Informatics in Medicine Unlocked 19 (2020) 100348

Contents lists available at ScienceDirect

Informatics in Medicine Unlocked

journal homepage: http://www.elsevier.com/locate/imu

Usability evaluation of 3D user interface for virtual planning of bone fixation plate placement

Kup-Sze Choi [a,*], Beat Schmutz [b]

[a] Centre for Smart Health, School of Nursing, The Hong Kong Polytechnic University, Hong Kong
[b] Institute of Health and Biomedical Innovation, Queensland University of Technology, Australia

ARTICLE INFO

Keywords:
Bone fracture
Fixation plate placement
Virtual reality
3D haptic device
Usability evaluation
Surgical planning

ABSTRACT

Universal pre-contoured plates are commonly used for internal fixation of bone fracture. Optimal plate placement can be determined through visual inspection of the relative position between the plate and the fractured bone as displayed on x-rays. While computer-assisted approaches have been developed to enable the manipulation of 3D models of the bone and the plate in virtual environments, as the 3D models are usually maneuvered using a 2D mouse with the virtual trackball paradigm, the process is counter-intuitive and could hamper system usability. An intuitive 3D haptic device was therefore employed to develop a virtual training system for fixation plate placement. A four-session study over two weeks were conducted with 15 subjects to evaluate the usability of the system, with 2D mouse and 3D haptic device employed as user interface. The effect of force feedback was also studied. A questionnaire was administered at the end of the study to assess user satisfaction towards the usability of the two input devices. User performance of virtual plate placement using a 3D haptic device was found to be superior to that using a 2D mouse, in terms of completion time and accuracy. The performance with and without force feedback was not significantly different. Preference toward 3D haptic device was reflected from the responses to the usability questionnaire. In conclusion, employing a 3D input device as user interface can potentially facilitate virtual planning of bone fixation plate placement.

1. Introduction

Placement of internal fixation plates on fractured bones is a common treatment approach in orthopedic surgery [1,2]. A wide selection of fixation plates that are pre-contoured to fit the anatomical shape of bones at different locations in the human body are available from surgical implant manufacturers for the operation. Nevertheless, since the morphology of bones can vary with various factors, such as age, gender and ethnic origin [3], and that universal pre-contoured plates are normally designed based on bones from cadaver specimen of limited sample size, it is not possible for the plates to fit exactly to the specific situation of bone fracture for every patient. Depending on the morphology of the fractured bone, orthopedic surgeons can select pre-operatively the plates that are most suitable for the morphology of a specific patient [4]. This is usually achieved through visual inspection of the fitting of two-dimensional templates of possible plates against the 2D images of the fractured bone as displayed on x-ray films. The selection of a universal pre-contoured plate and the optimal placement relies on orthopedic experts' experience with bone anatomy, and also their spatial ability to mentally rotate and transform the visual images. In situations where local regions of a best-fit plate still cannot match the shape of the bone sufficiently, manual plate bending is employed to reduce the morphological difference.

To facilitate pre-operative planning of fixation plate placement, virtual reality (VR) based methods have been developed so that three-dimensional (3D) models of the plate and the bone can be manipulated directly and interactively to identify the optimal placement. The 3D model of the bone can be readily reconstructed by using the volumetric medical imaging data acquired from computed tomography (CT). In fact, VR based methods can also be used for the design of fixation plates, where fit assessment of universal pre-contoured plates for specific bones can be conducted more conveniently in virtual environments [5].

In these systems, manipulation of the virtual objects in 3D space is usually made indirectly using a 2D computer mouse with the *virtual trackball* user interface paradigm, where the translation of an object in 3D space is achieved by making multiple translations along different coordinate axes. The user interface is therefore unnatural and adds

* Corresponding author.
E-mail address: hskschoi@polyu.edu.hk (K.-S. Choi).

https://doi.org/10.1016/j.imu.2020.100348
Received 24 March 2020; Received in revised form 27 April 2020; Accepted 5 May 2020
Available online 11 May 2020

cognitive burden.

To this end, a 3D user interface has been proposed to enable intuitive and direct manipulation of virtual models of the plate and bone, in attempt to improve the usability of a virtual plate placement planning system for orthopedic surgery [6]. Furthermore, a haptic device has also been incorporated to increase virtual realism by producing force feedback during plate-bone contact, considering that haptics is an important human perception channel that can complement vision, and that haptic interaction and proprioception would benefit the plate placement process [7]. The system, in its current form, could be used for resident training and medical education.

The aim of this study is to evaluate the usability of 2D mouse and 3D haptic device in determining the optimal fixation plate placement in virtual environment, with focus on the placement of a bone fixation plate for the distal medial tibia, a commonly fractured long bone in the human body [8,9]. The study hypothesized that there would be a difference in performance in completing the virtual task of plate placement using the two interface devices. It was further hypothesized that there would be a difference in performance in completing the virtual task using the 3D haptic device without and with feedback forces provided. The hypotheses were tested empirically with a trial in the study.

