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Subject specific biomechanical modelling of luxations of the human temporomandibular joint

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Matthijs Tuijt

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Keys to an open lock:
subject specific biomechanical modelling of luxations of the human temporomandibular joint

ACADEMISCH PROEFSCHRIFT

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Voor Jochem

Contents

Chapter I

General introduction

Introduction

The human masticatory system plays a vital role in respiration, communication, and mastication. Daily activities such as breathing, talking, laughing, biting, and chewing are usually performed easily. When normal activities become troublesome, one becomes aware of the problems that might arise from the masticatory system. One of these problems concerns symptomatic hypermobility. Often symptomatic hypermobility is only attributed to the temporomandibular joint itself, but will be addressed in this thesis in a broader perspective, as part of the whole masticatory system.

In severe cases of symptomatic hypermobility, a patient may suffer from so called open locks after opening the mouth widely. In this instance, the closing movement of the lower jaw is problematic or even not possible at all, in which case medical assistance is required. When these open locks become habitual, it is well understood that this hampers performing daily activities. Subsequently, hampered daily movements may have an influence on participation in roles in daily living. For these severe cases, various treatment options have been developed. However, these treatments often lack a biomechanical foundation. Therefore, the aim of this thesis was to investigate the role of morphological aspects of the masticatory system in open locks and to increase the understanding of the interplay of forces on the lower jaw during an open lock.

In this chapter, the normal morphology and function of the masticatory system will be addressed. Subsequently, the clinical problem of open locks will be explored as well as the clinical framework in which this condition is usually diagnosed. In addition, the biomechanics of the masticatory system will be presented, followed by a computational modeling approach toward a better understanding of open locks. Finally, the outline and aims of this thesis will be described.

The human masticatory system: morphology and main functions

The human masticatory system is a complex system containing the upper part of the digestive tract with the teeth, the tongue, the salivary glands, the upper and lower jaw, and the muscles of mastication . Below, only the musculoskeletal aspect of the masticatory system will be addressed.

The bony part of the masticatory system is formed by the cervical spine, the cranium, the mandible, and the hyoid bone. In this thesis, the cranium will be assumed stationary and therefore the movements of the cervical spine will be neglected in further analysis. The bilateral articulation between the cranium and mandible is called temporomandibular joint (Figure 1). It is formed by the glenoid fossa and the articular eminence situated on the temporal bone, and by the mandibular condyle at the collum of the mandible. The articular eminence protrudes caudally from the cranial base. Its posterior slope is a continuation of the glenoid fossa. The inferior-most point is coined the eminence and anterior of the eminence, the anterior slope of the eminence bends at an angle (anterior slope angle, ASA) in the cranial direction.

The temporomandibular joint is a synovial joint and has a loose capsule, encompassing the articular eminence and joint disc. Within this capsule, a large amount of anterior translation is allowed, for instance during a protrusion movement. Therefore, the temporomandibular joint is not a ball and socket joint, such as the hip in which translations are not allowed by its depth and joint capsule. Intra-articularly, a cartilaginous disc is present, which fills a large part of the depth of the glenoid fossa. The disc is situated on top of the mandibular condyle when the mouth is closed (Figure 1). Since the disc is very deformable and covers the whole condyle, it can be regarded to function as a load distributing structure.

The jaw muscles are divided into opening and closing muscles . The opening muscles consist of the lateral pterygoid muscle, the anterior belly of the digastric muscle, geniohyoid muscle, and mylohyoid muscle. The masseter muscle, temporalis muscle, and medial pterygoid muscle form the closing group (Figure 2). Almost all jaw openers and closers are innervated by the mandibular branch of the trigeminal nerve (CN V). The geniohyoid muscle gets its motor signals from the ventral rami of C1 and C2 .

The jaw muscles provide for basic movements of the mandible. The movements are opening and closing, which are combinations of translations and rotations of the lower jaw relative to the cranium in the sagittal plane. Furthermore, the jaw can be translated anteriorly and posteriorly in the transverse plane, called protrusion and retrusion, respectively. Also, laterotrusion, a sideways rotation in the transverse plane, can be performed.

The normal functioning masticatory system provides the possibilities to breath, yawn, speak, laugh, and eat. These activities contain different contributions of translations and rotations to the opening and closing of the mouth. This is most exemplified by the translation of the mandibular condyle during wide opening. In the normal population, the condyle then travels two to three centimeters anteriorly, from within the mandibular fossa to a position anterior of the articular eminence . During this wide opening, the interincisal distances amount to an average of 45 mm for women and 54 mm for men . Laterotrusion movements can be performed to a maximum of 10-12 mm translation of the lower central incisor, depending on age and gender (Buschang et al., 2001; Hirsch et al., 2006).

Clinical aspects of open locks of the temporomandibular joint: definition, epidemiology, and risk factors

Open locks may occur after opening the mouth widely. Provoking movements include yawning (Avidan, 2002), laughing out loud, biting from, e.g. an apple or hamburger (August et al., 2004), and fellatio (Cheng, 2010).

Prolonged dental treatment, intubation, bronchoscopy, direct trauma (punch or fall), and indirect trauma (whiplash) are also reported as provocation (Luyk and Larsen, 1989; Avidan, 2002; August et al., 2004).

Earliest descriptions of open locks go back to the Egyptians. In the Edwin Smith's Surgical Papyrus (NN, translation James P. Allan et al 2005), dated 1,700 BC, dislocations were described by the inability to close the open mouth. This was to be treated with a bilateral manual reduction of the lower jaw and followed by immobilization of the lower jaw (Figure 3).

In ancient Greece, Hippocrates (400 BC) also described open locks of the jaw joint in his extensive study of the human body. In “On the articulations”, he described unilateral and bilateral open locks (Hippocrates: translation Francis Adams, 1849b), and in “Instruments of reduction” the techniques to reposition the jaw (Hippocrates: translation Francis Adams, 1849a). In those days, the prognosis of a not repositioned jaw joint was dire with a questionable life expectancy of ten days (Textbox 1). Nowadays, the advent of general anesthesia has solved this problem and reducing the condyles to the mandibular fossa under sedation is performed easily.

In this thesis, the term open lock is used and defined as the inability to close the mouth subsequent to wide opening, despite a jaw-closing attempt. The focus will be on the situation that both mandibular condyles are situated anterior of the articular eminence and are unable to return to the glenoid fossa (bilateral open lock). In the recent Diagnostic Criteria for Temporomandibular Disorders (DC-TMD), open locks are classified as luxation of the temporomandibular joint (Peck et al., 2014; Schiffman et al., 2014).

In general, open locks are rare. Anamnestically, only 0.8% of men and 0.4% of women with a natural dentition indicate dislocations in the last couple of weeks (de Kanter et al., 1993). Signs and symptoms of symptomatic hypermobility are more prevalent in the general population. 12 to 19% of healthy adults can be diagnosed as symptomatically hypermobile (Huddleston Slater et al., 2007a).

At population level, incidences of open locks are not reported. However, patients suffering from open locks do seek medical attention at the emergency room (ER). In a Brazilian ER, one fifth of all visits involving the temporomandibular joint were related to open locks (Luz and Oliveira, 1994), while Cheng (2010) reported 37 out of 100.000 ER visits to pertain to open locks.

At maximal mouth opening, a position of the mandibular condyle anterior of the eminence has been proposed as a risk factor for open locks (Shorey and Campbell, 2000). However, in 50% of healthy subjects, the condyle was situated anterior of the eminence at maximum mouth opening in an MRI study (Kalaykova et al., 2006a). This was also seen previously by means of X-ray studies in the military (Wooten, 1966). Thus, an anterior position of the condyle can be interpreted as a normal phenomenon and not as a risk factor for open locks.

In summary, the mandibular condyle can make large translations anterior of the articular eminence, without necessarily leading to open locks of the temporomandibular joint. Therefore a deeper biomechanical insight into the causes of open locks is needed. A better understanding of these causes might aid to the conservative, and surgical treatment of recurrent open locks.

Biomechanical model of the lower jaw: free body diagram and modeling approach

In mechanical terms, the lower jaw is a bit of an oddity. In De Motu Animalium (Borelli, 1680), Borelli depicted the jaw as a static lever system Class III, oriented upside down (Figure 4). This was characterized by the fact that the fulcrum is located on top of the lever system. The muscle force of the temporalis is depicted at the coronoid process and a bite force is shown at molar level (the muscle force (effort) lies closer to the fulcrum than the external load, hence a Class III lever system).

