the information gained from the interviews and internet surveys. The key findings are summarised in table 4-11.

Table 4-11: Key findings of the user requirements gathering study.

Topic	Outcome
Medical training	Similar in Switzerland and the United Kingdom in the medical school, but the specialist training and the further education are kept separate in Switzerland, whereas in the UK they can be attended in parallel through advanced training posts.
Current issues in medical training	Restricted use of body parts, reduction of working time and unpredictable medical conditions in the hospitals.
Most frequent medical conditions	Carpal tunnel syndrome, ganglion cyst and stenosing tenosynovitis.
Most useful procedures to simulate	Carpal tunnel release, distal radius fracture, scaphoid fracture, surgical incision, trapeziectomy and wrist arthroscopy.
Surgical simulators in hand surgery	In contrast to other medical areas such as laparoscopy, no computer-based surgical simulator exists for hand surgery.

1. Rüedi, T.P., Buckley, R.E. & Moran, C.G. (2007) *AO Principles of Fracture Management*. Thieme Medical Publishers.

Topic	Outcome
Main advantages of surgical simulators	To be able to exceed the limit of what is permitted, the possibility of learning anatomy and getting an understanding of spatial relation, but the simulation has to be as realistic as possible, while certain anatomical structures which are less focused in a particular task can be visualised in a reduced quality.
Navigation in the virtual surgical site	All participants suggested to be able to alter the view onto the surgical site, such as refining fixed views, and preferably with mouse and keyboard at the moment instead of a 3D mouse.
Information shown in the simulation	Two thirds of the participants prefer to have the same information shown in the simulation as they would have in an operating theatre.
Evaluation	All participants expect evaluation functionality, such as quantitative parameters (time or injured anatomical structures), however comparing the performance of surgeons is difficult, currently the outcome is compared.
Integration	The surgical simulator should be integrated into a medical curriculum, as there is little motivation to use it after the working day.

The training of surgeons in Switzerland and the United Kingdom varies in the structure of the courses, but there are similarities in the overall structure. First, students complete the medical school, which takes five to six years. Then, the education is split into two stages, the specialist training and the further education in for example hand surgery. Whereas these two stages are kept separate in Switzerland, the specialisation in hand surgery in the UK can already be started during the specialty training with advanced training posts. Current issues that were noted are the restrictions on the use of body parts, the reduction of working time and the unpredictable medical conditions a hospital has to treat and the medical students see during their time in the different departments.

Several hand conditions have been mentioned that hand surgeons have to treat in their everyday work. The most frequently mentioned were carpal tunnel syndrome (5), ganglion cyst (4) and stenosing tenosynovitis (3), which corresponds with statistics from medical associations in the UK and in Switzerland. The participants suggested six surgical procedures that would be useful to simulate: carpal tunnel release (1), distal radius fracture (3), scaphoid fracture (1), surgical incision (1), trapeziectomy (1) and wrist arthroscopy (1).

In certain medical disciplines, surgical simulators are a commonly used tool in the education of surgeons, for example for minimally invasive surgery. But for hand surgery, no computer-based surgical simulator exists, plastic bones and anatomical specimens of arms are used instead. The acceptance of surgical simulators amongst surgeons is growing and they could be a reasonable addition to the current training, although only one participant had previous experience with stereoscopic surgical simulators. Some of the main advantages of surgical simulators surgeons can imagine are to be able to exceed the limit of what is permitted, the possibility of learning anatomy and getting an understanding of spatial relation. But it has to be as realistic as possible and the system has to be intuitive

and responsive. In addition, it is useful to have a cost-efficient system where complex surgical skills and techniques can be learnt, similar to the current education of pilots.

Two visual elements of surgical simulators have been investigated, the visualisation of medical instruments and anatomical structures. The medical instruments should be visualised as realistically as possible, whereas the visualisation of the anatomical structures depends on the surgical procedures. Generally, bones, bone fragments and nerves are required in the highest possible level of detail, the remaining structures should also be visualised as realistically as possible, but can be reduced if necessary. However, for different stages of the surgical procedure, different level of details can be used for the anatomical structures so that at the moment unused structures can be reduced in the visual level of detail, if needed.

In hand surgery, depending on the surgical procedure, the hand can be fixed during most of the time or the surgeon has to move and flip it to reach different areas of the hand. This can be realised in different ways in a surgical simulator, the participants favoured a head tracking solution, though, were not sure if it would be a benefit. But all participants suggested to be able to move and rotate the hand, for example based on fixed views which can be further refined. When asked how to navigate, it emerged that they prefer a paradigm which does not allow free movements, but rather a restricted one (in terms of axes and distance). They also chose to use mouse and keyboard instead of a six-degrees-of-freedom mouse. However, if these devices are more commonly used, they will also use such a 3D mouse.

Concerning visual feedback, two thirds of the participants prefer to see the same information that they would see in an operating theatre, one third prefer to have information relating to the currently selected medical instrument, implant or additional information they would not have in an operating theatre. One participant suggested having audio feedback, which would in his opinion not be that much more distracting than visual information. Haptic feedback was not discussed in depth, as the demonstrator application did not yet support it at the time the interviews were conducted.

Evaluation functionality was required by all participants. They suggested quantitative parameters such as time, number of changes of medical instruments or injured anatomical structures. Technical experts suggested logging every movement so that the simulation could be replayed and later evaluated by medical experts. Comparing the performance of surgeons is also difficult; at present, the outcome of studies analysing treatment methods are evaluated and compared, but not the performance of surgeons itself.

Most likely, the surgeons would use the surgical simulator in their office or in an open-plan environment. Also, a web-based solution has been proposed, however, this will be difficult due to having to attach and install haptic devices on the computer. Furthermore, there seems little motivation to use this surgical simulator at home after the working day.

During most interviews, preoperative planning was a topic surgeons were interested in. If the surgical simulator uses patient-specific data, a preoperative planning tool is technically feasible and would replace the current two-dimensional planning of surgical procedures using X-ray images.

4.7 Discussion

One of the most important findings of the interviews is that a surgical simulator should reflect what surgeons are confronted with in an operating theatre when used to train surgical skills and procedures, rather than using abstracted visualisation systems to teach a particular technical or navigational skill, as it is being done by ARTHRO Mentor (Simbionix, 2011). Simulators teaching complex surgical skills and procedures require a highly realistic anatomical model, evaluation functionality and a response system to confront surgeons with critical and unexpected situations, as also described by Dankelman and Di Lorenzo (2005). Such a simulator would not replace the current medical training structure, it would supplement it by adding a possibility for skills acquisition for early stages of the learning curve. This would also address the problem of the more and more restrictive practice on the use of body parts and increasing regulations and move from the currently common learning by doing to alternative, more efficient and safe education methods.

However, one possible limitation of this study is that the findings may not reflect the best solution to train surgical skills. Therefore, this study has been conducted in two different countries to compare the responses amongst them and the responses have also been compared with literature. It became apparent that although the training varies in different countries, similar principles are applied. In addition, simulator-based training is becoming widely used, however, some still have limited evidence-based data to support their validity and reliability (Hammoud, et al., 2008), but they are considered as the future of medical education and have already proven its worth in various surgical fields (for example Obdeijn, et al., 2015, Lateef, 2010). Although each medical expert has his own opinions about what is important, and as they are affected by their area of work, by interviewing medical experts from different orthopaedic fields and in different countries this concern is addressed as far as possible.

Six surgical procedures have been primarily suggested for simulating: carpal tunnel release, distal radius fracture, scaphoid fracture, surgical incision, trapeziectomy and wrist arthroscopy. To choose

the procedure which will be simulated, each is set in contrast with each other and evaluated relating to impact, technical feasibility or time required to learn the procedure. These evaluation criteria can be divided into technical, medical and other aspects. The following aspects were used to evaluate the surgical procedures and to choose the most promising one:

- Technical aspects:

  —*Visual complexity:* Medical simulations require a highly realistic visualisation that leads to high apparent visual complexity and thus high computational and rendering costs when combining FEM (finite element method), volume rendering for soft tissues and high resolution models.

  —*Haptic complexity:* Due to the anatomical and biomechanical complexity of the hand and wrist, the realistic simulation and haptics interaction of the involved hand and wrist part requires computation of many collisions and resulting forces within a minimal time interval.

  —*Required force of haptic devices:* The reduction of fractures requires force to be applied to the bone fragments to restore the correct alignment. Haptic devices have a maximum force output they can apply. Surgical procedures requiring high forces also require larger haptic devices, which are accordingly more expensive.

  —*Required computational power:* The resulting computational cost of the simulation consists of the computation of the visual complexity of the scene, the haptic feedback and the logging system. To gain consumer acceptance, the surgical simulator should be capable of running on consumer (high-end) hardware to bring it to the market at a reasonable price. Compared with haptic devices, the additional price of high-end over mid-range consumer hardware is insignificant.

- Medical aspects:

  —*Medical relevance:* The impact of the surgical simulator on the training of surgeons also depends on the medical relevance of the simulated surgical procedure. The acceptance amongst surgeons increases when using medically relevant procedures and if the simulator brings considerable benefits.

  —*Frequency of occurrence:* Very rare surgical procedures will most likely be less beneficial to a surgical simulator than procedures that are more frequent, because purchasing a system

which will rarely be used will have a longer payback period than a system that is heavily used during the education of surgeons.

—*Number of approaches:* A more frequently used surgical procedure is better suited for teaching using simulators. Different approaches can require different simulations and therefore higher cost.

—*Standardisation:* A standardised surgical procedure allows better evaluation amongst surgeons and a broader application area in different hospitals and countries.

—*Required medical instruments:* Surgical procedures, where different types of medical instruments are used, need a more sophisticated haptic engine to simulate the different aspects of each medical instrument type. Information regarding required medical instruments is based on the participants' answers and on information available from the AO Foundation about the treatment of the particular procedures.

—*Size of surgical site:* The surgical simulator is limited in the size of the surgical site it can realistically visualise. Trying to visualise an entire human body on a typical computer display will result in a less realistic simulation than a life-size simulation of only a part of the human body.

- Other aspects:

—*Learning curve:* Surgical procedures that have a steep learning curve are not well suited for teaching by surgical simulators. For example, a carpal tunnel release is learnt by observing experienced surgeons over a short period, after which trainee surgeons can perform it themselves. Instead, procedures that are complex, that poses high risk to patients and that have a steep learning curve can benefit from practice and repetition with a surgical simulator (Dasgupta, Ahmed, Jaye and Khan, 2014, p.74).

—*Existing products/research:* A medical application area where little research has been carried out or no commercially available products are available may have higher chances of success, however, it can also mean that the required technical achievements are still lacking.

—*Cost:* An important selling point is the cost, especially with the current economic outlook (end of quantitative easing and national debt in EU countries). Therefore, the surgical simulator should be aimed at a broad target group, be usable for common surgical procedures or techniques and be upgradeable for future scenarios.

In table 4-12, each of the above aspects has been weighted to reflect its overall importance and been rated on a scale of 1 to 5, with 5 being the best (weights in parentheses). The weight scale is based on the findings of the interviews and internet surveys and on technical aspects, which are based on the practical knowledge which resulted from the projects described in section 3.3. For example, a value of 2 for haptic complexity for scaphoid fractures means that this surgical procedure requires highly computational haptics.

Table 4-12: Evaluation of surgical procedures with regard to computer-based simulation.

	Carpal tunnel release	*Distal radius fracture*	*Scaphoid fracture*	*Surgical incision*	*Trapezi-ectomy*	*Wrist arthroscopy*
Visual complexity (5)	5	4	4	5	3	5
Haptic complexity (10)	4	3	2	4	2	4
Haptic force (5)	4	3	3	5	3	5
Computational power (2.5)	5	2	2	5	2	4
Medical relevance (20)	3	4	5	4	4	3
Frequency (10)	5	5	3	5	4	4
Number of approaches (5)	5[a]	4[b]	3[c]	4	4[d]	3[e]
Standardisation (10)	4	4	2	5	4	4
Medical instruments (5)	4	3	3	5	3	5
Surgical site (2.5)	5	4	3	5	4	5
Learning curve (5)	3	4	5	3	5	3
Existing products (10)	4	5	5	3	5	1
Cost (5)	5	4	3	5	3	5
Total	350	360	337.5	405	350	342.5

a. Mainly two approaches: endoscopic and open carpal tunnel release (Thoma, Veltri, Haines and Duku, 2004).
b. Five commonly used techniques (Diaz-Garcia, Oda, Shauver, and Chung, 2011).
c. Common techniques are percutaneous arthroscopic and open reduction (Geissler, et al., 2012).
d. Performed through either an anterior or posterior approach (Ritchie and Belcher, 2008).
e. Dorsal and volar approaches for several techniques (Villanova and Del Pino, 2011).

According to table 4-12, the most promising surgical technique is the surgical incision, followed by distal radius fracture, carpal tunnel release and trapeziectomy. From a medical point of view, an important surgical procedure is the treatment of a scaphoid fracture, as it is common and the diagnosis can be difficult, but surgery is typically required only for displaced fractures (Phillips, Reibach and Slomiany, 2004). In the opinion of one participant from the interviews, it is even the most important fracture for hand surgeons. Distal radius fractures and trapeziectomies are frequently occurring procedures which require different surgical techniques and a precise execution. Trapeziectomy in particular is a frequently performed surgery, however, it is rarely taught during medical education. Wrist arthroscopy has become the third most common joint to undergo arthroscopy[1], and several

commercially available products for knee and shoulder arthroscopy are available, but none for wrist arthroscopy (Obdeijn, et al., 2015). Surgical incisions are used for most surgical procedures and must be performed safely and efficiently. The decision concerning which blade to use is important, as well as where and how to cut to re-establish functional soft tissue structural support and to heal without scarring (Semer, 2007). According to the participants, in most cases the palmar approach is chosen and one type of scalpel is used.

In hand surgery, operating on fine blood vessels, tendons and nerves requires high precision and dexterity, therefore, they are mostly performed with surgical loupes, see figure 4-14. Typically, a magnification of 2.5 to 3.5 is used, up to a maximum of 4.5. The normal working distance is about 45 cm. The effect of using magnifying loupes for skill acquisition during preclinical dentistry courses for first-year students has been analysed by Maggio, Villegas and Blatz (2011). These students using loupes worked faster, completed more preparations and required less computer-assisted evaluation resulting in greater overall performance.



Figure 4-14: Using surgical loupes to enhance visualisation of tissues and to allow closer access to the surgical field using the example of a distal radius fracture treatment.

Medical instruments can require more than six degrees of freedom. A scalpel can easily be simulated by a six-DoF device by mapping the orientation of the end effector to the scalpel and thus simulating cutting (or even by a three-DoF device by only simulating the pressure point of the blade). However,

1. American Society for Surgery of the Hand (2014) *Wrist Arthroscopy — Purpose, Procedure and Recovery.* [Online]. 2014. Available from: http://www.assh.org/handcare/procedures-and-treatment/wrist-arthroscopy [Accessed: 14 November 2015].

simulating scissors requires an additional degree of freedom to open and close them, as well as haptic grasping of the hand to move or rotate it.

Surgical procedures that require more than one surgeon to perform need a simulator that can control the other virtual surgeons, if the system is designed for one user, or it has to be collaborative so that a team of surgeons can perform the procedure at the same time. All four surgical procedures can be performed by one surgeon and one assistant; typically, more people are involved in a hospital than in private practices. Wrist arthroscopy is typically performed by one surgeon.

The following table 4-13 elaborates on the pros and cons of simulating each surgical procedure or technique and on the evaluation criterion of table 4-12:

Table 4-13: Pros and cons of suggested surgical procedures for simulation.

Procedure	*Pros*	*Cons*	*Non-judgemental*
Carpal tunnel release	• Very common surgical procedure. • Not only hand surgeons perform this procedure, but also general practitioners. • Entry level surgical procedure, teaches basic principals. • Mainly one approach.		
Distal radius fracture	• Common surgical procedure. • Mainly two approaches. • Different surgical skills and techniques used.	• Involves manipulating.	
Scaphoid fracture	• Screw insertion is a tender point. • Requires spatial sense because of the shape of the trapezium. • Different surgical skills and techniques used.	• Involves manipulating. • Requires rebuilding mechanical behaviour of anatomical structures.	• Rather difficult surgical procedure, only operated by hand surgeons.
Surgical incision	• Used for most surgical procedures. • Currently trained on body parts.		
Trapeziectomy	• Difficult, as performing near arteries. • Different surgical skills and techniques used.	• Involves manipulating. • Requires rebuilding mechanical behaviour of anatomical structures.	• Only operated by hand surgeons.
Wrist arthroscopy	• Well-suited for software-based simulation.	• Similar to other arthroscopic procedures where simulators already exist.	

In summary, simulating only one particular surgical procedure or one technical skill would not be as promising as having a simulator which is able to provide a playground for learning anatomy, basic surgical skills and operating techniques. Therefore, although particularly suitable for computer-based simulation, wrist arthroscopy is similar to other existing arthroscopy simulators and would only expand the medical application area of arthroscopic training. Scaphoid fracture and trapeziectomy are technically equally challenging, with the outstanding problem of simulating the biome-

chanical behaviour of the ligaments and other anatomical structures in the hand to create a realistic simulator to train these conditions and procedures. In addition, these two surgical procedures involve manipulating the hand, which is difficult to simulate because of two aspects: first, a novel input device has to be developed for realistic manipulation of the hand, and second, as all anatomical structures act together in a highly complex biomechanical behaviour, this has to be rebuilt to a great extent to simulate realistic manipulation of the hand in the virtual simulation.
The remaining three, distal radius fracture, carpal tunnel syndrome and surgical incision, are all well-suited for using in medical education and would have the highest impact on training improvements. Possible scenarios include:

- *Carpal tunnel syndrome:* Simulation of approach, soft tissues and division of transverse carpal ligament into two.
- *Distal radius fracture:* Simulation of palmar or dorsal approach, reduction of bone fragments and fixation with plate.
- *Surgical incision:* Present the trainee with a problem and he has to decide where to cut.

For both carpal tunnel syndrome and distal radius fracture, the surgical incision is used to access the surgical site. The simulation of manipulating the hand to realign the bone fragments in a distal radius fracture is difficult due to the previously elaborated reasons; therefore, according to the participants, when the trainee successfully opened the surgical site, it may be feasible to skip this stage and to proceed with the fixation of the plate. Although there is no commercially available simulator for the training of carpal tunnel release (see section 2.3.2, *Training and Surgical Simulators in Hand and Wrist Surgery*), a low-cost hybrid prototype of a simulator is being developed by Johnson, Switalski and Jellings (2011). Therefore, choosing the distal radius fracture as the medical context in which the surgical simulator will be developed seems the most promising scenario.

Chapter 5

Requirements Analysis

5.1 Chapter Summary

This chapter first presents an overview of the chosen medical scenario, the treatment of distal radius fractures. Then, the requirements of a surgical simulator for this particular medical scenario are defined, based on the user requirements gathering study presented in the previous chapter. Finally, the previously identified use cases and requirements were assessed for their feasibility of implementation and a final decision was taken for the development of the surgical simulator.

5.2 Overview of the Treatment of Distal Radius Fractures

In this section, an overview of the distal radius fracture and its treatment is given. It is based on Siebert and Klonz (2005), who published a comprehensive overview of the anatomy of the fracture, the diagnosis and the various treatment methods and which also serves as a revision course for medical specialists.

5.2.1 Epidemiology

As seen in the previous chapter, the distal radius fracture is a relatively common occurrence with an estimated prevalence of about 2-3%. About 200,000 people in Germany suffer such a fracture each year (Raschke and Stange, 2009) and it accounts for almost 18% of all fractures in the elderly age group and 25% in the paediatric population (Nellans, Kowalski and Chung, 2012). Basically, two age groups can be distinguished:

- Young age between 9 and 18 years old: mostly leisure, sports and work accidents from high energy trauma.

- From the age of 50, predominantly women: typically from low energy trauma caused by falls due to frailty (home accidents), associated with postmenopausal osteoporosis.

5.2.2 Anatomy

Distal radius fractures affect the wrist, namely the radius bone, one of the two bones of the forearm. The end of the radius is adjacent to the head of the ulna and the two carpal bones scaphoid and lunate, see figure 5-1.

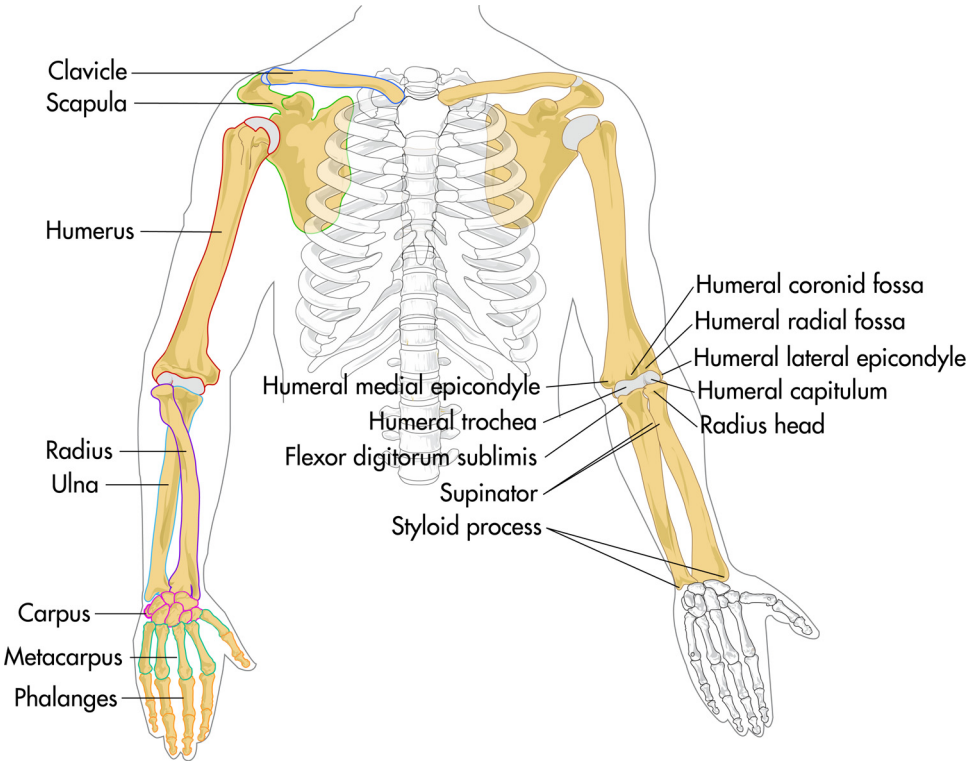


Figure 5-1: Upper part of body showing position of radius (outlined in violet), ulna and carpal bones.[1]

5.2.3 Treatment Methods

Distal forearm bone fractures (and fractures in general) can be classified according to the system AO/OTA Classification of Fractures and Dislocations (see section 4.3.1.1, *Scenarios and Use Cases*). For distal radius and ulna fractures, which are defined as the localisation 23 (2 for radius/ulna, 3 for distal), different fracture patterns are distinguished, see figure 5-2.

1. Image based on: WIKIMEDIA COMMONS (2007) *Human arm bones diagram*. [Online]. 2007. Available from: https://commons.wikimedia.org/wiki/File:Human_arm_bones_diagram.svg [Accessed: 7 May 2012].

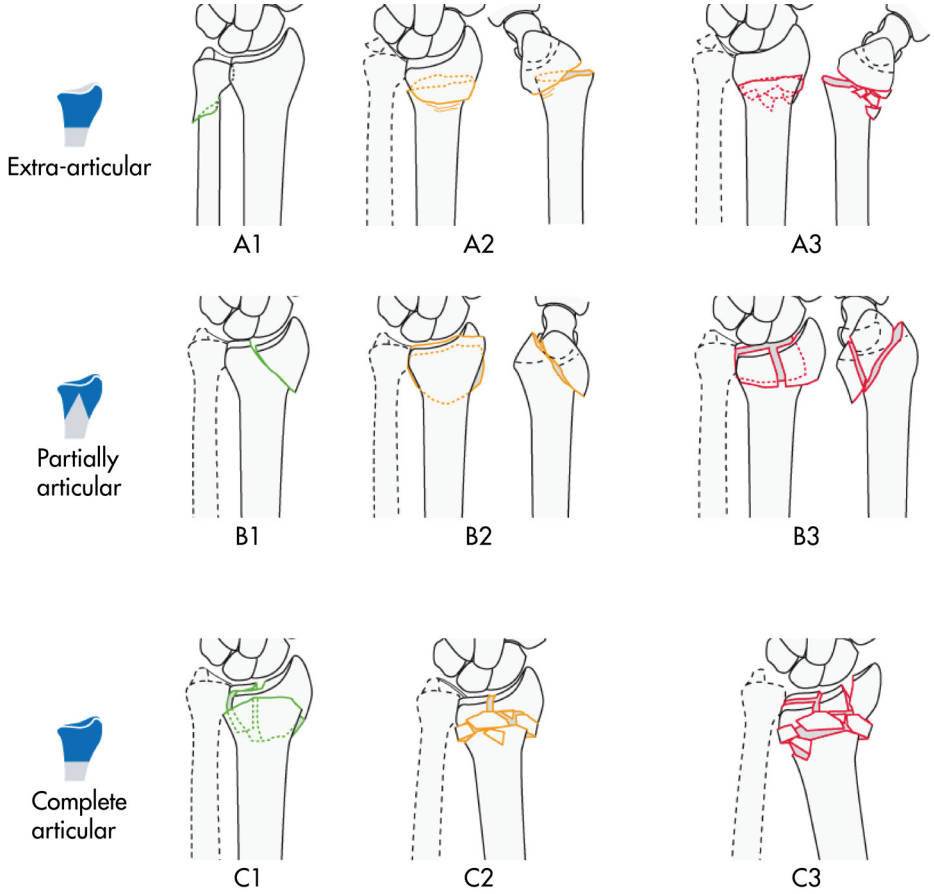


Figure 5-2: AO/OTA classification of distal radius fractures.[1]

Three methods exist for the treatment of distal radius fractures, depending if the fracture is displaced/undisplaced and additionally for displaced fractures, if it is stable/unstable. Undisplaced fractures, meaning the fracture fragments have not changed the anatomical alignment, can be treated conservatively (closed reduction) and by immobilising in an orthopaedic cast or a forearm splint (AO/OTA classification types B1 and C1). In addition, small displaced fractures can be reduced by manipulating the fragments so that their position is maintained without traction and can then also be treated conservatively (AO/OTA classification type A2) (Holz, 2004).

5.2.3.1 Operative Treatment Methods

Displaced, unstable fractures are treated clinically with osteosynthesis, either by minimally invasive surgery or open surgery. Different kinds of osteosynthesis are used:

- Kirschner wire fixation
- Screw fixation

1. Image based on: JUPITER, J. & RIKLI, D. (2012) *Distal forearm — Diagnosis — AO Surgery Reference*. [Online]. 2012. Available from: http://www.aosurgery.org [Accessed: 8 May 2012].

- Plate osteosynthesis with different approaches
- External fixation
- A combination of the above

Figure 5-3 shows in summary the indication for distal radius fractures.

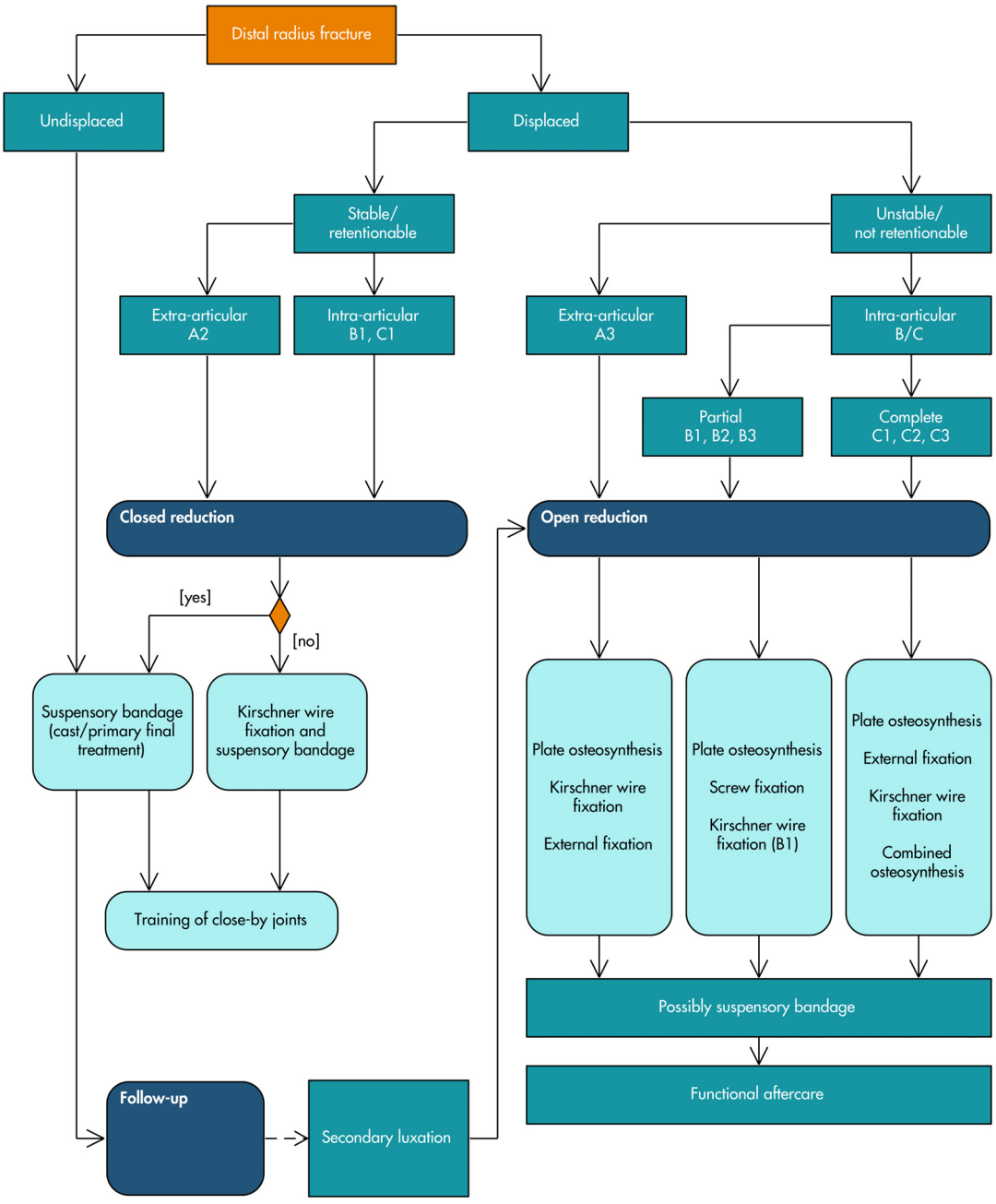


Figure 5-3: Indication of distal radius fractures (Dressing, 2015).

According to one of the participants, a commonly used treatment process is with a palmar plate using the palmar approach, AO classification type 23-A2.2 ORIF (open reduction internal fixation). Generally, if the method and fixation technique have been determined, the treatment consists of

three stages: preparation, approach and reduction/fixation. To prepare a patient for the distal radius fracture, the patient is positioned supine and the hand is outstretched on a hand table, see figure 5-4. To open the surgical site, two approaches can be used, the modified Henry approach (see figure 5-4, right), which exposes the radius, and the extended carpal tunnel approach, which exposes the distal radius and the median nerve and allows to combine carpal tunnel decompression.

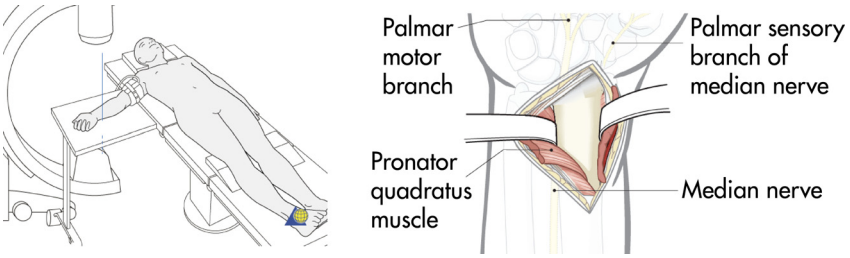


Figure 5-4: Patient position and modified Henry approach.[1]

Once the surgical site has been accessed, two options are available for reduction. Either by reducing the fracture with the plate or by manually reducing the fracture with traction and flexion of the fragments and by stabilising the fracture with a Kirschner wire. The fracture gets fixated by applying the plate and inserting screws distally and proximally through the plate, see figure 5-5.

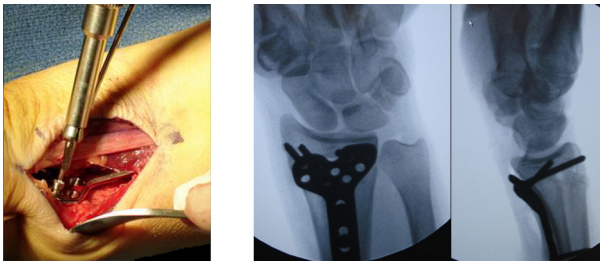


Figure 5-5: Screw insertion and finished plate fixation.[2]

About 7 to 10 days after surgery, the sutures are removed and the reduction is checked with an X-ray. Then, functional exercises are initiated and resistance exercises start about six weeks after surgery.

1. JUPITER, J. & RIKLI, D. (2012) *Distal Radius — Preparation and Approach.* [Online]. 2012. Available from: http://www.aosurgery.org [Accessed: 9 May 2012].
2. JUPITER, J. & RIKLI, D. (2012) *Distal Radius — Reduction & Fixation.* [Online]. 2012. Available from: http://www.aosurgery.org [Accessed: 9 May 2012].

An overview of the different user tasks involved in the operation is given in figure 5-6, presenting the modified Henry approach and the procedure which uses a plate to reduce the fracture.

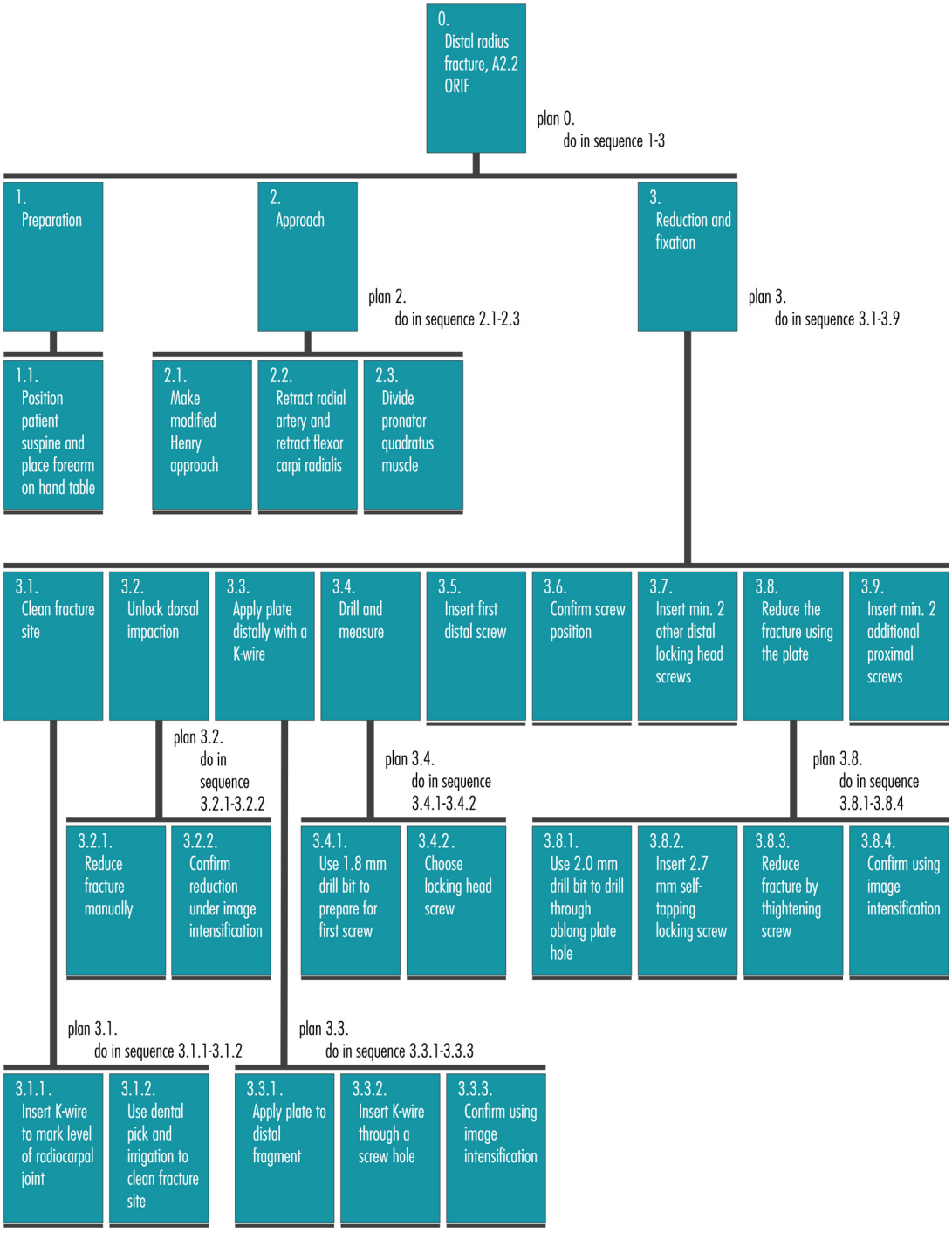


Figure 5-6: Elaborated hierarchical task analysis of distal radius fracture, AO type 23-A2.2 ORIF with plate reduction, according to the surgical management process proposed by the AO Foundation.[1]

1. According to JUPITER, J. & RIKLI, D. (2012) *Distal Radius.* [Online]. 2012. Available from: http://www.aosurgery.org [Accessed: 9 May 2012].

5.3 Requirements Specification

This section describes the user requirements on a computer-based surgical simulator to train the treatment of distal radius fractures.

5.3.1 General Description

Based on the analysis of the interviews, several important aspects can be deduced. Firstly, the surgical simulator should be as realistic as possible. This also includes the interaction with the simulator; haptic devices with custom end effectors, which resemble real surgical instruments in terms of handling should be used instead of the standard ones. Secondly, additional information during the simulation is useful, but should be minimised to that what surgeons currently have during real surgery, but with the option to augment if necessary. Thirdly, the surgical simulator should be able to respond to different actions such as cutting into a vein.

From an evaluation point of view, the simulator should be able to record all relevant user actions to replay the entire simulation for subsequent analysis of the trainee's performance and documentation of the training process. Since automated evaluation of surgical performance is difficult, two approaches could be followed: evaluation of quantifiable parameters such as cutting into anatomical structures and discussion of overall surgical performance.

Three user roles may be distinguished from the study:

- *Trainees* use the simulator to learn a surgical procedure or skill.
- *Evaluators* analyse the performance of trainees using the feedback they get from the simulator and by reviewing the trainees recorded actions.
- *Operators* can interfere to confront trainees with new conditions or can take corrective actions.

For a distal radius fracture simulator, the use cases in figure 5-7 have been identified after the analysis of the interviews. Most likely, new use cases will be added or existing ones will be refined during the design or implementation process according to the feedback of surgeons and medical students.

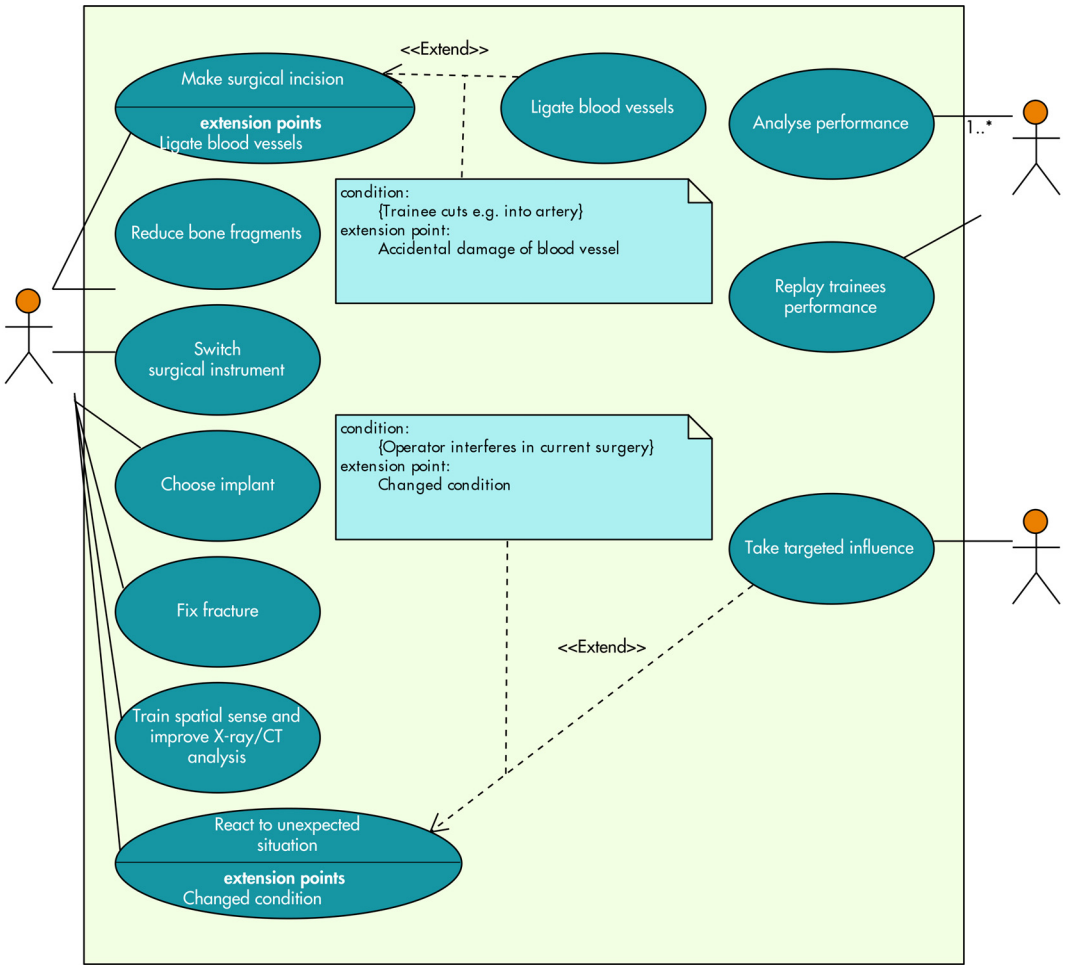


Figure 5-7: Different use cases for a distal radius fracture treatment training simulator.

Tables A-1 to A-11 in section A.2 of Appendix A elaborate further each use case.

5.3.2 Requirements

The requirements for the surgical simulator can be divided into functional and non-functional requirements. The functional requirements were derived from the defined use cases, whereas non-functional requirements were extracted from the responses of participants and from the behaviour they showed during the usage of the medical demonstrator application. Additionally, non-functional requirements were also defined by software architecture and engineering considerations (such as the programming language or software libraries). Figure 5-8 gives an overview of the requirements and specifies the capability and conditions the surgical simulator has to deliver.

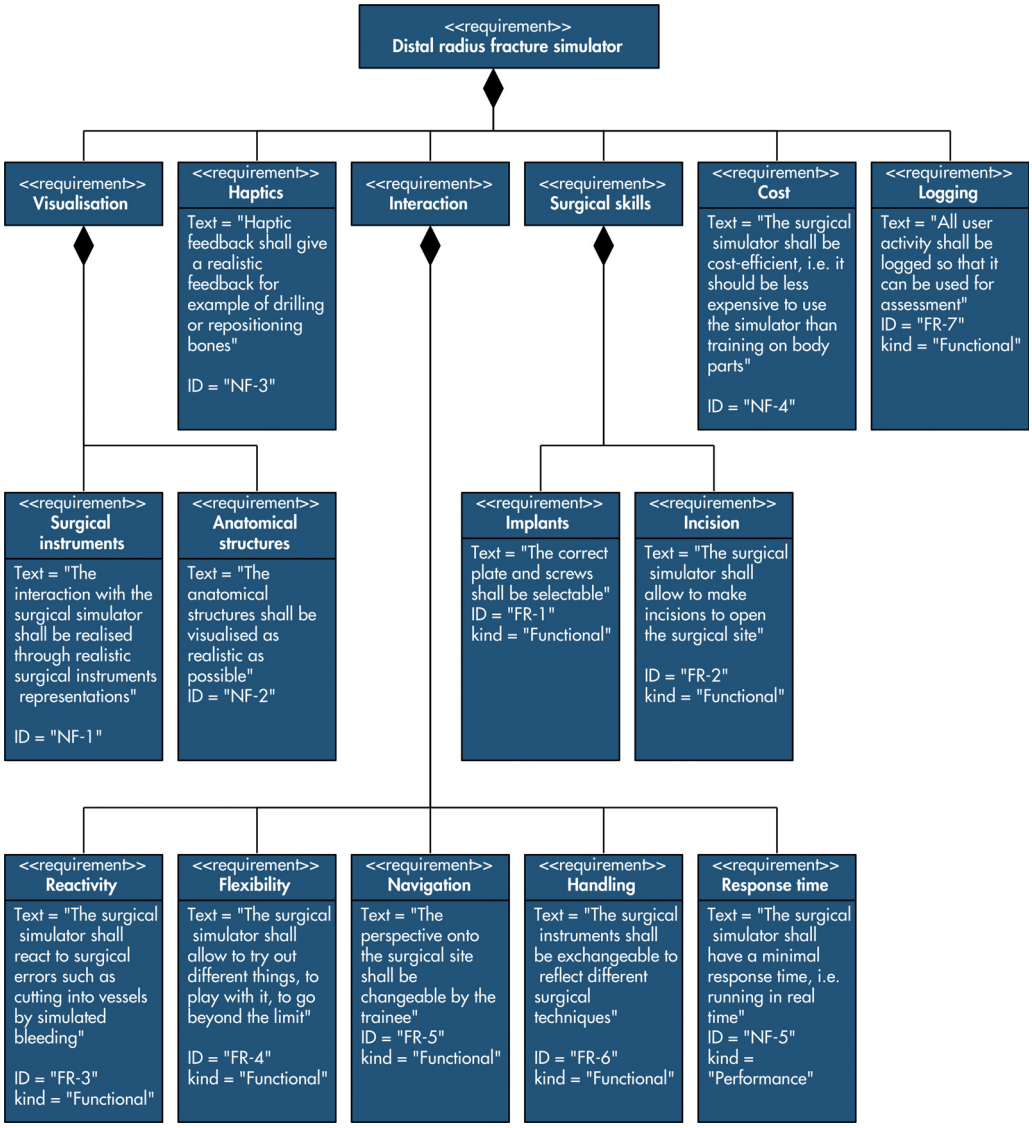


Figure 5-8: Overview of identified user requirements.

The functional requirements are detailed in section A.3.1 and the non-functional requirements are detailed in section A.3.2 of Appendix A.

5.4 Feasibility of Use Cases and Requirements

A computer-based surgical simulator which includes all uses cases identified in section 5.3.1 provides a training environment for surgeons to completely train the treatment of distal radius fractures. Due to the limited scope of this project, the most promising use case(s) regarding surgeons' needs, technical feasibility and scientific relevance have been implemented. Each use case is reviewed in table 5-1, based on the findings of the interviews and internet surveys and on technical aspects, which are based on the practical knowledge which resulted from the projects described in section 3.3, to choose the most promising one(s) for implementation.

Table 5-1: Review of use cases.

	UC-1 *Make surgical incision*	*UC-2* *Reduction of bones*	*UC-3* *Switch instruments*	*UC-4* *Choose implant*	*UC-5* *Fixation*	*UC-6* *Spatial Sense*	*UC-7* *React to unexpected*	*UC-8* *Analysis*	*UC-9* *Replay performance*	*UCE-1* *Ligate vessels*	*UCE-2* *Take influence*
Surgeons' needs	H	H	H	H	H	H	M	M	H	M	L
Existing products	L	L	M	H	M	L	L	M	H	L	M
Current research	M	L	L	H	M	L	L	M	L	L	L
Scientific relevance	H	H	L	H	H	H	M	H	L	H	L
Dependency for other use cases	M	M	H	M	L	L	L	L	H	L	L
Technical feasibility	M	L	H	H	M	H	L	L	H	M	H
Required equipment	L	H	M	L	H	L	L	L	L	M	L
Applicability to other areas	H	M	H	M	H	H	H	H	H	M	H

Key: Influence factor: H = high, M = medium, L = low.

5.4.1 Use Cases

A differentiation should take place between uses cases describing commonly used activities such as switching a surgical instrument and use cases describing a particular surgical activity. Use cases UC-3 and UC-9 are widely used in other use cases and can therefore be considered as mandatory. Implementing the functionality to switch surgical instruments as in UC-3 also includes having different end effectors to simulate the instruments or to provide an appropriate interface to interact with anatomical structures. From a technical point of view, implementing UC-3 is feasible and requires an intuitive paradigm to change instruments, and custom end effectors could be made by 3D printers, if the haptic device supports switching them.

The main complexity of use case UC-9 involves having a logging system, which is able to record all user activity with the haptic device(s) in real time. Since haptic rendering is executed at high update rates, the logging system needs to record the relevant parameters of the haptic devices in an efficient data structure, which does not interfere with visual rendering and other activities. A simpler solution would be to capture the viewport of the virtual reality simulator into a video file for later playback, with the disadvantage that the view onto the scene cannot be changed.

Use case UC-8 most likely requires that UC-9 is implemented, because according to the interviewees, analysing the performance of trainees is best done by a review of medical experts since it is difficult to automatically assess the performance besides basic parameters such as counting hand movements or the damage on anatomical structures. Work on assessing performance on a mastoidectomy virtual reality-based simulator (but is also applicable to other medical domains) to provide

constructive feedback to the trainee has been carried out by Sewell, et al. (2008), and furthermore, they found that the inclusion of metrics and visual feedback resulted in a more pleasing experience and likely more time being spent using the simulator.

Use case UC-1 is used in many operations, also in other medical domains, and therefore the surgeons suggested that this use case is of high significance. As one participant said about which phase of the surgery is the most important: "*I think the approach. Because if you get the approach right, then you have things in front of you and your operation is getting very easy. If you get the approach wrong, you cannot see where you are and what you are doing, and you struggle for the rest of the operation*". Research is being conducted in the field of deformation of tissue using the finite element method to simulate cutting, for example by Nienhuys and van der Stappen (2001) or Vloeberghs, et al. (2007). This use case is expandable with UCE-1, for example when a trainee cuts into an artery, to create a training simulator for surgical incisions, independent from the medical scenario.

Amongst surgeons, use case UC-2 is also of high interest and rated as the second most important phase of the surgery, because it is important that the bone fragments are at the right place for fixation of the fracture. However, reducing bone fragments includes applying traction to immobilise the hand and wrist in the reduced position. Simulating this use case leads to several issues, depending on the haptic device that is used:

- *Haptic forces:* Manipulation of the hand and wrist can exceed the maximum force a haptic device can exert or the maximum stiffness it can render.
- *Variety of movements:* The methods used for reduction can be difficult to simulate because of the different movements of the hand and directions. Furthermore, a customised end effector should be built to realistically simulate a wrist, which can be difficult to mount on the haptic device.
- *Size of working area:* The force feedback workspace is limited and can be too small for simulating the hand and wrist.

There is currently little or no research being conducted in the field of combining virtual reality with manipulating bones because of the biomechanical complexity of the hand and wrist and the high number of degrees of freedom in manipulation.

Use case UC-4 is also used for different fracture treatments and mostly consists of providing an intuitive user interface to view and select medical devices including implants, screws and Kirschner wires. This use case is neither technically challenging nor is it of high scientific interest; the main

task is to implement an intuitive (3D) model viewer to view and choose the appropriate ones for the current task.

The fixation of the fracture in use case UC-5 is a task which is mostly specified, according to the participants, and which is of high interest. This use case also applies to preoperative planning. Several research projects have addressed virtual reality-based reduction and fixation, also including haptic feedback, for example by Künzler, et al. (2009) and Fornaro, et al. (2010). The main complexity of the implementation consists in the real-time collision detection between the bone fragments, surgical instruments and implants.

Prior to operating on a distal radius fracture, a surgeon has to decide about the treatment options, the fixation method and the fixation technique. This is usually based on X-ray images and, if available, on CT images. Use case UC-6 confronts the trainee with an X-ray image and a number of possible corresponding CT images from which he has to choose the correct one and indicate the resulting surgery. Additionally, spatial awareness is important for X-ray and CT image analysis, which can be trained by a virtual simulator which allows the trainee to manipulate and explore anatomical structures. This use case is of high interest amongst surgeons, as the decision-making process is essential for a successful surgery. The main difficulties consist in getting enough CT images from distal radius patients and eventually in the real-time volume rendering for the virtual spatial sense trainer.

Use case UC-7 provides an increased level of difficulty to the trainees by confronting them with sudden changes in the patient's condition, which the trainee has to treat appropriately. These unexpected situations can either be caused by surgical errors, such as in UCE-1, or by an operator as in UCE-2, who confronts the trainee with a problem. The difficulty of the implementation of UC-7 differs, depending on which medical conditions the surgical simulator should provide.

In summery it can be said that use cases UC-1, UC-2, UC-5 and UC-6 are the most promising ones regarding the training and the most important surgical skills, and use case UC-9 is required for successful evaluation of the trainee's performance. However, additional use cases can be required by others, such as use case UC-3 for UC-5. Because UC-2 has several drawbacks such as the required haptic forces and biomechanical complexity, the development focused on UC-1, UC-5 or UC-6 and UC-9.

