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Randomized crossover study of immersive planning in craniomaxillofacial trauma comparing virtual reality and workstation workflows

Gou Yves Pargätzi[1,2,3,5], Benito K. Benitez[1,2,3,5]✉, Yoriko Lill[1,2], Jokin Zubizarreta Oteiza[1,2], Florian M. Thieringer[1,2,3,5] & Neha Sharma[1,2,4,5]

Preoperative planning for cranio-maxillofacial (CMF) trauma requires precise understanding of complex anatomy. Planning in CMF trauma benefits from advanced visualization and segmentation techniques. While conventional workstation-based software is established, it is often time-consuming and less intuitive. Virtual reality (VR) platforms offer stereoscopic visualization and intuitive spatial interaction with volumetric data and have demonstrated potential advantages in efficiency and user acceptance in previous studies. The aim of this study was to compare workflow efficiency and usability of a VR-based platform with workstation-based software for CMF trauma segmentation. In a randomized crossover study, 15 participants segmented five CMF trauma CT datasets using both platforms. Each case was segmented twice (once per platform) in randomized order with a one-week washout period. Segmentation time was recorded, and user experience assessed using the System Usability Scale (SUS). Statistical analysis used paired t-tests and Wilcoxon signed-rank tests. The VR platform completed segmentation significantly faster, with an average time reduction of 23 min (24%, $p = 0.008$). The SUS scores were higher for the VR platform; the VR platform exceeded the good usability threshold (73.0) while the workstation-based software scored below average (58.17). Participants rated the VR platform as less complex, easier to learn, and more intuitive. Both platforms received equivalent ratings for anatomical structure recognition and physical fatigue. VR-based segmentation demonstrated significant efficiency gains and favorable usability while maintaining equivalent anatomical visualization. These results suggest that immersive systems offer valuable benefits for CMF trauma planning.

Keywords Virtual Reality, User-Computer Interface, Cranio-maxillofacial Surgery, CMF Trauma, Image Processing, Computer-Assisted Methods Three-Dimensional Imaging, Maxillofacial Injuries

Cranio-maxillofacial (CMF) trauma represents a significant global health burden, with high prevalence in both civilian and military populations. Head and facial injuries account for up to 30–40% of all trauma cases in armed conflicts and remain a leading cause of long-term functional and aesthetic impairment[1–4]. Severe CMF injuries in warfare often lead to massive bleeding and acute airway compromise, making life-saving measures such as immediate hemostasis and airway management a priority[5]. Similarly, ballistic facial injuries in combat pose a particular challenge, as they often compromise multiple tissues and require a staged, interdisciplinary reconstruction[6]. In civilian settings, CMF trauma frequently results from traffic accidents, interpersonal violence, sports injuries, and occupational accidents. Reported incidence rates fall between 10 and 24% of all major trauma admissions depending on region, for example, approximately 10.5% at the Miami Valley Hospital,

[1]Oral and Craniomaxillofacial Surgery, University Hospital Basel and University of Basel, Spitalstrasse 21, Basel 4031, Switzerland. [2]Department of Clinical Research, Department of Biomedical Engineering, University of Basel, Basel, Switzerland. [3]Specialist Centre for Oral and Maxillofacial Surgery and Emergency Dental Medicine of the Competence Centre for Military and Disaster Medicine, Swiss Armed Forces, Bern, Switzerland. [4]Duke-NUS Medical School, National University of Singapore, Singapore, Singapore. [5]Gou Yves Pargätzi, Benito K. Benitez, Florian M. Thieringer and Neha Sharma contributed equally to this work. ✉email: benito.benitez@usb.ch

a Level-I trauma center in the U.S[7]., 15–24% in parts of England[8], and in Switzerland, facial trauma accounts for approximately 10.4% of all documented trauma cases in emergency departments[9]. The anatomical complexity of the CMF region makes diagnosis and preoperative planning particularly challenging. Precise visualization and segmentation of complex fractures are essential for accurate surgical planning, outcome prediction, and patient-specific reconstruction.

