Designing NeuroSimVR: A Stereoscopic Virtual Reality Spine Surgery Simulator

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Abstract. This paper contributes NeuroSimVR, a stereoscopic virtual reality spine surgery simulator that allows novice surgeons to learn and practice a spinal pedicle screw insertion (PSI) procedure using simplified interaction capabilities and 3D haptic user interfaces. By collaborating with medical experts and following an iterative approach, we provide characterization of the PSI task, and derive requirements for applying this procedure in a 3D immersive interactive simulation system. We describe how these requirements were realized in our NeuroSimVR prototype, and outline the educational benefits of our 3D interactive system for training the PSI procedure. We conclude the paper with the results of a preliminary evaluation of NeuroSimVR and reflect on our interface benefits and limitations.

Keywords: Immersive simulation, spine surgery, education

1 Introduction

Three-dimensional (3D) immersive simulation systems are common in many real-life contexts, aiming to better support learning and training [1]. Surgical education is one particular example wherein such simulation systems are becoming increasingly important to the extent of making them a part of the core medical curriculum (e.g., [2] and [3]). However, medical students and resident physicians are faced by many challenges when using these educational tools due to technical and user experience limitations. In particular, existing surgical simulation systems have focused primarily on accurate implementation of the surgical procedure (e.g., providing haptic feedback or having high-resolution rendering), while optimizing user interaction and user experience have been often weakly considered [4], [5], and [6]. Consequently, it is not surprising to perceive limited adoption of such simulation systems by some medical experts. Therefore, there is a need to mitigate the aforementioned challenges to widen the adoption of 3D simulation technology, and support medical experts with training and learning environment that better satisfies their needs and expectations.

One common task in surgical education and training pertaining to spine surgery is pedicle screw insertion (PSI) [7], which is the focus of our work. In

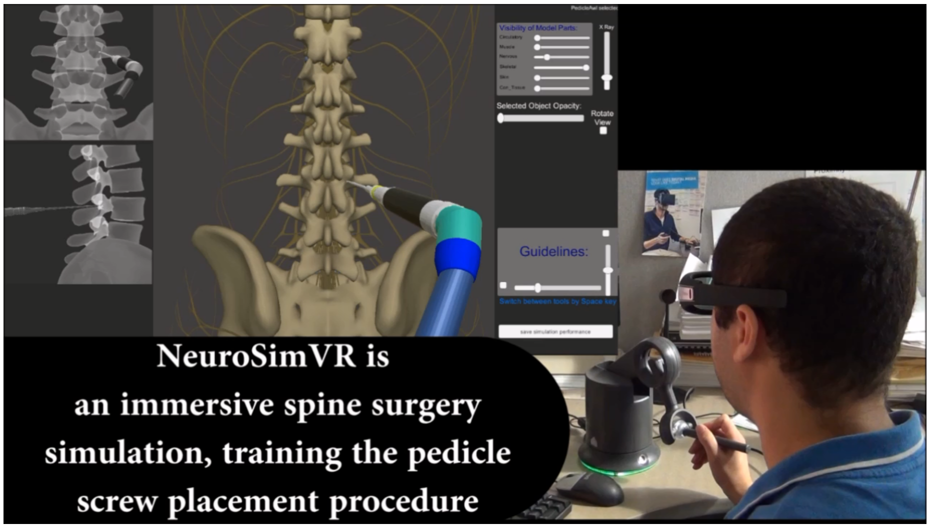


Fig. 1. The interface of NeuroSimVR Simulator: X-ray views (left), perspective 3D view (center), and GUI controls (right).

this task, the expert surgeon identifies abnormalities of the spine and performs spinal procedures including PSI aimed to reestablish normal alignment and stability. To ensure successful operation and mitigate the potential complications of the procedure, the surgeon requires expertise in anatomy and surgical technique. By examining many of the existing spine simulation systems (e.g., [8], [9], [10], and [11]), we found that they incorporate limited procedural context and only focus on visualizing the spine model and the needed surgical tools. With regards to interaction, operating many of these simulations can be complicated and cumbersome, requiring the user at certain moments, to interact via a variety of devices (e.g., keyboard, hand controller, tablet, foot pedal) at the same time without any interface guidance. In essence, our collaboration with experts revealed that users, particularly novice, need considerable training effort before they can use and operate many of such simulation systems. Therefore, we focus on supporting novice medical users with a 3D immersive environment that enables them to easily learn and train spine surgery procedures, while capturing all necessary elements in a simple and realistic way.

Along the way of developing an effective novel spine simulation system, we attempt to characterize the design process focusing on the challenges that pertain to optimizing the educational experience of PSI task. Our participatory design approach involves collaboration with experts from the fields of medicine and education including revisiting the design of educational aids for supporting spine simulation. We stress the importance of simplifying the simulation interface and interactions following the collaborators' feedback, and that the educational features should be integrated during the early design stage to maximize the quality of the immersive simulation and the overall user experience.

We propose NeuroSimVR, a 3D stereoscopic virtual reality simulation with unique educational features and simplified interface, wherein surgeons can learn and practice the procedure of pedicle screw insertion. The developed prototype includes intuitive integration of 3D display and haptic interfaces as well as interaction capabilities for supporting the education of spine surgery. We also report on the results of a preliminary evaluation we conducted reflecting on the efficacy of our prototype and the value of educational features in assessing the technical skills of surgical experts.

The contributions of this paper are as follows:

- Insight dervied from particpatory collaboration with medical experts regarding the design of spine surgery simulators.
- NeuroSimVR, an immersive simulation prototype with educational features that facilitate learning about and practicing the PSI procedure.
- The results of a preliminary evaluation of the developed prototype including reflections on benefits and limitations that could support future design efforts of spine surgery simulations.

