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Virtual Reality in Craniomaxillofacial Surgical Planning Education: A Feasibility Study on Usability, Cognitive Load, and Perceived Educational Outcomes

Neha Sharma [1,2,*,†,‡], Valentina Foehn [1,†], Jokin Zubizarreta Oteiza [1,2], Daniel Seiler [3] and Florian M. Thieringer [1,2]

[1] Clinic of Oral and Cranio-Maxillofacial Surgery, University Hospital Basel, 4031 Basel, Switzerland; jokin.zubizarreta@unibas.ch (J.Z.O.); florian.thieringer@usb.ch (F.M.T.)
[2] Medical Additive Manufacturing Research Group (Swiss MAM), Department of Biomedical Engineering, University of Basel, 4123 Allschwil, Switzerland
[3] Institute for Medical Engineering and Medical Informatics, University of Applied Sciences and Arts Northwestern Switzerland, 4132 Muttenz, Switzerland; daniel.seiler@fhnw.ch
* Correspondence: neha.sharma@duke-nus.edu.sg
† These authors contributed equally to this work.
‡ Present address: Duke-NUS Medical School, National University of Singapore, Singapore 169857, Singapore.

Abstract

Introduction: Digital surgical planning in craniomaxillofacial (CMF) surgery requires biomedical engineers who can navigate complex 3D anatomical data confidently, yet most engineering training programmes still rely on static 2D methods. This study evaluated the usability, cognitive demands, and perceived educational outcomes of a clinically derived virtual reality (VR) surgical planning platform for master's-level biomedical engineering students. **Methods**: A cross-sectional feasibility study was conducted assessing usability with the System Usability Scale (SUS), cognitive load with a modified NASA Task Load Index (NASA-TLX), and perceived educational outcomes using domain-specific rating scales, with open-ended responses analysed thematically. **Results**: Twelve of 15 enrolled students completed the survey (80% response rate). The platform achieved a mean SUS score of 72.5 (Above Average), with comparable scores across prior VR experience levels. All NASA-TLX demand dimensions remained below the scale midpoint. All participants rated VR as more engaging than traditional methods, and 91.7% rated the virtual anatomical models as realistic. Self-reported spatial reasoning benefits were most notable in landmark identification, while outcomes for translating digital-to-surgical planning were more limited. Haptic feedback was the most requested enhancement. **Conclusions**: VR surgical planning tools appear feasible to integrate into biomedical engineering training. Future studies should incorporate objective outcome measures and comparison groups to establish effectiveness.

Keywords: virtual reality; craniomaxillofacial surgery; surgical planning; spatial reasoning; biomedical engineering education; usability assessment; cognitive load; 3D visualisation

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1. Introduction

Virtual surgical planning is now considered a standard practice in craniomaxillofacial (CMF) surgery, moving clinical teams from two-dimensional (2D) computed tomography (CT) and magnetic resonance imaging (MRI) images toward interactive three-dimensional (3D) anatomical models that can be explored, manipulated, and rehearsed before the patient enters the operating room [1,2]. This shift demands a new collaborative competency where surgeons engage directly with patient-specific 3D anatomy to understand spatial relationships between vital structures, plan osteotomies, and optimise approach trajectories, while clinical engineers handle the technical workflow by segmenting imaging data, generating surface meshes, and designing patient-specific instrumentation, surgical guides, and implants [3,4]. The result is a clinical environment in which both groups must work seamlessly with the same 3D digital data, making spatial reasoning and familiarity with virtual planning tools a shared professional requirement rather than a purely surgical one [5].

Despite this shift, most biomedical engineering training programmes continue to rely on 2D images and static physical anatomical models that cannot be manipulated or examined from multiple angles [4,5]. These tools do not reflect the interactive 3D environment that engineers encounter in clinical practice, and are poorly suited to developing the spatial reasoning skills that modern CMF surgical workflows demand. Clinical engineers need to understand anatomical relationships in 3D, visualise surgical approach angles, and work with the same 3D data used in clinical planning, yet traditional educational tools do not provide this experience [1,2].

Virtual reality (VR) offers a direct response to this gap. By immersing users in interactive 3D anatomical environments, VR allows students to examine structures from any angle, navigate internal anatomy, and engage with surgical planning scenarios using the same imaging data and software employed in clinical practice [6,7]. Unlike physical anatomical models, VR supports unlimited case variations without material costs, enables non-destructive internal visualisation, and allows exploration of pathological complexity that static models cannot replicate [8]. In CMF surgery, VR has demonstrated benefits for anatomical understanding and planning accuracy in reconstructive and oncologic cases, and has shown significant efficiency gains in clinical CMF trauma segmentation compared to conventional workstation software [9,10].