Condensing the interplay of forces on the mandible leads to the free body diagram of lower jaw depicted in Figure 5. The following forces need to be incorporated in the free body diagram: gravity, bite forces (right molar, left molar, incisor), the bilateral joint reaction forces, and the muscle forces (anterior temporalis, posterior temporalis, masseter, medial pterygoid, lateral pterygoid, anterior belly of digastric, geniohyoid, and mylohyoid. Based on the Newtonian summation of forces, the translatory accelerations of the lower jaw can be calculated. Additionally, the angular accelerations of the lower jaw are derived from the cross product of the individual forces and their moment arms relative to center of gravity of the lower jaw. From there, the position of the lower jaw can be derived by double integration.

Since the development of computers and with the increasing power of the central processing units, an increasing number of biomechanical models and approaches have been developed to study the masticatory system. Over the years, this went along with increasing complexity from single equivalent to multi equivalent models and from static tasks to dynamic tasks. Studied species include the pig (Langenbach et al., 2002), macaque (Fitton et al., 2012), common marmoset (Eng et al., 2009), lizard (Curtis et al., 2010), and human (de Zee et al., 2007; Ferrario and

Sforza, 1992; Koolstra et al., 1988; Peck et al., 2000). For an extensive overview of these models, please refer to the following reviews (Curtis, 2011a; Hannam, 2010; Hylander et al., 2008; Peck and Hannam, 2007).

With the models of the masticatory system, maximum bite forces (Koolstra et al., 1988), chewing (Hannam et al., 2008), biting (Rues et al., 2011), jaw opening (Kuboki et al., 2000; Peck et al., 2000), jaw closing (Koolstra and Van Eijden, 1997), and the effect of surgical interventions (de Zee et al., 2007) have been investigated.

Two basic modeling approaches can be distinguished. In inverse dynamics (optimization), the activation levels of the different muscles are estimated based on a chosen optimization criterion such as minimization of muscle force, joint load, jerk, or energy expenditure (Curtis, 2011b). In forward dynamics, on the other hand, the activation levels of the muscles are used as input to the biomechanical model and this results in a prediction of the resultant forces, moments, and the subsequent movements of the lower jaw.

Disadvantages of inverse modelling are that the choice for an optimization criterion is often arguable based on ecological validity, and that it is computationally very expensive (Curtis, 2011b). On the other hand, the forward dynamic models follow the natural chain of events from muscle activation to resulting jaw movement, specifically for this thesis, ending in an open lock or not. Therefore, the forward dynamics approach will be used to investigate the biomechanics of open locks.

Aims and outline

In this thesis, the aims are to:

- increase the understanding of the interplay of morphological aspects, such as joint shape and muscle orientation, in open locks of the human temporomandibular joint.

- increase the understanding of the biomechanics behind open locks of the temporomandibular joint. The kinetics will be studied to provide insight in the net effect of the acting muscle forces and joint reaction forces and their resulting moments.

- improve the level of detail of the biomechanical model, to allow for tailor-made models at a patient level.

The first chapters will deal with the application of a biomechanical model to normal function and to open locks. Chapter 2 will deal with the normal opening and closing movement of the mouth and will focus on the differences in temporomandibular joint loading between opening and closing. A sensitivity analysis of critical model parameters will be included. In Chapter 3, the roles of joint morphology and muscle morphology are investigated in relation to open locks, as well as their potential interplay. Chapter 4 will investigate relaxation and laterotrusion activation strategies that might enable the lower jaw to get out of an open lock. In chapter 5, the predictions about morphological parameters for open locks from chapter 3 will be tested in patients with symptomatic hypermobility, and compared with healthy controls. The joint shape and muscle morphology from cone beam computed tomography (CBCT) scans will be used as input parameters to fine-tune the musculoskeletal model. Herewith, individualized musculoskeletal models can be obtained, and risk assessment for open locks can be performed at an individual level. In chapter 6, a general discussion will be held on the model as well as on the results from the patient study. Furthermore, a case report will be interpreted in the framework of the International Classification of Functioning, Disability, and Health (World Health Organization, 2001). Future directions for research will be discussed as well.

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Figure 1. Morphology of the temporomandibular joint.

Mid-condylar depiction of the temporomandibular joint. M: meatus acousticus; F: glenoid fossa; D: temporomandibular joint disc; E: articular eminence; ASA: anterior slope angle; C: condyle; LPM: lateral pterygoid muscle.

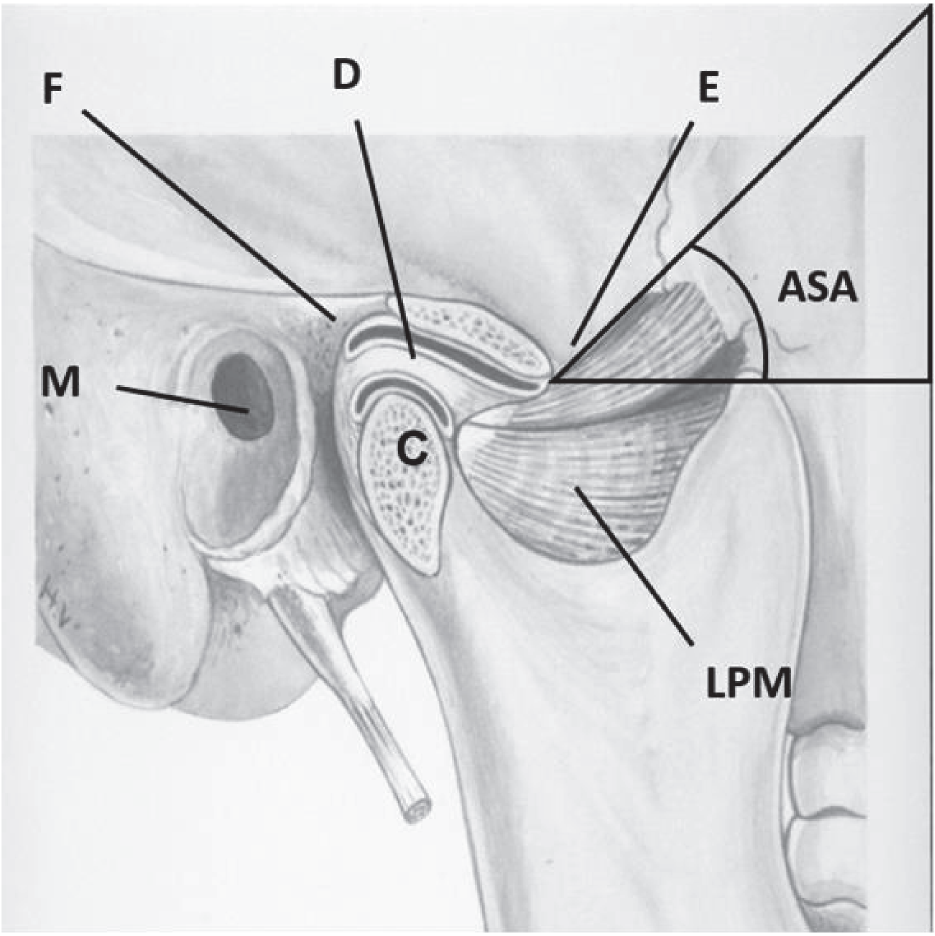


Figure 2. Muscles of the human masticatory system.

Jaw closing muscles: temporalis (TEMP, A), masseter (MASS), and medial pterygoid muscle (MPM). *Jaw opening muscles*: lateral pterygoid (LPM) and suprahyoidal muscles; anterior belly of digastric (DIGA), geniohyoid (GEN), mylohyoid (MYL).

