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Development of a mixed-reality-based simulation environment for surgical team training

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Abbreviations

AR	Augmented reality
CTA	Cognitive task analysis
MR	Mixed reality
NTS	Non-technical skills
OR	Operating room
TS	Technical skills
VP	Vertebroplasty
VR	Virtual reality

Summary

Introduction Simulators are becoming increasingly important in medical education, and the adaptation of virtual reality (VR)-based technology into surgical simulation environments offers many advantages. However, the implementation of VR simulators in the field of spinal interventions has been low so far. In addition, the majority of available simulators are aimed at training individual users and their technical skills instead of at teams and their non-technical skills. The goal of our research project and this doctoral thesis was to develop a simulation environment for the training and assessment of spine surgery that can train both individual users and surgical teams in both technical and non-technical skills.

Methods A variety of methods were used for this multi-step developmental process. As a first step, a systematic review was performed in order to give an accurate overview and synthesis of the current state of VR simulation in the field of spinal procedures (publication 1). This was followed by observations, interviews, and expert panels to gather information and requirements for the simulation environment of a vertebroplasty procedure (publication 2). As a next step, a simulation study was conducted to test the validity of the simulated procedure (publication 3). For this purpose, think-aloud protocols, user questionnaires, and expert ratings were applied.

Results In the systematic review, the current state of VR-based simulation in the area of spinal interventions was shown and the current evidence base was systematically synthesized. In publication 2, the individual steps of a vertebroplasty for the three participating surgical professions were systematically elicited and a novel method for the specification of simulation requirements was introduced. In publication 3, we presented a newly developed classification system that systematically categorized the surgeon’s comments expressed during the operation of the surgical simulator.

Conclusions Development projects like the one presented here are necessary to create new medical learning environments. Our work provides developers with tools for similar projects. In addition, we have developed a fully functional simulation environment designed for vertebroplasty training and assessment of surgical teams to train surgeons, anesthetists, and nurses.

Zusammenfassung

Einleitung Simulatoren gewinnen immer mehr an Bedeutung in der medizinischen Ausbildung. Besonders die Ergänzung von Virtual Reality (VR) in die Simulationsumgebungen bringt viele Vorteile mit sich. Allerdings ist die Verbreitung von VR Simulatoren im Bereich der Wirbelsäulenchirurgie bisher gering. Außerdem zielt das Gros der verfügbaren Simulatoren auf das Training von Einzelanwendern und deren technische Fähigkeiten, nicht jedoch auf Teams und deren nicht-technische Fähigkeiten. Das Ziel unseres Forschungsvorhabens und dieser Doktorarbeit war es, eine Simulationsumgebung für das Training und Assessment eines Wirbelsäuleneingriffes zu entwickeln, in der sowohl technische als auch nicht-technische Fähigkeiten von Einzelanwendern und chirurgischen Teams trainiert werden können.

Methoden Für den Entwicklungsprozess kam eine Vielzahl an Methoden zur Anwendung. Als erster Schritt wurde eine systematische Aufarbeitung der bisherigen Veröffentlichungen zu VR-Simulatoren für Wirbelsäuleneingriffe durchgeführt (Publikation 1). Für Publikation 2 kamen Beobachtungen, Interviews und ein Expertenpanel zum Einsatz, um Informationen und Voraussetzungen für eine Simulationsumgebung zu definieren. Daraufhin wurde in Publikation 3 eine Nutzerstudie auf der Basis von Think-aloud-Protokollen, Nutzerfragebögen und Bewertungen durch Experten durchgeführt, um die Validität der simulierten Prozedur zu testen.

Ergebnisse In der systematischen Literaturübersicht (Publikation 1) wurde der aktuelle Stand der Simulation im Bereich Wirbelsäuleneingriffe abgebildet. In der Publikation 2, wurden die einzelnen Schritte einer Vertebroplastie für die drei beteiligten chirurgischen Professionen systematisch erhoben und ein neues Verfahren zur Durchführung von Anforderungsanalysen von medizinischen Simulatoren vorgestellt. Ein weiteres Ergebnis, welches in Publikation 3 präsentiert wird, war die Entwicklung eines neuen Klassifikationssytems, um Kommentare von Chirurgen während der Simulatornutzung zu kategorisieren.

