A Novel Noninvasive Patient-Specific Navigation Method for Orbital Reconstructive Surgery: A Phantom Study Using Patient Data

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Background: The correction of orbital deformities is an ongoing challenge in maxillofacial surgery. Computer-assisted navigation can improve surgical outcomes. However, conventional registration methods for navigation are not appropriate for orbital reconstructive surgery. This study proposes an accurate, noninvasive, patient-specific navigation method and demonstrates its feasibility.
Methods: A noninvasive, patient-specific registration frame based on the external auditory canals and upper front teeth was designed using software developed in-house. A three-dimensional craniofacial model was segmented from patient computed tomographic data for the registration frame. A customized craniofacial phantom was also made using this three-dimensional model, with 20 embedded target points on the orbital model and 21 landmark points on the reference standard model. The proposed method was compared with two conventional registration methods: the dental splint–based method and the invasive marker frame–based method. Twenty trials were conducted for evaluation. Target registration error and surface registration error were computed to measure accuracy.
Results: The proposed method showed a target registration error of 1.05 ± 0.52 mm, with greater accuracy than conventional methods (dental splint, 2.10 ± 0.63 mm; invasive marker frame, 1.22 ± 0.46 mm). The proposed method yielded the best results for surface registration error, with 0.38 mm of deviation (dental splint, 0.82 mm; invasive marker frame, 0.60 mm).
Conclusion: The proposed noninvasive patient-specific registration method demonstrated superior results for both target registration error and surface registration error compared with other conventional registration methods for computer-assisted navigation in orbital reconstructive surgery. (*Plast. Reconstr. Surg.* 143: 602e, 2019.)
CLINICAL QUESTION/LEVEL OF EVIDENCE: Therapeutic, V.

Treatment of posttraumatic orbital deformities resulting from injuries or tumor resection has been a challenge in maxillofacial surgery. The goal of orbital deformity treatment is to restore lost three-dimensional anatomical boundaries and to avoid persistent complications.[1–3] Over recent decades, craniofacial surgical techniques have improved.[4] However, a narrow, deep, and dark surgical field makes orbital reconstruction and restoration of optimal orbital anatomical volume difficult. Thus, various postoperative sequelae, such as enophthalmos, exophthalmos, retrobulbar hematoma, and implant migration, can be induced by inaccurate restoration of the orbital anatomy.[5] Various surgical techniques have been introduced to improve surgical outcomes and reduce postoperative complications. Computer simulation based on a mirror image has been attempted, and individualized orbital prebent implants have recently been used. However, despite these customized applications, precise positioning of the implant is still necessary for restoration of the original orbital anatomy. Therefore, use of intraoperative computer-assisted navigation technology has been

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considered to reduce errors during surgical procedures and to evaluate postoperative results.[6,7] Several authors have shown improved surgical outcomes and reduced rates of repeated procedures with surgical navigation guidance in orbital reconstruction.[8–10]

Registration between the preoperative computed tomography data and the intraoperative patient data is an essential step in surgical navigation. Technically, registration is the process of transforming different sets of data into one coordinate system. In surgical navigation, it is important to determine the spatial relationship between medical imaging data and the patient. Thus, a surgeon could intraoperatively track the actual position and orientation of patient anatomy or surgical tools. Precise registration is a prerequisite because errors could propagate into all subsequent surgical tasks and induce patient trauma. Registration techniques for craniofacial surgery can be classified into two categories: (1) invasive and (2) noninvasive methods. Invasive methods rely on fiducial markers inserted in a patient's body, such as bone-implanted screws,[11] a head-implanted marker frame,[8] or a head clamp system.[12] The advantages of the invasive method are the extreme stability of the marker and high accuracy. However, wounds induced with the invasive method may cause problems after surgery. Thus, these methods are not adequate for the ultimate goal of surgery: to minimize patient trauma. To overcome this problem, noninvasive methods that minimize patient trauma have been developed, based on anatomical landmarks,[13] adhesive fiducial markers,[12] adhesive masks,[14] head-mounted frames,[15] dental splints,[16,17] surface laser scans,[18] augmented reality,[19] surface matching with a laser pointer (Z-touch; BrainLAB, Munich, Germany), and pattern recognition (PROFESS System; Stryker Corp., Kalamazoo, Mich.).

Most noninvasive registration methods are relatively unstable, as they are sensitive to geometric shape changes in marker sets that can be induced by surgical intervention. In addition, some methods require time-consuming procedures, as surgeons must palpate many points covering the entire face to minimize error because registration errors are affected by the geometric shape of marker sets and number of markers.[20] Furthermore, because target registration errors increase in proportion to the distance from the attached marker set location,[17] some registration techniques are not suitable for orbital reconstructive surgery, even though these methods show notable results in maxillary surgery. To address these problems, we propose a new noninvasive, patient-specific navigation method that is more stable and suitable for orbital reconstructive surgery. Our method designs a noninvasive, patient-specific registration frame based on the external auditory canals and upper front teeth. A phantom study with patient data was conducted to evaluate the feasibility of the proposed method.