5.4.2 Requirements

To prioritise the requirements, the MoSCoW method is used (International Institute of Business Analysis, 2009), which divides requirements into four categories:

- *Must:* This requirement must be satisfied.
- *Should:* A high-priority requirement that should be included if possible. Often a critical requirement, but could be implemented in other ways if needed.
- *Could:* A desirable but not necessary requirement. Included if time and resources permit.
- *Won't:* A requirement that will not be included, but may be included at a later stage.

Considering the focused use cases UC-1, UC-5, UC-6 and UC-9, the MoSCoW analysis applied to the relevant requirements is shown in table 5-2.

Table 5-2: MoSCoW analysis for user requirements relevant for use cases UC-1, UC-5, UC-6 and UC-9.

Requirement	*Priority*
FR-1, implants	S
FR-2, incision	M
FR-3, reactivity	W
FR-4, flexibility	C
FR-5, navigation	C
FR-6, handling	M
FR-7, logging	M
NF-1, surgical instruments	M
NF-2, anatomical structures	M
NF-3, haptics	M
NF-4, cost	S
NF-5, response time	S

The main requirements on a surgical simulator for simulating incisions and fracture fixation that must be implemented are FR-2 for simulation of cutting, FR-6, NF-1 and NF-3 for using different surgical instruments during the fracture fixation, NF-2 for the visualisation of the anatomical structures and FR-7 for assessing the trainee's performance.

In addition to the aforementioned requirements, FR-1 allows the trainee to choose the correct plate and screws for fracture fixation. FR-4 is crucial for developing a simulator that is ready for the market, but can be considered as rather unimportant at this stage. However, FR-4 should be considered during design and technological decisions. NF-5 should be fulfilled for a realistic and intuitive training environment, if possible.

Extensions include FR-4, a requirement which has been mentioned by the participants several times, but is difficult to implement due to its vast scope of possibilities a trainee can perform. FR-5 is dependent on the medical scenario, but less important for distal radius fractures, but can be implemented within a reasonable time.

FR-3 is related to FR-4 and increases the realism of the simulation, but is not needed for UC-1, UC-5 and UC-9. Realistic simulation of bleeding is still difficult and subject of research and development.

Considering UC-6, the relevant requirements are FR-4, FR-5, FR-7, NF-2, NF-4 and NF-5. FR-4 and FR-5 are used to create a virtual simulator to train spatial sense and correct positions of relevant anatomical structures. FR-7 is used to evaluate the trainee's progress of improving the decision-making process and interpreting X-ray and CT images. NF-2, in conjunction with NF-5, should be fulfilled for a realistic visualisation of the anatomical structures. NF-4 is relevant for creating a product which is ready for the market, but not at this stage.

5.5 Final Decision for Use Case Implementation

The remaining three use cases UC-1 (make surgical incision), UC-5 (fix fracture) and UC-6 (train spatial sense and improve X-ray/CT analysis) cannot all be implemented in the scope of this work and therefore require prioritisation. From a medical point of view, UC-6 aims to improve the decision-making process of the treatment of the fracture, which is mostly based on X-ray and CT images. Use cases UC-1 and UC-6 are both applicable for other medical scenarios, as they are not bound to a particular surgical intervention. As surgical incisions are needed for most of the surgical interventions (experimental approaches exist for example through natural orifices (Halim and Tavakkolizadeh, 2008)), a training simulator for UC-1 is of higher significance, as it can be used for the training for different surgical interventions. Yet, research has already been carried out and algorithms and systems have been developed. Use case UC-5 aims to train particular surgical interventions and is therefore bound to a medical scenario. It provides support in getting the medical skills for safely treating fractures. Based on the results of chapter 5 and the experience gained in the projects described in section 3.3, use case UC-5 has been selected, as it can offer an addition to the current training of surgeons by providing the possibility to repeat the same surgical intervention several times, which may currently not be possible. Furthermore, little research has been conducted in combining virtual reality, real-time 3D visualisation and haptics for open surgery, and several of the participants chose that particular training environment and use case to be of medical importance in the training of surgeons.

Chapter 6

Design and Development

6.1 Chapter Summary

This chapter evaluates three-dimensional graphics software frameworks and haptic libraries for their suitability to develop the surgical simulator based on the defined requirements. Five demonstrators have been developed and analysed, and the architecture, design and implementation of the surgical simulator, based on the latest technology demonstrator, is described. It includes the implementation of a six-DoF haptic rendering pipeline, which incorporates haptic effects and user interactions such as drilling or measuring for length.

6.2 Introduction

This chapter presents the work carried out in developing a surgical simulator for training the treatment of distal radius fractures. Readers who may not be interested in all the technical aspects of the simulator may want to consider which parts of this chapter they wish to study. Although a technical overview is given, there is also some detailed technical analysis both within the chapter and in appendix B that may not be of relevance to some. This chapter is split into appropriate sections as follows: the evaluation of software frameworks and demonstrators developed to assess haptic libraries, the iterative design which led to the final release, and finally the more technical analysis, which includes architecture, design and implementation aspects of the simulator. If this chapter is skipped, section 6.8.5 can be of particular interest, as it gives a brief overview of the functionality of the simulator and helps further understanding of the topics evaluated in the following chapter.

6.2.1 Concepts and Terminology

In addition to the glossary on page xiii, the following technical terms are used throughout the chapter and aggregated here for orientation, how they are related to one another and to review if needed.

C++. An object-oriented programming language.

DICOM. Digital imaging and communications in medicine; a standard in medical imaging used for volume visualisation and for communication between systems.

Fixed-function pipeline. A set of predefined functions (e.g. lighting, texturing) to alter the image on the screen used in older OpenGL standards. Superseded by the programmable rendering pipeline, which allows programs (called shaders) to be executed directly on the graphics card.

Geometric primitive. Simple geometric shapes such as cubes, spheres or cylinders.

GPU. Graphics processing unit; a specialised processor on a graphics card for fast calculations or image processing using a highly parallel structure.

Haptic rendering. The process of computing the force feedback using the position of the haptic device and information from collisions with objects in the virtual environment. An update rate of 1 kHz is typically required for plausible haptic simulation.

Hapto-visual. Rendering a 3D scene both visually and haptically.

I3D. A virtual reality software framework developed by the author and used for several research projects, including this PhD work.

Kinematics. The motion of bodies without referencing forces causing it. Used to model animations using jointed skeletons.

Mesh. A representation of the shape of a body; defined by vertices (points), edges (connects vertices) and faces (typically triangles).

Mesh to mesh, point to mesh. Terms used in collision detection; the process of two meshes colliding against each other (mesh to mesh), resulting in a set of collision points, as opposed to the collision of a 3D point with a mesh (point to mesh), resulting in a single collision point.

Particle system. Using a large number of very small graphic objects to simulate fuzzy phenomena such as fire, smoke, water or blood.

Pipeline. A set of serial connected elements, which process data. The result of an element is used as input of the subsequent element, such as processing a 3D scene to output a 2D representation.

Segmentation. The process of partitioning a 2D or 3D image into multiple segments, used in medical imaging for example to isolate anatomical structures.

Shader. A program to produce lighting and shading of 3D models; often executed on the GPU.

Thread. A set of program instructions that can be executed in parallel.

Transfer function. A term used in volume rendering; a function which maps data values to colour and opacity and thus makes part of the volume visible.

Virtual coupling. In haptic rendering, the movement of a controlled object is linked to the haptic device by a connection consisting of stiffness and damping.

Volume rendering/data. A technique to visualise 3D data sets (volume data) by computing 2D projections.

X3D, MedX3D. A standard to represent 3D graphics, and with MedX3D, to render volume data.

6.3 Motivation

From a technical point of view, computer-based surgical simulators consist of several core components. As presented in 2.6, *Requirements and Components of Surgical Simulators*, the two components most related to the technical development (besides input and output devices) are simulation and measurement of performance and training. They can be further refined into the following components, as shown in figure 6-1:

- Geometric modelling of anatomical structures, medical instruments and equipment.
- Interactions, representing the actions a user can perform within the simulation.
- Simulation core, consisting of performance measurement and application handling and logic.
- Physics and haptics simulation.
- Input and output such as visual and haptic rendering, which is mostly based on a scene graph and external libraries controlling the haptic devices.

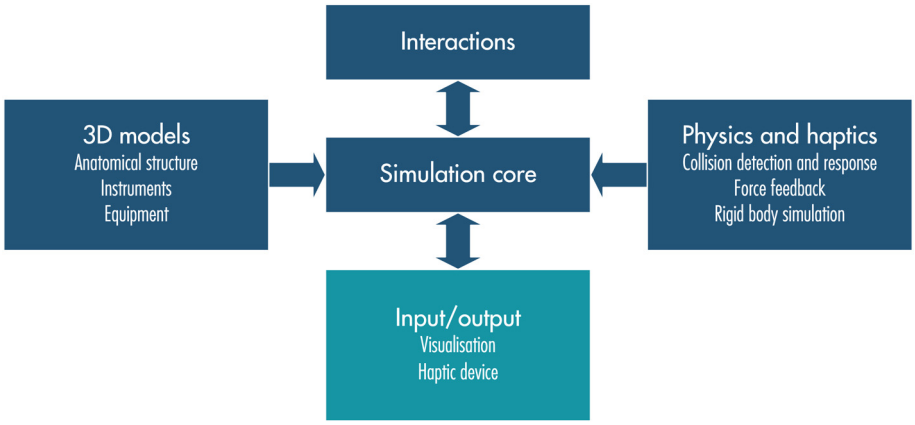


Figure 6-1: Core components of computer-based surgical simulators from a software engineering point of view.

The geometric modelling of anatomical structures can be based on three-dimensional medical images such as CT or MRI data sets or on surface models. Models for medical instruments and equipment can be created for example by 3D modelling software or obtained from commercial digital content providers. The interaction between the user and virtual models has to cater for collision detection and the associated response, computing haptic forces for surgical instruments, and real-time visualisation of the surgical site with appropriate visual feedback. Collision detection is an important component of physics and haptics simulation, but generating exact contact information demands high computational cost. Therefore, a two-phase approach is typically used to reduce the computation by first using bounding boxes (the smallest box enclosing the object) to exclude pairs

of objects which do not collide with each other (called broad phase). In a second step, commonly referred to as narrow phase, exact contact information, such as contact points, normal vectors and penetration depth, is generated for the potentially colliding objects, which is computationally much more costly and much less feasible for complex scenes. This contact information is then used to compute the collision response, which consists of computing contact forces and torques, etc. In addition, the dynamics of the user-controlled object has to be computed, which is used as force feedback output for the haptic device. This haptic rendering needs to run at high update rates of 1 kHz or more (Lin and Otaduy, 2008) to maintain the effect of smooth surfaces and plausible haptic feedback, which typically results in considerable computational cost. Additional modules for program logic may be required to simulate surgical tasks, evaluate performance or monitor the progress of surgical procedures.

Generally speaking, there are typically two ways of using haptic technology in an application: using a complete software framework (such as SOFA and H3D, see section 6.4.3.1) or using an existing library with the aim of integrating this into the application (such as osgHaptics, see section 6.5.1). As frameworks are more likely being developed by a company or a larger community, they are typically better tested and have a higher quality of code. However, customising such a framework is typically difficult and requires a more substantial effort. Libraries, especially haptic libraries, are often only active for a couple of years and are then discontinued, possibly due to lack of interest or the termination of the associated research project.

Based on previous experience and evaluation of the software frameworks, it transpires that haptics is not yet at the point where it works out of the box. Most haptic frameworks include simple examples on how to use the library and normally show the functionality with simple geometric objects such as cubes and spheres. This is reasonable, as it simplifies the program code, but examples showing haptics on complex geometric objects are often not provided. Therefore, an evaluation of potential haptic libraries was carried out to find the best combination of the application framework with visual rendering and a library for haptic rendering.

The parts which are challenging from a technical point of view are getting the required update rate during collision detection, the implementation of the haptic rendering pipeline and finding appropriate parameter values for a stable haptic performance. From a user perception point of view, the challenging parts are providing the haptic feedback that a user expects, and providing a user interface and interaction paradigms that can be used to transfer the skills to the operating theatre.

6.4 Software Framework Evaluation

The development of the surgical simulator involves using a software framework that caters for the implementation of the required functionality for the chosen use cases. Since numerous frameworks are available, the decision of which framework to use has considerable influence on the design and development of the surgical simulator. Several factors can have a significant effect such as the required time for the development, user experience of the graphical user interface or the continuous changes of the API (application programming interface). Therefore, evaluation of the software frameworks is necessary for assessing the required suitability.

This evaluation process is based on the work of Bohn, Korb and Burgert (2008), who defined an evaluation methodology for the development of computer assisted surgery (CAS) applications and has been adopted for the needs of the development of this surgical prototype. The evaluation process consists of four phases:

- Planning the framework evaluation
- Establishing requirements and criteria
- Collecting evaluation data
- Analysing evaluation data

The first phase includes forming an evaluation team, defining an evaluation goal and filtering the available software framework products by more general criteria such as application field or price range to limit the scope of the evaluation. Next, requirements and criteria are established based on the gathered user requirements and the chosen use cases. For each candidate software framework, data is collected by information available from the authors and by analysing the example applications. Then, these frameworks are assessed against the proposed user requirements, and on compatibility with the existing virtual reality framework.

6.4.1 Evaluation Planning

The main goal was to find a software framework that caters for building high-performance three-dimensional graphics applications with the ability to support haptic input devices. The scope of the framework has been narrowed based upon previous experience in developing similar medical applications and on a market survey for similar products, especially for volume rendering, as most of the software frameworks provide similar basic functionality for handling data, program logic and events (see section 6.4.3). Volume rendering was initially considered as it can be necessary to gather information from inside a bone, such as computing the drill resistance, to take X-rays, to visualise

soft tissues or for real-time deformation. However, whether volume rendering is ultimately needed depends on the medical scenario.

The following initial characteristics have been used for the market survey:

- Are the frameworks aimed at scientific simulation and visualisation?
- Do they have integrated real-time 3D computer graphics?
- Are they runnable on affordable commercially available high-performance PC technology?
- Do they support volume rendering or can it be integrated?

The identified candidate software frameworks can be divided into four categories:

- 3D graphics toolkits
- Software frameworks that resulted from research projects
- 3D engines aimed at game development
- Software development kits from haptic devices manufacturers

6.4.2 Establishing Requirements

The outcome of the software framework evaluation depends on the defined criteria. The previous criteria can be further divided into:

- Application field
- Code analysis of framework examples
- Ease of use
- Features

Each criterion is split into refined measurable attributes and resulted in 13 evaluation criterion, see table 6-1. Each criterion was weighted according to its importance, ranging from 0 (criterion is not fulfilled) to 5 (criterion is completely fulfilled) and taken into account in the analysis of the evaluation data.

Table 6-1: Software framework evaluation criteria.

Category	*Evaluation method*	*Criterion*
Application field	Review framework information and use cases on web.	• Is aimed at medical simulation. • Supports developing custom applications, i.e. it is not a self-contained system.
Code analysis	Analyse example projects; review developer information on web and forum or mailing list.	• Robustness of code by providing stable releases. • Missing functionality can be added by extensions or plug-ins. • An API description and documentation is available. • Support is provided by a sufficiently large user community.
Ease of use	Analyse example projects; review example information on web.	• The concepts of the framework are easily understandable. • New objects are created without large library overhead.
Features	Analyse example projects; review API documentation.	• Different haptic input devices can be attached and controlled. • Volume data can be visualised by integrated functionality. • Collision detection and response is available. • Haptics is available. • Integration into I3D is possible.

6.4.3 Candidate Software Framework Overview

Each candidate framework has been analysed and an overview for each has been constructed, the software framework along with any associated examples has been built (if possible) and also analysed.

In terms of programming languages, C++ and OpenGL have become the de facto standard for real-time 3D visualisation and are therefore more commonly used amongst the medical/scientific community. There are other competing APIs to OpenGL, the most prevalent being Direct3D, which provides similar functionality. It is however limited to the Microsoft Windows platform and is a proprietary API, whereas OpenGL is an open standard. OpenGL tends to be used for professional graphics, Direct3D is aimed more at game development, but both APIs can comparably be used for application development.

Another API is Java 3D, however it lacks support for high-performance 3D applications as well as a haptics API and is therefore rarely used in real-time 3D medical simulation. Development ceased in 2008[1].

1. RUSHFORTH, K. (2013) *ANNOUNCEMENT: Java 3D plans.* [Online]. 2013. Available from: https://java.net/projects/java3d/lists/dev/archive/2008-01/message/24 [Accessed: 20 October 2013].

6.4.3.1 3D Graphics Toolkits

Although these are 3D graphics toolkits, they are widely used for scientific and medical applications.

H3DAPI

H3DAPI (H3D), developed by SenseGraphics, is a cross-platform open-source framework that combines visual and haptic rendering in a unified scene graph. It is common amongst universities for research in various fields such as dental, medical and industrial visualisations. H3D contains a cross-platform haptics rendering engine for use with existing applications, and other toolkits such as a volume haptics toolkit.

Features of H3D include:

- Rapid development using C++, X3D and Python.
- Unified scene graph for visual and haptic rendering.
- Extendible for custom hapto-visual features such as custom-made nodes for real-time painting of a texture.

OpenSceneGraph

OpenSceneGraph (see Wang and Qian, 2010) is an open-source, real-time 3D rendering engine and is used in various fields such as visual simulation, medical and scientific visualisation, virtual and augmented reality applications and serious games. The cross-platform software runs on small devices such as embedded graphics platforms, phones and tablets, right up to desktops and large rendering clusters and immersive 3D displays. The main component of OpenSceneGraph is its feature-rich scene graph.

Features of OpenSceneGraph include:

- Feature-rich scene graph encapsulating the majority of the OpenGL functionality.
- Different modules such as volume rendering.
- Large user community (mailing list with a frequency of dozens per day and forums dedicated to different subjects with about 4500 members).

Simulation Open Framework Architecture (SOFA)

SOFA is a cross-platform open-source, real-time 3D simulation framework targeted at medical and physical simulations (Faure, et al., 2012). The main purpose is to help develop new models and algorithms, such as model deformation, collision simulation or object interaction, as well as efficient

prototyping; several demo applications have been realised for validating different aspects of SOFA[1].

Features of SOFA include:

- Multi-model representation concept, i.e. using different representations such as deformation, visual and collision models to represent the simulated model.
- Deformable, rigid and fluid models.
- Collision detection and response methods.
- Integration schemes using methods such as Euler or Runge-Kutta for predictions of tissue deformation.

In May 2015, the SOFA framework has been awarded the Dirk Bartz Prize for Visual Computing in Medicine at Eurographics 2015, the annual conference of the European Association for Computer Graphics. This therefore confirmed the necessity for its inclusion.

Visualization Toolkit (VTK)

VTK (Schroeder, Martin and Lorensen, 1996) is a cross-platform, open-source toolkit for 3D graphics, modelling, volume rendering and scientific visualisation and is used in commercial and research applications. As development began in 1993, it is now supported by a large, active community. VTK consists of two major modules, the graphics model, which abstracts the graphics language, and the visualisation pipeline, which transforms data into forms that the pipeline can further process and display. Although VTK is not aimed for visualising graphical scenes and virtual worlds, but rather for scientific visualisation and especially data visualisation algorithms, it has been used for minimally invasive surgery simulation, including haptics (Rodriguez-Florido, Escobar, Santana and Ruiz-Alzola, 2006). The evaluation will determine whether VTK can be extended with the functionality required to develop the surgical simulator.

Features of VTK include:

- Pipeline architecture with modules representing data, algorithms and to execute a pipeline.
- 3D graphics visualisation algorithms for surface and volume rendering.
- Data readers and writers for polygonal (such as lines or meshes) and volume formats (such as DICOM data sets) to import and manipulate data objects.

1. INRIA (2011) *SOFA — Features*. [Online]. 2011. Available from: http://www.sofa-framework.org/features [Accessed: 23 November 2012].

6.4.3.2 Libraries that Resulted from Research Projects

Several research projects have been carried out that have developed software frameworks for surgical simulations. Most of them are targeted at specific needs or medical fields and are mainly developed by research groups or institutes. Some are continually improved and used for subsequent projects, but most of them are discontinued after a couple of years for various reasons.

6.4.3.3 3D Engines Aimed at Game Development

Several open-source 3D rendering engines exist (such as OGRE[1]), which are targeted at game development. Their core component is a scene graph and loaders for different 3D databases and image formats. Physics is normally not directly supported by the engines, but can be easily added through extensions for example to include Bullet, ODE or PhysX. Although the user communities are large, these engines are rarely used for medical simulations.

Recently, the game development ecosystem Unity[2] became more and more popular, especially in the video game industry for different devices and web plug-ins. Although several projects used haptic technologies, no ready to use library or plug-in seems to be available as of end of 2013. Each project developed its own haptic technology integration as a plug-in. By the end of 2014, a simple haptic plug-in had been developed[3] to interact with geometries using OpenHaptics (HLAPI), which however is not suitable for complex scenes, as it is built upon deprecated OpenGL functionality.

Commercial 3D engines (such as CryEngine[4]) provide the best graphics and APIs, but are targeted at professional game development and therefore have limited support for medical simulation and can have high licence fees for commercial applications.

6.4.3.4 Software Development Kits from Haptic Devices Manufacturers

Haptic device manufacturers provide their own SDK to add haptics to custom applications and typically support only their own devices. As they only provide access to the device, the developer is responsible for implementing efficient force rendering and collision detection algorithms.

1. OGRE3D TEAM (2012) *OGRE – Open Source 3D Graphics Engine.* [Online]. 2012. Available from: http://www.ogre3d.org [Accessed: 28 November 2012].
2. UNITY TECHNOLOGIES (2013) *Unity — Game engine, tools and multiplatform.* [Online]. 2013. Available from: http://unity3d.com/unity [Accessed: 7 October 2013].
3. POYADE, M., KARGAS, M. & PORTELA, V. (2014) *Haptic Plug-In For Unity3D.* [Online]. 2014. Available from: http://radar.gsa.ac.uk/3575 [Accessed: 25 March 2015].
4. CRYTEK (2012) *CRYENGINE | The complete solution for next generation game development by Crytek*. [Online]. 2012. Available from: http://cryengine.com [Accessed: 28 November 2012].

6.4.4 Evaluation

From the four types of software frameworks, those resulting from research projects and those aimed at game development can be excluded from the evaluation process, because either they do not offer a guarantee that they will still exist in the future or can provide support for development issues, or the license fees are too high and they are not suitable for scientific purposes. However, functionality, algorithms and methods that resulted from such research projects could be used during the development process. SDKs from haptic device manufactures will also not be included due to the substantial effort required to integrate them into I3D and high-level APIs already provide such functionality. Therefore, the software frameworks described in section 6.4.3.1 will be set in contrast with each other for the implementation of use case UC-5 (fix fracture).

6.4.4.1 Gathering of the Evaluation Data

All candidate software frameworks were investigated on a Windows 8 x64 workstation with Visual Studio 2012. For each software framework the most recent stable version as of February 2013 has been used, or where appropriate, the most recent development version.

H3D

H3D is based on the open X3D standard and also supports the open interoperable standard MedX-3D[1], a volume rendering component for X3D which is currently in development by the Web3D Consortium. It can be used as a complete development environment providing a scene graph, haptics and various toolkits, or the standalone HAPI can be used to integrate haptics in existing applications. In H3D, a common approach is to store geometry and scene graph structure in the X3D format, to implement the event handling in fields and to use nodes as a container for fields (and field networks). The haptic properties of objects can be defined in the X3D scene description as elements, or programmatically.

Integration of H3D into I3D seems rather difficult due to the incompatibilities of the design concept and as the API is designed to build upon the X3D data format.

OpenSceneGraph

The core functionality of OpenSceneGraph is implemented in four libraries: scene graph elements, an object-oriented thread interface, readers and writers for 2D/3D data files and the OpenSceneGraph visual renderer. Several extra add-on libraries are available to extend the functionality of

1. Web3D Consortium (2013) *Medical | Web3D Consortium.* [Online]. 2013. Available from: http://www.web3d.org/working-groups/medical [Accessed: 7 February 2013].

OpenSceneGraph to include capabilities such as particle systems, volume rendering or terrain rendering for example, and numerous extra functionality has also been developed by the community.

In its simplest form, loading a 3D model file, creating a scene graph and visualising it can be done in a few lines of code: using the basic scene graph viewer, reading the 3D data file, which is then used as the default scene graph, and starting the main rendering loop. Visualising volume data is achieved by using the included volume rendering module. The 3D image data is coupled with an appropriate algorithm, which may define a particular rendering technique such as ray tracing (generating the image by following the path of light). Haptic rendering is not integrated into OpenSceneGraph. A custom implementation based on CHAI3D has been started in I3D to support haptics.

As OpenSceneGraph is already a core component of I3D, no additional work is required for its integration.

SOFA

SOFA with support for various features such as haptic devices or parallel computing with CUDA[1] has been tested. Several examples are provided, but not all are maintained and cannot be built without fixing code errors, which also applies for the framework itself. SOFA uses a scene graph to describe the scene and to split the computations of collision detection, visual and behavioural models. Physical properties are described in independent components, which can be easily replaced to use different physics algorithms without changing the other nodes (such as other physics parameters or geometries for example). Haptic devices are supported by plug-ins, but the functionality could not be evaluated as no forces were computed and sent as force feedback to the haptic device. The degrees of freedom (position and orientation data) of the haptic device are mapped to an object within the scene by a mechanical state controller. It gathers events from the haptic device and modifies a mechanical state, and by using a force feedback object, the bottom-up calculated forces are then sent to the haptic device.

Support for loading DICOM data sets is not included in SOFA, but a project[2] based on SOFA used volume rendering for simulating the treatment of strokes, therefore, an integration is theoretically possible.

Making SOFA usable in I3D may be time consuming, if indeed possible, however an integration with Ogre has been attempted, but development stopped due to lack of interest.

1. NVIDIA Corporation (2013) *Parallel Programming and Computing Platform | CUDA.* [Online]. 2013. Available from: http://www.nvidia.com/object/cuda_home_new.html [Accessed: 5 March 2013].
2. INRIA (2008) *SOFA :: Projects :: EVE.* [Online]. 2008. Available from: http://www.sofa-framework.org/projects/interventional/eve.html [Accessed: 6 March 2013].

VTK

In contrast to the previous frameworks, developing the surgical simulator using VTK would follow a different approach as it is not a scene graph-based framework. Therefore, can such a framework be used for medical real-time applications with haptic support? Building VTK is a straightforward process and does not rely on external dependencies. Examples are provided for a variety of use cases and show how VTK can be used. Five examples are provided for volume rendering, one using the GPU for rendering, and additional examples are available on the VTK website. VTK uses a render window and one or more renderers to visualise data. An image data object is used to store geometric structures such as volumes and pixmaps (pixel maps; a raster image consisting of a spatially mapped array of pixels), which can be used to compose a volume. Transfer functions for colour and opacity are used to map voxel (similar to pixels for 2D, a voxel represents a value in a three-dimensional space) intensities to colours and to control the opacity of different tissue types (see figure 6-2).

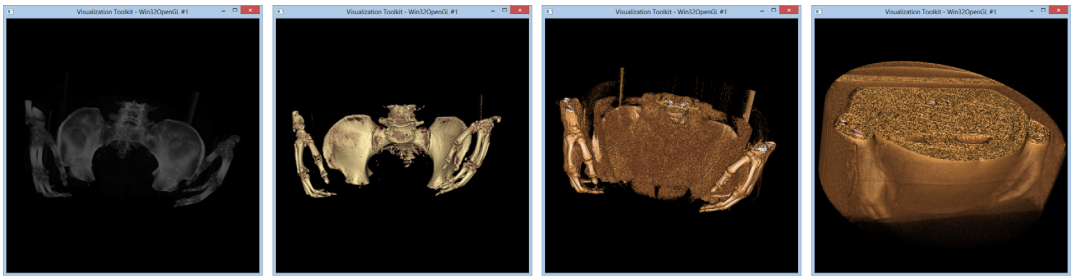


Figure 6-2: VTK volume rendering of a pelvis with different highlighted tissue types from the Visible Human Project[1].

VTK does not offer any haptic capabilities and little information is available on combining VTK with haptic applications. As of 2013, no software product or library is known to provide working haptics in VTK. Furthermore, integration into I3D seems difficult due to the different approach of the visualisation pipeline VTK uses.

6.4.4.2 Analysis of the Evaluation Data

Each criterion has been weighted to reflect its overall importance and has been rated on a scale from 0 to 5, with 5 being the best (see table 6-2, weight indicators in parentheses). The weight scale is based on experience gained from previously created applications, information from the internet (such as possible approaches to overcome limitations of the framework or missing functionality, which is mainly gained from forums, mailing lists and technical articles) and analysis of example applications provided by the software frameworks. The total score of a framework is calculated by ac-

1. U.S. National Library of Medicine (2012) *The National Library of Medicine's Visible Human Project.* [Online]. 2012. Available from: https://www.nlm.nih.gov/research/visible/visible_human.html [Accessed: 6 February 2013].

cumulating the criterion weights (in parenthesis) multiplied with the particular achieved scores, such as for H3D, the total score of 109 is calculated by $4 \times 3 + 4 \times 4 + 5 \times 3 + 3 \times 3$ and so forth.

Table 6-2: Evaluation matrix for analysed software frameworks.

	H3D	*OpenSceneGraph*	*SOFA*	*VTK*
Aimed at medical simulation (3)	4	4	5	3
Extensibility (4)	4	5	4	2
Robustness of code (3)	5	4	2	5
Ease of use (3)	3	5	4	3
Amount of modules, complexity (2)	3	4	3	3
Support for haptics (5)	5	1	5	0
Documentation, user community and support (4)	4	5	2	4
Integration into I3D (see section 3.3.6) (5)	2	4	2	3
Total score	109	112	98	78

Differences are concerned with support for haptics. As VTK is aimed at visualisation, it does not support haptic rendering. OpenSceneGraph does not support haptics by default, however in 2006, a project called osgHaptics (see section 6.5.1) integrated haptic rendering into the OpenSceneGraph framework. Unfortunately the project was discontinued and therefore does not support newer OpenSceneGraph versions. H3D and SOFA, both aimed at medical virtual reality simulation, are designed to provide haptics and support a range of different haptic devices.

As expected, none of the evaluated software frameworks fulfils all criteria. The three criteria which differed most between the candidates are “support for haptics”, “documentation, user community and support” and “integration into I3D”. As user requirement NF-3 (support for haptic feedback) is defined with the priority must and VTK achieved the lowest score, it is placed fourth (see figure 6-3). SOFA, which scored third, is a highly specialised software framework for medical simulation, but has a small user community and a small development team. Furthermore, a rewrite of the API is in progress and no stable releases are available. H3D takes a different approach than OpenSceneGraph. It combines haptic and visual rendering in a unified scene graph, which allows focusing on application development instead of synchronising between the two renderings. However, the supported 3D data formats are limited to X3D and an integration into I3D appears to be difficult, as H3D is intended to be best used as a standalone software framework. OpenSceneGraph received the highest score but also lacks support for haptics, therefore a custom implementation supporting haptic input devices is needed. This could be realised with CHAI3D, a multi-platform haptics rendering framework. Choosing OpenSceneGraph with a custom haptics implementation seems best

to facilitate the implementation of use case UC-5 (fix fracture by inserting a plate and screws). If required, concepts of SOFA for medical visualisation or simulation could be used for the development of the surgical simulator.

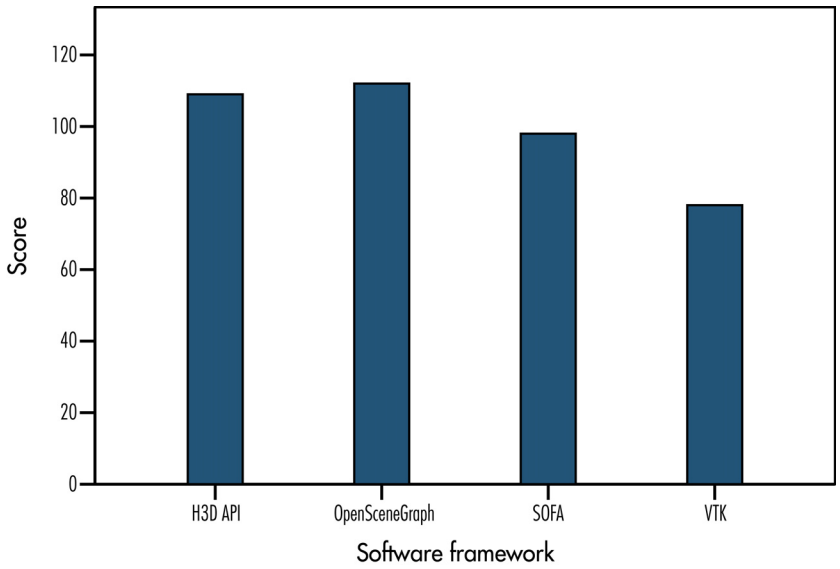


Figure 6-3: Ranking of the candidate software frameworks.

6.5 Haptic Libraries and Demonstrators

This section gives an overview of the prototypes created with the different haptic libraries that could be integrated into I3D and/or work with OpenSceneGraph. Amongst commonly used haptic libraries and frameworks, the scope of evaluation has been widened to get an overview of alternatives, as libraries, especially haptic libraries, often are only active for a couple of years and are then discontinued.

A similar product to OpenSceneGraph is OGRE. Two projects could be found that address the integration of haptics into OGRE: OgreHAL[1], which never came over the planning phase, and OgreHaptics, which seems to be aimed to simulate weapon recoil forces. It has been used in a virtual reality throat examination simulation (Ruthenbeck, Owen and Reynolds, 2008). OgreHaptics was also discontinued in mid-2009. Therefore, these alternatives have ultimately not been evaluated, as they do not provide any advantage over using OpenSceneGraph.

All demonstrators use three-DoF haptic libraries, as there were no haptic libraries supporting six-DoF haptic rendering out of the box or providing six-DOF algorithms as an add-on. It was assumed that either three-DoF algorithms could be extended to support mesh-to-mesh collisions (or react

1. VITEFALCON (2009) *OgreHAL*. [Online]. 2009. Available from: http://sourceforge.net/projects/ogrehal [Accessed: 7 October 2013].

similarly) or that the scenario could be adapted to only use three-DoF haptic rendering by for example adding additional haptic geometries, which simulate mesh-to-mesh haptic rendering, and therefore benefit from simpler algorithms and thus faster update rates due to the reduced complexity of the algorithms, see also section 6.6.2.

The hardware configuration for all developed demonstrators was similar (see figure 6-4): a workstation with two displays, a 3D mouse for navigating the virtual environment and a haptic device, in particular a Geomagic Touch for demonstrators 1 to 5 and a Force Dimension omega.6 for the six-DoF haptic rendering demonstrator (see section 6.7).



Figure 6-4: Hardware configuration for the developed haptic demonstrator applications consisting of a 3D mouse, a haptic device (Geomagic Touch or Force Dimension omega.6) and loudspeakers for sound effects, which were integrated into the distal radius surgical simulator.

The figures in sections 6.5.1 to 6.5.5 show screenshots of each demonstrator application. For a better understanding of the demonstrator, only the virtual environment and possible available consoles with debug information such as haptic collision data are shown (as on the left display in figure 6-4).

6.5.1 Demonstrator 1: osgHaptics

osgHaptics is a haptic rendering library that is based upon OpenSceneGraph and OpenHaptics (see figure 6-5). Although the original osgHaptics[1] library was discontinued in September 2007, the development was resumed at the end of 2010 until the beginning of 2011, when it was finally discon-

1. VRLAB, UMEÅ UNIVERSITY, SWEDEN (2007) *OpenSceneGraph Haptic Library (osgHaptics).* [Online]. 2007. Available from: http://www.vrlab.umu.se/research/osgHaptics [Accessed: 21 January 2013].

tinued. The build system has been fixed and the source code made runnable on OpenSceneGraph 2.6.

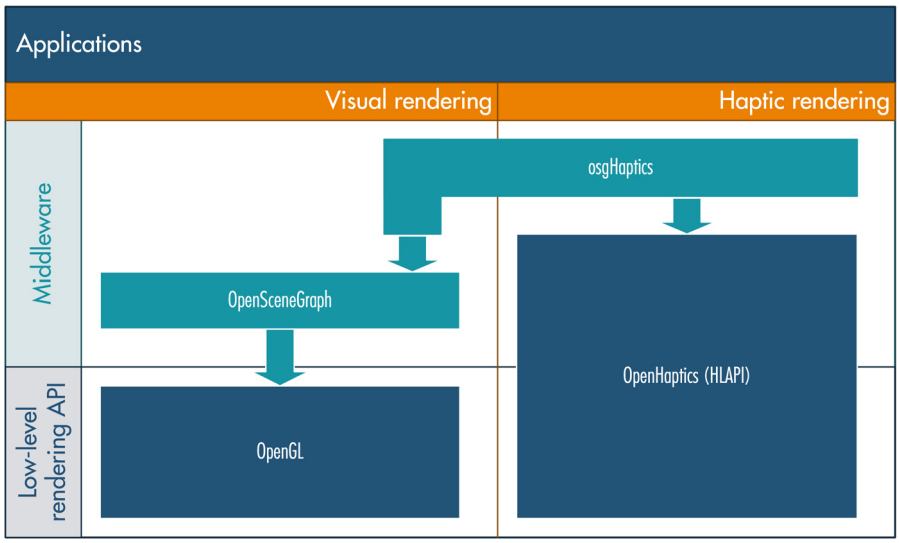


Figure 6-5: Software architecture of osgHaptics.

After adapting this code base to work with OpenSceneGraph 3.2, simple prototypes have been evaluated, see figure 6-6.

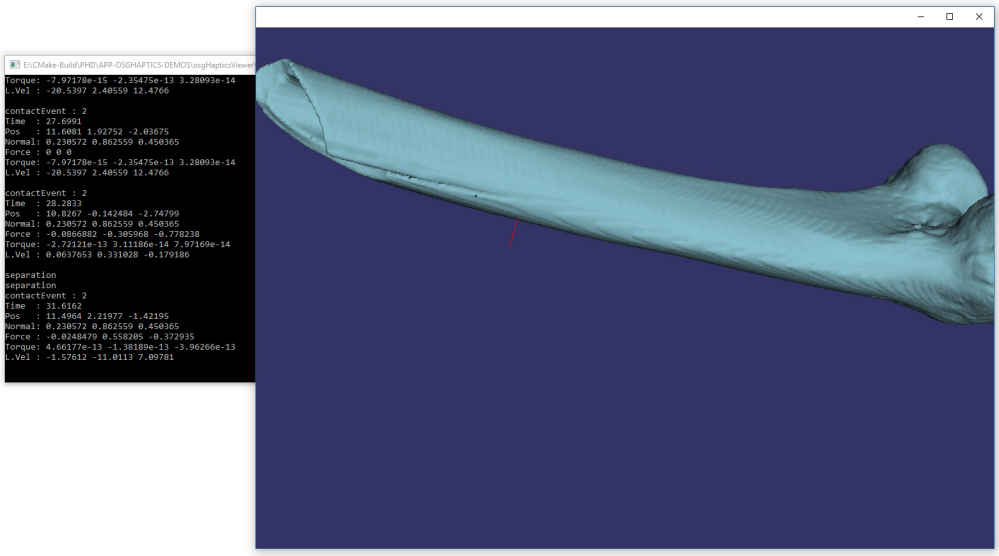


Figure 6-6: Demonstrator 1: collision detection with ulna bone model; the red line indicates the magnitude of the reaction force.

6.5.1.1 Limitations

It is not clear how geometric models can be mapped to the end effector of the haptic devices to simulate medical instruments. It appears that osgHaptics is designed to touch objects, rather than interact with them, meaning exploring the shape of the surface using a stylus instead of sensing the

forces that occur when two objects collide. This is by design, as osgHaptics only supports three-DoF interaction and visualises the end effector with a sphere pointer. Furthermore, it happens occasionally that the force calculations lead to vibrations of the end effector, especially on the backside of models or with complex models on intersections of polygons.

6.5.2 Demonstrator 2: I3D with Bullet and CHAI3D-Based Haptic Rendering

Based on the I3D framework, the existing haptics implementation has been improved by adding functionality to haptically render meshes, see figure 6-7. The physics library Bullet is used for collision detection and uses collision shapes to detect the collisions between different objects. The following collision shapes are supported: geometric primitives, which use very fast special collision algorithms, meshes (convex hull, convex triangle mesh, bounding volume hierarchy triangle mesh and others) and compounds, which are a combination of convex shapes and primitives. The haptic rendering implementation is based on CHAI3D, which has been modified to use Bullet for all physics calculations. This was required as Bullet was already integrated into I3D for physics support via the osgBullet extension. Basically, most CHAI3D classes have been rewritten to use Bullet and CHAI3D is mostly only used for device handling, as it provides an abstraction layer for haptic devices and supersedes the need to have device-dependent implementations.

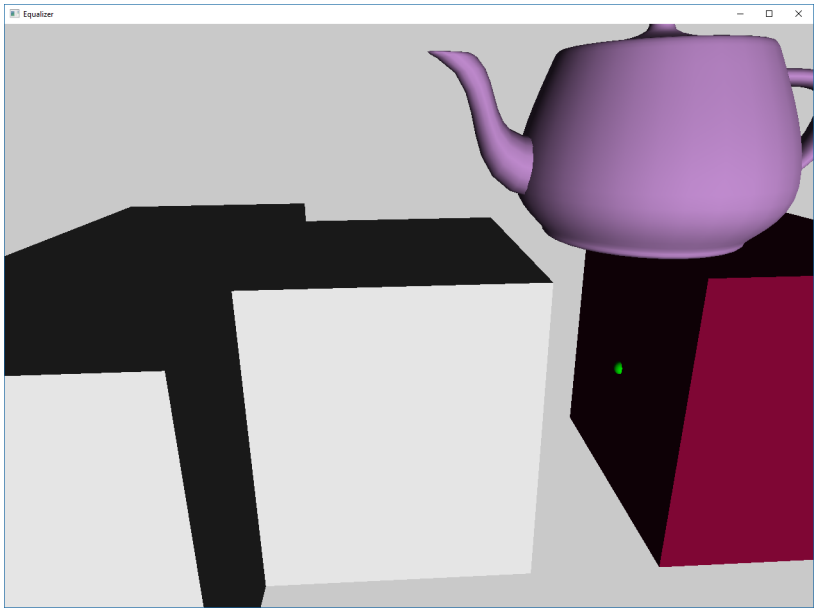


Figure 6-7: Demonstrator 2: replacement of Chai3D with Bullet and functionality to render meshes; the green sphere indicates the haptic device position in the virtual environment.

6.5.2.1 Architecture Overview

The haptic implementation consists of three parts: scene graph handling with OpenSceneGraph, haptic device handling with CHAI3D and physics calculations with Bullet (see figure 6-8).

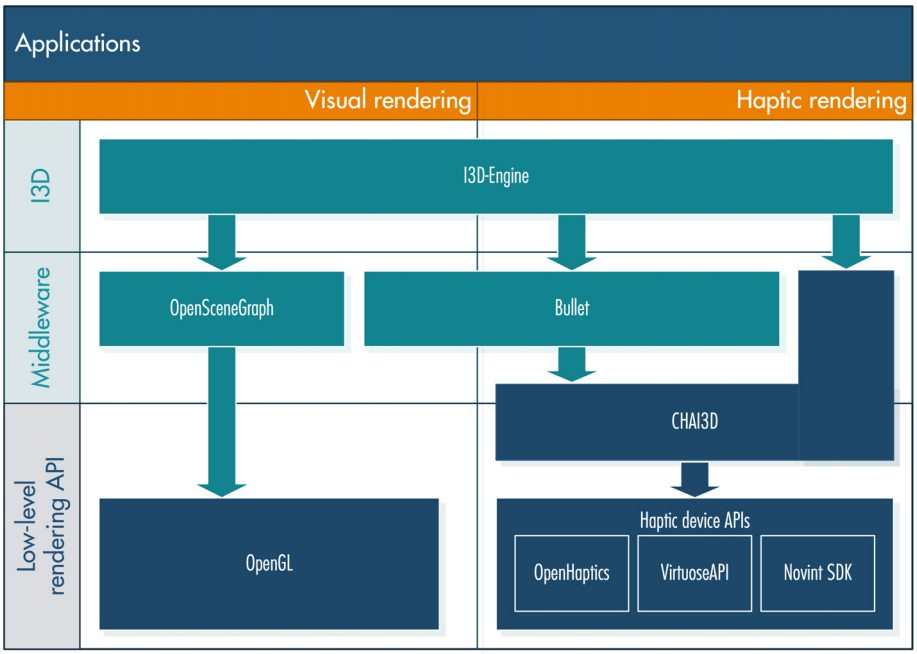


Figure 6-8: Software architecture of I3D haptic rendering (only relevant parts are shown).

Functionality for haptic nodes has been included, which allows adding haptic materials and effects. All scene graph nodes that are haptically rendered derive from this functionality, which itself is derived from an OpenSceneGraph matrix transform node, allowing each haptic node to be easily added to the scene graph. Basic physics is implemented in a class derived from the haptic node base class. From this physics base class, primitives (such as spheres and boxes) and meshes are derived.

The god-object haptic rendering algorithm (Zilles and Salisbury, 1995) is used to determine forces from geometries. This requires that the haptic device uses two spheres, one for the real position of the device (haptic interface point, HIP) and one for the god object (ideal haptic interface point, IHIP), which stays on the surface. The forces are calculated mainly in two instances:

- Implementation of the god-object algorithm with collision detection.
- Local interaction relating to haptic effects.

Haptic effects currently provide the following effects:

- *Magnet:* Magnetic field near the object; attracts along the centre of the field.

- *Stick-slip:* Sliding with friction; produces a jerking motion when an object slides over another one.
- *Surface:* Basic surface effect; calculates a reaction force using Hooke's law.
- *Vibration:* Vibration with subject to frequency and amplitude (could be used to simulate drilling).
- *Viscosity:* Simulates fluids by a resistance against motion (flow).

The implementation of the control of the haptic device is built from several classes. As haptics is currently implemented as point-to-mesh, it uses two spheres representing the HIP and IHIP.

6.5.2.2 Limitations

The main limitation is the handling of meshes. An example application from the CHAI3D library, which uses a drill mesh to haptically explore a tooth mesh, shows instabilities, as do other examples using the ODE physics engine for collision detection. In addition, ghost collisions occurred on edges of triangles, although they were on a flat plane and should be filtered out by the collision detection algorithm.

6.5.3 Demonstrator 3: SOFA

Since the end of 2011, no development or stable versions have been released. Development continued since then and the current version has been used for re-evaluation. At the end of 2012, SOFA underwent a new organisation of the source code.

6.5.3.1 Limitations

The haptics module could be built using the HAPI library from SenseGraphics, supporting Geomagic Touch devices. However, there were issues with the collision algorithms; for example moving the contact point behind the object actually allowed moving through it (see figure 6-9).

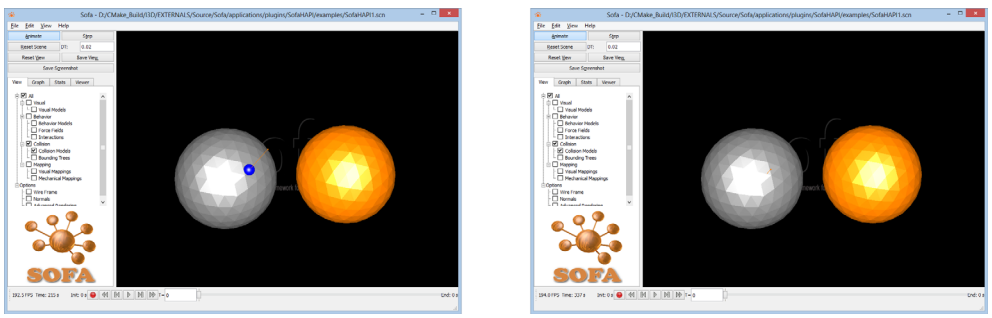


Figure 6-9: SOFA demonstrator: moving through haptic objects.

6.5.4 Demonstrator 4: Proof of Concept with Bullet and OpenHaptics

Due to the difficulties that arose with integrating full mesh-to-mesh haptics into the I3D framework, a simple prototype has been developed to isolate the debugging of the ghost collisions (see section 6.5.2.2). It contains only Bullet for collision detection and the required haptic device SDK, OpenHaptics (see figure 6-10).

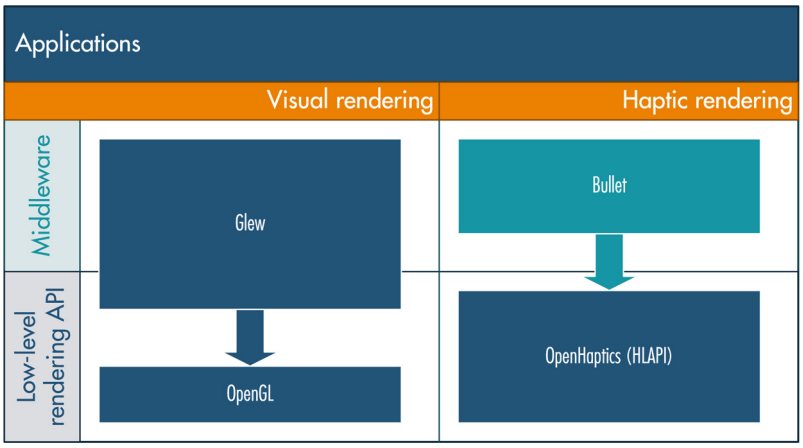


Figure 6-10: Haptic rendering with Bullet and OpenHaptics software architecture.

The prototype (see figure 6-11) is built upon an example program[1] demonstrating soft body simulation with Bullet.

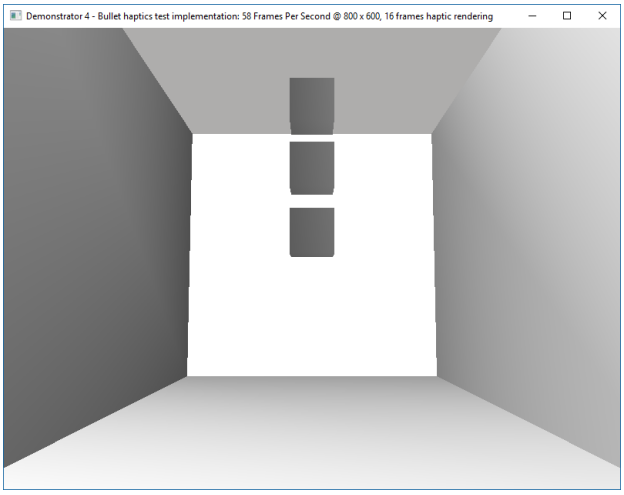


Figure 6-11: Bullet/OpenHaptics demonstrator: poor haptic rendering performance.

It is originally built with Qt[2], which had to be removed to keep the demonstrator as simple as possible. This required to modify the program in several steps:

1. SOMAPANAM (2011) *More Bullet soft bodies (with source code).* [Online]. 2011. Available from: http://somapanam.wordpress.com/2011/04/30/more-bullet-soft-bodies-with-source-code [Accessed: 3 October 2013].

1. The existing user interface software was replaced with a much more simplistic framework.
2. Implementation of the haptic rendering loop in a function which is executed repeatedly.

   This is the simplest way of separating visual and haptic rendering. However, the timing loop exhibited poor performance (with less than 100 Hz) due to the system needing to respond to all messages and not react responsively.
3. Encapsulation of haptic rendering into own thread.

   To increase the performance of the haptic rendering, it needs to be executed in its own thread. However, the need to access the device and associated attributes from two different threads (haptic render loop and force calculation/messages) results in unnecessary context switching. Furthermore, the demonstrator program still uses the deprecated fixed-function graphics pipeline. Similar problems arose with the haptic rendering, which is dependent from the graphics context and therefore should be accessed from two threads, which is not feasible (except from workarounds which lead to very slow performance and reduced functionality). Workarounds would be to share the graphics objects, or to create separate graphics contexts and switch between them. There still remains the problem that as OpenGL is asynchronous, threading is difficult due to the limited options for synchronisation.

6.5.4.1 Limitations

The main problem with this prototype still remains: there is only point-to-mesh haptic interaction at the moment. Additionally, it is not possible to conclude from this prototype whether Bullet is a valid option for collision detection and force calculations for complex geometries or not, as there were too many factors which could lead to the poor haptic rendering performance.

In addition, HLAPI is not suitable for complex haptic simulations, as it uses deprecated OpenGL functionality. Development of a new haptic rendering algorithm should therefore be built upon the HDAPI, which only provides access to haptic devices and is not dependent on the fixed-function pipeline of OpenGL. The initial problem with the ghost collisions on edges when using Bullet, which was revealed by the demonstrator 2, could not be analysed due to the poor haptic rendering performance.

2. THE QT COMPANY (2015) *Qt — Home.* [Online]. 2015. Available from: http://www.qt.io [Accessed: 19 December 2015].

6.5.5 Demonstrator 5: Proof of Concept with PhysX/Bullet and HDAPI

Following demonstrator 4, a new simple prototype has been developed using NVIDIA PhysX and Bullet for collision detection and HDAPI to access the data of the haptic devices, see figure 6-12. The first version of this prototype was developed using PhysX, and by abstracting the use of its function calls, Bullet was later integrated in a similar manner, with the possibility to add other physics engines in the future if required. No visual rendering was integrated at first, as NVIDIA provides the PhysX Visual Debugger (PVD), an application to visualise and debug the current state of the PhysX engine. Later, the Bullet integration was realised with OpenSceneGraph for visual rendering.