2. Methods

2.1. Virtual trackball paradigm

The virtual trackball technology is a common user interface paradigm that is used to manipulate 3D objects using a 2D mouse. It has been used for image-based surgical planning [10] and manipulation of virtual anatomical models in open surgery with augmented reality technology [11]. The paradigm was implemented in the proposed system to allow for plate fitting with an ordinary 2D mouse, where movement of the virtual plate in 3D space was achieved indirectly by making multiple rotations or translations along the x, y and z axis iteratively. As shown in the left of Fig. 1, a graphical user interface was created where checkboxes corresponding to the three axes and the “Rotation” box were provided. User checked a box to specify the axis along which the plate was to be translated, or checked the “Rotation” box to indicate that plate was to be rotated. After a box was checked, translation or rotation was achieved by dragging the mouse while pressing the left mouse button. Manipulation in 3D space was performed by repetitive rotations or iterative switching to one axis at a time until the desired position was reached.

2.2. Fit criteria

The fit criteria between distal medial tibia and the fixation plate were defined based on the spatial constraints set to meet the clinical requirements and to accommodate the bone morphology [5,6]. Refer to Fig. 2, the criteria were the plate-bone distances and alignment angle at four regions of the plate, with a total of eight as described below.

- Region A: The plate-bone distance at 5 points (i.e., 5 criteria) – 3 at the distal tip of the plate and the 2 most proximal points at the transition of metaphysis to diaphysis, is less than 2 mm.
- Region B: The plate-bone distance is less than 6 mm at the middle third of the plate.
- Region C: The plate-bone angle is less than 10° measured at 80 mm from the proximal end of the plate.
- Region D: The plate-bone distance is less than 4 mm within 20 mm from the proximal tip of the plate.

2.3. Virtual placement of bone fixation plate

The virtual placement planning system equipped with a 3D haptic device developed for determining the optimal placement of a bone fracture fixation plate on a distal medial tibia is shown in Fig. 1. It could also be operated using a 2D mouse with the virtual trackball paradigm. The virtual environment was the same regardless of the user interface device adopted. The system provided a 3D virtual environment containing (i) a fixed model of a distal medial tibia (referred hereafter to as “bone model”), and (ii) a movable model of a fixation plate, where the latter was to be fitted onto the former. The virtual scenario could be observed simultaneously from three angles, i.e., perspective view, top view and end view, to improve mental representation [12]. The 3D model of the tibia was reconstructed from computed tomography (CT) data. The user could use the haptic device equipped to manipulate the plate model around the bone model, changing its position and orientation in 3D space, in the process of locating the optimal placement. Here, the optimal location was defined by the set of eight fit criteria that constrained the alignment and proximity between the plate and the bone. The system computed these parameters on the fly and compared them with the fit criteria during the placement planning process. Indicators showing the extent to which the eight fit criteria were met were

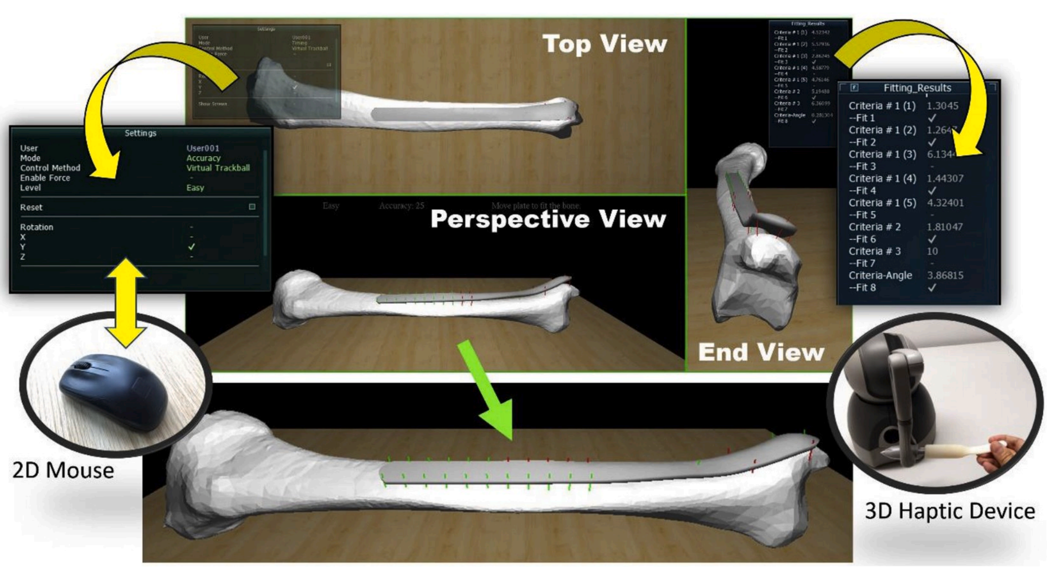

Fig. 1. The virtual planning system for fixation plate placement: graphical user interface for virtual trackball (left); fit criteria indicators (right); short line segments around the rim of the plate as visual cues (bottom).