MATERIALS AND METHODS

We compared our method with a conventional craniofacial registration method using a dental splint[17] and an invasive marker frame on the head.[8] Twenty in vitro experiments were performed on a three-dimensionally printed facial phantom generated from computed tomographic images using an optical tracking system (Polaris Spectra; Northern Digital, Inc., Waterloo, Ontario, Canada).

Three-Dimensional Craniofacial Model and Phantom Preparation

The three-dimensional craniofacial model and phantom were prepared for evaluation of the proposed method. To generate the three-dimensional model, a 512 × 512-pixel, 1-mm slice-thickness data set was acquired with computed tomography (LightSpeed 16; General Electric, Chicago, Ill.). Facial skin, orbits, and upper teeth were manually segmented from the computed tomography data set using three-dimensional medical image processing software (Mimics; Materialise NV, Leuven, Belgium). To simplify the experiment, the eyeballs, eyelids, and mouth were removed from the entire craniofacial model. After segmentation, landmark points on the facial skin and target points on the orbit were generated. Landmarks included 21 arbitrary anatomical feature points on the facial skin that were used for point-to-point registration as a reference standard (Fig. 1), with 20 arbitrary points on the orbit generated for the regional target of interest using three-dimensional modeling software (3-matic; Materialise). All of these points were created with a conical hole that could be accurately collected during navigation, and all true positions on the three-dimensional model coordinate were considered ground-truth data (Fig. 1). Based on this three-dimensional model, a phantom was fabricated with a high-resolution three-dimensional printer (Objet260 Connex2; Stratasys, Eden Prairie, Minn.).

Noninvasive, Patient-Specific Registration Frame Design

The noninvasive, patient-specific registration frame was based on unique anatomical features:

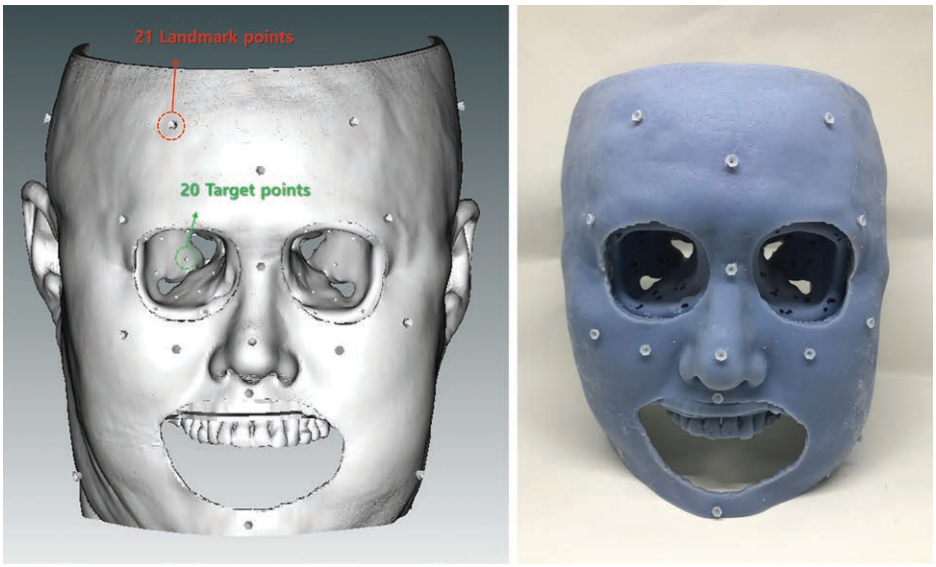

Fig. 1. Customized three-dimensionally printed craniofacial phantom. (*Left*) Three-dimensional segmented craniofacial model (21 landmark points for reference standard registration and 20 target points on the orbit). (*Right*) Three-dimensionally printed phantom.

