VRSpineSim: Applying Educational Aids Within A Virtual Reality Spine Surgery Simulator

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Abstract. We contribute VRSpineSim, a stereoscopic virtual reality surgery simulator that allows novice surgeons to learn and experiment with 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 the design of a 3D immersive interactive simulation system. We present how these requirements were realized in our prototype and outline its educational benefits for training the PSI procedure. We conclude with the results of a preliminary evaluation of VRSpineSim and reflect on our interface benefits and limitations for future relevant research efforts.

Keywords: Immersive simulation · Spine surgery · Education

1 Introduction

Three-dimensional (3D) surgical simulation systems are becoming increasingly important to educate and train medical students about critical procedures [3]. However, medical students are faced by many challenges when using such educational tools due to technical and user experience limitations. In particular, existing simulation systems have focused primarily on accurate implementation of the surgical procedure (e.g., supporting haptic feedback or high-resolution rendering), while optimizing the user experience and interaction have been often weakly considered leading to limited adoption by some medical experts [6]. Therefore, there is a need to mitigate the aforementioned challenges to widen the adoption of 3D simulation technology, and support medical experts with a learning environment that better satisfies their needs and expectations.

We focus on this work on the education and training of spine surgery and specifically the common task of pedicle screw insertion (PSI). In this context, we studied existing systems (e.g., [7]), collaborated with medical experts and identified key limitations that pertain to interaction and user experience aspects.

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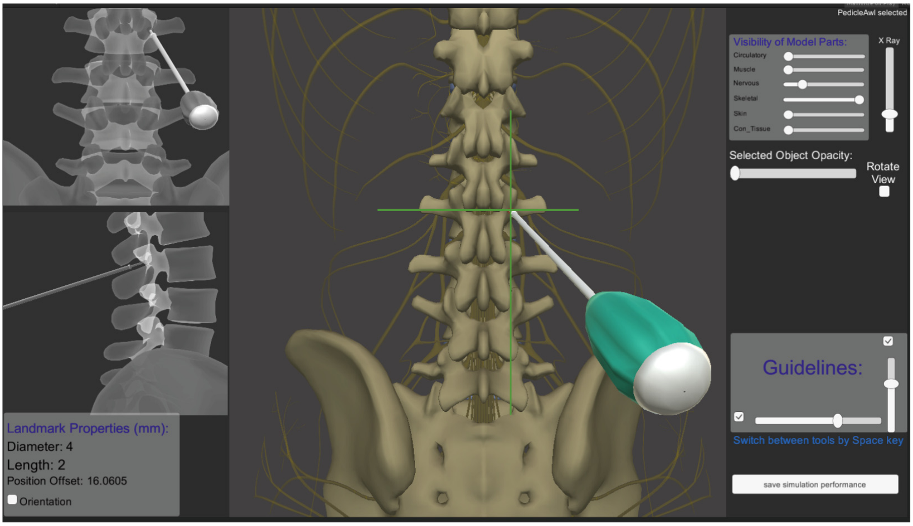

Fig. 1. VRSpineSim interface: X-ray views (left), contextual visualization around the spine showing yellow nerves and green guidelines (center), and GUI controls (right) (Color figure online)

As a result, we propose VRSpineSim, a 3D stereoscopic virtual reality simulation with unique educational features and simplified interactions, enriching surgeons when they learn about and practice the procedure of PSI. We also report on the results of a preliminary evaluation conducted reflecting on the efficacy of our prototype in assessing the technical skills of surgical experts.

The contributions of this paper are as follows:

- Insight derived from participatory collaboration with medical experts regarding the design of spine surgery simulators.
- VRSpineSim, 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

Virtual reality simulations are common in surgical education and training [13], and particularly spine surgery and the PSI procedure (e.g., [14], and [10]). Such simulations have been shown to improve surgeons' skills [19] and operation room performance [17]. A recent survey has studied the effect of 3D simulation on neurosurgical skill acquisition and performance [3]. The authors highlighted that 3D simulations are useful supplement to training programs and stressed the need for continuous improvement to warrant large-scale adoption of this technology.

Clearly, effective visualization in surgical simulations is critical as well as haptic feedback that is becoming increasingly important [4]. Unfortunately, usability and user experience elements are often poorly explored in the design of surgical simulation [6]. Thus, our work extends existing research and focuses on improving usability aspects to support novice surgeons when using simulation.