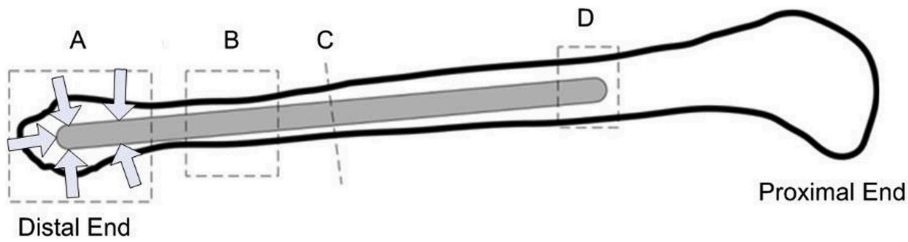

Fig. 2. Fit criteria.

displayed on the graphical user interface (right of Fig. 1). Interactive visual cues in the form of short line segments attached around the rim of the plate surface were also provided, where the color of the lines changed from red to green when the perpendicular distance between the corresponding regions of the plate were close enough to the bone (bottom of Fig. 1). In addition, force feedback was generated when the plate was in contact with the bone. Once the plate location was reached according to the fit criteria, the system would play a beep sound and the planning process was finished.

In this study, the haptic device adopted was the Touch device of the 3D Systems Inc., with 6 degrees-of-freedom spatial input (i.e., translation along x-, y- and z-axis and rotation around these three axes) and 3 degrees-of-freedom force output. The device was equipped with a pen-like stylus which was attached with a 3D-printed model of the fixation plate (see the photo in the lower right of Fig. 1). The 3D-printed plate model, and thus the haptic stylus, was moved by hand to maneuver the virtual objects.

2.4. Haptic feedback

When the virtual plate came into contact with the virtual bone, which was determined in real time by a collision detection algorithm, the corresponding feedback force was calculated based on a spring-damper model to drive the haptic stylus that the subject was holding and maneuvering to move the virtual plate. With the haptic feedback force, the subject would feel a force acting in opposite direction to resist the virtual plate (the stylus) from moving further toward the bone model. Details of the collision detection and response can be found in Ref. [6].

2.5. Modes of operations

To evaluate the usability of the system under different situations, three modes of operation were made available: (i) 2D mouse implementing the virtual trackball paradigm, denoted as M; (ii) 3D haptic device with force feedback disabled, denoted as HNF; and (iii) 3D haptic device with force feedback, denoted as HF. User performance of placement planning under these three modes were evaluated empirically. Two difficulty levels, namely, easy and hard, were available for further analyzing the usability. For the easy level, placement was considered optimal when the fit criteria described above were met. For the hard level, the spatial thresholds were tightened and reduced by 20% to increase the difficulty.

2.6. Performance metrics

The performance metrics adopted for usability evaluation were completion time and placement accuracy. Completion time was defined as the time elapsed from the beginning of the planning until all the 8 fit criteria were met. For fair comparison, the initial position of the plate in the virtual environment was fixed for all trials. The maximum time allowed for planning was set to 3 min, considering that subjects might take excessively long time to determine the optimal placement or even could not complete a trial. The limit was set based on a trail with a surgeon who was a first-time user of the system and could complete plate placement in around 3 min. Hence, if optimal placement could not be achieved within 3 min, the completion time would be set to 3 min with the attempt marked as "incomplete", and the planning process was terminated.

Placement accuracy was defined by the number of fit criteria met out of the eight. If fitting could be completed within 3 min, i.e., all the 8 criteria were met, the placement accuracy was 100%; otherwise the accuracy of the incomplete attempt was given by the number of criteria met within the 3 min divided by eight.

2.7. Usability evaluation

User feedback on the usability of 2D mouse versus 3D haptic interface were collected using the IBM Computer System Usability Questionnaire (CSUQ), which has been used for evaluating the usability of medical and healthcare applications, including motor rehabilitation [13], gait analysis [14], computer-based training of hemodialysis management [15] and virtual nasogastric tube placement [16]. The questionnaire concerns user perception on the easiness of use, effectiveness and satisfaction towards a computer system. It has high reliability ($\alpha = 0.93$) and validity. The questionnaire contains 12 items on a 7-point Likert scale, from 1 ("strongly agree") to 7 ("strongly disagree") for each item. That is, the lower the score, the stronger the agreement.