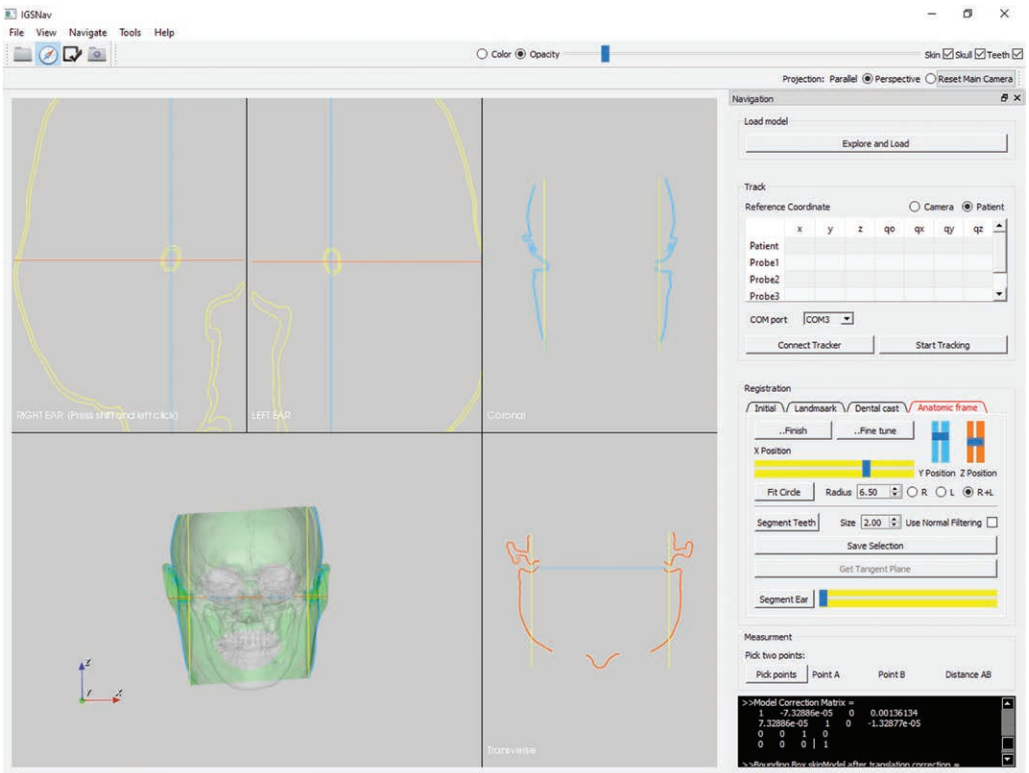

Fig. 2. Software developed in-house for registration frame design defined by four landmarks (two ear points and two tooth points).

(1) upper teeth and (2) external auditory canals. These anatomical features were more stable for fixing noninvasive markers than other craniofacial features, such as skin, because of rigidity and unique shape. Software developed in-house was used for registration frame modeling and real-time navigation (Fig. 2). This software was developed using C++, Qt 5.5 (The Qt Company, Espoo, Finland) and VTK 7.0.0 (Kitware, Inc., Clifton Park, N.Y.).

The noninvasive, patient-specific registration frame generation procedure was followed by several steps: (1) ear plug with landmark generation, (2) tooth block with landmark generation, and (3) frame generation and combining. Ear plugs with landmark points fitted into the external auditory canals were generated with a semiautomatic procedure. Initially, the outer and inner cutting plane regions of interest for the ear plugs were automatically generated (Fig. 3, *above*), and were then adjusted by a user. A three-dimensional model fitted to the region of interest of the external auditory canal was created and the center was collected for a landmark (Fig. 3, *below*). The conical hole was automatically generated from the ear plug surface to the landmark palpable during the intraoperative registration process.

The upper front teeth were used to collect landmark points for the tooth block. Centers of two front tooth surfaces were defined by the user. These two points were used as landmarks on the tooth block attached to the front teeth surfaces (Fig. 4, *above*). After modeling of the ear plugs and tooth block, the connective frame was created. All components were combined and a noninvasive, patient-specific registration frame with four landmark points was generated. This frame was fabricated with three-dimensional printing using low-rigidity material for the ear plugs and rigid material for the tooth block and frame (Fig. 4, *below*). Using this rigid frame, registration was performed for surgical navigation.

Navigation

A schematic of navigation with the proposed registration frame is shown in Figure 5. An optical tracking system (Polaris Spectra) was used for surgical navigation. The transformation matrix from the infrared camera to the patient coordinate T_c^w must be calculated for surgical tool tracking. This transformation matrix could be acquired from $T_w^p \cdot T_c^w$, where T_w^p is the transformation from the world to patient, and T_c^w is the transformation from the infrared camera to the world. T_w^p could be acquired in the registration procedure with

