# *Overview of Virtual Reality Technology for Surgery Training*

## Bachelor Thesis 1

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# Overview of Virtual Reality Technology for Surgery Training

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**ABSTRACT**

Surgery training followed its most common teaching principle, called "see one - do one - teach one" for more than a century. This training models' is simple and reasonably effective, however its efficiency is questioned, since operating room (OR) time is expensive and limited in time. The most realistic training models besides humans are animals, however this training model is expensive and controversial. The alternative are box trainers, simulators consisting of a training box, laparoscopic instruments, a camera and light source, that allow practicing basic tasks. Nonetheless, their simulations are often poor imitations and they are hard to customize to the trainee's needs. It is expected, that the development of new teaching methods reduce healthcare costs and accelerate learning curves of the surgeons. Virtual reality (VR) simulators have been introduced over the last decade. Their advantages are, that they provide an ethically suitable training method, that training scenarios can be selected in with respect to the trainees needs, the surgeon's performance can be measured, and complex surgical procedures can be practiced as often as needed. Several studies were found, that verified the effectiveness, of surgery simulation in VR, in training surgeons. VR surgery simulators have a wide field of application, from training specific technical tasks and procedures, to improving the coordinated teamwork of the whole operating team. Additionally, surgeons can use VR simulators as a warm-up before performing an actual surgery. The paper gives an overview of the effectiveness of surgery training in VR, give an insight on different application areas of VR simulation in surgery. Additionally an overview of the development of an VR surgery simulator will be given.

## 1 INTRODUCTION

Surgical training has traditionally followed the apprenticeship model: In small groups of peers and superiors, novice surgeons got trained. This process has not changed considerably throughout medical history. The most common and often the only setting where practical training is accomplished, involves the operating room (OR) and the patient. By observing experienced surgeons in action, novice surgeons acquire different skills. As their training advances and skill levels increase, trainees perform additional procedures, under diverse degrees of supervision (Basdogan et al. 2007, 1).

This principle called "see one - do one - teach one", showed to be simple and reasonable effective for more than a century. However, in order to provide patients with safe, evidence-based care and adequately train surgical residents, this teaching method needs to evolve with current changes in the medical system (Kotsis and Chung 2013, 1).

This training models efficiency is questioned. In 1999 a report from the Institute of Medicine of the National Academy of Sciences ("To Err is Human"), states that the number of deaths after medical mistakes each year is higher than the number of deaths in highway accidents, breast cancer or AIDS. The main reasons are inexperienced beginners, as well as the inexperience of experts with new surgical techniques and rare medical situations (Basdogan et al. 2007, 1).

OR time is expensive and only limited time is available for training surgeons (Basdogan et al. 2007, 1-2). Developing methods, that improve surgical performance for trainees and practicing surgeons is of significant importance. It is expected, that those methods reduce health care costs and accelerate learning curves of the surgeons, as well as ensure that reductions in duty hours for trainees do not lead to declining surgical education (Zhan 2003, 2), (Kohn, Corrigan, and Donaldson 2000, 1).

The most realistic training models available are animals. Animal's tissues respond similarly to applied forces as human's tissues. However, using animals for training is expensive since it requires expensive dedicated facilities. Additionally, this method is controversial, since the training session usually ends with euthanizing the animal (Basdogan et al. 2007, 2).

The alternative are box trainers, simulators consisting of a training box, laparoscopic instruments, a camera, and light source. Box trainers allow practicing basic tasks, including peg transfer, pattern cutting, clipping and dividing. They provide an environment that is similar to real surgery settings, but simulated surgical procedures are more often than not poor imitations of real surgeries. Box trainers are hard to customize to the trainee's needs, and their performance is not easy to measure. Both of these training methods suffer from the same disadvantages: an instructor or supervisor is needed and the trainee's performance is hard to evaluate (Basdogan et al. 2007, 2).

Physicians have used minimal invasive surgery (MIS) in various procedures since the early 1960s. MIS basically involves a small video camera and customized surgical instruments. Those get inserted into the body by the surgeon, through small skin incisions or natural orifices. Intern cavities can be explored without making large openings. Major advantages over conventional surgery are a shorter hospital stay, a quicker return to activities, and less pain and scarring (Basdogan et al. 2007, 1).

The introduction of MIS was the initial step towards simulation-based training. The "see one - do one - teach one" principle could no longer be effectively applied, since the novices could not observe what the surgeons were doing. Box-trainers were the first simulators, where surgeons were able to practice their skills on synthetic or inanimate models of human organs. Using actual endoscopic tools, the surgeons can acquire fundamental surgical skills, including hand-eye coordination and perception of depth of field. The tool-tissue interaction of those box-trainers provides realistic force feedback, which leads to a better training experience. Disadvantages are, that the training models need to be replaced by new ones after each trial. Additionally, the surgeons performance is hard to measure (Yaron Munz et al. 2007, 1).

Virtual reality (VR) simulators have been introduced as an alternative learning method for training in MIS over the last decade. 3D anatomical structures are displayed on a 2D monitor with which the trainee is able to interact. Those VR systems use highly sophisticated multisensory equipment, advanced computer graphics and physics based modeling techniques in order to provide realistic surgical scenarios (Mohammadi et al. 2010, 1).

VR simulators have the advantage that training scenarios can be selected in regard to the trainees needs. Further more, data can be measured in real-time and provide information on the surgeons performance.(Gor et al. 2003, 1) However, VR simulators often lack of realistic representation of organs and tasks, and are not providing a moderate sense of haptics during interaction. Additionally, VR-based training requires significant financial investment (Palter and Grantcharov 2010, 1).

This paper will focus on the effectiveness of surgery training in VR and if those simulations are reasonably effective in training surgeons. Additionally it will give an insight on different application areas of VR simulations in surgery. Furthermore the development of an VR surgery simulator will be explained.