Recent advances in three-dimensional (3D) imaging and digital workflows, including virtual reality (VR), augmented reality (AR), and mixed reality (MR) and 3D printing, have opened new opportunities to improve visualization, planning, and education in CMF trauma surgery[10–12]. Despite these advances, most clinical image segmentation workflows still rely on manual delineation on two-dimensional (2D) computed tomography (CT) or magnetic resonance imaging (MRI) slices using specialized workstation-based software. Although these systems have been established for years and offer extensive functionality, their use is often considered time-consuming and require considerable training and prior experience. The complexity of the user interfaces can be a barrier to entry, especially for less experienced users[13]. On the other hand, VR, AR, and MR allow immersive interaction with complex anatomical structures, which may be especially valuable in complex injuries, high-energy trauma, and cases intended for virtual surgical planning and 3D printing applications[14].

These immersive visualization technologies have increasingly been explored for surgical planning and anatomical education across multiple surgical specialties[13]. By allowing users to interact with volumetric imaging datasets in a fully 3D environment, these systems may improve spatial understanding of complex anatomical relationships compared with conventional 2D workstation interfaces. In head and neck and cranio-maxillofacial surgery, immersive technologies have been applied to surgical simulation, preoperative planning, and educational applications, with several studies reporting improved anatomical comprehension and favorable learning experiences among trainees and clinicians[15–17]. Systematic reviews have highlighted the potential of immersive visualization to enhance spatial perception, reduce cognitive workload when interpreting volumetric datasets, and facilitate more intuitive interaction with patient-specific anatomy[17,18].

However, only a limited number of studies have systematically compared the use of VR systems with established workstation-based segmentation solutions in the context of CMF trauma planning, and quantitative data on workflow efficiency and usability remain scarce[10,12,16]. Although VR has been suggested to simplify workflows and enhance user-friendliness, robust data to substantiate these assumptions in CMF trauma planning is lacking. The present study, therefore, aimed to evaluate whether VR-based segmentation improves workflow efficiency and usability compared to conventional workstation-based software for CMF trauma datasets.

This should contribute to the evidence base regarding the integration of VR technologies into routine clinical planning of CMF trauma in both civilian and military settings.

Materials and methods

Study design

This prospective, randomized crossover study compared segmentation performance using a VR-based platform and workstation-based software. Figure 1 depicts the study design workflow consisting of participants, imaging data, tasks and questionnaire.

The study was reviewed and approved by the Ethics Commission of Northwest and Central Switzerland (EKNZ) (approval protocol number 2025-00041) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to participation. Informed consent was obtained from the patients for further use of their data for research.

Software and segmentation platforms

To evaluate user workflow efficiency and perceived usability during segmentation, the systems were assessed in typical operating configurations representative in clinical settings.

Virtual reality system

VR-based segmentation was performed using a VR platform (Elucis™, Realize Medical Inc., Ottawa, Canada). The system utilized a head-mounted display (HP Reverb G2, HP Inc., Palo Alto, CA, USA) with dual hand-held controllers tracked directly through the headset without requiring external sensors. The software was operated on a standard PC [Blade 18 - RZ09-0484; NVIDIA GeForce RTX 4090 Laptop GPU, RAM: 32 GB, 13th Gen Intel Core i9-13950HX @ 2.20 GHz].

Workstation-based software

Conventional segmentation was performed using commercial segmentation software (Materialise Mimics, version 26.0, Materialise NV, Leuven, Belgium) on [HP Z2 Tower G9; Intel® UHD Graphics 770, RAM: 128 GB, Intel Core i9-14900 @ 2.00 GHz]. Segmentation operations in Materialise Mimics are primarily CPU-based processes, whereas the GPU mainly supports 3D visualization and rendering performance. The workstation was equipped with a desktop Intel Core with comparable computational capacity for segmentation tasks.

Participants

Fifteen participants were recruited from five professional subgroups ($n = 3$ per group) to ensure heterogeneity in experience levels and reduce bias from enrolling experienced segmentation users: (1) CMF surgeons (dual medical and dental licenses, clinically active); (2) surgical residents (one license completed, second in progress, active in CMF surgery); (3) dentists (trained, working in a Level 1 Trauma center); (4) biomedical engineers (PhD candidates, regularly performing clinical CMF segmentations); and (5) medical and dental students.

