Virtual Reality Simulator with Color-Guidance for Laminectomy

Kesavan Venkatesh
Student

Jonathan Wang
Student

Yi Wang
Student

David Usevitch
Mentor

Hisashi Ishida
Mentor

Adnan Munawar
Mentor

I. INTRODUCTION

A. Background

Laminectomy is a delicate surgical procedure that involves removing portions of the lamina, a vertebral bone that covers the posterior of the spinal canal covering the spinal cord (Fig. 1). This procedure is typically recommended for patients who experience spinal stenosis, or narrowing of the spinal canal, which can cause pain as the bony tissue pinches spinal nerves [1]. The surgeon must mill out enough lamina to alleviate the pressure on the spinal cord and nerves while also preserving enough bone to maintain the structural integrity of the vertebrae. In the U.S. alone, laminectomies are quite common [2] and require significant operative skill.

To ensure the safety of the procedure, the surgeon must be wary to not drill past the thick ligamentum flavum (LF). Drilling the superior-most and inferior-most parts of this anatomy requires careful navigation as the LF serves as a protective barrier between the spinal cord and the bony vertebrae. A single misstep during drilling could lead to inadvertent puncture of the spinal cord, resulting in life-altering consequences for the patient [3]. But even with the utmost care, incidental durotomy (puncturing of the dura) has been reported to occur with incidence rates ranging from 1.6% – 16% [4].

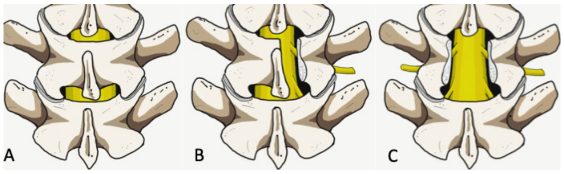


Fig. 1. Lamina removed during a laminectomy. (A) Initial lumbar spine, (B) partial removal shown, (C) complete removal. Taken from [1].

B. Motivation

Prior studies have found that simulation-based training for residents have improved surgical accuracy and speed, which have translated to enhanced care for patients [5]. Cadaveric training is common but also expensive, ethically controversial to use, and sometimes unsafe [6]. In contrast, VR simulation offers a low-risk, lower-cost, and highly customizable training platform for surgeons. Patient-specific anatomies can be uploaded into the platform for preoperative planning. Furthermore, quantitative performance data can be measured and tracked for surgeons throughout their training [7], allowing for standardizing surgical education. VR simulators have in fact been used with early success in mastoid drilling (Fig. 2) [8], [9] and spine surgery [10].

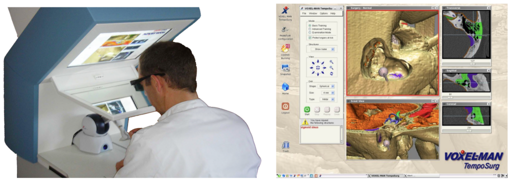


Fig. 2. VOXEL-MAN TempoSurg virtual reality system for mastoid drilling. Taken from [11].

A previous CIS II project, led by Hisashi Ishida and Juan Antonio Barragan, developed an AMBF-based VR simulator with multi-sensory feedback (haptic, audio, and visual) for mastoid drilling (Figure 3) [11]. However, the employed visual feedback system was distracting due to text-box warnings that occluded the field of view in the simulator. The results of their pilot user study evidenced this effect: no significant change in the number of unintended voxels removed was observed between the baseline (no feedback) and visual feedback (Figure 4). There exists a need to improve the simulator by implementing a less cognitively demanding visual display that can caution and guide surgeons while operating.

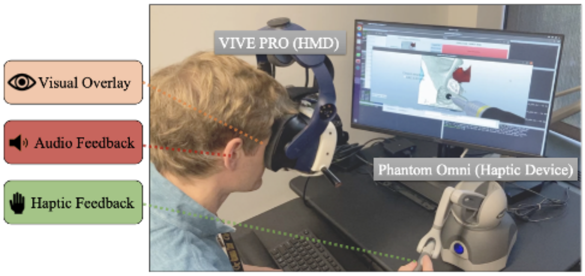


Fig. 3. AMBF-based VR simulator as presented by Ishida et al [12].

