Journal of Cranio-Maxillo-Facial Surgery 47 (2019) 1242–1248

Contents lists available at ScienceDirect

Journal of Cranio-Maxillo-Facial Surgery

journal homepage: www.jcmfs.com

A feasibility study of a new method to enhance the augmented reality navigation effect in mandibular angle split osteotomy

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ARTICLE INFO

Article history:
Paper received 15 August 2018
Accepted 16 April 2019
Available online 20 April 2019

Keywords:
Augmented reality
Navigation
Mandible
Surgery

ABSTRACT

The advantage of augmented reality (AR) is the combination of virtual reality, three-dimensional display and real–time interaction. Traditional augmented reality navigation systems lack the solution for deep perception and display errors. This study is designed to compare the different situation between the traditional image guide pattern and deviation-reminder pattern in the model trials. The deviation-reminder pattern is adding the position and rotation deviation in the scene. The AR system can track the model and surgical tools at the same time. Five craniofacial surgeons and engineers participated in this study. The navigation points were ensured with the traditional image guide pattern and deviation-reminder pattern for each one. Then, the position error, orientation error and time requirement were recorded for statistical analyses in the study. There was a statistically significant difference between the deviation-reminder pattern and traditional image guide pattern for both engineers and surgeons in orientation error and navigation time ($p < 0.05$). Additionally, there were no significant differences between engineers and surgeons in errors ($p = 0.117$) and time requirements by the team ($p = 0.913$). Our results suggest that the deviation-reminder pattern is better than traditional image-guided pattern for both engineers and surgeons. In addition, the extra information can improve the performance of surgeons in navigating position assurance.

1. Introduction

The major operative area in craniofacial surgery is the skull and jaw. However, the anatomy in the maxillofacial region is complex. There are many important nerves and blood vessels crossing the soft tissues. In order to maintain the balance of the functional and cosmetic results, the surgical incision is hidden in the small area that contains the operative area in a narrow field (Qu et al., 2015).

In these narrow operative areas, surgeons need to accomplish many delicate procedures such as drilling, grinding, cutting, shifting and fixation. The traditional method is to perform these according to the preoperational design according to the surgeon's experience with CT images. It is difficult to guarantee the accuracy and stability of the surgery.

Augmented reality (AR) is the key issue for this kind of research in recent years, which has been applied in neurosurgery (Li et al., 2018), urology (Porpiglia et al., 2018), orthopedics (Elmi-Terander et al., 2017), general surgery (Bong et al., 2017), among others. The characteristics of this technology are a combination of virtual reality, three-dimensional display and real–time interaction (Zhu et al., 2017). This technology can display the preoperational design in the operational area, which enhances the perception by the surgeon to avoid impairing the vital anatomical structures. Thus

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https://doi.org/10.1016/j.jcms.2019.04.005

it is a promising technology for craniofacial surgeons to obtain a "see-through" effect in the operating room.

However, there are still some problems with AR, such as depth perception and image shifting. The effect of the image display is not perfect for surgical navigation, and the difference between virtual reality and actual reality will result in bias for users. Thus it is not easy for surgeons to determine the target position and orientation by image navigation only.

Mandibular angle split osteotomy is a common procedure in Asian cosmetic surgery for patients who want to obtain a better facial curve. The traditional method is to design a straight line in the mandibular angle to make a proper cutting plan. It is relatively simple surgery for craniofacial surgeons to study in the model trials.

In this study, the AR system can track the model and surgical tools at the same time. We aim to use this system to help surgeons to improve the ability to judge position and orientation. This study is designed to compare the difference between the traditional image guidance pattern and deviation-reminder pattern that is used in the model trials.

2. Materials and methods

2.1. Model resource

The medical data were randomly chosen for mandibular angle prominence patients in the digital laboratory in the department of plastic and reconstructive surgery, Shanghai Ninth People's Hospital. The image information from computed tomography (CT) (GE LightSpeed 16, Milwaukee, WI) is input to Mimics 18.0 (Materialize Company, Bilgrim) software in DICOM format. With this software, we reconstructed the craniofacial bone by "Thresholding" for the CT value. Then, we used "Region growth" to separate the temporomandibular joint (TMJ) and mandible. The mandibular data are output to the three-dimensional printer (ProJet 660 Pro, 3DSYSTEM, USA) as STL files (Fig. 1). All experimental protocols were approved by the Independent Ethics Committee of Shanghai Ninth People's Hospital affiliated with the Shanghai Jiao Tong University, School of Medicine, and all methods were performed in accordance with the relevant guidelines and regulations.