3 Research Approach

We followed a user-centred iterative participatory approach [16], involving collaboration with medical and educational experts gathering their feedback and suggestions about our implementation. We also strived to follow existing usability guidelines [18] and design recommendations [15].

3.1 Task Description

We focused on the task of pedicle screw insertion (PSI) that pertains to back surgery for its simplicity. Key task steps are: (1) identifying landmarks or entry points for screw insertion to support particular vertebrae, (2) drilling pilot holes over the previously identified landmarks, and (3) placing screws of particular size/diameter in the created holes [11]. For effective task completion, spinal anatomy knowledge with x-ray guidance is needed. The unfortunate mistake during this surgery (e.g., touching a nerve or misplacing the screw so it skips the bone) may paralyze the patient or destroy the spine. Therefore, a simulated environment enriched with simplified interaction capabilities would benefit medical practitioners and allow them to better learn and train the PSI procedure.

3.2 Design Rationale

We studied and experimented with many of the existing back-surgery simulation systems (e.g., [8,9], and [7]). We identified that the limitations of current systems stem partially from the complexity of interaction and the lack of educational features for supporting simple and effective simulation. For instance, the visualization of the anatomical context is often limited and lacks support of visual guidelines. Also, the reported numeric performance score may poorly hint at specific improvement aspects. Finally, user interaction often requires simultaneous use of a variety of devices (e.g., hand controller and foot pedal), a complication that can be avoided with improved design. These issues were also highlighted by our medical collaborators and thus we focus our work on addressing the aforementioned limitations.

For our design, we focused on supporting specific usability criteria [12]. We aimed for *Learnability* (easy usage with no prior knowledge), *Feedback* (handling errors and reporting performance), *Efficiency* (simplicity and flexibility of interaction capabilities), and *Satisfaction* (intuitive interface and visualization).

Towards achieving *Learnability* and *Efficiency*, our prototype enables users to explore and customize the visualization of the anatomy around the spine (e.g., nerves and blood vessels) as shown in Fig. 1.

In terms of supporting *Feedback*, we decided to keep the user informed at all interaction steps. For instance, visual blinking occurs upon touching critical parts (e.g., nerves) around the spinal bones. We also support visual guidelines and 3D visual trajectory (following [11]) to guide users align insertion landmarks (Fig. 1). This GUI is only shown on-demand to simplify clutter and reflect an adaptive interface. Finally, after completing the procedure, simulation is frozen and ideal interaction paths, as defined by expert surgeons, can be shown for reflection and examination. Those designed features allow novice users to use the simulation without significant back-end technical support or a steep learning curve.

4 VRSpineSim

We propose VRSpineSim (VRSS) as an educational simulation prototype for spinal surgery. VRSpineSim supports visualization of the spinal context, haptic interaction capabilities, and X-ray views for guiding user interaction within the simulation similarly to real operation room (Fig. 1).

4.1 Implementation

We used a machine with Nvidia GTX 980 graphics card, NVIDIA 3D Vision (v2) with active 3D stereoscopic glasses and a 3D monitor from Asus for stereo rendering. For haptic feedback, we first explored Novint Falcon, but it was limiting by only having three degrees of freedom. Thus, we switched to using Touch 3D stylus from 3DS Systems that supports six degrees of freedom and feels more natural with a pen-like interface. For software integration, we used the Unity3D and Geomagic plug-in v1.7 to simplify accessing the haptic device interface.

The 3D patient data we used is organized into sub-models each representing an anatomical category (nerves, bones, etc). In VRSpineSim, a unique material is assigned to each sub-model to enable independent visualization and interaction. Also, special render-to-target cameras are used to enable fluoroscopy (X-ray) visualization of the spinal model (Fig. 1). Finally, haptic feedback is supported by adjusting properties such as stiffness and puncture-level based on user interaction. For example, when a rendered surgical tool collides with the bone, we update the haptic parameters to makes it feel harder or impossible to penetrate the structure, essentially providing the feeling of bone versus soft tissue.

5 Evaluation

We conducted a preliminary study to assess the usability of our prototype as an educational tool especially for supporting novice medical trainees. Our evaluation involved the use of VRSpineSim and ImmersiveTouch^{TM} (IT) [7], which is a commercial simulator used in many surgical education-based simulation scenarios [2] including the procedure of PSI.

We implemented a survey and semi-structured interview, and recruited two groups of participants gathering feedback from domain experts and user interface specialists. The first group involved 6 independent surgeons (5M/1F) of varying expertise including junior and senior residents as well as staff neurosurgeons. Two of our medical participants were familiar with the IT simulator, but not with the specific PSI task we focused on. The other group consisted of 6 design experts (3M/3F); computer science grad students working on visualization, design, and/or human-computer interaction.