Studies across surgical and medical education have increasingly examined immersive VR for anatomical and procedural training. In anatomy education, VR and AR environments have been shown to improve engagement and spatial understanding of complex structures compared to conventional 2D resources [6]. In surgical planning contexts, VR has demonstrated improved accuracy of simulated preoperative planning, as reported in temporal bone surgery, where immersive visualisation enhanced spatial precision [7]. Broader evaluations of VR-based anatomy and simulation training among undergraduate and postgraduate learners report favourable usability, increased motivation, and perceived improvements in spatial comprehension [11]. Across these settings, immersive visualisation is consistently associated with improved spatial reasoning, procedural confidence, and learning experience among trainees and clinicians. However, studies focusing specifically on the training needs of biomedical engineering students in clinical CMF surgical units remain scarce, and evidence on usability and cognitive load in this population is limited. Effective VR implementation requires evidence that the tools are usable, that cognitive demands remain manageable, that learning outcomes improve relative to existing methods, and that they are educationally meaningful for the specific audience [11]. Biomedical engineering students occupy a distinct position at the interface of clinical and technical practice, and their training needs differ from those of surgical residents or medical students [10,12,13]. Understanding how this group responds to VR in terms of usability, cognitive load, and the development of spatial reasoning is relevant not only to curriculum design but also to how surgical units structure the training of the clinical engineers they work with [14].

To our knowledge, this is the first feasibility study to evaluate the usability, cognitive load, and perceived educational outcomes of a clinically derived VR surgical planning platform specifically among master's-level biomedical engineering students training for roles in CMF surgical units, assessing whether such tools are acceptable and usable in this context. Unlike previous studies examining VR in medical or surgical education, which have primarily focused on surgical residents or medical students, this study addresses the distinct training needs of clinical engineers at the education-to-practice interface, using the platform and imaging workflows employed in active clinical use.

2. Materials and Methods

2.1. Study Design and Participants

A cross-sectional feasibility study was conducted with master's-level students enrolled in the joint Biomedical Engineering programme at the University of Basel and the University of Applied Sciences Northwestern Switzerland (FHNW). This programme trains engineers for professional roles in digital surgical planning, medical device development, and clinical collaboration, representing the engineering workforce that supports CMF surgical teams in practice. All students enrolled in the relevant elective course were invited to participate.

From September to December 2024, a VR module was integrated into an existing semester course on surgical planning and medical device development. Students used VR to explore CMF anatomy and practise surgical planning, replacing the traditional 2D images and static anatomical models used in previous course iterations.

2.2. VR Technology Learning Content and Implementation

A dedicated introductory presentation was provided to all students prior to the hands-on sessions, covering the application of VR in CMF surgery with multiple clinical showcases and real-world surgical planning scenarios to contextualise the learning objectives. Students then participated in two group VR sessions conducted over two consecutive weeks, each 120 min in duration, with a clinical engineer (J.Z.O.) and a CMF surgeon (N.S) present throughout both sessions to support navigation and respond to queries.

Session 1 focused on platform familiarisation. Students used the VR platform with multiple minor CMF cases to develop navigation confidence and familiarity with the software environment, including headset setup, controller functions, and anatomical exploration tools. No structured evaluation tasks were assigned during this session. Session 2 focused on structured learning and evaluation. Students worked through five structured tasks: (1) identifying anatomical landmarks in 3D space, (2) virtually reducing and realigning fractured mandibular segments, (3) assessing spatial relationships between bone fragments and failed hardware, (4) planning revised surgical approaches, and (5) developing 3D navigation skills. Students were expected to work through all five structured tasks during the session.

While multiple clinical CT cases were used for familiarisation in session 1, structured learning tasks in session 2 focused on a single complex case of a bilateral mandibular fracture with a failed osteosynthesis reconstruction plate. The case comprised a de-identified CT dataset sourced from the institutional surgical planning archive at the University Hospital Basel, acquired on a SOMATOM Force scanner (Siemens Healthineers, Erlangen, Germany; 120 kVp, 196 mA, 0.75 mm slice thickness, 0.5020 × 0.5020 mm pixel spacing, 512 × 512 matrix, Hr38s reconstruction kernel) and anonymised according to institutional protocols prior to use. The CT dataset was segmented in Elucis Next by a clinical engineer (J.Z.O.) and reviewed by a CMF surgeon (N.S.) prior to the sessions, resulting in surface mesh models of the mandibular segments, osteosynthesis hardware, and the surrounding craniofacial skeleton. These pre-segmented models were made available to all participants within the platform for use during the structured learning tasks. The case provided a precise visualisation of bone fragments, hardware failure, and surrounding maxillofacial anatomy, and was selected as representative of challenging revision surgery scenarios encountered in CMF practice (Figure 1).