2.2. Preoperative plan

The major complications of the mandibular angle split osteotomy are nerve damage and bone fracture. In order to prevent such complications during surgery, we marked the inferior alveolar nerve from the mandibular foramen to the mental foramen. According to our surgical experience, the cutting plan was chosen based on three points. The first point is the conjunction of the second molar perpendicular to the mandibular body. The second point is the conjunction of the alveolar curve parallel to the ramus of the mandible. The third point is 1 cm outside the line between the mandibular foramen and angle. There are nine navigation points designed under the cutting line (Fig. 2).

2.3. Navigational design

2.3.1. Data process

The preoperational plan is output as STL files. The coordinates for the different parts are adjusted in order to calculate for the deviation for the target points and surgical tools. Then, the unit is changed for the standard pattern. Finally, the navigational plan is output to Unity (Microsoft Corporation, Redmond, WA, USA) as FBX files.

2.3.2. Registration method

The optical navigation is developed by the augmented reality platform based on Vuforia (PTC Inc., USA). The best way to make tracking and registration for AR system is to mark the plate. The pattern will affect the speed and accuracy of recognition by the cameras. We designed two different patterns for the mandible and surgical tool registration because of the rich strong details and balanced distributed characters (Fig. 3).

2.3.3. Functional design

In order to improve the visual effect of the navigation system, the surgical tools and model are designed to be tracked in the same time. The surgical requirement is mainly about the position and orientation for the navigation point. Traditionally, the AR navigation systems have focused only on the registration method and image quality. In this study, we place emphasis on the interactive function and information delivery. In the surgical plan, the hidden and transparent choices are placed for each navigation point. All the selection tools can be controlled by gesture and voice to avoid extra keyboard manipulation. Surgeons can execute all of the functions in the vision space in the operation environment.

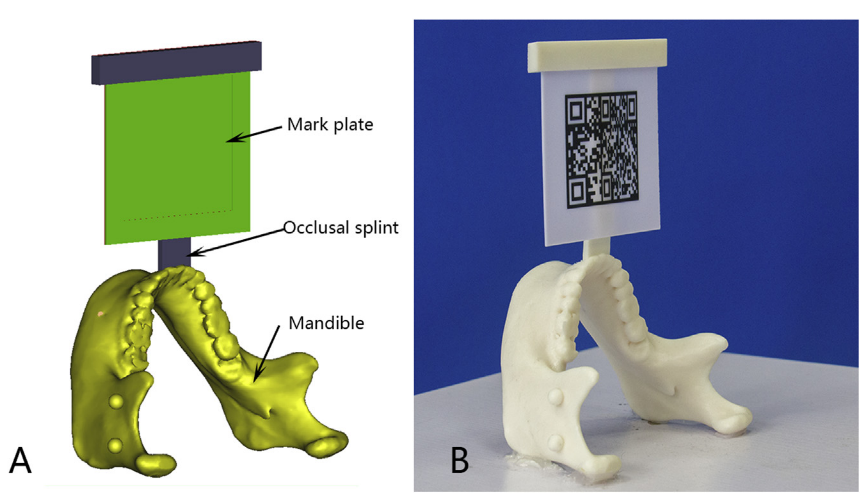

Fig. 1. Model obtained by image processing software and three-dimensional printing. (A) Effect by image processing. (B) Three-dimensionally printed model. After reconstruction of the mandible, the marking plate for registration is designed in the proper position (green). The marking plate is embedded in the occlusal splint part. Yellow: mandible; green: marking plate; gray: occlusal splint.