2.8. Research protocol

A four-session study over two weeks, with two sessions per week, was designed to evaluate the usability of the virtual planning system for fixation plate placement. The research protocol is shown in Fig. 3. At the beginning of the experiments, the subjects were explained the purpose of the study and the procedure, with a video demonstrating the operations of the system. A short hands-on familiarization period was also allowed for the subjects to gain understanding of the actual operations of virtual trackball with a 2D mouse and 3D haptic device respectively. In each session, subjects were required to use the virtual placement planning system to perform plate fitting under the three modes of operation, i.e., M, HNF and HF; and two difficulty levels, i.e., easy and hard. Thus, each subject had to perform plate fitting 6 times in each session, i.e. 6 trials. To prevent practice effect that could occur if the subjects always performed plate fitting following the same order of modes of operation, i.e., the performance for the later modes could be better due to the practice at the preceding modes, the order in each session was randomized to reduce the potential practice effect and achieve a fair comparison. For example, the order of the four sessions for a subject could be (HF, M, HNF), (M, HNF, HF), (HF, HNF, M) and (HNF, HF, M). It took about 30 min to finish a session of 6 trials. At the end of study, the subjects were asked to fill in the CSUQ based on their experience of virtual plate placement using a 2D mouse and the 3D haptic device respectively. The study was approved by the institutional review board (HSEARS20150817001). Informed consent was obtained from all the subjects before the study.

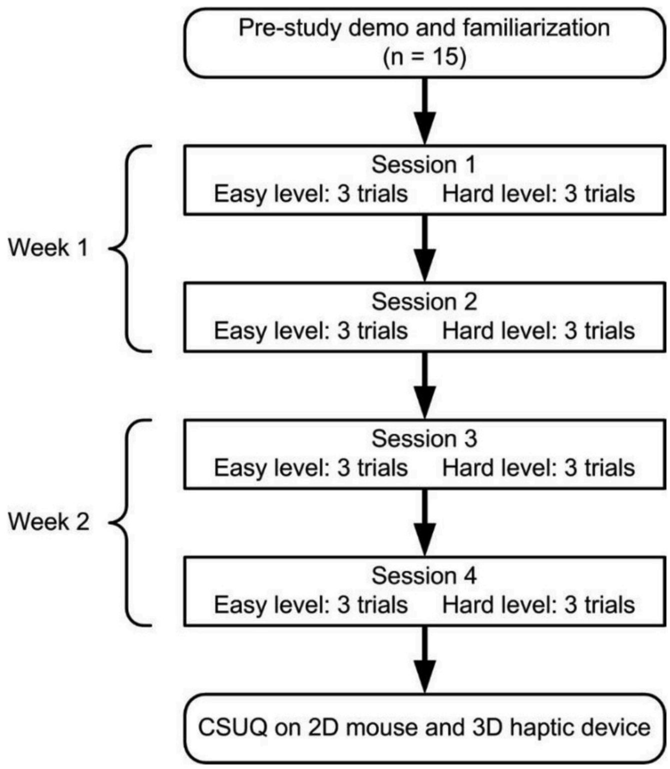

Fig. 3. Research protocol: in each session, a subject performed virtual placement once under each of the three operation modes (i.e., one trial at each mode), in the easy and hard level respectively.

2.9. Data analysis

The performance of the subjects, in terms of completion time and accuracy, over the four sessions was investigated respectively for both difficulty levels. Paired t-tests on their performance between the first and the fourth (last) session were conducted to evaluate the difference. Furthermore, ANOVA was conducted to access the difference in performance among the three operation modes for the two difficulty levels. Here, the performance of the four sessions under each operation mode was considered collectively as one group (60 samples per mode per difficulty level, i.e. 15 subjects × 4 sessions). If the ANOVA results were significant, post-hoc Tukey test was conducted to perform pairwise comparison of the difference in performance for the three operation modes. Besides, the total number of incomplete trials at each operation mode in each difficulty level was recorded for the four sessions. Paired t-tests on the responses to each item of the CSUQ on 2D mouse and 3D haptic device was conducted to assess the significance of the difference.

3. Results

The usability of the system was evaluated by 15 university students, 8 male and 7 female, with an average age of 25.1 years (SD = 6.0 years). Eleven of them were students of healthcare discipline, including physiotherapy and nursing. The subjects were all right-handed. The performance of the subjects in the four sessions of trials, in terms of average completion time and accuracy of virtual plate placement, is shown in Fig. 4 and Fig. 5. Paired t-test on the performance between the first and the last session was conducted, and the results are shown in Table 1.

As shown in Fig. 4, for the easy level, subjects using the 3D haptic device without or with force feedback, i.e. under modes HNF and HF, were able to conduct the virtual task faster than using the 2D mouse under mode M. Furthermore, the completion time was reduced over the four sessions under HNF and HF, by 26 (51%) and 56 (73%) seconds respectively. The results of paired t-tests between the first and the last session show that the reduction in completion time was statistically significant for HF ($p = 0.008$); whereas $p = 0.070$ for HNF. For mode M, the completion time stayed at the same level over the four sessions, and the change between the first and the last session was not significant ($p = 0.703$).

For the hard level, subjects operating under modes HNF and HF also conducted the virtual task faster than those under mode M, but the completion time stayed at the same level over the four sessions for all the three operation modes, and the change between the first and the last session was not significant ($p > 0.3$).