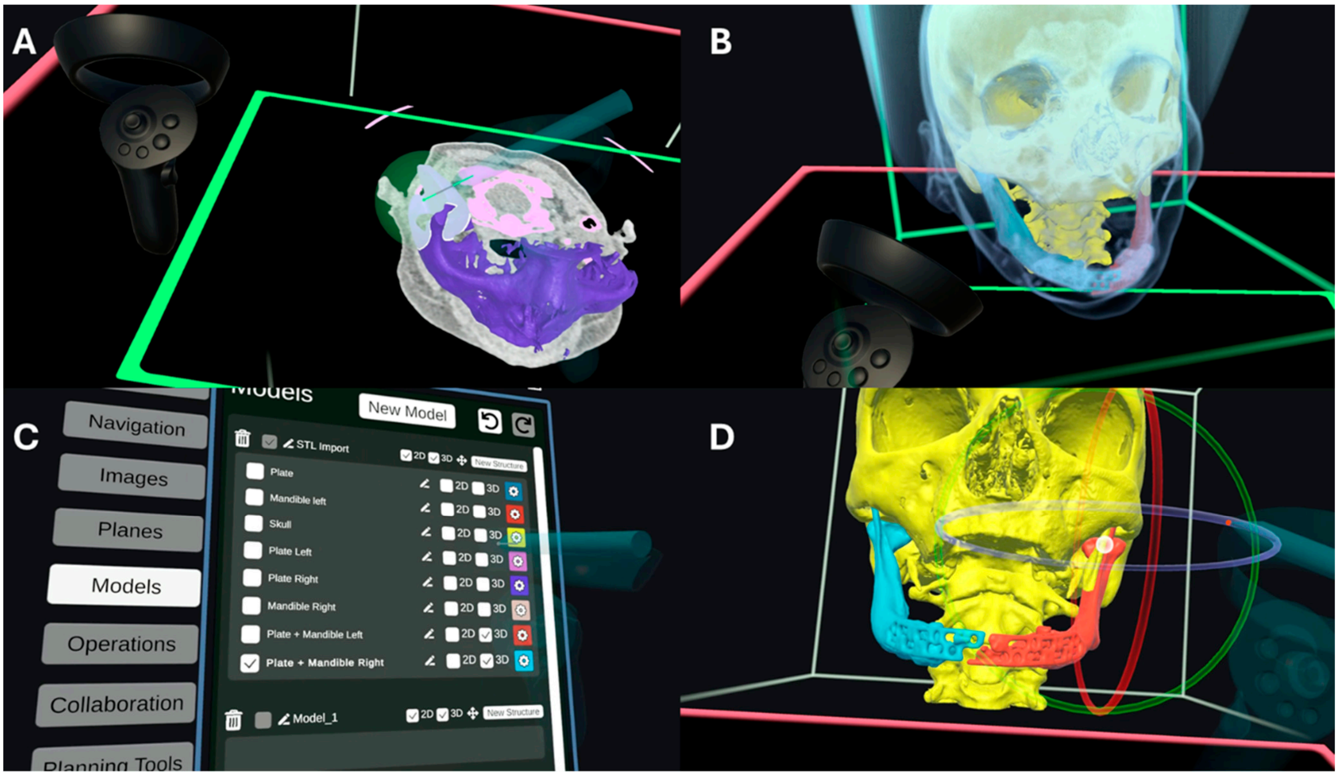

Figure 1. Virtual reality (VR) surgical planning environment for complex craniomaxillofacial (CMF) fracture education. (**A**) Volumetric rendering with segmented anatomical structures showing a semi-transparent skull and colour-coded CMF components. (**B**) Alternative perspective illustrating multi-angle visualisation capabilities with a transparent skull and highlighted mandibular segments. (**C**) Virtual reality (VR) platform user interface displaying selectable anatomical components, including bilateral mandibular segments and osteosynthesis plates. (**D**) Full case visualisation showing fractured bilateral mandibular segments (blue and red) and skull (yellow) used for virtual fracture reduction practice.

Students used a commercially available VR headset (HP Reverb G2, HP Development Company, L.P., Palo Alto, CA, USA) with dual hand-held controllers and specialised surgical planning software (Elucis Next, v. 1.11, Realize Medical, Ottawa, ON, Canada), operated on a dedicated workstation (Blade 18—RZ09-0484; NVIDIA GeForce RTX 4090 Laptop GPU, RAM: 32 GB, Intel Core i9-13950HX @ 2.20 GHz). The software is designed for surgical planning, research, and medical education, enabling examination of anatomical structures from multiple angles, zoom-in visualisation of specific regions, and surgical approach planning with high-quality 3D skull and facial anatomy models.

2.3. Data Collection

Data were collected via an online questionnaire developed in Google Forms, accessible from October 2024 to December 2024. Students were invited to complete the survey at any point following their sessions; some responded immediately after Session 2, and others at a later point during the semester. The questionnaire was reviewed by co-authors prior to deployment.

The questionnaire comprised seven sections: participant demographics (Section S1), system usability (Section S2), perceived educational outcomes (Section S3), perceived development of spatial reasoning and surgical planning (Section S4), cognitive load using a modified NASA Task Load Index (Section S5), comparison with traditional learning tools (Section S6), and open-ended feedback (Section S7). Usability was assessed using the System Usability Scale (SUS), a validated 10-item instrument measuring ease of use, system complexity, and user confidence, with scores ranging from 0 to 100 [15]. Cognitive load was measured using a modified five-point version of the NASA Task Load Index (NASA-TLX), covering six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration [16]. A uniform 1–5 Likert scale was adopted in place of the original 20-point scale to maintain a consistent response format across all survey instruments. All six dimensions were retained without modification to item wording, and each was scored as the mean of its single item. Scores are interpreted relative to the scale midpoint (3.0), with scores below indicating low perceived demand. Custom questions assessed perceived realism of anatomical models, perceived development of spatial reasoning, confidence in understanding 3D anatomical relationships, and engagement relative to traditional teaching methods. Open-ended responses were collected across four questions covering: liked features of the VR experience, suggested improvements to the software, views on the future role of VR in biomedical engineering education, and any additional comments. These items were developed to operationalise the competency domains for CMF surgical engineering education, as described in the existing literature [3–5,10,14]. The full survey instrument is provided as Supplementary File.

