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Direct and continuous localization of anatomical landmarks for image-guided orthognathic surgery

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Objective. The accuracy and consistency of a new image-guided method for orthognathic surgery using direct and continuous landmark localization was compared with that of a conventional method.
Study design. Maxillary and mandibular dental casts mounted on an articulator were used as a surgery phantom. We planned six types of surgeries including translations and rotations. The sequential positions of the landmarks determined before surgery could be traced and the difference between planned and actual positions of the landmarks could be visualized during surgery. The final deviation errors were determined with and without applying the pointing instrument to the landmarks.
Results. The mean RMS accuracy of 0.47 ± 0.22 mm by direct localization was significantly higher than that of 1.06 ± 0.49 mm by the manual localization. There were no significant differences in accuracies for surgeries using the direct localization method.
Conclusion. The direct and continuous localization method showed higher accuracy and consistency than conventional manual localization in all phantom surgeries. (Oral Surg Oral Med Oral Pathol Oral Radiol 2013;116:402-410)

In craniomaxillofacial (CMF) surgery, facial deformities are corrected through restoration of the maxillomandibular relationship using various craniofacial surgical techniques.[1] Correcting facial symmetry and accurate repositioning of the bone segment requires optimal reconstruction of its anteroposterior, vertical, and sagittal relationships. The main sources of poor reconstruction outcomes include treatment planning using 2-dimensional (2D) imaging for a 3-dimensional (3D) problem, difficulty in assessing the intraoperative position, projection, and symmetry of repositioned or deformed skeletal anatomy, and variability in the anteroposterior, vertical, and sagittal jaw and tooth position relative to each other.[2] Orthognathic surgical plans have to be established based only on 2D images and a model surgery using plaster casts mounted on an articulator; therefore, deformities in roll, pitch, and yaw are especially difficult to correct, and the outcomes depend largely on the surgeon's ability.

An image-guided surgery system consists of pre- or intra-operative computed tomography (CT), magnetic resonance (MR) imaging, preoperative planning, and transferring the surgery plan to the patient using navigation. The preoperative planning based on 3D-reconstructed images makes it possible to observe deep anatomic structures, to provide skeletal views from various different angles, and to establish a more accurate surgery plan, especially in conditions of deformity of pitch, roll, or yaw.[2-4] Computer-aided intraoperative navigation systems initially developed for neurosurgery[5,6] are now commonly used in endoscopic sinus surgery[7,8] and commercially available for CMF surgery.[9-12] Image-guided systems using various tracking technologies have been used in orthognathic surgery to improve the precision and quality of surgical movements of bone segments in highly complex surgical cases.[13-15]

Orthognathic surgeries require exact repositioning of bone segments according to the preoperative plan. In conventional image-guided surgery, an operator's pointing instrument, or surgical probe with a tracked localizer, represents the location of an anatomic landmark for transferring the preoperative plan to the patient's scene. The operator intervention of manually applying a pointing instrument to landmarks increases the potential for human errors. The image-guided methods of minimized operator intervention are, thus, more likely to decrease the overall error involved with surgery guidance. In this study, we developed a new image-guided method for orthognathic surgery using landmark localization that did not require manually applying a pointer for transferring the surgery plan. That is, the positions of landmarks of interest were traced and visualized directly and continuously without applying the hand-operated pointing tool to the landmarks during surgery. Our new method provides visualization of positioning differences for bone segments and also quantifies errors between planned and actual

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positions of anatomical landmarks. As a preliminary study, the accuracy and consistency of the developed method was evaluated and compared with that of a conventional method through a phantom surgery.

MATERIALS AND METHODS

Phantom and CT scanning

As an orthognathic surgery phantom, we used maxillary and mandibular dental plaster casts of a patient, which were mounted on the semi-adjustable articulator during surgery. The maxillary cast had stainless steel spheres (1 mm diameter) at six anatomical target landmarks (three on both sides)—the cementoenamel junction (CEJ) of the canine and the CEJ of the first molar, and the position between the first and the second premolars bilaterally (Figure 1*A*). These anatomical landmarks were used for quantifying the deviation error during surgery.

A splint was fabricated in centric occlusion of the maxillary and mandibular casts using an orthodontic self-curing acrylic resin (Ortho-Jet; Lang Dental Manufacturing Co., Wheeling, IL). The registration body was also made of the same kind of acrylic resin. Eight stainless steel spheres (1 mm diameter) were fixed at holes of different positions and depths drilled into the body (Figure 1*B*). The registration body was attached to the splint firmly by using a LEGO block (LEGO Group, Billund, Denmark) to relate the positions from physical spaces to the locations of the CT image (Figure 1*C*). Before obtaining the CT image, the maxillary and mandibular casts were occluded with the splint attached with the registration body (Figure 1*D*). The registration body could be attached to and detached from the splint for repeated uses. The CT image of the casts was obtained using a MDCT (SOMATOM Sensation 10; Siemens Medical Solutions, Munich, Germany) under 120 kVp and 80 mAs with slice thickness of 0.75 mm.

Preoperative planning

Our image-guided orthognathic surgery method consists of preoperative planning including selection of anatomical landmarks for quantifying the deviation error, and intraoperative tracking navigation for transferring the surgical plan. For planning, a 3D surface model was constructed from CT image data and the reference points for surgery planning were designated on the 3D models. The bone segments were repositioned based on the surgical reference points by 3D translation and rotation, in a manner similar to that of conventional paper surgery planning. Especially in consideration of rotational movement, two reference points for a rotational center and target were chosen. The bone segment was rotated around the rotational center by the rotation angle, which was calculated from the travel distance of the rotational target along *x*-, *y*-, and *z*-axes. We planned six types of surgeries in which the maxillary model was repositioned based on translations in the *x*-, *y*-, and *z*-axes and by rotations in roll, pitch, and yaw directions (Figure 2).

Anatomical landmark selection for quantifying the deviation error

For quantifying the deviation error during surgery, the initial positions of anatomical target landmarks were designated in 3D multiplanar views (Figure 3). Any anatomical landmark of interest could be selected as a target landmark used for quantifying the deviation error. In this study, we used the six landmarks indicated by the spheres on the maxillary cast. Then, the final positions of the target landmarks were calculated by applying the same translation and rotation determined in the planning stage to the initial positions. During surgery, the actual position of the target landmarks was also obtained sequentially by tracking. Then, the difference between the planned and actual positions of target landmarks were calculated and presented to a surgeon visually.

Registration using a registration body

Before starting the surgery, registration (M_{reg} in Eq. 1) was performed to match the phantom's physical space with the image space. The maxillary tracking tool was attached to the splint by using a LEGO block (Figure 4*A*). The locations of the spheres on the registration body were registered by point-to-point matching in sequential order with those identified on the 3D CT image (Figure 4*B* and *C*). Because registration could be performed using the coordinate system of the splint or the maxillary tracking tool, registration preceded independently before combining the splint with the articulator-mounted maxillary cast. Additionally, the positions of the matched points on the 3D CT image could be recorded and saved for registration in advance. These steps played an important role in reducing the operation time. After registration, the registration body could be removed from the splint because it was not necessary for subsequent tracking of the maxillary cast.

Intraoperative tracking and visualization for transferring surgical plan

During surgery, the splint, along with the maxillary tracking tool, was mounted on the casts and the reference tool was attached to the superior border of an articulator that replaced the patient's cranial base. The movement of the maxillary cast with respect to the reference point during repositioning the cast was tracked using an optical tracking camera system (Polaris Vicra; Northern Digital Inc., Ontario, Canada).