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Prediction of the articular eminence shape in a patient with unilateral hypoplasia of the right mandibular ramus before and after distraction osteogenesis—A simulation study

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ABSTRACT

The aim of this work was to predict the shape of the articular eminence in a patient with unilateral hypoplasia of the right mandibular ramus before and after distraction osteogenesis (DO). Using a patient-specific musculoskeletal model of the mandible the hypothesis that the observed differences in this patient in the left and right articular eminence inclinations were consistent with minimisation of joint loads was tested. Moreover, a prediction was made of the final shape of the articular eminence after DO when the expected remodelling has reached a steady state. The individual muscle forces and the average TMJ loading were computed for each combination of articular eminence angles both before and after DO. This exhaustive parameter study provides a full overview of average TMJ loading depending on the angles of the articular eminences. Before DO the parameter study resulted in different articular eminence inclinations between left and right sides consistent with patient data obtained from CT scans, indicating that in this patient the articular eminence shapes result from minimisation of joint loads. The simulation model predicts development of almost equal articular eminence shapes after DO. The same tendency was observed in cone beam CT scans (NewTom) of the patient taken 6.5 years after surgery.

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1. Introduction

Already in 1988 Nickel et al. (1988) proposed that the mechanical force of condylar loading shapes the articular eminence in healthy humans. This was supported by Trainor et al. (1995) and Iwasaki et al. (2003) who were able to show that eminence morphology was consistent with minimisation of joint loads using numerical models. This principle has the potential to be used in prediction of the eminence shape in clinical cases before and after surgery where there is a major change of the geometry of the mandible with for example mandibular distraction osteogenesis (DO). It is necessary though to investigate whether this principle holds for clinical cases as well.

In a numerical simulation, Cattaneo et al. (2005) analyzed a patient with unilateral hypoplasia of a mandibular ramus due to juvenile idiopathic arthritis (JIA). The patient's affected ramus had been lengthened by 15 mm using unidirectional intraoral DO. The aim of their study was to estimate the stress patterns in the TMJ areas before, during and after DO using the finite element method (FEM). The analyses in the Cattaneo et al. (2005) study showed a marked change in load transfer in the TMJ after DO. However, in the design of their study it was not possible to take a possible remodelling of the TMJ complex into account. It is likely though that remodelling of the TMJ will take place after DO (McCormick et al., 1995). This particular patient analyzed by Cattaneo et al. (2005) had CT and MRI scans taken for treatment planning purposes before distraction. The CT scans showed that the articular eminence shape on the affected side was much more flattened than on the non-affected side. Bearing in mind the results of Nickel et al. (1988), Trainor et al. (1995) and Iwasaki et al. (2003) it seems reasonable also in this clinical case to hypothesize that these differences in eminence morphology between left and right side are consistent with minimisation of joint loads. In order to test this hypothesis an estimation of the individual muscle forces and the reaction forces in the TMJ for a given bite force with a varying articular eminence shape is

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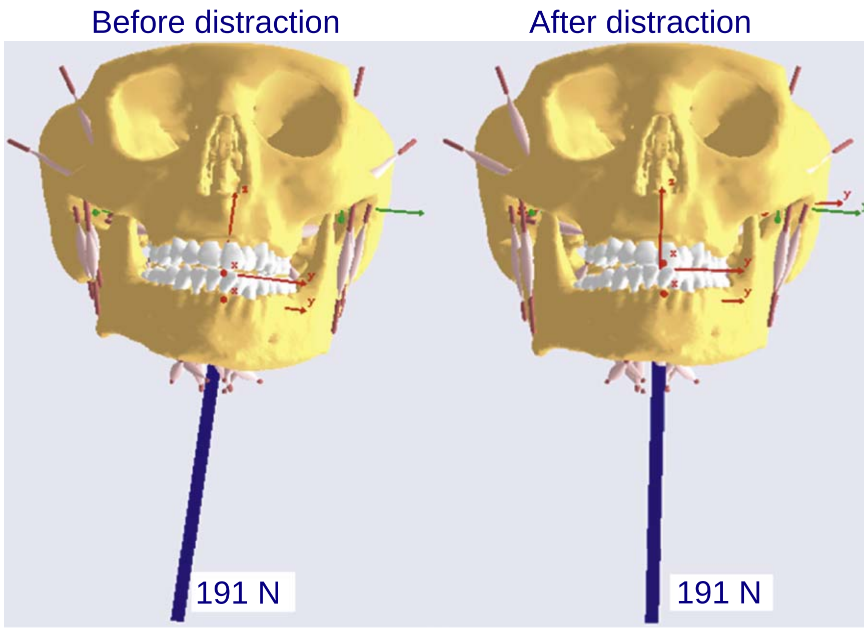

Fig. 1. A graphical representation of the three-dimensional musculo-skeletal model of the patient's mandible with unilateral hypoplasia of the right ramus before and after distraction osteogenesis. The red lines indicate the various muscles included in the model. The force vector of 191 N represents the clenching force on the midpoint between the two second premolars perpendicular to the occlusal plane. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

required. Recently, De Zee et al. (2007) presented a validated, generic musculoskeletal model of the mandible, which showed the potential of this methodology for predicting the mechanical effects on the TMJ before and after DO.