II. PROJECT CONTRIBUTIONS

In this project, we improve upon the AMBF-based simulator by developing an anatomical color overlay that guides and cautions users while drilling. We used OpenGL [13] to assign

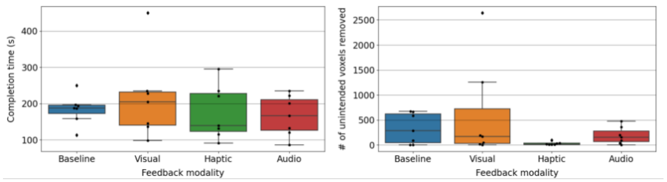


Fig. 4. Quantitative data from pilot user study for mastoid drilling with AMBF-based VR simulator. No significant changes observed in completion time and number of unintended voxels removed between baseline and visual feedback modalities. Taken from [12].

red/yellow/green colors to the different bone structures based on their relative distance to sensitive anatomies. We also evaluated the differential impact of this color-guidance on surgeons' accuracy and operation time while using our simulator. This involved a user-study conducted in collaboration with the Johns Hopkins Department of Orthopedic Surgery.

A. Deliverables

Over the course of this project, our deliverables were adjusted based on delays in critical dependencies. After our checkpoint presentation, our proposed deliverables and their statuses are in Table I. We have finished all of our minimum and expected deliverables.

TABLE I
DELIVERABLES

Level	**Activities**	**Results**	**Status**
Minimum	Familiarize segmenting a lumbar spine CT scan with 3D Slicer	A reproducible protocol for segmenting lumbar spine CTs using 3D Slicer software	Done
	Segmenting lumbar spine CTs following protocol	15 locally saved segmentation files of lumbar spines	Done
	Build VR simulator and upload 15 lumbar spine segmentations to GUI	Ready-to-use laptop with VR GUI for laminectomy user study	Done
Expected	Conduct 8 laminectomy sessions at JHH Orthopedic Surgery education sessions	Collect user VR session data for 8 subjects	Done
	Recruit and conduct 8 more laminectomy sessions at JHH	Collect user VR session data for 8 subjects	Done
	Performing data analysis	Figures for manuscript comparing user performance	Done
	Drafting results section for manuscript	Written results for upcoming manuscript	Done
	Point cloud visualization to "replay" user drilling	Video recap of all performed user-studies	Done
Maximum	Implement a C++ plugin for synchronized data extraction	Unit-tested and documented program for data extraction added into VR simulator	In-progress

III. VR SYSTEM DESIGN

Figure 5 outlines the implementation of the VR system.

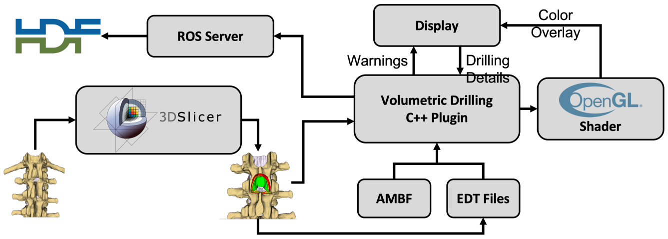


Fig. 5. Design of the VR system developed in this project. Diagram includes specifications of different interfaces and their relationships.

Five lumbar spines were segmented in 3D Slicer with the desired drilling cuts. These segmentations were uploaded as image volumes in the `./resources` folder using the Python script `seg_nrrd_to_pngs.py`. SDF volumes were generated from the image volumes using an offline C++ pipeline. At initialization, a graphical user interface (GUI) is launched from `./scripts/study_gui/study_gui.py` that lists all available anatomical scans for users to practice drilling (Figure 6). Once a spine and region is selected (e.g., spine P1, region L1), the AMBF simulator is run from `./plugin/volumetric_drilling/volumetric_drilling.cpp` to render this case. The composite SDF is based on distances from identified anatomies and structures that should not be drilled. The color overlay uses the composite SDF to caution users against drilling too far in any coordinate direction. Red regions highlight bone that is less than 2mm away from a sensitive anatomy, yellow regions color bone that is between 2mm and 4mm away, and green regions indicate bone that is greater than 4mm away. Text-based warnings are thrown based on whether the drill tip, in the coordinate frame of the simulator, is within either the yellow or red regions. These warnings are positioned to the side, beyond the central field of view, to limit occlusion.

If the recording button is pressed, the VR platform begins recording simulation data (e.g., coordinate and color of voxels removed, drill kinematics, drilling time) and publishing it to a ROS server. A parallel script `./scripts/study_gui/data_record.py` subscribes to the ROS server, queries the data, and locally saves it to HDF5 files (in chunks of 500). This asynchronous data extraction is a burden on the PC and contributes to laggy user sessions after extended drills; our technical developments tackle this issue with a proposed synchronized C++ plugin.