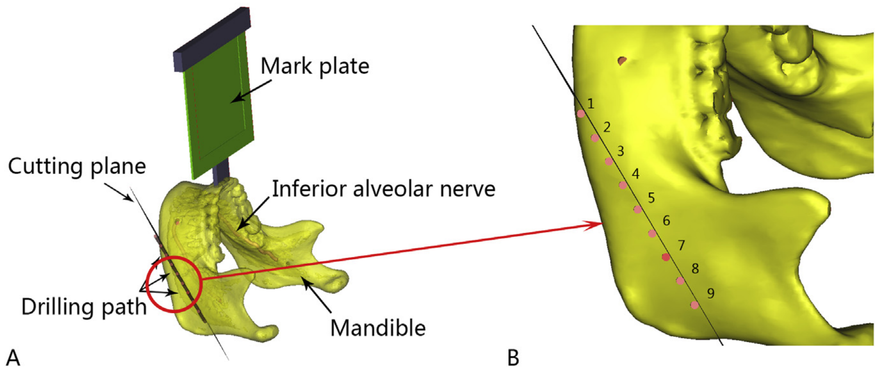

Fig. 2. Preoperational plan and navigation points. (A) Preoperational plan. (B) Navigation points. The nine navigation points are separately designed in the cutting plane, which can be selected in the AR system. Yellow: mandible; green: marked plate; gray: occlusal splint; light red: inferior alveolar nerve; dark red: navigation points; blue: cutting plane.

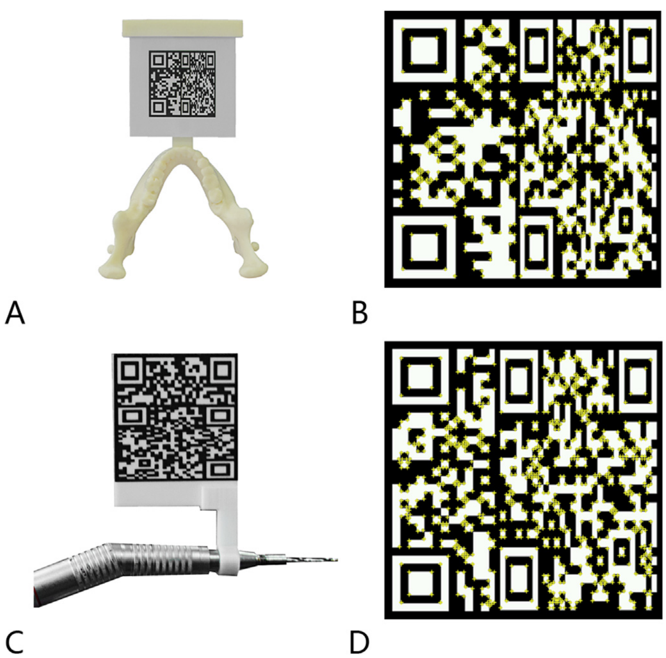

Fig. 3. Marking plate system. (A) Model marking plate. (B) Character detection for the model's marking plate. (C) Surgical tools' marking plate. (D) Character detection for the surgical tools' marking plate.

2.3.4. Interface design

In order to easily control the menu in the interface, the position of the menu is placed in the fringe of the mandibular model. The hidden menu can be set for each navigation point and mandible in order to improve the surgeon's vision. The error information can be guided for surgeons to place the surgical tool to the navigation point both for position and orientation accurately. Every navigation point can be hidden or transparent. Apart from the gesture control, the system also has the function of voice control. Every menu can be set with voice reaction (Fig. 4).

2.4. AR system

HoloLens (Microsoft Corporation, Redmond, WA, USA) is an augmented reality system. The advantage of this system is the combination of different sensors and cameras in one helmet. The instruments included the fixed measurement unit, optic sensor placement and four perception cameras. The cameras can capture the pictures or videos, and the four microphones can acquire the information on the environmental voice. The picture quality is 720p and the vision range is 30° in the horizontal and 17.5° in the vertical plane (Fig. 5).

2.5. Model trials

In the environment of simulated operation, the mandibular model and the navigation marking plate are fixed in the table. The AR system can track the marking plate and surgical tools at the same time. In the AR images, the position and orientation information can be shown in the interface selectively (Fig. 6).

In this study, we chose five craniofacial surgeons as an experimental team and five engineers as a control team. They are trained for 1 day to familiarize themselves with this system. The two teams are required to accomplish two tasks. The first step is to identify the nine navigation points without the position and orientation error information. The second step is to perform the same procedure with the position and orientation error information. The operation time and errors are recorded in the study, and finally, the results are analyzed in the statistics software (SPSS 22; IBM Corp., Armonk, NY, USA).