On the other hand, Fig. 5 shows that, for both difficult levels, the placement accuracy under modes HNF and HF was higher than that under mode M. The accuracy under mode M was increased over the four sessions, where the difference between the first and the last session was statistically significant ($p = 0.012$ for easy level, $p = 0.008$ for hard level). The accuracy under mode HNF did not change significantly for

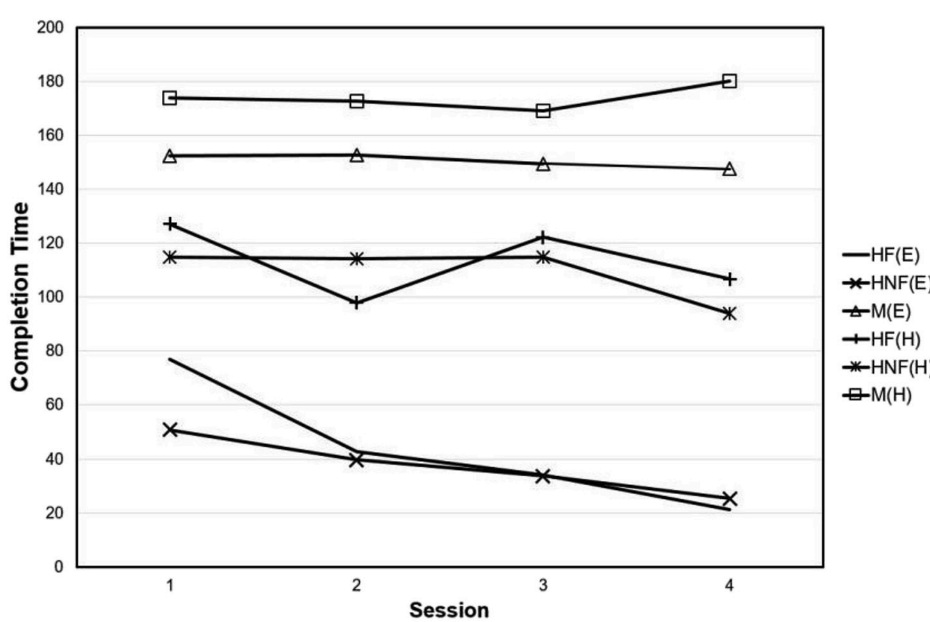

Fig. 4. Average completion time of virtual plate placement in the four sessions of trials.

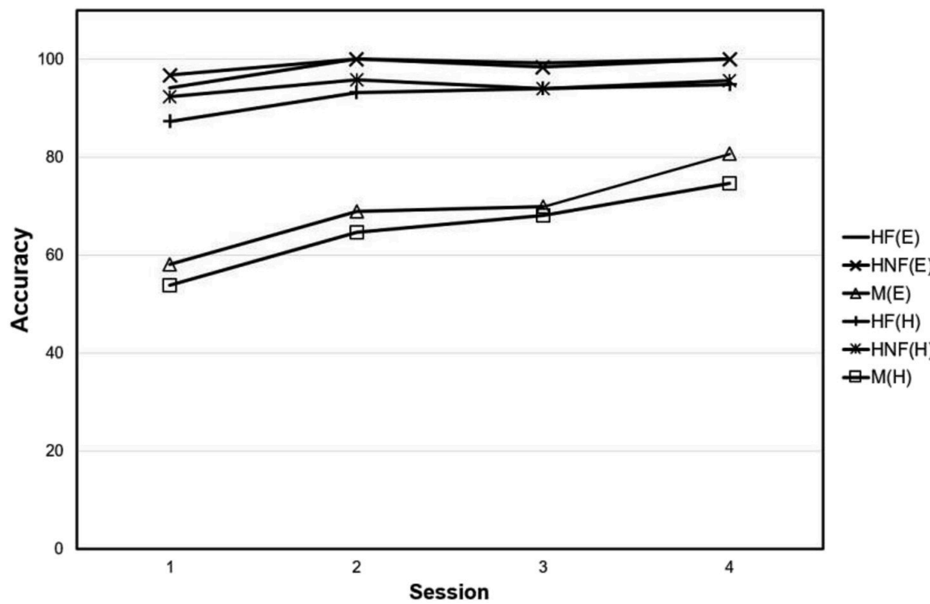

Fig. 5. Average placement accuracy of virtual plate placement in the four sessions of trials.

Table 1
Paired t-test on the performance between the first and the fourth (last) session (n = 15).

Level	Mode	Completion Time[a] (s)		p	Placement Accuracy[a] (%)		p
		Session 1	Session 4		Session 1	Session 4	
Easy	M	152.47 (43.75)	147.33 (53.60)	0.703	58.13 (39.57)	80.53 (29.59)	0.012
	HNF	50.73 (46.69)	25.4 (29.93)	0.070	96.67 (12.91)	100.00 (0.00)	0.334
	HF	76.87 (64.84)	21.33 (18.97)	0.008	94.13 (14.09)	100.00 (0.00)	0.129
Hard	M	173.73 (24.27)	180.00 (0.00)	0.334	53.87 (30.56)	74.60 (23.11)	0.008
	HNF	114.73 (68.88)	94.00 (67.96)	0.346	92.33 (9.31)	95.67 (6.34)	0.169
	HF	127.13 (70.96)	106.73 (73.53)	0.367	87.27 (15.12)	94.8 (6.59)	0.014

[a] Expressed as mean (standard deviation).

both difficulty levels while the accuracy under mode HF improved for the hard level ($p = 0.014$).