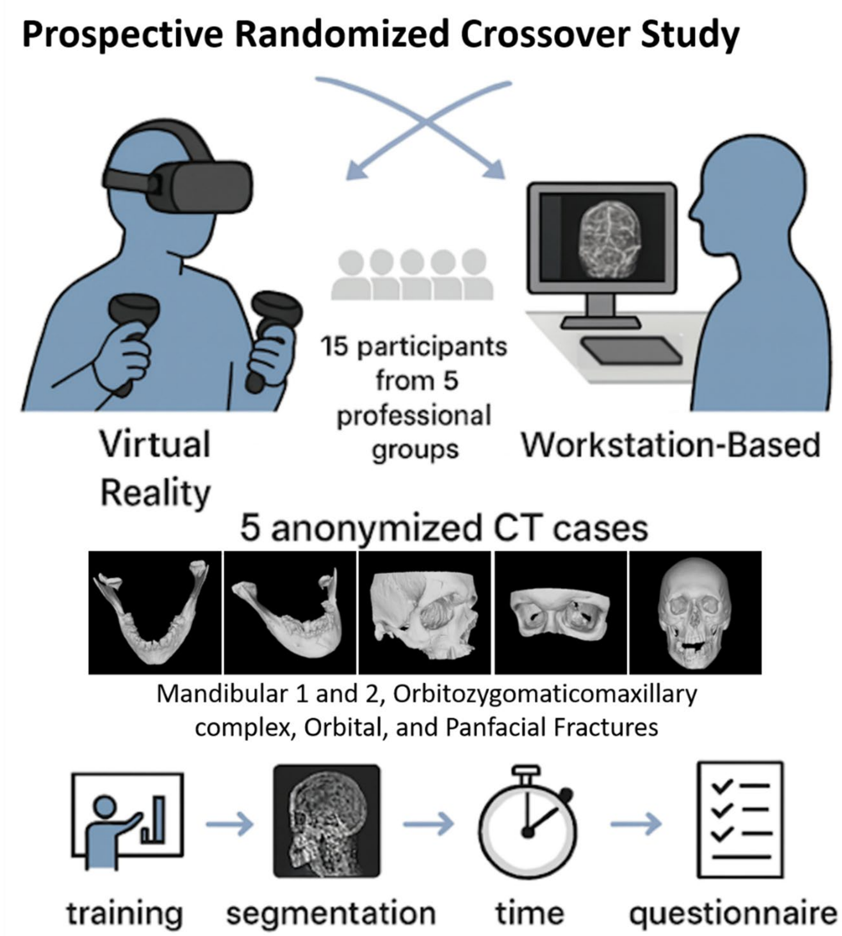

Fig. 1. Study design and its workflow of tasks performed by the participants.

Case	Anatomical description	Scanner model	kVp	Tube current (mA)	Slice thickness (mm)	Pixel spacing (mm)	Voxel size (mm)	Reconstruction diameter/FOV (mm)	Matrix size	Reconstruction Kernel
01	Mandible fracture	Emotion 16	130	128	0.75	0.4277 × 0.4277	0.4277 × 0.4277 × 0.75	219	512 × 512	H70s
02	Mandible fracture	SOMATOM Definition AS+	120	147	0.75	0.4180 × 0.4180	0.4180 × 0.4180 × 0.75	214	512 × 512	J30s
03	Orbitozygomaticomaxillary complex fracture	SOMATOM Force	120	143	2	0.4238 × 0.4238	0.4238 × 0.4238 × 2	217	512 × 512	Hr38s
04	Orbital two wall fracture	SOMATOM Force	120	144	0.75	0.4648 × 0.4648	0.4648 × 0.4648 × 0.75	238	512 × 512	Hr38s
05	Panfacial fracture	SOMATOM Force	120	196	0.75	0.5020 × 0.5020	0.5020 × 0.5020 × 0.75	257	512 × 512	Hr38s

Table 1. Computed tomography acquisition parameters of datasets used in the usability and segmentation comparison study.