2.4. Ethical Considerations and Data Analysis

This study was conducted as part of routine educational evaluation within an existing master's course curriculum. As data collection involved anonymous survey responses from students participating in standard course activities, formal ethics committee approval was not required under institutional guidelines. All participants provided written informed consent prior to participation, and involvement had no bearing on course grades or academic standing.

Quantitative data were analysed using descriptive statistics calculated in Microsoft Excel 2021. Medians and frequency distributions are reported as the primary descriptors for all Likert items, with means and standard deviations provided for reference. Open-ended responses were analysed thematically by two authors (N.S., V.F.) to identify recurring patterns across participant feedback. Responses were read in full, recurring topics were identified and grouped into candidate themes through discussion and consensus.

3. Results

3.1. Participant Demographics and VR Experience

Twelve of fifteen enrolled students completed the survey, representing an 80% response rate. The group comprised 7 (58.3%) female and 4 (33.3%) male students, with 1 (8.3%) choosing not to disclose gender. Ages ranged from 22 to 28 years, with a mean age of 24.6 years (SD = 1.6).

Ten of 12 participants (83.3%) were enrolled in their third semester of the programme. The academic backgrounds varied, with 4 (33.3%) holding bachelor's degrees in biomedical engineering, 3 (25.0%) in mechanical engineering, 2 (16.7%) in other engineering fields, including electrical engineering and computer science, 1 (8.3%) in biology or life sciences, and 2 (16.7%) in other disciplines. Regarding prior VR experience, 4 (33.3%) reported no prior VR exposure, 6 (50.0%) reported minimal experience through brief workshops or casual gaming, and 2 (16.7%) reported moderate familiarity with VR in educational or training settings.

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3.2. System Usability and Cognitive Load

The VR system achieved a mean SUS score of 72.5 (SD = 11.3), placing it in the 60th percentile of system usability ratings and corresponding to an "Above Average" classification [15]. Individual scores ranged from 57.5 to 90.0. Six of 12 participants (50.0%) scored the system 70 or above, and one participant scored it below 60 (Figure 2).

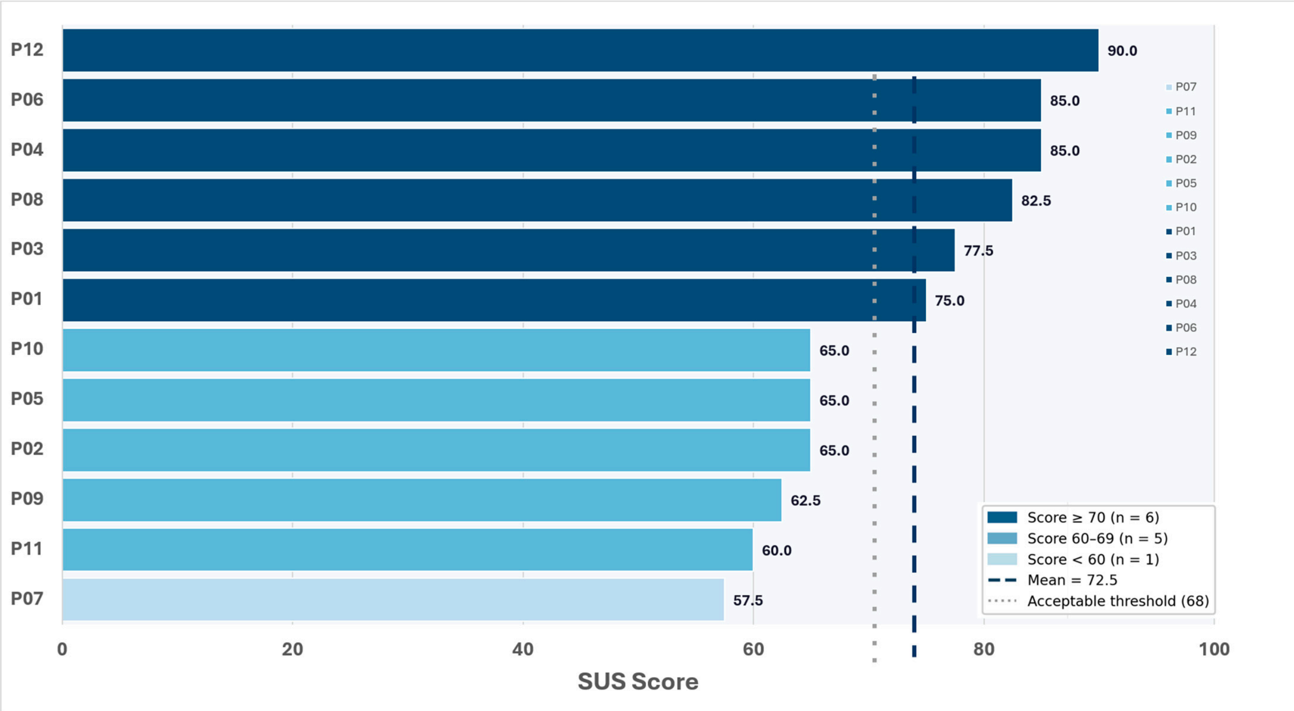

Figure 2. System Usability Scale (SUS) Score distribution for all participants (n = 12). Individual SUS scores are displayed in descending order. Colour coding indicates score ranges: dark blue = score $\geq$ 70 (above average, n = 6); medium blue = score 60–69 (n = 5); light blue = score < 60 (n = 1). The dashed vertical line indicates the group mean (72.5); the dotted vertical line indicates the acceptable usability threshold (68). SUS scores range from 0 to 100; scores above 68 are classified as above average.