2 Related Work

It is clear that enthusiasm and demand for simulation-based education exist in medical and surgical education [12]. Existing research highlight the importance of achieving an accurate simulation to allow for skill transfer (e.g., [1] and [13]) and for learning from mistakes in simulation [14]. More recentely, a survey has studied the effect of 3-Dimensional simulation on neurosurgical skill acquisition and surgical performance [15]. The authors highlighted that 3D simulations are useful supplement to training programs and stressed the need for improvement in surgical performance to warrant large-scale investment in this technology.

Virtual reality simulations especially that utilize stereoscopic displays (i.e., fish tank VR [16]) are common in surgery [17]. Various computer simulations have been developed for numerous medical and surgical specialties such as general surgery (e.g., [18] and [19]), vascular surgery (e.g., [20]), neurosurgery and critical care medicine (e.g., [21] and [22]). Also, Von Zadow and others have explored how tabletop-based immersive simulations can be beneficial for collaborative medical learning [23]. Ekkelenkamp et al. presented a systematic review of GI endoscopy simulation for learning and training purposes [24]. The authors concluded that the use of validated virtual reality simulators particularly for training novice medical users would accelerate the learning of their skills.

While it is clear that effective visual rendering in such surgical simulations is needed, haptic feedback has been also regarded as important for medical procedures (e.g., [25]). For instance, needle insertion procedures highlight having effective haptic feedback as a major contribution for achieving effective training systems (e.g., [26] and [27]). More recently, the use of 3D printing for supporting surgery has been examined and it has been found that it can ease the difficulty of complex spinal surgery [28]. Such examples reflect the importance and focus on having improved graphics and haptic while building surgical simulation. However, user experience elements are often poorly explored (see [4], [6] and [29]), so we argue that special user interface design is needed. Therefore, we focus on improving the simulation as a whole particularly the user interface elements, the supported interaction, and the system usability.

Immersive simulation systems for training spine surgery including the PSI procedure have been researched from both commercial and academic sources [30]. For instance, Klein and others proposed a CT-based patient-specific simulation for pedicle screw insertion [7]. Alaraj and others have explored the role of virtual and augmented reality spinal simulation utilizing the commercial Immersive Touch simulator for neurosurgical training [31]. More recently, a study investigating the use of patient-specific volume rendering combined with projected fluoroscopy (X-ray) for training junior surgeons about the pedicle screw insertion procedure was conducted [32]. The authors concluded that it is helpful to support trainee with X-ray projection as it can enhance their skills. Our work extends these works by focusing on improving usability aspects including simpler interaction capabilities and educational features in order to support novice surgeons while training the spine surgery simulation.

In summary, existing research acknowledge the importance of simulation for learning and practicing surgical procedures. However, the limited focus on simplifying user interaction and the overall experience in such simulations calls for an effort to carefully explore and design an immersive simulation with educational elements and simplified interaction especially for novice medial trainees.

3 Research Approach

In this research, we followed a participatory approach [33], working in collaboration with medical experts including residents, surgeons and education specialists. Our user-centred design follows existing guidelines (e.g., for 3D interaction and performing evaluation with domain experts [34]), and explores better ways of supporting the experts to practice and improve their skill acquisition [35]. We are re-visiting specific educational design elements related to surgical simulation in order to enrich medical users with a usable educational and training environment. We focused on the task of (open) pedicle screw insertion that pertains to back surgery as a simple procedure with room for various educational aspects.

3.1 Task & Context Description

A human spine is composed of various vertebra levels that are grouped to cervical spine, thoracic spine and lumbar spine. The pedicle screw insertion task is common in any of these spines with difficulty that varies accordingly. For effective task completion, knowledge about the anatomy of the spinal area is needed. The unfortunate mistake by any medical surgeon during such a surgery may leave the patient paralyzed or at the least destroy the spinal bones, a problem that is mostly irreversible. So, there is a strong need for a better training environment for all potential users (e.g., doctor, medical students). However, existing simulators are designed for only professional people and normally it is not fully available for all learners. Thus, safe and cost-effective simulator is needed.

An overview of the PSI task involves the following steps. First, the surgeon attempts to identify landmarks or entry points for screw insertion to support particular vertebrae, guided by x-ray images and using his or her understanding of the specific patient anatomy. Then, the surgeon drills carefully and makes pilot holes over the previously identified landmarks. Finally, screws of particular size and diameter are placed in the created holes. This simplified description of the task requires knowledge about the anatomy and mental reconstruction of all the things that could go wrong including touching a nerve (i.e., neurovascular injury), misplacing the screw so that it skips the bone, or creating a hole wider than needed. Therefore, we focus on supporting medical practitioners with an immersive surgical simulation prototype enriched with simplified interaction capabilities, allowing them to better learn and train the PSI procedure.

To verify our characterization of the specific field of spine surgery simulation, we developed a spine simulation prototype and conducted a study to evaluate its efficacy with regards to educational features and its simplicity for supporting the training of medical experts. It is worth noting that we used the task of pedicle screw insertion as our context, but our exploration and the developed simulation can easily be extended to support other surgical tasks.

3.2 Design Rationale

Our collaboration with the medical professionals involved studying some of the existing simulations as well as using them, as needed. In particular, we have experimented with two of the common surgical simulations that include support for the PSI task, namely ImmersiveTouch^{TM}(IT) [5] and NeuroTouch [36].