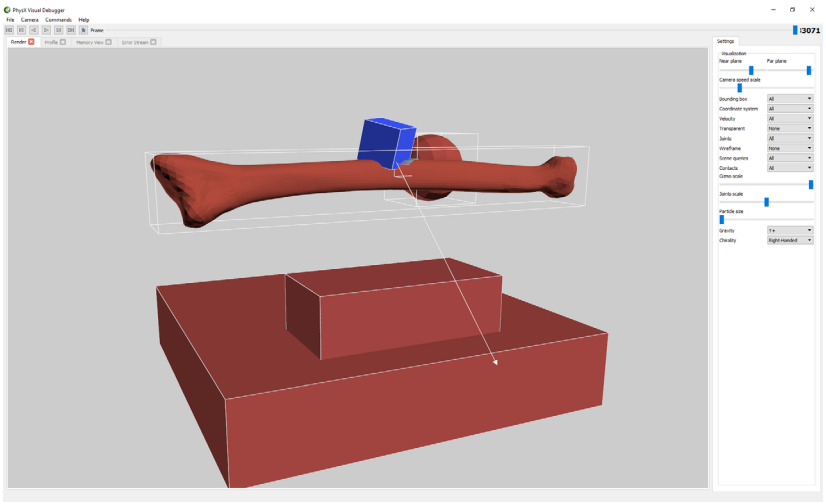


Figure 6-12: Demonstrator 5 with PhysX: geometric models and bone visualisation in PhysX Visual Debugger, the blue box is manipulated by the haptic device and indicates collision points and the velocity vector (computed by PhysX).

6.5.5.1 Architecture Overview

The first implementation uses PhysX for collision detection and PVD for visualisation, see figure 6-13. Base classes have been defined for a physics world (the physical representation of the world/scene) and haptic devices.

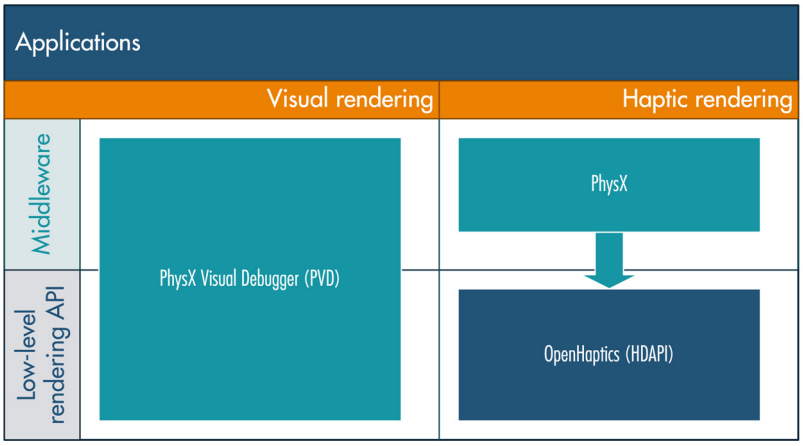


Figure 6-13: Haptic rendering with PhysX and HDAPI software architecture.

In a second step, Bullet was integrated and OpenSceneGraph was used for visual rendering, see figure 6-14. The library osgBullet[1] synchronises the physics models from Bullet with their visual representations in OpenSceneGraph.

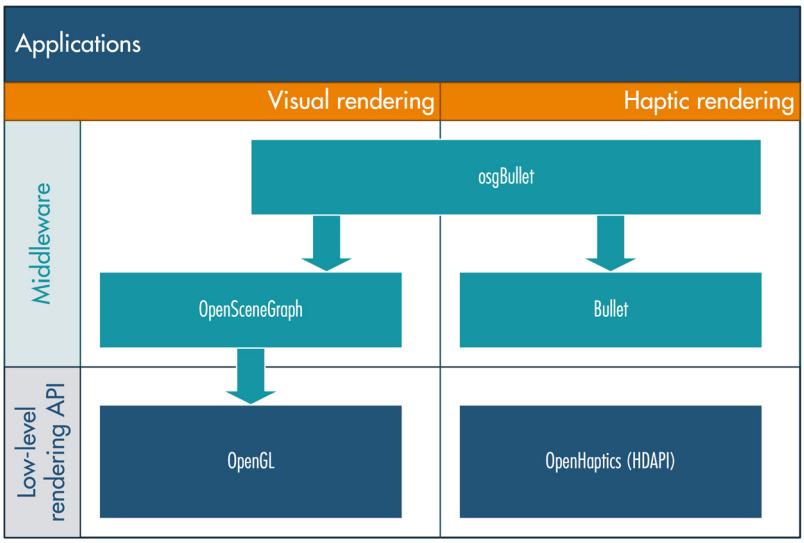


Figure 6-14: Haptic rendering with Bullet and HDAPI software architecture.

Due to its generic architecture, this prototype can build the foundation for implementing a new haptic rendering algorithm, based on the I3D framework.

6.5.5.2 Limitations

The collision detection and data transfer from the haptic device worked as expected. Haptic rendering was implemented only in its simplest form by applying the force directly based on the posi-

1. SKEW MATRIX SOFTWARE (2015) *osgbullet — Bullet physics and OpenSceneGraph integration.* [Online]. 2015. Available from: https://code.google.com/p/osgbullet [Accessed: 25 February 2015].

tion and the penetration depth of the haptic device (for one collision point), according to Hooke's law for linear springs, which is given by

$$F = -k \cdot n \cdot d,$$

where F is the resulting force (restoring reaction force), k is the stiffness, n the contact normal and d the penetration depth.

This simple haptic rendering algorithm has several issues, for example with thin objects, as when the HIP is pushed into the object further than the centre line, the HIP gets forced out of the wrong side, or if the HIP is equidistant to two sides and it cannot be determined in which direction the resulting force should be applied, as no history is kept (Laycock and Day, 2007, pp.51-52).

6.6 Analysis and Discussion of Demonstrators

The analysis of the developed haptic prototypes showed three major technical issues:

- Mesh-to-mesh haptics: all evaluated haptic libraries only support three-DoF haptics and support for mesh-to-mesh collision detection needed either custom implementation or is not supported at all.
- Typically poor haptic rendering performance in real-world usage.
- Limited, if at all, support for haptic rendering of geometrically complex objects.

The analysis of each haptic prototype is shown in table 6-3, listing the encountered problems, possible solutions and the chances of success for development of the surgical simulator. Additionally, the alternative of developing a new haptic rendering library based on existing algorithms has also been included, using demonstrator 5 as a foundation.

Table 6-3: Analysis of haptics demonstrators.

	Bullet/HAPI	*I3D and CHAI3D/Bullet*	*osgHaptics*	*SOFA*	*I3D with new implementation*
Three or six-DoF	3	3	3	3	6
Haptic stability	Good for primitives	Partial	Good, some inconsistencies	Depends on revision, tested revision poor	Depends on algorithms
Haptic rendering performance with simple scene	Poor, possibly due to soft body mesh collision calculations	Good with primitives, mesh depends on collision shape, good with btConvexHullShape	Seems good	Seems good with spheres	Not applicable; good with simple rendering of box geometry

	Bullet/HAPI	*I3D and CHAI3D/Bullet*	*osgHaptics*	*SOFA*	*I3D with new implementation*
Mesh-to-mesh haptics	Not yet included	Not yet finished	Not implemented, difficult to estimate	Not tested	Depends on implementation
Mesh loading	Not tested	Realised using OpenSceneGraph	Included	Possible	Depends on implementation, is possible
Technical issues/problems	Haptic and visual rendering synchronisation, mesh loading, deprecated OpenGL compatibility profile	Mesh-to-mesh haptics, mesh haptics in particular with btBvhTriangleMeshShape	Extension to mesh-to-mesh haptics	Unstable code basis, complexity, poor support for haptic issues in support forum	Expected to be high, e.g. haptic stability, performance
Possible solutions	Separate haptics and graphics, wrapping of haptic devices	Use a btConvexHullShape collision shape for meshes	-	-	-
Chance of success for working haptics	The required changes would lead to the implementation of a new haptic library	God-object algorithm is only for point-to-mesh haptics, but stable haptics should be possible	Small	Requires analysing framework and eventually fixing haptic rendering	Dependent on the used algorithms, implementation depends largely upon its documentation

6.6.1 Physics Engines for Collision Detection

As Lin and Otaduy (2008, p.164) note in the introduction to haptic rendering algorithms, collision detection can easily be the computational bottleneck of a haptic rendering system. Therefore, the physics engine library has also been re-evaluated. The existing physics engine Bullet, which is integrated in the I3D framework, uses a CPU rigid body and collision detection pipeline. But with graphics cards having even greater processing power, physics engines are switching more and more to a GPU rigid body and collision detection pipeline and therefore benefiting from the performance boost by using all available threads of a multi-core GPU. PhysX from NVIDIA already performs the processing for selected rigid bodies (i.e. cloths and particles) directly on the graphics card, Bullet is currently being converted to do likewise (Coumans, 2013). A recent review compared five physics engines and concluded that there is no particular best engine, it depends on the use (Hummel, et al., 2012).

Although these physics engines are not optimised for haptics, several projects have successfully used game physics engines, such as Chan and Choi (2009) to support such things as the rehabilitation of stroke patients for example, but they only used a simple haptic rendering algorithm based on

Hooke's law. Therefore, it cannot be determined if these physics engines are suitable to provide contact information in the desired performance for haptic rendering of complex models.

In addition, collision detection between dynamic, non-convex triangle meshes is mostly not supported in order to ensure real-time interactivity. One reasonable approach would be to decompose the non-convex mesh into convex meshes using the Hierarchical Approximate Convex Decomposition (HACD) algorithm by Mamou and Ghorbel (2009).

6.6.2 Discussion

Following the analysis of the demonstrators, using a three-DoF haptic algorithm and modifying it for mesh-to-mesh haptics does not appear to be promising. For example, for placing a plate on the bone, one approach could be to use several spheres on specific positions which imitate the extent of the plate and the haptic rendering algorithm would need to respect the contact information from all spheres to compute the resulting force.

Building the simulator on outdated haptic rendering libraries such as osgHaptics does not seem promising either. The advantage would be that no new implementation is required, but the changes to make it to work with the defined medical scenario would be highly specific to those use cases and adapting it for other scenarios could lead to increased complexity and unpredictable issues. The re-evaluation of SOFA confirmed the findings of the first evaluation (see 6.4.4.2, *Analysis of the Evaluation Data*); using it to develop the simulator would imply potentially modifying the framework and the haptic rendering pipeline.

Regarding the demonstrators, the first and second were built upon outdated libraries and only support point-to-mesh haptic interaction. However, demonstrator 2 showed that Bullet could be a potential option to compute contact information, as the tested scenes showed no significant disadvantage of Bullet over the collision detection algorithm of CHAI3D. However it involves research into the problem of the ghost collisions on the face edges and also on the performance with respect to complex scenes. It can be concluded from demonstrators 3 and 4 that using SOFA or HLAPI from OpenHaptics is not promising, or in the case of HLAPI, even impossible. These findings were taken into account during development of demonstrator 5, which uses HDAPI to communicate with the haptic device and defines an interface for using physics engines for collision detection, forming the foundation for an implementation based on a different haptic algorithm. As expected, demonstrator 5 showed a good performance for collision detection in a simple scene, but no statement can be made about haptic rendering, as no three-DoF or six-DoF algorithm was used.

Otaduy and Lin (2006) describe a stable six-DoF haptic rendering algorithm and a new collision detection algorithm named CLODs (contact levels of detail, Otaduy and Lin, 2003), which uses a multi-resolution representation (levels of detail) of the model and its bounding volume hierarchy (BVH) for accelerated collision queries. Implementing this haptic rendering algorithm seemed feasible, and to compute the collision information, an existing physics engine such as Bullet or PhysX could be used. If the collision detection algorithm cannot provide the performance required, CLODs or any better performing algorithm can be implemented in a second step.

To conclude, building the distal radius fracture treatment simulator based on demonstrator 5 with interfaces for collision detection algorithms, haptic devices and scene graph nodes enables certain components to be replaced if they cannot provide the required performance. However, implementing the haptic rendering pipeline according to Otaduy and Lin (2006) significantly increased the software development. It is therefore conceivable to use a hybrid approach, whereby simplifying the haptic rendering for certain user actions will potentially alleviate certain instabilities occurring, such as virtual drilling, which can lead to strong oscillations when a vibrating cylinder, representing the drill bit, is inserted into a hole (also known as the peg-in-hole insertion problem).

6.7 Six-DoF Haptic Rendering Demonstrator

Based on demonstrator 5, the haptic rendering pipeline of Otaduy and Lin (2006) has been implemented and PhysX is primarily used to compute the collision information, see figure 6-15. With this separation of the haptics from the contact information computation, the haptic algorithm is independent of the geometries used and therefore mesh-to-mesh collisions are implicitly supported, if the collision detection algorithm supports this contact generation. This is by reason of the haptic algorithm using linear approximations of an arbitrary number of contact forces and torques, which are computed by the contact information thread, and thus processes all occurring contact points instead of only a single one. Therefore, if the collision detection algorithm supports generating contact information for mesh-to-mesh collisions and computing their linear approximations, the haptic rendering algorithm generates six-DoF haptic.

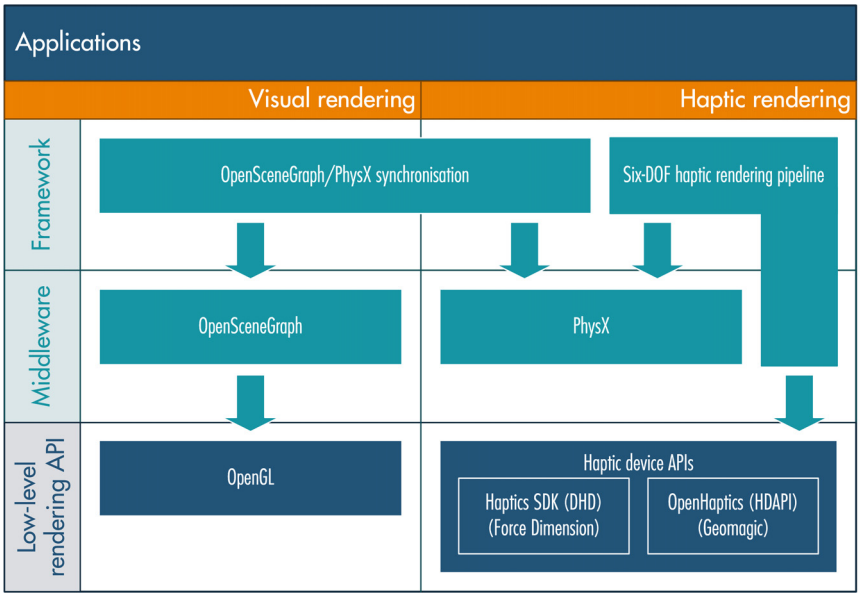


Figure 6-15: Six-DoF haptic rendering demonstrator software architecture.

PhysX, as well as Bullet, uses its own representation of the physics models, therefore a synchronisation between those physics models and the corresponding OpenSceneGraph nodes for visual rendering is required. A haptic device controller module manages the devices, currently all products from Force Dimension and Geomagic Touch and Phantom haptic devices are supported.

The demonstrator uses a haptic box as the user-controlled object, which can be used to interact with another larger haptic box, see figure 6-16. A sphere represents a magnetic field, which pulls the user-controlled object inside the sphere, once it is near the influence range. Such haptic effects can be used to guide the user, for example by using a magnetic line to indicate the direction a user-controlled object should be moved along.

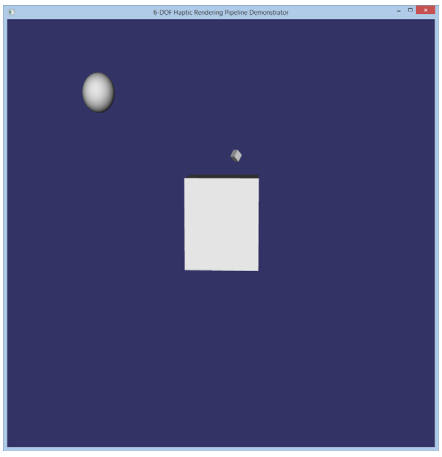


Figure 6-16: Six-DoF haptic rendering demonstrator with rigid body and magnetic field.

6.7.1 Analysis of the Six-DoF Haptic Rendering Demonstrator

The implementation of the demonstrator consists mainly of the following modules:

- *Collision detection:* An interface has been defined to separate accessing contact information and the physics engine from its implementation.
- *Haptic rendering pipeline:* The six-DoF haptic rendering algorithm reads the current state of the haptic device, computes the new state of the user-controlled object by implicit integration and computes the resulting coupling force and torque, which are sent to the haptic device. It is dependent on the collision detection module, which computes contact forces and torques that are used during computation of the new object state.
- *Haptic devices interface:* A base class has been defined, by which a range of compatible devices is supported.
- *Visual rendering:* Provides scene graph nodes for basic shapes (box, sphere and capsule) and meshes. It is based on a composite viewer from the OpenSceneGraph library.
- *Synchronisation of visual and physics nodes:* As the physics engine updates its physical representations of the objects in the scene, the corresponding visual representations have to be updated for each visual render loop.

For the simple demonstrator scene consisting only of boxes, the performance of the collision detection and haptic rendering algorithms was satisfactory. For more complex scenes, the haptic algorithm should still maintain an acceptable level of performance. This is because the contact information derived from the collision detection algorithm consists of the linearisation of the contact force and torque, and since this algorithm uses contact clustering to compute representative contacts for each cluster, there is no higher computational cost for the haptic rendering algorithm with complex scenes. However, the collision detection algorithm will take significantly more processing time as there are more contact points to process. If this results in unacceptable performance, then the scene complexity may have to be reduced or the physics library may have to be replaced to maintain a stable haptic rendering.

The stability of the haptic rendering algorithm also depends on several parameters, such as the shape and complexity of the colliding objects, contact stiffness and damping, as well as linear and angular stiffness and damping of the virtual coupling. This implies that appropriate values have to be found for each particular scene.

A haptic device state, which is used by the haptic rendering algorithm, is defined by the position, orientation, linear velocity and angular velocity of the haptic device. However, HDAPI has a bug and does not provide these velocities, although the corresponding API functions are available. This discrepancy is well known in the developer forum since 2011, but has yet to be resolved. As a result, the prediction of the new object state computed by the haptic rendering algorithm will be affected, and haptic effects relying on velocities, such as viscosity effects, will not function correctly. Those velocities could be calculated by keeping a history of the position and orientation data, but it has to be determined if the device loop will still run at the required rate of 1 kHz. Alternatively, a different haptic device can be used.

To conclude, the developed six-DoF haptic rendering demonstrator has taken the findings of section 6.6 into account and provides a promising framework to develop the surgical simulator. It was expected that the current implementation with regards to the visual rendering, integration of the haptic devices and synchronisation between physics and visual models will not lead to further significant issues.

6.8 Iterative Design of the Simulator

6.8.1 Introduction

The functional and non-functional requirements established in section 5.4.2 were used as a basis for the development of the first surgical simulator prototype. The medical scenario and the requirements specification defined the major components of the software architecture, such as the possible user interactions and the demands on the visual rendering system. However, it was not known exactly if the findings of the interviews and the resulting software prototype met the requirements of medical experts on such a simulator for medical training. In addition, it was also not known what the level of acceptance of such a simulator would be amongst the target user group.

Following the user-centred design approach, the two relevant activities to ensure the software prototype fulfils the requirements, are to produce design solutions and to evaluate the designs against user requirements, as defined by the usability engineering process, see section 4.2.1. If needed, the context of use or the user requirements may have to be refined. Two informal evaluation interviews have been carried out with three orthopaedic surgeons of whom two already participated in the user requirements gathering study and who agreed to take part in decision-making during the development process.

6.8.2 Procedure and Analysis of the Human-Centred Design Approach Evaluation

Two evaluation interviews were carried out (one with one participant and one with two participants) similar in type to the informal interview according to Robson (2011, p.289). As two of the three medical experts already participated in the user requirements gathering study, no introduction about the research project was needed (the third got an introduction by one of the two surgeons). No interview questions were prepared, but two topics were defined as a guide to let the interviewees speak freely in their own terms, and to get feedback about relevant parts of the simulator. The following topics were covered:

- *Medical scenario:* Are the relevant steps simulated and are they of medical relevance?
- *Interactions:* Are the implemented and intended interaction concepts intuitive and can a transfer to the operating theatre be expected?

The procedure included firstly providing information about the current state of the simulator and then guiding them through the simulated medical scenario by letting them try out the different interactions and providing an opportunity for an open discussion.

The interviews have been tape-recorded and notes have been taken concerning any important remarks. The relevant ideas, views and suggestions for improvement raised by the interviewees have been captured by the concept of memoing, described by Robson (2011, p.474).

Although only three participants took part in these interviews, the development of the surgical simulator was based on the insights gained from the user requirements study and therefore design fundamentals were already discussed and were taken into account. However, it is conceivable that a larger group of participants had come up with more ideas for improvement, but they will eventually also be proposed during the evaluation. The three participants were chosen based on the basis of their experience and their involvement in medical education and were suitable for this type of interview.

6.8.3 Version 1: Improvements to the Interactions and Feature Extension

Version 1 of the surgical simulator prototype has been developed as a proof of concept for the simulator and has been evaluated by one orthopaedic hand surgeon. The simulation included placing a plate onto the radius bone by using a haptic device, see figure 6-17. A 3D mouse is used to alter the view onto the surgical site as desired, and the implementation of the six-DoF haptic rendering pipeline was not yet completed (i.e. the haptic thread and parts of the contact point processing). In

addition to the discussion of version 1, the intended concepts for drilling and inserting screws have also been examined.

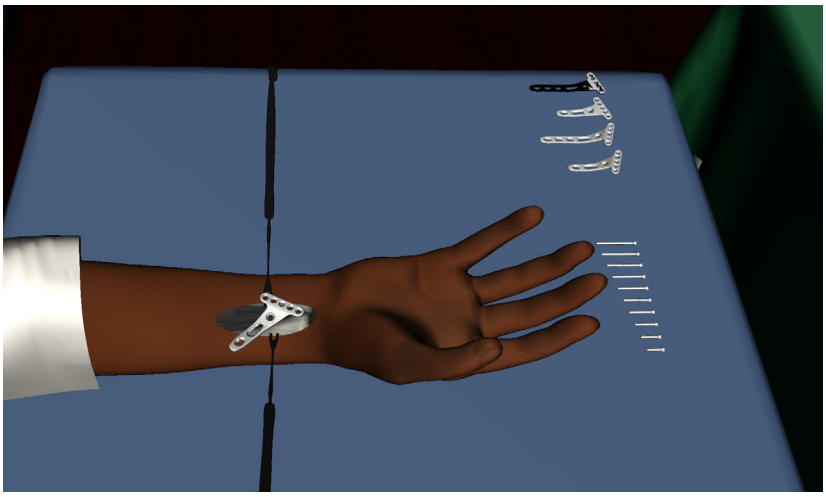


Figure 6-17: First version of the computer-based surgical simulator — placing a plate on the radius bone. The figure shows the application window with the virtual operating site and implants, manipulated by the haptic device.

The interviewee came up with the following improvements for drilling:

1. The direction of drilling should be fixed once the user starts.
2. It has to be considered if a drill sleeve (a medical instrument in form of a hollow steel shaft to guide the drill bit when drilling) should also be simulated.
3. The drill direction can be indicated if the user is in the range of the radius bone.

The following improvements for inserting screws were suggested:

1. Consider using haptic fields (a virtual sphere that attracts toward its centre/surface) at the position of drill holes to lock the screw position.
2. Insert the screw as long as the user keeps pressing the button on the stylus of the haptic device.

In addition, functionality to take X-rays was suggested and instead of only informing the user that the drill hole has a certain length, a depth gauge should be used to measure screw lengths. As a result of this, two new use cases were identified, see tables A-12 and A-13 in section A.2.1 of Appendix A.

From a medical point of view, the importance of the so-called watershed line was raised. It is a theoretical demarcation which has to be respected and plates should not be placed near to this line, as this could cause flexor tendon irritation or injury (if placed distal to this line). Furthermore, commonly used screw lengths for the shaft and distal area are discussed, and whether the simulator should point them out.

For the next version, suggestions one and three for the drilling action and suggestion two for inserting screws were implemented. Using a drill sleeve would require a second haptic device, as the surgeon holds the drill sleeve with one hand and the drill with the other. However, as the drill direction gets fixed with a haptic magnetic line once the user starts drilling, which imitates using a drill sleeve to a certain degree, it has been decided to use this approach instead of integrating a second haptic device. The first suggestion for inserting screws is not implemented for version 2, as it is possible to insert a screw with a minor deviation of the drill hole and it was decided, that the user should correctly align the screw with the drill hole orientation.

6.8.4 Version 2: Refinements of the Interaction Paradigms

Version 2 of the surgical simulator prototype has been evaluated by two orthopaedic hand surgeons. The findings and suggestions that resulted from the evaluation of the first version have been implemented and further concepts have been integrated. The simulator functionality included placing a plate, preparing holes with a simulated drill and measuring for screw length, see figure 6-18.

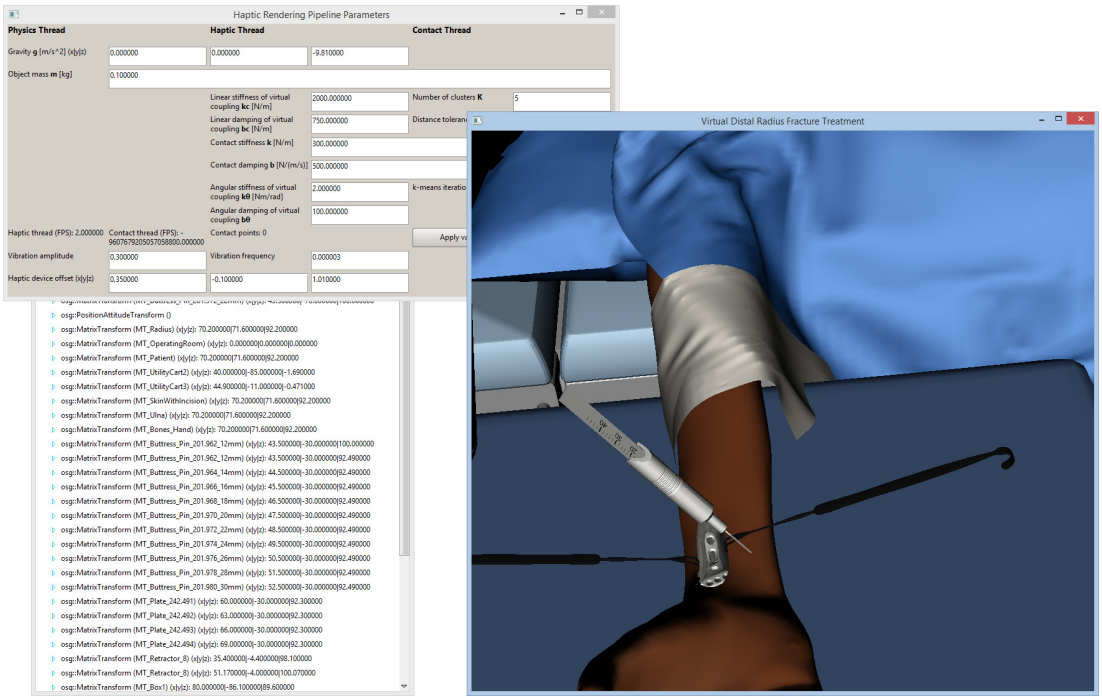


Figure 6-18: Second version of the surgical simulator with plate applied, depth gauge and simple GUI for modifying haptic rendering pipeline parameters.

The concept of inserting screws has been formulated but was not yet integrated. A simple graphical user interface has been added to modify parameters of the haptic rendering pipeline and to check the scene graph structure for debugging purposes. The state machine which controls the simulation logic was integrated and states, such as picking the drill or measuring using the depth gauge, are

changed via the keyboard. The simulated medical instruments and the plate are controlled by the haptic device. Haptic feedback during drilling through the cortical bone was integrated, the haptic feedback during plate placement was also integrated, but not yet finished and optimal parameters have not yet been defined for this particular medical scenario.

Several topics have been discussed, such as the required parts of the medical procedure which should be simulated, the implemented interactions and the concept for inserting screws.

The two interviewees came up with the following main improvements:

- *Medical scenario:* In their opinion, Kirschner wires are not necessarily required to be simulated, as the reposition is not included in the simulation and they are used only with specific plates. The idea of adding a collision area around the incision has been rejected, as there is no real static delimitation based on the soft tissues which could be used.
- *X-ray:* The new X-ray and the revised drilling functionalities were well-received. It has been pointed out that drilling in the shaft area requires a higher resultant force than drilling in the distal area, as the cortical bone is much thinner there. This ought to be simulated, as this is a well-known challenge for beginners, that they respect the small amount of force required to drill through the distal cortical bone and that they do not damage the soft tissues behind.
- *Measure for screw length:* As an improvement to the measuring functionality, it was requested that when the depth gauge is placed on the plate, an audible signal should confirm the correct measuring length once the sleeve is moved onto the plate.
- *Screw insertion:* Recalling the direction of the prepared hole is important when inserting a screw, as the screw head can be worn out if the screwdriver is not correctly aligned with the drill hole direction. Therefore, once the user has correctly aligned the screw with the drill hole, it can be automatically inserted. Two insertion paradigms have come up: once the screw alignment error with the drill hole is below a certain threshold, the screw gets automatically inserted, or that the user has to actively press the button on the haptic device to start inserting the screw.

In general, the simulator has been well-received and the comments on version 2 were consistent with the suggestions from the participant from version 1. Therefore, it was decided that the remaining functionality will be implemented for the final prototype.

6.8.5 Version 3: Summary of the Final Prototype

At this stage, the simulator included all functionality to complete the distal radius fracture scenario. It consists of a main display, where the virtual environment and the graphical user interface for the interactions is shown, a second display which is used to show the virtual X-rays simultaneously when working with the virtual environment, and the haptic device, 3D mouse and loudspeakers, as shown in figure 6-19.

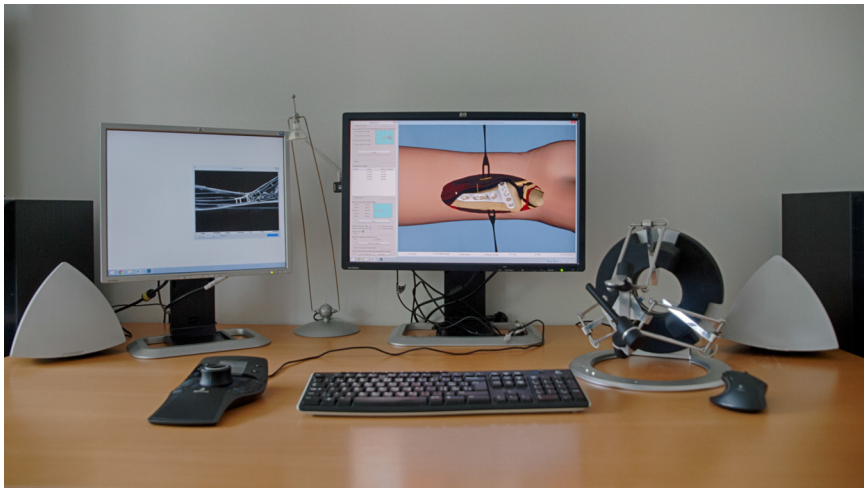


Figure 6-19: Final surgical simulator prototype setup with haptic device, 3D mouse and loudspeakers.

Firstly, the simulator allows the trainee to choose a plate from a selection of four (left and right hand, three-hole and five-hole plates) and place it on the radius bone with supporting haptic feedback. Then, drill holes can be prepared with a simulated drill with haptic feedback when drilling through the cortical bone. The prepared drill holes can be measured for length with a simulated depth gauge, which is used to determine the correct screw length. Screws are chosen from a range of different lengths (12 mm to 30 mm) and can be inserted, again with appropriate haptic feedback. Virtual X-rays can be taken at any stage to confirm correct plate or screw position.

Support is provided by a guided mode, which directs the user as to what they are required to do next. In the training mode, the user is only informed about how to use the functionality of the simulator (such as the haptic device or how to choose an action). Audible drilling sound effect is generated when drilling, an audible machine sound effect is generated when taking an X-ray and an alert sound is generated when the correct length is measured with the depth gauge and for error messages.

The simulator records all user actions and measurable values such as how much the participant drilled outside the far cortical bone. At this point, no automated user feedback is provided at the

end of the training, because it has yet to be determined what feedback should be provided in a follow-up medical evaluation.

To prevent the user getting lost at some point in the medical scenario, notifications are shown after an inactive period of time, instructing the user to ask his supervisor for help.

Under certain conditions, the plate could get pulled inside the bone to a distance of about 2 mm, which seems to be related to specific haptic parameters, in particular the stiffness and damping parameters of the virtual coupling and contact determination.

This version has been used for the medical evaluation, see section 7.4.

6.9 Software Design and Development

6.9.1 Introduction

The development of the framework for the distal radius fracture treatment simulator involved integrating modules with different computational expenses and requirements. The framework also needs to be generic enough for the implementation of the identified use case (fix fracture, see section 5.5, *Final Decision for Use Case Implementation*) and the different actions a surgeon has to perform in achieving this. This section presents the high-level software architecture and the low-level component and algorithm design that was used, as well as relevant implementation aspects. An in-depth technical description, which discusses the implementation in greater detail and provides information required to develop a similar surgical simulator based on the findings of this work, is available in appendix B. It has been moved to the appendix as it would go beyond the scope of this section and as it is more technical in nature and therefore aimed at a computer science audience. However, readers are invited to go through it, as it provides a more profound description of the surgical simulator and the interactions possible with it. But the description presented here is completely sufficient for the understanding of the following evaluation of the surgical simulator.

The software design and development description is based on a top-down approach by presenting the architecture of the surgical simulator and highlighting relevant design and implementation aspects at the particular sections. It is based on the 4+1 view model (Kruchten, 1995), which uses multiple, concurrent views for organisation of the description. Each view addresses a specific set of concerns of interest of the system, see figure 6-20. In addition, significant architectural decisions that have been made during the design and development process are described.

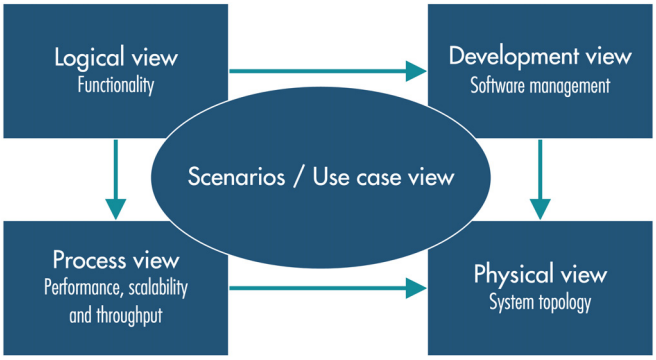


Figure 6-20: 4+1 architectural view model for describing system architecture using different views (Kruchten, 1995).

These views describe aspects as follows:

- *Scenarios / Use case view:* Uses a subset of use cases which are architecturally significant to show that the other four views work together seamlessly.
- *Logical view:* Describes functional aspects of the system.
- *Process view:* Describes dynamic aspects of the logical view, such as concurrency and synchronisation.
- *Development view:* Describes the software organisation from a software developer point of view.
- *Physical view:* Depicts the topology of software components onto the hardware and its distribution.

6.9.2 Architectural Goals and Constraints

Key requirements and system constraints that had a significant influence on the architecture are:

- *Force feedback haptic control:* The haptic devices used are impedance-controlled, i.e. they sense position, orientation and velocities as input and produce force and torque as output. This had a significant consequence on the haptic rendering algorithm, see section 2.4.1, *Haptics*.
- *Haptic and visual update rate:* A relatively high update rate of 1 kHz for haptic rendering is required, but visual rendering can be updated at significantly lower rates, such as at 60 Hz. This required decoupling haptic from visual rendering.
- *High computational cost of collision detection:* As stated in 6.6.1, *Physics Engines for Collision Detection*, the computational bottleneck of the haptic system is most likely the collision detection. The haptic rendering pipeline from Otaduy and Lin (2006) takes this constraint into account by decoupling collision detection from the simulation of rigid body dynamics and force

computation. As a result, the collision detection algorithm could be replaced by a better performing one, if needed.

- *Target user group:* As this simulator is aimed at medical students and young doctors in their first years in surgical training (*Assistenzärzte*, i.e. foundation doctors and specialty registrars in the early years in the UK), the focus was on educating the treatment of distal radius fractures rather than learning specific surgical skills, such as how to hold the drill or handle soft tissue for example. As the simulator makes use of haptic feedback, it is not merely a step-by-step guide in performing a surgical procedure, which could be achieved by a less complicated web application for example, it attempts to offer a realistic user experience. It also allows the user to experience the differing sensations when drilling through the cortical bone compared to the cancellous bone structure for example.
- *Environment:* The simulator was developed as a desktop application running on a workstation. The use of haptic devices and haptic rendering demands high computational performance and therefore could not yet be implemented as a web application for example. This is reasonable, as haptic devices are not yet widely adopted by the consumer market and therefore not yet viable as a web-based application.

6.9.3 Scenarios / Use Case View

The implemented scenario, fix fracture, contains significant central functionality. It can be subdivided into individual steps, i.e. use cases, which capture the functionality of the simulator as seen by users and which have a significant impact on the architecture. They are mainly the interactions of the user with the system, see figure 6-21, which are needed to successfully finish the given medical scenario:

- *Login:* Allows the trainee to log into the system with his own username, allowing user-based recording of performance and later comparison and evaluation of the training.
- *Place plate on radius:* Allows the trainee to place a chosen plate on the radius bone with haptic feedback. It also includes selecting a plate from a range.
- *Take X-ray:* Allows the trainee to create a virtual X-ray of the wrist with the already applied plate and screws. The trainee must be able to choose the imaging view, i.e. PA or lateral. The system has to differ between anatomical structures that should be rendered radiolucent and plates and screws, which are rendered radiopaque.

- *Prepare hole:* Allows the trainee to use a simulated drill to prepare holes for the screws, supported by haptic feedback to feel when drilling through the cortical bone.
- *Measure for screw length:* Allows the trainee to use a simulated depth gauge to measure a prepared hole for the screw length.
- *Insert screw:* Allows the trainee to insert a selected screw into a prepared hole.
- *Make selection:* Allows selecting from a given range of options, currently from plates and screws.

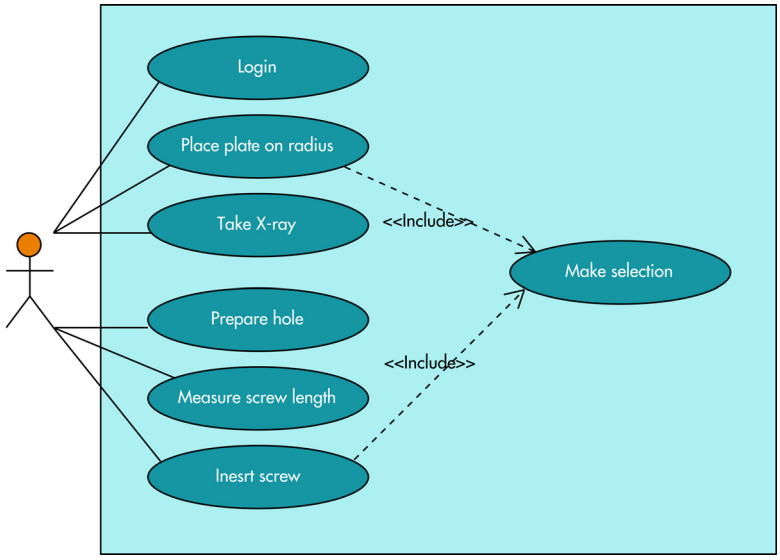


Figure 6-21: Architecturally significant use cases to fix a fracture.

In addition, there is a second group of features the surgical simulator provides, but which is hidden to the user or not architecturally significant, namely core functionality, which are as follows:

- *Switch plate or screw:* The user should be able to choose another plate or screw if he took the wrong one, for example the wrong size.
- *Finish training:* Once the plate is applied and the screws are inserted, the user can finish the training.
- *Record user performance:* All relevant user interaction is recorded for later evaluation of the training.
- *Check for valid actions:* The user can perform the different actions in any order, therefore they must be verified if they are valid at the current time. This helps the user by only providing those actions that are currently available, i.e. it should not be possible to choose or insert a screw if no hole is prepared.

- *Monitor user action:* The user should not be left in a situation where he does not know how to proceed. This requires monitoring the user action and provide assistance when needed.

6.9.4 Logical View

The surgical simulator can be divided into components that are used for rendering, handling of the simulation state and to communicate with input devices, see figure 6-22. It is built upon the six-DoF haptic rendering demonstrator, see section 6.7.

Each component is described in-depth with relevant implementation aspects in the following sections.

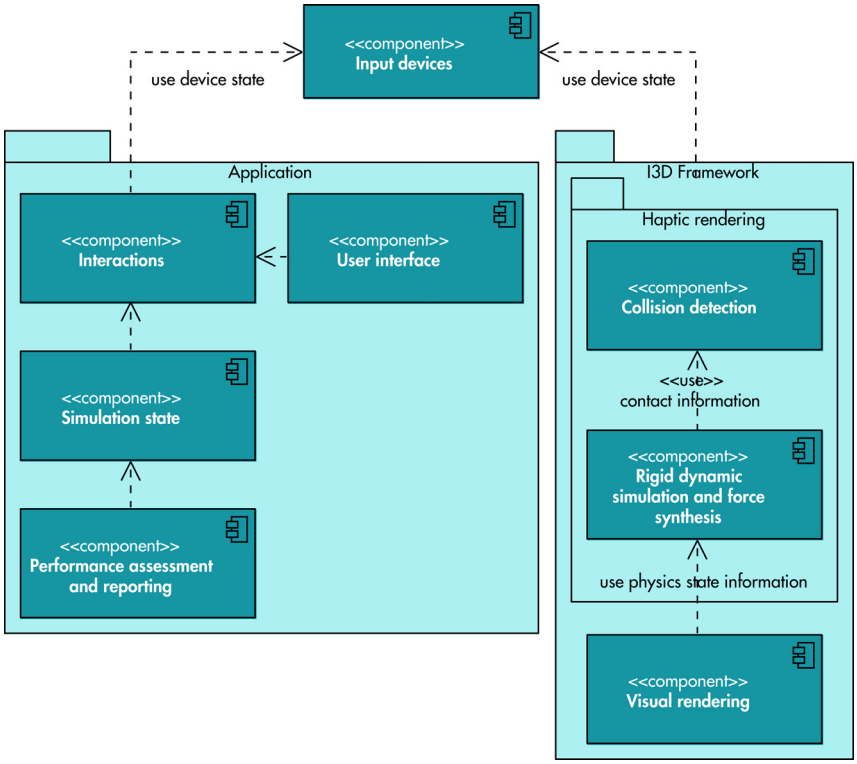


Figure 6-22: Architecturally significant components of the surgical simulator.

6.9.4.1 Haptic Rendering

Haptic feedback is used in several interactions to increase the realism of the simulation. The core of the haptic feedback engine is the six-DoF haptic rendering pipeline, which is responsible for the motion of the user-controlled object and the resulting force feedback. Haptic rendering is based on two components: collision detection and rigid dynamic simulation with force synthesis. For technical details relevant to the implementation see sections B.6 and B.7.

Collision Detection

The collision detection component is responsible for simulating the physics world, performing collision detection and computing a linear approximation of the contact force and torque for the contacts. This linear approximation is used by the haptic thread to compute the rigid body motion. Each model that gets haptically rendered is added to the physics world to be included for collision detection. A collision filter mechanism exempts certain pairs of potentially colliding objects from generating contact information, as the only simulation-relevant collisions occur between the user-controlled object (medical instruments, plates and screws) and the radius bone and plate objects. As filtering happens in the core of the PhysX engine, it is also performance relevant. Thus, limiting contact information generation to only the relevant objects decreases collision detection cost, as when complex objects interact with each other, they generate a large amount of contact points. Because collision detection between dynamic, non-convex triangle meshes is not supported by the physics engine, 3D geometries that are included in collision detection may be needed to be preprocessed by a convex decomposition algorithm.

Collision detection is performed using the NVIDIA PhysX library instead of the algorithm proposed by Otaduy and Lin (2003) to reduce development time. The computation of the contact points is split into two parts by first performing collision detection and second, filtering the simulation events (such as on contact, wake up or sleep) and extracting contact information. The collision detection system of PhysX uses a mixture of the separating axis theorem algorithm (SAT; basically states if it is possible to draw a line between two polygons) and a distance-based collision detection algorithm (checks if shapes are a small distance apart) to generate the contact points. Once the physics simulation has advanced by a collision-dependent time interval and generated the simulation results, the system extracts the contact information and fetches the parameters needed by the contact thread: the two points on the surface of the colliding objects, the contact normal of the user-controlled object and the penetration depth.

Rigid Dynamic Simulation and Force Synthesis

This component is the implementation of the haptic rendering algorithm by Otaduy and Lin (2006), with several modifications and corrections. In addition, a callback technique has been integrated to modify the six-DoF haptic rendering output in order to simulate the resistance that occurs when drilling through the cortical bone, to fix the drilling direction using a haptic magnetic line and to control the stylus' position when inserting screws. It is responsible for computing the state of the user-controlled object and the force feedback, which is sent to the haptic device.

Haptic Rendering Effects

The haptic feedback for drilling, drilling through the cortical bone and inserting screws are implemented as haptic effects.

Drilling and Drilling through Cortical Bone

Haptic effects are used to simulate drilling by providing a vibrating effect when the user drills, to fix the drill direction which simulates the behaviour of a drill sleeve, and to provide resistance when drilling through the cortical bone.

To simulate the vibration of the drill, the sinusoidal mathematical curve function of time t is used in its most basic form, without a phase change (i.e. $\varphi = 0$):

$$F = A\sin(2\pi \cdot f \cdot \Delta t)$$

This oscillating force is applied in a direction orthogonal to the drill axis and simulates a rotating drill bit. The magnitude of the reaction force F is controlled by the amplitude A and the frequency f.

The fixation of the drill direction is implemented using a haptic magnetic line, which is set once the user starts drilling and prevents the drill moving in an arbitrary direction, which therefore simulates using a drill sleeve. The calculation of the magnetic line is based on the magnetic field effect of CHAI3D. The line segment is constructed by starting from the position of the drill to the projected end position of drilling, extended by a certain length so that users are able to drill too far outside the far cortical bone (which should be avoided). The reaction force is dependent on the distance of the haptic device to the line segment, a maximal distance the effect is applied to and the stiffness and the maximal force the haptic device is capable to provide.

When drilling inside the cortical bone, a resistance F is applied using a linear damping effect with a damping coefficient c and the linear velocity of the haptic device v:

$$F = -c \cdot v$$

Using a linear damping effect has the advantage that if the velocity is high, the response force increases and it is not possible to slip through the cortical bone without sensing the resistance.

These three effects (vibration, magnetic line and damping) are accumulated and replace the force and torque computed by the six-DoF rendering algorithm. In addition, the state of the user-controlled object is overwritten with the state of the haptic device, as the six-DoF rendering algorithm would prevent this object from being inside the radius bone. A control mechanism ensures that the cortical bone can only be drilled through once by keeping a history of the already drilled depth.

As the resulting force and torque of the six-DoF rendering algorithm is overwritten when drilling, the collisions that occurred are used to determine if the drill bit is still inside the radius bone, once drilling has stopped. In this case, the haptic magnetic line is maintained and the output of the six-DoF rendering algorithm is not used until there are no further collisions, as the resulting force vector would immediately force the drill outside the radius bone with a large reaction force, potentially harming the device or the user.

Screw Insertion

The screw gets inserted as long as the button on the haptic device is pressed (or the length of the screw has been reached), and a haptic magnetic field effect is used to direct the end effector to the insertion direction, i.e. the end effector gets pulled to the current position of the screw. The implementation is similar to the haptic magnetic line and the force calculation is based on the CHAI3D magnetic field effect. Near the centre of the field, a linear model is used, and in a surrounding area, a quadratic model is used to provide a stronger magnetic effect, and the resulting force is multiplied by a damping component to prevent oscillation of the end effector.

6.9.4.2 Visual Rendering

This component updates the visual representations according to the state computed by the haptic rendering algorithm and is responsible for the visual rendering of the scene graph. A flat scene graph hierarchy is used, without nesting or grouping of models. The structure of the nodes used to render the 3D model depends on the geometry type (mesh or simple geometry) and whether physics is used, see figure 6-23.

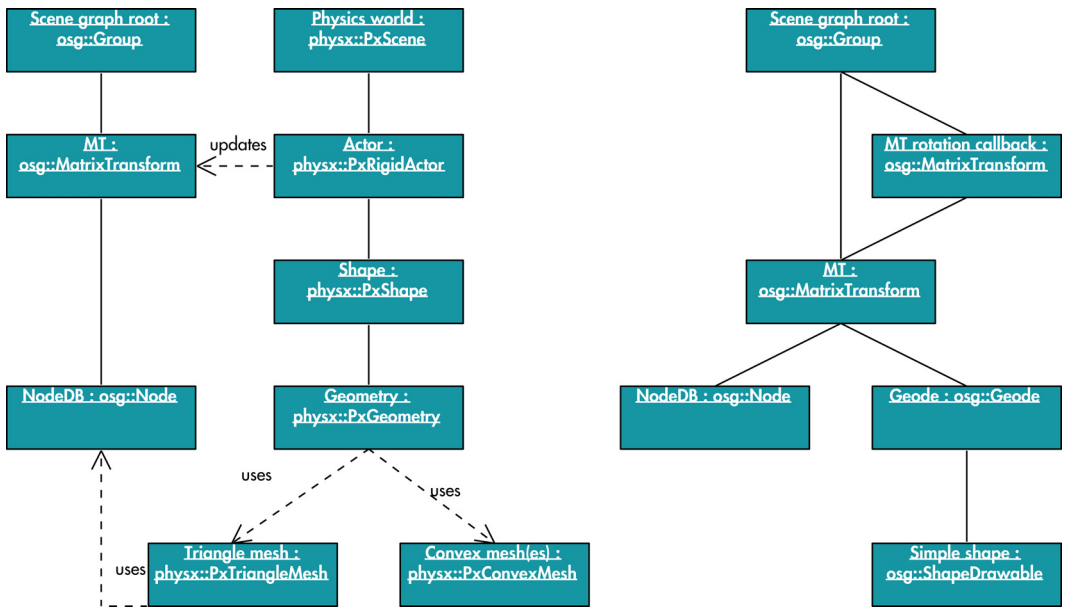


Figure 6-23: High-level structure of the scene graph nodes: physics enabled (left) and visual-only nodes.

Visual rendering and the physics world use two different data structures, therefore, the position and orientation, which get computed by the physics engine, are synchronised during the visual rendering loop.

The open OBJ geometry definition file format is used for the 3D models, which get serialised for faster subsequent application start-ups. For physics-enabled models, the physics representation of the visual node is either directly generated using the model used for visual rendering, or in case of a convex decomposed model, by loading all objects individually. Visual-only nodes are created similarly and orientated accordingly, such as the drill bit or the screw driver. Haptic nodes are basically physics-enabled nodes, but the position and orientation are set by the haptic thread during updating the IHIP.

6.9.4.3 Interactions

This component is responsible for providing the user with the actions needed to complete the surgical scenario and consists of the following five user interactions: plate application, preparing holes with a medical drill, measuring for screw length, screw insertion and taking virtual X-rays, with the possibility to later add further interactions such as skin incision.

Plate Application

A high-resolution mesh is used for visual rendering and to improve collision detection performance, a preprocessed mesh is used for the physics engine. This mesh is preprocessed by the hierarchical approximate convex decomposition algorithm (HACD, Mamou and Ghorbel, 2009), which decomposes a non-convex mesh into a set of convex meshes. From this set, meshes which do not capture perceptually relevant information of the original mesh, such as parts inside the mesh, are removed and thus reduce the number of objects in the physics world. As a result of this, the polygon count has been reduced for example for a three-hole plate from 3517 to 296 polygons with three convex meshes representing the original mesh, and in average for all four plates reduced to 8.72% of their original polygon count.

Plate application makes use of the six-DoF haptic rendering engine and the plate position and orientation are continuously updated and synchronised between the visual and physics meshes. Once the plate is applied, the preprocessed physics mesh is replaced with a PhysX triangle mesh representation of the high-resolution mesh used for visual rendering. This is required as a result of the preprocessing of the models with the HACD algorithm, which can remove the holes from the plate during its optimisation and therefore calculating hole positions when drilling would fail.

Drilling

A drill consists of two parts, the drill and the drill bit, which rotates during drilling. In addition to the visual-only meshes, a haptic sphere is created, which is placed at the tip of the drill bit and used for collision detection. Using a haptic sphere instead of the entire drill mesh for collision detection is reasonable, as the tip is most likely the only part which hits anatomical structures and in addition, using a sphere instead of a mesh increases the performance of the collision detection.

Once the user starts drilling by pressing the button on the haptic device, the projected drill hole is calculated and the drill hole depth and cortical bone thickness are determined. Mockenhaupt (1990) has measured the palmar and dorsal cortical thickness of a distal radius bone in reference to plate osteosynthesis. Using these results, equations have been formulated by using polynomial interpolation, which calculate for given start and end positions of the projected drill hole the relative thickness of the palmar and dorsal cortical bone (see section B.2). The drill angle is not taken into account, as screws are inserted directly with a small angle in the shaft area, and in the distal area the thickness is smaller and therefore the difference would have little effect, see figure 6-24. This approach enables the user to experience realistic differences between the near and the far cortical bone (which is thinner).