Schlussfolgerungen Entwicklungsprojekte, wie dieses hier, sind notwendig, um neue medizinische Lernumgebungen zu erstellen. Unsere Arbeit hat dabei geholfen, Entwicklern Werkzeuge für ähnliche

Projekte zur Verfügung zu stellen. Außerdem haben wir eine voll funktionstüchtige Simulationsumgebung entwickelt, die für das Training und Assessment von chirurgischen Teams anhand der Vertebroplastie bestimmt ist und Chirurgen, Anästhesisten und Pflegekräfte gemeinsam schulen wird.

Introduction

In the following section, I will give you an overview of the current state of research on medical simulators for training of individual users and surgical teams as well as on their development process. After that, I will discuss the publications that are part of this doctoral thesis and some further work. Finally, I will conclude our results and provide an outlook on future research.

Current state of medical simulation

Medical education is still predominantly based on the Halstedian approach of see one, do one, teach one [1]. However, this leads to patients being exposed to the learning curves of surgeons, which may put them at the risk of being treated by residents in education with insufficiently trained skills. Another problem with this concept of time-based residency training is the danger that time should represent the level of skill rather than competency [2]. In addition, working time restrictions and the increased complexity of treatment options lead to further problems in medical education [3, 4]. Therefore, new ways of residency training are necessary [5]. One approach is simulation.

Medical simulators have been around for a long time, but new-generation simulators bring many benefits due to new technologies [6, 7]. The integration of computer technology into simulation has led to the development of virtual reality (VR)-, mixed reality (MR)-, and augmented reality (AR)-based simulators. VR is a virtual computer-generated impression of reality. This can affect multiple domains (e.g., visual and audio) or just one. A combination of physical reality and VR is called MR. For example, an X-ray is generated virtually in combination with a synthetic patient model. The third kind is AR, where a real situation is superimposed, enriched, or enhanced by a virtual component, such as patient information on a head-up display in a real life surgery. For simplicity, in this thesis, VR, MR, and AR will be referred to as VR.

Medicals simulators, especially VR simulators, offer numerous advantages. First, simulators provide enhanced training opportunities for novices as well as experienced surgeons and improve surgical skills, such as speed and accuracy [8–10]. Moreover, these skills contribute to improved and safer care [8] as well as limited discomfort and risks for patients [11]. Additionally, VR-based simulators increase training opportunities and reduce necessary resources. Compared to other training modalities, they are independent of patient or cadaver availability. While cadavers are often ethically questionable and potentially hazardous, they are also expensive and time-consuming to prepare for a surgical course [12]. Realistic and valid virtual training environments make cadaver training less preferable [13]. Synthetic models for traditional training, on the other hand, are often not reusable and higher fidelity synthetic models are quite expensive compared with VR simulators [14]. Therefore, VR simulation training is often less expensive than traditional training [15]. Moreover, by adapting the difficulty level, training can be adjusted to the capabilities and competencies of trainees [11, 16]. Furthermore, VR-based simulation can provide immediate information regarding the performance of trainees, often labeled as performance metrics, that are based on clinical measurements [13]. These metrics need to be valid and thus help to assess and evaluate the skill levels of trainees [17]. This leads to better comparability between trainees [18, 19] and provides a base to assess and certify them (e.g., as done by the Royal College of Physicians and Surgeons of Canada) [20]. Finally, VR-based simulators offer research opportunities to safely investigate operating room (OR) behaviors and influential factors on the performance of surgeons (e.g., sleep-deprivation or adverse conditions in the OR) [21, 22].