ANOVA was conducted to assess the difference in performance observed under the three operation modes. The results are shown in Table 2. For the easy level, the difference in performance under the three modes was statistically significant at the $p < 0.05$ level for both completion time [F (2,177) = 110.80, $p < 0.001$] and accuracy [F (2,177) = 38.55, $p < 0.001$]. For the hard level, the difference was also found to be significant for both completion time [F (2, 177) = 25.26, $p < 0.001$] and accuracy [F (2, 177) = 46.56, $p < 0.001$].

Post-hoc analysis using the Tukey test was thus conducted. The results further indicate that the performance under modes HNF and HF was both significantly different from that under mode M, whereas the difference in performance between mode HNF and mode HF was not significant. The finding was valid for both performance metrics and in both difficulty levels.

Table 2
Results of ANOVA on the three modes of operation (n = 60).

Level	Performance	Mode			p
		M	HNF	HF	
Easy	Completion Time[a] (s)	150.47 (45.96)	37.38 (43.88)	43.77 (50.18)	< 0.001
	Accuracy[a] (%)	69.35 (34.91)	98.75 (7.17)	98.32 (7.47)	< 0.001
	Number of Incomplete Trials	38 (63.33%)	2 (3.33%)	4 (6.67%)	
Hard	Completion Time[a] (s)	173.88 (25.00)	109.42 (64.07)	113.5 (67.50)	< 0.001
	Accuracy[a] (%)	65.30 (29.00)	94.43 (7.90)	92.3 (10.77)	< 0.001
	Number of Incomplete Trials	56 (93.33%)	22 (36.67%)	26 (43.33%)	

[a] Expressed as mean (standard deviation).

As indicated in Table 2, the number of incomplete trials with virtual trackball using 2D mouse under mode M was higher than that with 3D haptic device under modes HNF and HF, for both the easy and hard level. The number for the hard level was larger than that in the easy level for all the three operation modes. Virtual placement under mode M was particularly difficult, where 56 out of 60 attempts (over 90%) were incomplete.

The results of CSUQ on the usability of a 2D mouse and a 3D haptic device are shown in Table 3. The average score of all items in the questionnaire for the 3D haptic device (2.80–4.20) was found to be significantly lower than that of the 2D mouse (5.33–6.07), with $p < 0.001$ for most items. This suggests that the subjects were more satisfied with the usability of the 3D haptic device. The difference for items Q3, Q4, Q5 and Q6 was particularly large, close to 3 points or above.

4. Discussion

The results of the study show that virtual fixation plate placement using the 3D haptic device significantly outperformed placement with a 2D mouse, in terms of completion time and placement accuracy. For the 3D haptic device, the difference in performance with and without forces was not significant. The finding suggests that a 3D user interface is essential for the virtual fixation plate placement task in the present

Table 3
Results of CSUQ on the usability of 2D mouse and 3D haptic device (n = 15). The lower the score, the stronger the agreement.

No.	Question	2D mouse[a]	3D haptic device[a]	Difference	p
Q1.	Overall, I am satisfied with how easy it is to use this system	5.87 (0.83)	3.60 (1.35)	2.27	< 0.001
Q2.	It was simple to use this system	6.07 (0.70)	3.33 (1.40)	2.73	< 0.001
Q3.	I can effectively complete my work using this system	6.07 (0.80)	3.13 (1.46)	2.93	< 0.001
Q4.	I am able to complete my work quickly using this system	5.93 (0.96)	2.80 (1.47)	3.13	< 0.001
Q5.	I am able to efficiently complete my work using this system	6.00 (0.93)	2.93 (1.53)	3.07	< 0.001
Q6.	I feel comfortable using this system	5.93 (0.80)	3.00 (1.46)	2.93	< 0.001
Q7.	It was easy to learn to use this system	6.00 (0.93)	3.87 (1.64)	2.13	< 0.001
Q8.	I believe I became productive quickly using this system	5.87 (0.99)	3.07 (1.53)	2.80	< 0.001
Q9.	The interface of this system is pleasant	5.80 (0.86)	4.07 (1.62)	1.73	< 0.001
Q10.	I like using the interface of this system	5.93 (0.88)	3.87 (1.60)	2.07	< 0.001
Q11.	This system has all the functions and capabilities I expect it to have	5.33 (1.18)	4.20 (1.74)	1.13	0.006
Q12.	Overall, I am satisfied with this system	6.07 (0.88)	3.53 (1.46)	2.53	< 0.001

[a] Expressed as mean (standard deviation).

study, whereas the incorporation of interactive forces feedback is not an added value.