## 2 The benefit of virtual reality training

Since flight simulator training has reduced costs and improved the expertise of pilots, virtual reality surgery training promised similar results (S. Haque 2006, 2). And indeed, the improvement of surgeons performance after VR training is proven (Seymour et al. 2002, 1), (**"textcite** )[1]Ganai2007, (Grantcharov et al. 2004, 1), (Youngblood et al. 2005, 1), (Hamilton et al. 2002, 1), (Hyltander et al. 2002, 1).

Hikichi et al. (2000, 1) developed, that virtual reality surgical simulators help surgical students and residents to train complex surgical procedures, before entering the operating room. They developed a practical system of vitreous surgery using VR technology. Several virtual patient eyes with retinal diseases were created in order to provide a realistic simulation and operating environment. This allowed trainees to learn to maneuver the surgical instruments and avoid complications Hikichi et al. (2000, 1).

The meta-analysis of S. Haque (2006, 1) focused on two study dependent variables, that were collated and analyzed, the task completion time and the error score. The meta-analysis revealed that training on virtual reality simulators did lower the completion time of a given surgical task, as well as clearly differentiate between the varying skill levels of the users (experienced and novice trainees) (S. Haque 2006, 1).

Accurate diagnosis and planning of surgical procedures is provided for the students and practitioners by the representation of information in three dimensions. Complex surgical procedures can be practiced by the trainees over and over again. Additionally, uncommon emergency scenarios can be practiced, so that trainees would not encounter them for the first time without the required experience. Virtual reality is an ethically suitable alternative to the use of animal and cadavers. A supplementary advantage of VR simulators is, that they can provide objective assessments like such as the task completion time, the errors that were made during the process and the efficiency of the movements that were needed to accomplish the task (S. Haque 2006, 1). S. Haque (2006) reported the meta-analysis of the effectiveness of VR simulators, focusing on:

- The transference of skills from the simulated training environment to the operating room.
- The ability of simulators to differentiate between the experience levels of their user.

The test results, of the transference of skills from the simulated training environment to the operating room showed, that the VR trained group improved in task completion times. A significant effect size was found using the fixed effect model, it took them much less time to finish the task than the traditionally trained group. However, the heterogeneity indicated inadequacy of the analysis. In order to confirm the effect sizes, a reanalysis using the random effects model was undertaken. The found effect size of -2.175 (95%CI - 3.865, -0.485) is a statistically significant finding. The error score showed, that VR trained users committed comparable errors to those of the traditionally trained group. This indicates, that training with VR simulators is comparable (and even perhaps better) to the well-validated traditional techniques (S. Haque 2006, 3-4).

In order to demonstrate the transference of skills from the simulated training environment to the OR, Seymour et al. (2002, 1) and Ganai et al. (2007, 1) used proficiency based, Grantcharov et al. (2004, 1) and Youngblood et al. (2005, 1) used repetition based, and Hamilton et al. (2002, 1) and Hyltander et al. (2002, 1) used time based training models. This six studies all randomized their subjects into VR training and control study groups. All six studies resulted in improved performance of the VR simulator trained groups.

Since there are no widely accepted norms for defining an adequate control group, it must be appreciated that the control groups characteristics might affect the results of the study to a great extend. An alternative to randomized trials of the type characterized as "VR-to-OR" might be using the correlation of performance in VR with contemporaneous performance in a gold standard training lab test, such as an objective structured assessment of technical skill evaluation (OSATS (Martin et al. 1997, 1)) (Seymour 2008, 6).

S. Haque (2006, 4-5) tested the simulators ability, to differentiate between the users experience levels, and showed that the task completion time had significant effect size, when using the fixed effect model. In order to confirm that finding, reanalysis using the random effects model was undertaken. Both model's effect size values expose, that the time taken to complete a task, differs between the novices and the experienced users. Additionally, the results show that the simulator is realistic and the measurement criteria appropriate, as otherwise the groups would not be so clearly differentiable.

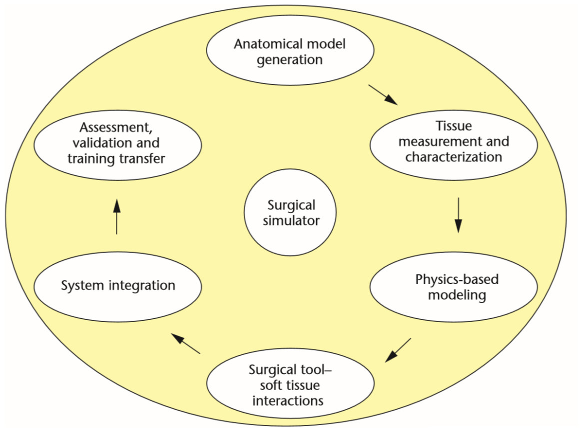


Figure 1: Simulator development steps for MIS (Basdogan et al. 2007, 2).

Furthermore they revealed, that the measurement criteria are appropriate. The measured effect size of the error score was highly heterogeneous. Since no obvious subcategories could be found, reanalysis with a random effects model was undertaken. The results revealed that the novices committed far more errors, than the experienced users (S. Haque 2006, 4-5).

## 3 Technical Requirements

Developing a VR-based simulator is a multidisciplinary field and requires expertise in different regions: Systems engineering, materials engineering, robotics engineering, biomedical engineering, computer science, medicine.

As seen in Figure 1 (Basdogan et al. 2007, 2), the development of a VR-based MIS simulator can be subdivided in six steps. At first, to generate a 3D anatomical model of organs from medical images, segmentation and reconstruction techniques of computer vision and computer graphics are used. Then the material properties of soft tissues are measured and characterized. These need to be integrated in organ-force models. To simulate the real-time interactions of simulated surgical instruments and manipulated organs, the next step is developing collision detection and response techniques. Then, a complete system is formed, consisting of hard and software components. Last, user studies are executed to validate the system (Basdogan et al. 2007, 2).