The simulator requires specific hardware components: a GPU-accelerated Linux machine to run the AMBF simulator software, HTV Vive Pro VR headset, Phantom Omni haptic device, headphones, and keyboard. Users are seated in front of the monitor and wear the headset to navigate the virtual world. The haptic device is used to manipulate the drill. A drilling sound will be played and the cutting force is used to set the signal pitch Fig. 6.

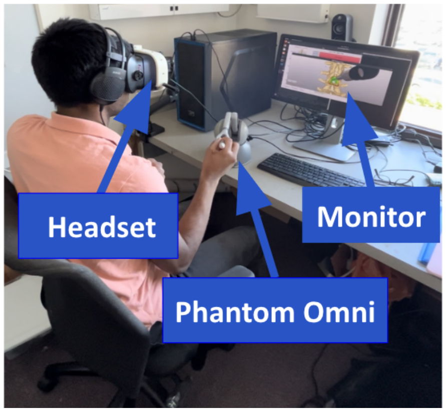


Fig. 6. Hardware setup for the simulator.

IV. TECHNICAL DEVELOPMENTS

A. *Implementing SDFs*

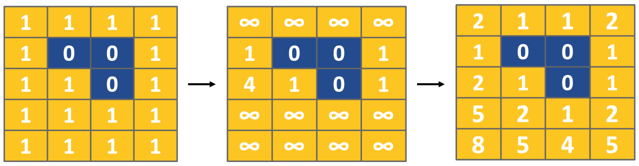
Signed distance fields (SDFs) are the backbone for the color-guidance implemented in the simulator. Different bone pieces are colored based on their relative distance to sensitive anatomies; these distances are queried from the SDF for each anatomy of interest. The SDF itself is computed from the 3D volume extracted from 3D Slicer.

Theory: We provide the mathematical details of computing an SDF in a 2D grid. (These results naturally extend to 3D volume.) An SDF grid can be calculated using a 2-step transform [14]. Figure 7 models this approach. The blue squares represent the sensitive anatomical structure and the yellow squares are the surrounding regions in the grid (in 3D, voxels in the CT scan). The first transform computes the minimum horizontal distance to the surface of the anatomy, and the second transform factors in vertical direction to compute the minimum overall squared distance to the anatomy. The transforms specified in 2D are as follows [14]:

$$g_{ij} = \min_{x}\{(i-x)^2; f_{xj} = 0; 1 \le x \le L\}$$

$$h_{ij} = \min_{y}\{g_{iy} + (j-y)^2; 1 \le y \le M\}$$

where f is the original binary grid (1 indicates anatomy surface, 0 indicates otherwise), and h is the final SDF grid.



1	1	1	1
1	0	0	1
1	1	0	1
1	1	1	1
1	1	1	1

→

∞	∞	∞	∞
1	0	0	1
4	1	0	1
∞	∞	∞	∞
∞	∞	∞	∞

→

2	1	1	2
1	0	0	1
2	1	0	1
5	2	1	2
8	5	4	5

Fig. 7. Two-step transform in the 2D Euclidean Transform used to compute the SDF grid. Adapted from [14].

In 3D, this approach would involve a third transform that accounts for the z-axis direction. However, faster implementations were used to compute these fields in C++ [14].

Note also that in Figure 7, the anatomy is completely filled in. However, in the plugin, distances are computed to the surface of the anatomy. Therefore, distances are signed positive or negative based on whether the voxel is outside or inside the anatomy surface.

Implementation in VR Simulator: Surgeons need a color-guidance that is not only layered depth-wise but also provides color boundaries in the plane of the screen. Therefore we decided to build our SDF volume based on three individual SDFs: the vertebral foramen (VF) behind the lamina (since this is the spinal cord and is strictly off limits for drilling), bone surrounding the lamina to be drilled, and bone in the lumbar vertebra beneath the lamina. A voxel's signed distance in the composite was the minimum across the three SDFs. Figure 8 shows how a sample composition of the three EDTs creates color gradients that extend both radially and along the z-axis.