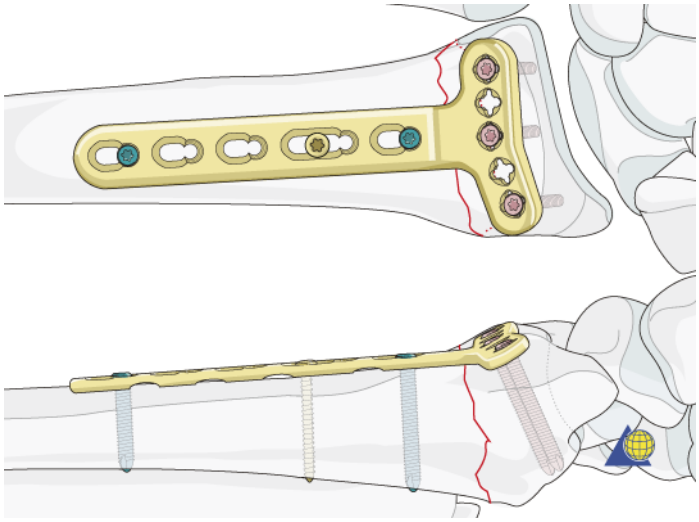


Figure 6-24: Recommended screw insertion angles[1] by the AO Surgery Reference.

The simulation of a perceptionally realistic vibration of the drill handle during drilling uses the equation detailed on page 163 with the following parameters, which are dependent on the haptic device type (see also section B.7.1): amplitude $A = 0.2$ and frequency $f = 0.000006$ for the

1. FRICKER, R., JUPITER, J. & KASTELEC, M. (2015) *Distal radius — Reduction & Fixation — Palmar plating — A2.2 — AO Surgery Reference.* [Online]. 2015. Available from: https://www2.aofoundation.org/wps/portal/surgery [Accessed: 13 July 2015].

Force Dimension omega.6. Drilling inside the cortical bone uses a damping coefficient detailed in the equation on page 163 which was set to $c = 22.0$.

When drilling, the maximum depth already drilled is calculated by using the Euclidean distance of the position of the tip of the drill bit projected onto the line segment of the drill hole and the entry position of the drill, which is used for the haptic feedback in the cortical bone. It is also used to prevent multiple drilling through the same cortical bone.

Once a drill hole is accepted by the user, the position on the plate located along the extension of the drill hole is computed, which is used for the measuring and screw insertion interactions. For this, the collision scene query function of PhysX is used, which allows the execution of a sweep test using a basic geometry. It finds the closest hit against objects in the physics world along a given direction by starting at a specified position and sweeping the geometry until it overlaps with a scene object or the maximum sweep length has been reached. The extended drill hole line segment is used, which passes through a hole in the plate, on which a sphere geometry with a diameter larger than the one of the largest hole of the plate is swept to find the centre of the corresponding hole. If it is found, a new drill hole is created, which is visualised with black spheres, as the radius bone mesh is not changed.

Measuring for Length

A depth gauge consists of two parts: a probe member with a barb at the distal end, and a sleeve which is shifted towards the bone, see figure 6-25. Similar to the drill, a haptic sphere is used for collision detection, placed at the top of the probe member.

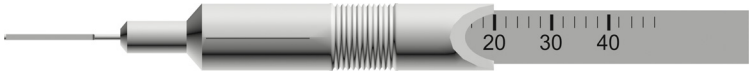


Figure 6-25: Depth gauge model used for measuring for length.

In real-life usage, the probe member would be inserted into the drill hole with the tip being beyond the opposite side, then the barb is hooked to the opposite side and the sleeve is shifted towards the bone until it abuts on the plate. The drill hole length can then be read on the indicated probe member markings. As it was not possible to haptically insert the probe member into a drill hole due to haptic discrepancies (see page 148), a slightly different approach was chosen. Each drill hole is indicated by a small sphere, onto which the tip of the depth gauge has to be moved. If the depth gauge is extended enough, it gets automatically inserted at the correct depth, such as if the barb would hook to the opposite side. The sleeve can then be shifted onto the plate by pressing the button on

the haptic device or by using the keyboard. The drill hole length can then be read on the markings on the depth gauge.

During movement of the depth gauge, the nearest drill hole in which no screw has been inserted, is searched for and the Euclidean distance is calculated. If this distance is below a position tolerance threshold and the depth gauge is extended enough to be fully inserted in this drill hole, it gets snapped to this drill hole with the same orientation by overwriting the IHIP position and orientation. If the depth gauge remains near the drill hole, i.e. below a distance threshold, the extension of the sleeve is checked if it is shifted enough towards the plate. As long as the sleeve is on the plate, an informative sound effect is played to inform the user that the correct length is reached and the depth gauge can be removed to read the drill hole depth.

Screw Insertion

The screw insertion interaction allows the user to choose a screw from a predefined range, exchange it if another length is needed, and insert it into a prepared drill hole. The procedure of inserting a screw is similar to that of measuring for length, the screw tip has to be moved to the same sphere that is used for measuring, and with the same orientation as the drill hole. Then, the screw can be tightened by pressing the button on the haptic device, until it has been inserted according to its length and a torque limiter sound effect is played, indicating that the screw is fully tightened.

Again similar to the drill and the depth gauge, a haptic sphere is used for collision detection. The screw mesh and the screwdriver are rotated during tightening, with the possibility to define a length threshold (based on the screw length), which stops rotating the screw and screwdriver shaft. By this, a torque limiter is simulated, as the screwdriver handle continues rotating, but the shaft and the screw stop rotating. As soon as the user starts tightening, the screwdriver and screw get fixed by overwriting the IHIP position and orientation. Once the limit is reached, the torque limiter sound effect is played to indicate that the screw is now fully tightened.

During tightening, the position of the screwdriver is used to update the position of a haptic field, which pulls the end effector along the insertion axis.

Taking X-rays

The X-ray functionality renders parts of the scene with custom vertex and fragment shaders. Predefined positions are used to render the bone, soft tissue, plate and screw models either from a PA or lateral imaging view. A dynamically created scene graph is used to differ between implants, which are rendered radiopaque, and bone and soft tissues, which are rendered radiolucent, see figure 6-26.

For the conversion of the RGB colour value to a greyscale value (based on the Rec. 601[1] standard) and the generation of the virtual X-ray images, see section B.3.

Following the golden rules of interface design (see 6.10.4, *Interface Design Rules*), an audible X-ray machine sound effect is played to give the user informative feedback that the action has been accepted and the X-ray is being created. In addition, a notification message informs the user that the new X-ray image can be opened in the X-ray viewer.

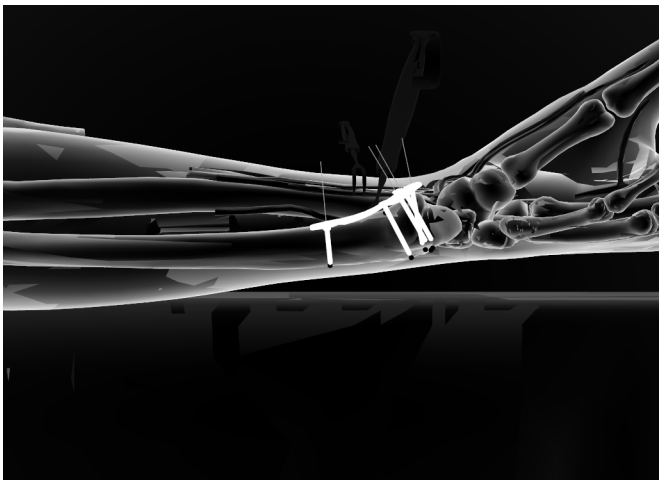


Figure 6-26: Computer-generated X-ray image collected during the hands-on of a medical student participating in the evaluation.

Graphical User Interface for Interactions

The interactions provide their own graphical user interface widgets (except the measuring interaction), which are used to select a plate or screw length, to open the X-ray viewer or to show screw alignment and drill hole information, see figure 6-27. The interactions user interface is dynamically created, allowing later additional interactions to be integrated, without the need to modify the other interactions.

1. ITU (2015) *Studio encoding parameters of digital television for standard 4:3 and wide screen 16:9 aspect ratios*. [Online]. Available from: http://www.itu.int/rec/R-REC-BT.601-7-201103-I/en.

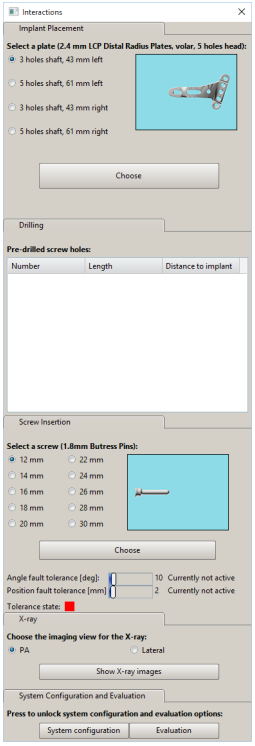


Figure 6-27: Graphical user interface for the interactions.

6.9.4.4 Simulation State

This component provides the application logic, maintains the simulation state and ensures that only valid actions at a certain point in the medical scenario can be executed. It is responsible to process user input, to manage the interactions and to proceed the simulation, whose behaviour is described by a finite-state machine. The event-driven system consists of six states, which can be mapped to the corresponding interactions, and one state which represents the default state, from which transitions to the interactions can be triggered, see figure 6-28.

The system enters the default surgical idle state when the application successfully finished starting up. As the plate is not yet applied to the radius bone and no hole has been prepared, the only valid transitions are picking a plate or taking an X-ray. As the medical scenario advances, the transitions to the remaining states occur, controlled by guard conditions. These guard conditions are executed first and can prevent the transition from firing, for example when the user tries to pick a drill but the plate is not yet applied.

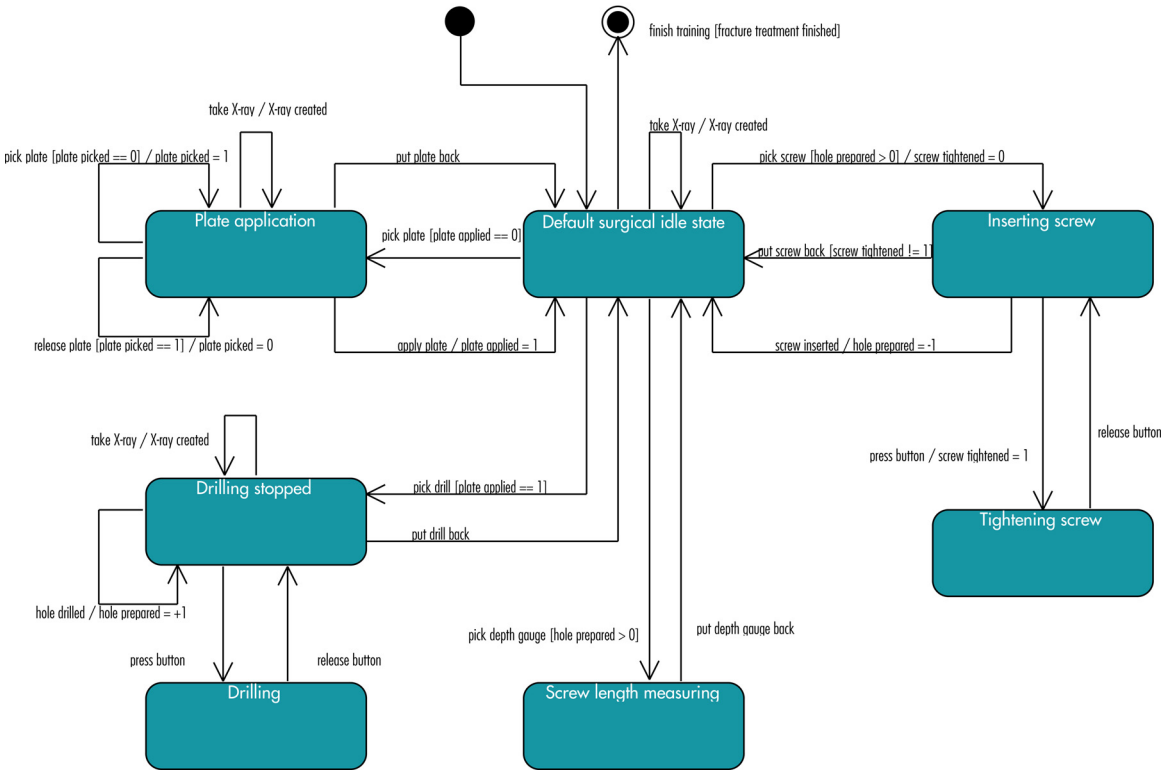


Figure 6-28: Simulation states and transitions of the finite-state machine.

6.9.4.5 Performance Assessment and Reporting

This component is responsible to record all relevant user data for training and performance assessment and manages the user login screen, which is used to store the recorded data in user-dependent files using the XML data format. The parameters presented in table 6-4 are currently recorded; each record is stored with a time stamp. After each new record that has been added, it is written to disk. It is not kept open in memory, as it could be lost in case the application quits unexpectedly.

Table 6-4: Recorded parameters for performance assessment.

Topic	*Parameters*
General	• Start and finish time of each interaction and of the whole training and manipulation time of each instrument. • Whether the guided mode is activated.
Plate application	• Which plate is chosen and if it has been put back. • The time the plate is moved. • When it is applied, the plate type and position.
X-ray	• Filename of the created X-ray image. • PA or lateral imaging view.
Drilling	• Drilling duration and start and stop time. • When a drill hole is accepted, the start and end positions, the position on the plate, the effectively drilled length and the error, i.e. how much too far has been drilled on the opposite side.
Measuring for length	• If the depth gauge has not been extended enough when moved into the drill hole. • If a hole has been measured, the measured length and hole number.

Topic	*Parameters*
Screw insertion	• Selected screw and if it has been put back. • Chosen drill hole. • When finished tightening, the insertion depth and the position and orientation deviation.

6.9.4.6 User Interface

The graphics user interface is technically split into two parts, an OpenSceneGraph window with the virtual operating theatre and the surgical site, and a Nana[1] (a cross-platform library for creating graphical user interfaces) window comprising of the interaction widgets and the X-ray viewer, see also "Graphical User Interface for Interactions" on page 169. This was necessary as the Nana library did not yet support OpenGL rendering at the time of development.

The messages and notifications, which are used to instruct the trainee about the next step in the medical scenario or for immediate feedback of user or system events (see figures 6-29 to 6-31), use the osgWidget module of OpenSceneGraph, controlled by an in-game GUI manager, which provides functions to show messages and notifications at predefined positions, with an optional audible feedback for error notifications.

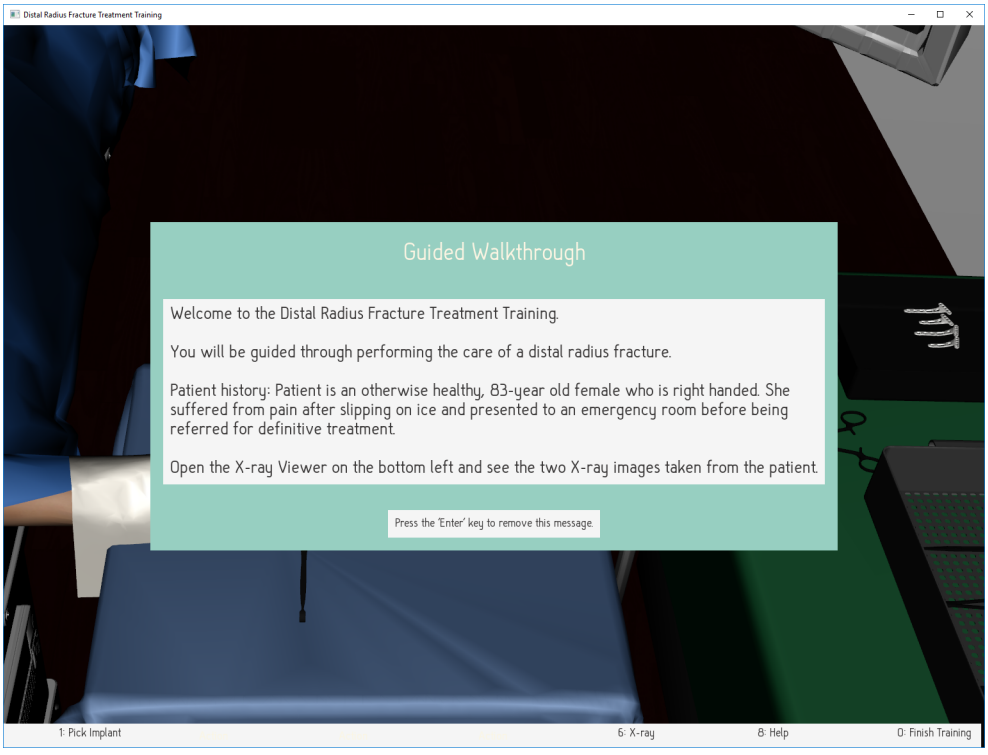


Figure 6-29: Instruction messages: large, clearly visible instructions which the user depends on to successfully proceed in the medical scenario and that are mandatory to acknowledge (by pressing a key).

1. JINHAO (2015) *Nana C++ Library — A modern C++ GUI library*. [Online]. 2015. Available from: http://www.nanapro.org [Accessed: 5 October 2015].

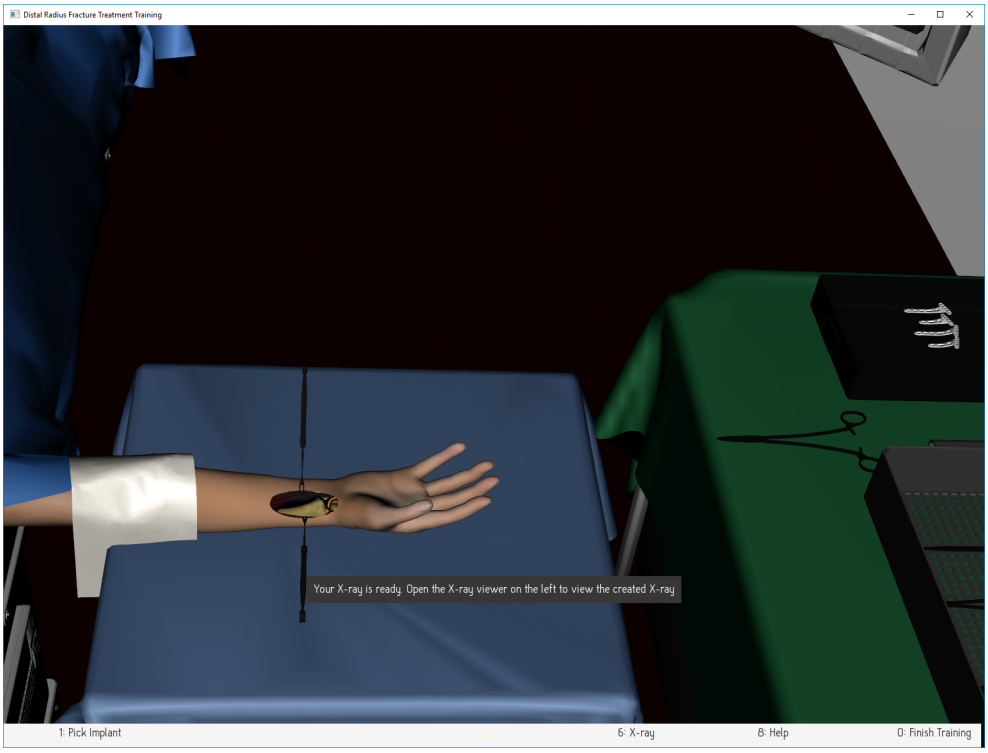


Figure 6-30: Notification messages: less clearly visible than instruction messages and automatically disappear after a period of time; used to indicate system events or confirm user actions.

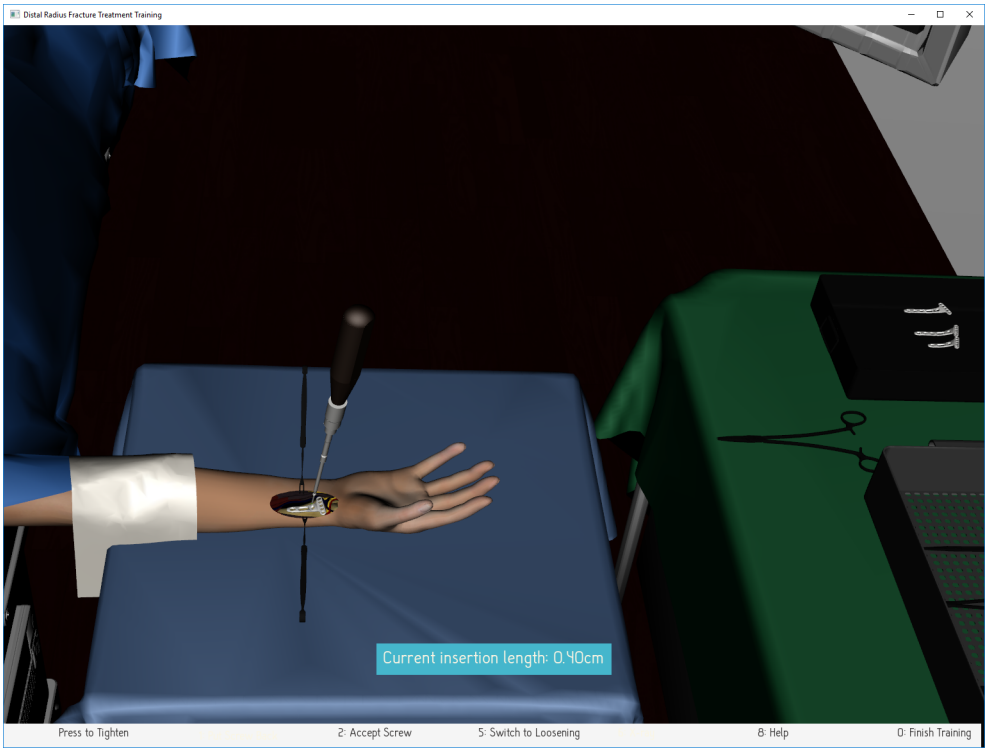


Figure 6-31: Information messages: shown more visible than notification messages and indicate real-time progress data such as the current insertion length of a screw.

6.9.4.7 Evaluation Functionality

With regard to the medical evaluation (see section 7.4, *Medical and Usability Evaluation*), additional visual-only geometries and information have been integrated to investigate if they would support the trainee in completing the medical scenario. A basic set is enabled by default, such as the drilling guide, the projected entry point on the radius bone when using the drill, or the spheres indicating the centres of the plate holes. During runtime, these options can be enabled and disabled through an evaluation widget, which can be opened in the interactions graphical user interface. The following geometries are available:

- A line to indicate the drilling direction and whether it points onto the radius bone.
- Spheres marking the entry and exit points on the radius bone for the current drill direction.
- A sphere representing the centre of the hole on the plate.
- Differently coloured spheres indicating the nearest drill hole for the currently active medical instrument.
- A line indicating the drill hole orientation for screw alignment (for only the nearest or all drill holes).

In addition, the following information can be shown using the implemented notification system:

- Depth of the drilled hole.
- Current extension of the depth gauge.
- Current insertion depth of the screw.
- After screw has been tightened, position and orientation deviations.

6.9.4.8 Input Devices

This component manages the access to hardware devices, such as getting position, orientation and (linear and angular) velocities from a haptic device or sending force and torque to a haptic device.

6.9.5 Process View

The surgical simulator consists of several components which run in distinct threads. It is mainly built upon five threads, as depicted in figure 6-32:

- *System thread:* Consists of the simulation state and reacts to external events, such as user input by the use of the haptic device or decisions taken during the simulation. It also creates, enables and disables interactions and manages their states.

- *Haptic thread:* Runs ideally at least at 1 kHz and computes rigid body simulation and force feedback.
- *Contact thread:* Runs asynchronously at the highest possible rate and performs collision detection and clusters the collision information into a set of representative contacts.
- *Visual thread:* Runs at about 60 Hz, synchronises position and orientation of objects that are affected by the haptic rendering with their visual representations and renders the scene.
- *Device thread:* Initialises the haptic device and runs the update thread which reads the device state (position, orientation and velocities of the end effector) and applies the computed force and torque of the haptic thread.

The system thread is responsible for managing the simulation state, which is maintained by a finite-state machine. The transition changes are triggered by the user when selecting a medical instrument, choosing a plate or screw, or by proceeding through the medical scenario. The interactions, which are enabled and disabled depending on the simulation state, share a common interface allowing the addition of new interactions if needed without changing the system architecture.

Haptic rendering consists of two threads, a haptic thread and a contact thread, which implement the six-DoF haptic rendering pipeline described by Otaduy and Lin (2006).

Since visual and haptic rendering each use their own representations of the models in the scene, the visual thread needs to synchronise its visual representations of the models with the information from the physics world, updated by the haptic thread. This is realised using an event handler, which is called each time the scene graph is traversed for rendering, reading position and orientation of all objects that the physics world manages and updates the corresponding visual representation in the scene graph.

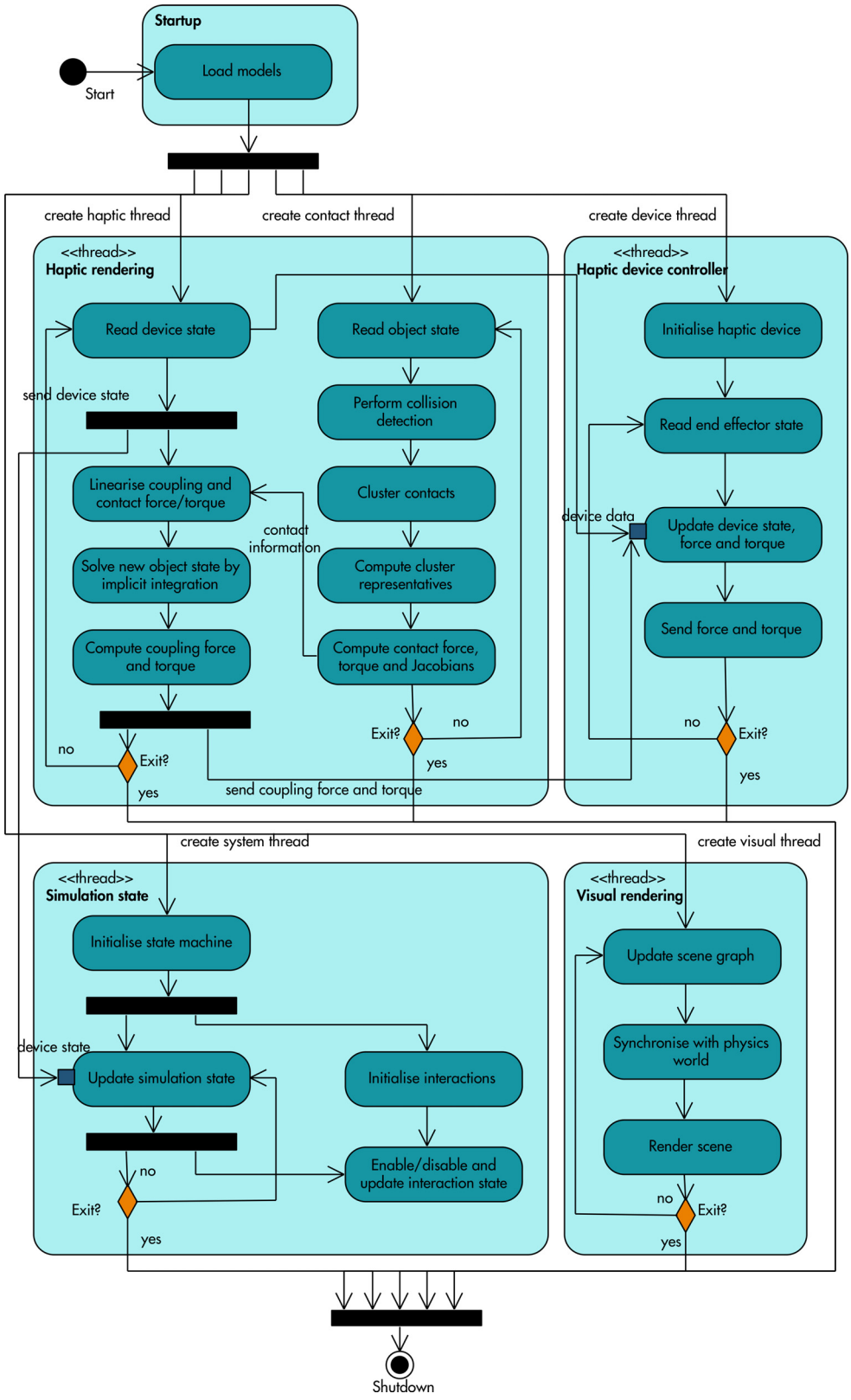


Figure 6-32: Overview of the process and threads of the surgical simulator.

6.9.5.1 Haptic Rendering and Collision Detection Threads

The implemented six-DoF haptic rendering pipeline consists of a haptic and a contact thread, as illustrated in figure 6-33. Both threads run asynchronously at the highest possible rate.

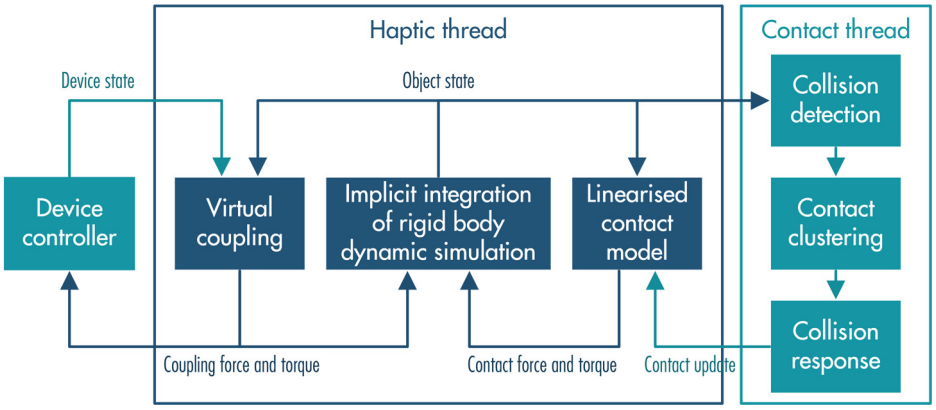


Figure 6-33: Overview of the six-DoF haptic rendering pipeline (Otaduy and Lin, 2006, p.753).

The haptic thread uses information from the haptic device and the contact update received from the contact thread to compute the new state of the user-controlled object by linearising the coupling and contact forces and torques of the previous frame and by implicit integration. The resulting force feedback is then sent to the device controller. The implementation is based on the rigid body dynamics, virtual coupling and linearised contact model equations by Otaduy and Lin (2006, pp.754-756, p.758) with several modifications and corrections as detailed in section B.5.

The contact thread performs collision detection and clusters the contacts by a proximity-based clustering technique to compute a fixed set of cluster representative contacts that capture perceptually relevant information of the geometry. The implementation is based on the contact clustering and penalty-based collision response equations by Otaduy and Lin (2006, pp.756-758), with modified initialisation and assigning functions, see section B.4 for further details. From these representatives, a linear approximation of the contact force and torque is computed, which is used by the haptic thread for linearisation of the contact force and torque.

6.9.6 Development View

Two different data structures are used: intermediate data that is used to exchange information between components, and global data structures that are used by major portions of the system architecture, such as 3D geometries.

6.9.6.1 Internal Software Data Structure

The haptic rendering pipeline is split into collision detection and response, i.e. a contact thread, and simulation of rigid body dynamics, i.e. a haptic thread. The contact update data from the contact thread is used in the haptic thread, and the object state is used by both threads. A contact update holds the following data:

- Viscoelastic penalty-based contact force and torque for each cluster representative.
- Derivatives of contact forces and torques, i.e. the first-order partial derivatives with respect to the state variables (position and orientation, linear and angular momentum).

The shared data between the contact and haptic thread holds the following data:

- Object state of the rigid body (position and orientation, linear and angular momentum).
- Contact update data.

The state of a haptic device is updated in the control loop by the implementation of the particular haptic device class and used by the haptic thread to compute virtual coupling. It contains the following data of the end effector of the haptic device:

- Position and orientation.
- Linear and angular velocity.
- Button mask to check if the user pressed a button on the haptic device.

6.9.6.2 Global Data Structure

The surgical simulator is a standalone application, therefore all data resides locally. There are mainly two different types of data: 3D geometries used for visual and haptic rendering, and text-based data such as user performance records and configuration settings stored in the XML data format. The 3D geometries are loaded during the start-up of the application, further geometries can be loaded upon user selection such as plates or screws. They are stored in the open OBJ file format and are read by OpenSceneGraph for visual rendering and by PhysX for collision detection. To decrease application start-up time, the visual and physics models are serialised into binary formats, by which the 3D models are serialised into blocks of memory which can again be loaded without allocation or copying.

6.9.7 Physical View

The surgical simulator is developed as a standalone application, therefore all logical components and processes run on a single computer, which also contains the 3D model repository as shown in figure 6-34. The two input devices are attached via USB connections.

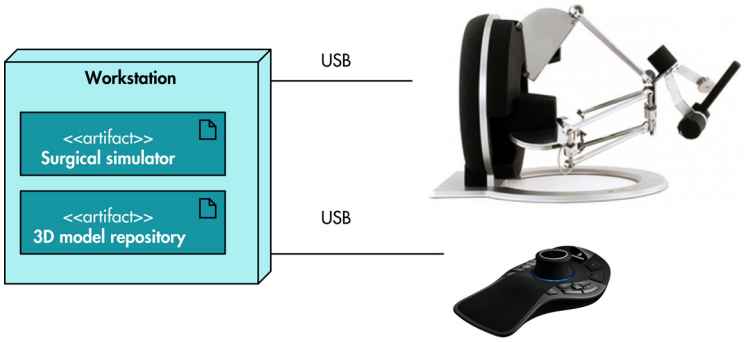


Figure 6-34: Hardware infrastructure of the surgical simulator.

6.10 Human Interface Design

The user interface consists of two screens: a login screen, which is needed to record performance per trainee, and the main screen with the simulated surgical site in a 3D view. Additionally, the main screen contains a menu bar through which the user can perform different actions, such as choosing a plate or taking an X-ray. The user interacts with the menu through mouse and keyboard, and executes those actions through a haptic device, which simulates the surgical instruments and implants.

6.10.1 Description of the User Interface

The main part of the main screen is occupied by the 3D view, which renders the virtual surgical site. Various GUI components such as labels, buttons and checkboxes are used for the menu. They are clearly arranged so that the user is able to quickly and efficiently make the appropriate selection. A feedback information system is used to inform the user about events that occurred or to instruct him how to proceed in the medical scenario.

6.10.2 Screen Objects and Actions

The user directly manipulates objects in the 3D scene with simulated surgical instruments, controlled by the haptic device. Using the object-actions interface (OAI) model (Shneiderman and Plaisant, 2004, pp.95), where the user first selects an object and then performs actions with it, allows to imitate the usage of the real world surgical instruments. The advantage for the user is that this interface is easier to learn and provides immediate feedback, as the usage of the simulated surgical instruments has an immediate effect when performing the action with it. For example, using

the drill to prepare a hole has the effect that a hole in the bone is immediately created once the user drills into the bone, which maps to real-life situations, instead of first choosing the action (drilling) and then choosing the drill.

6.10.3 Screen Images

Once the application has finished starting and the user has logged in (see figure 6-35), the main screen is shown, see figure 6-36. The surgical simulator provides two different modes: a guided mode, where the trainee is directed through performing the treatment of the distal radius fracture, and a training/assessment mode, where only essential information about the use of the surgical simulator is given. These two modes were proposed by medical experts during the user requirements gathering study, as they would allow using the simulator in self-directed learning and as an assessment tool for qualifications. This implements the recommendations Fischer and Scharff (1998, pp.5-6) proposed, that technology should not just be an addition to existing practices in education. Instead, richer, conceptual frameworks exploring new possibilities and limitations are needed and they formulate five requirements on such software environments, such as that they should be user-directed and with contextualised support on the user's task, be sufficiently complex and open-ended to allow breakdowns, provide means for modifications by users, support a range of expertise and must promote collaboration to learn from each other.

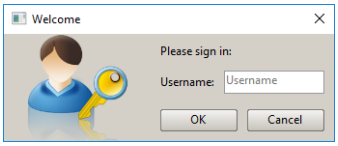


Figure 6-35: Screenshot of user login screen; used to record trainee's performance under his username.

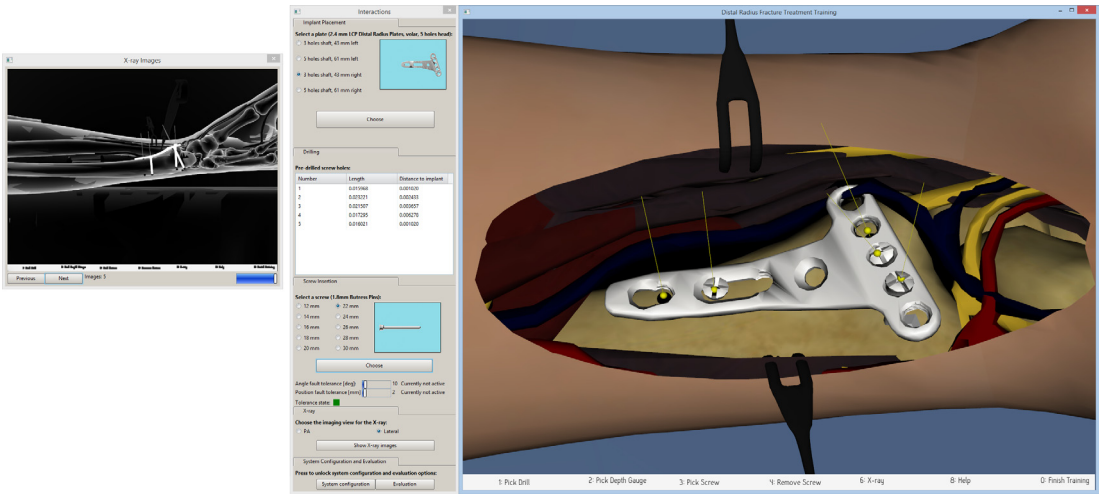


Figure 6-36: Screenshot of main screen with opened X-ray viewer.

The user interface is split into three parts: the main screen with the 3D visualisation of the surgical site, a menu bar on the bottom of the main screen to choose an action, and a widget on the left side, which provides access to options for the currently active action, such as selecting a plate for example.

The user can choose from different surgical instruments by selecting the corresponding menu bar field, which then gets shown in the main screen's 3D visualisation. The selected surgical instrument can be directly manipulated by the haptic device to perform the intended action. For several actions, further decisions have to be taken, such as choosing the screw length. These options are shown on the left side, which get dynamically adapted to the chosen action.

To learn the correct procedure of the surgical scenario, a guided mode leads the trainee through the entire surgical procedure by instructing him what he has to do next. These instructions are given by modal information dialogue boxes, shown in the middle of the main screen, see figure 6-37. Further message boxes are used to give the trainee immediate feedback about events that occurred, such as that he chose a particular plate, or about invalid steps he would make. This feedback is also shown in the main screen, and depending on the importance of the message, it can be shown unobtrusive by a smaller message box in the lower bottom or more distinctive by a larger message box, and to further attract the attention on the importance, an audible signal can be added.

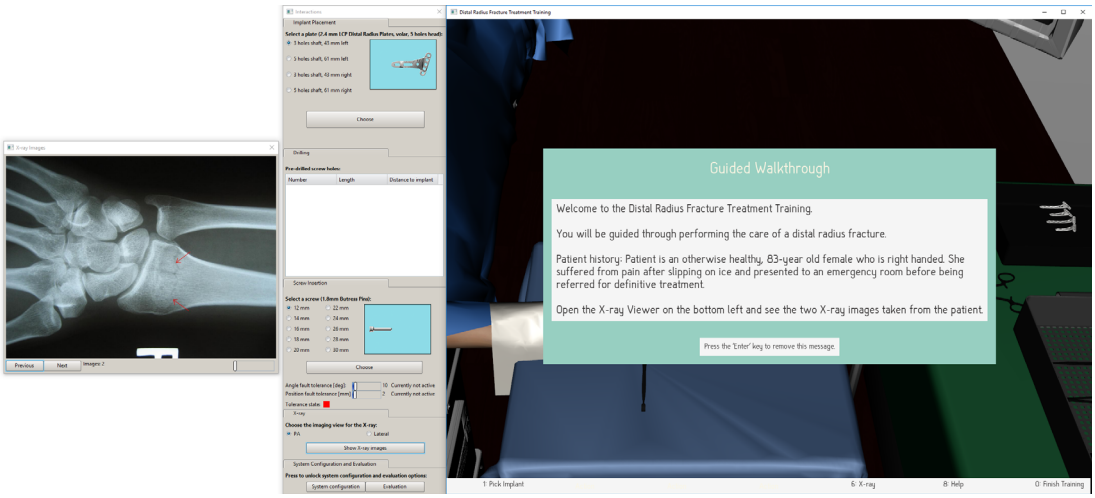


Figure 6-37: Screenshot of the main screen in guided mode.[1]

1. Image of X-ray: ERICKSON HAND SURGERY (2015) *Erickson Hand Surgery — Distal Radius Fractures.* [Online]. 2015. Available from: http://www.ericksonhandsurgery.com/patient_information/distal_radius_fracture [Accessed: 24 April 2015].

6.10.4 Interface Design Rules

Respecting the eight golden rules of interface design developed by Shneiderman and Plaisant (2004, pp.74), the user interface of the surgical simulator is designed to support the trainee in learning the correct procedure of the surgical scenario, instead of first learning a complicated user interface. The following list describes the implications of the eight golden rules to the user interface of the surgical simulator:

1. *Strive for consistency:* For each action, the use of the menu bar options is similar, such as when the user is satisfied with the position of the plate, he accepts this position with the same keyboard command as when he wants to accept a prepared hole. This also applies to the selection of the plate and screws. Furthermore, the terminology used in the instructions, the menu bar and the feedback notifications is consistent.
2. *Cater to universal usability:* For first-time users, additional instructions can be shown, which get reduced in subsequent training sessions. Furthermore, providing shortcuts is difficult, as the keyboard is less used than in traditional applications. However, it is possible to directly choose an option from the left side, which automatically selects the corresponding surgical instrument.
3. *Offer informative feedback:* Selecting a surgical instrument has the immediate effect, that it is shown in the main screen. Furthermore, decisions made and events that occurred can be confirmed by unobtrusive notification messages, shown in the main screen.
4. *Design dialogues to yield closure:* Once the trainee has finished a step of the surgical scenario, feedback and instructions on how to proceed can be given. Furthermore, notification messages are again used to confirm that an action completed successfully.
5. *Prevent errors:* From a user's perspective, options in the menu bar that are not valid at the current stage are disabled so that he would for example not be able to choose a screw when no prepared holes are available. A finite-state machine prevents that the surgical simulator can be forced into an undefined system state by preventing invalid actions and informs the user about the logical error.
6. *Permit easy reversal of actions:* In a real surgery, certain actions can be reverted, such as choosing the wrong screw length (before inserting it in the drill hole), others are almost irreversible, such as drilling a hole. It is possible to choose another plate or screw, and since this is a simu-

lator for training purposes, a trainee is also able to drill again if he is not satisfied with the hole he just prepared.

7. *Support internal locus of control:* The widget on the left side adapts itself to the current action, so that the user is not forced to search the information in complicated layouts or subforms, which first have to be opened. By obeying this rule, the interface is kept clean and easy to understand.

8. *Reduce short-term memory load:* Each action is self-contained and only requires few steps to complete. Using the guided mode, instructions given are only related to the next step instead of giving all instructions at the beginning of the training. In addition, the selected screw length or plate type is visible until it is inserted or applied. This also prevents that the wrong screw size gets selected unintentionally and the user is left unaware of it.

6.11 Discussion

This chapter is split mainly into three sections, from which the first two sections aimed to answer the question which software framework and which haptic library are most suitable to develop a surgical simulator with. The third section details the development steps that led to a distal radius fracture treatment surgical simulator, capable of training relevant tasks a surgeon has to perform during real surgery, and which is based on the insight gained from the user requirements gathering study detailed in chapter 4 and on the requirements specified in chapter 5.

Several software frameworks have been evaluated, with different areas of designated use, such as H3D, which supports haptic rendering, or SOFA, which is aimed at medical and physical simulations. Although SOFA appeared to be the most suitable based on comparing features and the applications that were developed with it, it emerged that it would require a substantial amount of time and work to overcome the current limitations it has (such as not working haptic feedback) and to become acquainted with the application interface. Therefore, OpenSceneGraph proved to be most promising option, as it has a large user community, a plug-in to support three-DoF haptics and is well-known from previous research projects, see section 3.3. As a result, the second step was to evaluate a haptic library which works best with OpenSceneGraph using developed demonstrators.

One of the key findings of the haptic library and software prototype evaluation was that although haptic rendering is used since the early 1990s with the introduction of three-DoF haptics and the PHANToM haptic device, still no library supports six-DoF out of the box and still is subject of current research, especially with deformable bodies. At the beginning of this PhD research project, it was assumed that using three-DoF haptic algorithms should allow developing the required func-

tionality and provide meaningful haptic feedback. However, the demonstrators showed that this is almost infeasible, as considerable work would be required to simulate mesh-to-mesh haptics with the evaluated three-DoF haptic libraries, and it would effectively lead to an almost complete rewrite of the haptic library, if even possible, see section 6.6.2. Therefore, implementing the six-DoF haptic rendering pipeline of Otaduy and Lin (2006) provided the basis to develop the haptic feedback for the available interactions in the surgical simulator. This algorithm uses contact information between colliding meshes, which can be computed either by the algorithm which was originally used in the publication of Otaduy and Lin, or by using an available game physics engine such as PhysX. To reduce the development time, PhysX has been used instead of additionally implement CLODs (Otaduy and Lin, 2003), with the possibility to later replace it if needed. It was considered that optimising the geometries (such as reducing polygon count or only consider collisions between the currently active geometries) will lead to a much higher performance increase as replacing the physics engine by another one. By using a convex decomposition algorithm (HACD, Mamou and Ghorbel, 2009), the average polygon count could be reduced by more than 90% (see page 165), which has an assumably higher impact than replacing physics engines, as Hummel, et al., (2012) found that five reviewed open-source physics engines performed equally.

The iterative design approach that was used revealed to new use cases (measuring for length and taking X-rays), which were initially considered to be less significant tasks by the interviewed medical experts. But when they were shown the first prototype of the surgical simulator (see section 6.8), they identified them as necessary, as they teach important aspects of a surgery (measuring) and provide a significant advantage over commonly used synthetic plastic bones or books and videos (taking X-rays), such as that the effect of an inserted screw can immediately be analysed on the X-ray, as it could protrude or bicortical screws could be fixated only in one cortical bone. In addition, using a second prototype, the currently implemented paradigms of using the simulated medical instruments were reviewed and refinements to those were proposed by medical experts. These reviews of the prototypes showed that following a user-centred design approach has proven advantageous, as it revealed functionality that was considered less important during the user requirements gathering study, but showed in a later stage that they are required for the understanding of the implemented medical scenario and provide an added value compared with the current training possibilities.

The development of the core functionality of the surgical simulator (such as application logic, rendering or device management) was straightforward, as commonly used software design patterns were used and the requirements were similar to projects detailed in section 3.3. Significant time was required for the implementation of the haptic rendering pipeline, as errors in the equations de-

scribed in Otaduy and Lin (2006) had to be corrected (see sections B.4 and B.5), and for the implementation of the interactions. The result of the framework evaluation, to choose OpenSceneGraph as the core framework and implement a custom six-DoF haptic algorithm proved to be successful, as a surgical simulator could be implemented that was based on the findings of the user requirements study, provided the discussed functionality and by following a user-centred design approach and adhere to human interface design rules (see section 6.10.4), the surgical simulator was expected to meet the expectations of both medical experts and targeted user group and thus to be ready for the medical evaluation, detailed in the following chapter.

Chapter 7

Evaluation

7.1 Chapter Summary

This chapter presents the medical evaluation which was carried out with the developed surgical simulator. First, the technical verification and validation process which was undertaken to ensure the simulator is ready to be evaluated with medical students, surgeons and experts is shown. Then, the medical evaluation process, which focused on usability, usefulness and medical relevance, is presented and the results are detailed. The chapter concludes with the discussion of the results and the whole purpose and implications of using such a surgical simulator in the medical training of orthopaedics.

7.2 Overview

During the development of the surgical simulator, feedback from medical experts has been collected when medical or anatomical input was required, or when significant design decisions had to be made, such as the implementation of the required interactions or how the user should receive meaningful feedback. These findings have been integrated into the refinements of the surgical simulator, see section 6.8. In preparation of the development, the demonstrators, which resulted from the software framework evaluation, have been validated on technical feasibility and against the non-functional requirements, see section 6.6. Overall, several verification phases and validation and evaluation interviews have been carried out, as indicated in figure 7-1. The evaluation can be divided into technical verification and validation, which concerns about software quality and meeting the users expectations, and medical evaluation, which reviews usability, medical significance and validity.

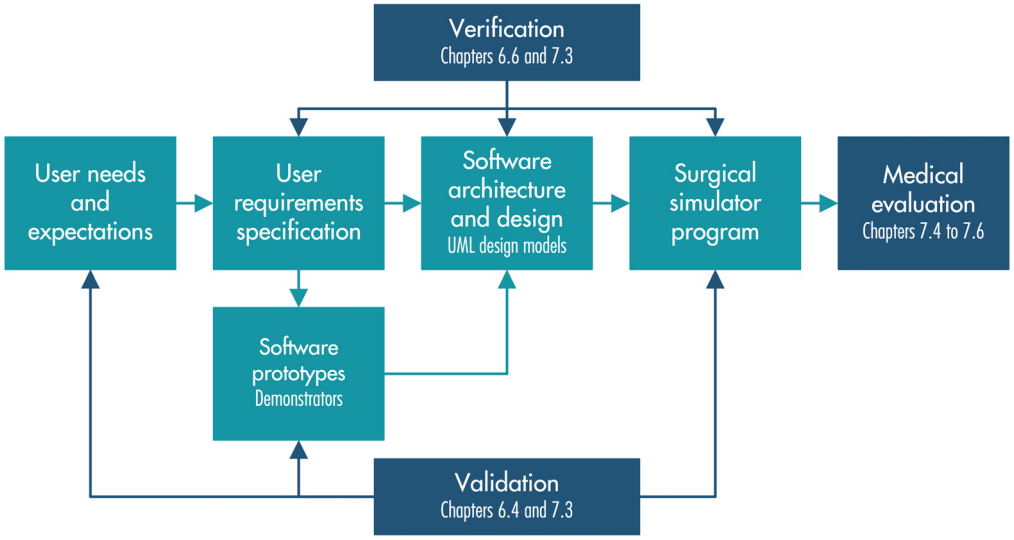


Figure 7-1: Overall stages of verification, validation and medical evaluation.

First, the process of verifying the software quality and ensuring that the requirements and the users expectations are met is presented. Then, the results of the medical evaluation, carried out with medical students, young (assistant) doctors and medical experts are shown and the limitations of the evaluation study are pointed out, and the chapter finishes with the discussion of the results of the medical evaluation study.

Both, the software verification and validation and the medical evaluation were carried out as informal, qualitative interviews, which were semi-structured and allowed to investigate topics that came up more in-depth than it were possible with structured interviews, following a set of closed questions (see sections 7.3.1 and 7.4.1 for an overview of the methodology of the interviews). In addition, using semi-structured interviews allowed to ask for clarification if needed and get a deeper understanding as the participants could speak in their own words and focus the discussion on topics that are relevant for them. However, this approach led to much more qualitative data than a closed set of questions would have and analysing these interviews was more time consuming, especially using thematic analysis, as relevant topics were discussed on several occasions during the interviews.

7.3 Software Verification and Validation

The verification and validation (V&V) process assures that the surgical simulator system meets the users' needs and fulfils its intended purpose. Verification checks if the software meets the functional and non-functional requirements, in contrast to validation, which is a more general process that aims to ensure that the software is meeting the users' expectations. That means, verification answers the question if we are building the product right, whereas validation answers the question if we are

building the right product (Boehm, 1979). Its main objectives are to discover defects of the system and to assess whether the system is usable in the designated situation. There are two approaches to verification:

- *Static verification*: Concerned with the analysis of static representations such as source code or documents to discover problems or to prove correctness of a program. Uses consistency techniques to ensure for example correct parameter usage or to detect ineffective code and bad practices (anti-patterns).
- *Dynamic verification*: Concerned with dynamically checking the behaviour during execution of the software and to find software bugs. Functional testing involves testing all system functions defined by the requirements.

The process of validating a system usually takes place at the end of the system development and looks at the complete system in the required context, as opposed to verification, which focuses on components or a system at a given development phase.

The surgical simulator is from a technical point of view not a highly-critical system, nor is it intended to be ready for the market. However, the users are expecting that the software is reliable and should rarely fail, but they may tolerate some missing features or shortcomings. Therefore, V&V has been focused mainly on automated static analysis of the source code, validation of the requirements and dynamic testing of the final release.

7.3.1 Methodology

Verification started once the user requirements had been defined and the surgical scenario had been chosen. The requirements were verified for relevance with a medical expert, who has participated in the user requirements gathering study. The software architecture and design has been verified to ensure it adequately fulfils the functional and non-functional requirements and provides the foundation for the development of the surgical simulator. At the end of the development phase (and also frequently during implementation), automated static code analyses of the source code using CppDepend[1] and Cppcheck[2] have been made to discover potentially erroneous conditions. Furthermore, the benefit of using static code analysis tools is to optimise the program execution, prevent unexpected behaviour and make the source code more readable, secure and maintainable, as common coding mistakes are detected.

1. CoderGears (2015) *CppDepend :: C/C++ Static Analysis and Code Quality tool*. [Online]. 2015. Available from: http://www.cppdepend.com [Accessed: 18 May 2015].
2. Daniel Marjamäki (2015) *Cppcheck — A tool for static C/C++ code analysis.* [Online]. 2015. Available from: http://cppcheck.sourceforge.net [Accessed: 16 May 2015].

Software validation has been done at the end of the development process in the form of a dynamic testing of the final product with one software engineer. He is working in the same research group, therefore no formal invitation was required. The data which was gathered consists of notes taken during the validation, which have been translated into English. This data has been analysed by a thematic coding analysis approach (Robson, 2011, pp.474), resulting in a categorised software issue list.