### 3.1 Anatomical model and training-scene generation

Anatomical techniques are required for generating anatomical models, such as computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound. Ultrasound suffers from a lower image quality compared to CT and MRI, and is therefore not suitable for anatomical modeling. The differences between CT and MRI are the spatial resolution, and their ability to distinguish different tissue types. Surface models or volumetric rendering are used, in order to build 3D models of organs from image data (Basdogan et al. 2007, 2-3).

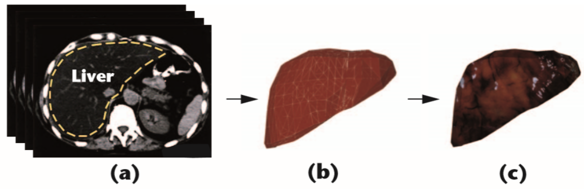


Figure 2: (a) A set of 2D medical images is segmented. Different tissue regions, lesions and pathologies get identified. (b) a 3D surface model is created out of the segmented contours. (c) A texture gets mapped over the surface to provide a realistic appearance of the model (Basdogan et al. 2007, 3).

Generating the surface models, that represent the external border of the organs, requires extraction of the structure's outer surface. Therefore simple segmentation algorithms, that provide the outer contour, are used, such as thresholding and region growing. With these methods, the isocontours, that serve as input to the marching cubes algorithm, gets extracted. The marching cubes algorithm creates a polygonal representation of the surface. An example of the segmentation and generation of a 3D surface model is shown in Figure 2 (Basdogan et al. 2007, 3).

Cagatay Basdogan et al. (2007, 3) show an alternative way, where the organ surfaces are extracted to use active contour models. The contour is received by adjusting splines, that fit the structure's outer surface. A physical description of the image datas external and internal forces is therefore used. The process, called boundary tracking, applies those found contours in one 2D slice, to the next neighboring slice, and starts a contour that is gradually refined. The organ's 3D contour and its surface representation get created that way.

The advantages of generating surface models from medical images (CT/MRI) are the reduction in data size, and the created triangulated meshes can be displayed using hardware acceleration of graphics boards. Direct volume rendering, like ray casting, is an alternative to surface modeling and surface data visualization. It provides high-resolution visualization, but it is slow (Basdogan et al. 2007, 3).

Textures are applied to the model's surfaces, in order to provide realistic appearance of the model (Figure 2 (c)). These textures are created by direct texture painting, or by mapping real volumetric data to surfaces (Reinig et al. 1996, 1).

### 3.2 Soft tissue measurement and characterization

Realistic organ-force models are needed, in order to provide realistic representations of soft tissues, that react to force and display accurate displacement. The material properties of organs must be measured in living condition in their native location. Incorrect material properties could lead to adverse training effects (Basdogan et al. 2007, 3).

Soft tissues show complex, nonlinear, anisotropic, non-homogeneous behavior. And since tissues are layered, each layer consists of varying material combinations. There are basically two types of measurement methods: ex vivo and in vivo (Ottensmeyer 2001, 1). Ex vivo measurement means, the measured tissue is dead and they can take place in or outside

the body. In vivo measurement takes place in living organisms, therefore mostly noninvasive tissue measurement like CT, MRI or ultrasound is used.
Researchers use standard material testing methods, such as tension or compression tests, for ex vivo measurements outside the body. However, the results can be misleading, because dead organ and muscle tissues stiffen over time.
Soft-tissue measurements distinguish in three levels of tissue damage: invasive, noninvasive and minimally invasive. Invasive measurement methods enter the instruments into the body through a puncture or an incision. Noninvasive tissue measurement methods (CT, MRI, ultrasound) require no incisions. Minimally invasive tissue measurements only require only small incisions. This is causing less tissue damage than invasive methods (Basdogan et al. 2007, 4).

### 3.3 Physics-based modeling

A system that reflects stable forces to the user and displays realistic smooth deformations in real time is required for developing realistic organ-force models (Basdogan et al. 2007, 1).
Developing real time, realistic organ-force models is challenging, because of the material properties and organ tissue structure. Additionally dynamic effects and contact between organs are difficult to simulate. Currently there are 2 physics-based approaches, mesh-free methods and mesh-based methods. The mesh-free approach uses vertices only for deformation and force computations. Mesh-based methods are generally more accurate, because this methods consider the deformable object a continuum(Basdogan et al. 2007, 4).
There are different mesh-based methods.

- finite-element method (FEM)
- boundary element method (BEM)
- long-element method (LEM)
- tensor-mass model (TMM)

FEM (Basdogan et al. 2007, 4) considers the organ as a continuous body, that is trying to minimize it's potential energy when being influenced by external forces. The geometric model gets divided into surface or volumetric elements. Then each element's properties get formulated, and the elements get combined to compute the deformation. FEM has the advantages (Sedef, Samur, and Basdogan 2006, 1), that it uses continuum mechanics, and is based on a solid mathematical foundation. An additional benefit is, that this method does not require many material parameters (Basdogan et al. 2007, 4). Drawbacks of FEM are, as shown by Bro-Nielsen and Cotin (1996, 2), its heavy computational load and complexity.
BEM calculates displacements at the boundary with integral equations, after an object is discretized into elements and patches. However, it is computationally to expensive for real time execution (James and Pai 2001, 2-4).
LEM discretizes the object into 2D long elements. A long element can be compared to a spring fixed in one extremity and having the other extremity attached to a point in the movable object surface. A long element does not occupy real space and has no mass. The real space inside the solid is occupied by some incompressible fluid. Pressure, density and volume parameters are easy to identify. However LEM provides accurate outcomes only for small deformations (Costa and Balaniuk 2001, 1).
TMM discretizes the object into tetrahedrons. Tensors are stored on its edges, and mass is stored in its nodes as mass points. TMM can handle topological modification and its time complexity is linear (Delingette, Cotin, and Ayache 1999, 2-5).
Two basic mesh-free methods are

- MSM (mass-spring model)
- PAFF (point-associated finite-field)

MSM represents each point by its own position, velocity and acceleration. The points move by applying inertial and damping forces. MSM allows real time execution, but the integration of tissue properties into particle models is problematic (Basdogan et al. 2007, 5).
PAFF is a point-based approach, that uses only the nodes of the 3D object to perform computations for displacement and force influence. This method is computationally intensive, but supports the simulation of large deformations and topology modifications in real time (De et al. 2006, 1).