Imaging data

Five anonymized CT datasets of CMF trauma cases with varying complexity were selected from the University Hospital Basel clinical archive. All imaging data were acquired on multi-detector CT scanners manufactured by Siemens Healthineers (Erlangen, Germany) for clinical purposes and anonymized according to institutional protocols prior to study use. CT acquisition parameters depended on the indication for the trauma case as determined during the initial radiological examination. Detailed acquisition parameters for each dataset are summarized in Table 1.

Segmentation procedure

Each participant segmented all five CT datasets twice, once with each software platform using a randomized crossover design. Randomization of platform order was performed using the sealed envelope method. A one-week washout period separated the two segmentation sessions to minimize learning and carryover effects. Within each session, the order of the five cases was randomized but remained consistent between platforms for each participant to control for effects related to case complexity.

Prior to each session, participants received standardized training consisting of: (1) a presentation explaining the study background, objectives, and segmentation quality criteria (Supplemental Data 1); and (2) a platform-specific instructional video demonstrating the standard operating procedure (Video 1: workstation-based software; Video 2: VR platform, Supplemental Data 2).

Segmentation quality criteria were defined as follows: (1) anatomical contours matching patient anatomy; (2) target region isolated from surrounding structures (mandible for mandibular fractures, both orbits for orbital fractures, skull for panfacial fractures, midface for orbitozygomaticomaxillary fractures); (3) no free-floating structures remaining; and (4) no artifacts at fracture sites (minimal artifacts in clinically irrelevant regions, such as minor dentition areas due to image quality, were acceptable).

Segmentation time was recorded from initiation to completion of a model meeting all quality criteria using manual recording by an investigator with a stopwatch. Representative segmentation workflows for both platforms are illustrated in Figs. 2 and 3.

Outcome measures

Primary outcome

Segmentation time (minutes) for each case.

Secondary outcome

User experience assessed according to the System Usability Scale (SUS), a validated 10-item questionnaire measuring system usability[19]. Participants rated statements on a 5-point Likert scale ranging from “strongly disagree” (1) to “strongly agree” (5). The SUS score (ranging from 0 to 100) was calculated using the standard formula: for odd-numbered items (1, 3, 5, 7, 9), the response score minus 1; for even-numbered items (2, 4, 6, 8, 10), 5 minus the response score; the sum of all converted scores is then multiplied by 2.5. Scores greater than 68 are considered above average and indicate good usability[20]. The questionnaire was adapted to include items specific to the segmentation task and the platforms, including interface design, ease of learning, physical fatigue during segmentation, anatomical visualization quality, and user confidence (Supplemental Data 3). The same questionnaire was administered for both platforms.

Statistical analysis

Descriptive analysis was carried out to summarize the data. Data normality was assessed using the Shapiro-Wilk test. Accordingly, paired t-tests or Wilcoxon signed-rank tests were performed to compare segmentation times and SUS scores between the VR platform and workstation-based software. The significance threshold was set at $p < 0.05$ (two-tailed). A sample size of $n = 15$ was chosen based on feasibility for this exploratory study. All statistical analyses were conducted using Python® (version 3.9).