4.1. Haptic feedback

There have been doubts about the effect of haptics on virtual reality medical training applications, e.g. neonatal intubation [17] and laparoscopic cholecystectomy [18], where the effect of incorporating haptics was found to be minimal. Inconsistency with real clinical settings, unrealistic force feedback and high cost of devices are among the critiques against haptic devices. For the 3D haptic interface in the study, haptic realism was limited by the haptic rendering algorithm adopted, i.e. virtual coupling [19], which employed a damped spring to model the feedback forces to maintain system stability. The forces produced to simulate plate-bone collision were felt like that of an elastic spring, rather than the impact of two hard rigid objects. Besides, the maximum exertable force of the 3D haptic device used in the study was 3.3 N only. In future work, haptic device that can generate stronger feedback force, e.g. Virtuose 6D of Haption SA, will be explored for virtual plate placement. Algorithms of rigid body collision response [20] will be employed to simulate the contact forces between the virtual plate and bone more realistically.

Nevertheless, subjects in the present study commented that haptic feedback was indeed a preferred option. The forces produced during plate-bone collision provided haptic feedback about the relative position between the plate and the bone, in coordination with the visual feedback that displayed two non-penetrating objects in contact to indicate collision. Without the force feedback, the stylus of the device could be moved further forward while, graphically, the plate was blocked by the bone and stayed on the bone's surface, thereby leading to inconsistency between visual and haptic perception. The presence of haptics improves realism in this regard by restricting further stylus movement upon plate-bone collision with the resistive force produced by the haptic device, even though the advantage of haptics realism here was not reflected from the performance metrics. The relatively small sample size might be a factor that could have influenced the results.

4.2. Placement accuracy

While it was clear that subjects conducting virtual placement with the 3D haptic device (modes HNF and HF) outperformed the 2D mouse setting, an interesting observation was that the placement accuracy with latter increased over the four sessions of trials although the completion time did not improve. Compared to the 3D haptic device, using a 2D mouse with the virtual trackball paradigm (mode M) to manipulate objects in 3D space is counter-intuitive and unnatural, the learning curve was relatively steep and it required more time and practice in order to be acquainted with the operations, especially for the hard level. Through the four sessions of practice, subjects were able to acquire the skills better, complete more trials and improve the accuracy. For the 3D haptic device, as it was easier to use, subjects could already complete more trials than conducting virtual placement with the 2D mouse, even in the initial attempts, improvement in accuracy over the sessions was therefore not as significant.

4.3. Completion time

On the other hand, the completion time of virtual placement with the 3D haptic device was reduced over the four sessions as subjects become more familiar with the operations. For the 2D mouse, there was no significant reduction in completion time with 2D, although the subjects could complete more trials and improve placement accuracy.

To ensure that the experimental sessions were conducted within reasonable time, the upper limit was 3 min, beyond which a trial was terminated and the time taken was set to 3 min. If the upper bound was not imposed, a subject might still complete a trail but use more time. Hence, the current arrangement may not accurately reflect the actual user performance and influence statistical analysis. However, this was indeed a compromise for it would not be feasible if subjects were allowed to try endlessly until a trial was completed. In fact, they might want to give up because of fatigue or frustration. In addition, time is of the essence in a clinical setting, therefore this necessitates a virtual planning system which facilitates the plate positioning in the shortest possible time.

4.4. Virtual trackball

Using a 2D mouse to manipulate objects in 3D space under the virtual trackball paradigm involved the abstract mental process that decomposes a translation or rotation, which could be made directly with the 3D input device, into a sequence of actions along or around the x-, y- and z-axis respectively. It was also inconvenient to undo or correct a transformation by returning to previous positions. Further, the need to repeatedly select to the desired axis in the graphical user interface, one at a time, using the 2D mouse for virtual placement was considered undesirable. This was evident from the negative response to CSUQ on items concerning effectiveness (item Q3), speed (item Q4), efficiency (item Q5) and the level of comfort (item Q6). Indeed, the overall response of the subjects to the CSUQ was unanimous – virtual placement employing the 3D user interface exhibited higher usability and offered better satisfaction.

4.5. Limitations

As a case study, the present system only simulated the fitting of one bone model (i.e. distal medial tibia) and the corresponding fixation plate. The 3D bone models can be changed to simulate and explore plate fitting for a set of tibiae with varying morphological shapes. However, the fit criteria were manually set/programmed specific for this plate model to meet the clinical requirements and bone morphology. In its current form, the system was therefore more suitable for resident training and medical education. The system can be turned into an open system where different bone and plate models, and the corresponding fit criteria, can be loaded for virtual plate placement. In principle, the predefined fit criteria for different plate-bone combinations can be automatically applied to the chosen plate model with algorithms, which is a future research direction to enhance the capability of the simulator for pre-operative planning.

The application of the system is limited to cases where fractured bones have undergone diagnostic CT so that the corresponding patient-specific 3D models can be made available for pre-operative planning. The system could be used instead to gain some insights by using generic bone models of the fractured sites to approximate the situations in real scenario.