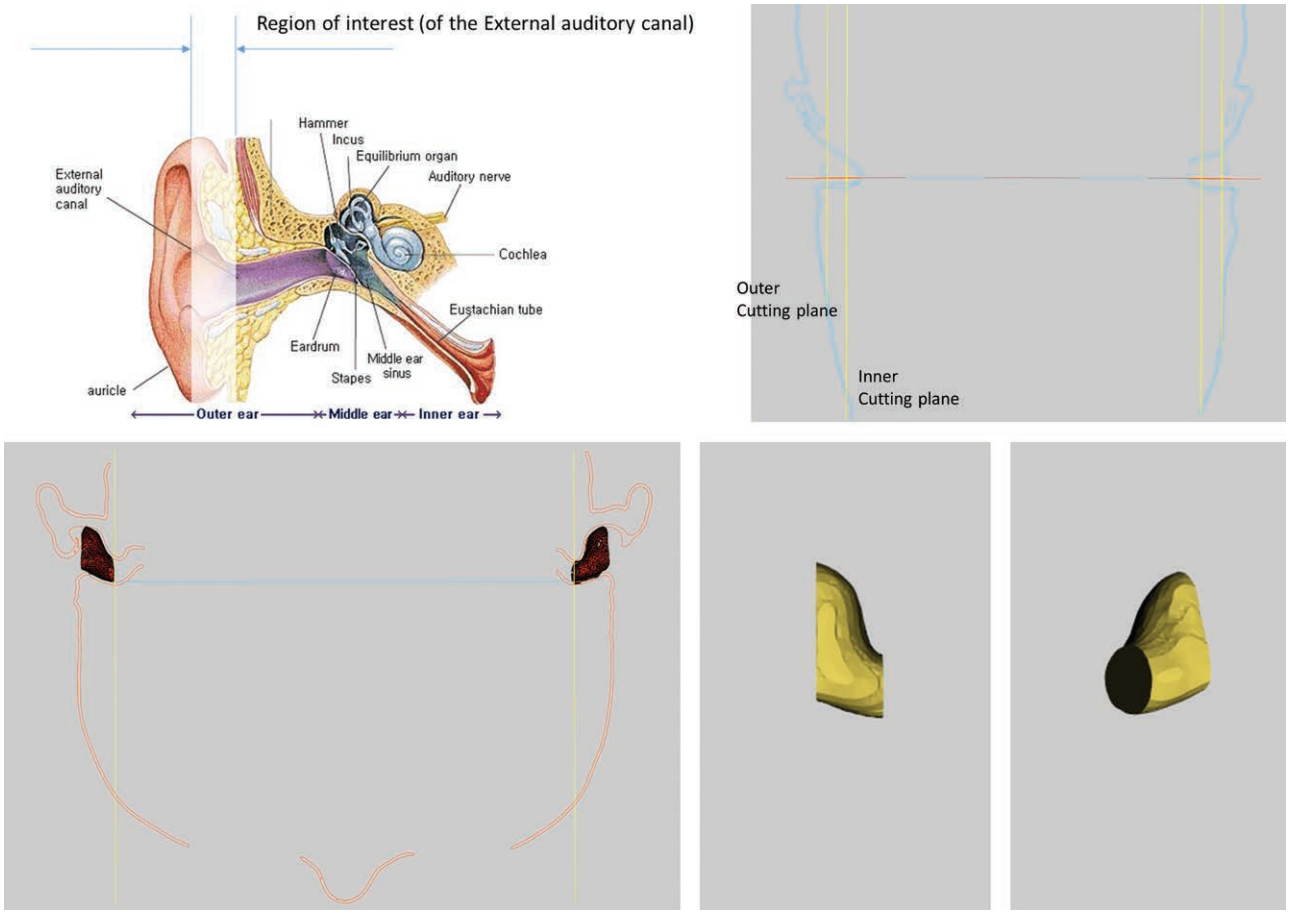

Fig. 3. Ear plug generation. (*Above*) Region of interest for ear plug. (*Below*) Generated three-dimensional model of ear plug with landmark points.

Fig. 4. (*Above*) Front tooth surface selection and tooth block generation. (*Below*) Designed and fabricated noninvasive patient-specific registration frame.

known landmark points for patient coordinates and by palpating landmark points for the world coordinates. With the transformation T_c^w, all surgical tools could be tracked.

Evaluation

For evaluation, an in vitro experiment with a customized craniofacial phantom was performed (Fig. 6). We compared our navigation method with two conventional methods. First, we examined a popular navigation method using a dental splint.[17] The model-specific dental splint with four landmark points was made using three-dimensional model data and a three-dimensional printer (Fig. 7). As another conventional navigation method, we used an invasive marker frame on the patient's head.[8] The invasive marker frame was attached to the right side of the head and tested. All navigation methods used the same craniofacial phantom described earlier under Three-Dimensional Craniofacial Model and Phantom Preparation, and the registration accuracy of each method was compared to that of the proposed method.

Accuracy was determined using the target registration error[21] and surface registration error.[22] The 20 known ground-truth positions of the craniofacial phantom on the three-dimensional model coordinate were compared with registered target points using the equation target registration error = $p_g - p_r$, where p_g was the ground-truth position and p_r was the registered position of the target. Surface registration error was the nearest surface deviation between the reference standard registration and each registration result.

RESULTS

In total, 20 registration trials were conducted for each method. Every trial involved collecting 20 target points on the orbit to calculate target registration error, and the orbital area was considered for surface registration error calculation. The experimental results for target registration error and surface registration error are shown in Tables 1 and 2. The proposed method shows a target registration error of 1.05 ± 0.52 mm and a mean surface registration error of 0.38 mm, including instrument and experimental error.