Based on our exploration of the aforementioned simulation systems and the discussions we had with our collaborators, we identified that the limitations of current simulation systems stem partially from the complexity of interaction and the lack of educational features for supporting simple and effective simulation. First, we found that the IT simulator requires simultaneous interaction and coordination across at least four different devices (e.g., an iPad, customized pedals, haptic device, keyboard, etc.) in order to use it, an apparent complexity that affects its usability. Second, the IT simulator only provided basic numeric score for reflecting user's performance, a limitation that poorly hints at specific improvement aspects. Third, the interface of IT lacks support of visual guidelines that are particularly important for alignment when inserting multiple surgical screws. Finally, users of IT are limited when it comes to exploring and/or manipulating the surgical context prior to starting the actual simulation.

We had bi-weekly meetings with our collaborators to gather their feedback about the implementation progress and their suggestions for improvement. In this regard, we followed user-centered design methodologies from the fields of human-computer interaction [37] and virtual reality (e.g., [18], [38], [34], and [19]) in order to guide our characterization of the PSI task.

Our medical collaborators highlighted the need to support novice users and to only show the important features on demand. They also stressed the importance of having a more detailed performance feedback after completing the simulation. In this regard, we followed an iterative prototyping approach for the design of our prototype and focused on having simplified interaction capabilities and improved usability. For example, novice users can run our simulation with no need of any specialized devices beyond the essential haptic stylus and one keyboard button to interact and completes the simulation.

3.3 Usability Exploration

During the consultation sessions with our collaborators and prior to designing our simulation prototype, we have identified and decided to focus on supporting educational features and specific usability criteria [39]. In particular, we aimed for *Learnability* (how easy is it for users to learn and use the simulation assuming no prior knowledge), *Feedback* (how errors should be handled and how user performance to be reported), *Efficiency* (the simplicity and flexibility of the interaction capabilities), and *Satisfaction* (intuitive visualization). The sections detailing our prototype design and implementation highlight how we addressed the aforementioned criteria.

Towards supporting *learnability*, the design of our spine simulation prototype has included various educational aids that were explored and integrated following our collaborators' insight. Firstly, our simulation supported three stages: pre, during, and post procedure training. At the pre-procedure stage, the simulation would inform learning of the task context by providing users with the ability to control the visualization of the relevant surgical anatomy around the spine including visualization of the neurovascular structures (i.e., nerves and blood vessels) as shown in Figure 2.

Secondly, the graphical user interface of our prototype has gone through various refinements. Most notably was hiding all unnecessary elements to simplify any potential occlusion or cluttering as suggested by our collaborators. One example here that reflects on having GUI on-demand is when the user is about to drill to make a hole at a particular location. In this regard, a 3D visual trajectory is shown to hint at the available depth and orientation of the drilled hole and to guide the user before the actual screw insertion (similarly to the approach proposed recently by Naddeo and others [40]). Such visual augmentation would simplify occlusion during the simulation and could support non-expert surgeons who have suboptimal screw placement. Other visualization decisions included showing guidelines that help users identify insertion points or landmarks consistently (Figure 3), as well as integrating interface-guidance aspects related to input and interaction (e.g., hinting that pressing the space-bar enables switching among the available medical tools). The proposed "guidance" allow novice users to utilize the simulation system without significant back-end technical support

