EPiC Series in Health Sciences
Volume 8, 2026, Pages 118–123
Proceedings of The 25th Annual Meeting of the International Society for Computer Assisted Orthopaedic Surgery

Enhancing Orthopedic Surgical Training With Interactive Photorealistic 3D Visualization

Roni Lekar[1]*, Tatiana Gerth[2]†, Sergey Prokudin[3,4]‡, Matthias Seibold[4]§, Reto Bürgin[2]¶, Benjamin Vella[5]‖, Armando Hoch[5]**, Siyu Tang[3]††, Philipp Fürnstahl[4]‡‡ and Helmut Grabner[12]§§

[1] Institute of Computer Science, School of Engineering, Zurich University of Applied Sciences, Winterthur, Switzerland {roni.lekar, helmut.grabner}@zhaw.ch
[2] Institute of Data Analysis and Process Design, School of Engineering, Zurich University of Applied Sciences, Winterthur, Switzerland {tatiana.gerth, reto.buergin}@zhaw.ch
[3] Vision and Learning Group, ETH Zurich, Zurich, Switzerland {sergey.prokudin,siyu.tang}@inf.ethz.ch
[4] Research in Orthopedic Computer Science, Balgrist University Hospital, University of Zurich, Zurich, Switzerland {matthias.seibold, philipp.fuernstahl}@balgrist.ch
[5] Department of Orthopaedics, Balgrist University Hospital, University of Zurich, Zurich, Switzerland armando.hoch@balgrist.ch
[6] Faculty of Medicine, University of Zurich, Zurich, Switzerland benjamin.vella@uzh.ch

https://panteroni.github.io/3dsurgerytraining

Abstract

Surgical training integrates several years of didactic learning, simulation, mentorship, and hands-on experience. Challenges include stress, technical demands, and new technologies. Orthopedic education often uses static materials like books, images, and videos, lacking interactivity. This study compares a new interactive photorealistic 3D visualization to 2D videos for learning total hip arthroplasty. In a randomized controlled trial, participants (students and residents) were evaluated on spatial awareness, tool placement, and task times in a simulation. Results show that interactive photorealistic 3D visualization significantly improved scores, with residents and those with prior 3D experience performing better. These results emphasize the potential of the interactive photorealistic 3D visualization to enhance orthopedic training.

*Corresponding author; software, conducting user study, writing - original draft
†Software, conducting user study, writing - original draft
‡Shaping user study, recordings and 3D reconstructions, writing - reviewing
§Shaping user study, writing - reviewing
¶Data analysis
‖Organizing participants
**Setting and verifying medical content
††Infrastructure, methodology and supervision
‡‡Infrastructure, methodology and supervision
§§Feedback, support, methodology and supervision

1 Introduction

Spatial awareness in orthopedic surgery remains challenging, requiring innovative teaching strategies [14]. Traditional tools like textbooks and videos [12, 3] lack interactivity, which is more effective for learning [15]. While videos outperform textbooks [2], their fixed angles and visual obstructions highlight the need for interactive modalities.

Extended reality technologies, including virtual and augmented reality (AR), are emerging in surgical education [13, 4, 18], particularly in total hip arthroplasty (THA), enhancing accuracy and skill assessment [6, 8]. However, AR hardware requirements can limit accessibility.

Advances in 3D reconstruction [19] now enable photorealistic, interactive models from 2D images via methods like Neural Radiance Fields [11] and 3D Gaussian Splatting (3DGS)[7], potentially improving procedural understanding in orthopedic training.

We introduce a novel approach combining photorealistic 3D reconstructions, using 3DGS, with interactive elements to immerse learners in THA surgery. A user study compared this method with traditional video recordings, detailing study design, participant recruitment, and evaluation methods.

2 Methods

The study involved 56 participants, including 40 students and 16 residents, with varying THA experience. A randomized controlled trial with a *pre–post* design was conducted on a laptop. Participants watched a THA overview video and completed a tutorial to navigate the virtual environment. Knowledge gain was assessed through three THA tasks identified by senior surgeons as indicators of procedural understanding (Figure 1).

Participants were randomly assigned to one of the following two groups:

Group A – Flyover Video (FV): A non-interactive dynamic video of a specific static scene from the surgical step, with labeled anatomical structures overlaid.

Group B – Interactive Visualization (IV): A photorealistic 3D model [7] reconstructed from FV footage, enabling free navigation and toggling of anatomical structures.