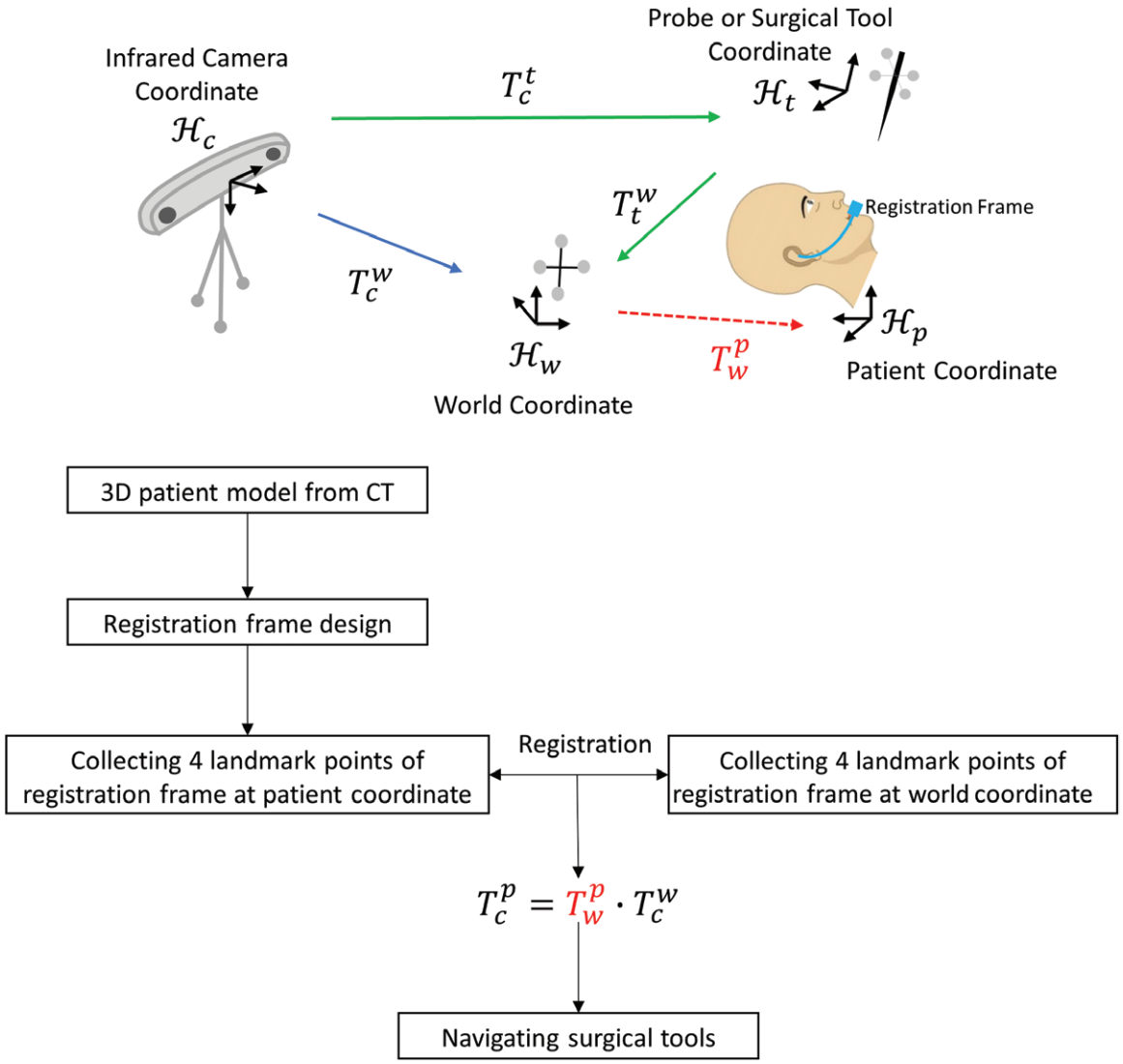

Fig. 5. Schematic of navigation with registration frame (T_c^p is the transformation matrix from infrared camera to patient coordinate, T_w^p is the transformation matrix from world to patient coordinate, and T_c^w is the transformation matrix from infrared camera to world coordinate). *3D*, three-dimensional; *CT*, computed tomography.

Figure 8 visualizes surface registration error of the orbital region for the best registration results with each method on a three-dimensional colored map (blue, 0.0 mm; green, 0.5 mm; red, 1.0 mm), and Figure 9 shows box plots for target registration error and surface registration error in all experiments. Our method shows superior target registration error and surface registration error results compared to those using conventional registration methods.

The notable result using the proposed method is the uniform error distribution in the region of interest compared with that using the dental splint or invasive marker frame. To be specific, the proposed method shows relatively uniform registration error distribution on the orbit, but conventional methods using a dental splint or invasive marker frame show more randomized or biased error distribution (Fig. 8). This implies that the proposed method can provide more reliable results for the orbital area compared with other navigation methods.