We used a within-subjects design approach where participants were asked to perform a simplified PSI task on both simulators in randomized sequence to avoid learning bias. Then, participants completed the survey and the post-study interview questions during the one hour study session. The study protocol is identical for both groups, but we asked the design group to additionally complete a system usability questionnaire (SUS) [1] as we wanted their feedback on the interface design of the simulation rather than its context of use.

6 Results and Discussion

Most participants liked the simplified interaction elements of VRSS and regarded our simulation as an educational tool. As one medical participant said, *"If I am a professor, I will get that tool [VRSS] because it is very easy to handle than this one [IT]"*. Also with regards to the capability of VRSS to customize the visualization, one expert expressed, *"having anatomical features that can be manipulated by making some parts transparent may be very beneficial to anatomical education"*. Such positive comments reflect on the potential of our simulator to address the *learnability* factor, and achieve face and content validity.

The medical participants rated how both simulators may support skill transfer to the operating room. The ratings were 4.1 and 4.6 out of 5 for the IT and VRSS respectively. Also, the participants rated key simulation features as reported in Fig. 2, which shows both simulators to be almost identical with slightly better rating of our simulator for most features except the haptic feedback. The design participants who completed the SUS questionnaire reported average scores of 80.41 and 37.5 out of 100 for VRSS and IT respectively. This seemingly large difference in scores is also reflected by qualitative feedback we received, and may reflect better usability and *learnability* of our prototype.

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 it. Another limitation is about how the IT reports post-simulation performance. As one medical expert stated, *"The [performance] measurement [of VRSS] are better than just the [IT] score 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"*. Most participants, however, highlighted that the haptic feedback was more realistic in IT. As another medical participant expressed, *"The haptic feedback [in IT] was not perfect but comparably better than this one [VRSS]"*. We argue that the limited haptics in VRSS is

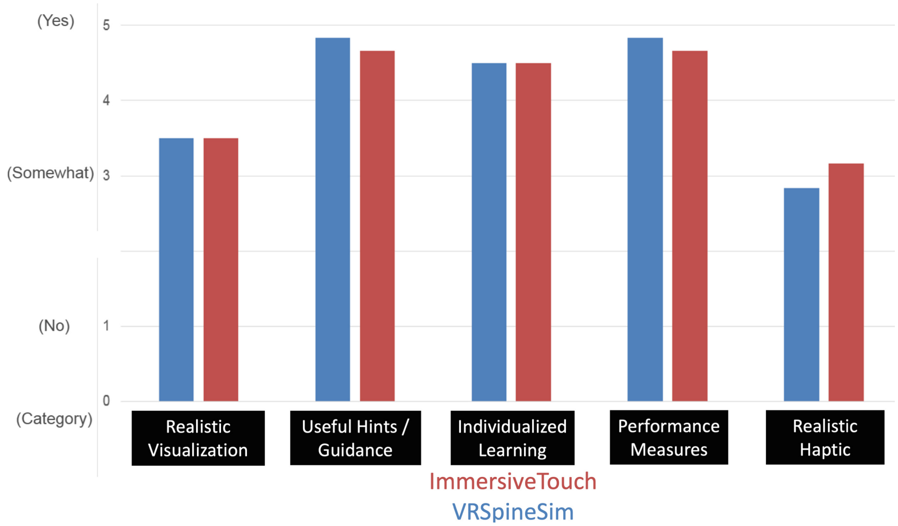

Fig. 2. Rating of simulator features by our medical participants

in part due to the expensive high-quality haptic device of the IT simulator (e.g., roughly 30 times more costly), and because the focus of this work is not about improving the haptic feedback. Nonetheless, we aim as part of our future work to improve our implementation of the haptic feedback. On the positive side, we received various comments about our simulation and the integrated educational elements. For example, one medical participant stated, *"The interactive thing [of VRSS] is quite helpful, with being able to see, I guess, bones and where the nerves are . . . , it just gives you a better idea of the anatomy"*. Such results reflect on the usability aspects of our prototype.

Our study had a small sample size, so we refrain from making any significance claims. We highlight our focus on usability aspects and claim that our approach gives more value to the subjective results received from the domain experts, and this rationale aligns with the argument proposed by Greenberg and Buxton [5].