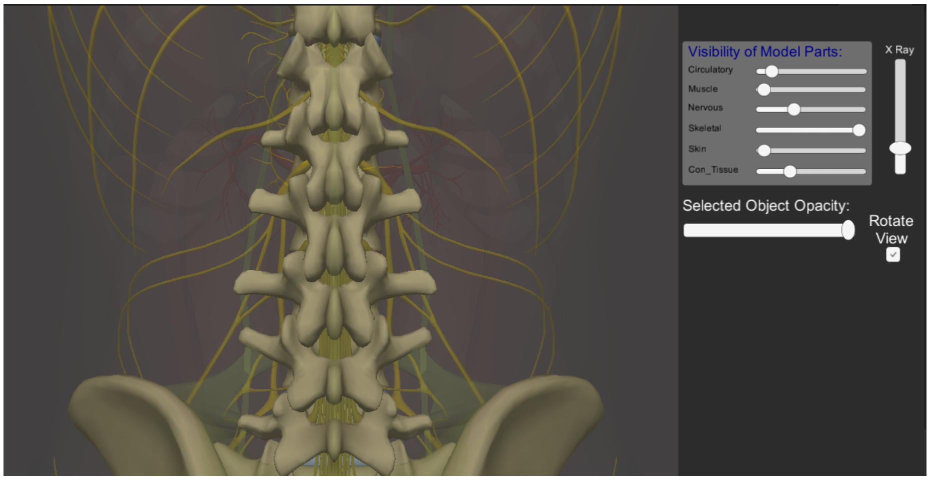


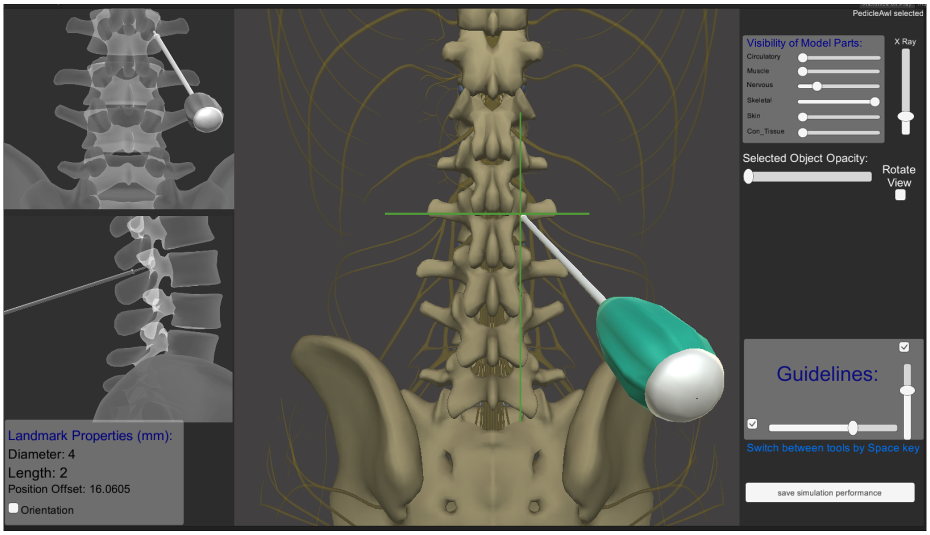
Fig. 2. Visualization of anatomical context around spine (e.g., connective tissues shown in light green, nerves shown in yellow, muscles shown in light pink, etc.).

or a steep learning curve. It is worth mentioning that a good system tutorial cannot replace the proposed "guidance", which we argue goes beyond an interactive user manual to a smart dynamic in-situ hint that automatically complements user's awareness of possible interactions and alternatives.

Our design of the spine simulation also included an instructor-like mode. In this a mode, a skilled surgeon can describe what an ideal surgery performance would look like by defining where landmarks, holes, or screws should be created. This enables easier assessment of semi-skilled users and provides a learning opportunity wherein residents and novice surgeons can see how an expert would do it. The design of this mode also utilizes a XML configuration file that stores not only the prototype simulation parameters (e.g., simulation mode and GUI stats) but also the information of the ideal trajectory for each inserted screw.

In terms of supporting *feedback*, we decided to keep the user informed by relevant feedback particularly during the simulation. For instance, visual blinking occurs upon touching critical parts around the spinal bones (e.g., nerves). Also, graphical panels become visible (on demand) giving numerical feedback about current interaction while it occurs. For example, when drilling a pilot hole, a panel shows information about the hole being drilled including its depth and the entry angle and location. It is worth noting that the aforementioned feedback ideas also contribute to supporting *learnability*.

By completing the simulation, the user is can rotate and move the spine model in order to see his or her performance from other perspectives including isolating a particular vertebra for visual analysis. These features represent a type of *feedback* that is particularly important for educational purposes, and for hinting at user mistakes that are difficult to notice from typical visualization.



PedicleAwl selected

Landmark Properties (mm):
Diameter: 4
Length: 2
Position Offset: 16.0605

Fig. 3. Guidelines are visualized (in green) to assist in screw placement.

4 NeuroSimVR

We developed NeuroSimVR (NS), a fish tank (stereoscopic) virtual reality spine simulation prototype to support learning and training the surgical procedure of pedicle screw insertion. NeuroSimVR supports visualization of the spine and its context, haptic interaction capabilities, and X-ray views for guiding user interaction during the simulation similarly to what actual surgeons have in real operation rooms (Figure 1).

4.1 Implementation

We aimed in our implementation of NeuroSimVR on utilizing a development environment that enables rapid prototyping. Therefore, we used Unity3D v5.4 and the MiddleVR framework v1.6 [41]. During the implementation process, we experimented with a variety of stereocopic displays and haptic interfaces for increased efficiency. Our experimentations focused on supporting depth perception during the simulation, and therefore, our prototype utilized an Asus 3D-monitor with NVIDIA 3D Vision and active 3D stereoscopic glasses.

Haptic feedback is one important element for *effective* surgical simulation. In this regard, we first explored Novint Falcon to support haptic feedback, but decided to look for another alternative due to the limited capability of that device (only three degrees of freedom and being less natural concerning how it is held). We switched to using Touch 3D stylus from 3DS Systems that supports six degrees of freedom and feels more natural with its pen-like interface. In fact, the physicality of the Touch is particularly suitable for attaching physical surgical tools to its end, simulating how a real medical tool is used in actual surgery. A challenge associated with attempting to support haptic feedback is finding simple and effective haptic software libraries, as many of them are quite complex and require understanding of low-level concepts of physics before using them. For our implementation, we used the Geomagic Unity plug-in v1.7 that acts as a layer of the well-known OpenHaptics toolkit [42].

By the end of using our simulation prototype, post-simulation data is displayed and the user then can check his or her performance/score and compare it to an ideal set of landmarks or screws, which have been previously recorded by an expert surgeon. Figure 4 illustrates an example of the simulation stats (e.g., time and screw depth), and shows an analysis that can be performed over the pedicle containing the user screw.

Simulation Stats:
Time(sec): 114.52
Distance to Ideal Entry (mm): 8.964998
Entry Angles (Lateral): 0.498657
Ideal Angles (Lateral): -6.999756
Nerve Contacts #: 12
Screw Depth (mm): 43.87574
Breach Grade: 0
Landmarks #: 1

Fig. 4. Analyzing screws post-simulation: user screw (right) and ideal placement (left).

4.2 Prototype Components

NeuroSimVR consists of three components. The first one renders the 3D model of the spine and its surrounding anatomy (e.g., nerves and muscles). The 3D patient data used is organized as a set of submodels layered by the category of each anatomy (muscles, nerves, bones, etc). This component renders the complete patient data by assigning a specific material to each anatomy group allowing the user to interact directly with specific parts such as selecting a particular vertebra and adjusting its opacity, thus visually revealing hidden neural structures behind the vertebrae. Figure 5 shows an example where the user has adjusted some of the sliders to control the opacity of various anatomy parts. The figure also shows the user selecting one of the spinal disks.