The current use of simulation across all medical disciplines is not clearly quantifiable, as it depends on the respective options and also differs within the medical disciplines [23]. Surveys on the frequency of simulation usage try to make a statement, but usually only examine individual countries or medical disciplines [24–29]. For example, there are differences between surgical specialties concerning the availability of simulators and their quality. While other specialties are advanced, in spinal surgery very few simulators are available for a small number of procedures [23]. Nevertheless, the comprehensive integration of simulation as an educational tool usually stagnates or fails due to a lack of resources, such as time, money, and human resources as well as organizational obstacles [24, 28]. Also, there are other challenges that need to be addressed (e.g., missing or low fidelity) [30]. Besides, further research, comprehensive curricula, and clear training goals are necessary for integration of simulation into medical education [24, 26, 28].

Concerning the effects of medical simulation, a systematic review of the transfer of simulation-learned skills to real situations shows good transferability of simulator training [31]. However, studies on the effectiveness of simulation are limited, since they mostly assess skills or knowledge as metrics instead of patient outcomes [32].

Simulation for teams

Medical teams play an important role in healthcare, as missing teamwork and communication contribute to suboptimal care or medical errors [33]. Nevertheless, in most cases, medical simulators are developed for individual users rather than involving a whole team [30, 34]. But ideally, surgical team training should include at least one participant from surgery, nursing, and anesthesia simultaneously [30]. This is important as OR teams that work together should also train together [35].

Moreover, current single-user simulators focus mostly on the training of technical skills (TS). These are defined as psychomotor actions or related mental faculties acquired through practice and learning pertaining to a particular craft or profession [36]. Non-technical skills (NTS) in the OR, on the other hand, are defined as "the cognitive and social abilities that complement surgeons' technical expertise, clinical knowledge, and procedural skills in the operating room" [37, p.1124]. They mainly include intraoperative communication, situational awareness, decision making, teamwork, and leadership [38, 39]. Missing NTS can be linked to adverse events in the OR [40, 41]. A study in orthopedic surgery revealed that failure in NTS was accountable for 44% of deaths, with missing situational awareness accounting for the majority (51.7%) of NTS-related incidents [42]. Therefore, NTS are fundamental for procedure efficiency, patient outcomes, surgical success, and patient satisfaction [41, 43]. Regarding the relationship between TS and NTS, low levels of NTS, especially situational awareness, are associated with a higher likelihood of technical errors [38, 44, 45]. Nevertheless, specific effects of NTS on patient outcomes as well as their interrelations to TS remain unclear [46]. However, surgical team training, regardless if VR-based or not, should incorporate collaborative learning and TS- as well as NTS-training [30, 34]. Still, due to higher complexity, costs, and logistics, NTS training and surgical team training are rare [47].

Development of surgical simulators

Surgical simulators for multidisciplinary OR teams as well as their respective methods for development and implementation are lacking [48]. For successful simulation environment development, a thorough understanding of the surgical task, its key characteristics, and boundary conditions in the OR are necessary [49]. It is indispensable to gather detailed information on the actual surgical procedure as an important step of the development process. Therefore, methods for gathering and structuring knowledge are in demand. However, guidance on these processes is lacking, producing a hindrance for simulation development [39, 40].

Simulator development in healthcare is mostly based on cognitive task analysis (CTA). While former methods of task analysis focused on observable tasks, modern work practices involve unobservable tasks such as decision-making, planning, and problem-solving [48]. Therefore, CTA has been introduced to reliably elicit information on the cognitive processes underlying the observable tasks [50]. CTA systematically elicits and identifies the cognitive aspects of expertise from subject matter experts through "… identifying, analyzing, and structuring the knowledge and skills experts apply when they perform complex tasks" [51, p.541]. One problem with expert interviews is that medical experts tend to omit information when describing a task (e.g., implicit expertise or non-conscious task cues). CTA reduces this risk of missing or failing information by structuring the elicitation procedure [52, 53]. Therefore, medical simulation that is based on CTA methods has various advantages, as it is efficient and associated with superior training outcomes compared with traditional methods of medical training and adheres to the needs of trainees, and saves training time [54–56].

