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Accuracy of three-dimensional soft tissue simulation in bimaxillary osteotomies

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ABSTRACT

The purpose of this study was to evaluate the accuracy of an algorithm based on the mass tensor model (MTM) for computerized 3D simulation of soft-tissue changes following bimaxillary osteotomy, and to identify patient and surgery-related factors that may affect the accuracy of the simulation. Sixty patients (mean age 26.0 years) who had undergone bimaxillary osteotomy, participated in this study. Cone beam CT scans were acquired pre- and one year postoperatively. The 3D rendered pre- and postoperative scans were matched. The maxilla and mandible were segmented and aligned to the postoperative position. 3D distance maps and cephalometric analyses were used to quantify the simulation error. The mean absolute error between the 3D simulation and the actual postoperative facial profile was 0.81 ± 0.22 mm for the face as a whole. The accuracy of the simulation (average absolute error ≤ 2 mm) for the whole face and for the upper lip, lower lip and chin subregions were 100%, 93%, 90% and 95%, respectively. The predictability was correlated with the magnitude of the maxillary and mandibular advancement, age and V-Y closure. It was concluded that the MTM-based soft tissue simulation for bimaxillary surgery was accurate for clinical use, though patients should be informed of possible variation in the predicted lip position.

1. Introduction

The introduction of three-dimensional (3D) virtual surgery planning software in the field of orthognathic surgery has provided orthodontist and surgeons with an opportunity to perform virtual osteotomies in order to obtain a favourable facial appearance (Westermark et al., 2005; Schendel et al., 2013). Since the final aesthetic result is reflected by the postoperative soft tissue facial profile, the predictability of the soft tissue changes that accompany the planned bony tissue movements has become the key issue in surgical simulations (Westermark et al., 2005; Mollemans et al., 2007; Marchetti et al., 2011). An accurate 3D simulation of the desired surgical result is essential in treatment planning and (shared) decision making (Mobarak et al., 2001; Marchetti et al., 2007; Kaipatur and Flores-Mir, 2009; Schendel et al., 2013).

Various computational strategies have been adopted to perform 3D virtual soft tissue simulations (Marchetti et al., 2007; Mollemans et al., 2007; Schendel et al., 2013). Mollemans et al. found that the highest accuracy was obtained by using a finite element model (FEM) or a mass tensor model (MTM), with a mean median error of 0.60 mm (90 percentile < 1.5 mm) (Mollemans et al., 2007). Considering significant time gain in simulation time compared to the two traditionally used models (FEM and mass spring model), MTM seemed to be the more favourable one for clinical use.

The importance of an accurate 3D soft tissue simulation increases with the complexity of the planned orthognathic surgery (Xia et al., 2011; Schendel et al., 2013). From a theoretical point of view, however, an increased complexity of the surgical intervention (bimaxillary surgery) is technically more challenging to manage

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compared to single jaw surgery. It can be expected that the induced error in soft tissue simulation would be higher as both the complexity of jaw movements and the number of jaw segments are increased in bimaxillary surgery. Up till today, no study on the predictability of computerized simulation of 3D soft tissue facial profile with a large number of homogeneous patients undergoing bimaxillary surgery has been published.

The aim of this study was to evaluate the accuracy of a MTM algorithm for computerized 3D simulation of soft-tissue changes following bimaxillary surgery and to identify patient and surgery related factors that may explain possible discrepancies between the initial 3D soft tissue simulation and the postoperative soft tissue profile.

2. Material and methods

The inclusion criteria were a non-syndromatic dysgnathia requiring bimaxillary osteotomy, and the availability of a CBCT scan before and at least six months after surgery. The exclusion criteria were non-native Dutch patients, the usage of a chin support during CBCT-scanning, previous history of Le Fort I osteotomy or BSSO, a chin osteotomy performed during bimaxillary surgery, presence of orthodontic labial appliances in the postoperative CBCT-scan, the absence of upper and/or lower incisors and extensive restorative dental treatment during the postoperative follow-up period.

This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research ethics. The approval of the regional medical ethics review board (CMO Arnhem-Nijmegen) was obtained for this study. All patient data were anonymized and de-identified prior to analysis.

