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An integrated orthognathic surgery system for virtual planning and image-guided transfer without intermediate splint

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ABSTRACT

Accurate surgical planning and transfer of the planning in orthognathic surgery are very important in achieving a successful surgical outcome with appropriate improvement. Conventionally, the paper surgery is performed based on a 2D cephalometric radiograph, and the results are expressed using cast models and an articulator. We developed an integrated orthognathic surgery system with 3D virtual planning and image-guided transfer. The maxillary surgery of orthognathic patients was planned virtually, and the planning results were transferred to the cast model by image guidance. During virtual planning, the displacement of the reference points was confirmed by the displacement from conventional paper surgery at each procedure. The results of virtual surgery were transferred to the physical cast models directly through image guidance. The root mean square (RMS) difference between virtual surgery and conventional model surgery was 0.75 ± 0.51 mm for 12 patients. The RMS difference between virtual surgery and image-guidance results was 0.78 ± 0.52 mm, which showed no significant difference from the difference of conventional model surgery. The image-guided orthognathic surgery system integrated with virtual planning will replace physical model surgical planning and enable transfer of the virtual planning directly without the need for an intermediate splint.

1. Introduction

Accurate surgical planning and transfer of the planning are very important for successful surgical outcomes with appropriate esthetic and functional improvements for orthognathic patients. Conventionally, paper surgery is performed based on a two-dimensional (2D) cephalometric radiograph and the results are expressed using cast models and an articulator. A complex three-dimensional (3D) bone repositioning procedure is simplified to a combination of 2D movements in paper surgery. Although surgical outcomes are expressed in 3D in model surgery, this only provides information on change in the dental region and predictions of craniomaxillofacial complex change are unavailable (Ellis, 1990; Turvey et al., 1982). Recently, computer-aided surgical planning for the maxillofacial area was introduced to provide a more accurate prediction of surgical outcomes (Bettega et al., 2000; Chapuis et al., 2007; Girod et al., 2001; McCormick and Drew, 2011; Song and Baek, 2009; Tepper et al., 2011; Troulis et al., 2002; Uechi et al., 2006; Westermark et al., 2005; Xia et al., 2000).

Intermediate and final splints are fabricated by the simulated postoperative relationships of the cast models in order to transfer the planning to the patient during orthognathic surgery. These splints are the essential means of transferring the surgical plan. An intermediate splint is used to reposition the maxillary bone segment to a goal position, and a final splint is used to reposition the mandibular segment to the final goal position in two-jaw 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, the accuracy of mandibular repositioning is crucially dependent on the exact prior repositioning of the maxillary bone. Studies have been performed to accomplish predictable condylar control through various techniques with varying degrees of success (Ellis, 1994; Epker and Wylie, 1986; Harada et al., 1996; Heffez et al., 1987; Leonard, 1985; Luhr, 1989; Mori et al., 1995; Polley and Figueroa, 2013; Rotskoff et al., 1991).

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However, these methods have not been popular due to difficulties in design, ease of fabrication, and their cumbersomeness (Polley and Figueroa, 2013).

In a previous study, we developed a new image-guided method for transferring the surgical planning for orthognathic surgery (Kim et al., 2013b). Based on this study, we developed an integrated orthognathic surgery system of virtual planning and image-guided transfer, which could replace physical model surgical planning and transfer the planning directly without the need for an intermediate splint. As a preliminary study, the maxillary surgery of orthognathic patients was planned virtually, and the planning result was transferred to the cast model by image guidance.

2. Materials and methods

2.1. CT scanning of patients and casts

We used the maxillary and mandibular dental plaster casts of 12 patients for orthognathic surgery simulation. The CT images of patients and their dental casts were obtained using multidetector CT (SOMATOM Sensation 10, Siemens, Munich, Germany) under 120 kVp and 80 mAs with a slice thickness of 0.75 mm. The maxillary and mandibular casts were occluded with a tracking splint with its attached registration body before obtaining the CT image (Fig. 1a) (Kim et al., 2013b). The splint used for patient tracking was fabricated in centric occlusion 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 for use as registration fiducial markers (Fig. 1b). The registration body was used to relate the positions from physical space to the locations of the CT image. The registration body could be attached to and detached from the splint for repeated use.