3. Results

The position error in the experimental team is 2.29 ± 0.93 mm and 3.26 ± 1.40 mm in the control team for engineers ($p = 0.056$). The position error is 1.89 ± 0.51 mm in the experimental team and 2.58 ± 1.06 mm in the control team for surgeons ($p = 0.035$). The orientation error is 2.74 ± 0.99° in the experiment team and 8.11 ± 2.67° in the control team for engineers ($p < 0.001$). The orientation error is 2.03 ± 1.15 °in the experimental team and 5.43 ± 2.60° in the control team for surgeons ($p = 0.002$). The operation time is 7.63 ± 1.18 min in the experimental team and 17.32 ± 1.86 min in the control team for engineers ($p < 0.001$).

The operation time is 7.74 ± 1.48 min in the experimental team and 13.22 ± 4.45 min in the control team for surgeons ($p < 0.001$). There is no significant difference between engineers and surgeons in errors ($p = 0.117$) and time for the experiment team ($p = 0.913$) (Tables 1 and 2).

4. Discussion

4.1. Medical research with augmented reality in craniofacial surgery

In recent years, surgical navigation has been applied in many disciplines with the development of computer-assisted surgery.

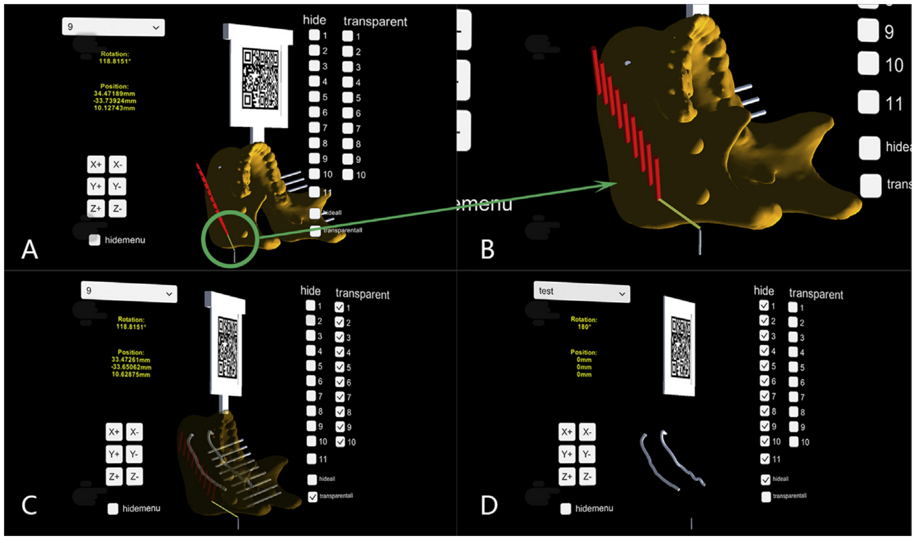

Fig. 4. Functional design and interface design. (A) General interface for navigation. (B) Local interface for navigation. (C) Transparent effect for navigation. (D) Hidden effect for navigation. There are nine navigation points (red) in the cutting line designed in the left side of mandible (yellow). The left side is the navigation information frame. All of the position and orientation errors are displayed on the upper side. The rotation means the orientation error for the surgical tool, while the position means the coordinate error in the three-dimensional place. There is a line (light-yellow) to remind the surgeons about the distance between the tip of the surgical tool and navigation point. The control buttons are on the right side and include the hidden and transparent choices for the mandible and each navigation point. The inferior alveolar nerve is shown all the time for safety purposes.