The static code analysis tools use similar investigation techniques, they group the results into categories, which allow to analyse the source code for specific conditions and to directly address the relevant parts of the source code.

7.3.1.1 Participants

One participant, a research assistant from the Bern University of Applied Sciences with a biomedical engineering background and with about 10 years of experience in software engineering, participated in the validation process. He was not involved in the system development.

7.3.1.2 Procedure of the Software Verification and Validation

The validation that was done at the end of the development process was carried out similar to the participant observation approach (Robson, 2011, pp.319). As the participant was already familiar with the use of haptic devices and the research topic, no introduction was needed. To determine the correctness of the surgical simulator with respect to the use cases and requirements, the participant was instructed to complete the medical scenario of the surgical simulator with the freedom to do whatever he wants to try out. The qualitative data gathered included the following:

- Identification of software bugs.
- Test for usability, such as user interface, efficiency of tasks or memorability.
- Amount and quality of provided information and instructions to complete the current task.
- Considerations and suggestions the participant came up with.

The information was recorded by note-taking and in the case of software bugs, notes have been added to the appropriate location in the source code if the fault could be clearly identified.

7.3.2 Results

7.3.2.1 Automated Software Verification

During the development, Cppcheck has frequently been used to inspect the source code. The most frequent issues found were variables for which their scope could be reduced and initialisation of variables which was not done in the constructor. Although unlikely to be performance relevant for trivial data types, reducing the scope aids readability and using C++ initialiser lists ensures that the proper constructor gets called.

CppDepend has been used to analyse the final release. The source code has been inspected for different aspects, such as code quality, object oriented design and modernising the C++ code. Treemaps are used to visualise the software metrics by using nested rectangles to display the tree-structured data. In figure 7-2, the cyclomatic complexity (CC) of the methods of the surgical simulator is analysed, which is a quantitative software metric to indicate the number of decisions taken in this particular method, i.e. the number of expressions such as if, while, for or case (McCabe, 1976). By this, it measures the number of linearly independent paths through the code of the particular method.

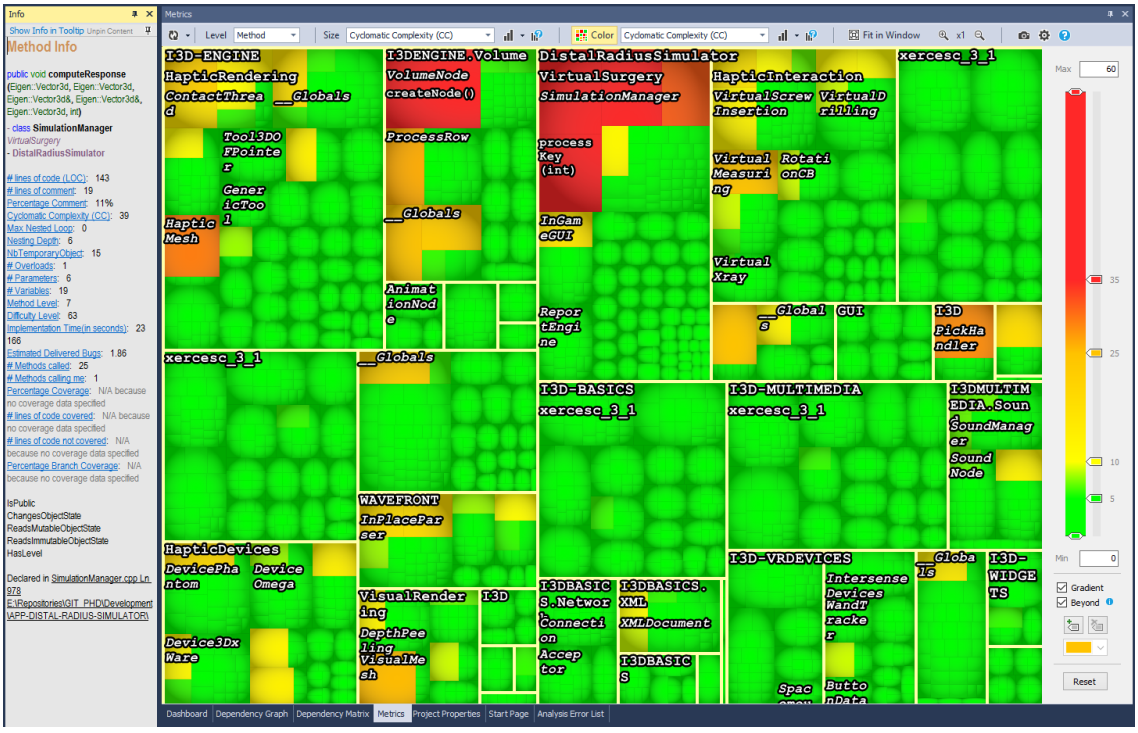


Figure 7-2: Treemap of the surgical simulator; each rectangle represents a method, its area is proportional to the cyclomatic complexity, and potentially too big or too complex parts of the source code are highlighted in red.

With this metrics, methods can be found which are potentially hard to understand (a CC higher than 15) or extremely complex (a CC higher than 30) and which should be split into smaller methods. For example, the bubble sort algorithm has a CC of 4, two for-loops and one compare statement for swapping elements.

Using this method, patterns have been identified that would be hard to find by just reviewing the code, for example code which is too big and too complex. These treemaps have the added advantage of localising issues or revealing interesting code structure observations, as it is a hierarchical view onto the source code. A few parts of the code show high complexity, and for each method, static information is available, such as for the computeResponse method (shown in the left widget in figure 7-2), which has a CC of 39. This represents an extremely complex method and should normally be split into smaller methods. But as this method is responsible to compute the force feedback vector of the haptic feedback, it depends on the current system state and therefore uses different conditional branches, which is also reflected by a nesting depth of 6, but is still maintainable and no further action is required.

According to the statistics of CppDepend, the surgical simulator (including the framework where the haptic rendering pipeline is implemented) consist of about 12,700 lines of code and out of 49 violated rules, three critical ones with 25 violations have been violated (too many parameters, too complex or too big types). The average CC for methods is 1.85 (maximum = 65) and for types 18.96 (maximum = 234). The implementation of the haptic rendering pipeline reveals a CC of 14 for the contact thread and 8 for the haptic thread, which was expectable, as the computations done in those threads are relatively straightforward with no relevant branches.

7.3.2.2 Software Validation

The main goal of the dynamic testing was to find show-stoppers, i.e. issues that prevent the surgical simulator from being usable and ready for the medical evaluation. In addition, observation of the participant using the simulator showed several usability issues, such as imprecise or missing information to continue the medical scenario or how to use the haptic device. Overall, 26 software issues were revealed by the dynamic testing, which can be categorised as follows:

- *Software bugs:* Besides small issues, one show-stopper could be identified which had an impact on both measuring and screw inserting. The application stopped functioning properly in rare cases when the depth gauge or the screw has been moved close to the drill hole, being below the tolerance limit which enables to measure or to insert the screw.

- *User interface issues:* No show-stoppers could be identified, but from a usability perspective, the two separate windows (the main 3D view and the interactions widget) required an additional step to choose a task from the menu bar, i.e. setting the context of the main 3D window active. This was a limitation of the 2D GUI framework, which did not support combining 2D user interface components with a 3D OpenGL view in the same application window at the time of development.
- *Not understandable information:* In one instruction message, it was not clearly stated if the drill bit had to be chosen by the user or if the drill is already usable.
- *Improvements to existing functionality:* Three improvements have been proposed. To have a 'homing' function, which resets the view onto the surgical site to the one from the application start, to visualise the drill hole immediately after the first contact of the drill with the bone, and last, to add several information messages which state what the next steps are or how to use the simulator.
- *Suggestions for new functionality:* The participant came up with several ideas, such as substituting the 3D mouse with predefined views, adding angle locking, cortical and cancellous screw types, or adding an introduction video at the beginning which explains the usage of the surgical simulator and the haptic device.

Most of the issues of the first four categories have been addressed prior to the medical evaluation. The limitations of the 2D GUI framework could not be removed, as it is currently in development and the focus is not on integrating 3D rendering. For a future version of the surgical simulator, the user interface library could be re-evaluated and this issue can be resolved. The suggestions the participant came up with have to be considered for a future version and the medical evaluation will show if there are similar request from medical students, young doctors or medical experts.

7.3.2.3 Requirements Validation

The requirements were reviewed to ensure that they for example accurately describe the functionality of the surgical simulator, that they are correctly derived from the results of the user requirements gathering interviews, that they are feasible and complete, or that they provide an adequate basis for the design and development of the surgical simulator. The relevant functional and non-functional requirements (see section 5.3.2, *Requirements*), which apply to the medical scenario of the treatment of a distal radius fracture, are:

- FR-1, selection of plate and screws.

- FR-4, flexibility of simulator, act as playground.
- FR-5, user-changeable view onto surgical site.
- FR-6, possibility to use different surgical instruments.
- FR-7, user activity logging.
- NF-1, realistic visualisation of surgical instruments.
- NF-2, realistic visualisation of anatomical structures.
- NF-3, haptic feedback.
- NF-5, performance constraint for the interactiveness.

As a result of the iterative design approach (see section 6.8), two new use cases were identified and implemented (measure for length and take X-ray). The related functional requirements are FR-6 and FR-7, as well as the non-functional requirements NF-1 and NF-3. However, these two new use cases did not interfere with the specifications of these requirements, as the use cases were already covered by the defined requirements.

All requirements were validated with acceptance and system criteria, which must be satisfied to be accepted by the trainees and medical experts. These criteria have been defined during the requirements analysis phase, see sections A.3.1 and A.3.2 (row *Requirements* in the tables). The result of the validation is shown in table 7-1:

Table 7-1: Acceptance criteria for requirements validation.

Requirement	*Acceptance/system criterion*	*Result*
FR-1	Implant can be chosen, exchanged and used for fixation.	Pass: Four different plates and different screw lengths are available and can be used in the simulation.
FR-4	The trainee is able to complete the medical scenario with random order of tasks.	Pass: Mostly fulfilled, but each interaction uses its own data which is currently not shared.
FR-5	The view can be set freely or by predefined views.	Pass: By using a 3D mouse, the view is controllable. However, as identified during the refinements, predefined views were not implemented, only the starting view is predefined.
FR-6	Different surgical instruments can be used and those required to finish the medical scenario are available.	Pass: Four surgical instruments/devices are simulated (drill, depth gauge, screwdriver and X-ray), but the end effector of the haptic device is not replaceable (due to technological reasons, i.e. not user-replaceable).
FR-7	The recorded metrics allow to assess and compare the trainees' performance.	Pass: The recorded metrics can be used to compare the trainees' performance and make statements about their performance; over 30 metrics have been defined and can be assessed.

Requirement	*Acceptance/system criterion*	*Result*
NF-1	The visualisation of the surgical instruments must be accepted by the user and no negative statements should be made about them.	Pass: The visualisation of the surgical instruments and the operating theatre equipment has been well-received by the trainees and medical experts.
NF-2	The visualisation of the anatomical structures must be accepted by the user and no negative statements should be made about them.	Pass: Besides the radius bone and to some extent the ulna bone, the remaining anatomical structures were not overly rated by the trainees, as they did not focus on them. However, some had anticipated to interact with them, such as damaging veins or moving soft tissue out of the surgical site.
NF-3	The haptic feedback should allow precise positioning of the plate on the bone, distinguishing between cortical and cancellous bone and generally support the trainee during the tasks.	Pass: The haptic feedback was plausible and supported the trainee with an additional channel of information (tactile sense).
NF-5	The simulation should be running in real time, i.e. the visual render loop at 60 Hz and the haptic render loop at 1 kHz or more, the contact loop at the fastest as possible.	Pass: Measured with the implemented medical scenario, the visual render loop runs at constant 60 Hz, while the haptic render loop runs at 3.5-4 kHz and the contact thread at approx. 0.6-0.7 kHz with 25 contact points (plate colliding with radius bone; tested on an Intel Core i7 920). No statements have been made from participants regarding poor rendering performance.

The requirements validation was based on the final release of the surgical simulator; all nine acceptance and system criteria passed the validation. By this, the developed surgical simulator provided the required functionality and met the system constraints to complete the defined medical scenario.

7.4 Medical and Usability Evaluation

An evaluation study has been carried out to find out whether the developed surgical simulator would be medically relevant, appeal to the targeted medical students and young doctors and if they would use it. Therefore, information is collected about the users' experience when using the simulator and to evaluate the outcome of the user-centred design process. The evaluation focuses on both the usability of the simulator, i.e. how easy is it to complete the medical scenario, and on the users' experience (UX), for example if they enjoyed using it and are motivated to use it for themselves. In addition, the medical relevance and usefulness is evaluated with medical experts to cover all four elements of user experience as described by Guo (2012), see figure 7-3.

Instead of focusing on training effectiveness, this surgical simulator is evaluated to a considerable extent on usability and medical relevance. It was shown that surgical simulators that do not meet the users' expectations (amongst other factors) may not be used more than once or twice (Walker, 2009). Therefore, it can be assumed that if the surgical simulator is not appealing to the targeted user group, training effectiveness will also be limited. However, possible effects on training effec-

tiveness were discussed during the interviews with the medical experts, such as the effect of haptic feedback to teach relevant aspects, which can be transferred to the operating theatre.

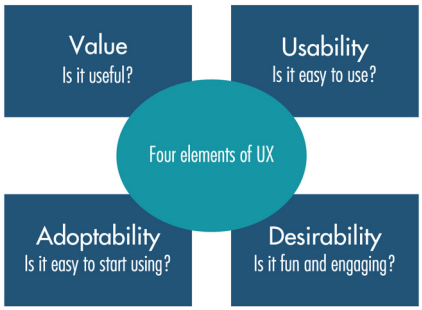


Figure 7-3: The four most fundamental elements of user experience according to Guo (2012).

Both qualitative and quantitative data has been collected during a near-natural usage of the simulator to understand the behaviour or attitude as close to reality as possible, but which also extends the possible topics that get investigated, as there is less control on the procedure of the evaluation. Therefore, the simulator has been evaluated directly at a basic principles course of the AO Foundation, which is one opportunity such a simulator conceivably could be used by young doctors, and in an office in a hospital, where it could be used by medical students.

An informal approach to usability testing was used, as described by Rubin and Chisnell (2008, p.25). The participants were asked to complete the given medical scenario, while automated user performance recordings and a video of the training session are captured. Afterwards, questionnaires, and in case of the medical experts, an additional open discussion, are used to not only get insight into usability aspects of the simulator, but also to get a feedback about other factors that influence the user experience.

The overall user experience is influenced by several factors, to which the three participant groups contributed insight to. Morville (2004) illustrated the facets of user experience as a honeycomb, with valuable as the core of UX, see figure 7-4. Although developed for explaining the user experience of websites, it is also analogously applicable to applications, as these facets describe aspects which are similar when using an application interface or when navigating through websites. In detail, medical experts helped mainly to understand the usefulness and relevance of the surgical simulator, young doctors and medical students provided insight into the remaining five factors, i.e. mainly usability aspects of the surgical simulator.

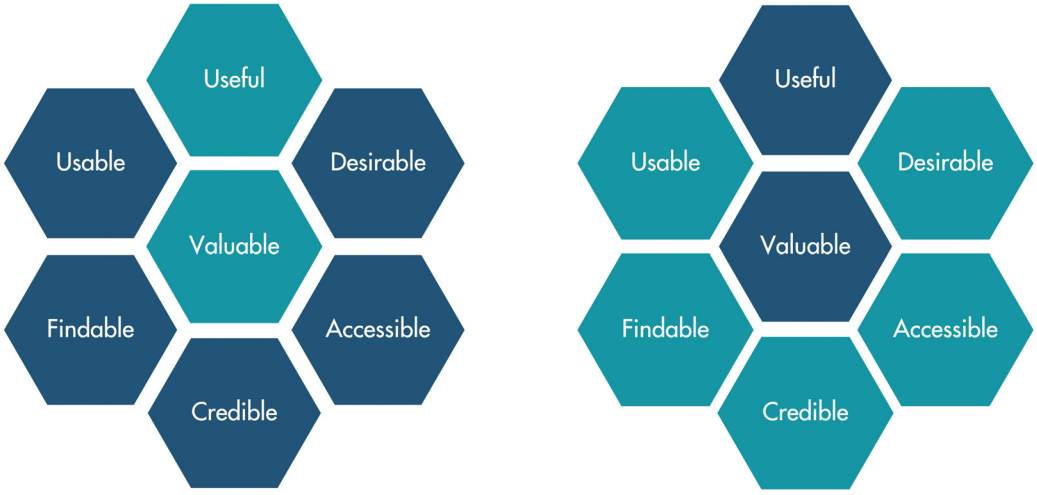


Figure 7-4: Main contributions of medical experts (left, marked in green) and young doctors and medical students to the overall user experience.

7.4.1 Methodology

7.4.1.1 Gathering Data

To evaluate if the developed surgical simulator meets the surgeons' expectations and to measure the acceptance amongst the target user group, i.e. medical students and young doctors, an evaluation study has been carried out. The gathered data includes both qualitative and quantitative data, such as interviews, video recordings of the training session and automated user performance recordings. After the interviews have been conducted, they have been transcribed and the German interviews have been translated into English. The interviews and performance data has been analysed using thematic coding analysis, capturing overall acceptance and suggestions for improvements.

7.4.1.2 Participants

There were three types of participants: medical students mostly in their 4th or 5th year, young (assistant) doctors with an average of three years of experience in orthopaedic surgery, and medical experts in the field of orthopaedic hand surgery. Those three groups provide different types of feedback, such as medical students focus on usability, in contrast to medical experts, which can evaluate the surgical simulator for usefulness and relevance, whereas young doctors can contribute to both types of feedback to some extent.

The medical students have been recruited from the Uniklinik RWTH Aachen in Germany and have been invited by the responsible hand surgeon, which already participated in the user requirements gathering study and a validation interview of the surgical simulator prototype. 14 medical students (2 males and 12 females, n = 14, mean average age = 25.0, standard deviation = 2.8) took

part in the one-hour training. Eleven of the 14 participants were in their 4th or 5th year, the three remaining participants were in the 3rd or 6th year. They had almost no experience in doing surgery in the operating theatre; four of the participants helped assisting a couple of times.

The young doctors were participants of the 58th AOTrauma Course I in Düsseldorf, Germany (Basic Principles of Fracture Management), where the surgical simulator has been showcased with the permission of the AO Foundation and the chairs of the course. 21 Participants (14 males and 7 females), aged between 25 and 38 (n = 21, mean average = 31.48, standard deviation = 3.57), took part in a short survey of about 10-30 minutes. Besides one participant, which was not an orthopaedic surgeon, all participants already had experience for a couple of years in orthopaedic surgery (1 to 8 years, n = 21, mean average = 2.76, standard deviation = 2.02).

The medical experts have either already participated in the user requirements gathering study, have been invited by personal contact of one of those medical experts, or were instructors at the 58th AOTrauma Course in Düsseldorf. The 10 participants (nine males and one female) have several years of experience in orthopaedic surgery (6 to 34 years, n = 10, mean average = 14.75, standard deviation = 8.3), are actively involved in the training of trauma surgeons and orthopaedists, and at least one also at the European level, and regularly take part as instructors at courses such as from the AO Foundation.

Overall, 45 participants from Switzerland and Germany participated in this medical evaluation, 14 medical students, 21 young doctors and 10 medical experts, see figure 7-5.



Figure 7-5: Overall number and country of origin of participants.

7.4.1.3 Trainee Instructions

The medical student participants got two documents, a short 'First Steps' and an overview of the possible actions, which explain how to use the trainer and how to manipulate with the haptic device and the 3D mouse. The 'First Steps' document explains the layout of the user interface, the feedback system with the instruction and notification messages, and the use of the input devices. The interaction overview lists all available actions (such as "Take drill", "X-ray" or "Accept hole") with a brief description and how to choose it. It would be possible to integrate these information into a short introductory video, which can be shown when the user starts the simulator for the first time.

7.4.1.4 Procedure of the Medical Evaluation

The medical evaluation for all three user groups was carried out similarly, with different topics investigated. The evaluation setup remained the same for all participants, a workstation running the surgical simulator with the attached haptic device and a 3D mouse. The one-to-one participant observation approach was used, supplemented by a semi-structured interview (Robson, 2011, pp.319 and pp.285). The overall medical evaluation process is shown in figure 7-6.

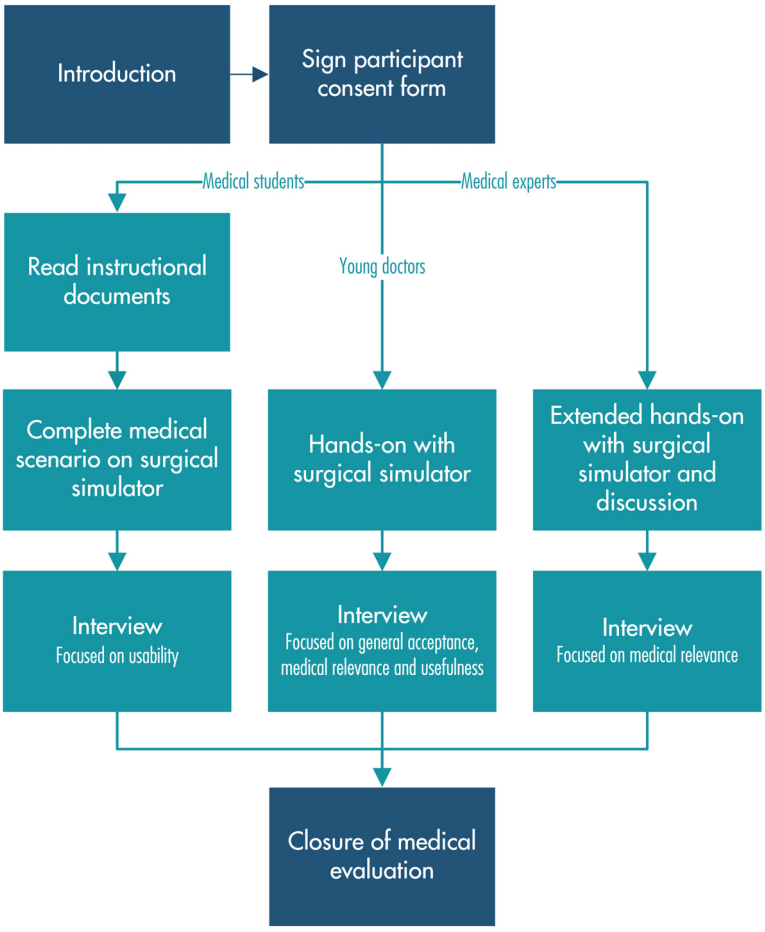


Figure 7-6: Medical evaluation process with different participant groups.

First, a short introduction was given, including the research topic and the purpose of the evaluation as well as the assurance of confidentiality and the permission to tape-record the interview. Second, according to the University of Nottingham ethics guidelines, all participants were handed out the participant consent form, providing information about their rights and confidentiality issues, which they had to sign and in addition, fill out demographic questions (affiliation, age, gender and orthopaedic experience). Two participants of the medical experts group gave verbal consent instead of written. The procedure for the different participant groups was as described in the following sections.

Medical Students

The evaluation was split into a first part, where the participants used the computer-based surgical simulator and completed the given medical scenario, see figure 7-7, and a follow-up interview as the second part.

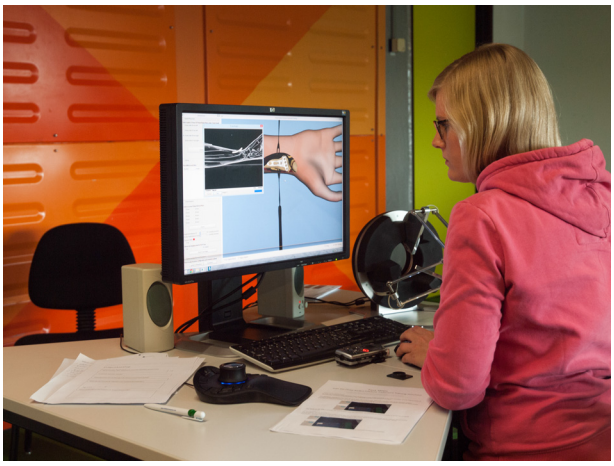


Figure 7-7: Medical evaluation setup for medical students at the Uniklinik RWTH Aachen.

First, the training instructions were handed out and discussed if not clear. Then, the participants had to rate themselves on the following predefined criteria on a Likert scale of 1 to 5, with 5 being the best (5 = strongly agree, 4 = agree, 3 = neither agree or disagree, 2 = disagree, 1 = strongly disagree):

1. I know the sequence of actions for the treatment of radius fractures.
2. I feel confident to assist a radius fracture treatment.
3. In general, the training on a simulator can be well transferred to practice.
4. In general, the training on a simulator is useful for understanding the sequence of actions of an operation.

5. Simulator trainings should be part of the students' education.

The surgical simulator was evaluated in the 'guided mode', which instructed the participants at certain points what the next step in the medical scenario is:

- At the beginning, the indication, patient preparation and approach were specified, based on which the participant had to start with choosing an appropriate plate.
- After the plate has been applied, the participant was instructed to use the drill to prepare the first hole (i.e. the oblong hole).
- After he drilled the first hole, the participant was instructed to measure for screw length and insert a screw which is long enough.
- After the first screw has been inserted, the participant was instructed to continue inserting additional screws (at least three distal locking screws and at least two further proximal screws).

The participants were instructed to say if they were missing information, were lost in the medical scenario or any other issues occurred with the interface or the use of the surgical simulator. The performance of the participants was video-recorded (by the system), a logging system recorded important steps, events and decisions the user made. When the participants finished the training, the same five questions with the predefined criteria were asked again to investigate improvements.

The questions of the follow-up interview were structured as follows:

1. Questions about the usability of the system, realism of the haptic feedback, user interface layout and feedback system of the surgical simulator.
2. Discussion of usefulness of supporting information such as lines that indicate the drill hole direction.
3. Review of the performed steps and acceptance of computer-based training.
4. Improvements and missing information.

The closure of the interview included to comment how satisfied they were with using the system, which was rated on a scale of 1 to 5 with 5 being the best.

Young Doctors

The participants restricted available time required to reduce the questionnaire and to focus on general acceptance, medical relevance and usefulness, as they were participating in the AOTrauma course and there was no planned time frame to participate in the evaluation. The young doctors

participated during their breaks between the workshop modules. Furthermore, there was no private office available, the surgical simulator was located in the entrance area, see figure 7-8.



Figure 7-8: Medical evaluation setup for young doctors and medical experts at the AOTrauma course in Düsseldorf.

The evaluation was split into the main part, where the participants could use the simulator and proceed through the medical scenario, and a short follow-up interview. The participants were instructed on how to use the simulator using the training mode, where no instructions on how to proceed were given by the system.

The questions of the interview that followed were structured as follows:

- Relevance of the medical scenario and integration into existing medical curriculum.
- Discussion about realism of haptic feedback and recorded parameters.
- Usage of this simulator for independent learning.

The closure of the interview included to comment about the satisfaction, which again was rated on the same scale of 1 to 5.

Medical Experts

The procedure of the evaluation by medical experts was similar to that of the young doctors. Part of the participants were from the AOTrauma course, the evaluation for the other participants was held in a private or home office, see figure 7-9. The evaluation was again split into using the surgical simulator (with discussion) and a follow-up interview.



Figure 7-9: Medical evaluation setup for medical experts, held at a home office.

The participants were using the simulator in the 'guided mode' to evaluate the value of the scenario instructions and were instructed on how to use the simulator to get an overview of the functionality and possibilities of the surgical simulator.

The questions of the interview that followed were structured as follows:

- Discussion of the recorded parameters, video and what feedback the user should receive upon completion of the medical scenario.
- Relevance of the medical scenario and possible integration into existing medical curriculum.
- Discussion about realism of haptic feedback and supporting information for example during drilling or screw insertion.
- Improvements and missing information.

The closure of the interview included to comment about the satisfaction, which again was rated on the same scale of 1 to 5.

7.4.1.5 Interviews

The evaluation of the surgical simulator was carried out with different groups of participants to investigate different aspects, such as usability or medical relevance of the surgical simulator. Therefore, the questions were adapted to the different groups to focus on the corresponding evaluation topics. Depending on the answers of the participants, additional topics could be discussed, which were originally not intended, therefore, the one-to-one semi-structured interview type was chosen. All participants of one group had the same questions, but depending on the time available (for the young doctors group), specific questions could be omitted or investigated in more detail.

Medical Students

The interviews for the medical students included the following questions:

Table 7-2: Demographic and general questions.

	Interview questions	*Rationale*
MSQ1	Name, age and nationality	Verify personal details, used for statistical data.
MSQ2	Year of medicine course	In which term they are, used for statistical data.
MSQ3	Plate osteosynthesis introduction	If they already had an introduction into plate osteosynthesis.

Table 7-3: Usability questions.

	Interview questions	*Rationale*
MSQ4	Enjoyable and effective	Did they enjoy using it and was the training effective?
MSQ5	Amount of information	Did they have enough instructional information to complete the medical scenario in the guided mode?
MSQ6	User interface	Was the user interface clear and understandable? Did they know where to choose a plate or screw?
MSQ7	Clarity of messages	Were the notification and information messages clear and understandable? Have they been noticed?
MSQ8	Supporting information	What is the value of the supporting information the simulator can provide?

Table 7-4: Medical education questions.

	Interview questions	*Rationale*
MSQ9	Learning effect	Could they state the steps they learned to treat a distal radius fracture, as they have done in the simulator?
MSQ10	Use it for learning distal radius fracture treatment	Would they use this simulator to learn the procedure of treating a distal radius fracture?
MSQ11	Use it for learning other procedures	Would they use such a simulator to learn other procedures as well?

Table 7-5: Simulator-related questions.

	Interview questions	*Rationale*
MSQ12	Improvements	What improvements do they suggest? Can actions be modified to make them more usable?
MSQ13	Missing information	Was there any information missing to complete the medical scenario or on the use of the simulator?
MSQ14	Enjoyed using it	Did they enjoy using the simulator?

Young Doctors

The interviews for the young doctors included the following questions:

Table 7-6: Demographic and general questions.

	Interview questions	*Rationale*
YDQ1	Name, age and nationality	Verify personal details, used for statistical data.

Table 7-7: Medical questions.

	Interview questions	*Rationale*
YDQ2	Medical scenario	What is the relevance of the simulated medical scenario?
YDQ3	Benefit/impact to current training	How could the simulator make a contribution to the medical education?
YDQ4	Integration into medical education	How could the simulator be integrated into the current medical education curriculum?
YDQ5	Use it for learning other procedures	Would they use such a simulator to learn other procedures as well?

Table 7-8: Simulator-related questions.

	Interview questions	*Rationale*
YDQ6	Supporting information	What is the value of the supporting information the simulator can provide?
YDQ7	Intended use	What would they use the simulator for? Self-learning, workshop,...?
YDQ8	Enjoyed using it	Did they enjoy using the simulator?

Medical Experts

The interviews for the medical experts were based on the same questions as for the medical students and young doctors. They were used as follows:

- The following questions were the same: MSQ1, MSQ4, MSQ8, MSQ12-13, YDQ3-4.
- The following questions have been added:

Table 7-9: Additional questions for medical experts.

	Interview questions	*Rationale*
MEQ1	Value of recorded parameters and videos	What is the value of the recorded parameters and the video from the training?
MEQ2	Cost	What would be justifiable system cost for such a surgical simulator?
MEQ3	User feedback	What information should be used for automated user feedback at the end of the training?

7.4.1.6 Usability Testing

The medical student participants spent the most time using the surgical simulator of the three participant groups (in average 35 minutes). The main purpose of the summative usability testing was to evaluate the surgical simulator and to find out if the participants, which are the representative users, were able to complete the medical scenario based on the two trainee instruction documents and the interface of the surgical simulator, to identify usability problems and to collect quantitative and qualitative performance data. Most participants had no previous experience in computer-based surgical simulators and had also no or limited knowledge about the treatment of distal radius frac-

tures. Therefore, the performance of the participants, for example how much time they needed to insert a screw, was not of substantial interest, instead, the focus was on usability and acceptance, but the performance data was used to evaluate for example time-consuming tasks which can show that the interaction is too complicated or challenging.

Tasks of the Medical Scenario

The participants were asked to proceed through the medical scenario provided by the surgical simulator and complete the following representative tasks while thinking aloud:

- Choose an appropriate plate for the given medical scenario.
- Apply the plate onto the bone.
- The following tasks are repeated for each screw, whereas one task could be executed more than once before continuing with the next task:
    - —Use drill to prepare a hole.
    - —Measure for length of the prepared hole.
    - —Choose an appropriate screw.
    - —Insert screw into prepared hole.

The tasks were developed based on the functionality of the surgical simulator and the elaborated hierarchical task analysis and represent the standard treatment protocol for distal radius fractures by the AO Foundation, see 5.2.3.1, *Operative Treatment Methods*.

Collected Data

The following usability metrics have been defined and data was collected during usability testing with the medical student participants:

- *Scenario completion:* Measures if the participants were able to complete the medical scenario without significant errors.
- *Errors and usability problems:* The impact and frequency of problems were recorded and whether they prevented proceeding in the medical scenario. They were differentiated into three categories: critical (users cannot complete the scenario), serious (participants are frustrated and may give up) and minor (participants are annoyed but can continue). The frequency is recorded, which is the percentage of participants who experienced the issue, and is also

differentiated into three categories: high (30% or more), moderate (11-29%) and low (10% or less). The severity level of an issue is a combination of the impact and frequency, see table 7-10.

Table 7-10: Severity levels for usability problems.

High	Problems that occur often and prevent the participant from completing the task or medical scenario.
Moderate	Problems with high frequency but minor impact or moderate to low frequency with serious impact.
Low	Problems with minor impact and low frequency.

- *Time on task:* Measures the time it took to complete the following tasks: apply plate on bone, insert depth gauge into prepared hole and insert screw. Drilling time was also measured but not correctly recorded due to a software error.
- *Quantitative performance data:* The following data was recorded: number of plate changes, number of drilled holes, plunge depths, measured screw lengths, chosen screw lengths, position and orientation errors for inserted screws and number of X-rays taken and their imaging view.
- *Subjective measures:* The overall satisfaction was measured when the session was completed.
- *Likes, dislikes and recommendations:* During using the surgical simulator and in the subsequent interview, the participants provided what they liked, did not like or what could be improved.

7.4.1.7 Thematic Coding Applied to Interviews

The information from the medical experts, young doctors and medical students has been gathered using one-to-one interviews (one of the interviews included three participants). They have been tape-recorded, transcribed and the German interviews have been translated into English, resulting in about 166 pages of qualitative data. The evaluation has been carried out in the general style of the thematic coding analysis approach (Robson, 2011, pp.474). The steps described in section 4.4.5 have been undertaken accordingly, except that step 4 has been omitted, as the questions were aimed at specific topics.

7.4.1.8 Analysis Structure of Results

The transcribed interviews have been imported into NVivo as internal sources and nodes have been created as initial codes, based on the interview questions. The coding of the sources resulted in up to 145 references per interview for medical experts, 30 references for young doctors and 40 references for medical students. Five main categories have been investigated: interactions, medical relevance, medical training integration, technical aspects and user experience (UX).

The coding of the sources is given in table 7-11, broken down by each category, whereas one particular data piece can be coded more than once if it fits into different categories.

Table 7-11: Coding of medical evaluation interviews.

Category	*Topic*	*Number of sources*	*Number of codes*
Interactions	Plate application	14	28
	Improvements to screw insertion	13	42
	X-ray	11	21
	Drilling	8	25
	Screw insertions	5	7
	Measuring	4	12
Medical relevance	Would they use it for themselves	32	37
	Advantage and usefulness of simulator	14	39
	Are they able to describe the learned steps	13	13
	Would they use it for other procedures	13	13
	What other procedures could be simulated	8	8
	Compared to other training opportunities	2	3
Medical training integration	Missing functionality	17	46
	Additional medical statements	7	38
	How to integrate into existing medical training	2	13
	Who is the target user group	2	5
	Cost of such a simulator	2	3
Technical aspects	Usefulness of helpers and guides	18	45
	Haptic feedback during plate application	18	28
	Visualisation	15	23
	Navigation with 3D mouse and input devices	14	24
	Haptic feedback from medical students	13	15
	General statements about haptic feedback	12	16
	Haptic device	9	10
	Haptic feedback during drilling	8	15
	Application errors	4	8
	Haptic feedback during screw insertion	4	6
	Discussion of recorded parameters and usefulness of them	2	23
	Instructional mode	2	10
User experience	General statements and what they think about it	30	78
	Was the training enjoyable and practical	21	26
	User interface	17	19
	Difficulties and improvements	16	29
	Suggestions for general improvements	15	34
	Notification system	15	16
	Did they have enough information	14	14
	Notes from observation	10	10

Category	*Topic*	*Number of sources*	*Number of codes*
	Missing information to complete medical scenario	8	8
	Surprising things of the simulator	5	5

As seen in figure 7-10, the most statements for a single topic have been given about the use and general acceptance of the simulator, which is explainable as the participants expressed their opinion and experiences all the time while using the simulator. Overall, the most statements have been recorded about UX and technical aspects, such as their impression about the haptic feedback.

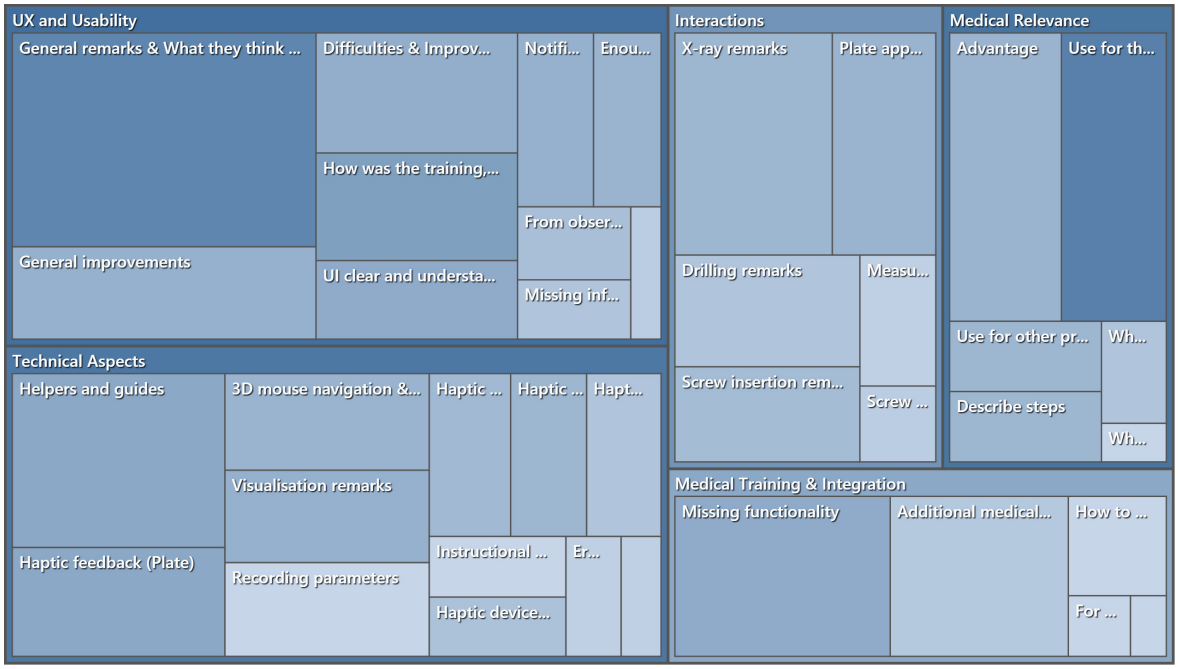


Figure 7-10: Visual representation of the coding: the size of the rectangles reflects the number of coding references, a darker colour indicates more items coded (see table 7-11 for truncated topic descriptions).

7.4.2 Evaluation Results

The results are structured according to the topics of the questionnaires. The medical experts from the AOTrauma course in Düsseldorf spent in average 21 minutes (n = 5, mean average =21.6, standard deviation = 13.18) commenting on the medical relevance, usefulness and functionality of the surgical simulator, whereas the medical experts, whose interviews were held in a private office, commented for about 110 minutes (n = 4, mean average = 110.0, standard deviation = 34.0).

The 14 medical students, which all completed the medical scenario during the evaluation interview, provided feedback about the implementation of the different interactions. They successfully inserted in average five screws (mean average = 5.0, standard deviation = 0.96) in a training session of about 35 minutes (mean average = 35.14, standard deviation = 9.45), measured from the time they

chose a plate for the first time (i.e. selected it in the simulator) until the last X-ray has been taken. An additional seven minutes in advance (mean average = 7.21, standard deviation = 1.76) was used for the introduction, reading the simulator instructions, answering the five questions and choosing the plate. The 21 young doctors spent about a quarter of an hour using the simulator and commenting primarily on usefulness and functionality of the simulator.

7.4.2.1 Simulator Functionality

Plate Application

Plate application was the first interaction the participants had to execute, and it was also perceived as the most difficult, as almost no participant had previous experience with haptic devices and they were not used to be trained with such computer-based simulations. About half of the medical student participants noted that they did not like that once they placed the plate and verified the position on the X-ray, that when they regrasped the plate it moved back to a starting position, which is the current position of the end effector of the haptic device. They found it more intuitive to be able to grasp the plate at a certain position and continue placing it instead of starting all over again.

It turned out that due to a software but, the haptic algorithm pulled the plate for a small amount into the radius bone under certain circumstances, which did not occur during the technical validation. Therefore, the haptic feedback has been rated mostly unfavourably if that occurred. In the other cases, about half of the participants liked the haptic feedback during plate application, the other ones would appreciate a more distinct haptic feedback, especially to differentiate between the parts that generate the haptic feedback, i.e. that they can clearer distinguish how they should manipulate the plate to apply it flat onto the bone.

Drilling

Drilling was well-received, they particularly liked that the resistance is sensible when drilling through the cortical bones and the drilling sound effect. Typical comments included "*that is cool*" or "*I like that*". For some of the participants, it was already pretty or very close to reality, especially when compared to the resistances that typically appear when drilling through the cortical bone of an older woman. In this case, the force needed to drill through is comparable, but is too weak for simulating younger patients, as their bone density is higher and not yet affected by osteoporosis, which decreases the bone strength. As it is the typical fracture common amongst elderly people, it is quite typical to have a small, noticeable, but not particularly high resistance there.

No clear statement could be made about the transition when drilling from the cortical bone to cancellous bone. For one young doctor the resistance loss was missing, but one medical expert pointed

out that he found it quite realistic with the resistance and loss of resistance when drilling through the cortical bone. This probably is related to the subjective perception of the haptic feedback, as a few participants did not sense the resistance when drilling through the cortical bone for the first time. However, when their attention was called to the resistance, the following drill attempts through the cortical bones were noticeable.

Three issues have been raised during drilling. First, some of the participants were not always aware that they could set their view according to their needs and therefore the drill shaft could occlude the view onto the plate when seen from above. One of the three participants who noted this solved the problem himself by turning the shaft out of the view. One possible solution one participant came up with was to hide the drill shaft if it is occluding the plate so that only the drill bit would be visualised, allowing viewing directly from above onto the plate. The second issue is related to customising the viewing direction. For two participants it was difficult to estimate the drill direction, mainly due to the perspective 3D view, with which they had difficulties to calculate the depth. And last, two participants remarked that it should not be possible to drill through the plate. This was possible as collision detection between the drill and the plate was disabled and preventing drilling when not aiming onto the radius bone was not enabled.

From a medical point of view, one medical expert remarked that normally the far cortical bone, i.e. the dorsal cortical bone, is thin and during surgery, it is drilled with extreme care to not damage the soft tissue behind it. Therefore, it is not drilled all at once, it is more repeatedly tipped with the drill bit.

Measuring for Length

Measuring for length of the screw was also well-received, in particular how the depth gauge is visualised and that it behaves in a similar manner as it does in real usage, that the sleeve is shifted towards the bone and that the length can be read on the markings on the depth gauge. A few participants remarked that it was difficult to both keep the hand still when the depth gauge is snapped to a drill hole and to use the keyboard to shift the sleeve onto the plate simultaneously. Medical experts have pointed out that it is important to indicate the correct lengths as they would occur in the operating theatre, as an experienced surgeon knows which lengths typically appear at a certain area of the bone. Therefore, it is important to teach the correct lengths to gain experience, which can be transferred to the operating theatre.

Screw Insertion

The participants showed some difficulties with aligning the screw to the drill hole, which can be traced back to the fact that they had to keep the hand still during the alignment and that they had to switch between observing the numerical values indicating the deviation of the position and orientation, and the line indicating the drill hole orientation. In addition, depending on the view direction, some participants had difficulties to estimate the depth, which led them to only use the numerical values for positioning and aligning. All of the participants appreciated to have a line indicating the drill hole direction and position, on which they could align the screw.

Two different strategies could be observed. One group first positioned the screw at the correct position and then corrected the orientation, whereas the other group did it in reversed order. A similar differentiation could be observed when the participants were asked where they look at to align the screw. Most did the rough alignment by using the line of the drill hole and the fine alignment by observing the numerical values for angle and position, whereas a minority group only used the numerical values.

Some participants remarked that the visualisation was not correct, as the simulator inserted the screw maximally for its length, and depending on the position difference, it occurred that the screw head stuck out and was not fully inserted.

All of the participants liked the haptic feedback when inserting the screw. Typical statements included "*quite good*", "*that is funny*" or "*I like it*". Several participants were positively surprised that the haptic device pulled the hand during screw insertion in direction of the drill hole, although they would in real life rather exert pressure on the screwdriver than get pulled.

Taking X-rays

The X-ray functionality has been rated as one of the most useful. As the evaluation was carried out with only one display, some participants would have liked that the X-ray viewer would be on a second display so they could review it from time to time. With only one display, they had to switch between the viewer and the simulator, which can be identified as a usability issue. In addition, some participants are used to examine the X-ray from an upright view and therefore would prefer if it could be rotated, and for better examination, a zooming function has been proposed by two participants. Several comments have been made about the visualisation of the X-ray, mainly for two aspects: that an X-ray is made of volume data and that the radial and palmar inclinations are not correct. As the X-ray was generated by shaders imitating the look of an X-ray instead of using volume data, some experienced surgeons remarked that this is not a real X-ray and one participant was

even confused and had difficulties interpreting the virtual X-ray. They criticised that the soft tissues were shown too distinctive and therefore had difficulties to distinguish the different anatomical structures. In addition, they noted that the projection is not correct. They were made perpendicularly from top and from the side, but should have a certain inclination, which is 23 degrees radial and 11-12 degrees palmar, to provide a better view in the joint space.

The participants liked the sound effect that indicates that an X-ray is being taken, which was taken from a real X-ray device. Similar statements have been made by the participants, such as "*this is quite cool*", "*that is really funny*" or "*not bad*". In contrast, regarding the visualisation of the anatomical structures, one participant remarked that "*I cannot get out of it what you see here. What are these contours? Is this...?*"

Suggested Improvements to the Interactions

During the evaluation, the medical expert participants made several suggestions to improve the interactions. The plate application has been considered as too difficult and that it could be made more realistic by limiting the possible movements of the plate. It was suggested that when a plate is chosen, that it gets placed directly on the bone and the movements should be limited to proximal-distal, radial-ulnar and turning. This simulates more realistically the hand movements needed during surgery and eliminates the difficulty some participants had, that the plate is too far up and is not placed flat on the bone. Instead, it should be added that once a screw has been inserted into the oblong hole in the proximal radial fragment, the position of the plate should be adjustable as necessary, and that the plate can be pulled onto the bone when tightening the screw.

For the remaining interactions, only smaller improvements have been suggested. Medical experts remarked that normally a drill sleeve is used for the particular plate which was used in the surgical simulation. This would require using a second haptic device which simulates the drill sleeve. In addition, they suggested that when the user drills too far and would hit the table, a resistance should be simulated. This can also be observed with synthetic plastic bones, as the trainees are not aware of the soft tissue surrounding the bone when only a bone model is used. And third, two medical experts suggested that the user should be informed when he is drilling into the joint, as this is absolutely avoidable.

For the measuring for length interaction, it was suggested by two medical expert participants that the depth gauge should not snap automatically based only on the distance to the drill hole, but also the direction should be taken into account. They remarked that the orientation is the difficulty, not the position.

Several suggestions to the screw insertion interaction have been proposed from individual participants. The most suggestions concerned the alignment of the screw. They came up with different ideas on how to support the trainee to make the alignment more intuitive, such as placing the numerical values directly into the main screen next to the screw, inserting it automatically if the screw is correctly aligned, or that the screw snaps to the drill hole, similar to measuring for length, so that only the orientation has to be aligned instead of both orientation and position. A second issue affects the maximum insertion depth, which is set to the length of the screw that gets currently inserted. As the positioning algorithm accepts a slight (predefined) position difference resulting in a start position to high, the insertion of the screw stops before it would reach its optimal end position. Therefore, it was suggested to compute the correct final position of the screw instead of using an insertion length based on the screw length. This issue also led to statements about the visualisation such as that the screw is protruding, or in case of a too low start position, that the screw is inserted too deep. Smaller suggestions included removing the clicking sound effect, as not all screws are locking screws, or that the screw should drop down if it hits against something.

Suggested Improvements to the Simulation

Two medical experts suggested that the simulator should not only provide a training and an assessment mode, but also different levels of difficulty. They suggested to start with only the radius bone model, without any surrounding soft tissue or other bones. By this, the trainee can focus on the optimal plate position, such as that the plate should end at the anatomic watershed zone. In a next level, important anatomical structures can be added, with the final level of difficulty being the simulation as it is currently implemented.

Another medical expert suggested to have a 3D visualisation at the end when the feedback of the trainee's performance is presented, showing only the radius bone, the applied plate and the inserted screws. This allows to examine the effect of overlapping screws for example, as it is visually easier to understand what a screw that protrudes 2 mm dorsal means and what impact it could make on the soft tissue, as the dorsal drill holes are not directly visible, only via X-ray.

Summary of Suggestions

Overall, 22 improvements to the functionality of the simulator have been reported, including correcting errors such as the inclination of the X-rays. The key points which advance the simulator's functionality are summarised in table 7-12:

Table 7-12: Suggested key improvements to the simulator functionality.

Key topic	Rationale
Add additional steps	Simulate incision and reduction before placing the plate.
Add levels of difficulty	Simplify visualisation to focus on key aspects and add difficulty by adding soft tissue for example.
Refine plate application	Allow refining position of plate by regrasping. Directly place on bone and only support moving proximal-distal, radial-ulnar and turning.
Refine screw insertion	Allow reposition of plate when a screw is inserted into the oblong hole, and allow pulling plate onto bone with tightening screws.
Result at end of training	Show final assessment after training is finished.
Bimanual manipulations	Use a second haptic device for simulation of a drill sleeve.
Increase force feedback	Simulate stronger resistance in cortical bone for simulating younger patients.
Improve navigation	Support the user by predefined views.
Stereoscopic rendering	Stereoscopic rendering may support depth perception.

7.4.2.2 User Experience

Several usability issues could be observed during the usability testing with the medical students. Three findings apply to the user interface. Most of the findings have a low or moderate severity level and were known before the evaluation, therefore the participants have been instructed on either how to overcome them or the missing information has been given. Overall, thirteen of fourteen participants were able to complete the medical scenario. For one participant, the application crashed during taking an X-ray when inserting the fifth screw after three-quarters of an hour using the simulator. However, the typical amount of quantitative data could be recorded and she completed the medical scenario except to the last X-ray to review her performance.

Finding 1: Awareness of Notification Messages

Some of the messages have not been noticed by five participants, one could not remember the content but noticed them. For two participants, the duration these messages were shown was too short, as one reasoned "*because maybe you are busy with all the equipment here, so that you cannot read that fast*". These notifications messages were shown in the lower part of the main view, see figure 7-11.

This had the consequence that those participants were not aware that for example the depth gauge was not extended enough or that they first have to put back an instrument before taking a new one. The severity level of this finding is moderate, as the participants figured out themselves how to overcome the issue and continued executing the particular task. One participant suggested to create a widget which holds a history of the notification messages, so that the last three messages can be read at a later time.

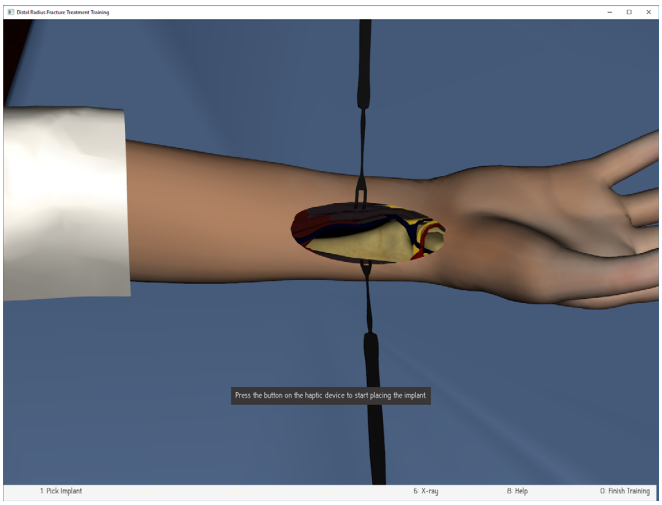


Figure 7-11: Notification messages are shown in lower third of the simulation window.

Finding 2: Application Window Handling and Switching

Two usability problems apply to the implementation of the application interface with the GUI library. As the used library did not provide functionality to integrate an OpenGL window into the graphical user interface, two distinct windows are used, one for the 3D rendering and one for the interaction widgets, see figure 7-12. Therefore, the participants had to switch between those windows (i.e. setting the focus to the particular window) when using a function from the interaction widgets or from the menu bar in the main window.