2.2. Coincidence of the CT image coordinate system with the articulator coordinate system

In conventional model surgery, the cast is repositioned according to a paper surgery result based on the articulator coordinate system. This articulator coordinate system does not coincide with the CT image coordinate system used in virtual surgery because the cast (patient head) is placed arbitrary during CT scanning. Therefore, the CT image coordinate system has to be aligned with the articulator coordinate system for the virtual surgery procedure in order to be compatible with conventional model surgery.

The registration between the CT image and articulator coordinate systems was performed using the registration body. The splint with the registration body was attached to the maxillary cast. Then, the maxillary cast was mounted on a specially designed 3D position measurement device composed of three digital Vernier calipers (Fig. 2a). The cast placed on the device was guaranteed to be in the same orientation as that placed on the articulator by using the same articulator mounting plate. The physical position of the fiducial markers on the registration body was measured in 3D using the device. As a result, the physical position of the fiducial markers could be measured in the same coordinate system with the articulator. The measured physical positions were registered by point-to-point matching in sequential order with those identified on the 3D CT image (Fig. 2b, c). After registration, the maxillary and mandibular surface models that had been reconstructed from the CT image data were aligned with the articulator coordinate system (Fig. 2d, e).

2.3. Virtual surgical planning compatible with conventional model surgery

During virtual surgical planning, a series of displacements were applied to the maxillary and mandibular virtual models in six degrees of freedom in the same manner as used in conventional surgery. For each procedure, during planning, the reference points used for the displacement were designated on the virtual surface model, and the desired amount of displacement was entered by a surgeon using a graphic user interface. The visualization and manipulation of virtual surface models was implemented using the Visualization Toolkit (VTK, Kitware Inc., New York, USA).

In translational movement, a bone segment was translated linearly along the x-, y-, and z-axes by a given amount of displacement. In rotational movement (roll, pitch, and yaw), when a bone segment was rotated around the rotation center, the amount of rotation between the target and goal points was given not by angular degree, but by linear displacement. In conventional paper surgery, the rotational procedure is performed in the same way using linear displacement instead of angular degree. The real rotation angle could be calculated mathematically by considering the geometric relationship between the points (Fig. 3). The target point (T) cannot reach the goal position (G) by a simple rotation about the rotation center (R). Additional linear displacement (C) is required in order to move to the exact goal position (G). The real rotational and compensational linear displacements are calculated according to the following equations (Eq. (1) and (2)). The required translational (along x-, y-, and z-axes) and rotational (pitch, roll and yaw) displacements were applied to the bone segment successively at every step of repositioning. The displacement of the reference points at each repositioning was compared with those from conventional paper surgery to guarantee accurate simulation of the procedure.

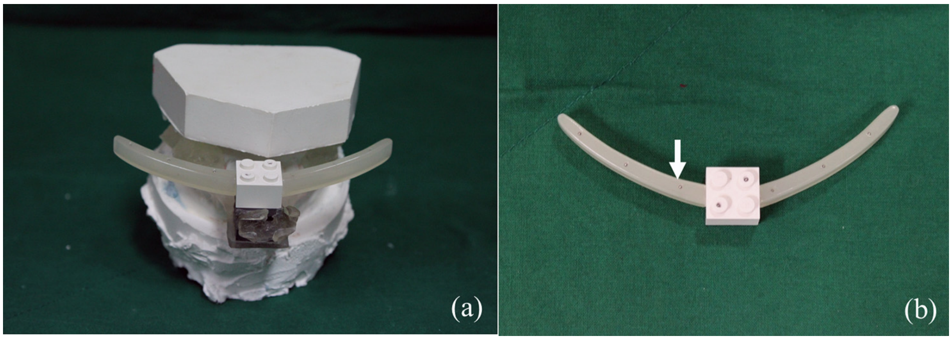

Fig. 1. Maxillary and mandibular casts occluded with a splint attached with the registration body (a), and a registration body with registration fiducial markers (white arrow) (b).