Assessment and Training of Medical Experts based on Objective Standards

In 2014, the interdisciplinary research project "Assessment and Training of Medical Experts based on Objective Standards (ATMEOS)" was launched. This project consists of scientists from the Technical University of Munich and the Ludwig-Maximilians-University Munich and has already worked together in parts on the forerunners of this project [22, 57, 58]. The collaborators have particular expertise in computer science, medicine, medical simulations, applied medical training, and occupational psychology. The common goal of this research project, which was funded by the German Research Foundation (DFG), is the development of a MR-based simulation environment for the training and assessment of surgical teams based on vertebroplasty (VP).

VP is a percutaneous, minimally invasive procedure where a needle (trocar) is inserted into a fractured vertebra under C-arm or CT guidance to inject bone cement for stabilization [59]. The main targets for VP are patients with osteoporotic compression fractures, with 2.8 million people in Germany suffering from osteoporotic vertebral compression fractures [60]. We decided on VP as the medical procedure for training for several reasons, as it is usually carried out in roughly half an hour and has a distinct sequence of steps. This makes this procedure well suited for simulation. Furthermore, the procedure is widely applied and carried out by different specialties, and the OR team consists of one surgeon, one anesthetist, and at least one sterile nurse. It is therefore suitable for multidisciplinary OR team training. Moreover, as communication is very important throughout this procedure, it is suitable for training NTS [61, 62]. Additionally, potential risks of VP (e.g., cement leakage) can lead to intraoperative crisis scenarios that increase the risk for adverse events. These non-routine events can be integrated into the simulation set-up for surgical skills training.

Publications

Below, I present three individual publications that have emerged from this simulation development process. The publications are listed chronologically, with some being developed concurrently and overlapping. This doctoral thesis is inextricably linked to the research project described above, because its outcomes served to fulfill subtasks of the overall simulation development process as well as the overall goal of developing the simulation environment. The following publications are **part of this doctoral thesis**. An overview can be found in Table 1.

Publication 1: Virtual reality-based simulators for spine surgery: a systematic review

Publication 2: Stepwise development of a simulation environment for operating room teams: the example of vertebroplasty

Publication 3: Say, What Is on Your Mind? Surgeons' Evaluations of Realism and Usability of a Virtual Reality Vertebroplasty Simulator

Table 1: Publications of my dissertation thesis and further work currently under review

	Publication	Aims	Methods	Key Results
Doctoral thesis	**Publication 1:** "Virtual reality-based simulators for spine surgery: a systematic review" *Pfandler et al., 2017*	To provide an accurate overview and synthesis of the current state of VR simulation in the field of spinal procedures;	Systematic review; peer-reviewed articles, including VR-, MR-, and AR-based simulators in spine surgery; qualitative data synthesis and quality appraisal;	19 studies with an overall medium-to-low quality; higher quality studies with patient-related outcome measures and long-term studies were needed; NTS and multidisciplinary team training was recommended;
	Original Study Publication 2: "Stepwise development of a simulation environment for operating room teams: the example of vertebroplasty" *Pfandler et al., 2018*	To develop and apply a customized CTA to obtain information on VP for all three OR professions;	CTA consisting of document reviews, in situ OR observations, interviews, and an expert consensus panel;	Specification of simulation requirements for a VP including all three OR professions;
	Original Study Publication 3: "Say, What Is on Your Mind? Surgeons' Evaluations of Realism and Usability of a Virtual Reality Vertebroplasty Simulator" *Koch et al., 2019*	Obtain feedback on preliminary simulator set-up from surgical experts; to develop a classification system for user comments;	Think-aloud protocols, senior surgical expert evaluations, performance metrics, and a post-simulation questionnaire;	Surgeon approved simulator as being realistic and useful; haptic feedback requires further improvement; classification system was provided;
Further work	**Further work A:** "3D-printed CT-based Bone Models for Spine Surgery Simulation" *Stefan et al., under review*	To introduce a novel 3D-printing method to inexpensively replicate synthetic spine models from patient CT data;	Optimizing printing parameters iteratively and evaluating X-ray images with the help of surgical experts;	Cortical and cancellous structures of the final model were haptically and visually comparable to human vertebral bone;
	Further work B: "Technical and Non-Technical Skills in a Vertebroplasty Procedure: A Simulated Operating Room Environment Study" *Pfandler et al., in press*	To investigate TS and NTS of surgeons in a simulation environment;	Observational simulation study; NTS and TS assessment; VP outcome assessment;	NTS of surgeons correlated significantly with technical performance and surgical outcome scores; association was attenuated when controlling for the experience of surgeons;