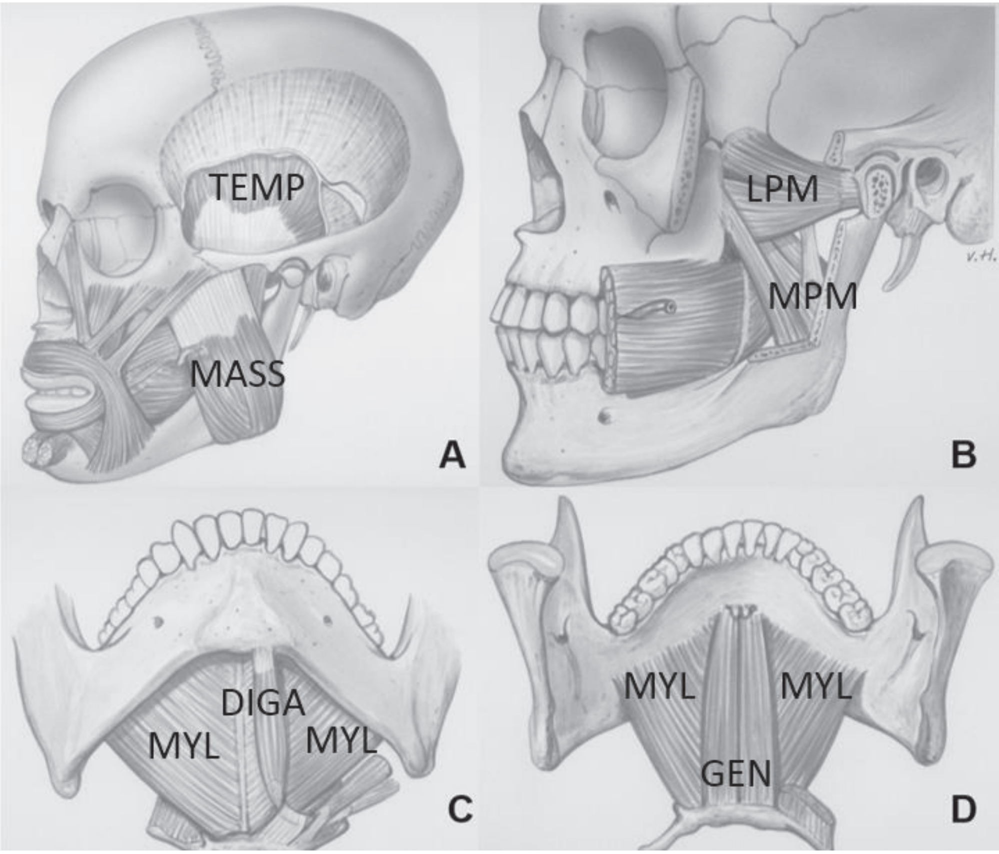
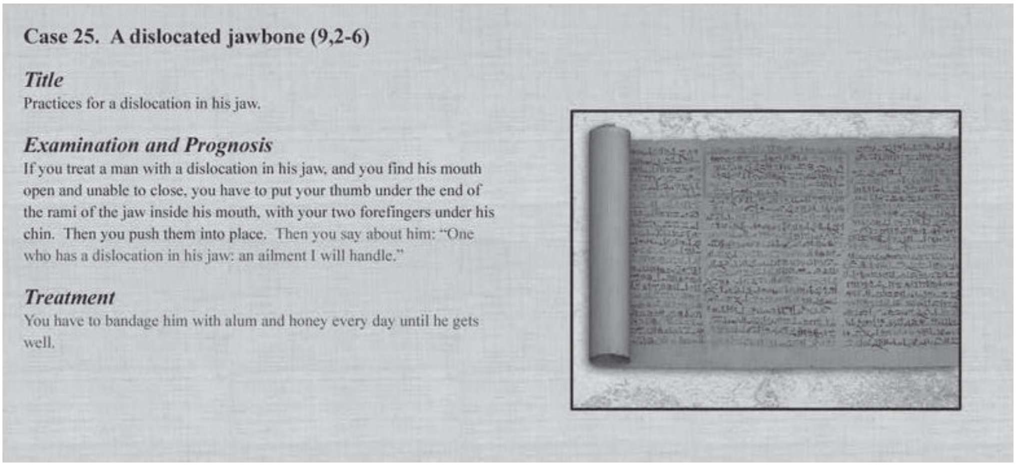


Figure 3. Egyptian case study of open lock.

Excerpt from Edwin Smith’s Surgical Papyrus rolls (translation James P. Allan et al., 2005). By NN, Egypt, 1700 BC.



Case 25. A dislocated jawbone (9,2-6)

Title

Practices for a dislocation in his jaw.

Examination and Prognosis

If you treat a man with a dislocation in his jaw, and you find his mouth open and unable to close, you have to put your thumb under the end of the rami of the jaw inside his mouth, with your two forefingers under his chin. Then you push them into place. Then you say about him: “One who has a dislocation in his jaw: an ailment I will handle.”

Treatment

You have to bandage him with alum and honey every day until he gets well.

Figure 4. Free body diagram of the mandible.

A. Borelli depicted biting force (R), the right temporalis muscle (F), and the right mandibular condyle (fulcrum: a). B. Class III lever system according to Borelli. Both from Borelli: De Motu Animalium (1680).

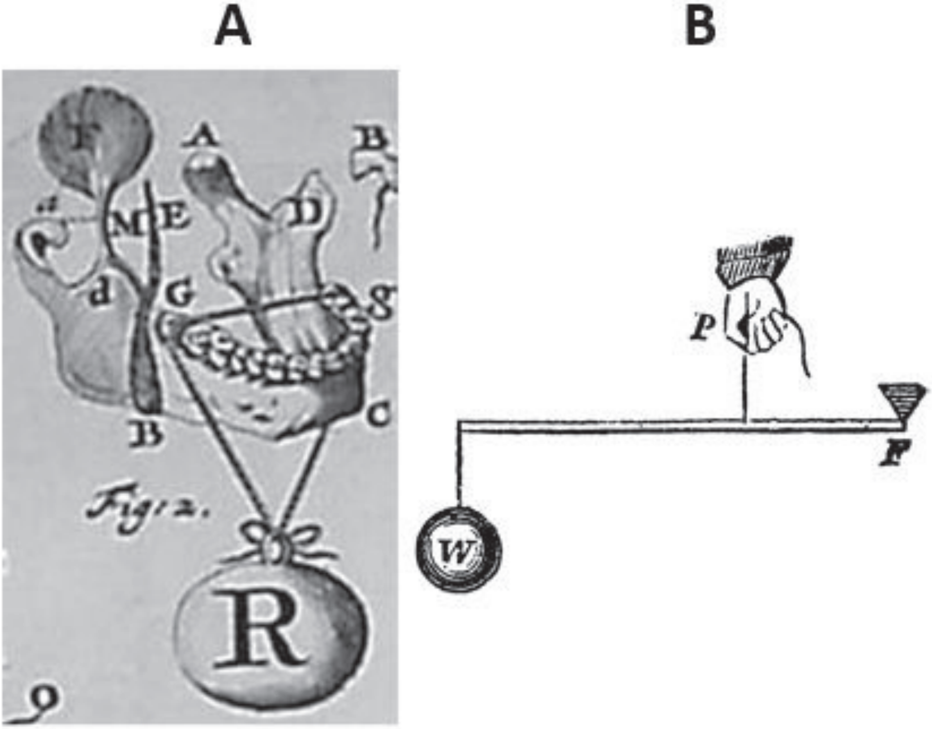
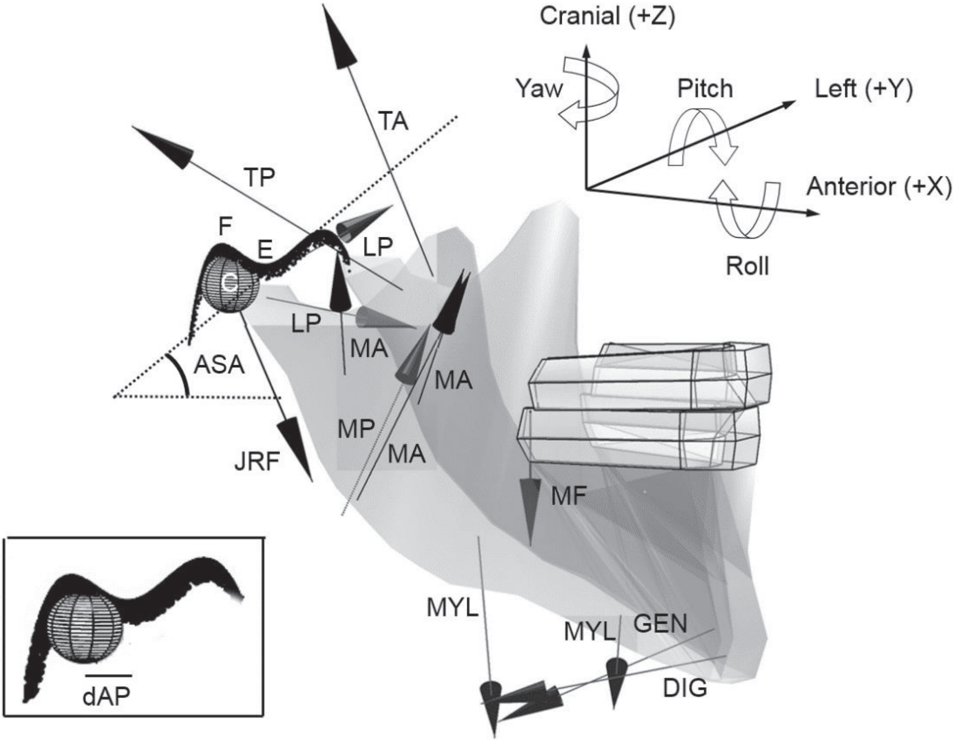


Figure 5. Free body diagram of the lower jaw and relation to the glenoid fossa.