Anatomical models were rated for realism and accuracy, with a mean score of 4.33 (SD = 0.65), and 11 of 12 participants (91.7%) rated them as realistic or very realistic. Ease of manipulating and examining anatomical structures from multiple angles received a mean score of 4.08 (SD = 1.24), with 9 participants (75.0%) rating this positively. NASA-TLX scores across the six dimensions are shown in Figure 3. Performance self-assessment received the highest rating (mean = 3.33, SD = 0.89), followed by mental demand (mean = 2.67, SD = 1.30), effort (mean = 2.33, SD = 0.78), temporal demand (mean = 2.17, SD = 0.83), and frustration (mean = 1.75, SD = 1.22). Physical demand received the lowest rating (mean = 1.25, SD = 0.62).

Mean SUS scores were comparable across academic backgrounds: biomedical engineering (n = 4, mean = 70.6), mechanical engineering (n = 3, mean = 70.8), and other backgrounds (n = 5, mean = 75.0). Participants with a mechanical engineering background reported lower mean mental demand on the NASA-TLX (mean = 1.7) compared to biomedical engineering (mean = 3.5) and other backgrounds (mean = 2.6). SUS scores did not differ substantially by prior VR experience, with participants reporting no prior VR exposure achieving a mean SUS of 69.4 (n = 4), compared to 77.5 for those with minimal experience (n = 6) and 63.8 for those with moderate experience (n = 2). These observations are descriptive and reflect the small and unequal subgroup sizes.

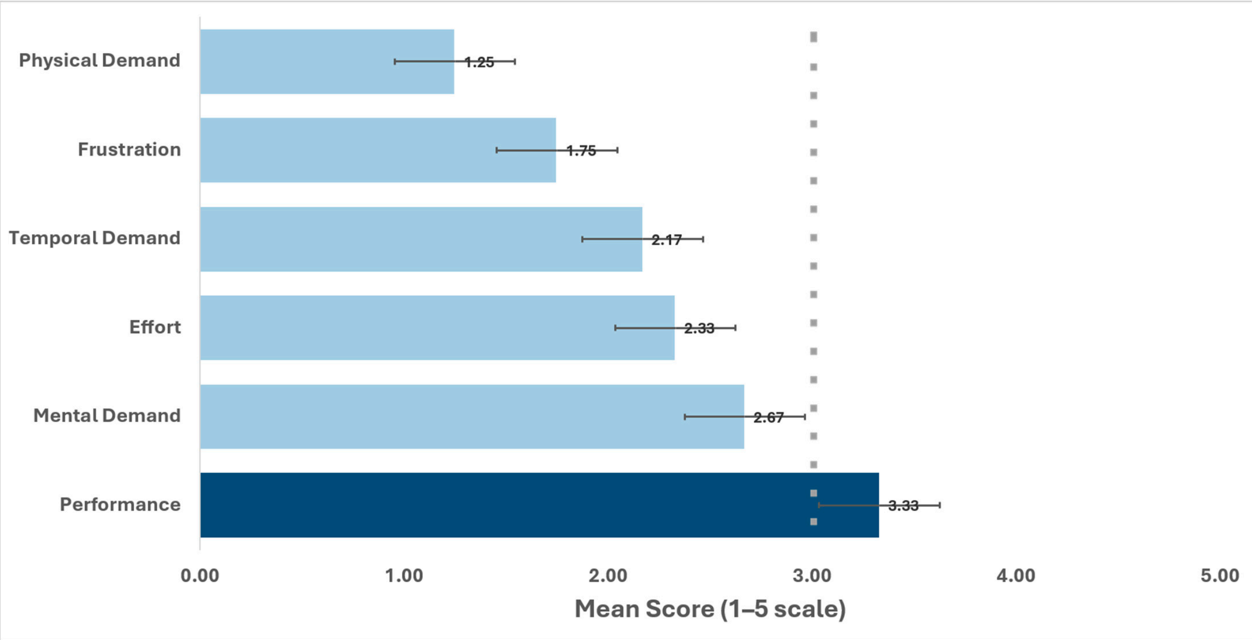

Figure 3. NASA Task Load Index (NASA-TLX)—Cognitive Load Profile (n = 12). Bars represent mean scores; error bars indicate standard deviation (SD). All dimensions were rated on a modified 1–5 Likert scale (1 = Very Low, 5 = Very High). The dashed vertical line at 3.0 indicates the scale midpoint; scores below this threshold indicate low perceived demand. Performance (dark bar) reflects self-assessed success, where higher scores are favourable; for all other dimensions (light bars), lower scores indicate lower perceived demand.

3.3. Perceived Educational Outcomes, Spatial Reasoning and Comparative Assessment

Engagement with VR relative to traditional learning methods received the highest rating across all perceived educational outcome items, with all 12 participants (100%) rating VR as more engaging or much more engaging than conventional approaches (median = 5; mean = 4.50, SD = 0.52). Motivation to learn more about CMF surgery through VR was rated positively by 7 participants (58.3%) (median = 4; mean = 3.75, SD = 1.14). Understanding of the relationship between digital planning and surgical procedures was rated good or excellent by 5 participants (41.7%) (median = 3; mean = 3.33, SD = 0.65). Six participants (50.0%) perceived VR as likely to improve their practical skills in professional digital surgical planning environments (median = 3.5; mean = 3.42, SD = 1.16).