Publication 1: Virtual reality-based simulators for spine surgery: a systematic review
Authors: Michael Pfandler, Marc Lazarovici, Philipp Stefan, Patrick Wucherer, and Matthias Weigl

In order to provide an accurate overview and synthesis of the current state of VR simulation in the field of spinal procedures, we carried out a systematic review. The objectives were to examine the existing research on VR-based simulators in the field of spinal procedures and to evaluate the quality of current studies on VR-based training in spinal surgery. Moreover, we aimed to provide a guide for future studies evaluating VR-based simulators in this field.

We conducted a systematic review where we searched five data sources systematically for peer-reviewed articles including VR-, MR-, and AR-based simulators in spine surgery. We performed a qualitative data synthesis for all included articles. Moreover, we assessed their quality using the Medical Education Research Study Quality Instrument tool [63]. Our systematic review process revealed 19 studies with an overall medium-to-low quality. We concluded that higher quality studies with patient-related outcome measures were needed. Moreover, future evaluations need to apply long-term study designs and examine NTS as well as multidisciplinary team training.

As first author of this review, I had primary responsibility for study planning, literature search process, literature selection process, data extraction, quality appraisal, and drafting of the manuscript. My co-authors were responsible for literature selection, quality appraisal, and review of the manuscript draft.

Publication 2: Stepwise development of a simulation environment for operating room teams: the example of vertebroplasty
Authors: Michael Pfandler, Philipp Stefan, Patrick Wucherer, Marc Lazarovici and Matthias Weigl

The results of our systematic review confirmed that there was a need for a simulation environment for spine surgery. In order to develop this environment, a systematic approach for the stepwise collection and specification of the simulation requirements was necessary. After an in-depth literature review and the comparison of different methods, we decided to carry out a CTA. The advantages of a CTA were already described above (see “Development of surgical simulators” in the introduction of this thesis).

Our specific aim for this study was to develop and apply a customized CTA to obtain information on VP for all three OR professions. For this purpose, we developed a modified CTA consisting of document reviews, in situ OR observations, interviews, and an expert consensus panel. Interviews and observations focused on both the TS and NTS of OR teams. They included five surgeons, four operating room nurses, and four anesthetists for interviews. Ten procedures were observed in five OR theaters. Following this approach, we identified all procedural steps and sub-steps of a VP for surgeons, nurses, and anesthetists. Additionally, information on intraoperative skills and requirements for all three OR professions were obtained. Obtained data was then discussed in an expert panel where we derived simulation requirements as results.

My contributions as first author to this publication were planning of the study, conducting the observations and interviews, reviewing and evaluating interview data through qualitative data analyses, and drafting the manuscript. My co-authors conducted observations, reviewed and evaluated observational and interview results, and reviewed the manuscript draft.

Publication 3: Say, What Is on Your Mind? Surgeons' Evaluations of Realism and Usability of a Virtual Reality Vertebroplasty Simulator

Authors: Amelie Koch, Michael Pfandler, Philipp Stefan, Patrick Wucherer, Marc Lazarovici, Nassir Navab, Ulla Stumpf, Ralf Schmidmaier, Jürgen Glaser, and Matthias Weigl

As a next step, our team carried out a simulation study with a preliminary simulator. The aim of this study, in terms of simulation development, was to get feedback on our preliminary simulator set-up from surgical experts and develop a classification system for user comments.