Temporomandibular joint: F: glenoid fossa, E: articular eminence, C: mandibular condyle. *Joint and dentition force*: JRF: joint reaction force, MF: molar reaction force. *Muscle forces*: 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).

Top right: degrees of freedom of the lower jaw. Translations in the cranial/caudal, left/right, and anterior/posterior direction. Rotations about the transverse axis (pitch), longitudinal axis (yaw), and sagittal axis (roll). *Bottom left*: relative position of the condyle with respect to the articular eminence in the anterior/posterior direction (dAP).For readability, only the right hand side is depicted.



Textbox 1. Early Greek description of open locks.

Excerpt from Hippocrates, Instruments for Reduction, 400BC.

Translation: Francis Adams (1849). Retrieved 4 May 2013 from http://classics.mit.edu/Hippocrates/reduct.html.

> When the jaw is dislocated on both sides, the treatment is the same. The patients are less able to shut the mouth than in the former variety; and the jaw protrudes farther in this case, but is not distorted; the absence of distortion may be recognized by comparing the corresponding rows of the teeth in the upper and lower jaws. In such cases reduction should be performed as quickly as possible; the method of reduction has been described above. If not reduced, the patient's life will be in danger from continual fevers, coma attended with stupor (for these muscles, when disordered and stretched preternaturally, induce coma); and there is usually diarrhea attended with billous, unmixed, and scanty dejections; and the vomitings, if any, consist of pure bile, and the patients commonly die on the tenth day.

Chapter II

Differences in loading of the temporomandibular joint during opening and closing of the jaw

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Abstract

Kinematics of the human masticatory system during opening and closing of the jaw have been reported widely. Evidence has been provided that the opening and closing movement of the jaw differ from one another. However, different approaches of movement registration yield divergent expectations with regard to a difference in loading of the temporomandibular joint between these movements. Because of these diverging expectations, it was hypothesized that joint loading is equal during opening and closing. This hypothesis was tested by predicting loading of the temporomandibular joint during an unloaded opening and closing movement of the jaw by means of a three-dimensional biomechanical model of the human masticatory system. Model predictions showed that the joint reaction forces were markedly higher during opening than during closing. The predicted opening trace of the centre of the mandibular condyle was located cranially of the closing trace, with a maximum difference between the traces of 0.45 mm. The hypothesis, postulating similarity of joint loading during unloaded opening and closing of the jaw, therefore, was rejected. Sensitivity analysis showed that the reported differences were not affected in a qualitative sense by muscular activation levels, the thickness of the cartilaginous layers within the temporomandibular joint or the gross morphology of the model. Our predictions indicate that the TMJ is loaded more heavily during unloaded jaw opening than during unloaded jaw closing.

Keywords: temporomandibular joint, jaw movement, TMJ loading, condylar movement

Introduction

The morphology of the human masticatory system is of a complex nature. Its temporomandibular joint (TMJ) is diarthrodial with incongruent joint surfaces (e.g. Rees, 1954; Nickel et al., 1988; Alomar et al., 2007), which allows movement of the lower jaw with six degrees of freedom (DOF) (for a review see, Koolstra, 2002). Additionally, its musculature displays an intricate spatial arrangement (Van Eijden et al., 1997). Given this complex morphology, a gain of insight into its loading behaviour is best served by analysis of simple movements like opening and closing of the jaw. Although opening may seem the reverse of closing, it has been shown that the opening movement of the jaw differs from the closing movement (e.g. Siegler et al., 1991; Leader et al., 2003).

As opening and closing trajectories of the jaw differ from one another, it is likely that the TMJ is loaded differently during these movements. Unfortunately, joint loads cannot be measured experimentally, due to the TMJ's inaccessibility. In a primate model, the TMJ was reported to be loaded during all sorts of activities such as drinking, screaming, biting, and mastication (e.g. Hylander and Bays, 1979; Hohl and Tucek, 1982; Boyd et al., 1990). However, simple opening and closing were not analyzed.

Loading of the human TMJ can be assessed in a qualitative way by inferences from movement registrations of the mandibular condyle. An indication, that the TMJ is loaded more heavily during opening of the jaw than during closing, can be derived from traces of the kinematic centre (Yatabe et al., 1995, 1997; Huddleston Slater et al., 1999; Naeije, 2003). In healthy subjects, the opening trace was found to lie above its jaw closing equivalent. This suggests that during opening, the condyle travelled closer to the articular eminence, thereby compressing the intermediate cartilaginous tissues more heavily. Conversely, an indication that the TMJ could be loaded more heavily during closing was provided by Gallo et al. (2000, 2008). They reported that the minimal distance between condyle and articular eminence, approximated by combining magnetic resonance images with movement registrations, was larger during opening than during closing.

To gain insight into the loading of the TMJ during unloaded opening and closing of the jaw, simulations were performed with a biomechanical model. The aim of this study was to predict joint reaction forces within the TMJ during these movements. The null-hypothesis was that the predicted joint reaction forces are of equal magnitude during opening and closing of the jaw.

Materials and methods

Model description

A three-dimensional mathematical model of the human masticatory system, adapted from Koolstra and Van Eijden (1995, 1997), was implemented in a Matlab environment (Matlab 7.0, Release 14, The Mathworks Inc., Natick (MA), USA). In short, the model consisted of 24 Hill-type muscle actuators, two TMJ's, and a simplified dentition (Fig. 1). The model allowed movement of the lower jaw with six DOF with respect to the skull. Jaw movement was determined by muscle forces, joint forces, bite forces, and gravity. Ligamentous structures (e.g., the lateral ligament) and the temporomandibular disc were not implemented. The system was damped with 0.1 Ns/mm for translations and 1 Ns/degree for rotations to represent the attenuating properties of the surrounding soft tissues (Koolstra and Van Eijden, 1995).

For both sides, the jaw closers were represented by the masseter (one superficial slip, two deep slips), medial pterygoid (one slip), and temporalis (two slips) muscles. Jaw openers included the lateral pterygoid (two slips), mylohyoid (two slips), anterior belly of digastric (one slip), and geniohyoid (one slip) muscles (Fig. 1). Morphological data (origin, insertion, physiological cross sectional area (PCSA), rest length, and sarcomere length) for these muscles were taken from Van Eijden et al. (1997). Maximal force of each muscle was calculated by multiplying its PCSA by the intrinsic strength of jaw muscles (Weijs and Hillen, 1985). The dynamic muscle properties were based on Van Ruijven and Weijs (1990). This resulted in a Hill-type muscle model, where muscle force depends on the instantaneous length and contraction velocity of the sarcomeres.

The articular surfaces of the TMJ's were modelled with 3D shell type meshes. For the mandibular condyle, they were shaped as a 3D ellipsoid with superior, anterior, and lateral radii of 5.0, 5.0, and 7.5 mm, respectively (2000 vertices). The centre of this ellipsoid was used to describe the movement traces of the mandibular condyle. The shape of the temporal part of the TMJ's was approximated by a polynomial of the third degree in the sagittal plane. Its mediolateral curve was represented by an additional polynomial of the second degree. This led to a doubly curved shape (3500 vertices), representing the mandibular fossa and articular eminence (Fig. 1). Both meshes were assigned a mediolateral orientation of 11 degrees with respect to the sagittal plane (Koolstra and Van Eijden, 1995). The right-hand side TMJ was mirrored in the mid-sagittal plane to produce the left-hand side TMJ.

Contact algorithm: contact detection

A penalty-type algorithm was developed to approximate contact between the TMJ meshes. For each vertex of the temporal mesh, a tangent plane was calculated. Contact was determined from the position of each condylar vertex relative to the temporal tangent planes in its vicinity. The amount of penetration was determined as the point-to-plane distance (p_i), if the vertex was located cranially of the tangent planes. To shorten calculation times, the instantaneous position of all condylar vertices was contained within a 10 mm by 10 mm by 15 mm search space. This space was subdivided in rectangular cells with sides of 3 mm in the axial direction of the condyle and sides of 2 mm perpendicular to it. Possible contact was only resolved when a cell contained parts of the condylar and the temporal surface simultaneously.