Participants reported perceived development in spatial reasoning, with 7 participants (58.3%) rating it positively (median = 4; mean = 3.67, SD = 0.89). Confidence in understanding complex 3D anatomical relationships was rated positively by 6 participants (50.0%) (median = 3.5; mean = 3.50, SD = 1.00). Among specific surgical planning competencies, landmark identification in 3D space received the highest rating, with 9 participants (75.0%) reporting improved confidence (median = 4; mean = 3.92, SD = 0.90). Understanding of surgical approach angles was rated positively by 8 participants (66.7%) (median = 4; mean = 3.83, SD = 0.94). Mental rotation and manipulation skills were rated positively by 9 participants (75.0%) (median = 4; mean = 3.67, SD = 1.15). Understanding of spatial relationships between anatomical structures (median = 4; mean = 3.58, SD = 0.79) and of how preoperative planning translates to surgical execution (median = 3.5; mean = 3.58, SD = 0.90) were each rated positively by 7 and 6 participants, respectively. The ability to plan surgical trajectories while avoiding vital structures was rated positively by 7 participants (58.3%) (median = 4; mean = 3.67, SD = 0.89). When comparing VR to traditional educational methods, 7 participants (58.3%) agreed or strongly agreed that VR felt more effective for understanding complex concepts (median = 4.0; mean = 3.67, SD = 0.89). Nine participants

(75.0%) rated VR as providing a more realistic representation of surgical scenarios than other educational tools (median = 4.0; mean = 4.00, SD = 0.95). Seven participants (58.3%) indicated they would prefer VR for similar learning objectives in the future over traditional methods (median = 4.0; mean = 3.58, SD = 1.08). All quantitative results are summarised in Table 1.

Table 1. Summary of quantitative outcomes across all measurement domains.

Measurement Item	**Mean (SD)**	**Median**	**Rated 4–5, n (%)**
System Usability Scale (SUS)			
Overall SUS score	72.5 (11.3)	70.0	6 (50.0%) scored $\geq$ 70
Anatomical model realism and accuracy	4.33 (0.65)	4.0	11 (91.7%)
Structural manipulation ease from multiple angles	4.08 (1.24)	4.5	9 (75.0%)
Cognitive Load—NASA Task Load Index (NASA-TLX)			
Mental demand	2.67 (1.30)	3.0	—
Physical demand	1.25 (0.62)	1.0	—
Temporal demand	2.17 (0.83)	2.0	—
Performance (self-assessed)	3.33 (0.89)	3.5	—
Effort	2.33 (0.78)	2.0	—
Frustration	1.75 (1.22)	1.0	—
Perceived Educational Outcome			
Engagement compared to traditional methods	4.50 (0.52)	4.5	12 (100.0%)
Motivation to learn more about CMF surgery	3.75 (1.14)	4.0	7 (58.3%)
Understanding of the digital-to-surgical planning relationship	3.33 (0.65)	3.0	5 (41.7%)
Perceived improvement of practical professional skills	3.42 (1.16)	3.5	6 (50.0%)
Spatial Reasoning and Surgical Planning Development			
Landmark identification in 3D space	3.92 (0.90)	4.0	9 (75.0%)
Understanding of surgical approach angles	3.83 (0.94)	4.0	8 (66.7%)
Mental rotation and manipulation of 3D structures	3.67 (1.15)	4.0	9 (75.0%)
Overall spatial reasoning for surgical planning	3.67 (0.89)	4.0	7 (58.3%)
Surgical trajectory planning avoiding vital structures	3.67 (0.89)	4.0	7 (58.3%)
Spatial relationships between anatomical structures	3.58 (0.79)	4.0	7 (58.3%)
Translation of preoperative planning to surgical execution	3.58 (0.90)	3.5	6 (50.0%)
Confidence in 3D anatomical understanding	3.50 (1.00)	3.5	6 (50.0%)
Comparative Assessment: VR versus Traditional Methods			
Realistic representation of surgical scenarios	4.00 (0.95)	4.0	9 (75.0%)
Effectiveness for understanding complex concepts	3.67 (0.89)	4.0	7 (58.3%)
Preference for VR over traditional methods in future	3.58 (1.08)	4.0	7 (58.3%)

SUS = System Usability Scale; NASA-TLX = NASA Task Load Index; CMF = craniomaxillofacial. The overall SUS score ranges 0–100; all other items were rated on a 1–5 scale. Median and "Rated 4–5" values are not applicable to NASA-TLX dimensions (—), where lower scores are desirable for demand-related items and higher scores for performance.

3.4. Student Perspectives and Implementation Insights

Open-ended responses provided context for the quantitative findings and identified specific features and limitations that the rating scales did not capture. Thematic analysis of these responses identified four themes.

Immersive 3D visualisation was the most consistently cited advantage. Participants highlighted the ability to view anatomy in any orientation, zoom into structures, and see the full anatomical context, features absent from traditional teaching methods. Representative comments included "the ability to view in 3D in any orientation/direction" and "dealing with anatomical parts in 3D is just a lot better and more intuitive."