This simulator did not yet have all the necessary technical features to simulate VP to its full extent. For example, it was not possible to inject cement into the vertebra. In addition, the simulation did not include a full-fledged C-arm, but this was virtually displayed in its relation to the patient on a screen and tilted by a control panel.

We conducted a study with 13 orthopedic, trauma, and neurosurgeons with various levels of expertise performing a simulated VP. Using think-aloud protocols, senior surgical expert evaluations, performance metrics, and a post-simulation questionnaire, we evaluated participants´ performance and opinions on the simulator [64–66]. We collected 244 comments on realism and usability of the simulator, including positive and negative remarks, questions, and specific suggestions for improvement. The feedback was that although surgeons approved the simulator as being realistic and useful, the haptic feedback of the VR patient's anatomy requires further improvement. With the novel classification system of verbal expressions during simulator operation, we provided a useful tool for systematically categorizing operator comments in similar evaluation studies of surgical or medical skills simulators.

My contributions as co-author to this publication were the planning of the study, creating the questionnaires, conducting the think-aloud-interviews, co-developing the category classification system and the expert evaluation system, and revising the manuscript. My co-authors were responsible for planning the study, creating the questionnaire, the category classification system and the expert evaluation system, and drafting the manuscript.

Further work

Furthermore, our research team has been working on studies that have been submitted and are currently under review but not yet accepted. These are **not part of this thesis.** Since I contributed substantially to the following works, I included both to expand on the progress and current status of the project. An overview can be found in Table 1.

- **Further work A:** 3D-printed CT-based Bone Models for Spine Surgery Simulation (submitted and under peer review, unpublished)
- **Further work B:** Technical and Non-Technical Skills in a Vertebroplasty Procedure: A Simulated Operating Room Environment Study (submitted and under peer review, unpublished)

Further work A: 3D-printed CT-based Bone Models for Spine Surgery Simulation

(submitted and under peer review, unpublished)

Authors: Philipp Stefan, Michael Pfandler, Marc Lazarovici, Matthias Weigl, Nassir Navab, Ekkehard Euler, Julian Fürmetz, and Simon Weidert

Our results from publication 3 called for further improvements of the simulator that could not be achieved with the implemented technology (i.e., shortcomings in haptic feedback). Therefore, we decided to replace the technology from a forced-feedback based model to a 3D-printed bone model. This means that the technology is not based on a mechanical device but on a synthetic bone, which can be treated more freely. We assumed that potential benefits were better haptic feedback, the use of familiar surgical instruments, the ability to inject real cement, and the cost-effective production of the patient-specific 3D models in the 3D printer. The disadvantages, however, were the long production time for a bone model, since current 3D printers require several hours per model.

Therefore, the objective of this publication was to present a novel 3D-printing method to inexpensively replicate synthetic spine models from patient CT data, optimized to reproduce realistic haptic behavior, for spine surgery simulation. Therefore, we printed spine models created from CT data on a 3D printer using two different materials for cortical and cancellous bone. It was necessary that the printed bone model in its composition and feel had to correspond to the underlying real bone. For this purpose, we optimized printing parameters iteratively with the help of surgical experts. Afterwards, three printed spine models were evaluated in a study regarding haptic appearance. Moreover, X-ray images were evaluated by surgical experts regarding fluoroscopic appearance. The results showed that cortical and cancellous structures of the final model were haptically and visually comparable to human vertebral bone. This led us to the conclusion that these 3D-printed bone models realistically reproduced the haptic feeling of trocar placement into the vertebral body. The models corresponded to real patient CT data and were suitable for our simulation environment.

Based on the results from the observations, the interviews, and the previous development work on the simulator as well as on the expert feedback on the printed bone models, we developed a comprehensive simulation environment for an entire OR team (which will be described in the following paragraphs).