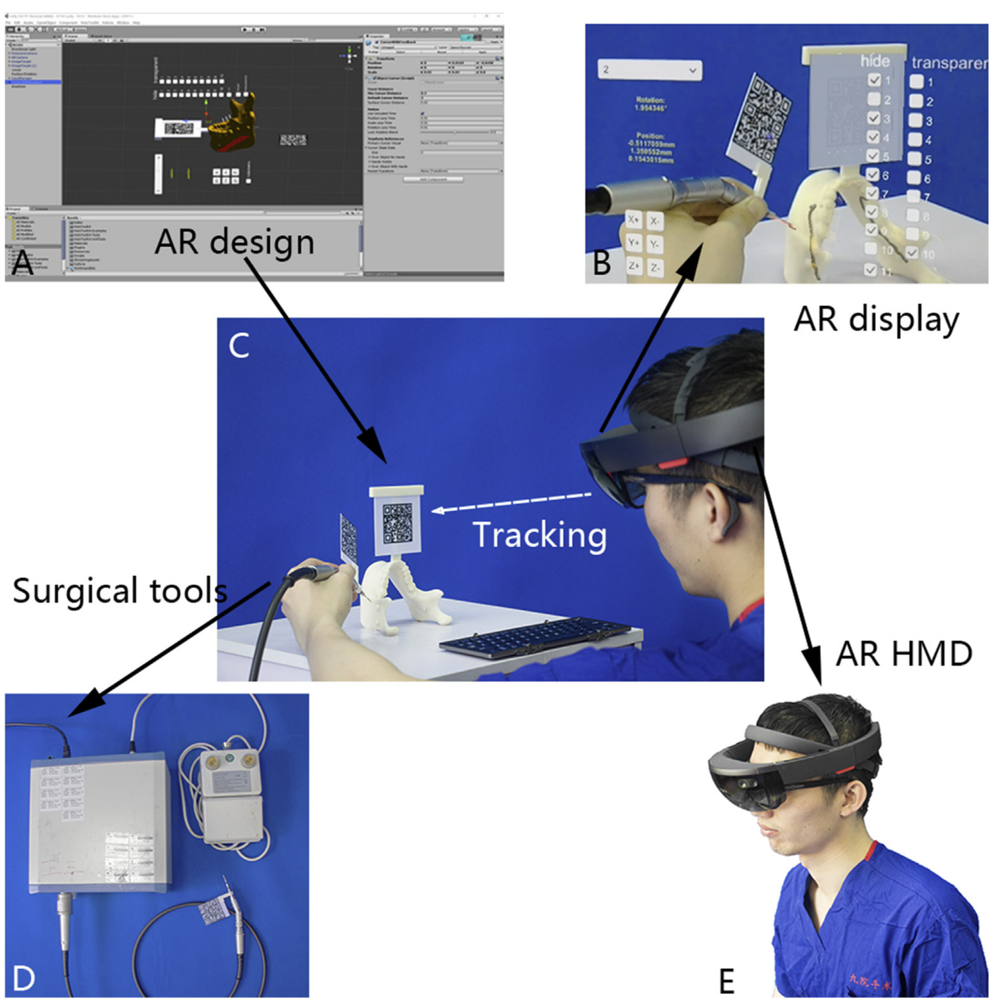

Fig. 5. Structure of the augmented reality (AR) system. The functional design and interface design are accomplished based on Unity software (A). Then, the surgical tools (D) and model (C) can be tracked at the same time by cameras in the helmet-mounted display (HMD) (E). On the screen, the navigation information shows the interface (B), which is registered by the marking plate.