A scoring system was developed with a senior surgeon to compare task accuracy, combining position and rotation scores into a final task score, as shown in task 1's formula:

$$\text{PositionScore} = \begin{cases} 100 & \text{if } distPos \leq 0.05\text{m} \\ 100 \cdot \left(1 - \frac{distPos - 0.05}{1 - 0.05}\right) & \text{if } 0.05\text{m} < distPos < 1\text{m} \\ 0 & \text{otherwise} \end{cases}$$

$$\text{RotationScore} = \begin{cases} 100 & \text{if } distRot \leq 0.2 \\ 100 \cdot \left(1 - \frac{distRot - 0.2}{1 - 0.2}\right) & \text{if } 0.2 < distRot < 1 \\ 0 & \text{otherwise} \end{cases}$$

$$\text{FinalScore} = \frac{\text{PositionScore} + \text{RotationScore}}{2}$$

distPos is the shortest distance from the saw tip to acceptable bone entry points in meters and *distRot* is the magnitude of the cross product between the normal vectors of the submitted and target saw planes. For the other tasks, rotation scores use rotation axes, but overall it remains consistent with thresholds and linear interpolation.

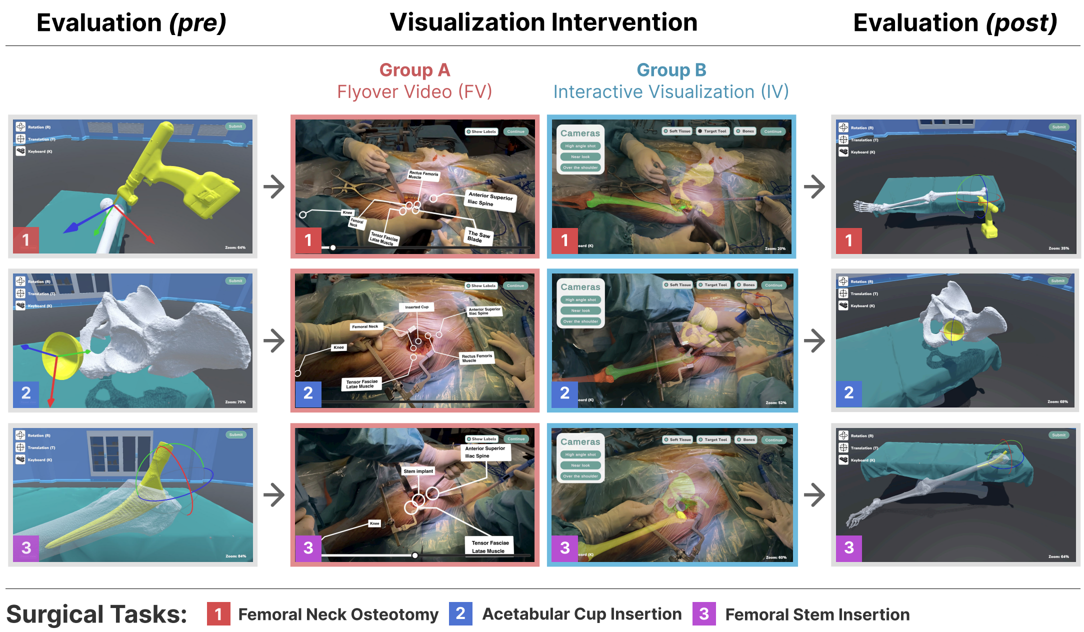


Figure 1: The evaluation scene is shown before and after the visualization intervention to measure learning outcomes for each modality. The three surgical tasks evaluated are: Femoral Neck Osteotomy (task 1), Acetabular Cup Insertion (task 2), and Femoral Stem Insertion (task 3). Each participant completed these tasks in sequence. IV enhances spatial awareness with **immersive navigation** for spatial exploration [16], **gizmo-based transformations** for intuitive tool use [9], **shadows** for depth perception [10], and **transparent bones** for clearer tool placement. It also provides unrestricted camera control and layer toggling, addressing the fixed angles of video-based methods.

The local ethics committee approved the study. Participants provided informed consent with safeguards for anonymity.

3 Results and Discussion

The statistical analysis employed linear mixed models [17] implemented in R with the lme4 package [1], enabling the examination of:

