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How muscle relaxation and laterotrusion resolve open locks of the temporomandibular joint. Forward dynamic 3D-modeling of the human masticatory system

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ABSTRACT

Patients with symptomatic hypermobility of the temporomandibular joint report problems with the closing movement of their jaw. Some are even unable to close their mouth opening wide (open lock). Clinical experience suggests that relaxing the jaw muscles or performing a jaw movement to one side (laterotrusion) might be a solution. The aim of our study was to assess the potential of these strategies for resolving an open lock and we hypothesised that both strategies work equally well in resolving open locks. We assessed the interplay of muscle forces, joint reaction forces and their moments during closing of mouth, following maximal mouth opening. We used a 3D biomechanical model of the masticatory system with a joint shape and muscle orientation that predispose for an open lock. In a forward dynamics approach, the effect of relaxation and laterotrusion strategies was assessed. Performing a laterotrusion movement was predicted to release an open lock for a steeper anterior slope of the articular eminence than relaxing the jaw-closing muscles, herewith we rejected our hypothesis. Both strategies could provide a net jaw closing moment, but only the laterotrusion strategy was able to provide a net posterior force for steeper anterior slope angles. For both strategies, the temporalis muscle appeared pivotal to retrieve the mandibular condyles to the glenoid fossa, due to its' more dorsally oriented working lines.

1. Introduction

Patients with symptomatic hypermobility of the temporomandibular joint (TMJ) report problems with the closing movement of their jaw (de Leeuw, 2008; Obwegeser et al., 1987). After opening wide, for instance while yawning, laughing, or eating an apple, they experience difficulty to close the jaw (August et al., 2004). In mild cases, the lower jaw does close, but the movement is jerky including a sideways movement (laterotrusion) (Kalaykova et al., 2006). Often this is accompanied by a dull click (Huddleston Slater et al., 2004). In more severe cases, the jaw remains in an open lock (Shorey and Campbell, 2000). In this case, one or both mandibular condyles stay trapped anterior of the articular eminences, and unassisted jaw closing is no longer possible (Westesson et al., 2003). According to the Diagnostic Criteria for Temporomandibular Disorders, this condition is classified in the hypermobility category as a luxation of the lower jaw (Peck et al., 2014; Schiffman et al., 2014).

The movement of the mandibular condyles is determined by the translations and rotations of the lower jaw. In right-side view, the lower jaw has to make a counter clockwise rotation to return to a closed position. To accomplish this rotation, a counter clockwise (jaw closing) moment has to be applied to the jaw by the jaw muscle forces and by the resulting joint reaction forces. It has been demonstrated that the net moment of the jaw-closing muscle forces is a clockwise (jaw-opening) one (van Eijden et al., 1997; Tuijt et al., 2012). This is due to the muscles' (on average) upward direction of pull, posterior of the centre of gravity of the lower jaw (Koolstra and van Eijden, 1995). Normally, the joint reaction forces provide the necessary jaw closing moment, while they travel in a caudal direction, posterior of the centre of gravity of the lower jaw.

The interplay of forces and of moments may become disturbed when both mandibular condyles touch the anterior slope of the articular eminence during wide jaw opening. When a condyle is situated just below the eminence, the joint reaction force is directed caudally. As the condyle translates further anteriorly, the anterior component of the reaction force increases. This could

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prevent the posterior translation of the lower jaw and as such the return of the condyle to the glenoid fossa. Furthermore, the line of action of the joint reaction force travels closer to the centre of gravity of the lower jaw, diminishing its moment arm. Herewith, the joint reaction forces provide a smaller jaw-closing moment. The combination of a net opening moment of the jaw-closing muscles and a decreasing closing moment of the joint reaction forces may ultimately amount to a net opening moment. In a previous study, we showed that after reaching an anterior position of the condyle despite a jaw-closing attempt, an open lock situation was reached for various combinations of joint shape and jaw-closer orientation (Tuijt et al., 2012).

It appears that an unfavourable morphology of the musculoskeletal system alone does not necessarily lead to an open lock. Based on extensive clinical observations (FL), various patients are able to close the jaw despite hypermobile jaw joints. Apparently, they have developed solutions to deal with open locks. One of these is a symmetric relaxation strategy, where the jaw closers initially remain relaxed to achieve a return of the mandibular condyles into the glenoid fossae, before active jaw closing. Another strategy is an asymmetric laterotrusion strategy, regaining the position of the condyles into the fossae one at a time.

These patients are able to provide a successful combination of forces and moments for jaw closing. However, it is not known how these strategies affect the instantaneous balance of forces and moments during jaw closing. Therefore, the aim of this study was to determine how the relaxation strategy and the laterotrusion strategy biomechanically are able to resolve open locks of the temporomandibular joint. We analysed the effect of both strategies on the balance of forces and moments, as generated by the jaw muscles and by the subsequent joint reaction forces. Our null-hypothesis was that both strategies were equally capable in resolving open locks.