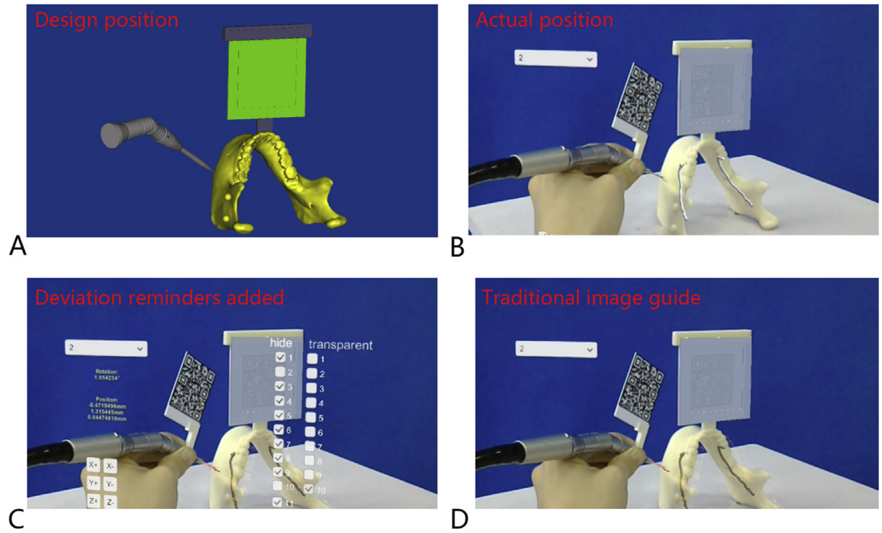

Fig. 6. Traditional image-guided pattern and deviation-reminder pattern. (A) Design navigation position and orientation. (B) Actual position and orientation. (C) Deviation-reminder pattern. (D) Traditional image-guided pattern. The preoperative design for the surgical tool's position and orientation are shown in the three-dimensional software (A). The traditional image-guided pattern (D) and deviation-reminder pattern (C) are performed in the model trials. The actual position for surgical tools (B) is also captured.

Table 1
Position error, orientation error and time for engineers.

		Engineer 1	Engineer 2	Engineer 3	Engineer 4	Engineer 5	Total	P
P.R (mm)	Exp.(Mean ± S.D.)	2.67 ± 0.97	2.97 ± 1.10	1.73 ± 0.67	2.01 ± 0.61	2.07 ± 0.56	2.29 ± 0.93	0.056
	Ctrl.(Mean ± S.D.)	4.81 ± 1.45	3.62 ± 1.20	2.88 ± 0.55	3.02 ± 0.96	1.97 ± 0.78	3.26 ± 1.40	
O.R.(°)	Exp.(Mean ± S.D.)	3.11 ± 0.51	3.26 ± 1.23	2.77 ± 0.76	2.30 ± 1.22	2.27 ± 0.52	2.74 ± 0.99	<0.001
	Ctrl.(Mean ± S.D.)	8.04 ± 2.37	7.45 ± 3.49	9.80 ± 1.60	8.72 ± 2.16	6.53 ± 2.11	8.11 ± 2.67	
Time (min)	Exp.	6.83	7.18	9.49	6.59	8.04	7.63 ± 1.18	<0.001
	Ctrl.	17.23	17.15	20.36	16.55	15.31	17.32 ± 1.86	

Abbreviations: P.R. = Position error; O.R. = Orientation error; Exp. = Experimental team; Ctrl. = Control team; S.D. = Standard deviation.

Table 2
Position error, orientation error and time for surgeons.

		Surgeon 1	Surgeon 2	Surgeon 3	Surgeon 4	Surgeon 5	Total	P
P.R (mm)	Exp.(Mean ± S.D.)	2.21 ± 0.65	1.95 ± 0.38	1.92 ± 0.37	1.60 ± 0.43	1.79 ± 0.44	1.89 ± 0.51	0.035
	Ctrl.(Mean ± S.D.)	3.70 ± 1.66	2.56 ± 0.58	2.21 ± 0.72	2.37 ± 0.39	2.08 ± 0.43	2.58 ± 1.06	
O.R.(°)	Exp.(Mean ± S.D.)	3.09 ± 0.91	1.41 ± 1.59	1.76 ± 0.66	1.98 ± 0.83	1.93 ± 0.76	2.03 ± 1.15	0.002
	Ctrl.(Mean ± S.D.)	5.34 ± 1.68	5.67 ± 2.50	4.32 ± 3.79	5.40 ± 2.11	6.42 ± 1.92	5.43 ± 2.60	
Time (min)	Exp.	8.90	9.66	7.12	6.95	6.08	7.74 ± 1.48	0.015
	Ctrl.	15.64	19.58	11.39	8.11	11.40	13.22 ± 4.45	

Abbreviations: P.R. = Position error; O.R. = Orientation error; Exp. = Experimental team; Ctrl. = Control team; S.D. = Standard deviation.

There are three main patterns. The first is the three-dimensional printing guide template based on a preoperative surgical plan (Yap et al., 2008). The second is the traditional optic navigation. The navigation images will present in the screen point-to-point by tracking the surface markers or external markers with a surgical probe (Zavattero et al., 2017). The third is the augmented reality (AR) navigation. The virtual images and reality objects will combine in the practical scene and the navigation method by a vision mode (Murugesan et al., 2018).