The second component manages the different GUI elements including specially render-to-target cameras (utilizing Shader programs) to provide a fluo-

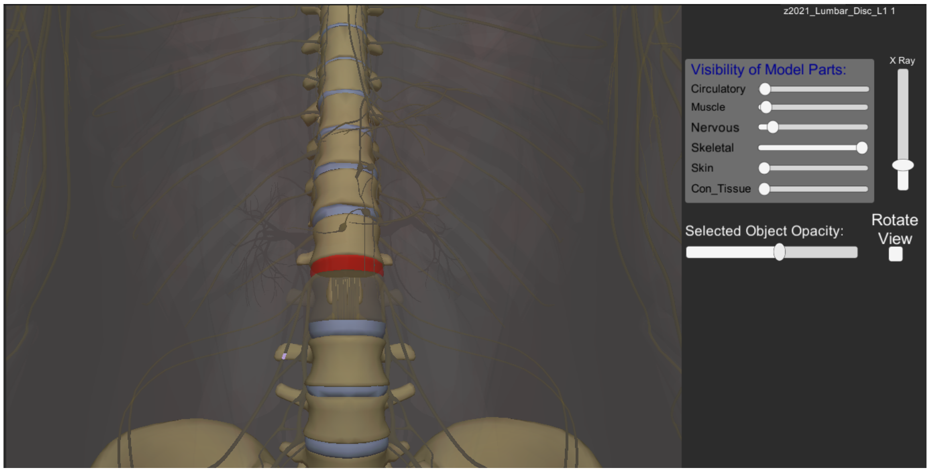


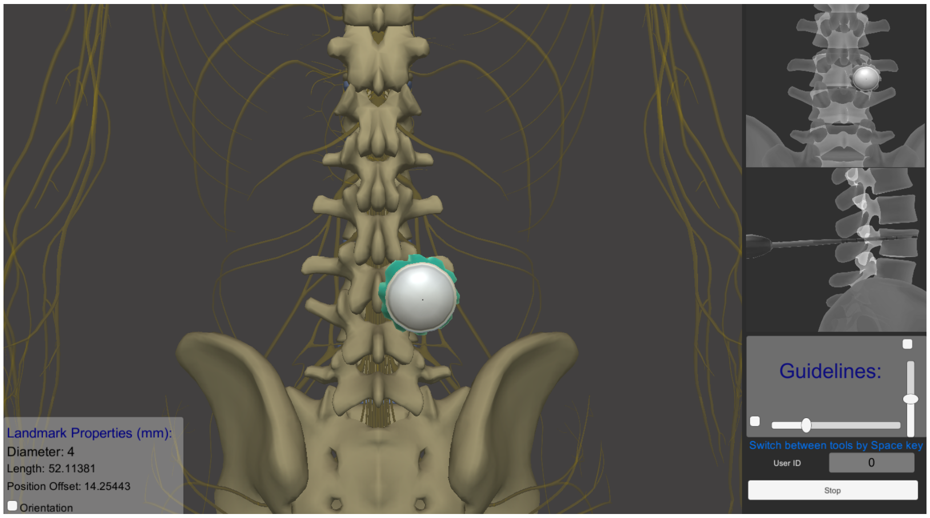
Fig. 5. A disk (shown in red) is selected with the lower vertebra transparent, highlighting behind neural structure.

roscopy (X-ray) view of the spine model (Figure 6). These cameras filter out and control the order of rendering specific 3D anatomical structure to achieve a realistic X-ray output (e.g., only the bones and the metallic tools are captured). Given that intraoperative fluoroscopy is one of the main sources of real-time feedback in spinal procedures, realistic representation of this component will allow direct transfer of surgical simulation practice into the clinical setting. In other words, our focus on this component and the first one highlights how we aimed for user *satisfaction*.

The third component is responsible for supporting haptic feedback and controlling the different haptic properties. In particular, through our implementation we adjust a set of haptic parameters including stiffness, friction, puncture-level to enable the feeling, for instance, of interacting with bone versus soft tissue. In particular, we update such parameters based on the result of colliding the surgical-tool with the patient 3D data. For instance, once the surgical tool's tip touches the bone structure we update the haptic paramters to provide feedback that it is harder or impossible to penetrate the structure. Finally, a simplified state-machine component is responsible for handling the flow of the task, and notifies the user of his or her mistakes. For example, if the user touches the spinal cord while attempting to insert a screw, this component would cause the spinal cord to viusally blink, and would record this touch as one of the user mistakes during the simulation.

5 Evaluation

We conducted a preliminary study to gather feedback from both design experts and surgeons about their experience towards our spine simulation system. We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Length: 52.11381
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Fig. 6. The pedicle-probe tool is selected to create the pilot hole, with a highlighting visualization in the X-Ray views.

hypothesized that providing educational features and simplifying the interface of spine surgery simulation would benefit medical experts who want to learn about and practice spine surgery. A secondary goal of our evaluation aimed to assess the usability and potential of our prototype as an educational tool without focusing on measuring immersiveness aspects. Towards validating our hypothesis, we asked our participants to go through the simulation of a simplified surgical task. We gathered subjective feedback through the implemented survey and interview questions we provided. Our evaluation involved the use of our prototype as well as a known commercial spine simulator called ImmersiveTouch$^{\text{TM}}$(IT) [5] and [43]. The IT simulator can be described as a system that seamlessly integrates haptic feedback with a head and hand tracking and a high-resolution stereoscopic display to enable objective education and proficiency training of various surgical procedures including spine surgery 7.