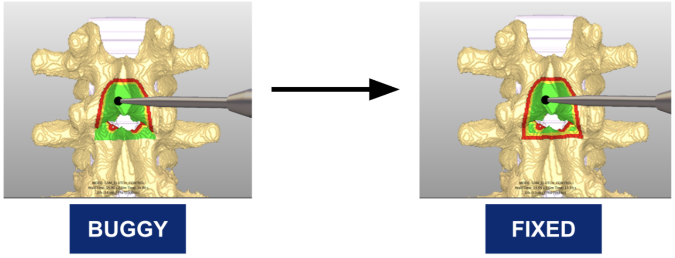


Fig. 8. (left) Inadequate EDT that only uses VF and surrounding bone in the current vertebra. (right) Correct composite EDT that uses all three regions (VF, bone surrounding the lamina, bone beneath the lamina). Notice that the radial and depth-wise boundaries guide the user while drilling

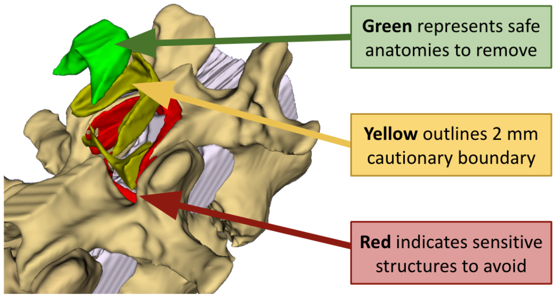


Fig. 9. Expanded view of the color overlay and distance thresholds.

Each anatomy's SDF volume was created and stored offline as a stack of 2D images; these were generated using the `./scripts/EDTImageGeneration/` workflow. In `./plugin/volumetric_drilling/volumetric_drilling.cpp`, we created three variables to load each SDF volume specified. However, in OpenGL, the shader was implemented to handle only two SDFs (one for the VF, one for the bone). This required us to combine the two bone SDFs offline using the `./scripts/EDTImageGeneration/combine_edt_images.py` script.

B. *Synchronous Data Extraction*

We proposed and outlined a synchronous method for AMBF data extraction (Figure 9). Instead of using the GUI to set the recording mode, we would modify the `keyboard_update()` function inside `./plugin/volumetric_drilling/volumetric_drilling.cpp` to toggle the recording mode based on a start and stop hotkey. Then, inside the `physics_update()` method, the `H5DataWriter` class will store the color, coordinates, and time of each voxel that is removed. This class will write to a local HDF5 file with a tunable buffer. By internally writing to HDF5 files inside the C++ plugin, we would eliminate the need for publishing and querying simulation data asynchronously over a ROS server. Obviating this multi-threading would lower the computational cost of the simulator on the PC.

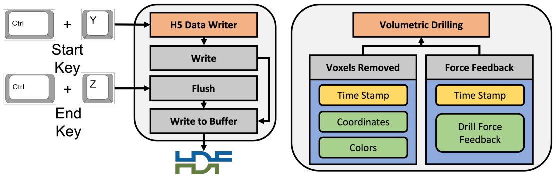


Fig. 10. Proposed scheme for C++ plugin to perform synchronized HDF5 data saving.

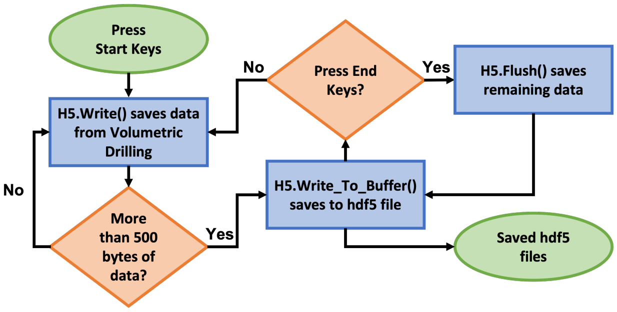


Fig. 11. `H5DataWriter` class and its usage.

Due to delays in conducting the user study, this approach has a preliminary implementation but has not been unit-tested or stress-tested. Both of these are part of our summer plans to improve the system.

C. *Replay GUI*

After conducting a VR session, surgeons need a way to visualize their drilling to receive performance feedback. The current simulator saves HDF5 files but does not include an expressive way to visualize them. We developed a replay system that creates a time-lapse video of the drilling (complete with colors and drill kinematics). Figure 12 shows a sample final state after the participant completed drilling.

V. USER STUDY

We conducted a user study to examine the impact of color-guided drill navigation while performing laminectomies using the VR simulator.