### 3.4 Simulating tool-tissue interactions

3D graphical models, that are consisting of polygons, of surgical tools are rendered in their exact dimensions and shape, in order to provide a realistic visual representation. However, to speed up collision detection between instruments and organs, it is assumed that the surgical tools consist of a set of geometric primitives (points, lines). In order to render force interactions between instruments and organs, collision detection algorithms are used to achieve real time update rates (Basdogan et al. 2007, 4-5).
In ray-based haptic interaction models, the probe consists of a finite line segment. When checking for collisions between the line segment and the objects, the line segments alignment gets taken into account by the collision detection algorithm. As additional feedback for the user, the forces are not only visualized, but can also be felt with an appropriate haptic device. Users can feel coupling moments that occur between the instrument and 3D organ models. They can detect side collisions between the instrument and organ models. Users can also detect collisions with organs internal layers, by rendering multiple tissue layers. And users are able to touch and feel multiple objects simultaneously (Basdogan et al. 2007, 5).
Once a contact between an instrument and tissue is detected, realistic graphical and haptic display of tissue behavior is the response. The response can vary depending on the instrument and the chosen surgical task that should be performed. The most basic collision response is tissue deformation. Tissue deformation is involved in the simulation of many basic surgery skills, such as palpating, grasping, stretching, translocating and clip applying. The simulation of surgical cutting falls into a different category, the tool-tissue interactions modify geometry and the underlying model. Surgical cutting included surgical skills like transsection (cutting across), dissection and coagulation. In Figure 3, several of these simulated interactions are shown (Basdogan et al. 2007, 5).

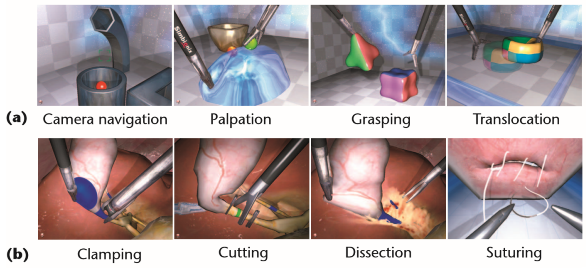


Figure 3: Simulations of MIS tasks. (a) basic tasks. (b) advanced skills(Basdogan et al. 2007, 5).

### 3.5 System integration

A VR surgical simulator is a human-computer interface that aims to provide a realistic training environment. Trainees should act in this environment as if they are operating on an real patient. There are basically 2 types of training systems, part-task trainers and full-task trainers (Basdogan et al. 2007, 7).
A part-task trainer focuses on one particular surgical task. It's hardware components usually consist of a computer with a 3D graphics accelerator, force feedback devices and auditory interfaces. During the simulation the auditory interface is used to give guidance. The trainee manipulates organs with real surgical instruments, that are attached to force feedback devices (Basdogan et al. 2007, 7).
A full-task (team) trainer is able to train additional trainees at the same time in a simulated OR. Sensors and mechanical actuators are positioned around the operating table and the mannequin (Basdogan et al. 2007, 7).
Usually hierarchical data structures (storing object properties), client server model, multithreading and multiprocessing programming techniques (to separate visual and haptic servo loops) are necessary to integrate a task trainer's software components. Each sensory loop has its own requirements, and needs a central processing unit accordingly. If a multithreading architecture is used, each sensory modality can have its own thread assigned. Threads can have priority levels attached. They can as well share the same database, but this requires synchronization in data access. This is important for accomplishing real-time update rates of graphical and haptic rendering. But there is a trade-off between realism and real-time performance nonetheless(Basdogan et al. 2007, 7-8).

## 4 A SHORT HISTORY OF VR SIMULATORS

In order to categorize simulators Maran and Glavin (2003, 1) uses the term "fidelity", that describes the realism or learning experience, provided by the simulator. Fidelity basically declares, whether a simulator represents what it is trying to represent (Maran and Glavin 2003, 1).

### 4.1 Low fidelity simulators

Since it is based on abstracted graphics, one of the first virtual reality surgery simulators was the MIST (minimally invasive surgery trainer) VR system. It was developed by Wilson et al. (1997) as part of a joint venture between the Wolfson Centre and VR Solutions in 1997. The MIST VR system provides a realistic environment and allows trainees to perform tasks using standard laparoscopic instruments. The system consists of a PC with a 200 MHz CPU and 32 Mb RAM. Linked to the PC are two laparoscopic instruments. The instruments have 6° of freedom, and their movement is translated in real-time (Figure 4). The operating volume of 10 $cm^3$ displayed as a 3D cube on the computer screen. In order to provide a variety of difficulties, the overall image size and the sizes of the target objects can be changed. Targets are randomly positioned in the 3D cube that represents the operating volume. The MIST VR system has different modes available: Tutorial, training, examination, analysis, configuration. To simulate basic functions, six tasks were designed. They simulate basic manoeuvres that are performed during a laparoscopic cholecystecomy (Figure 5). In order to learn a particular skill, users can refer to video demonstrations at any time. To simulate different operations, that require different skills with medical instruments, the system software can be adapted (Wilson et al. 1997).
After the completion of a task, data analyses, such as accuracy, errors and completion time, can be displayed. Training sessions and trainees can be compared. This quantification of performance was a powerful new tool for surgical training. The MIST VR system was reasonably priced and commer-

