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# Virtual skeletal complex model- and landmark-guided orthognathic surgery system

Sang-Jeong Lee [c], Sang-Yoon Woo [c], Kyung-Hoe Huh [a], Sam-Sun Lee [a], Min-Suk Heo [a], Soon-Chul Choi [a], Jeong Joon Han [b], Hoon Joo Yang [b], Soon Jung Hwang [b, **], Won-Jin Yi [a, *]

[a] Department of Oral and Maxillofacial Radiology, BK21, Dental Research Institute, School of Dentistry, Seoul National University, Seoul, South Korea
[b] Department of Oral and Maxillofacial Surgery, BK21, Dental Research Institute, School of Dentistry, Seoul National University, Seoul, South Korea
[c] Department of Biomedical Radiation Sciences, Graduate School of Convergence Science and Technology, Seoul National University, Seoul, South Korea

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A B S T R A C T

In this study, correction of the maxillofacial deformities was performed by repositioning bone segments to an appropriate location according to the preoperative planning in orthognathic surgery. The surgery was planned using the patient's virtual skeletal models fused with optically scanned three-dimensional dentition. The virtual maxillomandibular complex (MMC) model of the patient's final occlusal relationship was generated by fusion of the maxillary and mandibular models with scanned occlusion. The final position of the MMC was simulated preoperatively by planning and was used as a goal model for guidance. During surgery, the intraoperative registration was finished immediately using only software processing. For accurate repositioning, the intraoperative MMC model was visualized on the monitor with respect to the simulated MMC model, and the intraoperative positions of multiple landmarks were also visualized on the MMC surface model. The deviation errors between the intraoperative and the final positions of each landmark were visualized quantitatively. As a result, the surgeon could easily recognize the three-dimensional deviation of the intraoperative MMC state from the final goal model without manually applying a pointing tool, and could also quickly determine the amount and direction of further MMC movements needed to reach the goal position. The surgeon could also perform various osteotomies and remove bone interference conveniently, as the maxillary tracking tool could be separated from the MMC. The root mean square (RMS) difference between the preoperative planning and the intraoperative guidance was 1.16 ± 0.34 mm immediately after repositioning. After surgery, the RMS differences between the planning and the postoperative computed tomographic model were 1.31 ± 0.28 mm and 1.74 ± 0.73 mm for the maxillary and mandibular landmarks, respectively. Our method provides accurate and flexible guidance for bimaxillary orthognathic surgery based on intraoperative visualization and quantification of deviations for simulated postoperative MMC and landmarks. The guidance using simulated skeletal models and landmarks can complement and improve conventional navigational surgery for bone repositioning in the craniomaxillofacial area.



## 1. Introduction

The objective of orthognathic surgery is to correct maxillofacial anomalies related to innate or acquired craniofacial structure, sleep apnea, malocclusion problems or other orthodontic problems. Conventionally, intermediate and final splints are fabricated according to the simulated postoperative relationships of dental cast models, and are used to transfer the plan to the patient during orthognathic surgery. Positioning of the maxillary bone segment with an intermediate splint, however, has inherent limitations because the mandible may rotate and does not remain in the initial centric occlusion position during surgery (Chapuis et al., 2007). Although the final splint serves as a good guide for repositioning the mandibular bone segment, mandibular repositioning accuracy is crucially dependent on the exact repositioning of the prior maxillary bone. Some researchers developed a three-dimensional (3D) printed template-based method as an

* Corresponding author. Tel.: +82 2 2072 3049; fax: +82 2 744 3919.
** Corresponding author. Tel.: +82 2 2072 3061; fax: +82 2 766 4948.
*E-mail addresses:* sjhwang@snu.ac.kr (S.J. Hwang), wjyi@snu.ac.kr (W.-J. Yi).

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alternative to the dental splint. The template method reduces potential errors caused by autorotation of the mandible and eliminates the need for a conventional intermediate splint (Hirsch et al., 2009; Coppen et al., 2013; Hanasono and Skoracki, 2013; Li et al., 2013; Polley and Figueroa, 2013; Gander et al., 2015). However, these methods have some limitations in transferring the planned information accurately and in application to complex surgical procedures as such cases of short or thin maxillary anterior wall, because the templates require sufficient volume to be fixed rigidly on the wall for accurate reproduction of the planned maxillary position. Moreover, the osteotomy planning cannot be changed flexibly during surgery according to changes in the patient's intraoperative condition when an osteotomy guide template is used.