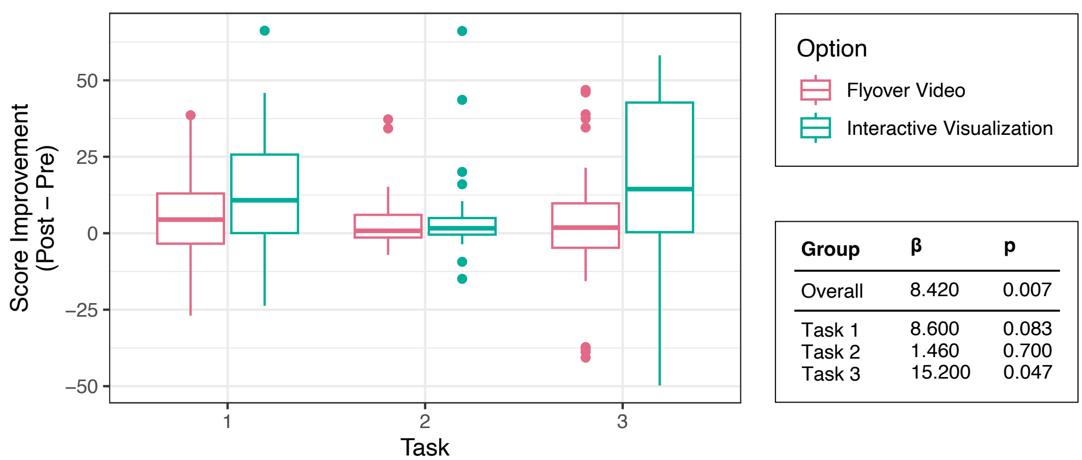
i Whether improvement from *pre* to *post* is greater for IV than FV.

ii The *post*-group difference, considering possible covariate effects and intra-individual correlations.

The models used computed scores as the response variable, with task, option (FV vs. IV), stage (*pre* vs. *post*), resident surgeon, and 3D experience as explanatory variables. Random intercepts accounted for intra-individual correlations. Bootstrap methods computed p-values. Regression coefficients (β) represent the estimated score difference when an explanatory variable changes by one unit, with p-values below 0.05 indicating significance at the 5% level.

Comparing *post* scores, the IV group performed slightly better, but the difference was not significant ($\beta = 4.230, p = 0.062$). For *pre* scores, they tended to score lower than the FV group across all tasks ($\beta = 4.200, p = 0.062$), despite random group assignment. This imbalance likely reflects random variation, not systematic bias. Based on these results, our analysis focuses on the *pre*-to-*post* score changes - **the learning effect**; reflecting improvements in performance after an intervention - rather than just the *post* results.

Across all tasks, IV resulted in a significantly greater learning effect than FV ($\beta = 8.420, p = 0.007$). Residents performed better overall ($\beta = 4.030, p = 0.012$), likely due to their subject familiarity, and those with 3D knowledge outperformed others ($\beta = 5.490, p = 0.007$), consistent with previous studies [5]. Regular use is crucial for tool effectiveness. Data showed minimal impact of time on task completion, with difficulty and familiarity playing larger roles.



Group	β	p
Overall	8.420	0.007
Task 1	8.600	0.083
Task 2	1.460	0.700
Task 3	15.200	0.047

Figure 2: Comparison of the learning effect within tasks between FV and IV, with the boxplot illustrating the distribution and mean of the learning effect. The table on the right illustrates how IV outperformed FV. The β and p values refer to the estimated extent to which the learning effect was higher for IV and the corresponding p-value, derived from a linear mixed model. Significant learning effects are observed overall ($p = 0.007$) and for Task 3 ($p = 0.047$), highlighting the advantage of IV.

The comparison of learning effects for each task, as shown in Figure 2, highlights the overall advantage of IV over FV. Task 1 showed a trend toward greater learning effect for IV. The smaller visible anatomy section makes interpreting the osteotomy's impact challenging, but IV simplifies this task significantly. Task 2 exhibited minimal differences between groups, reflecting the task's simplicity (high *pre* and *post* scores) and clear geometric structure. Notably, task 3 revealed a significant advantage for IV, emphasizing the importance of full femur visualization for accurate judgment of 3D position.

Although task 3 was the only one with a statistically significant result at the 5% level, this does not contradict the overall results, as task-specific tests use smaller sample sizes. These findings reveal that IV provides a significantly greater learning effect than existing tools like FV [12].

4 Conclusion and Future Work

The results showed that overall the new IV method led to significantly bigger improvement than the FV method ($\beta = 8.420, p = 0.007$). They also indicated that residents and participants with 3D experience tended to achieve better outcomes. These preliminary results show potential in the new method for better skill retention than traditional approaches, but further investigation is needed. The limited sample size may affect the robustness of these findings. Our limitations include the high cost of recording surgeries, requiring rental of specimens and operating rooms, while adhering to strict hygiene standards. Additionally, the objects must remain still to avoid blurriness in the model. Nevertheless, the study's findings could enable a library of surgeries featuring IVs of key steps, accessible across various platforms.

5 Acknowledgments

We thank the medical students, residents and orthopedic surgeons who participated. This study was conducted within the national "Proficiency" research project funded by Innosuisse.

References

[1] Douglas Bates, Martin Mächler, Ben Bolker, and Steve Walker. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1):1–48, 2015.

[2] Steen Buch, Frederik Treschow, Jesper Brink Svendsen, and Bjarne Worm. Video- or text-based e-learning when teaching clinical procedures? a randomized controlled trial. *Advances in Medical Education and Practice*, 5:257–62, 08 2014.