Contact algorithm: joint reaction force calculation

The force contribution of a penetrating vertex (F_i) to the total joint reaction force was related to its amount of penetration (p_i) by:

$$F_i = \frac{(F_{max} / n)}{e - 1} * \left(e^{\frac{p_i}{p_{max}}} - 1 \right) \tag{1}$$

where: F_{max} = 500 N [the upper boundary for the reaction force per joint (Raadsheer et al., 1999)], n = 100 (the maximum number of penetrating vertices, as determined in preceding test simulations), and p_{max} = 3.0 mm (the amount of penetration to produce F_{max}, associated with the thickness of the cartilaginous layers). The relationship between penetration and force contribution was chosen to be exponential, in order to approximate the hyperelastic properties of the TMJ's cartilaginous structures.

Dentition

The dentition in the upper jaw was represented by a single bite plane, which was aligned horizontally. One midsagittal 'incisor' and two second molars in the lower jaw were represented by three vertices. Reaction forces of the dentition were determined from the penetration of these vertices through the upper bite plane and were directed perpendicularly. The linear stiffness of the dental contacts was set to 1.000 N/mm.

Simulation procedure

The simulation started with a closed mouth. Position and orientation of the lower jaw corresponded with a situation where muscle forces (4% of maximum force in all jaw closers), gravity, reaction forces in the TMJ's and those in the dentition were in equilibrium. Subsequently, one unloaded open and close movement of 1.0 seconds was simulated with a time step of $1*10^{-5}$ seconds. The applied muscle recruitment patterns were based on EMG measurements during mastication (Møller, 1966). These measured recruitment patterns were assigned to the modelled muscle slips, according to Table 1. Symmetric muscle drive was achieved by averaging the working and balancing side activation levels (Møller, 1966). To achieve a (near) maximal jaw opening and a closing movement, resembling a habitual one, the maximum activation levels of the jaw openers and closers were set to 50% and 4%, respectively. To return to a closed mouth at the end of the simulation, it was assumed that the jaw closers maintained an activation level of 4% (Fig. 2).

Sensitivity analysis

The influence of the activation level of the muscles on predicted joint reaction forces and movement of the mandibular condyle was analysed by performing simulations with combinations of activation levels for the jaw openers of 25, 50 and 75% and for the jaw closers of 2, 4 and 8% of their maximal capacity.

The effect of the implemented cartilage thickness was investigated, by repeating the reference simulation procedure with different settings for maximum penetration of condylar vertices (p_{max} in Eq. 1). The value of p_{max} of 3.0 mm was raised and lowered with 1.0 mm.

The present model was based upon a geometry composed from a number of cadaverous specimens (Van Eijden et al., 1997). To analyze the influence of morphological differences, the vertical dimensions of the model were scaled with respect to the biteplane by +10% and -10%. With constant horizontal dimensions, this affected the ratio of all vertical and horizontal distances. For all muscles, the origin, insertion, length, fibre length, and tendon length were adapted accordingly.

Results

Joint reaction forces

The predicted joint reaction forces within the TMJ were markedly larger during opening than during closing (Fig. 3). A non-physiologically high frequency noise component was present within the predictions. Therefore, a 2nd order lowpass Butterworth filter with a cut-off frequency of 10Hz was applied. The maximum difference in the filtered joint reaction forces between opening and closing amounted to 35 N.

Condylar trace

Condylar movements were represented by the sagittal trace of the centre of the right mandibular condyle. They showed that during the jaw open-close movement, the condyle travelled in a smooth way along the surface of the temporal fossa and eminence (Fig. 4). The opening trace was located more cranially than the closing trace. The maximum difference between the traces, coinciding with the maximum difference between opening and closing joint reaction forces, was 0.45 mm.

Sensitivity analysis

The results of the sensitivity analysis on activation levels for jaw openers and closers are presented in Table 2. The predicted joint reaction forces were always larger during opening than during closing. In all cases, this was accompanied by a more cranial travel of the mandibular condyle during opening, as indicated by a positive trace difference.

The predicted joint reaction forces were not influenced by different cartilage thicknesses (Fig. 5 ACE). The concomitant difference between opening and closing traces decreased with 17%, in the case of a decreased cartilage thickness (Fig. 5B). For an increased cartilage thickness, the difference between traces increased with 23% (Fig. 5F).

With a 10% decrease of vertical cranial dimensions, the difference in joint reaction forces between opening and closing increased with 15% (5N) (Fig. 6A). The difference between the condylar traces increased with 2% (Fig. 6B). An increase of the vertical cranial dimensions by 10% led to a decrease of the difference in joint reaction forces by 13% (Fig. 6E) and a 23% decrease of the coincident difference between condylar traces (Fig. 6F).

Discussion and conclusion

To assess loading differences of the TMJ during unloaded opening and closing movements of the jaw, a forward dynamics simulation was performed with a biomechanical model of the human masticatory system.

Model limitations

The applied muscle recruitment patterns for unloaded jaw opening and closing were adapted from activation patterns obtained during mastication (Møller, 1966). To attain symmetric muscle drive, the activation levels of balancing and working side muscles were averaged. Furthermore, some muscles slips were assigned the activation pattern of a homologous slip or that of a synergist. Despite these assumptions, the resulting movements of the mandible, and the resulting movement trace of the mandibular condyle were not different from habitual movements (Yatabe et al., 1995, 1997; Huddleston Slater et al., 1999). Furthermore, it has been demonstrated that even simpler patterns hardly affect jaw kinematics (Koolstra and Van Eijden, 1995).

The predicted joint reaction forces contained a non-physiologically high frequency noise component (Fig. 3). This can be attributed to the discretisation of the temporal and condylar articular surfaces into planar patches, creating discontinuities in the articular contact surfaces. The effect of this discretisation process did not affect the stability of the simulations nor the smoothness of the resultant movement patterns, because of the damping which was applied to the system.

The magnitude of the predicted joint reaction forces was 0 N at the beginning of the anterior translation of the mandibular condyle (Fig. 3). Also, the mandibular condyle initially travelled slightly upward (Fig. 4). Both indicate that contact between the meshes was absent at the start of the simulation. This phenomenon was considered a start-up artefact and was therefore ignored in further analysis.

The joint was simplified by a homogeneous cartilage layer of equal thickness stretched out over the temporal aspect of the TMJ. This layer was assumed to be representative for the combined temporomandibular disc, the temporal cartilage, and the condylar cartilage. The articular disc, however, has an uneven thickness, being thinnest in its centre. It can be assumed that the disc's position between the articulating bones is only dependent on the amount of jaw opening and not the direction of movement (opening or closing: Rees, 1954). Therefore, the influence of the applied simplification on condylar movement and joint reaction forces was deemed negligible.

Ligaments and capsule of the TMJ were not implemented in the current model. Their absence was justifiable, because they have been demonstrated not to limit the normal opening and closing movements of the lower jaw (Koolstra et al., 2001).

Sensitivity analysis

All performed simulations showed that the predicted joint reaction forces were larger during opening than during closing (Table 2, Figure 5 & 6). Also the mandibular condyle followed a more cranial path during opening than during closing (Figure 5 & 6). This is also indicated by a positive difference between opening and closing traces (Table 2). This was even true when the resulting muscle forces during closing exceeded those of the opening phase (25% activation of jaw openers and 8% activation of jaw closers, Table 2). This is due to the fact that during closing, the larger muscle forces primarily caused larger accelerations of the mandible and thus a shorter closing time. At the end of the closing cycle, this resulted in a relatively large impact on the dentition with a concomitant reaction force in the joints.

The predicted joint reaction forces were hardly dependent on the simulated cartilage thicknesses (p_{max}, in Eq. 1), see Fig. 5 ACE. A thicker cartilage layer resulted in a larger difference between opening and closing traces (Fig. 5 BDF). For a thinner cartilage layer, the result was reciprocal.

There was an effect of the ratio between horizontal and vertical cranial dimensions on the difference between joint reaction forces and condylar traces. During opening, the joint reaction forces were larger with decreased vertical height than with normal or increased vertical height. This indicates that for a decreased vertical cranial height, the jaw openers are faced with a more difficult task in pulling the mandible out of the mandibular fossa, onto the articular eminence. This is also illustrated by a 1.3 mm shorter travel in the anterior direction, when compared with an increased vertical cranial height (Fig. 6B, 6F). It must be noted that the applied changes in morphology were not intended to mimic the so-called "short face" or "long face" morphology, as these include more cephalometric differences (Bishara and Jakobsen, 1985; Van Spronsen et al., 1996; Raadsheer et al., 1999) than vertical cranial height only.