Interactive engagement with clinical scenarios was a second theme. Students described the experience as "closer to a real-life scenario" and noted a perceived shift from passive classroom learning to active engagement with surgical planning tasks. One participant described it as "a change from what we usually do in class."

Technical considerations formed a third theme. Several participants described the system as easy to use, while others noted controller sensitivity issues, with one reporting the system "felt overly sensitive at times." Haptic feedback was the most frequently requested enhancement, with multiple participants identifying the need for tactile cues when anatomical structures overlap or approach vital areas. One participant articulated this specifically: "Is my (the) jaw overlapping the skull base? Are the segments touching at all?" One participant also reported experiencing dizziness during VR use, a known adverse effect not captured by the NASA-TLX instrument.

Future educational applications formed the fourth theme. Participants described VR as a potential alternative to physical planning materials: "it can be used as a surgical planning tool without the need for physical materials or 3D printing of models." Applications beyond CMF surgery were also suggested, including integration into anatomy and physiology courses and broader XR education programmes.

4. Discussion

Training engineers for digital CMF surgical workflows requires tools that reflect the clinical environment in which they will work. The findings from this study suggest that a VR platform built around patient-specific CT/MRI data and surgical planning software can serve this purpose, with perceived benefits for foundational spatial skills and practical implications for how surgical units structure engineer training alongside existing 3D printing workflows. These findings contribute to a growing body of evidence supporting VR in surgical and medical education [6,7,10,11,14], extending it specifically to the biomedical engineering student population for whom such evidence has been lacking.

From a practical adoption standpoint, the usability findings are reassuring. The VR system performed above the threshold considered acceptable for educational technologies, and participants with no prior VR experience achieved usable scores comparable to those with some familiarity, suggesting that VR adoption does not require selecting for technically experienced students or investing in extensive onboarding. A recent randomised crossover study using the same VR platform reported a SUS score of 73.0 among a heterogeneous group of clinical professionals and students, of whom only a subset performed regular digital segmentations, virtually identical to the 72.5 achieved by master's students in this study [9]. This consistency across user groups with different professional and digital backgrounds supports the view that the platform's usability is robust and accessible rather than context-dependent. One participant reported dizziness during use, a known side effect of VR that should be monitored in any implementation, particularly in longer sessions.

The cognitive demand profile is also relevant for clinical settings where training time is limited. All demand dimensions remained below the scale midpoint, while performance confidence was rated highest among the six items. Participants were able to engage with a complex bilateral mandibular fracture case without becoming overwhelmed by the technology, leaving cognitive capacity available for the actual surgical planning tasks. This is consistent with evidence that task-specific VR environments built from clinical imaging data impose lower cognitive demands than general immersive environments, in which unfamiliar interfaces and simplified models can increase extraneous load [17]. Furthermore, the VR platform can be integrated into existing course structures without requiring dedicated acclimatisation time beyond a short orientation.

Spatial reasoning outcomes were strongest for landmark identification and understanding of surgical approach angles, which are directly relevant to engineers working on virtual planning and medical device design. Three-quarters of participants reported improvement in mental rotation skills, which underpin the ability to work fluently with 3D anatomical data across different viewing angles and orientations. Outcomes were less pronounced for translating preoperative planning into surgical execution and for confidence in complex spatial relationships. This pattern is consistent with what would be expected from a brief intervention with a single case used for structured assessment. Higher-order planning competencies are more fully challenged by cases of greater complexity, such as oncologic resections involving both bone and soft tissue that require reconstruction with patient-specific implants. More extensive exposure to a range of case types over a longer curriculum period would be needed to develop these competencies, regardless of educational modality. The weaker outcomes in planning translation are more likely to reflect the intervention's brevity and single-case assessment rather than inherent platform limitations. The distinction between technology and educational design limitations was informed by participant feedback, as the absence of haptic feedback was the only platform-specific constraint identified, whereas brevity of exposure and single-case assessment are educational design factors independent of the platform used. Students from non-biomedical engineering backgrounds, including mechanical engineering and computer science, achieved usability scores broadly similar to those of biomedical engineers, suggesting the platform is accessible across the interdisciplinary student cohorts typical of modern CMF surgical units. Notably, participants with a mechanical engineering background reported lower mean mental demand compared to biomedical engineering students, which may reflect prior familiarity with 3D spatial tools such as computer-aided design (CAD) software. These outcomes reflect self-reported gains in confidence rather than objectively measured changes in ability. While participants consistently reported perceived improvements in spatial reasoning, pre- and post-assessment with validated instruments would be required to determine whether these perceptions correspond to genuine gains in spatial reasoning ability.

For surgical units currently using 3D-printed anatomical models, the practical comparison with VR is worth considering. 3D printing has an established role in CMF surgical education, with three decades of development underpinning its current use in anatomical model production and surgical planning [18]. 3D-printed models carry per-case material costs, cannot be modified once produced, and offer a fixed perspective on anatomy [19]. VR, on the other hand, allows the same dataset to be explored from any angle, at any scale, with different anatomical layers visible simultaneously, and the same setup can accommodate an unlimited number of cases and participants [20]. The same clinical study that validated the platform's usability also demonstrated a 24% reduction in segmentation time with VR compared with conventional workstation software, suggesting that familiarity with VR workflows translates into measurable efficiency gains in clinical practice [9]. The most frequently requested enhancement in this study was haptic feedback that allows users to feel when structures touch or overlap. This is where physical 3D-printed models retain an advantage [21]. Based on the complementary strengths identified in this study and the existing literature, a hybrid approach combining VR for spatial exploration with 3D printing for tactile assessment is proposed as a direction for future investigation. Furthermore, an objective comparison of VR-only, 3D print-only, and hybrid workflows would be required to determine whether this approach offers measurable advantages over either modality alone [22–25].

