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A novel navigation system for maxillary positioning in orthognathic surgery: Preclinical evaluation

Jean-Christophe Lutz [a, b, c, *], Stéphane Nicolau [b], Vincent Agnus [b], Frédéric Bodin [a], Astrid Wilk [a], Catherine Bruant-Rodier [a], Yves Rémond [c], Luc Soler [b]

[a] Maxillofacial and Plastic Surgery Department (Head: C. Bruant-Rodier, MD, PhD), Strasbourg University Hospital, 1, place de l'Hôpital, 67091 Strasbourg Cedex, France

[b] IRCAD, Computer Science Research and Development Department (Head: L. Soler, PhD), 1, place de l'Hôpital, 67091 Strasbourg Cedex, France

[c] ICUBE-CNRS – Fédération de Médecine Translationnelle de Strasbourg (FMTS), UMR 7357 – Engineering, Computer Science and Imaging Laboratory (Head: Y. Rémond, PhD), Télécom Physique Strasbourg, 300, Boulevard Sébastien Brant – CS 10413, 67412 Illkirch Cedex, France

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ABSTRACT

Appropriate positioning of the maxilla is critical in orthognathic surgery. As opposed to splint-based positioning, navigation systems are versatile and appropriate in assessing the vertical dimension. Bulk and disruption to the line of sight are drawbacks of optical navigation systems.

Our aim was to develop and assess a novel navigation system based on electromagnetic tracking of the maxilla, including real-time registration of head movements. Since the software interface has proved to greatly influence the accuracy of the procedure, we purposely designed and evaluated an original, user-friendly interface.

A sample of 12 surgeons had to navigate the phantom osteotomized maxilla to eight given target positions using the software we have developed. Time and accuracy (translational error and angular error) were compared between a conventional and a navigated session. A questionnaire provided qualitative evaluation.

Our system definitely allows a reduction in variability of time and accuracy among different operators. Accuracy was improved in all surgeons (mean t_{error} difference = 1.11 mm, mean a_{error} difference = 1.32°). Operative time was decreased in trainees. Therefore, they would benefit from such a system that could also serve for educational purposes.

The majority of surgeons who strongly agreed that such a navigation system would prove very helpful in complex deformities, also stated that it would be helpful in everyday orthognathic procedures.

1. Introduction

Appropriate positioning of the maxilla is critical in orthognathic surgery as it is usually the first step of the procedure and will greatly influence the quality of the outcome, especially in terms of facial aesthetics and smile harmony (Kretschmer et al., 2009). Maxilla position is traditionally achieved thanks to an intermediate splint manufactured in the prosthodontics laboratory. Such a process requires specific training and time-consuming careful preparation.

Computer assistance has contributed to substantial improvement in maxillary positioning. Numerous software packages, relying on similar data processes from computed tomography (CT) scans, allow intuitive preoperative planning and are today widely spread (Neumann et al., 1999). One of the main challenges remains in the transfer of computer planning to the operating theatre. It is a critical step which will affect the quality of the surgical outcome. Based on the traditional planning method, computer-assisted designed (CAD) splints (Swennen et al., 2009; Hernández-Alfaro and Guijarro-Martínez, 2013; Polley and Figueroa, 2013), CAD cutting guides (Seeberger et al., 2011; Bell, 2011) and plating systems (Philippe, 2013a,b) allow surgical accuracy. Nevertheless, they restrain the surgeon to a single intraoperative workflow, allow limited versatility regarding unexpected surgical occurrences and generate repeated additional costs. Intermediate splints help to

* Corresponding author. Maxillo-Facial Surgery Department, Strasbourg University Hospital, 1, place de l'Hôpital, 67091 Strasbourg Cedex, France. Tel.: +33 6 86 21 77 01, +33 3 88 11 52 80; fax: +33 3 88 11 51 88.

E-mail address: jean-christophe.lutz@chru-strasbourg.fr (J.-C. Lutz).

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achieve an appropriate occlusal relationship, but are not perfectly suited to help correcting the vertical dimension intraoperatively. Intermediate splints are useless for surgeons who cut both jaws from the start, fix them together in the desired position for occlusion and then achieve manual placement of the maxillomandibular block based on clinical criteria.

As a result, in surgical routine, many experienced surgeons choose not to use any intermediate splint, and achieve free-hand maxillary positioning under sole visual control.

External positioning tools (Borumandi et al., 2013) have been proposed but they are bulky and their use is often not intuitive.

Navigation systems therefore appear as an alternative to improve accuracy and favourably let the surgeon decide whether virtual positioning information is to be followed. Navigation systems mostly rely on optical-based tracking systems (Zinser et al., 2013) and have been used for a long time for various purposes of orthognathic surgery (Bettega et al., 1996; Bettega and Leitner, 2013). Their main disadvantages are the bulk of optical fiducials and the disruption of line of sight where intraoral surgical exposure is so critical (Benassarou et al., 2013). Optical-based navigation either uses steady head support with a Mayfield clamp or fixation of bulky fiducial markers on the patient when head tracking is intended (Mischkowski et al., 2006, 2007; Zinser et al., 2013). Recent studies have proved electromagnetic (EM) tracking systems can provide sufficient accuracy (<1 mm) considering the thickness of cutting devices (1 mm) (Cartellieri et al., 2001b; Seeberger et al., 2012). Most notably, since electromagnetic sensors are tiny and allow free surgical movements between the sensors and the generator, EM systems seem relevant for orthognathic surgery.