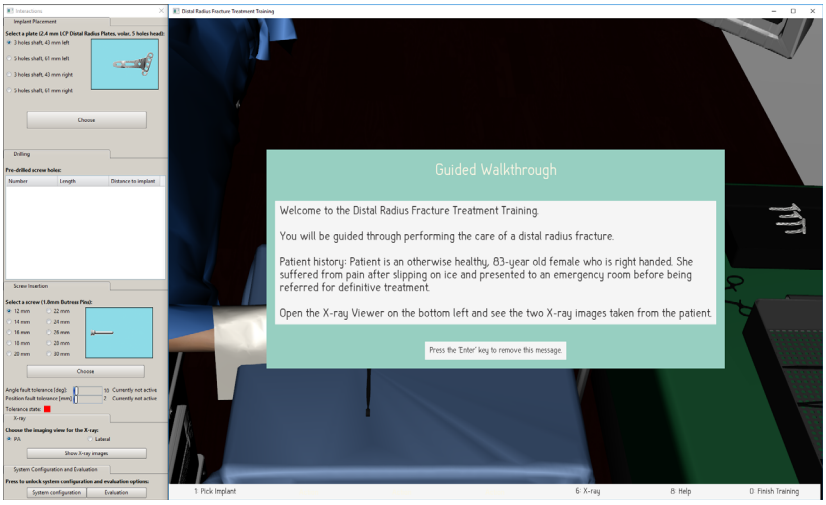


Figure 7-12: Two distinct application windows, interactions on the left and main window on the right.

Similarly, the X-ray viewer, which opens as separate window, cannot be opened again once it is closed. This issue was known for the evaluation and the participants were instructed to not close the X-ray viewer. In addition, as the X-ray viewer opens in a separate window, the participants had

to switch to it by clicking the appropriate icon on the taskbar. The severity level of the window switching finding is low, as the impact is low and the participants accepted the additional step required (activating the appropriate window). The severity level of the X-ray viewer finding is high, as it eventually prevents completing the medical scenario as the plate position cannot be checked anymore with the X-ray functionality. Both findings can be addressed by integrating the OpenGL window into the main application interface and by extending the X-ray interaction widget to recreate the X-ray viewer once it is closed. Four participants recommended to integrate it directly into the application or to have a second display which can be used for the X-ray viewer. Thereby, they would be able to review the taken X-rays from time to time.

Finding 3: Numerical Values for Screw Alignment Not Adjacent to Visualisation

Intended as an assistance to aligning the screw with the drill hole, the current position and orientation deviations are indicated in the interaction widget for the screw insertion interaction. But most participants aligned the screw using only these values instead of using the line indicating the drill hole direction in the main screen. Therefore, three participants suggested to have these two values shown right next to the screw in the main window so that they do not have to switch between these two locations. The severity level is moderate, as it took the participants longer to align the screw by only using the numerical values.

Finding 4: Regrasping of Plate

About half of the medical student participants intuitively tried to regrasp the plate to correct the position after reviewing the X-ray, which was not possible, as the plate gets reset to the current position of the end effector each time it is grasped. The severity level of applying the plate without regrasping is moderate, as the participants needed more time to apply the plate as they cannot refine a previous position, but were able to complete the particular step of the medical scenario.

Finding 5: Using Input Devices for Choosing Tasks

Two participants were overwhelmed by the four input devices (haptic device, keyboard, mouse and 3D mouse) and sometimes did not know with which to choose a particular action or did not know when to choose from the interaction widgets (one participant). Twelve participants had nothing to criticise on the user interface and thought it was clear, understandable and self-explanatory, or at least they got used to it shortly. The severity level of the interaction with the user interface finding is low, as the participants could refer to the trainee instruction documents, which explained the usage of the interface. However, the interface could be simplified by changing the function of the button of the haptic device to only use it for the interaction and not to also take the drill. Thus, the menu bar would consistently be used to pick and put back the medical instruments, screws or plate,

the haptic device to control objects and perform actions with them, such as drilling or shifting the sleeve of the depth gauge towards the bone.

Additional Findings with Low Severity Level

Several statements have been made about smaller usability issues with low impact and which did not prevent proceeding in the medical scenario, mostly supported only by one participant:

- *Plate description:* One participant mistakenly assumed the left/right of the plate description refers to the plate and not to the application on the radius bone. She first selected the wrong plate, realised their mistake and exchanged it for the correct plate. Therefore, the severity level is low and by providing a more elaborate description in the interaction widget, this issue could be eliminated.
- *User interface language:* Two participants would have preferred to have the instructions and user interface in their first language, i.e. German. During the evaluation, they asked for words which they did not understand, especially medical terms such as the oblong hole. The severity level is low and technically, creating a multi-language application user interface (and following cultural conventions) is feasible; commonly known as internationalisation and localisation (or i18n and l10n).
- *Which spheres to use for alignment:* One participant was uncertain whether she has to align the screw head with the spheres on the plate or directly with the drill hole, as also for measuring with the depth gauge. The severity level is low, the participant could review the deviation values in the screw insertion widget to decide where she has to align, as also for measuring, as the depth gauge automatically snaps to the drill hole when moving it near the sphere. To address this problem, a short introduction video could be shown each time a new step starts, instructing the trainee on how to use the devices and helper objects for the following interaction.

User Satisfaction

The assessment of user preference was rated based on the closing question: "*Did you enjoy using it (on a scale of 1 to 5)*?", with the endpoints 5 = very satisfied and 1 = very dissatisfied. The average user satisfaction amongst medical student participants was 4.36 (n = 14, mean average = 4.36, standard deviation = 0.63) and the young doctors rated it with 4.19 (n = 16, mean average = 4.19, standard deviation = 0.75). Half of the medical expert participants did not rate the simulator, but their statements included "*I think it is funny"*, and the remaining five rated the user satisfaction with 3.8 (n =5, mean average = 3.8, standard deviation = 0.84). If the distribution of the scores is analysed (see figure 7-13), the surgical simulator was well-received amongst the two relevant user

groups (medical students and young doctors). Most of those participants rated it with a 4 or 5, four participants only partly enjoyed using the surgical simulator, but still rated their satisfaction with a 3. Overall, no participant was dissatisfied with using the surgical simulator, as no one rated it with a 1 or 2.

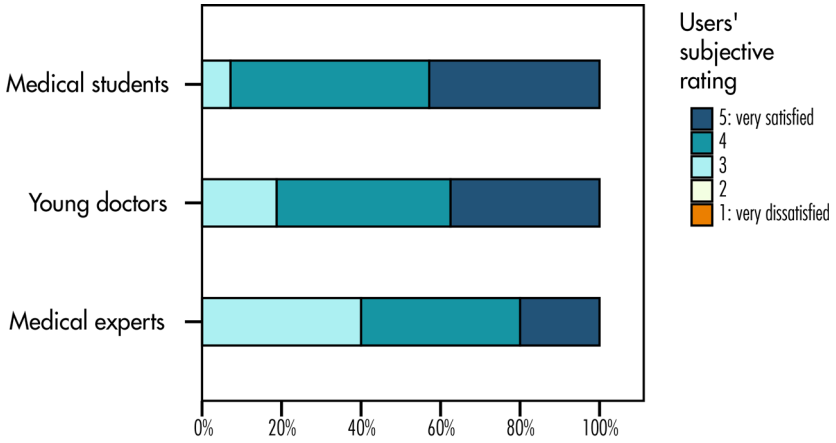


Figure 7-13: Distribution of user satisfaction ratings for each participant group.

Additional Remarks on User Experience

During the hands-on with the surgical simulator, the medical student participants gave statements about various aspects of user experience. They can be grouped according to the UX honeycomb, see figure 7-4.

- *Accessible:* Most participants have never seen or used a haptic device. At the beginning, they were largely focused on the handling and one participant suggested to have short introduction videos at the beginning of the training, explaining the use of the different input devices, as well as before each new step explaining the aims and objectives of the task.
- *Credible:* Due to an application error, the oblong hole could occasionally not be drilled. Therefore, one participant expected to be advised that she is not following the standard procedure when she drilled another hole instead of the instructed one, for example the oblong hole, which is prepared first. Another participant gave some thought to the X-ray radiation the virtual patient would be exposed to after she took a couple of X-rays. Therefore, indicating the overall X-ray radiation at the end of the training could create an awareness for the radiation dosage to which the patient and the theatre personnel are exposed to.
- *Desirable:* Judging from the statements of the medical participants, the surgical simulator evoked emotions. They included "*pretty good*", "*pretty cool*", "*makes fun*" or "*I did not know this is possible, that you can program something like this*". However, they also added that "*it is just a*

simulator and not real. But it is extremely good". In addition, two medical experts especially enjoyed using it and expressed amusement when they realised that they took the wrong plate or inserted the wrong screw.

- *Findable:* As detailed in finding 5 (see page 216), 12 participants had nothing to criticise on the user interface. Judging from observation, one participant was not always certain where she can choose an action, but she rated the user interface to be clear and understandable. Regarding the information content of the instructional messages and the trainee documents, 13 participants had enough information to complete the medical scenario. Three participants needed active involvement of the author but remarked that without those explanations, they would have needed longer to complete the medical scenario, but would eventually have succeeded.
- *Usable:* Several participant remarked that although the surgical simulator is just a prototype, it is already quite advanced and had little issues using it. However, 11 participants remarked that the 3D mouse is difficult to use and that they had difficulties with setting up their view onto the surgical site.
- *Useful:* Five of the medical student participants remarked that from a practical point of view, they learned something about the medical scenario, or as one participant said, "*because first it is just so fun and yet, you can learn the steps*". All other participants also agreed that it was suitable to learn and practise the medical scenario, which is also reflected in the increase of the score of one of the questions they answered, about the understanding of the treatment of this fracture (see also figure 7-14 on page 228).
- *Valuable:* As the medical experts also pointed out, one medical student confirmed that she learned not only the sequence of treating such a fracture, but also what screw lengths she would typically need, which can be directly transferred to the operating theatre.

Two medical students and four young doctors noted that in their opinion, treating the distal radius fracture on the surgical simulator is more difficult than in a real operation. One of these medical students had consistently difficulties as she had no experience in the treatment of a distal radius fracture and has never assisted one. She also rated herself with a 1 on the two relevant questions at the beginning of the evaluation (questions 1 and 2, see "Medical Students" on page 199). Most of the young doctors and the medical experts remarked several times during the hands-on with the surgical simulator that it is "*good*", "*great*", "*cool*" or similar terms, or that it is "*a really good idea*". One young doctor remarked that it was not helpful, compared to the real surgery, as the viewing angle

was different and the manipulation of the instruments with the haptic device is also different and he was unsure if it would be better with improvements. Five young doctor participants remarked that it takes some time to get used to, but that generally the simulator is an appropriate medium to teach the basics of open surgery, as they have to orient themselves in three dimensions or that the contact of the plate with the bone or drilling through the cortical bone is noticeable by the haptic feedback.

Observations during Hands-On with the Surgical Simulator

It could be observed that all medical student participants were interested in using the surgical simulator and as they stated, accepted that the surgical simulator is still in a prototype state. Two participants were hesitant and repeatedly asked for advice or what they should do next, as one had difficulties with understanding the English language and the other participant found that the given task was difficult. However, both liked using the simulator, one wanted to prepare an additional hole and insert a screw prior to answering the questionnaire. In contrast two different participants used the surgical simulator very confidently and one of these participants aligned the screws without helping lines, the other one was quite satisfied with his performance after reviewing the final X-ray. Three participants especially pointed out that they liked the simulator and some participants asked if they could continue inserting screws after the interview was finished.

Additional Suggestions to Improve User Experience

The medical student participants proposed several enhancements and ideas for new features during completing the medical scenario. One participant thought it would be useful to have a widget (such as a progress bar) on the side indicating the current step in the medical scenario the trainee is currently working on. However, this is difficult as long as only the plate fixation is simulated and from a medical point of view, plate fixation is a single step. But splitting it into smaller steps such as applying plate, drilling, measuring and inserting screws could support the trainee deciding which action is performed next. Another participant suggested to include soft tissue simulation, which has also been proposed by other medical expert and young doctor participants. The medical experts had several ideas, such as:

- Support a second haptic device for bimanual manipulations such as using a drill sleeve for drilling.
- Use mock-ups of real instruments instead of the generic stylus of the end effector on the haptic device.
- Support soft tissue interaction that for example the veins start bleeding when damaged.

One young doctor made the proposal of setting the view onto the surgical site with the haptic device instead of using the 3D mouse. This would technically be feasible, the zoom and rotate navigation paradigm (see section 4.5.4.2) could be implemented by using the haptic device to set the camera position and the keyboard to zoom in and out.

7.4.2.3 Technical Aspects

Performance Assessment

Some of the medical expert participants have been interviewed about the usefulness and practical usage of the recorded performance data. Two types of data were available, automatically recorded quantitative data and a video recording of the training session.

When asked which parameters are the most important, all participants first mentioned time, from start to end, and secondly the end result. Recording how far the trainee drilled outside the second cortical bone, i.e. too far, has been rated as important and that the trainee should be advised of this difference, as they could harm for example the extensor tendons during real surgery. A discussion ensued regarding measuring quality based on the number of hand changes, i.e. the less instruments are put back and taken again, the more experienced a surgeon is. One participant pointed out that this is an indicator of quality and that it correlates well with time. But only measuring the number of hand changes would not be reasonable, as this could lead to the result that the trainee prepares all holes at once, which is not desirable. In addition, measuring if the trainee has shaking or trembling hands or is performing unnecessary movements has also been mentioned as an indicator of quality, but is difficult to assess.

At the end, the end result is the most important criteria, which consists of the position of the plate and screws, if the screws are inserted in the correct angle and if they are not too long. As the medical scenario is predefined, there also exists an optimal plate position and orientation and the participants agreed that the deviation could be measured and used for the analysis of the users' performance.

To have a video of the training session in combination with the automatically recorded performance data has been determined to be good by one participant, but she was not sure about the usefulness of it for assessing the performance of the trainee. She highlighted that it is valuable to analyse the hand movements, how they manipulate and which decisions they took, but concluded that the video itself is of most value for the trainees themselves. The other participants remarked that there is no time to evaluate each user's performance individually and that the simulator needs to generate an automatic feedback based on the recorded data, as they could imagine that the intended use of

the surgical simulator is a playground, to try things out. They pointed out that the video could be optionally shown after the training so that the trainees can review their performance, which could be of higher value for them than just having a final numerical score.

3D Navigation

The majority of the participants had difficulties using the 3D mouse to adjust the view. It seemed that they were overextended with mapping the six degrees of freedom the mouse supports to the movement of the camera of the 3D scene. The camera navigation paradigm was used (see 4.5.4, *Functional Aspects*), which allows to interact with the cameras perceived location from a fixed starting point, to which they could always return in case they were lost, as suggested during the user requirements gathering study. It could be observed that participants which had experience in playing computer games, especially fist-person shooters, adapted the navigation paradigm quickly and had almost no difficulties with setting their view as needed. One usability issue that could be observed applies to the handling of the 3D mouse. When the participant intended to zoom in our out, i.e. pushing the cap forward or backward, it was often associated with a rotation around the pitch axis, as they did not push the cap straight forward, but instead pushed the upper part of the cap resulting in a simultaneous zoom and rotation movement. This was eliminated by instructing the participants on how to use the 3D mouse correctly.

Several suggestions have been proposed to alternatively set the view. One participant proposed to have a plastic hand model on the table, which can be set as needed and that the simulation sets the view according to the plastic model. This input paradigm has also been proposed by one (different) participant from the user requirements gathering study. Two participants suggested to use the mouse and keyboard for setting the view.

Although they had difficulties with using the 3D mouse, two participants remarked that it needs some time to get used to it and one participant would like to have such a 3D mouse at home.

As proposed by participants of the user requirements gathering study, having fixed views such as anteroposterior or lateral as a starting position have not been proposed, the participants were satisfied with the default starting position and that they could adjust the view to their needs.

Helper Objects

Different helper objects can be enabled to support the trainee either in orienting in the 3D scene or during executing a task. The most useful the participants found is the indication of the drill hole orientation when inserting screws. 15 participants remarked that they needed it and found it helpful (eight medical students, three young doctors and four medical experts). Some argued that they

had difficulties with the 3D view and therefore benefited from these lines to estimate the depth. As they also had numerical values indicating the position and orientation of the drill hole, one participant remarked that it can be done without such lines and one participant has not seen this line, as she used only the numerical values. One young doctor proposed to enable the line only in the training mode of the surgical simulator, as they should remember how they drilled when inserting the screw. In an assessment mode they should not have any helper objects to make it as realistic as possible.

During plate application, the watershed line could be indicated. One medical expert remarked that it should not be shown by default, but only upon request or if the trainee would like additional information about it, but they should be aware that it exists and that they have to respect it. Regarding indicating the optimal plate position, one medial expert remarked that it could be used to review the correct position once the plate is applied, with optional possible corrections so that the trainees do not have to complete the medical scenario with wrongly placed plates.

Several helper objects can be enabled for the drilling interaction. A line indicating the drill direction and where the drill hole will be created is helpful as three medical experts stated, with the option to have spheres indicating the projected drill hole. One medical expert remarked that "*no matter what, but you have to see where it hits the bone*". Whether showing the current depth during drilling is helpful cannot be inferred from the statements, as one medical expert was against showing it, one was for it. The advantage would be that the trainee learns the lengths that typically appear at a certain part of the bone, the participant against it remarked that she does not see any benefit of showing it. However, showing the overall drill hole length after the drill hole has been created has not been well-received, as "*this is actually the step which you should learn, to insert the depth gauge*", as one participant said. The same applies to showing the currently measured depth of the drill hole when using the depth gauge, two medical experts argued against showing it as it does not correspond to reality.

When asked about the spheres indicating the centre of the implant hole, which are also used to measure for length and to insert screws, two medical experts would rather prefer to use the effective drill hole instead of the spheres to snap the depth gauge or to insert screws. However, one of these participants liked the differently coloured spheres indicating the nearest one to the currently active medical instrument or screw (a green sphere indicates the nearest hole, yellow spheres indicate available holes).

Showing the current insertion depth of the screw would be appreciated by one medical student, but two medical experts do not see any benefit of it and would not show it. However, indicating the fi-

nal position and angle difference to the drill hole right after the screw is inserted has been well-received by four participants.

Three participants remarked that during a real surgery they would not have such helper objects, but they can support the trainees in learning particular aspects such as typical screw lengths. These supporting helper objects, which can gradually be removed once the trainee is more proficient, can promote learning of new concepts and skills, which is also known as scaffolding, see section 2.5.3.

Visualisation

The visual representation of the anatomical structures, medical instruments and operating theatre equipment has been well-received by the participants. They remarked that the medical instruments look very similar to reality and one medical student participant suggested that the anatomical structures could be labelled to additionally teach anatomy. Three participants criticised that the fracture was not visualised, especially in the X-ray.

Four participants remarked that they had difficulties estimating the depth in the 3D scene, they misjudged the position and realised when changing the perspective that they were not where they believed they had placed the instrument. Whether 3D glasses would address this difficulty and if the surgical simulator could benefit of using them cannot be inferred from the participants' remarks. Four participants were of the opinion that when using 3D glasses, it would be easier to estimate the depth and to align the screws, three participants did not believe that they would be useful and one remarked that using such 3D glasses can get feeling queasy. One participant asked if it would be possible to use a 3D display.

Some visual inconsistencies have been remarked, such as that it could not be identified where the radius and the ulna bones end, or that the soft tissues should be pushed away a little further so that the view onto the surgical site is improved. One medical student preferred to have both a top and a side viewport simultaneously, which would help estimating the depth as the same scene is viewed from different perspectives.

7.4.2.4 Integration

The medical experts have been asked how such a simulator could be used during medical education. They noted that it should be used during specialised courses or seminars such as offered by the AO Foundation, and that hospitals likely will not buy such simulators as there are not enough assistants which could use them and therefore would be unused most of the time and would not justify the costs. But they could imagine that it could be rent or purchased together by several institutions.

They pointed out that a structured training is needed, then the use of such a surgical simulator can also be beneficial. They gave the example of first using the simulator to educate the basic principles of the procedure and to discuss important aspects, then synthetic plastic bones can be used as before. One participant proposed to use the surgical simulator to earn points and credits, which can be used as a benchmark to ensure trainees reach a certain limit before they are allowed to perform this procedure in an operating theatre, as it is already done in the laparoscopic training.

7.4.2.5 Medical Relevance

One medical expert defined the target user group as students in their practical year or internship who already learned traumatology and orthopaedics and who developed a certain interest in this subject, as not every student needs to know how to apply a plate, or if he is already affected by a different medical speciality such as internal medicine or neurology.

When asked about the advantages and the potential of such a simulator, the medical experts highlighted three features that can be superior to current training possibilities:

- Possibility to take X-rays.
- Use it as a playground to try out different types of screws and plates and experience the resulting effect.
- Learn the procedure step by step in a visual, modern and interactive manner.

They also pointed out aspects which the simulator is currently not capable of simulating, such as soft tissue interaction, a reduction which cannot be held (i.e. fragments cannot be stabilised without implants), or missing steps of the procedure such as the approach or the reduction. Therefore, three medical experts were not sure if the simulator is beneficial, one of them also remarked that it may not be beneficial for learning manual skills but to teach the theoretical sequence.

Most of the medical experts agreed that young learners, i.e. digital natives, have changed radically (how they receive information) compared to previous generations and will be open to new training methodologies and contents (see Prensky, 2001). In addition, most of them have not seen or used such plates, screws or instruments at this stage, and using computer-based simulations can be an exciting approach to gain an impression of the steps of a procedure before they are trained on synthetic plastic bones or go to the operating theatre. But for a later stage, when they already had an introduction into the procedure or already assisted in the operating theatre, the benefits are smaller.

As also noted during the user requirements gathering study, one medical expert pointed out that with the reduction of the working time, especially assistants get less contact with the patient in the

operating theatre and they have to learn the skills somewhere else. In his opinion, the best for learning would be training on the body or during the real operation, followed by synthetic plastic bones, but which are already extremely abstracted, and a computer-based simulation is even more abstracted. Therefore, he does not see any advantage over these training methods. He also added that the more haptic a training material is, the better, which is also the opinion of another medical expert. But he was also aware of the reduced availability and limitations of these training methods and that it could be beneficial to be able to use such a simulator during a quiet moment. When compared to the AO Skills Lab, one participant remarked that a computer-based simulator is easier to transport, as this skills lab requires a lot of material and equipment. He also believes that the next step in developing computer-based surgical simulators should be to digitalise this skills lab to teach clearly defined basic principles such as the effect of blunt or sharp drill bits or the heat generation during implant drilling.

The participants proposed other procedures that would be valuable to simulate, which often also expressed their personal preferences and interests. They include femur fractures, such as femoral head or neck fractures, orthopaedic surgery in general, as it involves a lot of measuring and about accuracy, intramedullary nailing such as of the femoral shaft, joint aspiration (arthrocentesis, drain fluid from a joint) or arthroscopic surgery, especially with the haptic feedback. One medical expert added that such a simulator could be a very good education system to practice orthopaedic elective surgery such as for a prosthetic, to learn making incisions, and that it would be even more useful than for fractures, as the anatomy is defined in contrast to fractures, which are always different.

Medical Students Self-Assessment

The medical student participants were asked if they would use such a surgical simulator to train the presented medical scenario of the treatment of a distal radius fracture, and in addition more generally, if they would use such simulators to train other procedures and interventions. Thirteen out of 14 participants agreed that they would use such a simulator for both cases, one participant thinks that she will not use it too often, only to internalise the process and to learn the procedure, as the simulation is too far away from reality. As already medical experts pointed out, several participants noted that it is primarily aimed to understand the procedure and to familiarise with the process of the treatment, and that if they are already at a more advanced stage, they would probably not use it anymore. But they highlight that it is an excellent opportunity as an addition to the current training methods, to also see it visually and use it interactively to get a basic knowledge when they proceed to the operating theatre, or as one participant said, "*that you do not stand there awkwardly*". In addi-

tion, they also liked to use it as a playground in a meaningful training where they could try out for example drilling completely wrong without harming patients.

One participant raised the important question whether it would not also be possible to learn it by observing it several times and have instructions in the operating theatre. She reasoned that this would be possible, but using computer-based simulations where no patients are harmed is the better way to do it. Another medical student noted that the understanding and learning effect when using it visually and interactively is better than learning just from books.

Two participants proposed to also simulate the access with the incision, as they have the possibility to drill during real surgery, but are not allowed to make an incision. They would prefer if the entire operation is simulated, which was also suggested by young doctors and medical experts.

The young doctor participants also all agreed that they can imagine using such a simulator to learn new procedures and to get an understanding of it. Typical statements included "*this is really a very good idea*", "*sure, I am always for games*", or "*I believe, for practicing that is super*".

The medical students all noted that after using the simulator for the evaluation, they could describe the steps to treat a distal radius fracture to the extend they just learned. They found that the advantage of proceeding through the entire scenario is that they could do everything, not only one hole as they are allowed in the operating theatre, that they have to decide themselves in which direction they drill, which is normally instructed by the surgeon, or that it is better memorised as they performed it visually and completely by themselves.

The first self-assessment of the medical students, which was carried out at the beginning of the evaluation process, aimed to classify prior knowledge, skills and attitudes about the medical scenario and computer-based simulation in education. As not all participants had experience with using surgical simulators, some did not answer question three, as they could not estimate if the training on a simulator can be transferred to the operating theatre. The results showed that the participants had only little background of the distal radius fracture treatment (Q1, 2.14 on Likert scale; see page 199) and as only three participants already assisted during surgery a couple of times, felt also not very confident to assist such an operation (Q2, 2.57). What can be observed is that the participants are open for new training options (Q5, 4.43) and that they believe training on simulators is useful for the understanding of an operation (Q4, 4.36). They also believe that training on simulators can be transferred to practice to some extent (Q3, 3.78).

The second self-assessment after the hands-on with the surgical simulator confirmed their opinion about using simulators for education and the average acceptance slightly increased by about 3% to

4.57 (Q5). Similarly, the hands-on with the simulator seemed to have a positive impact on the impression that simulator training is useful for understanding the tasks of a procedure and slightly increased by about 8% to 4.71 (Q4). The attitude about the skills transfer to the operating theatre remained constant with a less than 2% increase to 3.85 (Q3). However, the main purpose of the simulator, to get an understanding of the treatment of a distal radius fracture increased by about 67% to 3.57 (Q1) and also the transfer of this understanding to the operating theatre increased by about 33% (Q2), as seen in figure 7-14.

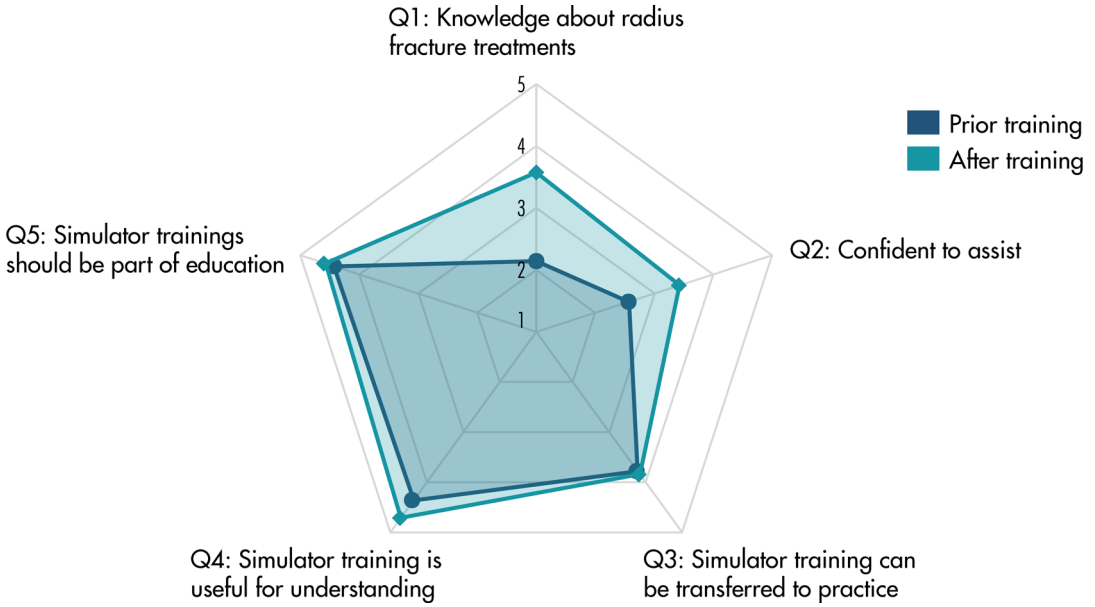


Figure 7-14: Participant self-assessments (n = 14, average values) showing significant improvements in the understanding of the treatment of a radius fracture (Q1) and in confidence in assisting it (Q2).

The hypothesis H_1 is that there is a substantial improvement in the scores between prior and after the training, i.e. the median difference is not zero (with significance level $\alpha = 0.05$; the null hypothesis H_0 is that there is no tendency in either direction). Because some of the data significantly deviates from normal distribution (Shapiro-Wilk test values are smaller than 0.05), the Wilcoxon signed-rank test using SPSS[1] was run to compare knowledge, skills and attitudes prior and after the hands-on with the surgical simulator to test for statistical significance. There was a significant difference indicated in the scores for the understanding of the treatment of a distal radius fracture (Q1) prior hands-on (mean average = 2.14, median = 2.0) and afterwards (mean average = 3.57, median = 4.0); $Z = -2.976$, $p = 0.003$, and the increase was large ($r = -0.795$). There was also a significant difference indicated in the scores for the confidence to assist a radius fracture treatment

1. IBM (2016) *IBM SPSS Statistics.* [Online]. 2016. Available from: http://www.ibm.com/software/analytics/spss/products/statistics [Accessed: 11 March 2016].

(Q2) prior hands-on (mean average = 2.57, median = 2.5) and afterwards (mean average = 3.43, median = 4.0); Z = -2.585, p = 0.01, and the increase was large (r = -0.69). There were no significant differences in the scores for the remaining three topics Q3, Q4 and Q5, as seen in table 7-13.

Table 7-13: Self-assessment Wilcoxon signed-rank test results.

Topic	*Mean average prior hands-on*	*Median prior hands-on*	*Mean average after hands-on*	*Median after hands-on*	*Z*	*p*	r
Q1	2.14	2.0	3.57	4.0	-2.976	0.003	-0.795
Q2	2.57	2.5	3.43	4.0	-2.585	0.01	-0.69
Q3	3.78	4.0	3.89	4.0	-0.577	0.564	-0.192
Q4	4.36	5.0	4.71	5.0	-1.89	0.059	-0.505
Q5	4.43	4.5	4.57	5.0	-1.414	0.157	-0.378

If taken into account the previous experience of the participants, whether they already assisted during surgery or had another introduction into the distal radius fracture, then those participants with no or little background increased their self-assessment to a larger amount than those with previous experience.

7.4.2.6 Medical Students Performance Assessment

During the evaluation of the medical student participant group, performance parameters have been recorded of their training session. The participants have not been instructed to complete the medical scenario the best as possible, but it could be observed that for many participants the ambition has been aroused after the first screw has been inserted and they tried to improve the subsequent screw insertions.

Prior to their average 35 minutes training session, the first task was to choose an appropriate plate out of four available plates. Seven participants chose the correct plate at beginning, only one of the remaining participants needed more than two attempts. It took them in average 110.55 seconds (standard deviation = 79.09) effective manipulation time to apply the plate to the radius bone, with in average 70.35 seconds manipulation time per plate (standard deviation = 69.3). What could be observed was that more than a third of the participants successfully applied the plate in under 50 seconds and only three participants needed longer than 150 seconds, see table 7-14.

Table 7-14: Distribution of the manipulation times the participants needed to apply the plate.

Manipulation time [s]	Absolute frequency	Relative frequency
25 - less than 50	6	43%
50 - less than 75	3	22%
100 - less than 125	1	7%
125 - less than 150	1	7%
150 - less than 175	1	7%
200 - less than 225	1	7%
250 - less than 275	1	7%
Total	14	100%

When observing the preparation of the drill holes, the participants made several attempts to drill, especially for the first drill hole, as they were trying out the drilling and were familiarising themselves with it. Counting all drill attempts, they made in average 3.24 attempts (standard deviation = 2.21). Ignoring the first attempt, as it often included instructions on how to drill which increased the attempts for the first drill hole, lowered the average attempts to 2.91 (standard deviation = 2.03). Looking at only the last drill hole results in 2.57 attempts (standard deviation = 1.22, using the second last drill hole for one participant as she took 10 attempts for the last one due to the system not accepting the drill hole because of a system error). This is an improvement when compared to the second drill hole, which took in average 3.0 attempts (standard deviation = 1.57), as this was the first hole the participants prepared on their own with having understood the drilling interaction. Looking at the absolute participant numbers (ignoring the first drill hole), seven participants improved, five remained constant and two needed more attempts to prepare the last drill hole.

What is particularly important is that the trainee does not drill too far after the second cortical bone, as soft tissue can be damaged The amount the drill bit protrudes past the far cortical bone, which is called plunge depth (PD), was measured for each hole the participants drilled, see figure 7-15 (including the first drill hole).

Almost all participants managed to drill with less than 0.5 cm plunge depth. Outliers can generally be explained with the participants not having noticed the haptic feedback of the second cortical bone and therefore did not stop drilling. No statement can be made whether they improved or not, as about a third of the participants minimised their PD, a third increased it and a little less than a third had more or less constant PDs. For example, participant 1 increased her performance, as the large PDs occurred during the first few holes, having the lowest value at the last drill hole, whereas participants 9 and 12 had their outliers in the middle of the drilled holes, and participant 3 had her

lowest PDs at the beginning. Due to a software error, the time on task for drilling was not recorded correctly.

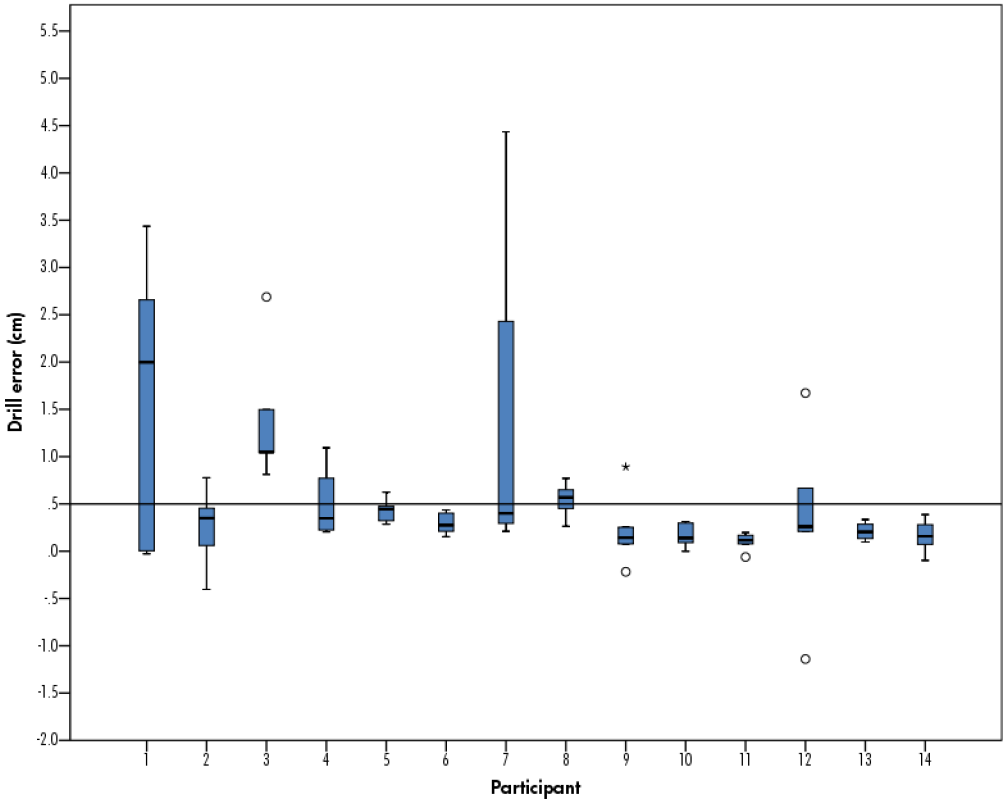


Figure 7-15: Plunge depths of drilling the radius bone.

The depth gauge, which is used to measure for length, was reset to 2.0 cm each time the participant took it. If they tried to insert it without having it extended enough, a notification message was shown explaining that they should extend it before inserting it into the drill hole. This message has been shown in average 4.86 times (standard deviation = 1.75). Some participants did not realise why they could not insert the depth gauge, as they have not completely read the notification message or have not noticed it at all. The participants needed in average 58.56 seconds (standard deviation = 29.79), measured from taking the depth gauge to snapping it into a drill hole, see figure 7-16. The first measuring task was ignored, as it included instructions on how to use the depth gauge, which resulted in a considerably longer time needed to measure the first hole. These durations differ between the participants, as a few had to modify the view, which is also included in these periods of time and explains the rather large bandwidth of measurement values. In addition, some participants measured several drill holes at once, for example participant seven, which measured three holes at once resulting in a longer measure time. Separating these durations into single measure-

ments for only one drill hole, the average time taken drops to 54.47 seconds (standard deviation = 27.6).

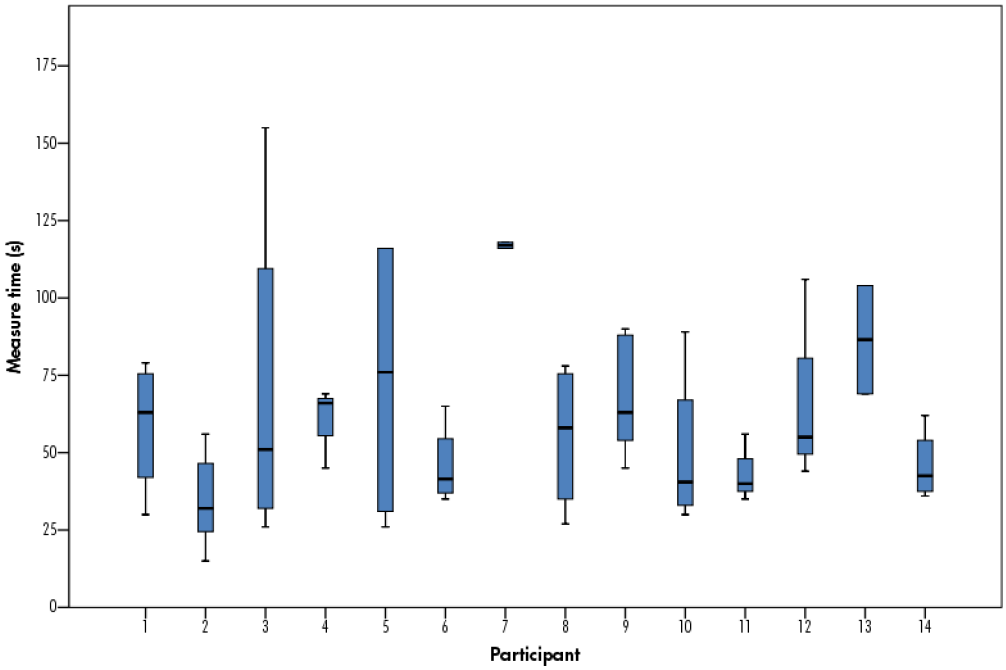


Figure 7-16: Time needed to successfully insert the depth gauge in the drill hole(s).

Regarding the screw selection based on the measured length, the participants chose the correct length indicated by the depth gauge for 49 screws from the total of 71 inserted screws. Only for three screws one size larger than indicated has been chosen, 17 screws have been chosen in one size smaller, and one screw each in more than one size smaller and larger.

The angle and the position difference of the inserted screw have been recorded. The angle difference represents the deviation to the angle with which the drill hole has been drilled, the position difference represents the distance to the centre of the drill hole. The average position error is 1.62 mm (standard deviation = 1.25), as seen in figure 7-17. The screw could only be inserted if the difference is below 2.0 mm. For values in figure 7-17 which are higher, the threshold has been lowered as the screw has been inserted with instructional comments or as the participant could not insert the screw in a reasonable time.

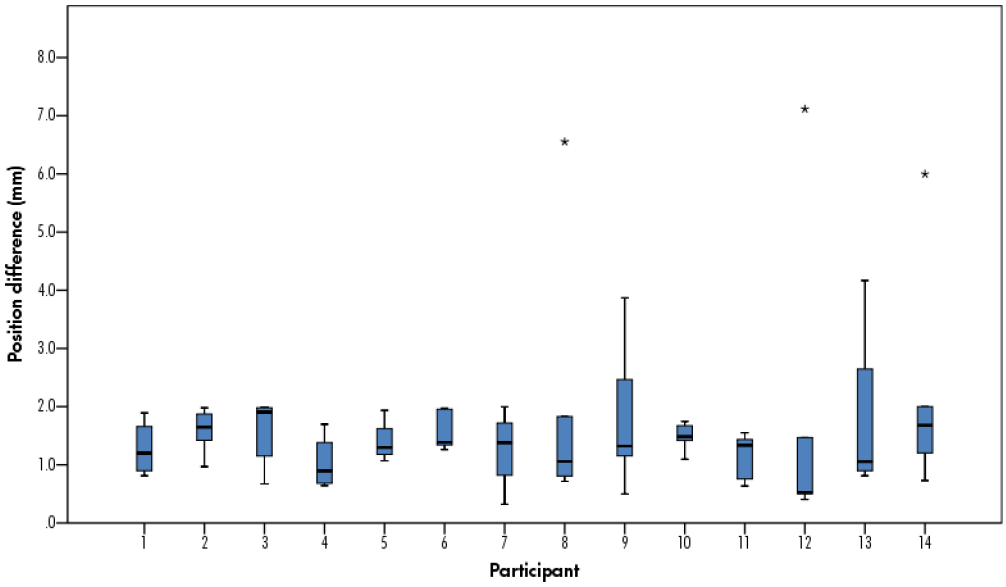


Figure 7-17: Position difference of the inserted screw compared with the centre of the drill hole.

The average angle difference is 3.57 degrees (standard deviation = 2.29). Compared to the position difference, the angle deviations are distributed over a broader range (see figure 7-18), as aligning the direction represented a more difficult task for the participants than finding the correct position.

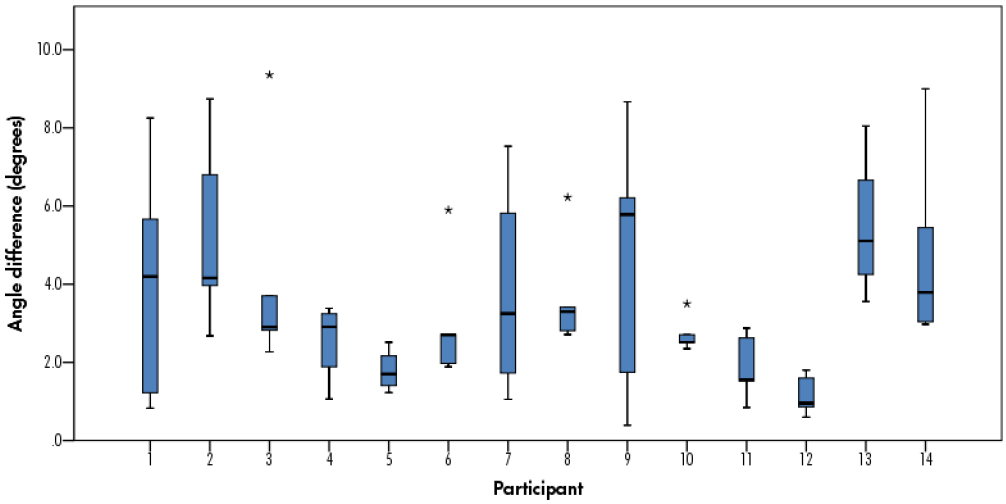


Figure 7-18: Angle difference of the inserted screw compared with the orientation of the drill hole.

As the position deviations are not widely dispersed and the interquartile range is not broad (compared with the angle deviations), there was also no considerable improvement from the first screw to the last one, as 9 out of 14 participants had similar deviations for all screws. The angle difference has improved for six participants, only three performed worse for the subsequent screws. In average, 83.82 seconds were needed to insert the screw (standard deviation = 41.26), including the aiming

and tightening of the screw (see figure 7-19). Most participants improved (6) or performed similar (6), only two participants needed more time for the subsequent insertions of the screws.

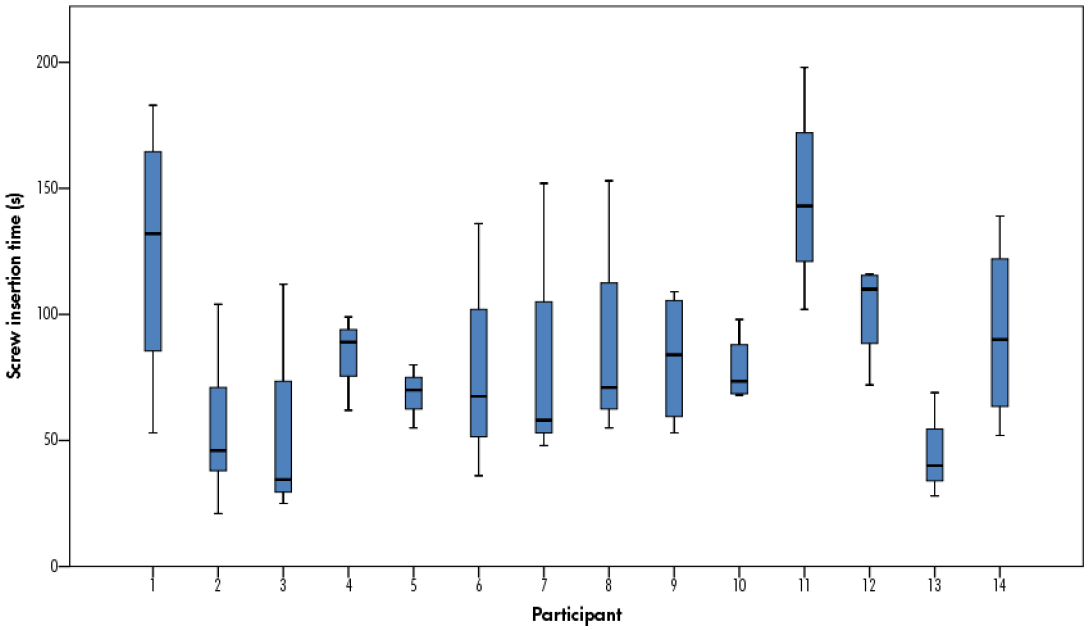


Figure 7-19: Time needed to successfully insert the screws, including aligning it to the drill hole orientation and position.

The participants took in average 8.93 X-rays (standard deviation = 4.01), see figure 7-20. Eleven participants favoured the lateral view, only one participant took more PA than lateral X-rays (with only one X-ray difference).

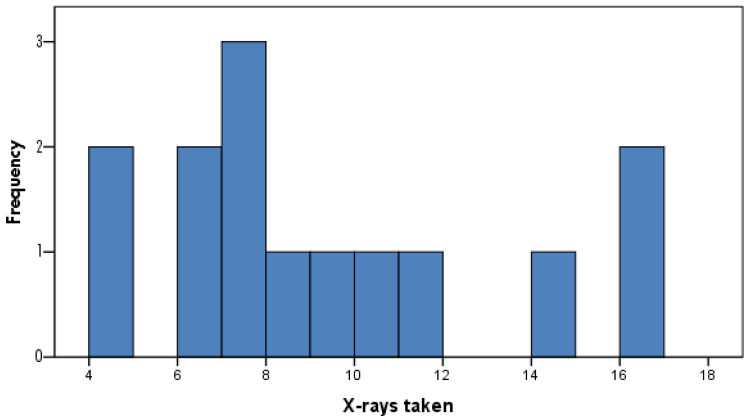


Figure 7-20: Number of X-rays taken by the participants.

During plate application, most participants took the same number of PA X-rays as lateral ones. Whereas, most X-rays taken during screw insertion were lateral, only one participants took again the same number of X-rays for both views. Most participants took lateral view X-rays for reviewing their inserted screws and took both a lateral and a PA X-ray at the end of the training.

7.5 Results Summary

This section summarises the results of the software verification and validation and the outcome of the medical evaluation study. The key findings are summarised in table 7-15. The goal of the analysis was to find out whether the surgical simulator meets the users' needs and fulfils its intended purpose, and whether the developed surgical simulator would be medical relevant, appeal to the targeted medical students and young doctors and if they would use it.

Table 7-15: Key findings of the software verification and validation and the medical evaluation study.

Topic	Outcome
Code quality	Repeatedly, automatic software verification was used to analyse the source code for common errors and using software metrics, complex parts were identified which are prone to errors.
Software validation	One participant (software engineer) tested the software for its readiness for the medical evaluation study by playing with the simulator based on his individual choice. As a result, one show-stopper was identified which led to a software error during measuring or aligning the screw under rare conditions. Further suggested improvements have been integrated into the surgical simulator.
Acceptance amongst surgeons	Apart from one young doctor, all participants were convinced that surgical simulators are a reasonable medium to teach the steps to perform a surgery and additional medical topics not possible by traditional materials.
Plate application	This task was perceived as the most difficult with half of the participants had expected a more distinguished haptic feedback, the other half liked it. To improve realism, limiting the movements proximal-distal, radial-ulnar and turning directly on the bone, make it movable along the oblong hole once a screw is inserted and pull it onto the bone while tightening a screw were suggested.
Drilling	Drilling through cortical bones was well-received, in particular the haptic feedback was appreciated, as the simulated forces were similar in realism to those that occur in bones of older women. In addition, drilling was one of the meaningful advantages over traditional teaching materials.
Measuring for drill hole length	Measuring was also well-received, the participants liked the visualisation and that they had to operate the virtual depth gauge like a real one. The measured length, i.e. typical cortical bone thicknesses, was one aspect that could be transferred to the operating theatre according to medical experts.
Inserting screws	This task was again more difficult; the challenge was to align the screw exactly as the drill hole orientation. Suggested improvements were to snap to the drill hole to only align the orientation and to be able to remove a screw if it was wrongly inserted.
Taking X-rays	This has been considered as the most useful functionality, as this is currently hardly doable with current training possibilities. Medical experts suggested to correct the viewing angle and that volume data is used instead of a surface model.
Usability	The targeted groups enjoyed using the surgical simulator and rated user satisfaction with 4.36 (medical students) and 4.19 (young doctors). Smaller usability issues were detected and using real surgical instruments instead of the generic end effector of the haptic device was proposed.
Measuring performance	According to medical experts, the time required and the end result are the most important parameters. They suggested having an automated feedback at the end of the training, with the possibility to review the training session on the recorded video.
Input devices	The participants showed difficulties using the 3D mouse to adjust the view onto the surgical site and some were overwhelmed by the different input devices regarding which to use for which task.
Instructional resources	From the possible helper objects the surgical simulator is capable of showing, indicating the drill hole orientation to align screws, a line indicating the drill direction and contact with the bone, and indicating the final position and angle difference after a screw has been inserted were the most useful according to the medical experts, as they teach the trainee relevant aspects.

Topic	Outcome
Visualisation	The participants liked the realistic visualisation of the medical instruments, but had expected a more realistic visualisation of the fracture, especially in the X-ray, as no volume data was used.
Advantages	The medical experts considered this surgical simulator as an appropriate possibility to teach young learners at an early stage basic steps of a procedure. They highlighted the virtual X-ray, to be able to use it as a playground for different implants and the modern interactive manner as features which can be superior to current training methods. However, such simulators have to be integrated into the medical curriculum with a structured training to have success.
Acceptance and improvement	The acceptance amongst the medical students was high, almost all confirmed that they would use such a simulator to train procedures and interventions. These students also significantly improved their understanding of treating a distal radius fracture and their confidence in assisting such a procedure by using this surgical simulator, assessed by a self-report questionnaire prior and after the training. The remaining questions remained at a high agreement level.
Performance results	Most participants applied the plate in under 75 seconds, kept their plunge depth under 0.5 cm, needed 54.47 seconds to measure a hole for length and inserted in average four screws in 83.82 seconds per screw (including aligning and tightening) with an average position error of 1.62 mm and angle difference of 3.57 degrees. In average, the participants took 8.93 X-rays with about the same amount of PA and lateral X-rays during plate application and favoured lateral X-rays for screw insertion. They improved in the attempts they needed to prepare a drill hole, in the time needed to insert a screw and in the accuracy of the orientation of the screw (but not for the position).

During the development of the surgical simulator, automatic software verification has been performed by using static code analysers to discover potentially erroneous conditions. Primarily, issues have been found such as variables for which their scope could be reduced or where the initialisation of variables was not done in the constructor. At the end of the development, the source code has been inspected for quality, design and complexity. This led the focus to review methods which seemed too complex or which violated critical rules defined by the analyser.

The software validation was carried out with one participant with a technical background who tested the simulator for software bugs, usability issues, unclear instructions and improvements. One show-stopper could be identified, which could lead to an application crash during measuring or aligning the screw to the drill hole. Improvements have been suggested, such as additional information messages on how to use the surgical simulator or to immediately show a drill hole once the trainee started drilling into the bone. Most of the issues have been resolved for the evaluation study, limitations resulting from the 2D GUI framework could not be removed, as it was still in development.