Joint reaction forces

Despite the assumptions made on TMJ morphology and muscle drive, the magnitude of the predicted joint reaction forces was within the range reported in other model studies (Langenbach and Hannam, 1999; Peck et al., 2000; Koolstra and Van Eijden, 2005; Hannam et al, 2008). From these studies and the performed sensitivity analysis on maximum activation level, it can be appreciated that peak joint reaction forces are highly dependent on the chosen levels of maximum muscle activation (Table 2).

Condylar trace

The trace of the condylar centre (Fig. 4) showed a very similar pathway as the trace of the kinematic centre derived from movement registrations (Yatabe et al., 1995, 1997; Huddleston Slater et al., 1999; Naeije, 2003). In the sagittal plane, the ellipsoid representing the condyle is almost circular. This ellipsoid combined with the homogeneous cartilage layer on the cranial part of the TMJ can be interpreted as a spherical condyle-disc complex and therefore as the kinematic centre (Naeije, 2003). The predicted opening trace was located above the closing trace. The maximum difference between traces corresponded well with the average of 0.43 mm, as reported by Huddleston Slater et al. (1999). The similarity between the presented model predictions and the results of the earlier performed experimental studies can be considered as a validation in a qualitative sense for the employed simulations.

Comparison with experimental studies

The loading of the TMJ was predicted to be larger during opening of the jaw than during closing. This result corroborates the findings and the interpretation given to the experiments performed by Huddleston Slater et al. (1999), who found a diminished difference between opening and closing traces of the kinematic centre, after enforcing a larger condylar loading during closing by an additional manual loading of the mandible.

The finding that the minimum intra-articular distance was larger during opening than during closing (Gallo et al., 2000; 2008) seems to be in contrast with our results. In the sensitivity analysis on maximum activation level, we were not able to reproduce a situation, where the joint forces during closing were larger than during opening. Even when the total muscle forces during closing exceeded those during the opening phase, the joint reaction force remained below the opening one. An explanation might be that the location of the minimum intra-articular distance is not necessarily the location where the joint forces are transmitted. In our simulations for instance, the predicted point of application of the joint reaction forces during the beginning and end of the simulation was located at the top of the condyle. In contrast, the smallest intra-articular distance is often found at the anterior aspect of the condyle closest to the articular eminence (Gallo, 2005; Gallo et al, 2008). Moreover, these locations regularly differed from the ones where the largest stresses were predicted in the articular disc (Koolstra and van Eijden, 2005). Furthermore, it must be realized that due to the presence of an articular disc with uneven thickness, the location where forces are transferred, is not unambiguously related to the site of the minimum intra-articular distance.

Conclusion

The joint reaction forces of the TMJ were predicted to be larger during opening than during closing of the jaw. Therefore our null-hypothesis, assuming similarity between opening and closing, was rejected. It was found that a more cranially located

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Figure 1. Graphical representation of the mathematical model of the masticatory system. Oblique frontal view of the initial position. The shape of the mandibular fossa and eminence is depicted by a simplified doubly curved mesh (grey). The shape of the mandibular condyle is depicted by an ellipsoid (black). For illustration purposes, schematic drawings of the mandible and dentition were added and only forces acting on the right side of the mandible were depicted. The forces are represented by vectors, consisting of joint reaction forces (JRF) and dentition forces (MF), not to scale. Furthermore, the line of action of the muscles was displayed. T-A: temporalis anterior. T-P: temporalis posterior. MP: medial pterygoid. MS: superficial masseter. 1: anterior deep masseter. 2: posterior deep masseter. 3: inferior lateral pterygoid. LPS: superior lateral pterygoid. GEN: geniohyoid. DIG: anterior belly of digastric. MYL-A: anterior mylohyoid. MYL-P: posterior mylohyoid.

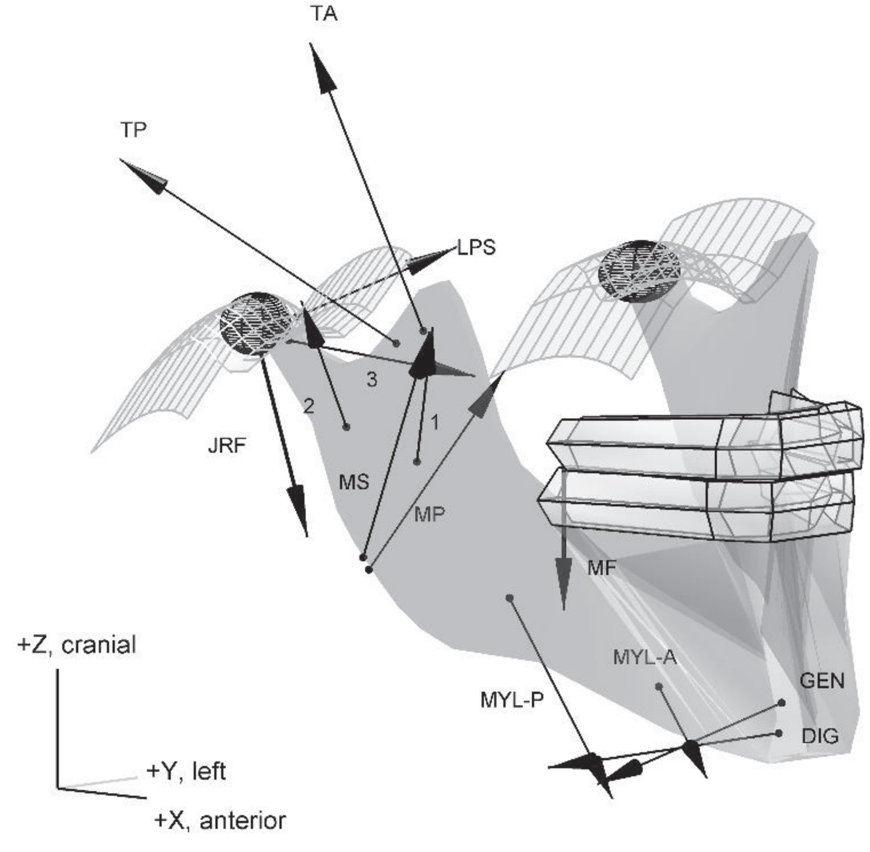

Figure 2. Activation pattern of the jaw muscles with respect to time. Jaw openers and closers were activated up to 50% and 4% of their maximum, respectively.

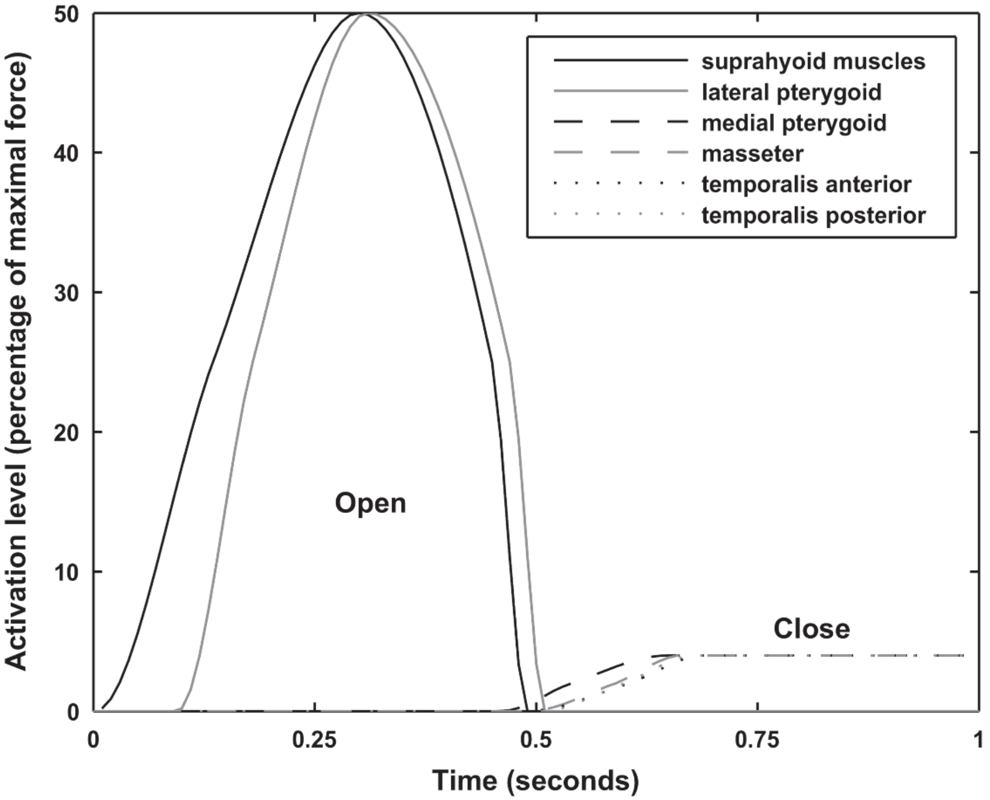

Figure 3. Predicted (grey) and lowpass filtered (black) magnitude of joint reaction forces with respect to anterior translation of the centre of the mandibular condyle. Solid lines: opening movement. Dashed lines: closing movement.