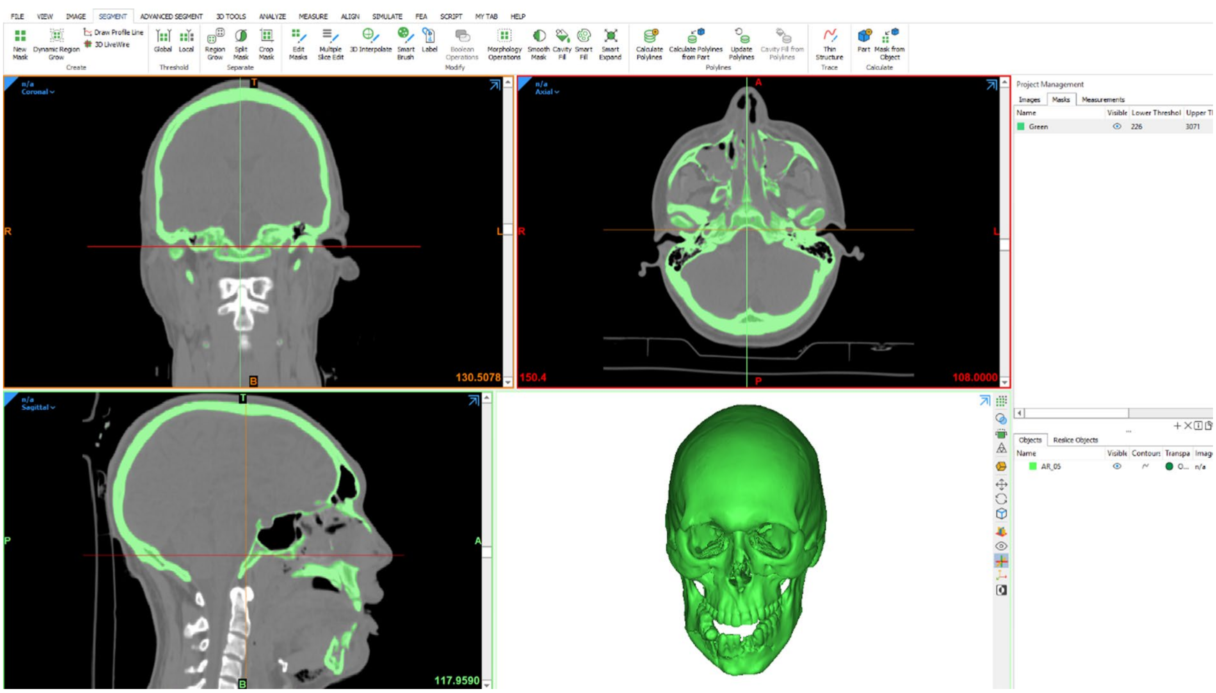

Fig. 2. Workstation-based software with simultaneous view of the sagittal, coronal and axial planes of the CT scan and additionally the reconstructed 3D model in editing window.

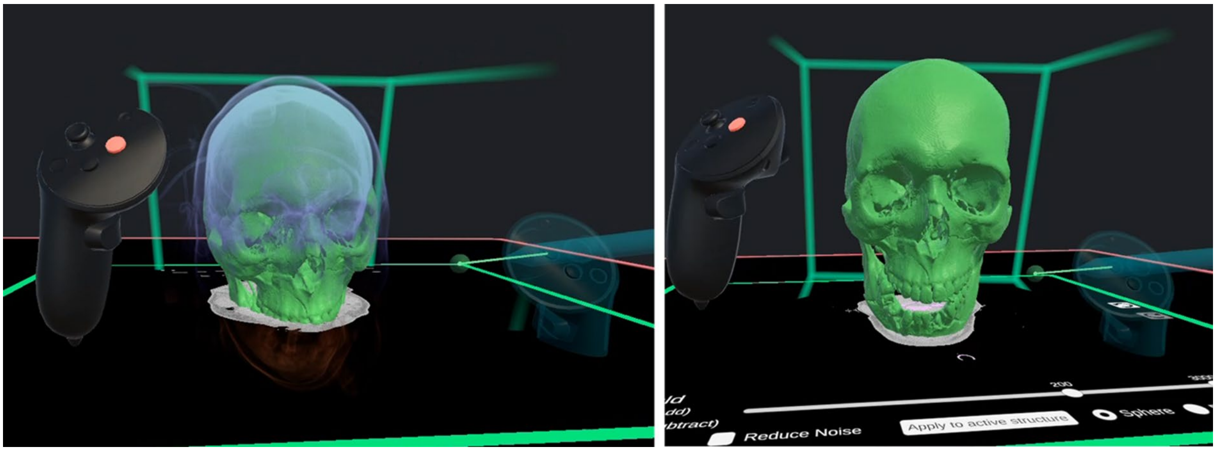

Fig. 3. The model (green) can be manipulated freely with the tools (controllers in black and transparent turquoise), which allows an overview of the segmentation progress from all angles facilitating efficient working. The corresponding CT cross-section, is shown in the working surface.