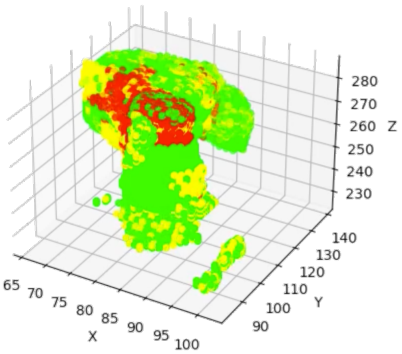


Fig. 12. Final state of drilling time-lapse.

Each participant was asked to complete a series of laminectomies with and without color-guidance. Following each session, participants were asked to complete a short survey about the drilling and navigation method tested. This survey asked about the effectiveness of the drilling platforms tests and participant's preferences to these systems. The survey will also ask if participants are a medical professional or not. If so, it will ask how many years participants have been a practicing medical professional, and if participants perform drilling procedures on a frequent basis.

The NASA-TLX survey was also used to measure perceived workload across a variety of tasks and settings. By evaluating different dimensions of workload such as mental demands, physical demands, and time pressure, the survey can identify areas where a task may be particularly challenging or where improvements can be made.

A. *Segmenting the Spine CTs*

Our first task was producing accurate segmentations of surgical cuts from spine CT scans using the software 3D Slicer. Our clinical collaborators indicated that previous laminectomy segmentations were not accurate or realistic for orthopedic surgeons. Given that we had to segment 5 different spines, each with 3 different segments (L1, L2, & L3), we first developed a reproducible segmentation protocol (available in our design documents). We then generated 20 revised segmentations (an example is shown in Figure 13) that were validated by Dr. Amit Jain for use in our VR platform.

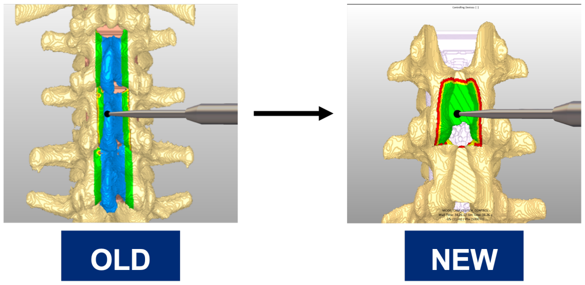


Fig. 13. Example of a revised segmentation following our protocol.

B. Study Design

Eleven participants were recruited as part of this study. Participants were be seated with their drilling arm resting on an arm rest while holding a robotic haptic device (Phantom Omni). The device mimicked a handheld surgical drilling tool by providing force and stiffness feedback as the user probes different anatomy in view. The VR headset immersed users in the operating room. Subjects were asked to mimic a laminectomy drilling with or without colored-navigation. Subjects were be timed on 10 operations and the stated objective was to do these cases as accurately and quickly as possible.

The colored navigation system had red voxels indicating sensitive structures that should not be drilled; drilling red volumes resulted in a breach that flashes a red warning alert. Yellow voxels indicated the user is drilling near a sensitive anatomy, and a yellow warning will recommend caution. Green voxels were safe drilling regions, and no continuous warnings will be provided for drilling here. Blue voxels indicated anatomy is optional for drilling. Subjects were first be given two practice cases, one with colored-guidance and one without, to become accustomed to this platform.

Figure 14 outlines the comparative study design. The collection of 10 spines were presented in randomized order. The first two cases were the aforementioned untimed practice cases; the subsequent 10 cases were timed, 5 with colored-guidance and 5 without. Each subject saw the cases in a different randomized order, to counterbalance navigation conditions. After the practice phase, subjects received a 1 min break; during the evaluation phase, subjects received a mandatory 1 min break after 4 cases.

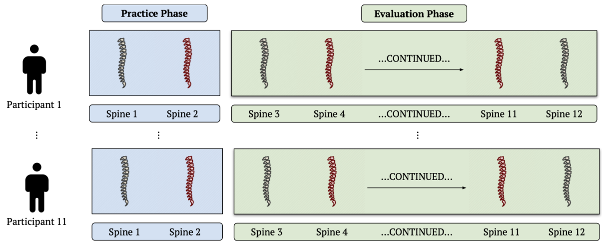


Fig. 14. Comparative study design between color-guidance and no color-guidance.

VI. RESULTS

We collected data as part of our user study from March – May 2023. Eleven participants each completed a 45 minute - 1 hour session of 12 laminectomies.