The medical evaluation study investigated several aspects of the surgical simulator, such as the implemented interactions, user experience, acceptance amongst the target user group or medical relevance. Generally, the simulator has been well-received with only one participant who was not convinced that such a surgical simulator can be a suitable medium to teach the basic steps of a procedure. The plate application has been perceived as the most difficult, and it revealed that a software

bug prevented a distinct haptic feedback of the plate with the radius bone in certain circumstances. In the other cases, half of the participants liked the haptic feedback, the other half expected a more distinct feedback. Medical expert participants suggested to limit the possible movements of the plate to only proximal-distal, radial-ulnar and turning directly on the bone to make the application more realistic. Additionally, the plate should not be fixed once it is applied, it should be possible to move it along the oblong hole when a first screw is inserted, or that it can be pulled onto the bone when tightening a screw. For drilling, the participants pointed out that sensing the resistance when drilling through the cortical bone is quite realistic and similar to the force needed for treating an older woman. Measuring for length has also been well-received and the participants liked that the depth gauge behaves in a similar manner as a real one. It has been remarked by a few participants that it was difficult to hold the hand still when shifting the sleeve onto the bone. Medical experts pointed out that the lengths indicated by the depth gauge must correspond to those during real surgery, as this can be transferred to the operating theatre. Inserting screws was again more difficult, as the screw has to be aligned to the same orientation as the drill hole. Medical experts suggested to automatically snap on the drill hole so that only the orientation has to be aligned, or that the screw can be removed again. The X-ray functionality has been proved to be the most useful, mainly two improvements have been suggested, to use the correct view angle and to use volume data instead of a surface model. Medical experts additionally pointed out that the surgical simulator should also simulate the approach and the reduction, as well as soft tissue interaction.

Five usability issues could be identified: smaller notification messages have not been noticed by about half of the medical student participants, the application consists of three separate windows which have to be activated accordingly to perform a task, the deviations when aligning screws are not shown adjacent to the screw visualisation, it was not possible to regrasp the plate for correction and a few participants were overwhelmed with the different input devices. Several additional issues have been mentioned, supported by mostly only one participant such as the user interface language or unclear plate descriptions. But overall, the participants were enjoying using the surgical simulator, the average user satisfaction of the target user group was rated with 4.36 amongst medical students and with 4.19 amongst young doctors (of a maximum of 5), with no negative scores (1 or 2). Additional improvements have been suggested, such as using real instruments instead of the generic end effector of the haptic device.

To assess the trainee's performance, the medical experts mentioned that the time required for completing the medical scenario and the end result are the most important parameters. A video recording of the training session can be useful for the trainees themselves when shown after the training,

but most medical experts pointed out that there is no time to evaluate and discuss the performance individually and that therefore, an automated feedback based on predefined parameters should be shown at the end of the training. Using the 3D mouse to adjust the view seemed to make difficulties for the majority of the participants, two suggested to use the mouse and keyboard instead, another two participants remarked that it needs some time to get used to it. The surgical simulator is capable of displaying helper objects to support the trainee in orientating in 3D or in the task. The most useful according to the medical expert participants are: indicating the drill hole orientation to align screws, a line indicating the drill direction and contact with the bone, and indicating the final position and angle difference after a screw has been inserted. The participants liked the realistic visualisation of the medical instruments but criticised that the fracture is not properly visualised, especially in the X-ray. For a few participants, the estimation of the depth in the 3D scene was difficult, however, if the use of 3D glasses would address this problem could not be concluded, as its acceptance amongst the participants was limited.

Overall, the majority of the medical experts considered the use of such a surgical simulator to teach the basic steps of a procedure to be appropriate. They highlighted three features which can be superior to current training methods: to take virtual X-rays, to use it as a playground with different types of plates and screws and to learn the procedure in a modern and interactive manner. Especially for young learners at an earlier stage, teaching procedures using computer-based simulators can be beneficial, also in consideration of current issues such as the reduced availability of material for dissection courses. Such simulators could be used in specialised courses or seminars, as most of the medical experts think that hospitals likely will not purchase them, as they do not have enough assistants which can use them for a longer period of time, which would justify the costs. They also suggested that they have to be integrated into the medical curriculum with a structured training, so that the basics of a new procedure could be learned on such a simulator with a subsequent discussion of relevant aspects of this procedure, and continue as it is currently done with for example synthetic plastic bones or on the patient.

Almost all of the medical student participants confirmed that they would use such a surgical simulator to train procedures and interventions, primarily to understand the procedure and the process of the treatment or to try out actions such as drilling incorrectly without harming patients for example. In a self-assessment, these participants rated their understanding of the treatment of a distal radius fracture with 2.14 (on a Likert scale) before the training, which significantly increased to 3.57 after it. Similarly, their confidence in assisting such a procedure significantly increased from 2.57 to 3.43. The acceptance of using computer-based surgical simulators in the medical curriculum

or to learn procedures using them remained at a high level, and the participants also support the opinion that a transfer of skills to the operating theatre is possible.

During the medical student participants' averagely 35 minutes hands-on with the surgical simulator, performance parameters have been recorded. The assessment showed that most of the participants successfully applied the plate on the bone in under 75 seconds, managed to keep their plunge depth under 0.5 cm, needed 54.47 seconds to measure a hole for length and inserted in average four screws in 83.82 seconds per screw (including aligning and tightening) with an average position error of 1.62 mm and angle difference of 3.57 degrees. In average, the participants took 8.93 X-rays with about the same amount of PA and lateral X-rays during plate application and favouring lateral X-rays for screw insertion. Improvements in the performance could be found for the attempts the participants needed to prepare a drill hole, for the time needed to insert a screw and the accuracy of the orientation of the screw (but not for the position).

To conclude, these findings identify broader issues that would apply when developing a haptics-based medical simulator. Generally, haptics should only be used if it supports and improves the experience of a task and if it is clearly distinguishable. Poor haptics not only alienates the trainee, it can also provide a wrong basis for decision-making and therefore counteracts on the goal of the training. However, this work showed that the technical foundations for using haptics in a meaningful manner in medical simulations are laid, and by building on them a surgical simulator could be developed that supports the trainee and teaches medical relevant aspects, which were not possible without haptics.

7.6 Limitations of the Evaluation

The methods used in the evaluation of the surgical simulator focused on measuring variables and on direct interaction with participants to collect qualitative and quantitative data. There were 45 medical experts, young doctors and medical students who participated in the medical evaluation from different hospitals, institutions of education or private hospitals to have as many different opinions and different user groups as possible, but care must be taken when generalising the results. As the participants were all volunteers, they may have biased the results in that they could be positive towards computer-based simulation technology (medical experts) and open for new training possibilities. This was highlighted by comments of a few of the participants, such as "*I am always for games*". But there were also participants which do not have such an affinity and remarked about themselves for example "*I am so bad at such things*". Further research should examine the results of the same evaluation with more participants to investigate if the findings are also relevant for the tar-

geted user group with different background, such as carrying it out on participants of a complete medical class to have a greatest possible varying background and interest. Similarly, as only one participant took part in the in the software validation and who had a technical background and was familiar with medical simulations, he may have biased the result in that he did not test the software in a way an inexperienced user would use it for the first time. In addition, he had a sound understanding of what virtual environments are capable of and what is impossible. Therefore he would not try actions which are technically not possible or he would less misinterpret feedback of the virtual environment.

The potential of further development of the surgical simulator and medical scenario is large, as the ideas of the medical experts for improvement have shown. Several proposed extensions would add value and increase the realism of training with the medical scenario, such as a more realistic plate application, being able to refine the plate position once it is applied, or being able to remove misplaced screws or such ones with a wrong length.

There were limitations in the technical implementation of the surgical simulator, such as the software error with the haptic feedback that occurred occasionally during plate application, that the oblong hole could occasionally not be used or that the time on task for drilling was not recorded correctly. These two bugs and the proposed changes to the interactions (see "Suggested Improvements to the Interactions" on page 212) need to be eliminated should the surgical simulator evaluation be repeated or for a following version of the simulator.

A more elaborated performance data recording method for example to record the hand movements with the haptic device, combined with custom-built end effectors mimicking real surgical instruments should be integrated in a later version to assess the confidence in using the medical instruments.

Limitations exist to measuring the time on task due to the open simulation state, which allowed the trainees to execute tasks in an almost arbitrary sequence, such as measuring more than one drill hole at once. Therefore, the time required to finish a self-contained task is difficult to estimate. In addition, when the trainees were busy (high workload), such as with aligning screws, they sometimes did not notice notifications of the system, resulting in more time needed to find the reason of the simulator not accepting user inputs.

In addition, as the participants used the simulator only once, it was not feasible to measure effective performance improvements resulting from using it. As there was only one predefined time frame where the students were available, the focus was laid more on user experience and medical relevance,

rather than on training effectiveness. As detailed in section 2.3.3, more and more studies are demonstrating transfer of skills from virtual reality-based training, but further research is needed, also the establish metrics on how to measure. Therefore, in a following step, a larger study can investigate training effectiveness and transfer of skills using the developed surgical simulator. An intermediate study could evaluate the surgical simulator on the impact on using haptics, such as having one participant group completing the medical scenario with haptic feedback, and a control group without haptic feedback. Then, improvements to surgical skills and knowledge could be assessed by comparing their performance in an operating theatre or on anatomical specimens. But it can be expected that particular aspects which depend on haptic feedback, such as the plunge depth when drilling, will considerably improve compared to training without haptics.

7.7 Discussion

The evaluation detailed in this chapter was carried out to determine if the developed surgical simulator is an appropriate and meaningful medium for learning the steps of a procedure or surgical skills and if it is well-received by the targeted user group.

Probably the two most important findings of this carried out medical evaluation are:

- The developed surgical simulator is capable of teaching the relevant steps of the implemented medical scenario with an added level of realism by using haptic feedback.
- The targeted user group has well-received the way of educating relevant knowledge and the steps of the procedure in a safe and controlled environment.

Although the functionality of the surgical simulator has been refined several times during the development phase, it has been suggested to simplify the plate application to eliminate navigational issues which could be observed during the hands-on (which can also be attributed to some extend to the software error with the haptic feedback), but at the same time make the plate application also closer to reality, as it is performed during a real surgery. The question why this suggestion has not been brought up during the refinement stages of the surgical simulator (see section 6.8, *Iterative Design of the Simulator*) can be answered as the involved medical experts had previous experience in using computer-based surgical simulators and are already used (to some extent) to navigate in a three-dimensional environment or focused more on the medical aspects of this task and therefore did not consider the full control over all degrees of freedom when manipulating the plate as highly demanding regarding spatial sense and manipulation.

As expected, several of the medical experts suggested to extend the functionality of the surgical simulator to for example be able to additionally learn the approach or reduction, or to add different levels of difficulty. This could be based on experience they already have with minimally invasive surgical simulators and that they draw a comparison with the functionality of these simulators, which provide a broader range of training tasks. But generally, especially with regard to the current issues in the medical training (see section 4.5.3.1, *Hand Surgery*), all agreed that the developed simulator is a meaningful tool to provide a structured learning experience to educate the medical students/young doctors about the steps of the fracture treatment and relevant aspects supported by haptic feedback, the decision-making process or in general, the impact of incorrectly executed actions. In addition, they highlighted that the objective performance measurement and assessment functionality are needed for continuous evaluation and feedback and are an important aspect of self-directed learning.

The score of the five criteria on which the medical students had to rate themselves indicate that the current generation of medical students is open for computer-based training, which is supported by the quite strong agreement to the two relevant statements (Q4: 4.36 and Q5: 4.43) before the hands-on with the surgical simulator, and slightly improved in the second assessment. It is also supported by statements from the medical students such as "*for me this brings me a lot more than if I read through books or something*". This is reasonable as when learning with traditional media such as books or videos, only one or two of the five traditional senses are used (visual and auditory senses), in contrast to actively doing it on a simulator which addresses more senses (visual, auditory and tactile senses). From the significantly improved scores for the first two criteria (Q1 and Q2), it can be implied that the participants improved their understanding of the treatment of a distal radius fracture in a quite short time during the hands-on (in average 35 minutes) and they are also confident that they can use this newly gained knowledge in the operating theatre. However, this improvement should be compared with an additional participant group using only traditional media (i.e. the control group) and later assessed in a standardised test for example by observing both groups in an operating theatre assisting a real distal radius surgery, which was not possible in the scope of this evaluation. By this, statements can be made about the effectiveness of these types of surgical simulators for teaching purposes, in addition to the existing approach of the medical curriculum, as Dutta, Gaba and Krummel (2006; see page 20) pointed out.

The performance analysis of the medical students revealed that most of the participants performed similarly. Participant 13 showed the best overall performance (female, with a self-assessed score of 1 for the understanding of the medical scenario). A second group of five participants with scores

ranging from 36 to 39 and a third group with a score higher than 45 can be distinguished, if all recorded metrics are weighted equally and with accumulating the task ranks, see figure 7-21. By this, the screw insertion task weights three times higher than the other tasks, as three metrics are recorded for it (position/angle difference and insertion time) instead of one (time on task for plate manipulation and measuring, as well as plunge depth).

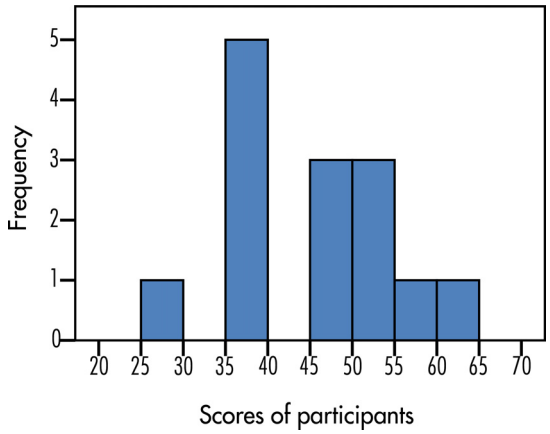


Figure 7-21: Participant scores with equal weights for each recorded metric (plate application, plunge depth, position/angle difference and screw insertion time).

If the tasks are weighted equally, the same three groups can be distinguished, with again participant 13 which performed best, the second group with scores ranging from 21 to 30 and the third with scores higher than 32, see figure 7-22. Two participants improved thereby in the group, as they had difficulties inserting the screws.

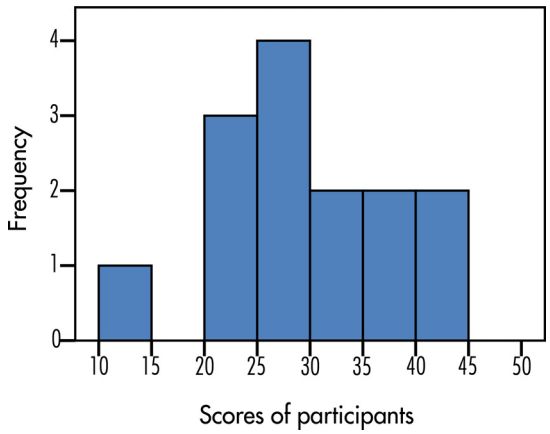


Figure 7-22: Participant scores with equal weights for recorded metrics per interaction (plate application, drilling, measuring and screw insertion).

The largest difference amongst the participants could be observed for the plate application task, where the time required to apply the plate ranged from 31 to 253 seconds. However, this can be ex-

plained with the software error of the haptic algorithm, which pulled the plate into the bone. The four of the participants which needed the most time for applying the plate were affected by this bug (as seen in table 7-14 with manipulation times over 100 seconds).

The measured plunge depths can be compared with real world data. Most of the participants managed to drill with less than 5 mm plunge depth. However, just 1 mm can damage a dorsal tendon if it is precisely in the wrong place[1]. Praamsma, et al. (2008) measured the influence of distracting noise on the performance of bone drilling using a femur of a lamb. Three groups were measured, based on their training levels. The novice group, which were medical students in their first year had plunge depths of about 25 to 30 mm (for 10 bicortical holes, no distracting noise), whereas the intermediate and expert groups performed similarly with 5 to 10 mm. Using a computer-based simulator, the medical participants performed significantly better (up to five to six times) than those with the femur of a lamb. Although these results are not directly comparable, it could be observed that the medical students drilled very carefully and slowly, relying only on the haptic feedback. In a real surgery, the different bone density produces changes in the drill pitch, which is also used by experienced surgeons to judge the depth. As the drill sound was constant during the virtual drilling, the only information available was the haptic feedback; no visual judgment was possible as only parts of the drill bit were visible due to the viewing direction. This leads to the conclusion that the drill depth is appropriately assessable with the implemented haptic feedback.

By analysing the performance data using SPSS, the Pearson product-moment correlation revealed a medium to strong, positive correlation between the plunge depth and the time required to measure a drill hole, which was statistically significant; $r(12) = 0.56$, $p = 0.037$. Interpreting this result is rather difficult, as if there were a correlation between tasks, then it was expected that there would also be a correlation between measuring for length and position difference, as both included moving the end effector of the haptic device to a given position and hold the hand at exactly this position. However, it might be the case that when drilling and sensing the cortical bone resistances, the participants developed a feeling for small, distinct movements, which are required for positioning the end effector at a certain position, required for measuring and inserting screws. In addition, the position error is dependent on the angle difference error, therefore there may be no correlation between measuring time and position error. The correlations between the recorded metrics which were not statistically significant is shown in table 7-16.

1. Nelson, D.L. (2014) *Distal Fractures of the Radius Treatment & Management*. [Online]. 2014. Available from: http://emedicine.medscape.com/article/1245884-treatment [Accessed: 28 October 2015].

Table 7-16: Pearson product-moment correlation of not statistically significant metrics at 0.05 level.

Relationship of metric	N	p	r
Plate manipulation and plunge depth	14	0.533	0.182
Plate manipulation and drill hole measuring time	14	0.626	0.143
Plate manipulation and position difference	14	0.748	-0.095
Plate manipulation and angle difference	14	0.274	-0.314
Plate manipulation and screwing time	14	0.748	0.095
Plunge depth and position difference	14	0.383	-0.253
Plunge depth and angle difference	14	0.771	-0.086
Plunge depth and screwing time	14	0.958	-0.015
Drill hole measuring time and position difference	14	0.67	-0.125
Drill hole measuring time and angle difference	14	0.169	-0.389
Drill hole measuring time and screwing time	14	0.911	0.033
Position difference and angle difference	14	0.164	0.393
Position difference and screwing time	14	0.759	-0.09
Angle difference and screwing time	14	0.149	-0.407

The identified usability issues are mostly technical issues and can be eliminated for future versions of the surgical simulator. Silvennoinen and Kuparinen (2009) investigated the usability of a laparoscopy surgical simulator and found 42 usability problems. Most concern the visual design and layout (17), help and guidance (6) and system feedback (5). Additional topics such as ergonomics, application crashes or language have also been mentioned, but to a smaller amount (<5). By following the eight golden rules of interface design (Shneiderman and Plaisant, 2004, pp.74), most of these usability issues could be prevented by addressing them during the development and therefore have not been complained either at all or to such an extent.

As the user satisfaction score of the medical students was quite promising with 4.36, it can be concluded that most participants distinguished between errors which are annoying, but do not make the completion of the medical scenario impossible, and those which affect the user experience adversely, such as not being able to regrasp the plate for position refinements. Compared with Tergas, et al. (2013), which evaluated the usefulness of learning suturing on the da Vinci simulator, similar scores were achieved. On the same 5-point scale, the majority of the twenty participants found with an average score of 4.6 that the training is useful (4.76 amongst the medical participants (Q4)) and that they would attend future training sessions (average score of 4.6). Similarly, all of the medical students would use it to learn a new procedure, and thirteen would use it also for other cases.

The surgical simulator is an attractive medium to teach relevant knowledge and the steps of the task or procedure can also be concluded from the motivation the participants had to use the simulator and although not instructed, the ambition to complete the medical scenario with a performance as

good as possible, and as some of them asked if they could continue after the interview. This addresses a factor Walker (2009) observed about the use of laparoscopic and endoscopic simulator, where the trainees were not motivated using it. That could be explained with that either the user group is more open to computer-based surgical simulation, or that the developed simulator meets the expectations of the medical students on a usable and meaningful medium that challenges and motivates them.

The high acceptance rate and motivation of the participants to complete the medical scenario can also be attributed to using game-based techniques, making the simulation more engaging and fun (see section 2.3.4). For example when inserting screws, by indicating the deviation values from the drill hole orientation in form of a metric for precision promotes accuracy. By adding visual and sound effects or by providing a guided mode creates a similar mental setting as when performing the operation, as similar decisions have to be taken, such as considering the patients condition when applying the proper force during drilling.

Based on the remarks and observations of the participants on UX, general suggestions on the development and planning of surgical simulators can be drawn to improve the acceptance amongst the users. Basically, UX should be considered right from the start of the development and throughout the process, as it has considerable impacts on it. One important aspect is to consider the use of potentially unknown hardware, which can form an obstacle and thus prevent using the simulator. As already pointed out, the simulator and the instruments should be as realistic as possible, reflect real-life usage and build on paradigms they already know, such as for the user interface by following general guidelines. Furthermore, depending on the target user group, introductory information such as short videos or getting started levels are reasonable ways to teach how to use the simulator and can help overcoming the users' usual reserve on adapting new technology. To conclude, UX, as it has been followed in this PhD project, contributes to each product development phase and works towards a better product, which eventually becomes better accepted by the target user group.

Chapter 8

Discussion and Conclusion

8.1 Chapter Summary

This chapter describes how the work of this thesis fulfilled the aims of the PhD research project and examines the novel contributions to research and towards a training in medical education using haptic technology. First, how the three aims have been achieved is discussed, then contributions of this work to literature and recommendations for further research are presented, and the chapter finishes with the conclusions that can be drawn from the work and outcome of this PhD research project.

8.2 Aim 1: Gather User Requirements to Create a Specification for a Surgical Simulator in Hand Surgery Based on the Current Needs of Hand Surgeons

The success or failure of a software project depends on several factors and normally projects do not fail for one single reason. A common reason software projects fail are inadequate requirements (Cerpa and Verner, 2009), as not enough time was spent defining these requirements, which lead to unrealistic customer expectations, and therefore changes arise during the project. Chow and Cao (2008) found six factors which have an influence to the success of a software project (using agile software development methods, an incremental approach with early delivery, evolutionary development and continuous improvement) by analysing 109 agile projects through multiple regression analysis, whereof two of these six factors, project management process (such as the requirement management) and customer involvement (such as good customer relationship or strong customer commitment and presence) applied to this PhD research project. They have been implemented by constantly producing software features to keep a constant pace for completed work as well as by

having face-to-face conversations between researchers in the research group (as far as possible), and by satisfying the surgeons needs by developing several prototypes which provide functionality which is valuable for them and by working closely with the medical experts as far as possible and involving them into the different development phases. The remaining aspects mostly do not concern this project due to its extent and amount of involved people: a correct delivery strategy, proper practice of agile software engineering techniques, a high-calibre team and an agile-friendly team environment (Chow and Cao, 2008,p.969).

Therefore, first analysing the current state in medical education in orthopaedic hand surgery and analysing the medical experts' needs and expectations by undertaking a user requirements gathering study allowed to define requirements on a surgical simulator, which (with refinements) ensures the simulator met the intended use by the targeted user group. The findings of the user requirements study, which is presented in chapter 4, showed that there is a need for research in the field of medical education in open surgery, which is also supported by analysing the relevant medical literature and technology in chapters 2 and 3. The interviews with medical experts showed the following issues in the current medical education:

- The use of anatomical specimens in research or training is more and more regulated and its availability limited.
- The experience of the young doctors coming out of medical education has lowered due to the working time regulations.
- Medical students and young doctors in the foundation training would benefit from having a series of the same operations to gain experience in a particular operation.

From a technical point of view, the main challenges were expected to be the implementation of realistic haptic feedback, having the system to react to the users input and depending on the simulated procedure, soft tissue simulation, deformation and interaction with it. Compared with simulators for minimally invasive surgery, the freedom of motion is considerably larger as well as the required anatomical structures and thus more difficult to simulate. What could be concluded from the interviews with the medical experts was that the expectations on such a simulator are that it behaves and provides a realism similar to a real patient. In addition, visual objects that assist the user (such as lines) or tasks (such as grasping spheres or other abstract tasks) were not considered of high value or usefulness. But they distinguished between a simulator for educating basic skills or the sequence of an operation, and between a simulator which could act as a playground. Similar to currently used task trainers, which teach a particular topic with a simplified simulator, a computer-based surgical

simulator for teaching basic skills or the sequence of an operation can make use of omitting or reducing parts of the simulation in its complexity, such as for inserting a screw, the soft tissue surrounding the surgical site can be visualised by static 3D geometries. In contrast to the developed procedural simulator, a surgical simulator which would be aimed as a playground needs to provide as much functionality as possible to react to the user's input, such as it should be possible to interact with the surrounding anatomical structures, react to unexpected events (controlled by an operator), or to try out different approaches or the effect of wrongly or imprecisely executed actions or decisions.

Based on this starting position (the needs and expectations of the medical experts), the success of the PhD research project, which can ultimately be measured by the acceptance of the targeted user group and the medical experts, depended on the outcome of the analysis of the interviews and internet surveys, i.e. the requirements specification (see section 5.3, *Requirements Specification*) and the decision of which use cases to implement. The analysis of these requirements also defined in which direction the project was heading to. For example, a simulator to train repositioning bone fragments seemed at that time unrealistic, as it was not possible to recreate the biomechanical complexity of the hand and the haptic devices were unsuitable as an input device for this task. In contrast, simulating the incision would position the simulator more as a decision-making learning application, as where the incision is made has a significant impact on the whole surgery, i.e. if it is poorly executed, the surgical site is differently presented and probably leads to new challenges. From this point of view, this aim was essential to the success of the developed surgical simulator and the intended integration into the medical curriculum. Therefore, the results of the user requirements gathering study, the analysis of the current state in medical education for orthopaedic hand surgery in respect to virtual surgery, as well as the specification of requirements on a simulator for the implemented medical scenario are contributions which are important to researchers with closely related research interests.

The process undertaken to gather the user requirements by one-to-one semi-structured interviews was successful, as it allowed to focus on the main topics of interest, but still offered the flexibility to explore promising topics that arise or change the direction of the interview to a certain extent. In addition, incorporating the medical experts' (and later in the project, the users') perspective early into the software design and development process allowed to get a very good understanding of the context of use, i.e. the user characteristics, their goals and tasks they will perform. The capturing of contextual information, which were gained for example by observing real surgeries, helped to specify the user requirements and establish a sound basis, on which the surgical simulator could be eval-

uated. In addition, the elaborated hierarchical task analysis (see figure 5-6 on page 112) further helped to understand what the user will be required to do during the real treatment of a distal radius fracture, and which tasks or cognitive processes (such as when deciding which plate to choose) are used to achieve such a task.

Including technical experts in the interviews proved advantageous, as from their experience in medical simulation could be benefited. However, it also showed different opinions and preferences they hold from medical experts, such as which input devices to use. Technical experts favoured the 3D mouse to alter the perspective onto the surgical site, however, the medical evaluation showed that a considerable number of participants had difficulties using it and preferred mouse and keyboard. But from a technical point of view, their suggestions and opinions about what and how to visualise anatomical structures, what information to show or how to assess the surgeons' performance, overlap to a large degree with those of the medical experts. To summarise, using the semi-structured interview process in conjunction with a demonstrator and a questionnaire (see section 4.4, *Methodology*) proved to be appropriate, and compared with other conventional techniques such as focus groups, observation or studying documentations, is in the authors opinion the most appropriate for such projects, where the outcome is not precisely specified at the beginning.

The process of analysing the interviews by first transcribing them and using thematic coding analysis (TBA) was a time consuming process (transcription) and resulted in approximately 1600 codes. But it was required and correct for the early fact-finding phase, to get an understanding of the medical field and the work of orthopaedic hand surgeons, as well as to establish the requirements specification. The use of TBA matched the semi-structured interview technique, as statements to a particular topic could be made at any point in the interview, or different topics have been discussed, which were initially not intended. TBA allowed to capture any information of the interviews and assign them to themes, which themselves emerged to main and sub-themes, which could be incorporated into the requirements specification.

However, there was a limitation to the requirements specification. As the number of participants of the user requirements gathering study was rather small (n = 13) and each participant could suggest a different procedure for which the details were worked out, the functional requirements were based on a small number of opinions and kept on a high-level language. In contrast, the non-functional requirements have been discussed in greater detail, as they were less procedure-dependent. This resulted in missing functional requirements, such as the measuring for length. It may be appropriate to either include more participants in the requirements gathering study, or what seems more

appropriate, to repeat the process with a second study, focusing with orthopaedics specialised in the particular medical scenario on more detailed requirements.

By following the human-centred design approach, the main aim was not only building a system that meets the requirements. It was also emphasised to design the system to be usable and thus keep the users motivated, resulting in a greater willingness in using this surgical simulator over a longer period of time (Maguire, 2001). In addition, it also helped overcoming the limitation of the requirements specification, as some missing functionality was revealed during the evaluation of the prototypes (see section 6.8.3, *Version 1: Improvements to the Interactions and Feature Extension*). The identified key requirements for open surgery simulation are:

- Allow to perform an entire procedure and choose from various medical implants to improve decision-making.
- React to users' action such as when drilling into vessels.
- Real-time visualisation with a minimal response time.
- Realistic haptic feedback.
- Record user activity for performance assessment.
- Use of high-fidelity graphics for surgical instruments and anatomical structures.
- Use of real-life surgical instruments instead of generic end effectors of haptic devices.
- User-modifiable view onto the surgical site.

Depending on the medical scenario, additional requirements are needed, which define the functionality of the simulator, such as being able to take X-rays for example.

8.3 Aim 2: Develop a Virtual Environment to Simulate Surgical Procedures, Techniques or Tasks

The second phase was the design and development of a computer-based surgical simulator using a human factors-led approach. The human-centred design approach that was used started with the people the system was designed for, i.e. the orthopaedic hand surgeons, by learning directly from them, immersing into their work and understanding their needs, which led to the achievement of the first aim. The second phase took a substantial part of the time available for this PhD thesis and was also undertaken entirely by the author. The relevant steps of the HCD process were to produce design solutions to meet user requirements and to evaluate the designs against requirements (see 4.2.1, *Human-Centred Design (HCD)*), but moreover, the iteration. By this, validation was gained

as the feedback from the medical experts was introduced into the evolving software prototypes. This continuous refining and improving of the prototype allowed to get a system that was accepted and embraced more quickly than when using a traditional approach with little user involvement (such as the waterfall model (Royce, 1970)), as according to experience, the best solution is mostly not found the first time, or the second.

The development of a virtual surgery simulator consisted of integrating several components, such as collision detection, haptic feedback, user action handling, and in general, user interface or 3D rendering. Therefore, a significant amount of time was spent for the evaluation of the software framework on which the simulator was built. This was split into two parts, the evaluation of a generic software framework and of the haptic library. As virtual surgery has specific requirements (such as haptics or geometry deformation), commonly used software frameworks for computer games are not particularly suitable, as it can be difficult adding such functionality. Only a few frameworks for surgical simulation were available, i.e. H3D and SOFA, which would had required to build the simulator entirely with these. As this would have meant spending a lot of time to become acquainted with it, and there was still no haptic rendering supported out of the box, it was opted for using OpenSceneGraph and implement the haptic rendering pipeline based on the work of Otaduy and Lin (2006). This is the main finding of the software framework and haptic library evaluation (see section 6.6.2, *Discussion*), which is based on five demonstrators that were developed to evaluate different approaches of using haptics. The prime reason to implement a new haptic algorithm was that the evaluated haptic libraries all only supported three degrees of freedom (DoF), but for applying a plate to the bone, mesh-to-mesh collision detection and haptic feedback was required and thus a six-DoF haptic rendering pipeline. Extending an existing library to support mesh-to-mesh haptics was considered as not feasible, or only with a large amount of time, as the algorithms required are different and it would have meant implementing a new haptic pipeline. CHAI3D provides a unified interface to a number of different haptic devices, enabling to add a different device at a later point if needed. Therefore, using the haptic rendering pipeline described by Otaduy and Lin and using a similar software architecture as CHAI3D for device management was the starting point of implementing six-DoF haptic rendering, as detailed in section 6.9.5.1, *Haptic Rendering and Collision Detection Threads*.

During the development phase, a new attempt of developing an open-source surgical simulation framework has been started in 2013 (OpenSurgSim by SimQuest Solutions (2014)). They used the same core software libraries (such as for 3D rendering and linear algebra), but the functionality is still limited. This is not the first attempt to build a generic surgical software framework, and about

the reasons why the development ends after a certain amount of time can only be speculated. It is supposed that as most of them were part of a research project and after the project was finished, the development also ended (or still continued for some time). Additionally, the number of involved developers is typically small and the use cases of such frameworks are highly specific, the interest to continue is limited and new projects in a similar research area may not start until years after its. Therefore, the time required to analyse such a framework (if it is publicly available), modernise it and to add the required functionality seems too time-consuming and therefore, a new software framework is developed or an existing one is extended, which was also the case in this PhD research project. It was built on a virtual reality software framework (also developed by the author, see 3.3.6, *Virtual Reality Rendering Framework I3D*), which evolved from previous research projects. However, although it is likely that at some point, the development of this framework will also end, the work is not useless, as future projects can benefit from the findings, the problems that arose and how they were overcome, or which approaches were more promising. And it is to expect that computer-based surgical simulation will become as generally used in training as flight simulators in the training of pilots (Gaba, 2004, Halvorsen, Elle and Fosse, 2005). Compared with commercially available surgical simulators for minimally invasive surgery, they are typically built on a proprietary software framework, which resulted from research projects (for example VirtaMed[1]) and evolved to start-up companies. It is in the opinion of the author that as currently no virtual reality surgical simulators are available for open surgery, a potential successful product will follow a similar path, developed in a research project and brought to market by a start-up/spin-off company (or acquired by an existing company).

During the development, three live prototypes have been evaluated. They allowed to convey ideas and to get feedback from the medical experts. First, the functionality and the visualisation has been investigated, which resulted in two additional interactions: measuring for length and taking X-rays. The visual appearance of the surgical site, equipment and operating theatre was similar to the final release and has been tested if it was adequate. Some of the 3D geometries showed texture failures (wrong surface normals due to erroneous exports from the 3D modelling software) and soft tissues were rendered translucent, but no negative statements have been made by the medical expert. Similar to the user requirements gathering study, where a demonstrator has been used to investigate visualisation aspects, the use of live prototypes enabled the medical experts to try out the simulator prototype themselves and discuss on a more practical level than it would be possible with only ques-

1. VIRTAMED (2016) *VirtaMed | Medical education with virtual reality simulators*. [Online]. 2016. Available from: http://www.virtamed.com [Accessed: 10 March 2016].

tionnaires. By integrating the feedback and iterating the process (the next prototype refined the interactions), the final prototype could be developed, which met the medical experts' needs and it was expected to present a motivating virtual learning environment for the targeted user group by focusing on providing a valuable and meaningful user experience.

Design decisions had to be made during the development, which had a significant impact on both technical aspects as well as the use of the interactions. By using high-resolution meshes for visualisation, colliding those (such as when the plate hits the bone) would generate too much contact information. They would not be computable within a reasonable period of time and result in large forces exerted by the haptic device due to insufficient contact information. Therefore, preprocessed meshes were used for the physics simulation, which limited the simplicity of using any 3D geometries in the simulation. In a further development step, this preprocessing could be integrated into the application to dynamically generate physics representations if they not already exist. However, the preprocessed mesh is currently manually optimised in a second step by removing meshes which do not capture perceptually relevant information, such as internal ones. Therefore, an algorithm has to be found which automates this manual step. A second limitation was the decision to not use deformable objects for soft tissues. The implemented haptic rendering pipeline has the constraint of using only rigid bodies, which is appropriate for the implemented medical scenario, as the focus was on the use of medical instruments to apply or insert implants on/in bones, which are all rigid bodies. However, as a few participants remarked, it would have been interesting to also interact with the soft tissue, which would require haptic interaction with different types of bodies, such as rigid, elastic and fluid. This would mean replacing the current six-DoF haptic rendering pipeline with for example the algorithms described by Cirio, Marchal, Otaduy and Lecuyer (2013). A third limitation concerns the data sets used. No volume data was used, which had an impact on the X-ray visualisation and on drilling through the cortical bone. As the information of the inside of the radius was not available by using surface meshes, the X-ray image had to be altered by using shaders to mimic the cortical bone. By disabling depth testing and using the face normals to set the colour, a convincing virtual X-ray image could be created which contained the relevant information needed to interpret it. Drilling through the cortical and cancellous bone would also require volume data to estimate the drill resistance. This problem of missing information has been overcome by using the measured thickness of palmar and dorsal cortical bone from Mockenhaupt (1990) and by calculating the bone resistance using the drill depth and those thicknesses'. From a user's point of view, not using volume data had no influence or negative impact. However, medical experts and experienced young doctors pointed out that the simulated X-ray was not correct, i.e. it is not a summation image

of all structures laying in the viewing direction, but the medical students had little or no difficulties interpreting it.

Prior evaluating the surgical simulator, a technical validation has been carried out by validating the requirements and the application and by automated software verification during the development. Although all components have continuously been tested, it is in the very nature of testing self-written software in a manner it is supposed to be used. By letting a participant, which was not involved in this PhD research project, using it the way he wants, revealed several software issues, such as missing or ambiguous information or a software error which occurred under certain circumstances during drilling and measuring. This step turned out to be important, as the medical evaluation could only be carried out once in the scope of this PhD project and there was little time correcting errors, which would be discovered during this evaluation.

The conclusion of the development is that it is possible to build a virtual reality surgical simulator for open surgery for medical students/young doctors to teach the sequence and relevant aspects of selected orthopaedic procedures by using high-end consumer hardware and commercially available haptic devices. By following a human-centred design approach, the outcome was well-received by the relevant target user group, and medical experts responsible for education in trauma and orthopaedics were satisfied, which is discussed in the next section.

8.4 Aim 3: Evaluate the Benefit of Using this Prototype in Addition to the Current Training and Education Concept in Hand Surgery

This aim involved two main topics to evaluate the benefit: the evaluation of the surgical simulator and its intended use in medical education. A medical evaluation study has been carried out with three groups of participants (medical experts, young doctors and medical students) and is presented in section 7.4, *Medical and Usability Evaluation*. The reason for using three participant groups was to examine different aspects, to which not all participants could contribute to the same extent. The first group, medical experts, contributes to the questions of how to integrate such a simulator into the medical curriculum, what relevant topics need to be taught at which level of experience, or what the educational objectives are. In contrast, the medical students group allowed to make statements primarily about the user experience (UX) of the simulator and whether they accepted the way technology is used to educate them about the medical scenario. The young doctors group is to be ranked in-between, as they belong to the targeted user group, but already may have some experience in the treatment of distal radius fractures or similar procedures and could provide feedback about medical accuracy, but which may reflect personal experiences they gained during education. The user per-

formance, attitudes and motivation of the medical students have been measured, which can be used for comparison with real world data, such as the plunge depth when drilling (Praamsma, et al., 2008). For the medical experts and young doctors, qualitative data has been gathered.

This medical evaluation study aimed at investigating mainly user experience, acceptance and medical relevance. However, training effectiveness, transfer of skills to the operating theatre and effectiveness to train surgical skills was not evaluated. This would have required a longer study with more participants, a control group and follow-ups on the surgical simulator, which were not possible in the scope of this PhD research project.

8.4.1 Distal Radius Fracture Treatment Surgical Simulator Evaluation

The outcome of the evaluation of the surgical simulator regarding UX, which is presented in section 7.4.2.1, *Simulator Functionality*, showed that the targeted user group liked using the simulator, was motivated to solve the given task of treating the distal radius fracture to their best possible (although not directly instructed to do so) and can imagine using it for learning new procedures. Given the short time available with the participants, they accustomed themselves quickly to the use of the surgical simulator, and although several usability issues could be identified, none prevented completing the medical scenario. None of the medical participants had previous experience with a haptic device and some were irritated at first on how to use it, but after a short adaptation phase were more challenged with the three-dimensional thinking. It has been decided to not use stereoscopic displays, as there are still challenges such as the need to wear glasses, crosstalk between images and thus possibly transient headache (Lambooij, IJsselsteijn, Fortuin and Heynderickx, 2009). But recent studies showed novices performing better in standardised laparoscopy tasks using stereoscopic displays (such as Schoenthaler, et al., 2015). Using them would supposedly support the trainee in depth perception, as it is used for example in the da Vinci surgical system. In addition, the task of positioning the end effector exactly at the indicated spheres (for measuring or inserting screws) would get significantly easier and more important, more realistic, as the main objective is for example to decide at which angle to insert the screw, but the position is given by the plate holes. However, it has to be investigated if adding an additional, possibly unknown hardware device would not be too excessively demanding and therefore have a negative effect on the UX.

Simulating open surgery from a UX point of view is more difficult than minimally invasive surgery (MIS), as the surgeon has more freedom of motion during surgery and the area of interest is the entire surgical site. In MIS, the surgeon is used working with the enlarged surgical site shown on a display and with surgical instruments handled via tubes inserted through small incisions. This results

in a limited range of motion and indirect interaction with tissues, which is more suitable for computer-based simulation than for example simulating actions performed by hand, such as applying a plate to the bone. Thus, paradigms had to be found by which the relevant aspects can be learnt and transferred to the operating theatre. For the implemented medical scenario, relevant medical aspects have been identified, which could be educated (with the exception of the depth gauge barb hooked on the opposite side, see "Measuring for Length" on page 167) and at the same time maintaining a good UX. They were:

- *Plate application:* Use of correct plate type and length, alignment along the shaft, position proximal-distal (with respecting the watershed line).
- *Preparation of holes:* Depth of the hole (monocortical/bicortical), plunge depth, sensing of difference between cortical and cancellous bone, prevention of drilling into joint.
- *Measurement for length:* Indication of correct lengths, depth gauge sleeve fully shifted onto the plate, depth gauge barb hooked on opposite side (bone).
- *Screw insertion:* Use of correct screw length (prevents protruding from opposite side), matching of insertion angle with drill hole orientation.
- *X-ray:* Number and moment of X-rays taken.
- *General:* Sequence of steps.

According to the participants, several of these topics can directly be transferred to the operating theatre, such as the sequence of the steps required to treat the fracture, the gain in experience about typical bone thicknesses, the sensing of the resistance when drilling through cortical bone, keeping the plunge depth minimal and the consequence of misplaced plates or screws. These medical relevant aspects contribute to the aim of this PhD project, if using this simulator will lead to improved quality and patient safety in surgery. For example, teaching the plunge depth using conventional training material such as books or videos is difficult and as the participants confirmed, inserting a screw by themselves, feeling the resistance of the cortical bone and immediately seeing the result on the simulated X-ray helps to increase the understanding of patient safety-relevant aspects. Additionally, the training is designed to give the users confidence in performing these skills and in acquiring them, as they have permission to examine the results of poorly carried out tasks, and therefore to improve their skills, and by learning that skills that are acquired by surgical simulators are relevant and can be transferred to the operating theatre. But to achieve this, haptic feedback must be realistic and should be reduced to teachable topics, and medical relevant topics should be taught. However,

more research and studies examining improvements of quality and patient safety are needed, also to examine if there are other, possibly more cost-efficient training possibilities to acquire these skills. The remaining topics also contributed to the understanding of the medical scenario, however, more information would be needed to be taught so that the same level of confidence could be reached, if possible. But further research with more participants is needed to measure the actual (if any) transfer of skills to the operating theatre. In addition, different plates types, which require different techniques (such as volar/dorsal plating) exist, as well as steps such as the reduction, but are not yet implemented.

In addition to using meaningful paradigms, one aspect to focus on was the wow factor, which can have a huge impact on the user. To keep users motivated using the simulator, details were added which can for example be unexpected or rewarding. Young learners are used to almost lifelike graphics in computer games and may expect a similar fidelity. In addition, commonly criticised topics in studies evaluating computer-based surgical simulators are the lack of tactile feedback and slow simulation response time due to the required computational power (as in Tsai, Hsieh and Jou, 2001, Hariri, et al., 2004, Aggarwal, et al., 2006). These aspects have a direct influence on UX, when the use of the application is frustrating or does not satisfy the expectations. Preventing these negative emotions is one of the core objectives of UX (Hassenzahl and Tractinsky, 2006, p.93), therefore, great importance was attached in running the simulation in real time and providing high-fidelity graphics. This also addresses a research direction highlighted by Basdogan, Sedef, Harders and Wesarg (2007; see page 39), which emphasised improving visual quality, amongst others. In addition, a second research direction is addressed by this work, namely the integration into a medical curriculum by involving medical experts into the development process at relevant stages and by establishing potential integrations into the medical education (discussed in the following section).

For a few participants, a software error prevented accurate haptic feedback when applying the plate to the bone. The impact on user satisfaction could be measured, but with only five respectively six participants which were clearly not affected respectively affected, the significance is limited. Those which were affected by the software error rated the user satisfaction with 4.2 (including the only participant who rated user satisfaction with a score of 3), which improved to 4.5 amongst those which were not affected (with an overall average of 4.36). By following human factors methods (such as HCD, interviews, questionnaires and task analysis) and the eight golden rules of interface design (Shneiderman and Plaisant, 2004, pp.74), several usability issues which could potentially appear (and have been reported by other usability evaluations, such as Silvennoinen and Kuparinen (2009)), could already be prevented during the development phase. But during the evaluation, dif-

ferent usability issues could be identified (see section 7.4.2.2). Most of these can represent consequences on the performance or the educational objective, see table 8-1.

Table 8-1: Possible consequences of identified usability issues, grouped according to Silvennoinen and Kuparinen (2009, p.457).

Usability area/issue	*Possible consequences*
System feedback: awareness of notification messages.	Loss of time, feeling lost, missed information.
Aesthetics and visual design: separate application windows, screw insertion values.	Loss of time, not accepted user input, feeling lost, reduced user satisfaction.
Help and guidance: regrasping of plate, plate description.	Loss of time, missed information, reduced motivation.
Authenticity and ergonomics: use of different input devices, use of generic devices.	Memory overload, lack of transfer of skills to operating theatre.
Efficiency: ambiguous spheres.	Feeling lost, loss of time.
Language: no localisation.	Missed information, lack of understanding of medical scenario.

Most of the identified issues had a low (5) or moderate (3) severity level, only one had a high level (closing X-ray viewer prevented reopening it). Although the user satisfaction was good, they should be addressed for a future product. These findings, along with results from other usability testing studies, can point the direction to virtual reality-based surgical simulators to educate basic principles in open surgery in a meaningful and motivating manner.

One of the most important areas for improvement regarding user experience, medical relevance and facilitating transfer of skills to the operating theatre is using real medical instrument mock-ups as input devices, instead of the generic haptic device used in this work. By using generic devices, the manual skills used to operate these devices are, depending on the simulated medical device, similar (certain drill sleeves) or completely different (as when using a depth gauge or a drill), and the trainee is occupied with learning using the haptic device instead of the medical aspects educated through the simulator.

The conclusion of the evaluation is that by systematically orienting to the users' and medical experts' needs and expectations, the developed simulator not only fulfilled the requirements. Furthermore, the targeted user group would, according to their statements, use such a simulator not only for learning the treatment of a distal radius fracture, but also use it to get acquainted with new procedures and basic principles and skills. This could be achieved by adhering to the following principles:

- Focus on relevant medical aspects that should be taught with regard to the transfer of skills to the operating theatre.
- Follow design standards.

- Provide an intuitive user interface.
- Do not let the user feeling lost.

8.4.2 Implications for Medical Training

During the prototype evaluation and particularly in the medical evaluation with the medical experts, it became apparent that the developed simulator is, as intended, aimed at learning basic principles of procedures at early stages, i.e. for medical students or young doctors. Depending on the medical scenario, targeting medical students may be too early, as orthopaedic basic principles are not needed in every medical domain. Therefore, targeting young doctors with an experience in orthopaedic surgery with less than a couple of years and not having already experience in the taught medical scenario proved to be the correct approach.

Using virtual reality-based surgical simulators offers some advantages over or in addition to the current training, with the primary concern being patient safety. They are not limited to educating open surgery, but also apply to other medical fields, as discussed in many studies (such as Satava, 1993, Seymour, et al., 2002, Hammoud, et al., 2008; non-exhaustive enumeration):

- Safe and controlled environment.
- Possibility to make mistakes without harming patients.
- Acquire knowledge repetitively in reusable medical scenarios.
- Objective performance assessment with immediate feedback.
- Opportunity for independent learning.
- Better prepared when assisting in the operating theatre.

In addition, the developed surgical simulator offers features which make it advantageous in using it in addition to the current medical education:

- Qualitative and quantifiable assessment of trainee's performance by recording various metrics and the possibility to create levels of difficulty and learning targets that must be reached.
- By simulating the mass of the medical instruments/implants, the trainees have a more realistic sensation of the virtual instrument.
- Use of haptic feedback for increased realism when applying plate, preparing drill holes or inserting screws.

- Virtual X-ray based on actual 3D geometries for immediate review of plate and screw placement.
- By using high-fidelity representations of real-life situations, trainees get acquainted earlier with the look and use of relevant medical devices, instead of not until learning and assisting in the operating theatre, or instead of using abstract and simplified tasks.

Integrating the surgical simulator in the medical education is dependent on various factors. One of the most determining is that the simulator is embedded in a structured training and not meant to be optional (e.g. Sikder, 2015, De Visser, Watson, Salvado and Passenger, 2011). By this, learning targets and competency milestones can be defined, which have to be reached prior continuing for example assisting in the operating theatre. Three possible approaches are shown in figure 8-1 for the educational objective of learning the distal radius fracture (DRF) treatment.

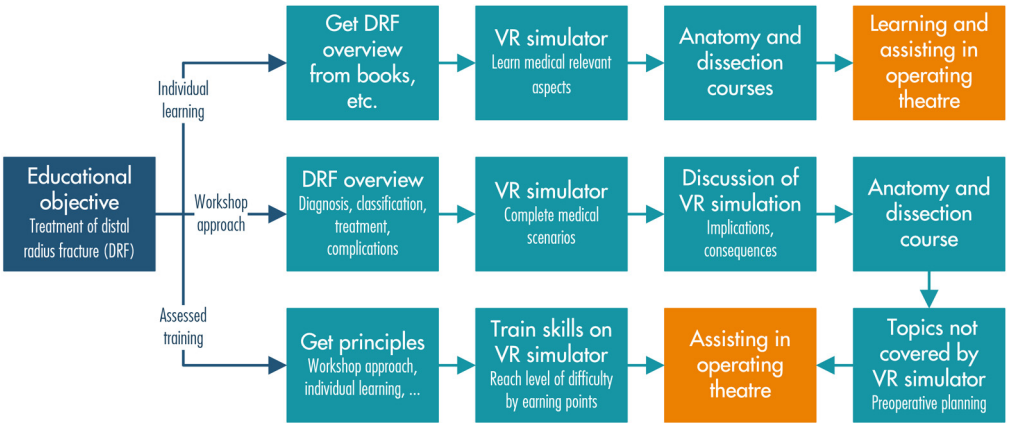


Figure 8-1: Possible approaches for integration of the surgical simulator into the medical education.

The least invasive is by using it for individual learning with pointing out relevant medical aspects which are difficult to teach through traditional media (particularly experiences based on tactile feedback). Traditionally, the medical students acquire knowledge by reading and learning from more experienced surgeons. By using the surgical simulator, the educational objective that is taught can take account of prior knowledge and establish new competencies, instead of teaching abstract theory, which eventually makes sense not until in the operating theatre, where they do it the first time on a patient and can make the connections there. In-line with the paradigm shift to competency-based medical education (Carraccio, et al., 2002), the surgical simulator allows to define performance levels for competencies (such as manage distal radius fractures by standard techniques), once the benchmarks have been specified. As the virtual reality-based training is not a substitution to cur-

rent training methods, anatomy and dissection courses complement training on simulators and allow the trainees to be better prepared when proceeding to the operating theatre.

The second approach is more applicable to workshops such as focus days/weeks or principle courses such as from the AO Foundation. There, different modules can be offered, with being the first an introduction into the treatment of the DRF. Then, on the surgical simulator, the entire medical scenario is completed, learning the relevant steps and at the same time having the possibility to explore for example the implications of badly placed plates/screws. Afterwards, the simulator session is discussed, reviewing commonly occurring implications and consequences and the simulation training, as suggested for example by Ramsey-Marcelle (2011, p.256) or Lateef (2010). Additional modules can include anatomy and dissection as well as topics not yet covered by the surgical simulator. By this, the trainees should have the understanding of the educational objective and in the future, similarly as with minimally invasive surgery simulators, could use the surgical simulator for assessed training (approach three) to get the required skills and reach a certain level of proficiency, for example by earning points for successful completion of given tasks with increasing difficulty. Sikder, et al. (2015) showed that following such an approach by using a surgical simulator for cataract surgery (with haptic feedback) as an assessment tool significantly improved performance on the simulator which also correlated with cataract surgery experience in the operating theatre. Using these two approaches, the benefit is that each trainee has completed the entire medical scenario on his own, instead of only inserting one, possibly two screws, as it is currently done at basic principle courses due to the limited time available for each module. There are however also critical voices which do not yet see that simulation training in orthopaedic surgery is a viable way to improve surgical skills. Templeton-Ward and Solan (2014) argue that there are no papers showing long-term impact of a structured simulation course and that there are only few papers showing that an orthopaedic curriculum containing a high level of simulation trainings would be superior to the current apprentice-style program, and thus have major concerns about replacing current surgical learning opportunities with simulation (Templeton-Ward and Solan (2014, p.362).

High-fidelity surgical simulators are often expensive equipment, which tends to be kept under lock (Walker, 2009) and thus possibly prevents further adoption in the medical training. By using a conventional workstation for the developed simulator, the hardware cost could be kept under roughly 10,000 euros (by using Geomagic Touch devices) depending on the haptic devices used (which can increase to additional tens of thousands if using six-DoF haptic devices). Not included are customisations for using real medical instrument mock-ups and the development cost, which could be sold by a one-time software purchase and per seat/user licensing fees. It can be estimated that the cost of

such a commercially available open surgery simulator is comparable with those for minimally invasive surgery, as both require a large amount of development work and similar equipment. Differences are within the use of haptic technology and the medical instruments used.