2. Methods

The forces and moments acting on the lower jaw and the resulting movements were simulated with a 3D-biomechanical rigid body model of the masticatory system (Koolstra and Van Eijden, 1997; Tuijt et al., 2010). This model was implemented with Matlab (Matlab 7.0, The Mathworks Inc., Natick (MA), USA).

2.1. Model configuration

The model has been described extensively in Tuijt et al. (2010). Briefly, it consisted of 24 muscle models representing jaw openers and jaw closers. Furthermore, two temporomandibular joints, the lateral ligaments, and a simplified dentition were incorporated (Fig. 1).

A Hill-type muscle model was applied, where muscle force depended on the instantaneous length and contraction velocity of the sarcomeres. The dynamic muscle properties were based on van Ruijven and Weijs (1990). Maximal force capacity of each muscle was approximated by multiplying its physiological cross sectional area by the maximum tension of the jaw muscles (Weijs and Hillen, 1985).

Two polynomials described the shape of the cranial articular surface of the temporomandibular joint (TMJ). In the posterior/anterior direction, a fifth-order polynomial defined the shape of the glenoid fossa and the articular eminence. The steepness of the anterior slope of the eminence was changed by adapting the polynomial parameters. For the reference simulation an anterior slope angle (ASA) of 45° was applied (Tuijt et al., 2012). In the medio-lateral direction, a third-order polynomial described the

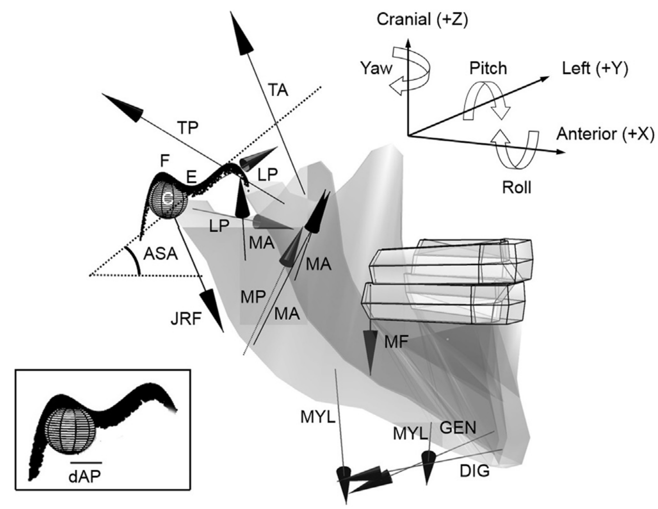

Fig. 1. Right anterior view of the 3D-biomechanical model of the human masticatory system. Forces indicated by solid arrows (right side only). TA: anterior temporalis, TP: posterior temporalis, MP: medial pterygoid, MA: masseter (three parts), LP: lateral pterygoid (two parts), DIG: anterior belly of digastric, GEN: geniohyoid, MYL: mylohyoid (two parts). JRF: joint reaction force. MF: molar reaction force. ASA: anterior slope angle of the articular eminence. C: mandibular condyle. E: articular eminence. F: glenoid fossa. Insert: Horizontal distance in anterior/posterior direction (dAP) between mandibular condyle and articular eminence. Positive values in anterior direction.

curvature of the fossa and eminence. The temporal surface was approximated by a mesh of 2.500 vertices.

The mandibular condyle was shaped as a 3D ellipsoid with superior, anterior, and lateral radii of 5.0, 5.0, and 7.5 mm (1000 vertices). The centre of this ellipsoid described the condyles' movement relative to the articular eminence.

The joint reaction force was directed perpendicular to the contacting surfaces. Its magnitude was approximated by a penalty based contact algorithm. Shear forces were considered negligible due to low friction coefficient of approximately 0.0145 (Tanaka et al., 2004).

2.2. Kinematics and kinetics

The model allowed movement of the lower jaw with six degrees of freedom (DoF) with respect to the skull. Apart from the bite plane and the bilateral articular surfaces in the cranial base, no spatial constraints were imposed. The muscle forces were the result of a predefined activation scheme (M¢ller, 1966). The forces generated by the joints, bite points and ligaments were predicted in reaction to the muscle forces and the inertia of the system. An Euler approach was used for the double integration process from acceleration to position of the lower jaw.

The lower jaw was damped with 1.0 N s/cm for translations and 1.0 N s/degree for rotations to represent the attenuating properties of the surrounding soft tissues (Koolstra and van Eijden, 1995). Gravity was taken into account, by assigning a mass of 0.44 kg to the lower jaw.

All moments (i.e. roll, pitch, and yaw, see Fig. 1) generated by the acting forces were determined by the cross product of the force vector with its moment arm with respect to the instantaneous location of the centre of gravity of the lower jaw. This centre of gravity, coinciding with the local reference frame of the lower jaw, was located between the apices of the second molars (Koolstra and van Eijden, 1995).

A successful closing of the jaw was determined by the translation of the mandibular condyles posterior of the eminence and a closing movement of the entire jaw. Therefore, we restricted our report to the anterior/posterior direction (distance between the

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