Considering the above elements, our aim was to develop and assess a novel navigation system based on electromagnetic tracking of the maxilla, including real-time registration of head movements, therefore making steady head support unnecessary. Since researchers have underlined the influence of the navigation system interface on the accuracy of the procedure (Traub et al., 2006a,b), we purposely designed and evaluated an original, user-friendly interface.

2. Material and methods

We designed a phantom experiment in which the osteotomized maxilla had to be navigated to a given target location.

2.1. Experimental design

We used a medical plastic head model (Airway management Simulator "Bill I", VBM Medizintechnik GmbH, Germany) consisting of a realistic maxillofacial skeleton coated with a skin-mimicking layer of soft material (Fig. 1).

A standard LeFort one osteotomy was performed and the maxilla was fixed in an unchanged position using a standard titanium plating system (Modus 1.5 Medartis, Switzerland).

Afterwards, a CT scan (SOMATOM Definition AS+, Siemens, Germany) of the model was acquired. The field of view was $256 \times 256 \times 304$ mm^3 and voxel size was $0.5 \times 0.5 \times 1$ mm^3. Segmentation of the CT data was performed using VR-Med Software (D'Agostino et al., 2012) resulting in three different virtual models, the maxilla, the remaining superior facial skeleton, and the mandible which was not considered in our study.

Rigid fixation was then removed from the maxilla in order to allow free 3D movements.

2.2. Navigation system

An electromagnetic (EM) tracking system (Aurora, NDI, Canada) (Fig. 2) was used to achieve registration from the real environment

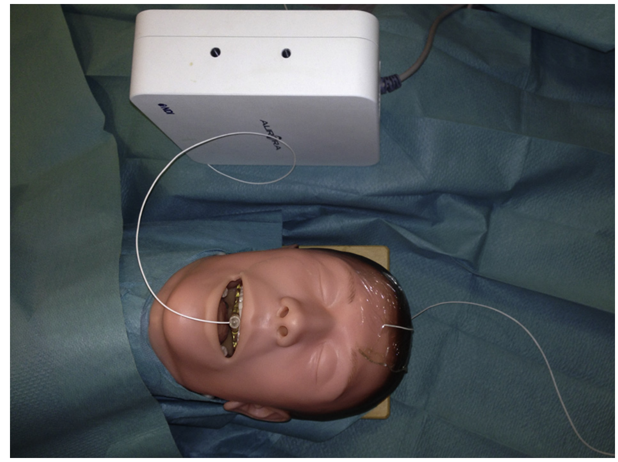

Fig. 1. Experimental Phantom equipped with two electromagnetic (EM) sensors placed laterally from the EM generator. One sensor is attached to the middle of the forehead using a Velcro band (purposely removed in the picture) to track head movements during the procedure. Another sensor is embedded in a custom-made surgical splint attached to the maxillary dental arch in order to track surgical position of the maxilla. The third sensor, used for registration and accuracy control was not included in the picture.

(plastic model) to the virtual one (segmented CT scans) of both the head model and the maxilla and their real-time tracked position. Three flexible catheters containing 6 degrees of freedom sensors were used (Aurora 6DOF catheter, Type 2) with a 1.3 mm diameter. Sensor accuracy allowed 95% of position errors to be smaller than 0.9 mm and 95% of orientation errors to be smaller than 0.5°. The field generator was positioned at a set distance of 100 mm laterally from the head model. Tracking volume was $50 \times 50 \times 50$ cm^3 and acquisition frequency was 20 Hz.

One sensor was attached to the middle of the forehead using a Velcro band in order to track head movements during the procedure. Another sensor was embedded in a custom-made surgical splint attached to the maxillary dental arch using stainless steel wires (Fig. 1). A third sensor was used for registration and accuracy control.

2.3. Software

We developed navigation software using the open source FW4SPL framework (https://code.google.com/p/fw4spl/wiki/poc1) and the Virtual Toolkit library.

This software allowed display of the real-time position of both the 3D model of the segmented maxilla and the upper facial skeleton. In order to match the actual position of the plastic model in the electromagnetic frame and the position of its virtual segmented clone in the CT scan frame, an initial 6-point registration procedure was conducted. It consisted in clicking on six facial anatomical landmarks, both on the virtual model and on the mannequin, using the third dedicated sensor. Correlation between these two sets of points is established by calculating the transformation matrix (Rotation R, Translation T) that minimizes the sum:

$$\sum_{i=1}^{n} \left\| (R \times p_i) + \vec{T} - q_i \right\|^2$$

p_i and q_i being the positions of, respectively, the n points in the 3D model and the n points recorded through tracking (Arun et al., 1987).

Once the splint was fixed to the dental maxillary arch, the embedded sensor position was recorded when the maxilla was held in an unchanged position to ensure calibration.