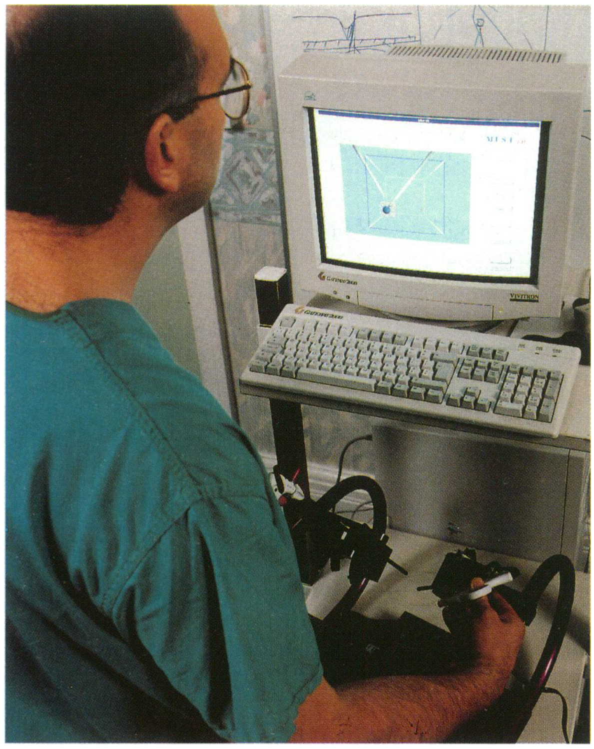

Figure 4: The MIST VR system: two laparoscopic instruments on a jig with motion-detecting potentiometers linked to the PC (Wilson et al. 1997).

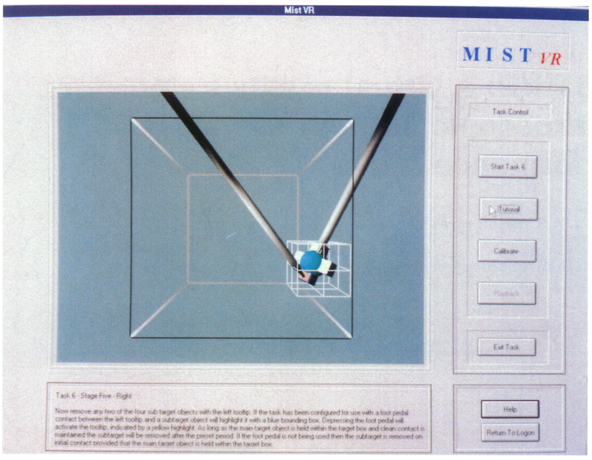


Figure 5: An example of a complex task. The ball is grasped by one instrument and then passed to a second instrument. Then it is placed and held in a randomly positioned graphics 'cage'. The first instrument gets revoked from view and exchanged for another medical instrument, a diathermy tool tip. Next, nodes appear on the ball. They disappear after contacting them for a few seconds using a foot pedal control (Wilson et al. 1997).

cially available at that time. It used a high-end PC and was portable (Wilson et al. 1997).
Since it showed not to enhance training, the MIST VR system set the appearance of virtual organs aside, and is based on abstracted graphics. This has the advantage, that the system runs on an affordable computer. Additionally it makes the system multidisciplinary since it can be used for acquiring different skills with using the same training environment (Wilson et al. 1997).

### 4.2 High fidelity simulators

Simulators that focused on a high fidelity, using a visually realistic training environment are the LapSim (Surgical Science, Gothenburg, Sweden), the Lap Mentor (Simbionix, Chicago, USA) and the ProMIS VR simulator (Haptica, Dublin, Ireland). The LapSim laparoscopic simulator was developed in 2000 (Hart and Karthigasu 2007, 2). In 2010, it was the most commonly used VR surgery simulator. It consists of two medical instrument grips, a foot pedal (diathermy pedal) and a PC with Windows XP with the LapSim software installed (Maschuw, Hassan, and Bartsch 2010, 1). The basic skill training modules of the LapSim simulator are similar to the MIST VR trainer. Additionally, the LapSim simulator introduced tasks such as "clip and cut" and "suture" that are more relevant to surgeons. Those tasks were visually realistic, using tissues that could be manipulated and could bleed. The LapSim was one of the first VR simulators that allowed practicing parts of operations (Hart and Karthigasu 2007, 3). The system allows three different degrees of difficulty. In order evaluate the trainees simulation performance, following parameters are measured:

- Completion time (s)
- Damage through dilation (%)
- Loss of blood (ml)
- Instrument navigation (m)
- Angulation (degrees)
- Lost clips (n)
- Insufficient placed clips (n)
- Segments that are not reached by clips (n)
- Number of tissue compressions (n)
- Size of the tissue compressions (mm)
- Lack of focus (mm)

(Maschuw, Hassan, and Bartsch 2010, 1-2)
In 2002 the LAP Mentor surgery simulator was developed. In contrast to previous simulators, it divides modules into abstract tasks, procedural tasks and full length operations. Additionally, this simulator combines the extensive range of procedures with advanced haptic feedback hardware. Since it is present in the operating room, haptic feedback is an important part of VR simulation training. Resistance is transmitted when tissues or objects are encountered during a simulated task (Andreatta et al. 2006, 1). This provides realistic simulations, and therefore it is widely used for training of surgical trainees (Aggarwal et al. 2009, 1).
The ProMIS VR simulator combines VR technology with traditional box trainer simulation, and was developed in 2002 as well. The laparoscopic is included in a traditional box trainer. In order to track the motion of the laparoscopic instruments from three different angles, the box trainer contains three cameras (Van Sickle et al. 2005, 2). The ProMIS VR system provides six modules to train laparoscopic skills (Carter et al. 2005, 3). It has abstract tasks as well as procedural tasks. In order to measure and analyze the surgeons performance in real-time, the instruments are tracked in 3D space. On completion of a task, the trainee is given immediate feedback with summary of their metrics. The measured metrics include completion time, path length, economy of movement, hand dominance and task specific errors (Lewis et al. 2011, 2). Additionally, the trainee is able to view a graphical replay of their performance (Van Sickle et al. 2005, 2).