Further work B: Technical and Non-Technical Skills in a Vertebroplasty Procedure: A Simulated Operating Room Environment Study (in press)

Authors: Michael Pfandler, Philipp Stefan, Christoph Mehren, Marc Lazarovici, and Matthias Weigl

The aim of this study was to investigate TS and NTS of surgeons in our newly established simulation environment for VP procedures. We employed our MR and full-scale simulated OR environment. It included a 3D-printed synthetic bone model based on real patient CT data, a decommissioned C-arm, tracking cameras, a cement injection system, and all necessary instruments to perform a VP. Eleven surgeons performed the procedure in the simulation environment with the help of scripted confederates performing the roles of anesthetist, scrub nurse, and circulating nurse. TS and NTS were assessed using valid and reliable scales and senior expert evaluated VP outcome assessments. The results showed that the NTS of surgeons correlated significantly with their technical performance ($\tau=0.63$; $p=0.006$) and surgical outcome scores ($\tau=0.60$; $p=0.007$). This association was attenuated when controlling for the experience of surgeons.

Publication 1: Virtual reality-based simulators for spine surgery: a systematic review

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Published as

Pfandler M, Lazarovici M, Stefan P, Wucherer P, Weigl M. **Virtual reality-based simulators for spine surgery: a systematic review.** The Spine Journal, 2017; 17 (9), 1352–1363.

and can be found here

https://www.thespinejournalonline.com/article/S1529-9430(17)30208-5/abstract

Publication 2: Stepwise development of a simulation environment for operating room teams: the example of vertebroplasty

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https://advancesinsimulation.biomedcentral.com/articles/10.1186/s41077-018-0077-2

Publication 3: Say, What Is on Your Mind? Surgeons' Evaluations of Realism and Usability of a Virtual Reality Vertebroplasty Simulator

Amelie Koch[1], Michael Pfandler[1], Philipp Stefan[2], Patrick Wucherer[2], Marc Lazarovici[3], Nassir Navab[2], Ulla Stumpf[4], Ralf Schmidmaier[5], Jürgen Glaser[6], and Matthias Weigl[1]

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Conclusions and outlook

The overarching objective of the publications of this thesis was to provide scientific contributions to the development and implementation of VR-based simulation for surgical team training and assessment. Following, I will outline a brief overview on the potential contributions of the publications to the current knowledge base as well implications for future research and surgical practice.

Contributions to the current knowledge base

Looking at the results of the published and unpublished manuscripts, we first systematically reviewed the existing research based on VR-based simulators in spinal procedures in publication 1. Therein, we summarized and extended the knowledge base in this field, which has been dominated by technical reviews prior to our research synthesis. Through qualitative data synthesis, we showed that simulation environments for team training, including NTS, are necessary in the field of spinal surgery. This is in line with the results of studies and reviews within other fields of surgical simulation [30, 67]. A further contribution was that we suggested several options for further research and evaluation practices in VR-based simulation in spine surgery, with a strong emphasis on comprehensive reporting practices of evaluation in this field.

After that, in publication 2, we developed a novel CTA approach to elicit information on intra-operative demands and to define requirements of the simulation environment. To our knowledge, this is the first publication to offer a guideline for simulator development including OR teams and NTS. Our stepwise and multi-method procedure may serve as a blueprint for other researchers who pursue the construction and implementation of valid surgical simulation environments. Moreover, we achieved a detailed description of VP, including TS, NTS, and teamwork demands for all OR professions. This expands previous rather solely technical task-oriented procedure descriptions with enhanced depth and thus broadens the VP literature.

In the preliminary simulator study (publication 3), we were able to develop a classification system that categorizes the experiences of surgeons during usability evaluation of a VR-based simulation for VP. Therein, our novel approach allows other simulator developers to identify the verbally communicated impressions of surgeons while handling the simulator. Through its generic approach, it can be applied regardless of the specific surgical procedure. This will allow us and other researchers in future studies to gain an enhanced and comprehensive understanding of the immediate experiences of surgeons while being immersed in operation of the simulator.