The stability (or precision) of each method is shown in Figure 9. The error distribution for all trials using each method is represented by the interquartile range that is the width of the box plot, and can determine the stability of the registration method. A small interquartile range means that the method represents consistent results and is directly related to the stability of the method. According to Figure 9, the registration method using the invasive marker frame has

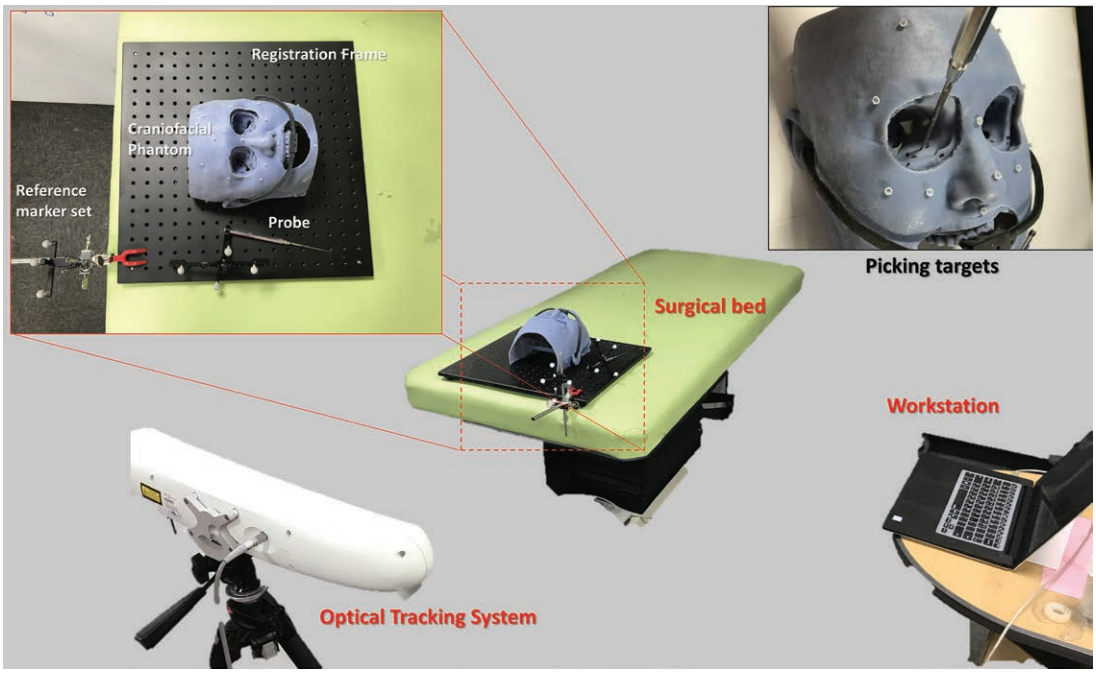

Fig. 6. In vitro experimental setup.

Fig. 7. Dental splint–based registration for comparative evaluation.

Table 1. Target Registration Error of the Orbital Area*

	Dental Splint (mm)	Invasive Marker Frame (mm)	Proposed Method (mm)
Mean	2.10	1.22	1.05
SD	0.63	0.46	0.52

*20 target point per trial, 20 trials for each method.

Table 2. Surface Registration Error of the Orbital Area*

	Dental Splint (mm)	Invasive Marker Frame (mm)	Proposed Method (mm)
Mean	0.82	0.60	0.38

*20 target point per trial, 20 trials for each method.