### 4.3 Modern simulators

Traditional surgical simulations have aimed to train procedures and tasks that are likely to be encountered in the operating room. However, modern advances in technology have enabled the development of a new kind of simulators: They simulate complex surgeries and replicate unique anatomical variations and disease states of actual patients (Vakharia, Vakharia, and Hill 2016, 1). Since surgeons are able to practice the specific surgery they will be performing later, these patient-specific surgical simulators provide a really high level of fidelity (Badash et al. 2016, 1). Using patient imaging

data in a VR surgical simulator is another way to practice a procedure preoperatively. The risk of human error could be reduced, when using anatomically accurate VR simulations with patient-specific anatomy. Additionally this allows the visual communication of the surgical plan with the team members as well as the patients (Endo et al. 2014, 1-2, 6-7).
Newer technologies, including increasing resolution of cameras, higher speeds of internet connectivity and the introduction of augmented reality (AR), allow surgeons to collaborate remotely. One systems that provides remote surgical cooperation is VIPAR (Mahesh B Shenai et al. 2011, 1). It allows projecting the visual field of a surgeon in one location to a simulation to a surgeon elsewhere. This can be used for guiding the operating surgeon in real time by a more experienced surgeon. Additionally the overall surgical approach can be discussed by participants at different locations (Mahesh B. Shenai et al. 2014, 1).

## 5 Application areas

The following chapters focus on the different application areas of VR surgery training, including methods to train specific MIS tasks, team training and surgery warm up with VR.

### 5.1 Minimally Invasive Surgery

Since time and resources to train surgeons are increasing, finding innovative ways to teach surgical skills outside the operating room is important. Virtual reality training has been proposed as a method, that allows instructing surgical students and evaluate their psychomotoric skills (Gallagher et al. 2004, 1, 5). One application area for VR surgery simulation is task training in minimally invasive surgery (MIS).
Gallagher et al. (2004, 2-3) compared the performance of 100 novices to that of 12 experienced and 12 inexperienced laparoscopic surgeons. Each participant completed six tasks on the Minimally Invasive Surgical Trainer - Virtual Reality (MIST-VR). Their performance was measured through the time needed to complete all six MIST-VR tasks, number of errors, economy of movement of the right instrument, economy of movement of the left instrument and economy of diathermy use during tasks five and six. All tasks were completed five times per trial for each hand. The economy of movement was measured for each hand separately, and was defined as the ratio of the overflow distance traveled and the optimal distance (Gallagher et al. 2004, 2-3).
The outcome of the study showed, medical students had significant improvement in each metric with each trial. Additionally the variability of the measured performance was reduced with each trial. Overall, the medical students quickly climbed the learning curve. The completion times of the medical students improved with each trial. In measurements of error and economy of movement of the right hand, there was no difference among the groups (medical students, novices, less experienced surgeons, experienced surgeons). The measurements of economy of movement of the left hand showed a difference between medical students and the experienced group for trial one. The medical students performed similar to the experienced group of surgeons on the economy of diathermy and scored slightly better then the less experienced group on all three trials (Gallagher et al. 2004, 3-4).

In order to compare VR training to other MIS training methods, Gurusamy et al. (2008, 2) included randomized clinical trials, that assessed the effectiveness of VR training compared with video training or no training or standard laparoscopic training in his systematic review of randomized controlled trials on the effectiveness of virtual reality training for laparoscopic surgery. The resulting data was extracted for following components:

- time taken to perform the evaluation task on the simulation model (after training)
- operating time (after training)
- error score
- number of undesirable movements
- accuracy
- improvement in task performance

(Gurusamy et al. 2008, 2)

#### 5.1.1 Virtual reality compared to video trainer training

The time taken to perform the job or speed with which the job was completed showed no statistically difference between the two training methods (Gurusamy et al. 2008, 3). It showed no difference between the two training methods. The comparison of the composite score showed no difference as well (Y. Munz et al. 2004, 6), (Madan and Frantzides 2007, 3). However, the VR training group indicated statistically significantly better accuracy than the video trainer group, a similar result was reported by Jordan et al. (2001, 3-4). Additionally the VR trained group tended to perform shorter distance movements and a smaller number of them for both hands (Y. Munz et al. 2004, 7).

#### 5.1.2 Virtual reality compared to no training

The time taken to perform the job favored the VR training group. They overall performed the tasks more quickly than the group without training (Y. Munz et al. 2004, 6), (Madan and Frantzides 2007, 3), (Tanoue et al. 2005, 4-5). The VR training group scored lower error scores than the other group. However, the results were not statistically significant in the trials of Y. Munz et al. (2004, 6) and Madan and Frantzides (2007, 3) and in the third trial the significance was not known (Tanoue et al. 2005, 4-5). The accuracy was only reported by one trial, which showed statistically significantly better accuracy in the VR trained group (Gallagher et al. 1999). There was a trend towards increased composite scores in the VR group compared with the no training group (Lucas et al. 2008, 2-3). The number of movements decreased significantly (Rajesh Aggarwal et al. 2007, 4-6), (Torkington et al. 2001, 2) and the distance of the right hand movements tended to decrease (Torkington et al. 2001, 2) compared with the no-training group. The left hand indicated a trend towards a decreased number of movements and distance of movements (Torkington et al. 2001, 2).

### 5.1.3 Virtual reality compared to standard laparoscopic training

The only patient-oriented outcome included, showed no statistically significant difference in the rate ratio for conversion between the VR trained and the SLT group (Ahlberg et al. 2007, 6). In all three duration reporting trials, the operating time was lower in the VR group than in the standard laparoscopic training (SLT) group. The error scores where statistically significantly lower in the VR group than in the SLT group (Grantcharov et al. 2004, 4), (Seymour et al. 2002, 2-3), (McClusky et al. 2004), (Ahlberg et al. 2007, 5-6). The VR trained group additionally improved in the economy of movement (Grantcharov et al. 2004, 4).