	Mean [sd]		Paired t-test Workstation vs. VR			
	Workstation-Based	**VR-Based**	**Mean [sd] Difference**	**95% CI Difference**	**Cohen's d**	***p*-value**
Segmentation time (min)	95.16 [39.45]	72.08 [22.56]	23.08 [29.03]	[7.01, 39.16]	0.80	0.008**
Composite SUS score†	58.17 [21.93]	73.00 [14.98]	−14.83 [30.44]	[−31.69, 2.02]	−0.49	0.080

Table 2. Result of comparative analyses between workstation-based and VR-based platforms; Segmentation times and Composite SUS scores ($n = 15$ participants, crossover design). p-value: ***$p < 0.001$** $p < 0.01$* $p < 0.05$.
† SUS score $= 2.5\left(20 + \sum (\mathit{scores\ of\ odd\ no.\ questions}) - \sum (\mathit{scores\ of\ even\ no.\ questions})\right)$.

Results

All 15 participants completed the segmentation tasks with both platforms and were included in the analysis.

Segmentation time

Segmentation with the VR platform was completed significantly faster than with workstation-based software (Table 2). The mean completion time including all five segmentations was 72 min for the VR platform compared to 95 min for workstation-based software. The mean difference was 23 min, which was statistically significant ($t(14) = 3.08$, $p = 0.008$, Cohen's $d = 0.80$). The 95% confidence interval ranged from 7 min to 39 min, indicating that the VR platform reduced segmentation time by approximately 24% on average.

System usability

Overall usability ratings favored the VR platform. The mean composite SUS score was 73.00 for the VR platform and 58.17 for workstation-based software. The mean difference was 14.83 points in favor of the VR platform, though this did not have statistical significance due to the large variability relative to the observed difference ($t(14) = -1.89$, $p = 0.080$, Cohen's $d = -0.49$). A score above 68 is generally considered above average[20]; the VR platform exceeded this threshold while the workstation-based software scored below it.

Item-level analysis revealed distinct patterns in user experience between the platforms (Fig. 4). The VR platform demonstrated advantages in several usability dimensions. The summary of the comparisons is presented in Table SI1. Although the adjusted p-values did not show statistical significance in the score differences, participants tendentially rated VR platform as less complex than the workstation-based software (Q2: mean 1.93 vs. 2.67), indicating a simpler user interface. The VR system was also rated as easier to learn (Q7: mean 4.00 vs. 3.07) and more intuitive (Q9: mean 4.07 vs. 2.73), with participants reporting less need for prior learning before becoming proficient (Q10: mean 1.67 vs. 2.53). While the VR platform showed a trend toward being rated as easier to use overall (Q3: mean 4.07 vs. 3.27),

Both platforms were rated similarly for critical surgical planning considerations. No significant differences were observed in the ability to recognize and distinguish anatomical structures (Q8: mean 2.13 vs. 1.93), suggesting comparable anatomical visualization quality. Physical fatigue during segmentation was also comparable between systems (Q6: mean 2.67 vs. 2.60), indicating that the immersive nature of VR did not impose additional physical burden. The perceived need for technical support was similar for both platforms (Q4: mean 2.53 vs. 2.93).