The completion percentage and number of unintended voxels removed are reported in Figure 15. While there was no significant difference in the number of unintended breaches made between the baseline and color-guided conditions, providing a color overlay significantly increased the mean drilling accuracy from 31% completion to 47% ($p < 0.05$).

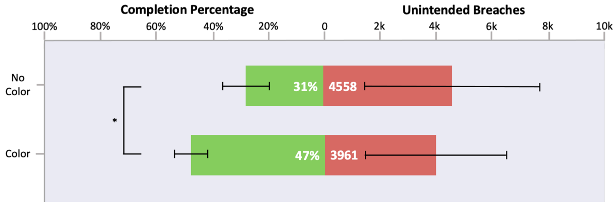


Fig. 15. Comparison of completion percentage (left) and number of unintended breaches (right) between no color-guidance and color-guidance conditions. Color-guidance significantly improved completion percentage and decreased the mean number of unintended breaches made.

The drilling times under both conditions were compared in Figure 16. There was no significant difference found between baseline and color-guided conditions.

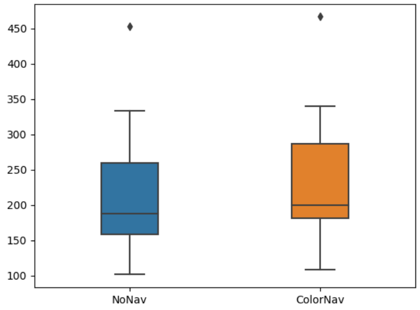


Fig. 16. Drilling time did not significantly change between color-guidance and baseline conditions.

Survey results from the NASA-TLX assessment were collected for 7/11 participants (Figure 17). Color-guidance significantly reduced the mental demand (14.43 vs. 9.14, $p < 0.05$), required effort (16.86 vs. 11.86, $p < 0.05$), and frustration with the VR platform (12.86 vs. 8.14, $p < 0.01$).

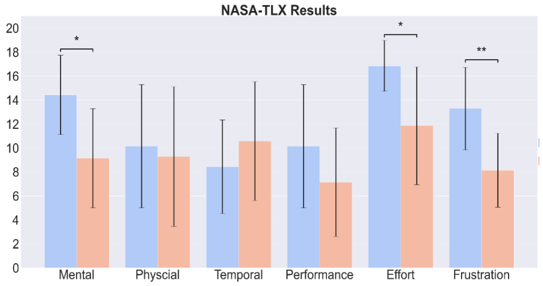


Fig. 17. NASA-TLX survey results indicated reduced cognitive load with color-guidance than without.

VII. DISCUSSION

We evaluated the differential impact that color-guidance had on drilling accuracy and operation time. We collected both quantitative data through AMBF and qualitative feedback from participant drilling sessions.

Comparing drilling accuracy between navigation conditions indicated that participants were equally able to avoid sensitive anatomies but removed more of the lamina with color guidance. This is likely due to participants having a better intuition of where not to drill (e.g., most surgeons clearly know not to drill out the spinal cord) rather than how much is safe to drill. Anecdotal evidence from our collaborators at JHMI Orthopedic Surgery corroborates this, as they indicated that differing standards exist for how thick the remaining lamina should be. To this end, our color-guided VR platform could provide a standardized education tool for resident surgeons training to perform laminectomies.

Total drilling times did not significantly vary between the baseline and color-guided conditions. This is in agreement with previous results with the AMBF-based simulator [12] and suggest that this platform might be better suited for improving surgical accuracy rather than speed.

NASA-TLX survey results indicated that participants generally benefited from the color-guidance. However, a few participants indicated that the platform lagged after extended drills. This was likely due to the asynchronous data extraction pipeline implemented during the user studies; future technical developments will focus on testing and incorporating the native C++ extraction code into the system. During the user studies, it was also necessary for the proctors to adjust the angular offset between the haptic stylus and the visualized drill in the AMBF simulator. This inconsistency occurred because the Phantom Omni stylus required repeated recalibration.

One participant also commented that the simulator graphics could be more physically representative. For example, if a user drilled out a closed path around a piece of bone, only the voxels along that path will be removed. A more physically representative design would also eliminate the central isolated island of voxels. To alleviate this, future iterations of the simulator could incorporate a connectivity check inside the `graphics_update()` subroutine.

VIII. SOFTWARE

Code will be made publicly available upon journal submission here.