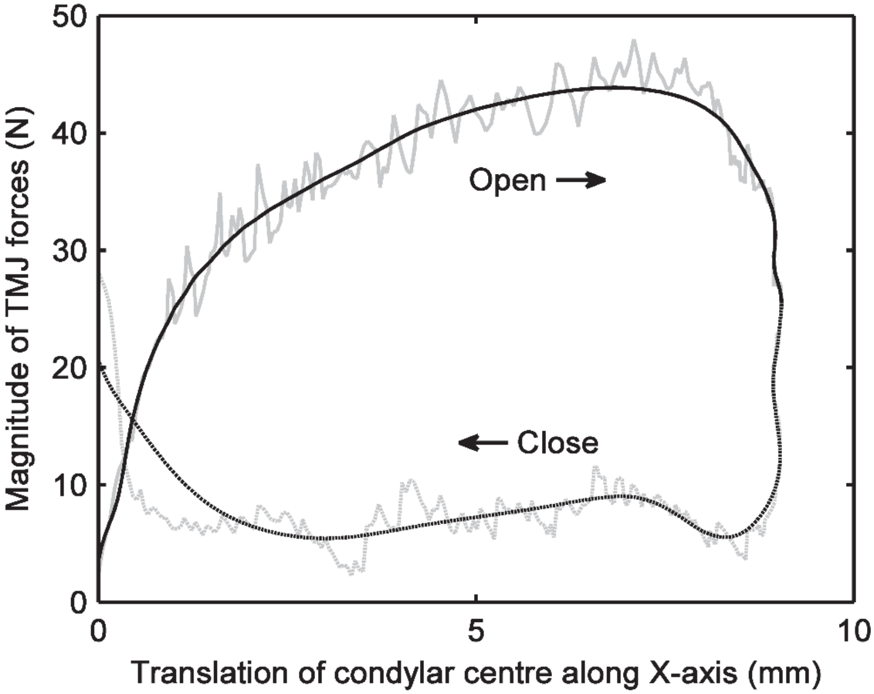

Figure 4. Trace of the centre of the mandibular condyle during opening and closing in a sagittal projection. The opening trace (solid line) is located above the closing trace (dashed line).

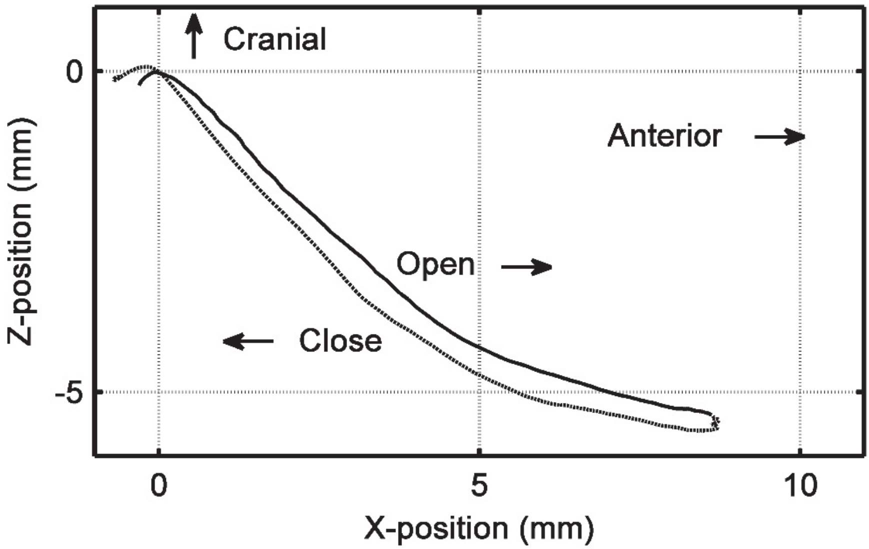

Figure 5. Influence of the modelled thickness of the articular cartilage layer. Left panels: lowpass filtered joint reaction forces. Right panels: condylar trace. A, B: decreased thickness of cartilage. C, D: reference. E, F: increased thickness of cartilage. Line types and axes as in Fig. 3 and 4, respectively.

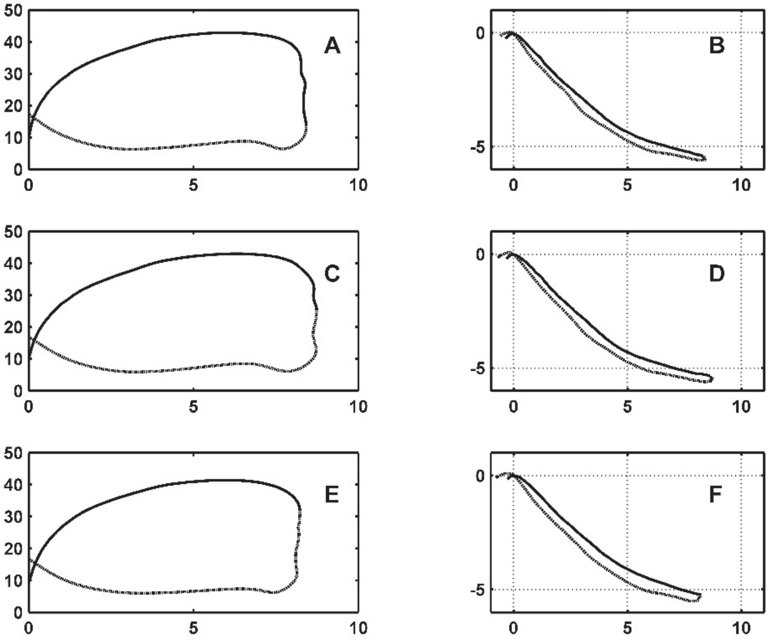

Figure 6. Influence of vertical cranial morphology. Left panels: lowpass filtered joint reaction forces . Right panels: condylar trace. A, B: reduced vertical cranial height. C, D: reference. E, F: increased vertical cranial height. Line types and axes as in Fig. 3 and 4, respectively.

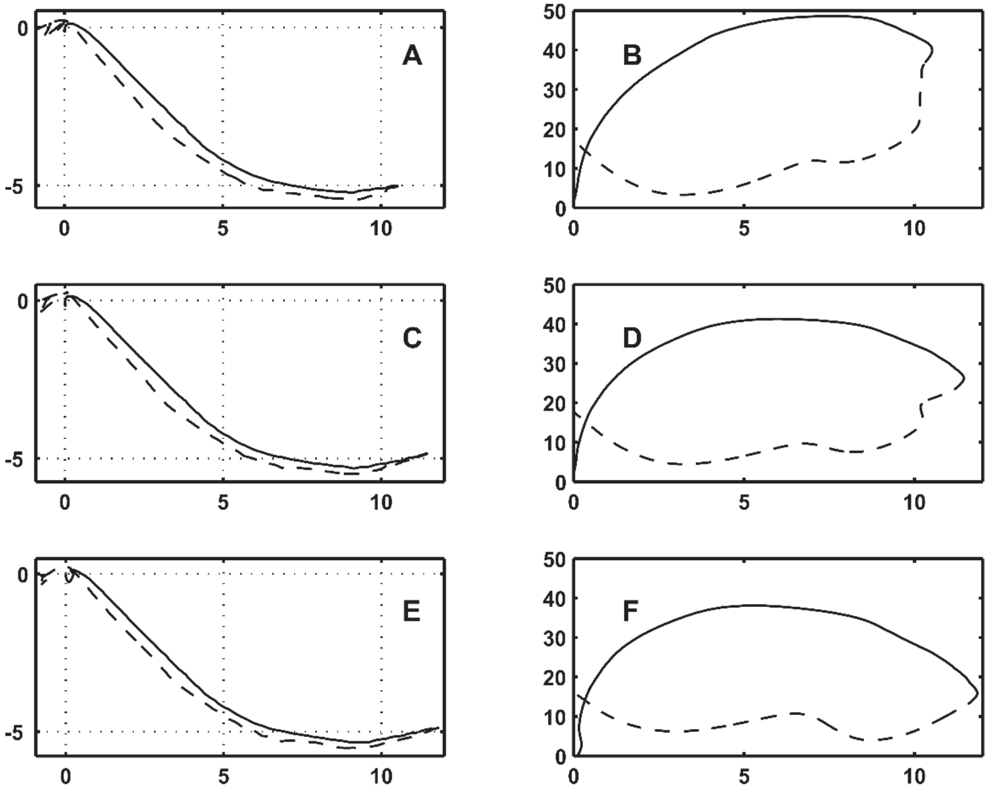

Table 1. Measured EMG recruitment patterns as recorded by Møller (1966) and the muscles within the current model, which were assigned to these recruitment patterns. The number of slips within each muscle is stated between parentheses.