7 Conclusion and Future Work

We proposed VRSpineSim, 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 following an iterative design approach in collaboration with medical experts. We presented a preliminary evaluation highlighting the potential benefits of our 3D simulation in supporting education and training for the PSI spine surgery procedure. We argue that by including educational aids and following the feedback of medical collaborators, as we demonstrated in this work, the usability and the training quality of immersive medical simulation can be improved.

For future work, we are considering the feedback we received, for instance, to support loading and displaying patient-specific data for enhanced contextuality. We also plan to conduct a formal expanded study with more participants and with additional focus on quantitative measurements.

References

1. Brooke, J., et al.: SUS - a quick and dirty usability scale. Usability Eval. Indus. **189**(194), 4–7 (1996)
2. Brunozzi, D., Shakur, S.F., Kwasnicki, A., Ismail, R., Charbel, F.T., Alaraj, A.: Role of immersive touch simulation in neurosurgical training. In: Alaraj, A. (ed.) Comprehensive Healthcare Simulation: Neurosurgery. CHS, pp. 185–198. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-75583-0_14
3. Clark, A.D., Barone, D.G., Candy, N., Guilfoyle, M., et al.: The effect of 3-dimensional simulation on neurosurgical skill acquisition and surgical performance: a review of the literature. Surg. Educ. **74**, 828–836 (2017)
4. Coles, T.R., Meglan, D., et al.: The role of haptics in medical training simulators: a survey of the state of the art. IEEE Trans. Haptics **4**(1), 51–66 (2011)
5. Greenberg, S., Buxton, B.: Usability evaluation considered harmful (some of the time). In: Proceedings of SIGCHI, CHI 2008, pp. 111–120. ACM (2008)
6. Henriksen, K., Patterson, M.D.: Simulation in health care: setting realistic expectations. Patient Saf. **3**(3), 127–134 (2007)
7. ImmersiveTouch: A leader in simulation based surgical training. http://www.immersivetouch.com/ (2017)
8. Klein, S., Whyne, C.M., et al.: CT-based patient-specific simulation software for pedicle screw insertion. Clin. Spine Surg. **22**(7), 502–506 (2009)
9. Mostafa, A.E., Ryu, W.H.A., Takashima, K., et al.: ReflectiveSpineVR: an immersive spine surgery simulation with interaction history capabilities. In: the 5th Symposium on Spatial User Interaction, SUI 2017, pp. 20–29. ACM (2017)
10. Mostafa, A.E., Ryu, W.H.A., et al.: Designing NeuroSimVR: a stereoscopic virtual reality spine surgery simulator. Technical report, University of Calgary (2017)
11. Naddeo, F., Cataldo, E., Naddeo, A., Cappetti, N., Narciso, N.: An automatic and patient-specific algorithm to design the optimal insertion direction of pedicle screws for spine surgery templates. Med. Biol. Eng. Comput. **55**, 1549–1562 (2017)
12. Nielsen, J.: Usability metrics: tracking interface improvements. IEEE Softw. **13**(6), 12 (1996)
13. Pelargos, P.E., Nagasawa, D.T., Lagman, C., Tenn, S., et al.: Utilizing virtual and augmented reality for educational and clinical enhancements in neurosurgery. Clin. Neurosci. **35**, 1–4 (2017)
14. Pfandler, M., Lazarovici, M., Stefan, P., Wucherer, P., Weigl, M.: Virtual reality based simulators for spine surgery: a systematic review. Spine J. **17**, 1352–1363 (2017)
15. Ryu, W.H.A., Mostafa, A.E., Dharampal, N., et al.: Design-based comparison of spine surgery simulators: optimizing educational features of surgical simulators. World Neurosurg. **106**, 870–877 (2017)
16. Schuler, D., Namioka, A.: Participatory Design: Principles and Practices. CRC Press, Boca Raton (1993)
17. Seymour, N.E., Gallagher, A.G., Roman, S.A., et al.: Virtual reality training improves operating room performance: results of a randomized, double-blinded study. Ann. Surg. **236**(4), 458 (2002)

18. Stanney, K.M., Mollaghasemi, M., et al.: Usability engineering of virtual environments (VEs): identifying multiple criteria that drive effective VE system design. Int. J. Hum.-Comput. Stud. **58**(4), 447–481 (2003)
19. Xiang, L., Zhou, Y., Wang, H., et al.: Significance of preoperative planning simulator for junior surgeons' training of pedicle screw insertion. Spinal Disord. Tech. **28**(1), E25–E29 (2015)