[3] Samy Cheikh Youssef, Abdullatif Aydın, Alexander Canning, Nawal Khan, Kamran Ahmed, and Prokar Dasgupta. Learning surgical skills through video-based education: A systematic review. *Surgical Innovation*, 30:155335062211201, 08 2022.

[4] Nadja Farshad, Rahel Kubik-Huch, Christoph Kolling, Cornelia Leo, and Joerg Goldhahn. Learning how to perform ultrasound-guided interventions with and without augmented reality visualization: a randomized study. *European radiology*, 33, 11 2022.

[5] Thorsten Jentzsch, Stefan Rahm, Burkhardt Seifert, Jan Farei-Campagna, Clément Werner, and Samy Bouaicha. Correlation between arthroscopy simulator and video game performance: A cross-sectional study of 30 volunteers comparing 2- and 3-dimensional video games. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 32, 03 2016.

[6] Eustathios Kenanidis, Panagiotis Boutos, Grigorios Voulgaris, Aikaterini Zgouridou, Eleni Gkoura, Zakareya Gamie, George Papagiannakis, and Eleftherios Tsiridis. Effectiveness of virtual reality compared to video training on acetabular cup and femoral stem implantation accuracy in total hip arthroplasty among medical students: a randomised controlled trial. *International Orthopaedics*, 48, 11 2023.

[7] Bernhard Kerbl, Georgios Kopanas, Thomas Leimkühler, and George Drettakis. 3d gaussian splatting for real-time radiance field rendering. *ACM Trans. Graph.*, 42(4):139–1, 2023.

[8] Kartik Logishetty, Wade Gofton, Branavan Rudran, Paul Beaulé, and Justin Cobb. Fully immersive virtual reality for total hip arthroplasty: Objective measurement of skills and transfer of visuospatial performance after a competency-based simulation curriculum. *The Journal of Bone and Joint Surgery*, 102:1, 01 2020.

[9] Tiago Madeira, Bernardo Marques, Miguel Neves, Paulo Dias, and Beatriz Santos. Comparing desktop vs. mobile interaction for the creation of pervasive augmented reality experiences. *Journal of Imaging*, 8:1–13, 03 2022.

[10] Pascal Mamassian, David Knill, and Daniel Kersten. The perception of cast shadow. *Trends in Cognitive Sciences*, 2:288–295, 08 1998.

[11] Ben Mildenhall, Pratul P. Srinivasan, Matthew Tancik, Jonathan T. Barron, Ravi Ramamoorthi, and Ren Ng. Nerf: representing scenes as neural radiance fields for view synthesis. *Commun. ACM*, 65(1):99–106, December 2021.

[12] Orthobullets. An educational resource for orthopedic surgeons, 2025.

[13] Isabel Silva, Gerson Klein, and Denise Brandão. Segmented and detailed visualization of anatomical structures based on augmented reality for health education and knowledge discovery. *Tsinghua Science & Technology*, 2:469, 05 2017.

[14] Charlotte Silén. Advanced 3d visualization in student-centred medical education. *Medical Teacher*, 30(5):e115–e124, 2008. PMID: 18576181.

[15] Mohammadamin Talebi and Mohammad Safaei. Measuring user engagement in educational platforms: A study on interactive vs. passive learning. *International Journal of Advanced Human Computer Interaction*, 1(1):53–62, 2022.

[16] Tina Vajsbaher, Holger Schultheis, Paphon Sa-ngasoongsong, Ratthapoom Watcharopas, Myat Su Yin, and Peter Haddawy. The role of spatial cognition in surgical navigation in arthroscopic surgery. In *The Role of Spatial Cognition in Surgical Navigation in Arthroscopic Surgery*, 05 2020.

[17] West. Linear mixed models: A practical guide using statistical software (3rd ed.), 2022.

[18] Luohong Wu, Matthias Seibold, Nicola A. Cavalcanti, Jonas Hein, Tatiana Gerth, Roni Lekar, Armando Hoch, Lazaros Vlachopoulos, Helmut Grabner, Patrick Zingg, Mazda Farshad, and Philipp Fürnstahl. A novel augmented reality-based simulator for enhancing orthopedic surgical training. *Computers in Biology and Medicine*, 185:109536, 2025.

[19] Yiheng Xie, Towaki Takikawa, Shunsuke Saito, Or Litany, Shiqin Yan, Numair Khan, Federico Tombari, James Tompkin, Vincent Sitzmann, and Srinath Sridhar. Neural fields in visual computing and beyond. In *Computer Graphics Forum*, volume 41, pages 641–676. Wiley Online Library, 2022.