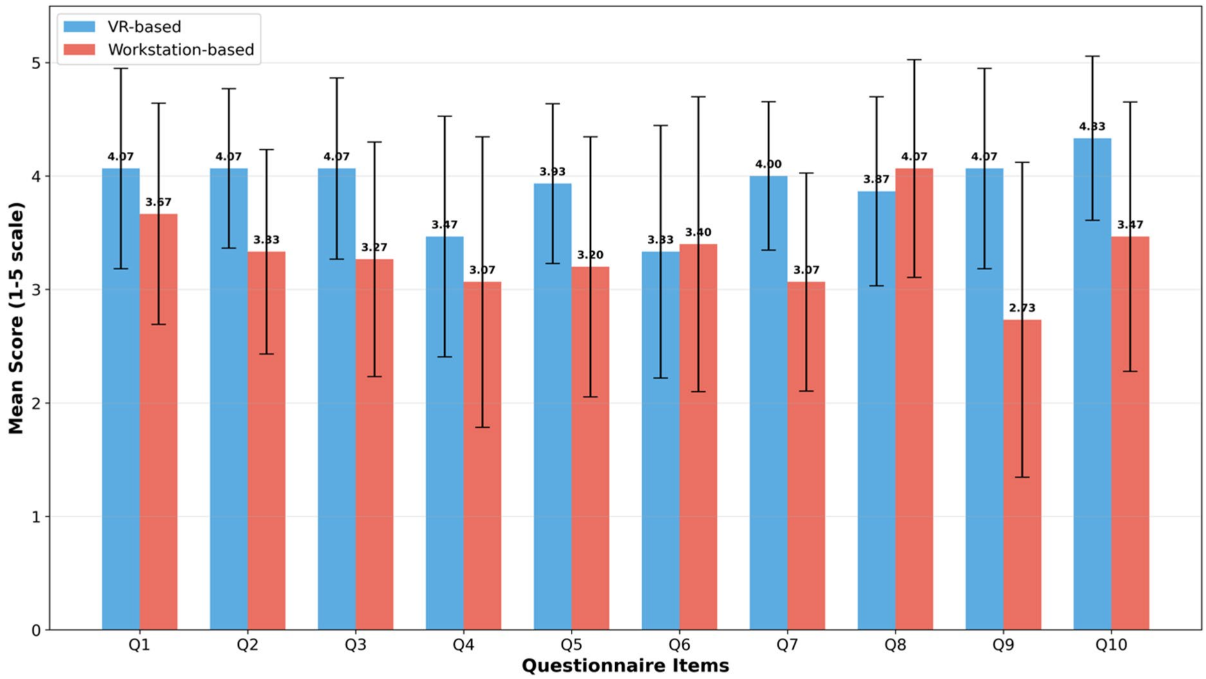

Fig. 4. Item-by-item usability comparison between VR-based (blue) and workstation-based (red) segmentation platforms. Mean scores ± SD on 5-point Likert scale. Reverse-scored items (Q2, Q4, Q6, Q8, Q10) are recoded for the visualization such that higher values indicate more favorable ratings. Anatomical recognition (Q8) and physical fatigue (Q6) were comparable between the platforms. See Table SI1 (Supplemental Data 4) for detailed statistical results and question content.

Discussion

This prospective randomized crossover study compared workflow efficiency and usability of VR-based with workstation-based segmentation for CMF trauma planning. Our findings demonstrate significant time savings with the VR platform alongside favorable usability characteristics, suggesting that immersive visualization may offer practical advantages for clinical workflows.

The 24% reduction in segmentation time with the VR platform represents a clinically meaningful improvement for routine trauma planning workflows. Given that CMF trauma accounts for 10–24% of major trauma admissions[7–9], even modest per-case time savings can translate to substantial cumulative efficiency gains at the institutional level. Our findings align with Belec et al., who reported 41–58% time reductions for VR-based craniospinal contouring[21], suggesting that the efficiency advantages of immersive visualization extend across diverse anatomical regions and clinical applications. Similar observations have been reported in studies investigating immersive visualization for surgical planning and anatomical modeling, where direct interaction with volumetric datasets has been associated with improved task efficiency and user engagement[17,18,22]. The mechanism underlying this efficiency gain likely relates to the intuitive spatial interaction afforded by VR. Traditional segmentation workflows require users to translate their 3D mental models into 2D slice-by-slice manipulations using mouse and keyboard, whereas VR enables direct volumetric manipulation with six degrees of freedom. The resulting reduction in cognitive translation effort likely contributes to the observed time savings and high ratings for ease of learning and intuitiveness. The VR platform's higher ratings for simplicity, ease of learning, and intuitiveness may indicate a different interaction paradigm rather than merely an incremental improvement. This has important implications for training and adoption. Systems that are easier to learn may lower barriers to entry for surgeons who perform segmentation occasionally, potentially democratizing access to advanced planning tools beyond specialized biomedical engineering teams. Previous studies investigating immersive visualization environments have similarly suggested that direct manipulation of 3D datasets can shorten the learning curve for complex spatial tasks and improve user confidence when interacting with patient-specific anatomy[16,23,24]. The lack of statistical significance in overall SUS scores ($p = 0.080$) should be interpreted cautiously given the moderate effect size (d = 0.49) and low statistical power (0.42). The direction and magnitude of the difference, combined with the VR platform exceeding the "good usability" threshold while the workstation-based system did not[20], suggest usability advantages that warrant confirmation in larger studies.