REFERENCES

[1] M. Estefan, S. Munakomi, and G. O. Camino Willhuber, "Laminectomy," in *StatPearls*. Treasure Island (FL): StatPearls Publishing, 2023. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK542274/

[2] Z. Li, G. Yu, S. Jiang, L. Hu, and W. Li, "Robot-assisted laminectomy in spinal surgery: a systematic review," *Annals of Translational Medicine*, vol. 9, no. 8, p. 715, Apr. 2021.

[3] J. Y. Du, A. Aichmair, J. Kueper, C. Lam, J. T. Nguyen, F. P. Cammisa, and D. R. Lebl, "Incidental Durotomy During Spinal Surgery: A Multivariate Analysis for Risk Factors," *Spine*, vol. 39, no. 22, p. E1339, Oct. 2014.

[4] H. Ishikura, S. Ogihara, H. Oka, T. Maruyama, H. Inanami, K. Miyoshi, K. Matsudaira, H. Chikuda, S. Azuma, N. Kawamura, K. Yamakawa, N. Hara, Y. Oshima, J. Morii, K. Saita, S. Tanaka, and T. Yamazaki, "Risk factors for incidental durotomy during posterior open spine surgery for degenerative diseases in adults: A multicenter observational study," *PLoS ONE*, vol. 12, no. 11, p. e0188038, Nov. 2017. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5708748/

[5] W. C. McGaghie, S. B. Issenberg, E. R. Cohen, J. H. Barsuk, and D. B. Wayne, "Does Simulation-Based Medical Education With Deliberate Practice Yield Better Results Than Traditional Clinical Education? A Meta-Analytic Comparative Review of the Evidence," *Academic Medicine*, vol. 86, no. 6, p. 706, Jun. 2011.

[6] M. A. Aziz, J. C. Mckenzie, J. S. Wilson, R. J. Cowie, S. A. Ayeni, and B. K. Dunn, "The human cadaver in the age of biomedical informatics," *The Anatomical Record*, vol. 269, no. 1, pp. 20–32, 2002, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ar.10046. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/ar.10046

[7] K. W. van Dongen, E. Tournoij, D. C. van der Zee, M. P. Schijven, and I. A. M. J. Broeders, "Construct validity of the LapSim: Can the LapSim virtual reality simulator distinguish between novices and experts?" *Surgical Endoscopy*, vol. 21, no. 8, pp. 1413–1417, Aug. 2007. [Online]. Available: https://doi.org/10.1007/s00464-006-9188-2

[8] G. Reddy-Kolanu and D. Alderson, "Evaluating the effectiveness of the Voxel-Man TempoSurg virtual reality simulator in facilitating learning mastoid surgery," *Annals of The Royal College of Surgeons of England*, vol. 93, no. 3, pp. 205–208, Apr. 2011. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3291135/

[9] R. Leuwer, A. Petersik, B. Pflesser, A. Pommert, B. Tolsdorff, K. H. Höhne, and U. Tiede, "VOXEL-MAN TempoSurg A Virtual Reality Temporal Bone Surgery Simulator," *JOURNAL OF JAPAN SOCIETY FOR HEAD AND NECK SURGERY*, vol. 17, pp. 203–207, Jan. 2007.

[10] M. Pfandler, M. Lazarovici, P. Stefan, P. Wucherer, and M. Weigl, "Virtual reality-based simulators for spine surgery: a systematic review," *The Spine Journal*, vol. 17, no. 9, pp. 1352–1363, Sep. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1529943017302085

[11] "VOXEL-MAN TempoSurg." [Online]. Available: https://www.voxel-man.com/gallery/temposurg/

[12] H. Ishida, J. A. Barragan, A. Munawar, Z. Li, P. Kazanzides, M. Kazhdan, D. Trakimas, F. X. Creighton, and R. H. Taylor, "Improving Surgical Situational Awareness with Signed Distance Field: A Pilot Study in Virtual Reality," Mar. 2023, arXiv:2303.01733 [cs]. [Online]. Available: http://arxiv.org/abs/2303.01733

[13] "OpenGL - The Industry Standard for High Performance Graphics." [Online]. Available: https://www.opengl.org/

[14] T. Saito and J.-I. Toriwaki, "New algorithms for euclidean distance transformation of an n-dimensional digitized picture with applications," *Pattern Recognition*, vol. 27, no. 11, pp. 1551–1565, Nov. 1994. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0031320394901333