To conclude, using this developed surgical simulator addresses different issues of the current medical education raised by participants of the user requirements gathering and the medical evaluation study. Firstly, it allows to enhance the knowledge about particular procedures by repeating the medical scenario. As noted by medical student participants, they may not experience similar operations for a longer period of time. Using a computer-based simulator allows to repeat parts or the entire operation until they have reinforced what they have learned or what was not yet fully understood. Secondly, by using interactive high-fidelity visualisations (which could in the future possibly be improved to be photo-realistic), basic knowledge of anatomy can be taught with using less body parts, whose use is becoming more restrictive and limited. Thirdly, providing that sufficient simulators are available in the courses/workshops, medical students could complete the medical scenario themselves instead of working in small groups, which allows to perform only parts of the medical scenario on their own. And lastly, by using haptic feedback technology in a meaningful manner to support the trainee adds a third sense (in addition to the visual and auditory senses) and thus not only improves realism of the simulation and the relevant aspects that are thought (particularly for novices, see also van der Meijden and Schijven, 2009), but new medical topics can be educated which are not possible without haptics, such as sensing the difference between cortical and cancellous bone. Attention should be paid to using virtual reality-based surgical simulators with haptic feedback, as they require a meaningful integration into a structured training curriculum to ensure the advantages of the simulator optimally complement current training methods.

8.5 Contributions

The following are the main research contributions of this work:

- **An analysis of current state in medical education** focused on the current training methods, the use of surgical simulation and the potential for supporting medical students and young doctors in acquiring basic skills and the understanding of surgical procedures by providing a virtual reality-based simulator with haptic feedback (see chapter 4). The insights were gained from interviews and an internet survey with 13 orthopaedic hand surgeons and technical experts in England, Switzerland and Germany. It highlighted current issues in the training such as the limited training possibilities, common medical conditions that have to be treated, the

use of surgical simulators in certain medical fields, their advantages and the requirements on a virtual reality-based simulator for orthopaedic hand surgery.

- **A requirements specification for a surgical simulator** to learn and train the treatment of distal radius fractures. Based on the analysis of the state in medical education, use cases and requirements have been identified and reviewed for medical relevance and technical feasibility, and a medical scenario has been specified to support learning relevant aspects of treating distal radius fractures (see chapter 5).
- **An analysis of software libraries providing haptic feedback** with demonstrators showing their potential to be used for implementing a surgical simulator (see sections 6.5 and 6.6). Focused on six-DoF haptic rendering, haptic and physics libraries have been evaluated if they could be used or extended to support mesh-to-mesh collisions. Demonstrators have been developed to identify the potential and their limitations with the conclusion that none was suitable for six-DoF haptic rendering and a custom implementation was needed.
- **A software framework for surgical simulation** with six-DoF haptic feedback. Based on C++ and core libraries such as OpenSceneGraph, PhysX and Eigen, a virtual reality framework has been developed (see sections 6.9 and 6.10). It allows to develop interactive medical simulations (but is not limited to) and provides a basis for future research and by a generic, module-based approach, integration of future extensions and application purposes.
- **A virtual reality-based simulator for distal radius fracture treatment** with haptic feedback was developed, which allows to learn medical relevant aspects of applying plates, preparing and measuring holes and inserting screws (see section 6.8.5). Virtual X-rays allow to review the progress and position of the implants. Performance metrics data is recorded to compare and assess the users' performance and to allow defining educational objectives that must be reached.
- **A methodology for designing surgical simulators** focused on medical relevance and user experience. This work can be interpreted as priorities when designing simulators for open surgery which use a meaningful manner to educate trainees while maintaining a motivating user experience (see chapters 7, 8.3 and 8.4). The human-centred design approach and the undertaken medical evaluation revealed key issues which eventually have an influence on the success of an open surgery simulator and as such is a first step towards the use of virtual reality-based simulators in the training of open surgery basic skills and procedures.

8.6 Recommendations for Further Research

Exploring the following topics as further research can facilitate to achieve the goal of introducing virtual reality-based surgical simulators in the training of open surgery:

- *Further development of the simulator:* Refinements should be made to the interactions, particularly to the plate application, and the paradigms for using the input devices could be re-evaluated. Different modules of functionality and interactivity could be added, such as interactive soft tissue deformation, additional medical instruments (such as a drill sleeve), or additional steps of the distal radius fracture treatment, such as the approach or the reduction. For commercialisation, real medical instrument mock-ups should be developed.
- *Implement additional medical scenarios:* Based on the developed software framework, additional relevant medical scenarios or surgical skills should be evaluated, implemented and assessed on their benefit to the medical training.
- *Investigate impact of realism and immersiveness on training effectiveness:* The developed surgical simulator should be evaluated in a future study whether adding immersive elements such as stereoscopic rendering and head tracking as well as improved realism of the visualisation have an impact on the training effectiveness. Some of the participants had difficulties estimating the depth in the simulation, which could be addressed with stereoscopy.
- *Investigate effect of extended audio feedback:* Integration of additional or extended immersive audio feedback such as ambient sounds, conversations between medical staff or drill speed dependent drill sounds should be evaluated for its effect on the perceived realism and the effect on the performance.
- *Investigate effect of using gamification aspects on user engagement and performance:* By adding game design elements, such as earning points or badges for excellent performance, multi-user capability to compete against each other or a ranking list, the use of simulators can be increased and therefore the estimated cost per hour of simulator use reduced (Kerfoot and Kissane, 2014). Research is needed if adding such elements to the surgical simulator increases user engagement and performance and if the effect can be kept up in the long-term.
- *Expand user requirements specification:* To get a more precise requirements specification, the process should be repeated with orthopaedics specialised in the treatment of distal forearm fractures (in case for refinement of the implemented scenario), or in case for a new scenario, specialists in that particular medical area.

- *Repeat medical evaluation and focus on users' performance:* The evaluation carried out in this work focused on user experience and medical relevance. It should be repeated with more participants to establish simulator data for the implemented metrics by focusing on the performance, which allows comparison with real world data, such as with synthetic plastic bones. The simulator provides the possibility to conduct studies to establish quantitative data based on the implemented metric or by defining additional metrics. Such a study should be done with control groups to gain insight on the training effectiveness by comparing the qualitative data of a group undergone training on the simulator and the control group without training, or by comparing a simulator-trained group with a control group which is trained conventionally.
- *Measure transfer of skills to operating theatre:* The knowledge and skills imparted by the simulator should be analysed for transfer to the operating theatre. Although the medical students have well-received the manner of teaching the medical scenario and rated themselves to have a significant increased understanding after using the simulator, the actual benefit should be assessed.

8.7 Conclusion

This thesis posed the question if a novel virtual reality-based surgical simulator in open surgery can be used in a meaningful, effective and practical manner to educate medical students and young doctors similarly as existing simulators for minimally invasive surgery do. By using a human factors-led design and development process, an immersive, high-fidelity simulator with haptic feedback has been created, which allows to educate the relevant medical aspects and steps of the treatment of distal radius fractures. Including medical experts early in the decision-making process and during the progression of the work allowed to create a system according to their needs and expectations, which would have been more difficult to achieve at the same level of acceptance and in the same amount of time if traditional, less human-centred approaches had been used. This research showed that current technology can be used in a meaningful manner, despite computational restrictions that still apply, to create a system overcoming often criticised areas in prior research, such as insufficient graphics quality or missing haptic feedback. By investigating the acceptance of using such simulators amongst the target user group, this work contributes to the understanding of the effectiveness and usefulness, as well as to the possible integration in medical training of this simulator in open surgery. It is in the authors' belief that using virtual reality-based surgical simulators (respecting future technologies advances), aimed at educating particular relevant aspects of orthopaedic basic

skills and procedures, if integrated in a meaningful, structured competency-based curriculum in addition to current training possibilities, is an effective pedagogical strategy and can overcome identified limitations such as working hour restrictions, limited access to anatomical specimens or unpredictable medical conditions in hospitals and thus in the training. To refer back to Dutta, Gaba and Krummel (2006; see page 20), who stated that the question is not whether simulators are better than other training tools, but if they provide advantages if they are part of a competency-based curriculum, this work supports this approach and encourages for further research. As a result, medical students and young doctors can learn and train the educational objectives repeatedly in a safe and controlled environment without the risk of harming real patients and thus be better prepared when proceeding to the operating theatre and ultimately improve quality and patient safety in open surgery.

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Appendix A

Requirements Description

A.1 Overview

This appendix gives a detailed overview of the intended behaviour of the surgical simulator and interactions between the user and the surgical simulator in the form of user requirements and use cases.

A.2 Use Cases

Tables A-1 to A-11 elaborate further each use case (UC) shown in section 5.4.1.

Table A-1: Use case specification make a surgical incision.

Name	**UC-1: Make surgical incision**
Rationale	The trainee makes an incision with a surgical knife to open the surgical site.
Users	Trainee
Priority	High
Scenario example	The trainee has to decide where he wants to make the incision, take the scalpel and open the surgical site. He can verify the incision with the underlying anatomical structures.
Outstanding issues	The realistic virtual cutting of 3D meshes with virtual tools.
Extensions	UCE-1

Table A-2: Use case specification correctly align bone fragments (reduction).

Name	**UC-2: Reduce bone fragments**
Rationale	The trainee restores the correct alignment of the bone fragments.
Users	Trainee
Priority	Low
Scenario example	The trainee manipulates the hand to reduce the fragments. For this, he turns, pushes and pulls the hand to realign their normal anatomical position.

Outstanding issues	Simulating the manipulation of bone fragments requires reconstruction of biomechanical behaviour of anatomical structures.

Table A-3: Use case specification switch surgical instrument.

Name	**UC-3: Switch surgical instrument**
Rationale	To use different surgical instruments, the trainee has to select another instrument in a list of available instruments in the simulation.
Users	Trainee
Priority	High
Scenario example	Different surgical instruments require different handling. To use another instrument, the trainee selects the appropriate one in the list of available instruments in the simulation and optionally also has to change the end effector of the haptic device.
Outstanding issues	

Table A-4: Use case specification choose a plate or screw.

Name	**UC-4: Choose implant**
Rationale	The trainee has to choose the appropriate implant and screws for the fixation of the fracture.
Users	Trainee
Priority	Medium
Scenario example	Based on the reduced fragments, the trainee chooses the appropriate implant and its correct size to use for fixation of the fracture.
Outstanding issues	

Table A-5: Use case specification apply plate and screws to a bone (fixation).

Name	**UC-5: Fix fracture**
Rationale	The trainee fixes the fracture by inserting a plate and screws.
Users	Trainee
Priority	High
Scenario example	Based on the chosen implant and screws, the trainee inserts the plate, drills the holes for the screws and inserts the screws.
Outstanding issues	Collision detection computation between bone fragments, instruments and implants.

Table A-6: Use case specification train spatial sense and improve X-ray/CT image analysis.

Name	**UC-6: Train spatial sense and improve X-ray/CT analysis**
Rationale	The trainee uses an anatomical virtual simulator to train spatial sense and improve the analysis of X-ray and CT images.
Users	Trainee
Priority	High
Scenario example	The trainee has to choose from a number of CT images the one that corresponds to a given X-ray image. He can train his spatial sense by for example analysing and moving bone fragments at the correct position in a virtual trainer.
Outstanding issues	Getting medical data, separating the CT data and volume rendering.

Table A-7: Use case specification react to unexpected medical condition.

Name	**UC-7: React to unexpected situation**
Rationale	The trainee is confronted with unexpected conditions and has to react accordingly. These conditions can be triggered by the operator or by the simulation.

Users	Trainee (primary), operator
Priority	Low
Scenario example	The trainee is fixating the fracture by placing the plate and injures or raptures a tendon. He has to repair it first before he can continue with the fixation.
Outstanding issues	
Extensions	UCE-2

Table A-8: Use case specification analyse trainee's performance and create automatic report.

Name	**UC-8: Analyse performance**
Rationale	During or after the training session, the evaluator analyses the overall performance and gives a feedback or creates a report.
Users	Evaluator
Priority	Medium
Scenario example	The evaluator gives a feedback to the trainee based on the ongoing monitoring during the training or the automatically generated evaluation after the training by the simulator.
Outstanding issues	Defining parameters to benchmark surgeons performance.

Table A-9: Use case specification replay trainee's performance for analysis and discussion.

Name	**UC-9: Replay trainees performance**
Rationale	The evaluator can observe and analyse certain tasks or the entire training by replaying the simulation.
Users	Evaluator
Priority	Medium
Scenario example	The evaluator replays the task of placing the plate to verify the correct placement.
Outstanding issues	Logging all trainee's action, especially haptics, can require considerable computational power.

Table A-10: Use case specification ligate injured blood vessels.

Name	**UCE-1: Ligate blood vessels, extends UC01**
Rationale	The trainee has to ligate a blood vessel after it has been injured.
Users	Trainee
Priority	Low
Scenario example	During the surgical incision, the trainee injures a blood vessel. Then, he has to clamp the vessel with a haemostat and secure it with a ligature.
Outstanding issues	Modelling a physical simulation to realistically simulate the behaviour of blood vessels.

Table A-11: Use case specification take targeted influence confront trainee with unexpected situation.

Name	**UCE-2: Take targeted influence, extends UC05**
Rationale	The operator can interfere during the training to confront the trainee with a new condition.
Users	Operator
Priority	Low
Scenario example	The operator simulates an emergency call which the trainee has to answer and gets distracted.
Outstanding issues	

A.2.1 Use Cases Identified During Iterative Design of the Surgical Simulator

Functionality to take X-rays was suggested and instead of only informing the user that the drill hole has a certain length, a depth gauge should be used to measure screw lengths, as shown in tables A-12 and A-13.

Table A-12: Use case specification measure a drill hole for its length.

Name	**UC-8: Measure for length**
Rationale	The trainee measures the drill hole for length of the required screw.
Users	Trainee
Priority	High
Scenario example	The trainee uses a depth gauge, inserts it into the drill hole and shifts the drill sleeve towards the bone. The required length can be read on the scale on the depth gauge.
Outstanding issues	Inserting the depth gauge into the drill hole leads to the peg-in-hole problem.

Table A-13: Use case specification take an X-ray.

Name	**UC-8: Take X-ray**
Rationale	The trainee takes an X-ray.
Users	Trainee
Priority	High
Scenario example	The trainee takes a virtual X-ray, which can be examined.
Outstanding issues	Rendering the current scene so that it mimics a real X-ray image.

A.3 User Requirements

This section gives a detailed overview of the identified functional and non-functional requirements of the surgical simulator, see also section 5.4.2.

A.3.1 Functional Requirements

Based on the use cases, the following functional requirements (FR) were identified:

Table A-14: Functional requirement specification of selecting plates and screws.

Name	**FR-1: Selection of plate and screws**
Summary	The correct plate and screws shall be selectable.
Rationale	In surgery, a surgeon has to choose the correct plate shape and size and the appropriate screws. The simulator needs to provide a selection of plates and screws from which the user can choose.
Requirements	When a user invokes the plate selection function, a list of all available plates must be shown. By default, either the plate chosen by the user during preoperative planning can be selected, or the first one in the list. After a plate is chosen, the available screws for this plate must be shown for selection by the user.
References	UC-4: Choose implant

Table A-15: Functional requirement specification of making incisions to open the surgical site.

Name	**FR-2: Making incisions to open the surgical site**
Summary	The surgical simulator shall allow to make incisions to open the surgical site.
Rationale	Incisions are used for most of the operations. Therefore, a user needs to be able to cut the skin at the intended position.
Requirements	When a user begins to make an incision, the simulated skin has to open accordingly to the cutting and the anatomical structures underneath are shown.
References	UC-1: Make surgical incision

Table A-16: Functional requirement specification of the simulators response to user errors.

Name	**FR-3: Response to user errors**
Summary	The surgical simulator shall react to surgical errors such as cutting into vessels by simulated bleeding.
Rationale	During the training, the user can make surgical errors because of carelessness. The surgical simulator needs to be aware of that and response according to the circumstances.
Requirements	When the user makes a mistake, the system has to decide if it can response, i.e. a reaction is implemented for this particular mistake, if it only needs to log the mistake or if it has to end the simulation. If a blood vessel has been damaged, UCE-1 can be activated.
References	UC-7: React to unexpected situation, UCE-1: Ligate blood vessels

Table A-17: Functional requirement specification of the desired flexibility of the simulator.

Name	**FR-4: Flexibility of simulator, act as playground**
Summary	The surgical simulator shall allow to try out different things, to play with it, to go beyond the limit.
Rationale	The user needs to be able to try out different techniques and to get practical experience and surgical skills.
Requirements	The system should be implemented in a manner that it is as flexible as possible and should be generic in a way that functionality can be shared amongst similar data models.

Table A-18: Functional requirement specification of user-changeable view onto the surgical site.

Name	**FR-5: User-changeable view onto surgical site**
Summary	The perspective onto the surgical site shall be changeable by the trainee.
Rationale	Depending on the surgery, a surgeon changes his view onto the surgical site. Therefore, the system needs to allow manual control over the perspective to simulate these view changes.
Requirements	When a user needs to change the perspective, he can use the keyboard, mouse or 3D mouse. The user can either choose predefined views or manually modify the perspective. By default, the view is fixed to a standard starting position, defined in advance by medical experts.
References	UC-1: Make surgical incision, UC-2: Reduce bone fragments, UC-5: Fix fracture, UC-7: React to unexpected situation, UCE-1: Ligate blood vessels

Table A-19: Functional requirement specification of the possibility to use different surgical instruments.

Name	**FR-6: Possibility to use different surgical instruments**
Summary	The surgical instruments shall be exchangeable to reflect different surgical techniques
Rationale	In typical surgical operations, different surgical instruments are used. The system needs to allow changing these instruments according to the user's actions.

Requirements	When a user invokes the change surgical instrument functionality, the system needs to provide a list of available instruments from which the user can choose. Depending on the surgical instrument, the user also needs to change the end effector of the haptic device, which cannot be done by the software. Instead, a message should be displayed with advice on how to replace the end effector.
References	UC-7: React to unexpected situation, UCE-1: Ligate blood vessels

Table A-20: Functional requirement specification of logging relevant user activity.

Name	**FR-7: User activity logging**
Summary	All user activity shall be logged so that it can be used for assessment.
Rationale	For the assessment of the users' performance, all user activity needs to be recorded by a logging system.
Requirements	During all user activities, the position and orientation of the surgical instruments needs to be logged. By default, monitoring of the surgical system should be sufficient if the entire simulation is deterministic. Otherwise, all relevant parameters must be logged as well.
References	UC-8: Analyse performance, UC-9: Replay trainees performance

A.3.2 Non-Functional Requirements

Based on the interviews and the usage of the medical demonstrator application, non-functional requirements (NF) were identified and had to be considered during the development process:

Table A-21: Non-functional requirement specification of a realistic visualisation of surgical instruments.

Name	**NF-1: Realistic visualisation of surgical instruments**
Summary	The interaction with the surgical simulator shall be realised through realistic representations of the surgical instruments.
Rationale	If the surgical instruments are not visualised realistically enough, users my be confused about which instrument they are using at the moment.
Requirements	Surgical instruments should strongly resemble to known instruments, but the particular model is secondary.
References	UC-1: Make surgical incision, UC-3: Switch surgical instrument

Table A-22: Non-functional requirement specification of a realistic visualisation of anatomical structures.

Name	**NF-2: Realistic visualisation of anatomical structures**
Summary	The anatomical structures shall be visualised as realistic as possible.
Rationale	If the anatomical structures are not visualised realistically enough, the training effect is of limited value and users will avoid using the simulator.
Requirements	Anatomical structures should be visualised so that the characteristic is maintained and landmarks are anatomically correct.
References	UC-1: Make surgical incision, UCE-1: Ligate blood vessels

Table A-23: Non-functional requirement specification of haptic feedback.

Name	**NF-3: Haptic feedback**
Summary	Haptic feedback shall give a realistic feedback for example of drilling or repositioning bones.
Rationale	Haptic feedback provides adequate realism and must simulate forces experienced during surgery. If no haptic feedback is provided, users may not be able to sense the consistency of the anatomical structures, which is an important reference point in surgery.

Requirements	Haptic rendering needs to compute collisions fast, i.e. at 1 kHz or more, otherwise the models may feel unstable or soft.
References	UC-1: Make surgical incision, UC-2: Reduce bone fragments, UC-5: Fix fracture, UCE-1: Ligate blood vessels

Table A-24: Non-functional requirement specification of the initial cost of the surgical simulator.

Name	**NF-4: Initial cost of surgical simulator**
Summary	The surgical simulator shall be cost-efficient, i.e. it should be less expensive to use the simulator than training on anatomical specimens.
Rationale	Hospitals need to consider cost-efficiency and therefore will not be able to purchase expensive equipment if the new equipment does not offer a significant improvement over the existing equipment.
Requirements	Use of conventional hardware, possibly consumer hardware, which still fulfils complete functioning usage instead of highly specialised, expensive equipment.

Table A-25: Non-functional requirement specification of performance constraints for running the simulator in real time.

Name	**NF-5: Performance constraint for the interactiveness**
Summary	The surgical simulator shall have a minimal response time, i.e. running in real time.
Rationale	If the interactiveness is not high enough, users will avoid using the simulator.
Requirements	The visualisation of the simulator should run at frame rates at a minimum of 25 to 30 FPS, ideally at 60 FPS (frames per second); haptic rendering needs to run at considerable higher frame rates (1 kHz or more). CPU load is insignificant if the entire system (including visualisation, haptics, interactiveness and logging) is able to run in real time.

Appendix B

Technical Description

B.1 Overview

This appendix gives an overview of implementation aspects relevant to implement the discussed functionality of the surgical simulator.

B.2 Cortical Thickness of Distal Radius Bones

Using polynomial interpolation, the relative thickness of the palmar and dorsal cortical bone on a range of -4.0 to -1.0 (which are the world coordinates of the shaft area of the radius bone) can be calculated:

- Palmar cortical bone thickness:

$$0.2x^3 + 1.85x^2 + 8.45x + 23.3$$

- Dorsal cortical bone thickness:

$$0.316667x^3 + 2.7x^2 + 9.88333x + 23.3$$

For the palmar thickness, position five and for the dorsal thickness, the average of positions one and two have been used, see figure 3a in Mockenhaupt (1990, p.164). No data is available for about 2 cm of the distal end (not measured due to extremely thin cortical bone) and from 6 cm on in proximal direction, therefore constant values of 0.75 mm (distal) and 2.4 mm (proximal) are assumed for thickness in that areas.

B.3 Generating a Virtual X-ray

For the conversion of the RGB colour value to a greyscale value, the luminance is calculated according to the Rec. 601[1] standard, which gives a perceived brightness Y for a colour:

$$Y = 0.299R + 0.587G + 0.114B$$

The following vertex and fragment shaders[2] are used to render the nodes radiolucent:

Program listing B-1: Radiolucent vertex shader.

```
varying vec3 N;
varying vec3 I;
varying vec4 Cs;
void main()
{
    vec4 P = gl_ModelViewMatrix * gl_Vertex;
    I = P.xyz - vec3(0);
    N = gl_NormalMatrix * gl_Normal;
    Cs = gl_Color;
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Program listing B-2: Radiolucent fragment shader.

```
varying vec3 N;
varying vec3 I;
varying vec4 Cs;
void main()
{
    float opac = dot(normalize(N), normalize(-I));
    opac = 1.0 - abs(opac);
    float gray = dot(opac * Cs, vec3(0.299, 0.587, 0.114));
    gl_FragColor = vec4(gray, gray, gray, opac);
}
```

The following vertex and fragment shaders are used to render the nodes radiopaque by simply setting the fragment colour to white:

Program listing B-3: Radiopaque vertex shader.

```
void main()
{
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Program listing B-4: Radiopaque fragment shader.

```
void main()
{
    gl_FragColor = vec4(1.0, 1.0, 1.0, 1.0);
}
```

1. ITU (2015) *Studio encoding parameters of digital television for standard 4:3 and wide screen 16:9 aspect ratios*. [Online]. Available from: http://www.itu.int/rec/R-REC-BT.601-7-201103-I/en.
2. Code based on METHIUS (2008) *X-Ray Shader — User Code & Projects — jMonkeyEngine Hub*. [Online]. 2008. Available from: http://hub.jmonkeyengine.org/t/x-ray-shader/8308 [Accessed: 15 July 2015].

X-ray images show the internal structure of the body, which would require volume data for appropriate recreation. As no volume data was available, the OpenGL depth test has been disabled for the scene graph nodes to imitate the look of X-ray images, so that objects which are in the background still get rendered, as the depth buffer is not updated and depth comparison is not performed.

B.4 Implementation Details of the Contact Thread

The INIT_CLUSTERS method has been extended to use the k-means++ algorithm (Arthur and Vassilvitskii, 2007) for choosing the initial set of contact points. This way, the initial cluster centres are not set arbitrarily as in the original k-means algorithm, but are chosen based on a weighted probability distribution proportional to the squared Euclidean distance from the centres already chosen. Although this initialisation takes additional computation time, the k-means part converges faster and results in lower overall computational cost, according to Arthur and Vassilvitskii.

Under rare conditions, clusters can get empty. This occurs if the targeted number of clusters is wrong, making it hard to divide the contact points into clusters. Therefore, the ASSIGN_CLUSTERS method has been extended to check for empty clusters at the end of the proximity-based reclustering. In such cases, the contact point furthest away from the cluster representative of the cluster with the maximum squared Euclidean distance is taken as a new cluster. This implementation is based on a function of the mlpack library[1].

Furthermore, an error was corrected in algorithm VI.1, INIT_CLUSTERS (Otaduy and Lin, 2006, p.757), the correct equation in the pseudocode listing for finding the closest pair is:

$$(C_j, S'_k) \leftarrow min_{C_j \in \{C\}} min_{S_k \in \{S\}} \left|\left|C_j.p(-S'_k.p)\right|\right|$$

The contact thread executes the same sequence of operations as described by Otaduy and Lin (2006, p.753) with an additional first step to dynamically update haptic rendering parameters:

1. Update haptic parameters.
2. Fetch the state of the user-controlled object.
3. Perform collision detection using PhysX.
4. Cluster contacts and compute cluster representatives.

1. *mlpack::kmeans::MaxVarianceNewCluster::EmptyCluster()*, see CURTIN, R.R., CLINE, J.R., SLAGLE, N.P., MARCH, W.B., ET AL. (2013) MLPACK: A Scalable C++ Machine Learning Library. *Journal of Machine Learning Research*. [Online] 14(Mar), 801–805. Available from: http://www.jmlr.org/papers/v14/curtin13a.html.

5. For each cluster representative, solve the contact force and torque equations and compute their Jacobians.

Step four has been extended by a control mechanism to check for duplicate contacts occasionally created by PhysX. These duplicate collision contacts are ignored when creating the new set of contacts for the CLUSTER_CONTACTS method.

B.5 Implementation Details of the Haptic Thread

The implementation is based on the rigid body dynamics, virtual coupling and linearised contact model equations by Otaduy and Lin (2006, pp.754-756, p.758) with several modifications and corrections as follows:

- To have more precise control during plate positioning and also as the haptic device used during development has only three-DoF force feedback, the orientation of the user-controlled object has been fixed to the orientation of the end effector after each haptic frame. The drawback is that it is therefore possible to unintentionally move the object into the radius bone for a certain small extent, until the position gets corrected by the collision detection in the contact thread.
- A control statement has been integrated to check if the orientation of the user-controlled object is identical to that of the end effector. This was needed, as if the haptic thread is running too fast, under rare conditions it could happen that these two orientations are actually the same. This would lead to the derivative of the axis of rotation (equation 25 in Otaduy and Lin, 2006, pp.755) becoming an undetermined form, as Δq_s becomes 1.0 and Δq_{xyz} becomes 0.0. Thus, the limit of equation 25 should be computed when the relative rotation tends to zero, but as this occurs in only very rare cases, this haptic frame is simply skipped and continued with the next time interval, where these orientations most likely have changed.
- The computed coupling force and torque that are sent to the haptic device can be modified, so that they can be adjusted depending on the simulation state or can completely be overwritten in case for drilling or screw insertion, where different haptic effects are rendered, which are not integrated into the six-DoF haptic rendering algorithm.

Furthermore, the partial derivatives of the rotation matrix R have been corrected (equations 12 in Otaduy and Lin, 2006, pp.755) as follows:

$$\frac{\partial R}{\partial x} = 2\begin{pmatrix} x & y & z \\ y & -x & -s \\ z & s & -x \end{pmatrix}, \frac{\partial R}{\partial y} = 2\begin{pmatrix} -y & x & s \\ x & y & z \\ -s & z & -y \end{pmatrix}, \frac{\partial R}{\partial z} = 2\begin{pmatrix} -z & -s & x \\ s & -z & y \\ x & y & z \end{pmatrix},$$

$$\frac{\partial R}{\partial s} = 2\begin{pmatrix} s & -z & y \\ z & s & -x \\ -y & x & s \end{pmatrix}$$

In addition, instead of sending the coupling force and torque of equation 14 to the haptic device, the opposing vectors are used, as F_c and T_c point towards the haptic device.

The haptic thread executes the same sequence of operations as described by Otaduy and Lin (2006, p.753) with the aforementioned modifications and additional steps to dynamically update haptic rendering parameters and to switch the user-controlled object:

1. Update haptic parameters.
2. Read state of the haptic device at time t_i.
3. Optionally attach the user-controlled object.
4. Linearise the coupling force and torque at time t_{i-1}.
5. Linearise the contact force and torque at time t_{i-1}.
6. Solve the state of the user-controlled object at time t_i using implicit integration.
7. Compute the coupling force and torque at time t_i.
8. Execute callback to modify coupling force and torque and overwrite the user-controlled object state.
9. Send the coupling force and torque to the haptic device and update HIP and IHIP.

B.6 Implementation Details of the Haptic Effects

This section gives implementation details of the code used for the haptic effects. It is written in C++ and uses the Eigen[1] library for linear algebra such as matrices, vectors, numerical solvers, and related algorithms.

B.6.1 Magnetic Line

Program listing B-5: Resulting force used to fixate drill along drill direction.

```
if ((distance < _maxDistance) && (_stiffness > 0))
{
    // get parameters of magnet
    double forceMagnitude = 0;
    double d = _maxForce / _stiffness;
    if (distance < d)
        forceMagnitude = _stiffness * distance;
    else
    {
        double dx = _maxDistance - d;
        if (dx > 0)
        {
            double k = _maxForce / dx;
            forceMagnitude = k * (_maxDistance - distance);
        }
    }
    // compute normal
    Eigen::Vector3d normal = toolPosition - interactionPoint;
    Eigen::Vector3d interactionNormal;
    if (normal.squaredNorm() > 0.0)
    {
        normal.normalize();
        interactionNormal = normal;
    }
    else
        interactionNormal = Eigen::Vector3d(0, 0, 1);
    // compute reaction force
    force = interactionNormal * -forceMagnitude;
}
```

B.6.2 Vibration

Program listing B-6: Resulting force used to simulate vibration of drill handle.

```
double time = std::chrono::high_resolution_clock::now().time_since_epoch().count() - _startTime;
force = Eigen::Vector3d(0, 0, -1.0) * _vibrationAmplitude * sin(2.0 * I3DBASICS::Mathd::PI * _vibra-
tionFrequency * time);
```

B.6.3 Viscosity

Program listing B-7: Resulting force used to simulate resistance in cortical bone using viscosity.

```
force = toolVelocity.normalized() * -_viscosity;
```

1. JACOB, B. & GUENNEBAUD, G. (2016) *Eigen*. [Online]. 2016. Available from: http://eigen.tuxfamily.org [Accessed: 3 July 2016].

B.6.4 Magnetic Field

Program listing B-8: Resulting force used to simulate inserting screws.

```
// compute distance from object to tool
double distance = Eigen::Vector3d(toolPosition - _pos).norm();
if ((distance > 0) && (distance < _maxDistance) && (_stiffness > 0))
{
    // get parameters of magnet
    double forceMagnitude = 0;
    double limitLinearModel = _maxForce / _stiffness;
    boost::algorithm::clamp(limitLinearModel, 0.0, 0.5 * distance);
    if (distance < limitLinearModel)
    {
        // apply local linear model near magnet
        forceMagnitude = _stiffness * distance;
    }
    else
    {
        // compute quadratic model
        Eigen::Matrix3d sys;
        sys(0, 0) = limitLinearModel * limitLinearModel;
        sys(0, 1) = limitLinearModel;
        sys(0, 2) = 1.0;
        sys(1, 0) = _maxDistance * _maxDistance;
        sys(1, 1) = _maxDistance;
        sys(1, 2) = 1.0;
        sys(2, 0) = 2.0 * limitLinearModel;
        sys(2, 1) = 1.0;
        sys(2, 2) = 0.0;
        sys.inverse();
        Eigen::Vector3d param = sys * Eigen::Vector3d(_maxForce, 0.0, -1.0);
        // apply quadratic model
        double val = distance - limitLinearModel;
        forceMagnitude = param.x() * val * val + param.y() * val + param.z();
    }
    // compute magnetic force
    force = (_pos - toolPosition).normalized() * forceMagnitude;
    // add damping component
    Eigen::Vector3d viscousForce = toolVelocity * -_viscosity;
    force += viscousForce;
}
```

B.7 Algorithm Parameters

This section gives an overview of the parameters used for the calculations of the haptic rendering effects and the six-DoF haptic rendering pipeline. All parameters are haptic device type dependent and apply to the Force Dimension omega.6.

B.7.1 Haptic Effects

B.7.1.1 Vibration

- Amplitude $A = 0.2$
- Frequency $f = 0.000006$

B.7.1.2 Viscosity

- Damping coefficient $c = 22.0$

B.7.1.3 Magnetic Line

- Maximum distance 0.05
- Maximum force 2.25
- Maximum stiffness 1.75 (multiplied by maximum stiffness of haptic device)

B.7.1.4 Magnetic Field

- Maximum distance 0.02
- Maximum force 3.0
- Maximum stiffness 3.0 (multiplied by maximum stiffness of haptic device)
- Damping coefficient $c = 22.0$

B.7.2 Six-DoF Haptic Rendering Algorithm

- Contact stiffness $k = 3000$
- Contact damping $b = 500$
- Linear stiffness of the virtual coupling $k_c = 7500$
- Linear damping of the virtual coupling $b_c = 10$
- Angular stiffness of the virtual coupling $k_\theta = 0.6$
- Angular damping of the virtual coupling $b_\theta = 100$
- Maximum number of clusters $K = 5$

Appendix C

Medical Evaluation Performance Data

C.1 Performance Data Overview

The collected performance data is presented in the following sections. Each cell is sorted chronological, meaning that for example the he first row in a cell is the drill hole which is prepared first. The symbol "-" indicates that no data is available for this screw, as the participant did not insert a screw which happened at the end of the hands-on, as not in all prepared drill holes a screw has been inserted.

C.2 Implant Application Data

Table C-1: Implant application data for medical students.

Participant	*Changes (including final)*	*Manipulation time(s)*	*Overall manipulation time*	*Interaction duration*
1	2	30.135 148.166	148.166	644
2	1	39.034	39.034	100
3	2	15.763 28.913	44.676	276
4	1	38.721	38.721	222
5	1	253.58	253.58	667
6	1	67.074	67.074	178
7	1	204.156	204.156	543
8	1	36.262	36.262	162
9	2	64.311 189.351	253.662	489
9 - Second try	1	33.581	33.581	146

Participant	*Changes (including final)*	*Manipulation time(s)*	*Overall manipulation time*	*Interaction duration*
10	2	21.894 104.805	126.699	313
12	2	31.442 - (crashed) 31.602	63.044	732
12	1	169.269	169.269	337
13	2	9.277 51.683	60.96	181
14	4	26.554 22.722 14.873 55.158	119.307	287

C.3 Drilling Data

Table C-2: Drilling data for medical students.

Participant	*Number of prepared holes*	*Number of drill attempts*	*Accepted hole depths (cm)*	*Drill length errors (cm)*	*Overall drill lengths (cm)*
1	5	8	1.659131	1.997729	3.65686
		8	2.036932	3.437272	5.474204
		2	2.34302	2.657336	5.000356
		2	1.761356	-0.027546	1.761356
		4	2.322804	0.003839	2.326644
2	8	2	2.16528	-0.070813	2.16528
		3	0.285975	-0.404835	0.0
		2	2.370242	0.361033	2.731275
		2	1.502599	0.337354	1.839953
		2	1.600595	0.191876	1.792471
		4	2.178363	0.776907	2.95527
		2	1.877126	0.483754	2.36088
		2	2.357191	0.425315	2.782506
3	5	5	1.76284	1.044105	2.806945
		3	2.238463	0.812546	3.051009
		2	1.554062	1.048186	2.602248
		4	1.619569	1.496511	3.11608
		10	1.699116	2.688395	4.387511
4	4	6	2.197961	0.449012	2.646974
		2	1.791018	0.246134	2.037152
		6	1.619254	1.093088	2.712342
		2	2.212512	0.203522	2.416034
5	5	2	1.50888	0.623909	2.13279
		4	2.175589	0.323047	2.498636
		9	1.795868	0.444714	2.240582
		2	1.672129	0.285020	1.957149
		1	1.757743	0.475741	2.233484

Participant	*Number of prepared holes*	*Number of drill attempts*	*Accepted hole depths (cm)*	*Drill length errors (cm)*	*Overall drill lengths (cm)*
6	5	3	1.487605	0.401735	1.88934
		3	1.830517	0.153795	1.984311
		2	2.221017	0.210697	2.431714
		2	2.272246	0.435610	2.707856
		2	1.966966	0.275774	2.242741
7	4	2	1.663908	0.210457	1.874365
		2	2.261138	0.377698	2.638836
		1	2.185794	0.424801	2.610595
		2	1.749422	4.434847	6.184269
8	5	7	1.679659	0.262749	1.942408
		2	1.693947	0.770777	2.464724
		1	1.856535	0.649645	2.506180
		1	2.269175	0.569098	2.838272
		2	1.523793	0.450979	1.974772
9	2	7	1.199947	-0.217839	1.199947
		4	1.805381	0.187934	1.993314
9 - Second try	4	2	1.582588	0.077783	1.660371
		3	1.959128	0.892234	2.851362
		3	2.215614	0.098500	2.314114
		5	1.797815	0.253795	2.05161
10	5	9	1.651125	-0.000381	1.651125
		3	1.978093	0.139339	2.117432
		2	2.329735	0.29671	2.626445
		2	2.130751	0.090751	2.221502
		3	2.037104	0.313459	2.350563
12	5	2	1.869792	0.197027	2.06682
		3	2.331476	0.1158521	2.447313
		2	1.690668	-0.061325	1.908613
		3	1.871329	0.167853	20.39182
		2	1.525724	0.076332	1.602056
12	5	3	2.250395	0.260692	2.511087
		2	1.660329	1.67254	3.332870
		2	1.173539	-1.140559	1.173539
		3	1.372663	0.667067	2.039730
		4	1.583891	0.208435	1.792326
13	4	6	1.70789	0.096571	1.804461
		2	2.402971	0.172519	2.57549
		1	1.853203	0.334082	2.187286
		1	1.616717	0.236398	1.853115
14	6	3	1.654554	0.072581	1.727135
		2	2.109187	-0.097532	2.109187
		2	2.142696	0.200679	2.343375
		10	1.663522	0.11763	1.781152
		2	1.79517	0.386659	2.181829
		2	2.197016	0.280196	2.477212

C.4 Measuring for Length Data

Table C-3: Measuring for length data for medical students.

Participant	*Measure durations*	*Measured lengths (m)*	*Number of not extended enough*
1	86	0.022858	3
	72	0.026459	
	79	0.0344	
	30	0.033486	
	54	0.037931	
2	89	0.023568	4
	51	0.0	
	42	0.025574	
	56	0.016823	
	28	0.01767	
	21	0.02409	
	15	0.02199	
	32	0.026195	
3	84	0.021481	4
	155	0.023865	
	38	0.021591	
	26	0.018438	
	64	0.021663	
4	135	0.023578	2
	69	0.01988	
	66	0.016193	
	45	0.023752	
5	22	0.020325	8
	116	0.028388	
	36	0.027375	
	116	0.021624	
	26	0.026999	
6	101	0.017472	4
	65	0.022224	
	44	0.02387	
	35	0.023708	
	39	0.022434	
7	116	0.023723	5
	-	0.024202	
	-	0.024314	
	118	0.021335	
8	128	-	3
	78	0.017783	
	73	0.029614	
	27	0.030158	
	43	0.025274	
9	67	0.014991	1
	63	0.02233	
9 - Second try	90	0.018887	3
	88	-	
	54	0.028091	
	45	0.026194	

Participant	*Measure durations*	*Measured lengths (m)*	*Number of not extended enough*
10	56	0.016914	7
	89	0.024835	
	36	0.025611	
	45	0.025303	
	30	0.024675	
12	120	0.022241	6
	-	-	
	35	0.021867	
	56	0.023127	
	40	0.016104	
12	93	0.028383	6
	106	0.02543	
	55	0.029656	
	55	0.02449	
	44	0.015839	
13	69	0.022734	5
	104	0.032198	
	-	0.027641	
	-	0.022903	
14	95	0.016923	7
	46	0.022442	
	-	-	
	39	0.017741	
	62	0.023557	
	36	0.022311	

C.5 Screw Insertion Data

Table C-4: Screw insertion data for medical students.

Participant	*Selected screw lengths (cm)*	*Angle errors (°)*	*Position errors (m)*	*Insertion lengths (m)*	*Insertion durations (s)*
1	2.0	5.663955	0.000812	0.020041	113
	2.6	8.254211	0.001657	0.026011	183
	2.6	1.223641	0.001202	0.026026	146
	3.0	4.196121	0.000897	0.030042	118
	3.0	0.828705	0.001891	0.030032	53
2	2.2	4.167517	0.001921	0.022011	87
	2.2	8.17582	0.001603	0.022049	48
	2.6	2.678258	0.000969	0.026045	46
	1.6	4.050704	0.001826	0.016017	104
	1.8	8.738726	0.00198	0.018006	21
	2.4	3.879798	0.001387	0.024050	39
	2.2	5.423226	0.001454	0.022043	94
	2.6	4.149107	0.001691	0.026008	37
3	2.0	3.704285	0.000673	0.020016	99
	2.2	9.356697	0.001151	0.02204	34
	2.0	2.90371	0.001995	0.020054	35
	1.8	2.82109	0.001905	0.018034	112
	2.2	2.268233	0.001979	0.022005	25

Participant	*Selected screw lengths (cm)*	*Angle errors (°)*	*Position errors (m)*	*Insertion lengths (m)*	*Insertion durations (s)*
4	2.4	3.105854	0.000722	0.024041	102
	2.2	3.385987	0.001696	0.022118	99
	1.6	2.713181	0.000642	0.016086	89
	2.4	1.060895	0.001070	0.024013	62
5	2.0	2.513499	0.001937	0.020041	70
	2.8	1.586256	0.001307	0.028034	80
	2.6	1.228309	0.001069	0.026045	70
	2.2	1.819300	0.001288	0.022011	55
	2.6	-	-	-	-
6	1.8	5.898530	0.001262	0.018053	94
	2.2	2.715516	0.001342	0.02203	136
	2.4	1.973106	0.001956	0.024006	67
	2.4	2.703629	0.001387	0.024041	68
	2.2	1.885461	0.001976	0.022005	36
7	2.4	1.055912	0.001442	0.024028	86
	2.2	2.401253	0.001996	0.022005	152
	2.6	4.100264	0.000323	0.026048	58
	2.6	7.532539	0.001318	0.026008	48
8	1.8	2.80845	0.001057	0.018141	118
	1.6	2.710025	0.000717	0.01612	70
	2.8	3.299997	0.006553	0.028009	72
	3.0	6.222274	0.001828	0.030092	153
	2.4	3.411044	0.000808	0.024141	55
9	1.4	8.664874	0.001155	0.014053	71
	2.2	-	-	-	-
9 - Second try	1.8	0.391954	0.001323	0.018037	66
	2.4	5.783879	0.000498	0.024050	109
	2.6	1.746257	0.002465	0.026011	53
	1.6	6.209464	0.003871	0.016023	102
10	1.6	2.708854	0.001095	0.016023	63
	2.4	3.5005	0.001485	0.024041	98
	2.4	2.514907	0.001746	0.024006	69
	2.4	2.505566	0.001671	.0.24013	78
	2.4	2.349962	0.001418	0.024063	68
12	2.0	1.555002	0.000637	0.020019	62
	2.4	2.874747	0.000756	0.024013	198
	2.0	2.626173	0.001336	0.020079	146
	2.2	0.846906	0.001551	0.022062	102
	1.6	1.525292	0.001434	0.016032	140
12	2.8	0.862374	0.000404	0.028028	50
	2.6	0.954402	0.001467	0.026058	105
	3.0	0.598162	0.000524	0.030039	116
	2.0	1.599787	0.007116	0.020026	72
	1.6	1.799909	0.000503	0.016001	115
13	2.2	3.555955	0.000811	0.022121	65
	3.0	4.939199	0.001125	0.030013	28
	2.8	5.273259	0.004169	0.028018	40
	2.2	8.046344	0.000985	0.022115	69

Participant	*Selected screw lengths (cm)*	*Angle errors (°)*	*Position errors (m)*	*Insertion lengths (m)*	*Insertion durations (s)*
14	1.6	2.972808	0.001679	0.016164	76
	2.2	3.788292	0.00073	0.022124	75
	-	-	-	-	-
	2.0	5.446174	0.001203	0.020045	52
	2.0	8.99999	0.005998	0.020154	139
	2.2	3.039266	0.002	0.022011	105

C.6 X-ray Data

Table C-5: X-ray data for medical students.

Participant	*X-rays taken*	*PA*	*Lateral*	*Distribution plate/screws (PA/lateral)**
1	16	6	10	5/5, 1/5
2	14	7	7	1/1, 6/6
3	6	1	5	1/1, 0/4
4	4	1	3	1/1, 0/2
5	7	4	3	4/3, 0/0
6	6	3	3	1/1, 2/2
7	11	4	7	3/6, 1/1
8	7	2	5	2/1, 0/4
9	6	3	3	2/2, 1/1
9 - Second try	10	3	7	3/3, 0/4
10	10	4	6	3/2, 1/4
12	7	3	4	1/1, 2/3
12	9	4	5	2/2, 2/3
13	4	1	3	2/2, 0/2
14	8	3	5	2/2, 1/3

*: For example, 2/1, 0/4 indicates that two PA and one lateral X-rays have been taken during plate application, and zero PA and four lateral X-rays have been taken during screw insertion.

Appendix D

Interview and Internet Survey Questions

D.1 Functionality Requirements Study

D.1.1 Interview Questions for Medical Participants

Table D-1: Interview questions for medical participants.

Demographic	Can I confirm your name and title (age and nationality, m/f)?
	What is your position/job title?
	How long have you worked in this position and where did you get your training?
	How many surgeons are practising in your medical field (country, regions, counties, canton)?
General questions	What are the current methods of training surgeons in hand surgery (in which country)?
	Have you already used or are you using surgical simulators for training of surgical procedures: In hand surgery? In other medical domains?
	If yes, did/do you like it and why?
	What is the acceptance of surgical simulators by surgeons?
	From your point of view, does the use of surgical simulators for training purposes lead to higher patient safety?
	If you had a surgical simulator, what would you do with it: In the next month? In four years?
	What amount of time does it take to incorporate such a simulator into the existing training concept, or to create a new training concept?
	What are the regulations for using surgical simulators for the training of surgeons?
	Do you know the AO Surgery Reference website from the AO Foundation?
	Which surgical procedures are the most common in your medical domain?
	Which scenario/approach/surgical procedure should be implemented at first?
	Which others are important as well?
	What are the different stages of the surgical procedure in question 15?
	Which stage(s) of this surgical procedure would be the most valuable for training?
	What surgical instruments are needed for this surgical procedure?
Functionality: visualisation	If you have already used surgical simulators, do you prefer surgical simulators using a 2D or a 3D visual representation?

	Which objects should be shown in the surgical simulator?
	If not all objects can be shown in the simulator, which three can be omitted?
	What minimal level of detail is needed for that objects?
	Do different stages of the surgical procedure require different levels of detail?
	How should surgical instruments be visualised?
Functionality: navigation	How and why should the anatomical structures in the surgical simulator be moved?
	Which navigation paradigm is appropriate for moving the anatomical structures?
	What input device(s) would you use for navigation?
Functionality: displaying information	Would you benefit from information shown in the surgical simulator, such as suggested nail length or thickness of cortical bone?
	If yes, where, how much, how and what information should be shown?
	What is the value of such real-time information?
Patient-specific data	Would the surgical simulator benefit from using patient-specific data?
	What is the value of patient-specific data for training purposes?
	Is there a major difference between generic and patient-specific data?
Evaluation	Should this surgical simulator provide evaluation functionality?
	How can the performance of surgeons in the surgical simulator be measured?
	Which evaluation parameters are required for benchmarking?
Environment	Where would you place and use the surgical simulator?
	Are there any (research) questions not been covered by this interview?

D.1.2 Interview Questions for Technical Participants

Table D-2: Interview questions for technical participants.

Demographic	Can I confirm your name and title (age and nationality, m/f)?
	What is your position/job title?
	How long have you worked in this position and where did you get your training?
General questions	Have you already used virtual reality-based simulators for training or education purposes?
	If yes, did/do you like it and why?
Functionality: visualisation	If you have already used virtual reality-based simulators, do you prefer simulators using a 2D or a 3D visual representation?
	What minimal level of detail is needed for that objects?
	How should surgical instruments be visualised?
Functionality: navigation	How and why should the anatomical structures in the surgical simulator be moved?
	Which navigation paradigm is appropriate for moving the anatomical structures?
	What input device(s) would you use for navigation?
Functionality: displaying information	Would a surgical simulator benefit from information shown in the surgical simulator, such as suggested nail length or thickness of cortical bone?
	If yes, where, how much, how and what information should be shown?
	What is the value of such real-time information?
Patient-specific data	Would the surgical simulator benefit from using patient-specific data?
Evaluation	Should this surgical simulator provide evaluation functionality?
	How can the performance of surgeons in the surgical simulator be measured?

	Which evaluation parameters are required for benchmarking?
Environment	Are there any (research) questions not been covered by this interview?

D.1.3 Internet Survey Questions

Table D-3: Internet survey questions.

Demographic	Can I confirm your name and title (age and nationality, m/f)?
	What is your position/job title?
	What is your experience in hand surgery and in orthopaedic surgery (in years)?
Training and surgical procedures	What are the current methods of training surgeons in hand surgery in the UK or where you got your training (state if not UK)?
	Have you already used or are you using surgical simulators for training of surgical procedures in hand surgery? (Which products?)
	Have you already used or are you using surgical simulators for training of surgical procedures in other medical domains? (Which products?)
	If yes, did/do you like it and why?
	What is the acceptance of surgical simulators by surgeons?
	From your point of view, does the use of surgical simulators for training purposes lead to higher patient safety, less compilations?
	What amount of time does it take to incorporate such a simulator into an existing training concept or to create a new training concept?
	What are the regulations for using surgical simulators for the training of surgeons?
	Which surgical procedures are the most common in your medical domain?
	For which approach/surgical procedure should a surgical simulator be created at first?
	Why is it important to have a simulator for the chosen approach/surgical procedure?
	Which others are important as well?
	What are the different stages of the selected surgical procedure?
	Which stage(s) of this surgical procedure would be the most valuable for training purposes?
	What surgical instruments are needed for this surgical procedure?
Functionality	Which objects should be shown in the surgical simulator?
	If not all objects can be shown in the simulator, which three can be omitted?
	How should surgical instruments be visualised?
Displaying information	Would you benefit from information shown in the surgical simulator, such as suggested nail length or thickness of cortical bone?
	If yes, where, how much, how and what information should be shown?
	What is the value of such information shown in real time?
Patient-specific data	Would the surgical simulator benefit from using patient-specific data, for example for the bone?
	What is the value of patient-specific data for training purposes?
	Is there a major difference between generic and patient-specific data?
Evaluation	Should a surgical simulator provide evaluation functionality?
	How can the performance of surgeons in a surgical simulator be measured?
	Which evaluation parameters are usable for benchmarking?
Environment	Where would you place and use the surgical simulator?

D.2 Medical Evaluation

Table D-4: Medical evaluation questions.

Interview questions for medical experts	Can I confirm your name, age and nationality (m/f)?
	What is the value of the recorded parameters and the video?
	What is the advantage/benefit/impact when using this surgical simulator in the current education curriculum?
	How could the simulator be used in the medical curriculum?
	What would be justifiable initial system cost of such a simulator?
	Discussion of usefulness of the information which can be enabled and disabled.
	Discussion of automated feedback which should be provided to users when the training is finished.
	What improvements do you suggest?
	Is there any information that is missing to complete a task or the medical scenario?
	Would you like to add something?
Interview questions for young doctors	Can I confirm your name, age and nationality (m/f)?
	What do you think about the surgical scenario?
	What can be the benefit/impact when using this simulator to the current training?
	How can it be integrated into an existing curriculum?
	Would you use it to train other procedures in the same manner?
	Discussion of usefulness of the information which can be enabled and disabled.
	What can be the possible intended use?
	Did you enjoy using it (on a scale of 1 to 5)?
	Would you like to add something?
Interview questions for medical students	Can I confirm your name, age and nationality (m/f)?
	In which term of your medical course are you?
	Did you already have an introduction into plate osteosynthesis?
	Have you found the training to be enjoyable and practical?
	Did you have enough information provided by the guided walk-through?
	Was the user interface clear and understandable, did you get where to select which type of plate or screw?
	Was the notification and message system clear and understandable?
	Discussion of usefulness of the information which can be enabled and disabled.
	Do you feel capable of describing the particular steps needed to treat a distal radius fracture? Why not?
	Would you use this simulator to learn this procedure? If not, why?
	Would you use such a simulator to train different procedures in a similar way?
	What improvements do you suggest?
	Is there any information that is missing to complete a task or the medical scenario?
	How was the haptic feedback during plate application, drilling and inserting the screw?
	Did you enjoy using it (on a scale of 1 to 5)?
	Do you have further questions or remarks?