At present, medical research of AR is mainly focused on surgical planning (Olsson et al., 2015), surgical navigation (Wang et al., 2017) and surgical training (Alaraj et al., 2015). The criteria for measuring the performance of the AR system is as follows: the frequency of image refreshment; the consistency of virtual scene image and real scene image in lighting, color, texture and other physical characteristics; the registration accuracy of the virtual scene and real scene; the consistency of the scene with the user's viewpoint change and the degree of freedom in the enhanced scenario. In previous AR study in craniofacial surgery, research has been concerned with the wireless system (Mischkowski et al., 2006; Zinser et al., 2013), image-guided system (Badiali et al., 2014; Wang et al., 2017) and clinical application (Zhu et al., 2016). However, the authors did not focus on the problem of the deep perception.

Tepper et al. (2017) is the first to report the application of HoloLens in plastic surgery. They compared the function with the Oculus Rift and Google Glass. In fibula free flap mandibular reconstruction surgery, they used the preoperative plan to show the model in the operation room. This study showed several advantages as follows.

First, it is useful in the sterile environment using gesture and voice interaction. Second, the virtual image has high quality, which combines the preoperative plan and three-dimensional models in the operative field. Third, AR will not affect the surgical procedures and efficacy; on the contrary, it provides the additional information for surgeons to improve decision making in the surgery. Fourth, in some short operations, it is also convenient to fit the virtual operative plan and intraoperative field of vision. However, their research did not apply the accurate navigation to the surgery.

4.2. Navigation accuracy and additional information assistance

The accuracy factors of augmented reality are concerned mainly with deep perception (Choi et al., 2016) and display errors. The human eyes first take in two-dimensional information, so there is some difficulty in the perception of depth. In addition, an AR system is not able to solve the problem of pupil distance calibration, which means a “double shadow” effect on the image display.

The pupillary near reflex includes accommodation, convergence and myosis. In the natural environment, stereo vision is accomplished by the former actions. However, there is only one fixed focal plane in the helmet-mounted display (HMD). This problem results in failure of accommodation ability. It is difficult to focus on and to fuse images simultaneously, which cause visual discomfort and fatigue.

The display error is caused by registration method and camera performance, which results a “misalignment” effect in the subjective perception for virtual and reality image. The data calculation of the cameras for image scans, image process and image reconstruction leads to the system errors. The image drift (Lowe, 2004) is related to the camera acquisition frequency, deep perception ability and hardware data process.

The registration error is divided into static registration error and dynamic registration error. The static registration error refers to the error caused by the system when the user's viewpoint is still at rest with the object in the real environment, whereas the dynamic registration error refers to the error that occurs when the object has relative motion in the user's view or environment, which is also the main system registration error. Time delay is the main cause of dynamic registration error. When the user's head or the object changes, the system delay will produce virtual information displacement in the real environment (Ozuysal et al., 2010).

In order to solve these problems, we applied the method to combine the image navigation and coordinates navigation information in the HMD. The first step is to track the target model to provide the image information for surgeons. This procedure is accomplished purely by subjective feelings/perception. The second step is to adjust the coordinates information by tracking the surgical tools. In this study, we aimed to compare the different situations to determine whether the extra information is helpful to surgeons.

In terms of orientation error and navigation time, our results (Fig. 7) suggest that the deviation-reminder pattern is better than traditional image guide pattern for both engineers and surgeons ($p < 0.05$). However, the results of position error suggest that surgeons are more adaptive to the deviation-reminder pattern, which means this pattern is more useful to surgeons than engineers. This may be concerned about medical experience. In addition, in this study, there was no significant difference observed between engineers and surgeons in regard to errors ($p = 0.117$) and time requirements for the experimental team ($p = 0.913$).

4.3. Prospects and limitation

At present, the important problem in surgical practice is to apply the preoperative plan in the operation room. Surgeons need to convert two-dimensional images into three-dimensional images to accomplish preoperative planning. Medical imaging technology has begun to use stereo vision to reduce the differences in perception. HoloLens is suitable to apply in the preoperative design, image guided surgery and remote medicine (Sauer et al., 2017).