The usability of the virtual plate placement planning system was currently evaluated with students considering that the maneuvers in plate placement could be regarded as that of a generic virtual manipulation task, and the usability was thus evaluated from the perspective of general users. However, orthopedic surgeons may perform differently and probably better attributed to their knowledge of anatomy, bone morphology and plate placement. As surgeons are supposed to be the major end-users, it is necessary to recruit them for usability evaluation. Furthermore, when the experience of plate placement is taken into account, the study will provide further insights into the effect on the system usability, e.g., by comparing the performance of novice and experienced surgeons with reference to the results obtained in the present study. Finally, in the study, the bone model was fixed and only the plate was movable for all situations. It would be interesting to investigate the performance of plate placement when both virtual models are movable.

5. Conclusion

Virtual planning of bone fixation plate placement using a 3D haptic device offered superior usability than the use of a 2D mouse in conventional systems. A study with surgeons with relevant skills and experience and a large sample size will be conducted to further investigate and verify this finding. The usability of the 3D haptic will be comprehensively studied with the simulation of plate placement for bones at other anatomical sites. In the meantime, the usability of the present prototype system will be further developed to incorporate depth cues, i.e. shadows and shading, as well as stereoscopic vision to enhance virtual realism by providing rich visual feedback.

Ethical statement

The work reported in the manuscript was supported by an internal research grant provided by the Hong Kong Polytechnic University which the first author (K.S. Choi) affiliates with, under grant number G-UC93.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgement

The authors thank orthopedic surgeon Dr. Wing-Leung Chan for his advice on the study design, and Xue-Jian He for his effort in developing the software.

References

[1] Augat P, von Rüden C. Evolution of fracture treatment with bone plates. Injury 2018;49:S2–7.
[2] McRae R, Esser M. Practical fracture treatment. Churchill Livingstone; 2008.
[3] White TD, Folkens PA. The human bone manual. San Diego: Elsevier Academic Press; 2005.
[4] Macleod A, Pankaj P. Pre-operative planning for fracture fixation using locking plates: device configuration and other considerations. Injury 2018;49:S12–8.
[5] Schmutz B, Wullschleger ME, Kim H, et al. Fit assessment of anatomic plates for the distal medial tibia. J Orthop Trauma 2008;22:258–63.
[6] Choi K-S, Schmutz B, He X-J, et al. Virtual haptic system for intuitive planning of bone fixation plate placement. Informatics in Medicine Unlocked 2017;9:145–53.
[7] Overvliet KE, Smeets JBJ, Brenner E. The use of proprioception and tactile information in haptic search. Acta Psychol 2008;129:83–90.
[8] Larsen P, Elsoe R, Hansen SH, et al. Incidence and epidemiology of tibial shaft fractures. Injury 2015;46:746–50.
[9] Wennergren D, Bergdahl C, Ekelund J, et al. Epidemiology and incidence of tibia fractures in the Swedish Fracture Register. Injury 2018;49:2068–74.
[10] Essert C, Joskowicz L. Chapter 32 - image-based surgery planning. In: Zhou SK, Rueckert D, Fichtinger G, editors. Handbook of medical image computing and computer assisted intervention. Academic Press; 2020. p. 795–815.
[11] Sadri S, Kohen SA, Elvezio C, et al. Manipulating 3D anatomic models in augmented reality: comparing a hands-free approach and a manual approach. In: 2019 IEEE international symposium on mixed and augmented reality (ISMAR); 2019. p. 93–102.
[12] Garg AX, Norman G, Sperotable L. How medical students learn spatial anatomy. Lancet 2001;357:363–4.
[13] Medina JLP, González M, Pilco HM, et al. Usability study of a web-based platform for home motor rehabilitation. IEEE Access 2019;7:7932–47.
[14] Braga Rodrigues T, Ó Catháin C, O'Connor NE, Murray N. A Quality of Experience assessment of haptic and augmented reality feedback modalities in a gait analysis system. PloS One 2020;15:e0230570.
[15] Pun S-K, Chiang VC-L, Choi K-S. A computer-based method for teaching catheter-access hemodialysis management. Comput Inf Nurs 2016;34.
[16] Chiang VCL, Choi TKS, Ching SSY, Leung KLK. Evaluation of a virtual reality based interactive simulator with haptic feedback for learning NGT placement. J Probl Based Learn 2017;4:25–34.
[17] Agarwal A, Leviter J, Mannarino C, et al. Is a haptic simulation interface more effective than computer mouse-based interface for neonatal intubation skills training? BMJ Simulation and Technology Enhanced Learning 2015;1:5.
[18] Thompson JR, Leonard AC, Doarn CR, et al. Limited value of haptics in virtual reality laparoscopic cholecystectomy training. Surg Endosc 2011;25:1107–14.
[19] Venkata SA, Mohit T, Andinet E, et al. High fidelity virtual reality orthognathic surgery simulator. Proc SPIE Int Soc Opt Eng 2018;10576:1057612. https://doi.org/10.1117/12.2293690.
[20] Wang J-H, Setaluri R, James DL, Pai DK. Bounce maps: an improved restitution model for real-time rigid-body impact. ACM Trans Graph 2017;36. Article 150.