2.1. Data acquisition

CBCT imaging data were obtained two weeks prior to and at least six months following bimaxillary surgery using a standard CBCT scanning protocol (i-CAT, 3D Imaging System, Imaging Sciences International Inc, Hatfield, PA, USA) in “Extended Field” modus (field of view: 16 cm diameter/22 cm height; scan time: 2x20 s; voxel size: 0.4 mm). Patients were scanned while seated in a natural head position. Patients were asked to swallow and to relax their lips and facial muscles and to keep their eyes open. The acquired CBCT data were stored in DICOM format and exported into Maxilim® software (Medicim NV, Mechelen, Belgium). In Maxilim, a 3D virtual augmented head model was rendered (Swennen et al., 2009).

2.2. Simulation of soft tissue profile

The pre- and postoperative 3D virtual head models were superimposed using voxel based registration on an unaltered subvolume that consisted of the cranial base, forehead and zygomatic arches (Nada et al., 2011). Virtual Le Fort I and BSSO osteotomies were made on the preoperative 3D virtual head model according to the actual osteotomies performed during surgery (postoperative scan).

In order to eliminate discrepancies between the planned skeletal movement and the actual displacement of the bimaxillary complex at surgery, the virtually osteotomized maxilla and mandible were aligned with the position of the maxilla and mandibula in the postoperative scan using surface based registration (Besl and Mckay, 1992). In this way, the simulated skeletal movements duplicated the actual jaw displacements during surgery. In Maxilim, a soft tissue simulation was carried out based on the simulated skeletal movements using a MTM soft tissue simulation algorithm. The result of the soft tissue simulation could subsequently be compared with the actual postoperative soft tissue profile (Fig. 1).

2.3. Analysis of soft tissue simulation

The accuracy of the soft tissue simulation was evaluated by cephalometric analysis (method A) and 3D distance mapping (method B).

A) Cephalometric analysis.

Differences between the soft tissue simulation and actual soft tissue changes were calculated using 11 3D cephalometric landmarks. Following the set-up of a 3D hard tissue reference frame, 6 midline soft tissue landmarks (subnasale, labrale superius, stomion, labrale inferius, sublabiale, and soft tissue pogonion), 3 midline hard tissue landmarks (upper incisor landmark, lower incisor landmark, and pogonion) and 1 bilateral hard tissue landmark (mental foramen) were identified through the validated method described by Swennen et al. (Swennen et al., 2006). The Euclidean distances were computed for all corresponding landmarks between the soft tissue simulation and the actual postoperative result as a measure for the accuracy of soft tissue simulation. The Euclidean distances between the corresponding landmarks in the pre- and postoperative scans were also calculated, to assess the actual surgical movements.

B) 3D distance mapping.

The overall differences between the soft tissue simulation and actual postoperative soft tissue profile were calculated using 3D distance mapping, generated by the application of an inter-surface distance algorithm. Differences between the 3D soft tissue profiles were visualized by using colour scaled distance maps. From these distance maps the absolute mean difference between the simulation and surgical result was calculated. Scattered radiation artifacts were removed to prevent bias. The soft tissue located in the neck area and around the nasal tip was also omitted. The soft tissue outline in the neck area is highly influenced by the position of the head and cervical spine and was considered to be poorly reproducible. The exclusion of the nasal region is due to the poor segmentation and 3D rendering of the soft tissue nasal tip.

The absolute mean differences were computed for the face as a whole, and for three specific regions of interest, the upper lip, lower lip and chin region, defined by the aforementioned cephalometric landmarks (Fig. 2). For each specific region, a distance map was generated to calculate the mean absolute difference between the simulation and the actual postoperative result.

2.4. Statistical analysis

IBM SPSS software, version 20.0.1 (IBM Corp., Armonk, NY, USA) was used to perform the statistical data analysis. The 3D cephalometric data were used to compute the mean amount of advancement and jaw of the bimaxillary complex at labrale superius and labrale inferius as the result of surgery. The Euclidean distances between the corresponding soft tissue landmarks subnasale, labrale superius, labrale inferius, sublabiale and soft tissue pogonion on the simulated soft tissue profiles and actual postoperative soft tissue profiles were calculated as a parameter for the accuracy of simulation. The mean absolute error, standard deviation, range and 95th percentile were computed for the soft tissue profile face as a whole and for the three subregions of interest using the distance maps derived from the 3D virtual head models. To be able to compare our results with previous studies, the percentage ratio between the number of simulations with a high and medium degree of accuracy (error level less or equal to 1 mm and 2 mm, respectively) and the total number of scans was calculated.