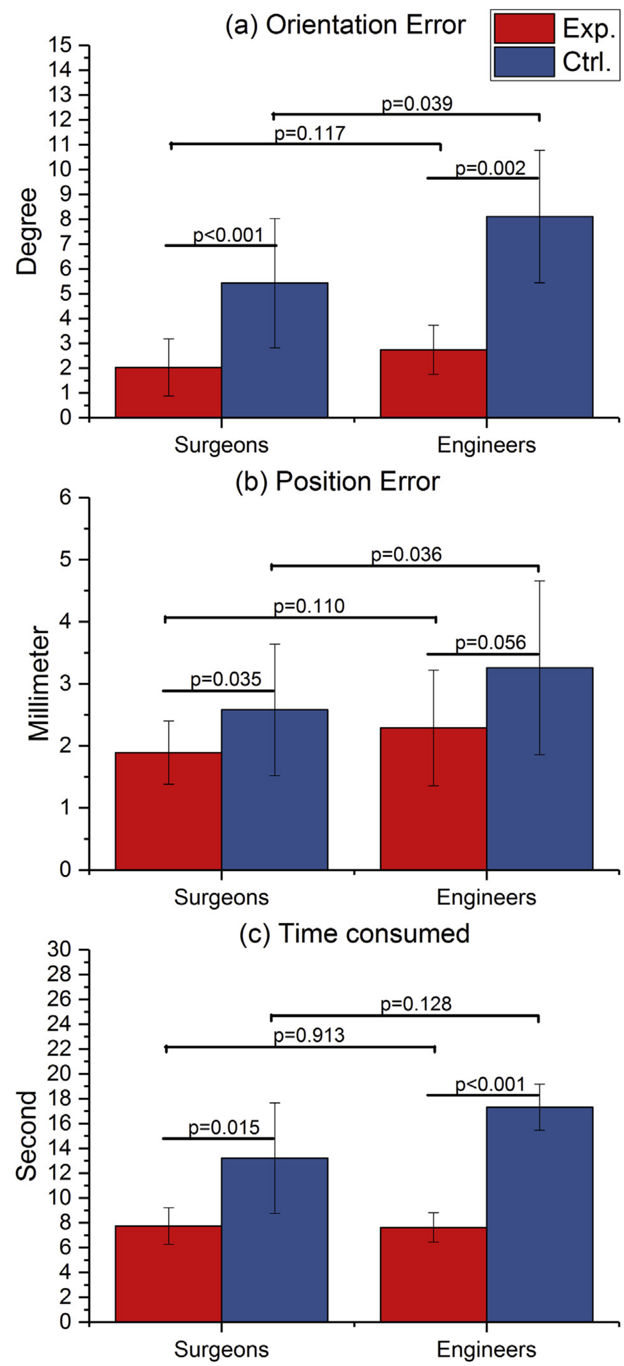

Fig. 7. Comparison of the position error, orientation error and time requirement for surgeons and engineers.

This study discussed the differences between the traditional image guide pattern and deviation-reminder pattern performed in the model. The latter method seems superior in orientation results in statistics. Before being used in clinical practice, this method needs more in vivo experiments to verify the stability.

5. Conclusion

We developed deviation reminder and traditional image guide information for AR navigation system which has performed in the model trials. Our results suggest that the deviation-reminder pattern is better than traditional image-guide pattern for both engineers and surgeons. In addition, the extra information can improve the performance for surgeons in navigation position assurance.

Author contributions

L.X. and G.C. designed experiments; Y.G. designed the software and the system. L.L and Y.G. carried out experiments and wrote the manuscript; L.L. analyzed experimental results. All authors reviewed the manuscript.

Conflicts of interest

The authors confirm that there are no known conflicts of interest associated with this publication.

Acknowledgements

This work was supported by the Natural Science Foundation of China (No. 61672341), the National Natural Science Foundation of China (No. 61190124, 61190120), the Science and Technology Commission of Shanghai Municipality (No. 17441903800, 18DZ2201900 and 19441912300), the Key Project of SJTU Medical and Engineering Cross Research Fund (No. YG2017ZD03), and the Shanghai Jiao Tong University and Chinese University of Hong Kong Joint Research Fund Programme, and the Science and Technology Department of Hainan Province (ZDYF2018022).

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