## 5.2 Surgery warm-up

D. et al. (2010, 1) and Lee et al. (2012, 1) stated, that the performance of surgical tasks, benefits of surgical simulation, that is executed immediately before those surgical tasks.
Surgery does not involve a prescribed warm-up or presurgical practice yet, although it requires intense pychomotoric and cognitive efforts. Especially for robotic surgery, the benefits of a warm-up can be important. Since the surgeon gets increased information presented through the visual monitor and has to process visual cues to derive forces applied by the tools, the cognitive arousal could profit of a warm-up (Lendvay et al. 2013, 1).
In order to explore the role VR robotic warm-up has on robotic surgery tasks, Lendvay et al. (2013, 2, 5) studied the impact of a VR robotic warm-up: Participants were randomized in one of two groups. The first group would receive a up to 5 minute VR warm-up. The other group would instead read a leisure book for 10 minutes. Then both groups would be performing robotic surgery tasks. The primary outcomes analyzed and compared are

- task time
- tool path length
- economy of motion (EOM)
- technical errors
- cognitive errors

In all trial sessions, the warm-up group performed a Pegboard Level 3 VR task (Figure 6), that took 3 to 5 minutes. In contrast to the proficiency curriculum, the error rate did not matter. In the meantime the other group spent 10 minutes on reading a leisure book. Session 4 became the FLS intracorporeal suturing task. It should demonstrate whether warm-up generalized to more complex and dissimilar tasks (Lendvay et al. 2013, 5).
To measure performance, the following metrics were chosen:

- Total task time (seconds).
- Cognitive errors (total count): rings placed on incorrect pegs, incorrect sequence of pegs.
- Technical errors (total count): dropped rings, peg touches.
- Tool path length (total distance traveled for instruments (mm).
- Economy of motion: path length/task time (mm/s).

During the 4th session, additional performance metrics were added based on FLS valdidation of the knot-tying exercise (Peters et al. 2004).

- Error: breaking the suture.
- Error: not placing the suture through the premarked entrance and exit spots.
- Error: gap left in suture knot (air knot).

In the study of Lendvay et al. (2013, 6-8), in session 1 to 3, where the performance with similar VR and criterion tasks was tested, the warm-up group improved compared to the control group. Lendvay and Colleagues observed a statistically significant decrease in task time (-29.29 seconds; $p = 0.001$; 95% CI, -47.03 to -11.56), as well as a statistically significant decrease in path length (-79.87 mm; $p = 0.014$; 95% CI, -144.48 to -15.25). Although not being statistically significant, the economy of motion, the cognitive errors and the sequence errors (placing the rings on incorrect pegs) favoured the warm-up group. Technical errors, as dropping rings or touching the pegs with the instruments, did not show statistically significant differences. In the 4th session, that was supposed to demonstrate if a dissimilar VR task can warm-up surgeons for a more complex task, no significant improvements, from the warm-up group, in task time, economy of motion, or path length, were observed. However, each error was reduced in the warm-up group individually, although not being statistically significant. Technical errors reduced to nearly 25%. Altogether, Lendvay and Colleagues demonstrated that VR warm-up, before executing a surgery, does improve task performance and error reduction (Lendvay et al. 2013, 6-8).
Additionally Lee et al. (2012, 1) showed, that laparoscopic warm-up decreases the operative times of experienced surgeons in the operating room.

## 5.3 Team training

Most of the focus in surgical simulation has been on task training of surgical skills. However, being an effective surgeon takes more than just technical skills. Successful operating room performance depends a lot on coordinated teamwork of the surgeon, anesthesiologist, nurses, hospital staff, and clinical information systems (Abelson et al. 2015, 1-2). As the importance of teamwork in the operating room was recognized, the development of simulations has shifted from training relatively simple surgical tasks to more sophisticated simulating environments (Aggarwal 2004, 2-4).
One troubleshooting module, was integrated into the modified ICE STORM (Integrated Clinical Environment; Systems, Training, Operations, Research, Methods) platform. In this scenario ("loss of laparoscopic visualization") the team was performing a laparoscopic cholecystectomy. Suddenly the laparoscopic monitor went dim, and it was the task of the surgeon to solve the problem (Abelson et al. 2015, 2).
The module was completed successfully, when the surgeon identified every critical element:

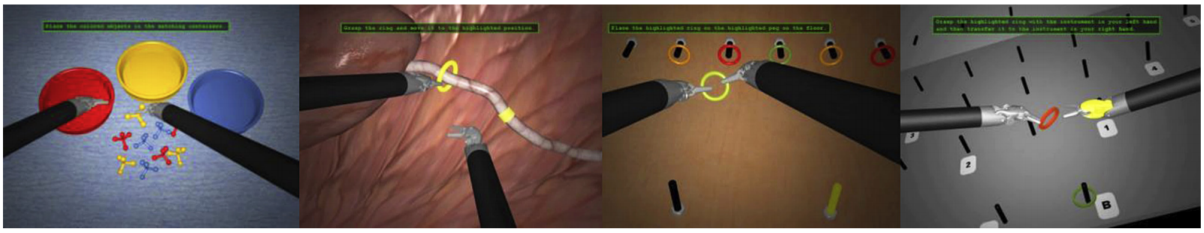

Figure 6: MIMIC dV-Trainer VR simulation modules from left to right. Pick and Place, Ring Walk Level 1, Pegboard Level 1, Pegboard Level 3 (Lendvay et al. 2013, 4).