5.1 Participants

We gathered feedback covering two different perspectives about our simulation prototype. Therefore, the participants of our study were distributed in two separate groups. The first group involved 6 independent participant surgeons (5 M / 1 F) of varying expertise including junior and senior residents as well as staff neurosurgeons. Two of our medical participants had some familiarity with the ImmersiveTouch simulator, but not with the specific PSI task we focused on. All of our participants tried the simulators and provided feedback. It is worth noting the recruited medical experts represents more than half of the residency program, which is comprised of no more than 10 experts. The other group con-

Fig. 7. Overview of the ImmersiveTouch simulator used in our study.

sisted of 6 design experts (3M / 3F); computer science (CS) graduate students whose work involves visualization, design, and/or human-computer interaction.

While the consideration of CS/design participants may seem unnecessary as they are not the intended target audience of such simulation, we still included them because we wanted to gather some feedback about the design elements and the interface of the simulation. This feedback would be valuable for ensuring that the design of our prototype follows common design guidelines.

5.2 Study Design & Procedure

We used a within-subjects design approach where we asked each participant to perform a simplified PSI task using our simulator as well as using the commercial ImmersiveTouch simulator. The IT simulator utilizes specialized pedals for specific interactions as well as a high-quality haptic robotic arm. Our choice of the IT simulator, as our baseline, was because of its common use in many surgical education-based simulation scenarios [44] including the procedure of PSI [45].

The two simulators used in the study were set up next to each other with the participants performing the procedure in randomized sequence (Figure 8).

Prior to doing the study task, participants received training of the simulation and its usage. Then, each participant tried the PSI task and completed a survey using a 5-point Likert-scale for all questions. Finally, a post-study interview was administered, with the duration of each study session being around one hour.

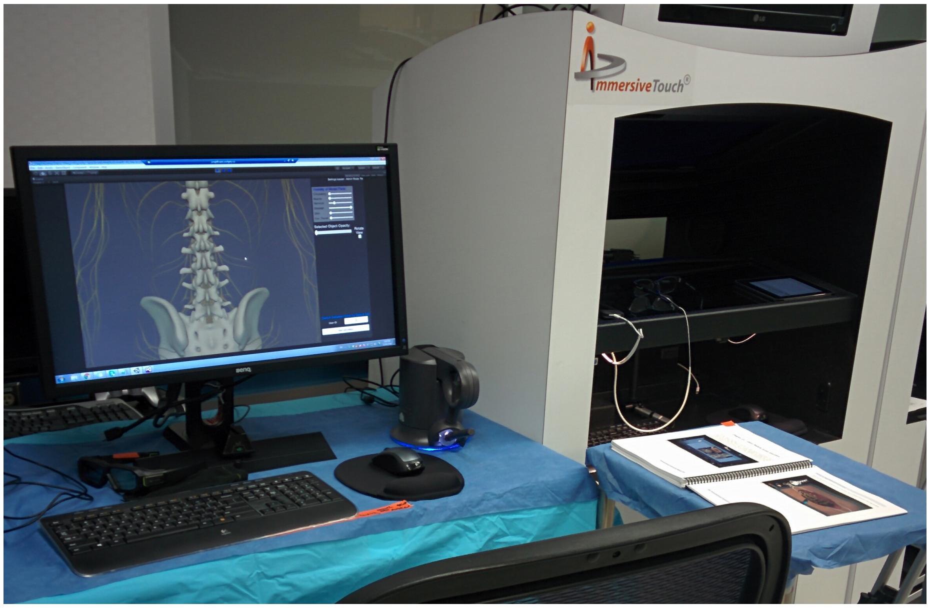

Fig. 8. Study simulators setup: our prototype (left), and the ImmersiveTouch (right).

The two different groups we had followed the same study protocol (i.e., going through the same simulation training, performing the same task and completing the same questionnaires), but since the goal of inviting CS participants was to focus on evaluating the design elements and the interface of the simulation rather than its context of use, we additionally asked the CS group to complete a system usability questionnaire [46]. The survey used in the study also differed slightly since some of the questions deemed less applicable to the CS group (e.g., asking if each simulation supports skills applicable to the operating room).

6 Results & Discussion

Most participants liked the various educational design elements we integrated in our simulation and hinted at their usefulness. On one hand, surgical trainees can use our prototype to practice and improve their surgical skill with regards to the PSI task, one of the most common spinal procedures performed by neurosurgeons and orthopedic surgeons. On the other hand, experts of medical education can use the prototype to illustrate certain concepts that relate to spinal surgery such as the importance of avoiding major complications such as injury to the spinal cord. Such insight is supported by the subjective feedback we received as well as how our participants have rated the different features of the developed simulation. As one of the medical participants said, *"If I am a professor, I will get that tool [referring to our prototype] because it is very easy to handle than* *this one [IT]"*. Such a comment reflects positively on our simulation's potential to address the *learnability* factor.

We divided the analysis of the study results differently for each group, and in the next part we first detail the CS-specific results followed by results of the medical group, and finally we describe the shared results from both groups.

6.1 Design Experts' Results

We asked all CS participants to complete a System Usability Scale questionnaire [46] for our simulation as well as the ImmersiveTouch simulator. The average SUS usability score for our simulator was 80.41 out of 100, and 37.5 out of 100 for the ImmersiveTouch simulator. This result supports the *satisfaction* of CS group participants with regards to our simulator. This seemingly large difference in scores may reflect that our system was judged to be more usable by our design participants who went through the simulation and performed the simplified task, which contributes to the *learnability* aspect of our system. Furthermore, the qualitative feedback reported in the Discussion section below supports this interpretation. Finally, it is worth noting that all CS participants reported that they felt mentally and physically more comfortable in our simulator.