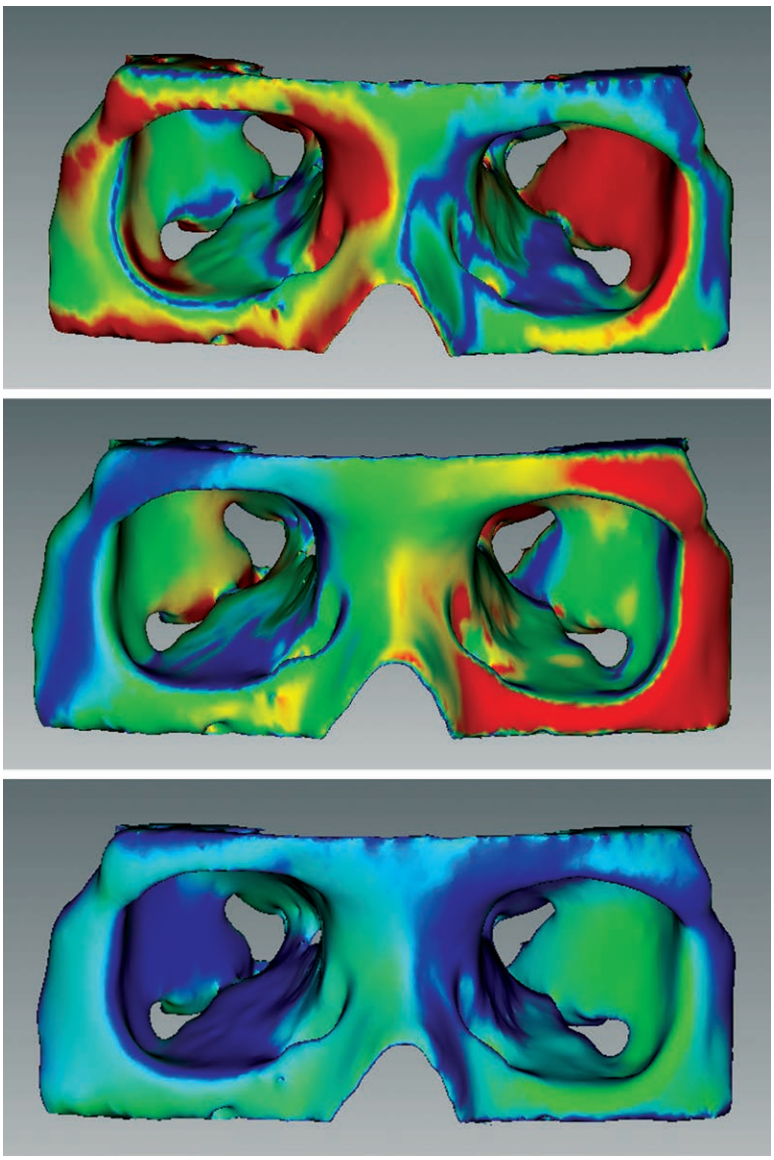

Fig. 8. Surface registration error visualization of the best registration result for each method (blue, 0.0 mm; green, 0.5 mm; red, 1.0 mm). (*Above*) Dental splint (mean ± SD, 0.57 ± 0.39 mm). (*Center*) Invasive marker frame (mean ± SD, 0.52 ± 0.35 mm). (*Below*) Proposed method (mean ± SD, 0.20 ± 0.17 mm).

the best stability outcomes. However, although the proposed method has lower stability than the invasive method, its stability is greater than that of other noninvasive methods for the orbital region, such as the dental splint.

DISCUSSION

Orbital anatomy is different for each individual. Various curvatures and cone shapes with diverse bulges in orbital anatomy make complete reconstruction much more difficult. This is why a computer simulation based on mirror images has been used in reconstruction of the orbits. Although a customized, ideal, prebent orbital implant has been used, precise positioning is still crucial. However, as the operative visual field using the transconjunctival or subciliary approach is very limited, correct positioning of the implant can be challenging. In addition, in cases with a deeper posterior orbital wall fracture, a surgeon may be reluctant to dissect close to the optic nerve. Among various methods, navigation systems are optimal. However, the limitations of a navigation system include the time for preparation, invasiveness, and lack of precision. To overcome these

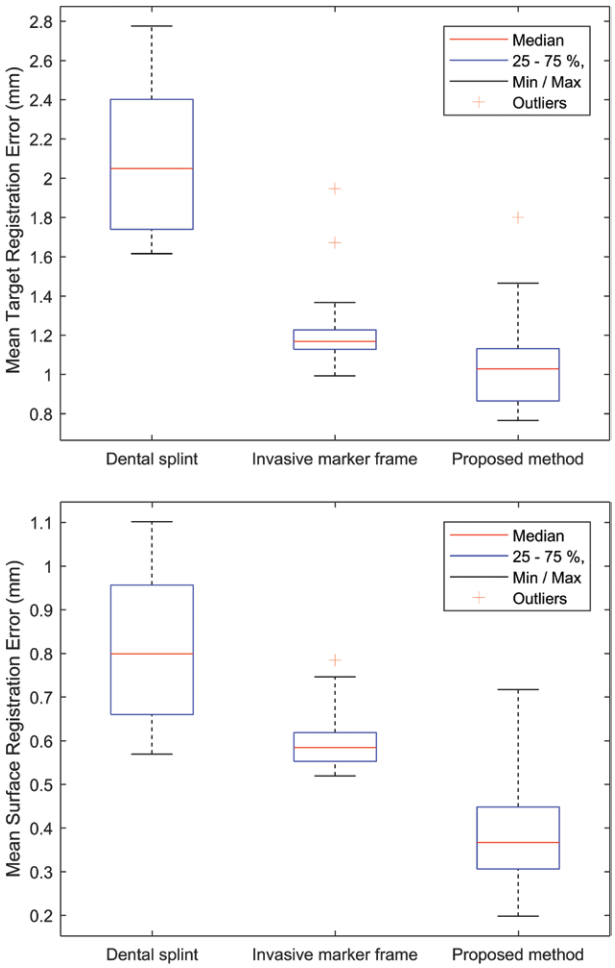

Fig. 9. Box plot of 20 trials for each method. (*Above*) Mean target registration error. (*Below*) Mean surface registration error.

obstacles, we developed a new noninvasive system using a three-dimensionally printed registration marker based on the external auditory meatus and upper teeth.