In this paper we shall present a patient-specific version of the model by De Zee et al. (2007). The model represents the patient previously analyzed by Cattaneo et al. (2005). The simulation will test the hypothesis that the observed differences in this patient in the left and right articular eminence inclinations are consistent with minimisation of joint loads. Moreover, a prediction will be made of the final shape of the articular eminence after DO when the expected remodelling has reached a steady state. The predictions will be compared with CT scans taken before DO and with cone beam CT scans taken 6.5 years post DO.

2. Methods

2.1. Patient studied

The patient was a 12.5 year old male suffering from a polyarticular JIA with early involvement of the right TMJ. The inflammatory process caused growth deviation mainly of the right side of the mandible including the eminence and condyle of the joint, the ramus and lower mandibular border, which is a characteristic development related to JIA (Stabrun., 1991). Also, the soft tissue and muscles were affected by the growth deviation. The patient was CT-scanned in order to design the distraction therapy. The patient was treated with unidirectional intraoral DO in order to correct the mandibular asymmetry. More details regarding the treatment planning and the surgical procedure on this patient have been described by Kofod et al. (2005b) and Pedersen et al. (2006).

2.2. Description of the model

A three-dimensional musculoskeletal model of this patient's mandible with unilateral hypoplasia of the right ramus was built using the AnyBody Modeling System (AnyBody Technology A/S, Aalborg, Denmark). The mathematical and mechanical methods of the software were described in detail by Damsgaard et al. (2006). For a graphical representation of the model see Fig. 1.

The model of the mandible was based on CT scans of the patient before surgery. Taking these CT scans and the subsequent processing have already been done and described in detail in earlier studies (Cattaneo et al., 2005; Kofod et al., 2005a, b). In short the CT-scan data were processed using a visualization software package (Mimics 7.10, Materialise, Leuven, Belgium). The entire skull was segmented, after which the mandible was virtually separated from the rest of the skull. These two separate 3D geometries were exported in a triangularised file-format (STL). The two STL files were then imported into the AnyBody Modeling System and used for defining the muscle insertions and for visualization purposes.

The present model has many similarities with the generic, symmetric mandible model, which has been described recently (de Zee et al., 2007), with the main difference being that the present model is asymmetric due to the hypoplasia of the right ramus and condyle. The insertions of the different muscle fascicles were determined with the help of the MRI and CT scans of the patient analyzed by Cattaneo et al. (2005). The peak isometric force of the masseter, medial pterygoid, and lateral pterygoid on the affected side were weaker by 17%, 3% and 6%, respectively, compared to the healthy side. These values were based on the cross-sectional area of the muscles measured with the help of MRI scans.

The mandibular fossa was modelled as a planar constraint as described in De Zee et al. (2007), but the inclination of the articular eminence on both left and right sides were made parametric. In this way parameter studies and optimization studies with the inclination on the left and right sides as separate design variables can be performed.

2.3. Parameter analysis of the inclination of the articular eminence

Corresponding to the real patient the right ramus of the model was lengthened by 15 mm. The distraction was simulated by changing the coordinates of the joint on the right side in the local coordinate system of the mandible. In this way the attachments of the muscles were tied to the geometry of the mandible and automatically changed their relative position after DO with respect to the joint centres. The input to the model was a symmetric clenching force of 191 N on the midpoint between the two second premolars perpendicular to the occlusal plane (see Fig. 1) both before and after DO. The value of 191 N was taken from a measurement on a healthy subject as described in De Zee et al. (2007). Both before and after distraction a parameter analysis was performed by changing the inclination of the articular eminences of the left and right sides systematically with a step size of 1.0° from 0° to 35°. An angle of zero degrees is the angle where the inclination of the articular eminence is parallel with the occlusal plane.

The muscle and joint forces were solved by an inverse dynamics algorithm. A kinematics algorithm first determines the position of each segment in the model. From this and from the knowledge of the bite force, all external forces acting on the system are collected in a right-hand-side vector, **R**. On the left-hand side of the dynamic equilibrium equations we find a coefficient matrix, **C**, and all the internal forces, **F**, i.e. muscle and joint forces. This system of equilibrium equations turns out to be indeterminate in the sense that there are more muscles available than strictly necessary to drive the movement and the system therefore has more unknowns than equations. Furthermore, muscle forces are by nature always tensile, so the solution must be restricted to the positive domain for muscles and for unilateral joints. The problems are addressed by formulating the muscle

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