The contribution of further work A is the development of a cost-effective 3D-printed synthetic bone model that is based on real patient CT data. Since the results showed that it is very similar to human bone in terms of haptics and optics (in X-ray), this development offers a wide range of possibilities for future surgical procedure simulations employing synthetic bones. It can both reduce costs and increase training frequencies and opportunities, thus contributing to better training of surgeons. Nonetheless, further investigations into the transfer and translation of synthetic bone model simulation in surgical education need to be carried out in order to demonstrate superior effectiveness compared to conventional training approaches.

Finally, we were able to show that our full-scale simulation environment can be employed to realistically simulate a VP procedure and to assess and evaluate both TS and NTS (in further work B). Building on this, further studies will be possible, such as training of surgeons in the simulator, as well as the training of entire OR teams in both TS and NTS. Furthermore, we investigated the relationship between TS and NTS and showed the effect of surgical experience on this relationship. This further adds to the knowledge base, as previous studies on the relationship between TS and NTS showed inconsistent results [68–70]. We showed that it is possible that these inconsistencies can be attributed to the influence of experience on the relationship between TS and NTS.

Limitations

The findings reported here as well described in the respective publications should be interpreted in the light of several limitations. Each of the publications contains a thorough discussion of potential limitations. Notwithstanding the above described contributions, some questions remain unanswered and shortcomings in the current knowledge base remain. So far, we could not do any training with the simulation environment and therefore cannot make any inferences concerning shortand long-term effects on surgical skills. Furthermore, no statement is yet possible as to whether the performance metrics relate to particular patient outcomes or procedure safety. Moreover, our development approach prioritized surgeon performance, thus disregarding the performances of anesthetists and nurses in the simulator. Therefore, comprehensive evaluations of OR team performance should identify, specify, and assess valid performance metrics for involved anesthetists and OR nurses. It needs to be further acknowledged that this work was based on minimally invasive spine surgery. Other surgical procedures include different socio-technical characteristics of OR team performance and use of equipment and technology (i.e., open or robotic-assisted procedures).

Implications for future simulator research and development

Over the next few years, we expect to see a multitude of new simulators for a variety of disciplines and their integration into education and training.

Nevertheless, the usability of surgical simulators for training needs to be further investigated. As a result, it is necessary to prove the validity of the performance metrics used before a simulator is implemented into training curricula. Respective studies need to be based on high-quality designs that allow valid and robust inferences concerning the effectiveness, and researchers need to incorporate and adhere to respective guidelines in reporting health care simulation research [71]. In addition, they will also need to include long-term studies to assess the impact of simulation on patient-related outcomes [72, 73].

On the technical side, various forms of simulators with various levels of technical elaboration will be developed. However, developers are expected to match the technical elaboration of the simulator to its goals. Not every simulator has to be high-tech, but it has to have the necessary degree of technology to be used effectively. Particularly, the question of how important realism is for constructive simulation should be addressed in further studies [74]. Moreover, standards for developing VR-based simulation environments (e.g., software frameworks) are necessary to support exchange among developers and researchers, which eventually saves resources and reduces costs [75]. Finally, development of automated feedback based on metrics assessed by software is highly recommended for future VR-based simulation environments. This would significantly speed up the assessment process of a trainee’s performance and thereby facilitate integration into practice, training, and education.

Implications for surgical practices

In the future, simulators will be widely used not only for training but also for assessment. With valid metrics and scientifically reliable assessments of the performance of surgeons, simulators can be used as an objective standard, basis or support for decisions, such as whether a resident is already capable of performing a surgical procedure or not [72].

However, simulators, especially VR-based technologies, bring many more possibilities to surgery, such as the preparation and training of upcoming interventions and warm-up exercises. Moreover, the safe study of various research questions during surgical treatments with potential risks for patients or adverse events are possible [76, 77].

Conclusion

This doctoral thesis and its publications offer new insights into team simulation, including NTS, in spine interventions and therefore broaden the scope of simulation research in this particular field. Its results can serve as a template for other developers of surgical simulators, helping to make medical education safer. Ultimately, it should be the goal to establish improved, high-level training opportunities in multidisciplinary OR team settings that ensure successful and safe surgical care. I am convinced that this thesis contributed in some parts to this vision.

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