Two findings deserve emphasis for their clinical relevance. First, equivalent ratings for anatomical structure recognition indicate that VR's efficiency gains do not compromise diagnostic accuracy, which is a critical consideration for surgical planning. Second, comparable physical fatigue levels contradict common concerns about prolonged VR use, supporting feasibility for routine clinical implementation. These findings align with broader literature demonstrating VR's effectiveness in anatomical education[25] and emerging applications in surgical planning and simulation[26,27]. In head-and-neck and cranio-maxillofacial surgery, immersive visualization has increasingly been explored for tasks such as fracture assessment, surgical rehearsal, and patient-specific preoperative planning, where improved spatial understanding of complex anatomical relationships may support clinical decision-making[15,17,24].

Limitations and future directions

Several limitations constrain interpretation and suggest directions for future research. The modest sample size ($n = 15$) limited statistical power and precluded subgroup analysis by experience level, a particularly important consideration given the heterogeneous participant backgrounds ranging from students to experienced surgeons. Whether VR's advantages are more pronounced for novice users or persist across experience levels remains unclear. Future studies should include larger samples with stratified groups based on the level of experience to address this question.

Our evaluation focused on time and subjective usability; objective segmentation quality was not assessed. Whether the observed time savings affect volumetric accuracy, anatomical landmark precision, or 3D printing suitability requires investigation through quantitative comparison with expert-defined gold standards or inter-rater reliability analyses.

The brief standardized training provided may have favored the simpler VR interface. Longitudinal studies examining learning curves over multiple sessions would clarify whether initial advantages persist or diminish with extended workstation-based software experience. Additionally, our study evaluated isolated segmentation tasks; integration into complete clinical workflows, including case import, surgical simulation, and intraoperative navigation requires investigation.

The two systems were evaluated using their typical operating configurations rather than identical hardware environments. The VR platform required a high-performance GPU to support immersive visualization and real-time interaction. The workstation-based segmentation was performed on a standard clinical workstation configuration with an Intel Core desktop processor with comparable computational capacity. While differences in graphics hardware may influence visualization smoothness and interaction responsiveness, they are unlikely to fully account for the observed differences in segmentation workflow efficiency.

Beyond addressing these limitations, future research should explore VR's potential for collaborative planning through multi-user environments, enabling simultaneous visualization and discussion among multidisciplinary team members, a functionality particularly valuable for complex cases or teaching scenarios. Extension to intraoperative applications, where VR's intuitive spatial manipulation could assist real-time surgical navigation, also warrants investigation.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions
Conceptualization: BKB, NS; Methodology: GYP, BKB, NS; Investigation: GYP, BKB, YL, JZO; Formal Analysis: GYP, YL; Data Curation: GYP, JZO; Writing—Original Draft: GYP, BKB; Writing—Review & Editing: GYP, BKB, YL, JZO, FMT, NS; Visualization: GYP, BKB; Supervision: BKB, NS; Project Administration: BKB, NS; Funding Acquisition: GYP, BKB, FMT, NS. All authors have read and approved the final manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Ethical approval
The study was reviewed and approved by the Ethics Commission of Northwest and Central Switzerland (EKNZ) (approval protocol number 2025-00041).

Patient consent
All patients signed a general informed-consent form for further use of their health-related information in scientific investigations.

Additional information
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Correspondence and requests for materials should be addressed to B.K.B.