6.2 Medical Experts' Results

We describe the analysis for the survey questions reflecting the average rating of the survey questions from the perspective of the medical participants. As shown in Figure 9, both simulators were effective with slightly better rating for our simulator for most features except the haptic feedback.

6.3 Results from Both Groups

There were some survey questions that deemed applicable to the CS group as well as the medical participants' group. We report the results of such questions reflecting the different perspective of each group with regards to the following simulation features: how realistic the visualization was, the availability of hints and guidance, whether the simulation supports individualized independent learning, and how each simulator provides support of objective performance measures.

The results of CS group reflected better rating for our simulator for the aforementioned questions (Figure 10) while the medical participants' rating for both systems is almost identical. This result could be related to the difference in background and perspective that the non-medical participants possess about the design of the interaction and the interface. In general, our preliminary results reflect positively on the usability criteria we considered earlier.

6.4 Simulators' Strengths & Limitations

As a resident commented, *"The limitations of these two simulators are the limitation of any simulation; it is never going to be exactly [like] what it is in the*

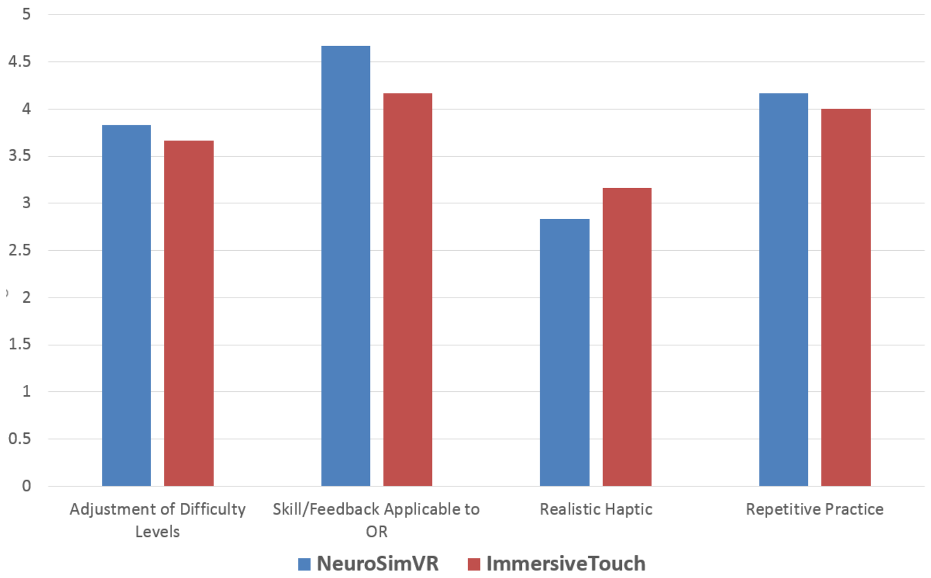

Fig. 9. Rating of medical specific features by our surgeons' participants

OR. In terms of strength, they are great for learning experiences". In this part, we reflect on some of the key strengths and limitations in each of the simulators we used, particularly with regards to supporting education.

Many participants mentioned the dispersed controls and the various devices for controlling the IT simulator as one of its key limitations, hinting at the difficulty of interacting with and operating the IT simulator. As P1 (a medical expert) stated, *"I think that with this one [IT], it was harder to figure out where the buttons and stuff needed to be. By having something in the first one [NS] that tells me where the pedicle is, my landmarks, and so on, it was perfect"*. A similar comment by a CS participant hints at the limited usability of the IT simulator, when he or she said, *"when I am using it [IT], I felt like operating an aero plane ... so I think I needed a lot of effort for using it, which was not the case for the other one"*. Another limitation of the IT simulator relates to performance feedback, which is displayed after completing the simulation as a basic numeric score. As one medical expert stated, *"The measurement [of the performance feedback of NS] are better than just the score [provided by IT]. As it tells us what angle was wrong and it shows us where we entered [the bone] as compared to the ideal trajectory, which is very useful for getting oriented. In fact, this helped me orienting myself with respect to the model"*. Interestingly, another medical expert participant suggested to adapt performance feedback according to learner's skills by providing real time feedback (at all times) for juniors and only showing it at the end for senior users.

Most participants, however, highlighted that the haptic feedback was more realistic in ImmersiveTouch. As one medical expert participant expressed, *"The*

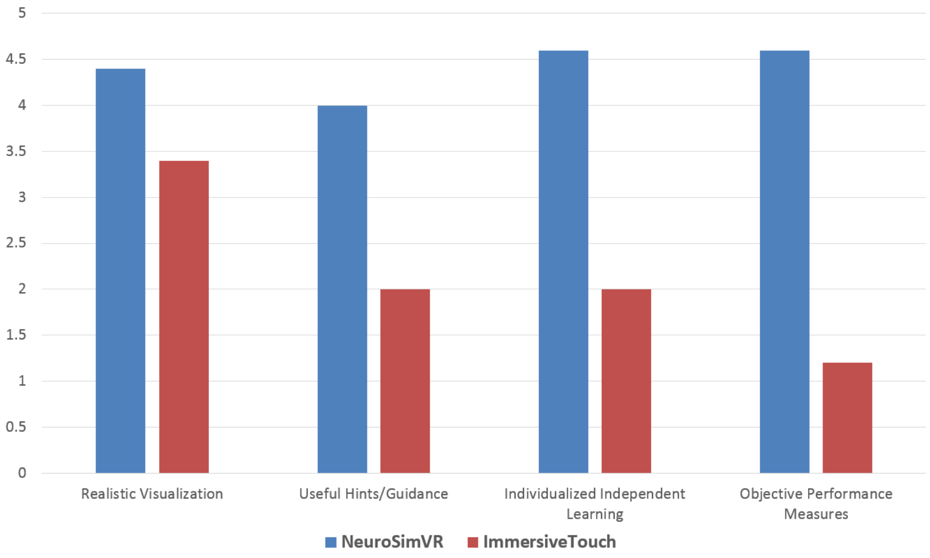

Fig. 10. Rating of simulation features by the CS participants for both simulators

haptic feedback [in IT] was not perfect but comparably better than this one [NS]". Also, one of the CS design participants felt that the rendering seemed a bit more realistic in IT due to the use of shading.