The finding that fewer than half of the participants strongly rated their understanding of the translation from digital to surgical planning warrants careful interpretation. Engineers in CMF surgical units need to understand not only how to navigate a 3D model but

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also how virtual planning decisions become operational steps. Two group sessions using a single case are unlikely to fully build this understanding. A recent study examining VR in maxillofacial trauma education found that VR delivered comparable educational insights to traditional approaches, but noted that exposure duration and case complexity were key determinants of learning depth [26]. Closer integration with actual clinical planning workflows, exposure to multiple case types, and longitudinal curriculum embedding are likely needed before this competency develops meaningfully.

Several limitations apply. The single-institution design and small sample size restrict generalizability. Without a pre-/post-design or control group, perceived learning gains cannot be attributed specifically to VR rather than to the learning session itself, novelty effects, or pre-existing spatial ability. All outcome measures were self-reported; self-reported improvements in spatial reasoning confidence cannot be interpreted as evidence of actual changes in ability. Future studies would benefit from including validated objective spatial reasoning assessments, such as the Mental Rotation Test [27] or the Purdue Spatial Visualisation Test, alongside self-report measures used here, and from including comparison groups that use traditional methods and 3D-printed models. Longitudinal follow-up tracking student performance in subsequent coursework would help determine whether gains transfer to practical planning tasks. Future studies with larger sample sizes should incorporate stratified analyses by academic background, prior anatomical knowledge, and VR experience to better understand how user characteristics influence platform usability and educational outcomes. Formal psychometric validation of the modified NASA-TLX scale and custom survey items is recommended for future iterations of this evaluation framework.

This study provides a practical evaluation framework that surgical units and engineering programmes can adapt when assessing VR platforms for training. The combination of usability, cognitive load, and domain-specific outcome measures gives a more complete picture than engagement ratings alone. As digital surgical planning becomes standard in CMF practice, training the engineers who support it requires tools that match that environment. The near-identical usability scores achieved by students in this study and by clinical users in the parallel segmentation study suggest this platform may bridge the education-to-practice gap more directly than tools designed purely for educational simulation. VR appears to be a viable and scalable option for this purpose, most effective when implemented around clinical cases, integrated with existing curricula, and paired with physical modelling where hands-on assessment remains necessary. The findings from this feasibility study support progression to a controlled study incorporating pre- and post-assessment with validated spatial reasoning instruments, a comparison group receiving traditional instruction, and a larger multi-institution sample to establish whether the perceived benefits observed here translate into measurable learning gains.

5. Conclusions

This pilot feasibility study provides preliminary evidence that clinically derived VR surgical planning tools can be feasibly integrated into biomedical engineering training programmes for CMF surgical units. The platform showed acceptable usability across experience levels, with scores consistent with those reported for the same platform in clinical use, suggesting that training on this technology prepares engineers for tools with demonstrated value in surgical practice. Perceived benefits were clearest for foundational competencies such as landmark identification and surgical approach angles, whereas outcomes for deeper translation into surgical planning were less pronounced. A hybrid model combining VR for exploratory spatial learning with 3D printing for tactile assessment is recommended to directly address the haptic feedback gap identified by participants. Future studies should incorporate objective pre- and post-spatial reasoning assessments, comparison groups using traditional and 3D-printed models, and longitudinal follow-up to determine whether gains transfer to clinical planning tasks.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app16136492/s1. Supplementary File: Complete Survey Instrument—Virtual Reality Software Usability and Educational Impact Survey (42 items across 7 sections). Section S1: Participant Demographics; Section S2: System Usability Scale (SUS); Section S3: Perceived Educational Outcomes; Section S4: Spatial Reasoning and Surgical Planning; Section S5: NASA Task Load Index (NASA-TLX)—Modified; Section S6: Comparison with Traditional Learning Tools; Section S7: Open-Ended Feedback.

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Institutional Review Board Statement: Ethical review and approval were waived for this study. Data collection involved anonymous survey responses from students participating in standard educational activities within an existing master's curriculum. Under the Swiss Federal Act on Research involving Human Beings (Human Research Act, HRA), educational evaluation of this nature, not involving health-related personal data, falls outside the scope of research requiring formal ethics committee approval. The single clinical case used for the structured learning task consisted of fully anonymised archival CT data, exempt from separate consent requirements under the HRA.

Informed Consent Statement: Informed consent was obtained from all participants prior to their involvement in the study.

Data Availability Statement: The datasets of this study are available from the corresponding author upon reasonable request.

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Abbreviations

2D	Two-dimensional
3D	Three-dimensional
CAD	Computer-Aided Design
CMF	Craniomaxillofacial
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
SD	Standard Deviation
SUS	System Usability Scale
TLX	Task Load Index
VR	Virtual Reality

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