Our experiment demonstrates the feasibility of the proposed method, with improved registration accuracy for the orbit and moderate stability in performance compared with conventional methods. The key factors contributing to improvement are as follows: (1) the registration marker set is located closer to the orbit; and (2) the geometric shape of the registration marker set is extended to cover the orbit.

The spatial and geometric properties of the registration marker set directly affect the registration results. First, registration errors are determined by the location where the marker set will be attached. Typically, most conventional methods attach the registration marker set on one side of the head to avoid intraoperative interference. However, registration errors propagate in proportion to the distance from the marker set. This is shown by our experiment using the invasive marker frame (Fig. 10, *left*) and previous research using dental splints.[17] Thus, unforeseen errors could occur if the region of interest is placed far from the registration marker set. Second, the ability of the geometric shape of the registration marker set to contain the target region is also a critical factor in registration error. Our previous research[20] demonstrated that the target points must be kept within the region of the registration marker set. The proposed method can cover

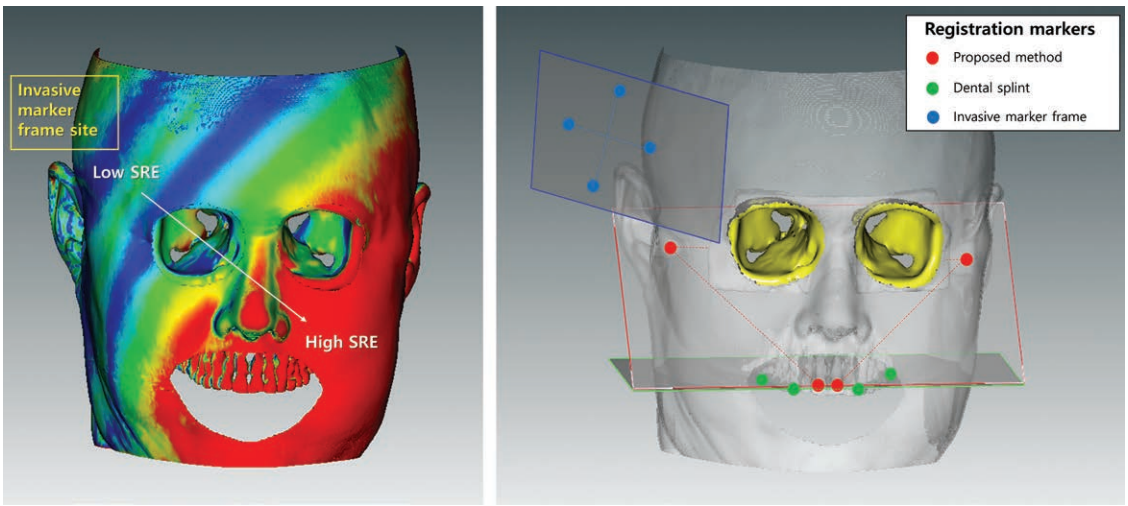

Fig. 10. (*Left*) Tendency for error propagation in a registration method using an invasive marker frame attached to the right side of the head (*blue*, 0.0 mm; *green*, 0.5 mm; *red*, 1.0 mm). (*Right*) Regional visualization of registration marker set for each method

larger spatial craniofacial areas than other conventional methods we investigated (Fig. 10, *right*). In our method, the orbital region is positioned inside the geometric shape formed by connecting all registration markers. In contrast, conventional methods use a condensed geometric marker set shape, and are not able to cover the orbit. Therefore, our method can successfully reduce the causes of registration error using this extended geometric marker set shape, with improved registration results.

Secure positioning to the designated location or prevention of displacement of the marker set is a critical issue in this noninvasive registration method because loosening or incorrect placement of markers during the registration procedure could result in unforeseen errors.[23] Our approach using the external auditory canal as an additional anatomical landmark point improves marker stability. The human external auditory canal has a unique shape with a steep slope. The proposed registration frame uses patient-specific ear plugs that are well fitted to this steep slope (Fig. 3, *below*). Because of the unique geometric features of the external auditory canal, our noninvasive, patient-specific registration frame shows little displacement. Through experiments, we demonstrated the ability of the proposed method to secure positioning by examining the reproducibility of registration marker position collection using a probe. The right ear plug registration marker point was collected in seven trials with a deviation of 0.44 ± 0.23 mm from the average picking points, and the left ear plug registration marker point was acquired with a deviation of 0.87 ± 0.44 mm. Considering an optical tracker error of 0.3 to 0.5 mm (Polaris Spectra) and a three-dimensional printing error of 0.1 mm (Objet260), the ear plug was considered to have good reproducibility. The more stable characteristics compared to other methods shown in Figure 9 are also based on this structural feature of the proposed registration frame.

CONCLUSIONS

We proposed an accurate, noninvasive, patient-specific navigation method and studied its feasibility. The proposed method is based on modifying the three-dimensional spatial properties of a registration marker set using the patient's external auditory canals and front teeth. Our next step is to improve the stability of the proposed method to the same level as that of an invasive method and to conduct clinical trials.

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