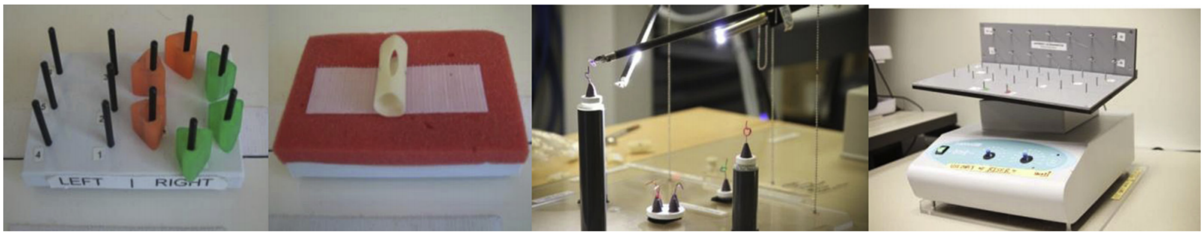


Figure 7: Da Vinci dry laboratory modules from left to right FLS block Transfer, FLS intracorporeal suturing (Task 4), Ring Tower, Rotating Rocking Pegboard (Task 1-3) (Lendvay et al. 2013, 5).

- The camera box and the camera cord had to be checked.
- The light-source box and the light-source cord had to be checked.
- The laparoscope had to be checked or replaced by a spare one.
- The camera had to be exchanged by a spare one.

The concept of this ”full cycle test” ensured, that all participants understand the most critical elements of the troubleshooting scenario (Abelson et al. 2015, 2).
A total of 33 participants completed the virtual simulation, including 26 trainees and 7 attendings. Overall, it took the trainees more time to complete the simulation than the attendings (271 vs 201 seconds, P = .032). The participants overall liked the simulator (median = 5, P = .00), and disagreed with the statement, that they disliked the simulator (median = 2, P = .000). They thought that the training environment was realistic (median = 5, P = 0.14) and did not find it difficult to communicate with the VR environment (median = 2, P = .000) (Abelson et al. 2015, 3-4).
Study participants did not feel that their performance would improve with the simulation (median = 4, P = .534) and they overall did not agree with the statement, that they would like to do VR training before going to the operating room (median = 4, P = .607). This could be caused by the short simulation session, and the limited scope of the pilot simulation. It may also be caused by the current lack of acceptance using VR simulation, and could change once VR simulation gains more traction (Abelson et al. 2015, 4-5).

### 5.4 Conclusion

The advantages of virtual reality surgery simulators are, that they provide an ethically suitable alternative to the use of animals and cadavers in traditional surgery training. Additionally they can save expensive and limited available operating room time (Basdogan et al. 2007, 1). Furthermore, surgical students and residents are able to learn to maneuver their surgical instruments, avoid complications and train complex procedures before entering the operating room (Hikichi et al. 2000, 1). More complex surgical procedures can be practiced as often as it is needed. Moreover, VR simulators provide objective assessments to measure the trainees performance, and trainees are able to view a replay of their simulation (S. Haque 2006, 1), (Van Sickle et al. 2005, 2).
VR surgery simulators can be categorized into low fidelity and high fidelity simulators (Maran and Glavin 2003, 1). Low fidelity simulators like the MIST VR system are based on abstracted graphics. A big disadvantage of low fidelity simulators is the lack of realism that is provided (Wilson et al. 1997, 1). High fidelity simulators like the LapSim provide a realistic environment using tissues that could be manipulated and could bleed (Maschuw, Hassan, and Bartsch 2010, 1). The LAP Mentor surgery simulator introduced haptic feedback. Resistance is transmitted when tissues or objects are encountered. Additionally, the LAP Mentor divided modules into abstract tasks, procedural tasks and full length operations (Andreatta et al. 2006, 1). The ProMIS VR simulator combines VR technology with traditional box trainer simulation (Van Sickle et al. 2005, 2).
The effectiveness of surgery simulations in VR varies, but VR simulators are overall proven to be reasonable effective in training surgeons. Test results, of the transference of skills from the simulated training environment to the oper-

ating room showed, that VR trained surgeons can improve in task completion time and their error scores are comparable to those of traditionally trained surgeons (S. Haque 2006, 1), (Seymour et al. 2002, 1), (Ganai et al. 2007, 1), (Grantcharov et al. 2004, 1), (Youngblood et al. 2005, 1), (Hamilton et al. 2002, 1), (Hyltander et al. 2002, 1). VR surgery simulators are able to differ between differently experienced users, using indicators like the task completion time and the error score (S. Haque 2006, 1).

The development of a VR-based simulator can be subdivided in six steps: At first, computer vision and computer graphics techniques are used to generate a 3D model out of CT or MRI images. Second, the material properties of soft tissues are measured, categorized and integrated in organ force models. Next, collision detection and response techniques are needed to simulate real-time interaction between simulated surgical instruments and organs. Then, the software and hardware components are put together to form a complete system. The last step is executing user studies to validate the system (Basdogan et al. 2007, 1).

VR surgery simulators have different application areas. Systems like the MIST VR, LapSim, LAP Mentor and ProMIS are used, to train specific surgical tasks, procedures or even full length operations. However, being an effective surgeon takes more than just technical skills. In order to provide a team training environment, a troubleshooting module was integrated into a modified ICE STORM platform. The test results for that team training environment showed, that participants liked the simulator and thought that the environment was realistic. However they did not feel that their performance would improve with the simulation, and the would not want to do VR training before going to the operating room (Abelson et al. 2015, 1). Another application area of VR surgery simulators is the simulation of surgical tasks immediately before executing those tasks in the OR. This warm up simulation improves task time, and decreases the path length. The economy of motion, cognitive errors and sequence errors improved as well, but those findings where not statistically significant (Lendvay et al. 2013, 1).

Modern VR surgery simulators are able to replicate anatomical variations and disease states of actual patients which leads to a high level of fidelity (Endo et al. 2014, 1). Additionally the introduction of augmented reality and high speeds of internet connectivity allows surgeons to collaborate remotely, in order to guide less experience surgeons, or discuss the surgical approach in general (Mahesh B Shenai et al. 2011, 1), (Mahesh B. Shenai et al. 2014, 1).

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