Surgical navigation systems are commonly used in the craniomaxillofacial area to overcome the disadvantages of conventional methods (Nijmeh et al., 2005; Strong et al., 2008; Eggers et al., 2009; Zhang et al., 2011, 2012; Seeberger et al., 2012; Kim et al., 2014; Li et al., 2014; Bobek, 2014). Generally, the navigational surgery method consists of patient computed tomographic (CT) imaging, preoperative planning, and transfer of the plan to the patient. An orthognathic tracking and guiding system was used to transfer the surgical plan to the patient more accurately (Nijmeh et al., 2005; Farrell et al., 2014; Kim et al., 2014; Li et al., 2014). However, intraoperative registration between the patient and image has increased the complexity of surgical procedures and the operative time and labor within the surgical navigation system (Li et al., 2014). The treatment plan based on CT images was used for preoperative planning by capturing the hard and soft tissues and teeth (Xia et al., 2001; Popat et al., 2010). However, patient CT images have severe metal artifacts and relatively low resolution, and cannot be used to designate adequate anatomical landmarks on the tooth model during planning. Optically scanned dentition provided higher resolution and accuracy than CT imaging, as well as an increase in the accuracy of the physical models, regardless of their type (Frisardi et al., 2011). Therefore, combining the CT image with optically scanned dentition provided a high-quality image of the tooth surface and enabled the use of anatomical landmarks on the skeletal model in the planning stage (Nkenke et al., 2004; Sohmura et al., 2004; Blackwell et al., 2007; Naether et al., 2012).

In previous studies, we developed an integrated orthognathic surgery system for virtual planning and image-guided transfer based on CT imaging of a patient's cast models (Kim et al., 2013, 2014). In surgery planning, 3D displacement of bone repositioning was compatible with conventional model surgery, and the image-guided surgery system accurately guided the maxillary cast to the desired position (Kim et al., 2014). In the present study, surgery planning was performed using the patient's virtual skeletal models fused with optically scanned 3D dentition. The virtual maxillomandibular complex (MMC) model of the patient's final occlusal relationship was generated by fusion of the maxillary and mandibular models with the scanned occlusion. Our method provided accurate and flexible guidance based on intraoperative visualization and quantification of deviations of the MMC and landmarks in bimaxillary orthognathic surgery.

## 2. Material and methods

### 2.1. Acquisition of patient CT scans and 3D dentition data

CT images were obtained with an MDCT (SOMATOM Sensation 10, Siemens, Munich, Germany) under 120 kVp and 80 mAs with a slice thickness of 0.75 mm. The patient was occluded with a splint attached to a registration body before CT imaging. The dental splint was manufactured using an orthodontic self-curing acrylic resin (Ortho-Jet; Lang Dental Manufacturing Co, Wheeling, IL). The registration body, which had eight holes with stainless steel spheres 1 mm in diameter, was attached to the splint with a LEGO block (LEGO Group, Billund, Denmark) for registration. Postoperative CT scanning was also performed to evaluate the accuracy of the orthognathic surgery result.

The 3D maxillary and mandibular dentition surface models were acquired by optically scanning the patient's dental plaster casts using a 3D scanner (Identica Blue, Medit, Seoul, Korea). The scanned dentition from the maxillary and mandibular casts provided artifact-free high-resolution dentition surface models (Fig. 1). The final occlusal surface model of the postoperative maxillomandibular relationship was also obtained by scanning the maxillary and mandibular casts positioned in accordance with the postoperative maxillomandibular relationship, as used in orthognathic surgery (Fig. 1).

### 2.2. Generation of the virtual skeletal MMC model fused with 3D scanned dentition

We used an iterative closest point (ICP) algorithm provided by the software (MeshLab, ISTI-CNR, Pisa, Italy) for registration between a 3D CT skeletal model and a scanned dentition surface model. 3D virtual maxillary and mandibular models fused with artifact-free high-resolution dentition were generated as a result of the registration (Fig. 2a, b). The virtual maxillomandibular complex model (MMC) was also generated by two successive registrations of the maxillary and the mandibular models with the final occlusion model. The virtual MMC model after virtual surgery planning represented the simulated postoperative maxillomandibular relationship (Fig. 2c, d).

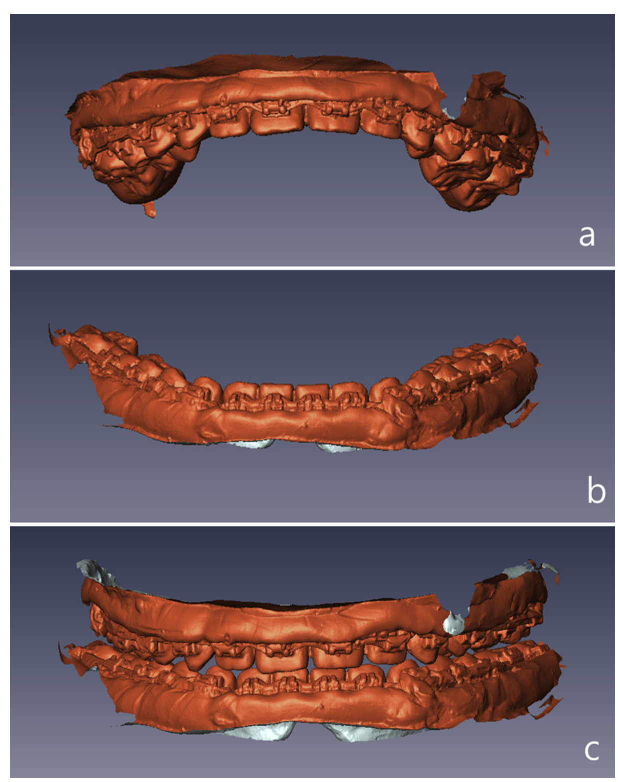


**Fig. 1.** 3D scanned dentition surface models of the maxilla (a), the mandible (b), and final occlusion (c).