Our prototype also had clear feedback regarding its limitations. A key one as noted by numerous participants was that the NeuroSimVR lacked realistic haptic feedback. In this regard, we argue that this finding is in part because of the expensive high-quality haptic device [47] that is integrated with the IT simulator (e.g., the cost of our haptic device is roughly 30 times less than the IT one), and because the focus of our work is not about improving the haptic feedback. Nonetheless, we aim as part of our future work to improve our implementation of the rendering and the haptic feedback.

On the positive side, most participants liked the our simulation and the various integrated educational elements. These include the flexible and simplified interaction, the real-time x-ray visualization, and the post simulation performance measures. The following qualitative comments are examples of the positive feedback we received. One CS participant commented about the availability of hints and guidance in design by saying, *"these are definitely useful. If I am someone who does not have any clue, hint or feedback would be useful to learn what is going on. If nothing happens, like in the existing systems [IT] there was no feedback for anything so I could have literally drilled holes across the person's spine and nerves and everything, and I would have no idea so I would keep thinking that I am okay; it is kind of pointless"*. Along the same line, one medical expert participant mentioned, *"I did like its 3D [referring to NS] as you can appreciate at the anatomy better than looking at the text book and that you can look the* *relationship between structures, and I like the fact that you can isolate one of the structures [levels] and see what is wrong [in your performance] and things like that"*. Another medical expert comment also reflects on how the flexible interaction within NS supports learning about the anatomy and the context of PSI, when he or she expressed: *"The interactive thing [of NS] is quite helpful, with being able to see, I guess, bones and take away the bones and see where the nerves are and with the muscles on top, it just gives you a better idea of the anatomy"*. Such results reflect on the usability aspects of our design rationale.

We had a limitation of small samples' size; 6 CS and 6 medical experts. We only performed basic statistical analysis on our data. Therefore, we refrain from making any significance claims. We are currently expanding our study with more participants, so a more comprehensive study is a future work of this research.

6.5 Implications for Future Spine Simulation Design Efforts

Beyond having a more realistic haptic feedback, we argue that the following educational aids can be helpful for supporting future efforts of designing immersive spine simulations. First, we strongly suggest simplifying the design of interactions when building surgical simulation, as an important step towards providing more individualized independent learning. Second, the ability to adjust the visualization of each anatomy part should be supported. This includes giving the user the option to hide or show various contextual components as well as controlling their opacity. Third, as all participants stressed, it is important to provide performance measures that are meaningful beyond the simple numerical score provided by the IT simulator, similarly to the detailed reporting provided by our simulator. Fourth, integrating feedback in a timely manner can be useful especially whenever something goes wrong. For example, our simulator followed this approach and provided a basic notification (blinking) that informs the user when he or she touches a critical anatomy part during the simulation. Finally, it is worth noting how various participants highlighted that the rendering does not need to be realistic, especially for educational purposes, and reported that playing with visual perceptual cues would be more helpful (e.g., rendering nerves as contours and blurring out-of-focus parts).

Designing an immersive medical simulation requires multidisciplinary collaboration, which can be challenging. In order to ensure a successful research collaboration with medical experts, it is crucial to build a common language of communication. It was useful for us to work closely, either sharing the same space at the hospital, or meeting regularly at our lab and using simplified jargons to discuss needs and expectations. We engaged in learning and practicing some of the various existing simulation systems, which the experts have used; we examined these systems hands-on, not only from the technical perspective, but also from the eyes of the medical users).

To summarize, we argue that by including simple educational aids and closely following the feedback of medical collaborators, as we demonstrated in this work, the usability and the training quality of immersive medical simulations could be considerably improved. Furthermore, we suggest that educational features should be incorporated from the inception of the model rather than as an afterthought to maximize the chance of enhancing quality of the immersive simulation, the 3D interfaces provided to the medical practitioner, and the overall user experience.

7 Conclusion & future Work

We proposed NeuroSimVR, a 3D stereoscopic virtual reality spine simulation designed to support surgeons with a convenient environment to learn about and train the procedure of pedicle screw insertion (PSI). Our prototype was developed in close collaboration with medical experts and involved various design iterations to meet the expectations and needs of our users. We presented a preliminary evaluation highlighting the potential benefits of our 3D simulation in supporting education and training for the PSI spine surgery procedure.

NeuroSimVR is a work in progress prototype, and we are still improving it. First, we are considering the feedback we received to refine our implementation, for instance, by integrating external educational resources that pertain to back surgery and embedding them within the simulation interface for a better training experience. Also, we aim to support loading and displaying patient-specific data on the fly as deemed valuable. Finally, we are currently conducting a formal study focusing on PSI for different spinal parts (e.g., cervical, thoracic) to assess the practicality of our prototype for simulating different spine surgical procedures. This study is planned with actual medical surgeons and it would involve comparison with existing simulation systems.

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