Measured EMG, Møller (1966)	Driven muscle (#slips)
Jaw closers	
Superficial masseter	Superficial masseter (1) Deep masseter (2)
Medial pterygoid	Medial pterygoid (1)
Anterior temporalis	Anterior temporalis (1)
Posterior temporalis	Posterior temporalis (1)
Jaw openers	
Lateral pterygoid, inferior head	Lateral pterygoid, inferior head (1) Lateral pterygoid, superior head (1)
Digastric, venter anterior	Digastric, venter anterior (1) Geniohyoid (1) Mylohyoid (2)

Table 2. Sensitivity analysis on the maximum activation level of jaw openers and jaw closers.

Activation level (% of maximum)		Maximum muscle forces (N)		Maximum joint reaction force (N)		Maximum difference between opening and closing condylar trace (mm)
Jaw openers	Jaw closers	Jaw openers	Jaw closers	during opening	during closing (at same jaw position)	
25	2	74	29	24	5	0.54
25	4	74	65	24	9	0.28
25	8	74	135	24	13	0.19
50	2	134	29	43	7	0.65
50	4	134	65	43	10	0.45
50	8	134	148	43	13	0.40
75	2	179	29	54	7	0.72
75	4	179	65	54	10	0.50
75	8	179	150	54	13	0.47

Chapter III

Biomechanical modelling of open locks of the human temporomandibular joint

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Abstract

Background: Patients with hypermobility of the temporomandibular joint may have problems closing their mouth after opening widely. In the worst case, the mandibular condyles become trapped in front of the articular eminences and the jaw muscles cannot reposition them into the fossae (open lock). The difference in ease of closing the jaw between patients and non-patients is presently not well understood.

Materials and methods: Wide opening and subsequent jaw closing were simulated with a biomechanical model in a forward dynamics approach. The effect of anterior slope angle and orientation of jaw-closing muscles on condylar travel was determined.

Findings: The mandibular condyles traveled anterior of the eminences and back into the fossae uneventfully with backwardly oriented jaw closers and eminences with a gentle anterior slope. However, combinations of relatively forward oriented jaw closers and a steep anterior slope caused the condyles to continue traveling anteriorly upon jaw-closing attempts, ending in an open lock position.

Interpretation: Our results indicate that for the masticatory system to reach an open lock, various unfavorable combinations of jaw-closer orientation and anterior slope angle exist within normal physiological ranges. These findings could be relevant for maxillofacial surgeons, both for the diagnostic process and for clinical decisions, regarding patients suffering from open locks.

Keywords: temporomandibular disorders, jaw biomechanics, anatomy, risk factors, dislocations, mathematical modelling

Introduction

Healthy people open their jaws widely with ease. Yawning and laughing out loud are performed effortlessly. Also, the subsequent closing of the jaw is usually smooth. During jaw opening, the mandibular condyles travel anteriorly and inferiorly along the articular eminences (e.g. Yatabe et al., 1997; Chen et al., 2000; Gallo, 2005). Often they end up in front of the eminences at maximum mouth opening (Ricketts, 1950; Wooten, 1966; Obwegeser et al., 1987; Kalaykova et al., 2006). The jaw-closing muscles appear to be well aligned to direct the condyles from this anterior position back into the glenoid fossa, enabling the jaw to close normally. However, patients with a hypermobile temporomandibular joint (TMJ) may have problems closing their mouth after opening wide. In these patients, the condyles also travel in front of the eminences upon jaw opening. However, the return of the condyles towards the fossae occurs less smoothly. Then the lower jaw displays jerky lateral deviations (Kalaykova et al., 2006), often accompanied by a dull click (Huddleston Slater et al., 2004). In patients with even more severe symptomatic hypermobility, opening the jaw widely may result in a so-called open lock. In that case, the mandibular condyles become trapped in front of the articular eminences and jaw closure is blocked. Typical open-lock-provoking movements include yawning, laughing, screaming, and vomiting (August et al., 2004).

Both abnormal and normal jaw movements are determined by muscle forces and joint reaction forces (Koolstra, 2002). Jaw closing is performed when these forces create a net jaw-closing moment. The resultant of the jaw-closing muscles alone is not able of producing such a moment. Its line of action runs upwardly behind the center of gravity of the lower jaw. In contrast, the joint reaction forces do have this ability since they run in the opposite direction (Koolstra and van Eijden, 1995). The instantaneous balance between the opening and closing moments produced respectively by the jaw-closing muscles and the joint reaction forces determines whether or not jaw closing can be completed.

When the jaw has acquired an open lock following maximal mouth opening, it can be assumed that the joint reaction forces fail to create a closing moment which is sufficient to overcome the muscles' jaw-opening moment. Either the jaw-opening moment of the jaw closers has been enlarged or the jaw-closing moment of the joint reaction forces diminished. Since the magnitude of the joint reaction forces is proportional with the resultant muscle force, it must be the length of their moment arms that plays a major role. This length depends on the point of application and the direction of the relevant forces. The points of application of muscle and joint forces with respect to the mandible are assumed to be relatively constant. Consequently, the lengths of the moment arms primarily depend on their directions.

Presently, it is not clear how the direction of muscle and joint forces contribute to the occurrence of an open lock of the TMJ. Therefore, the influences of the direction of both muscle forces and joint forces were combined in a qualitative approach. The direction of a joint reaction force is determined as perpendicular to the surface of the eminence at the point of contact with the mandibular condyle. Since the problem of open locks occurs anterior of the eminence, only the anterior slope angle of the eminence was considered to be relevant. We investigated how this angle, in combination with the direction of the resultant muscles force, might contribute to the susceptibility for an open lock. To this end, we numerically simulated wide opening and subsequent closing of the lower jaw. The moment arm of the joint reaction forces reduces with increasing steepness of the articular eminence and the moment arm of the resultant muscle force increases with a more forward inclination. Therefore it was hypothesized that a combination of a steep anterior slope and forwardly inclined lines of action of the jaw closers, is responsible for the masticatory system to reach an open lock situation more easily.

Materials & Methods

Simulations

Simulations were carried out to explore the combined role of the anterior slope angle of the articular eminences and the global orientation of the jaw closing muscles in contributing to open locks of the TMJ. For various combinations, we determined whether the condyles would return to the fossa upon jaw-closing attempts after a wide jaw opening.

Model description

Jaw opening and closing movements were simulated with a biomechanical model of the masticatory system, which was described in detail previously (Tuijt et al., 2010). In short, the model is symmetrical and consists of 24 Hill-type muscle actuators, two TMJs, lateral ligaments, gravity, and a simplified dentition. Jaw closers are: deep masseter (two muscle lines), superficial masseter (one muscle line), medial pterygoid, and temporalis muscles (two muscle lines). Jaw openers are: lateral pterygoid (two muscle lines), mylohyoid, anterior belly of digastric, and geniohyoid (two muscle lines). The curl of the lateral pterygoid around the articular eminence is implemented by a via-point 0.5 cm below the apex of the eminence. In the reference configuration, the origins and insertions of the muscle slips were taken from van Eijden et al. (1997), and the anterior slope of the articular eminence was set at 40 degrees with respect to the occlusal plane. The joint reaction forces were estimated with a contact algorithm (Tuijt et al., 2010). The lateral ligament of the TMJ was incorporated by an anterior slip and a posterior slip with an oblique, spatial arrangement (Sato et al., 1996), implemented as spring-like elements with a linear stiffness of 100 N/mm. All forces and moments were determined with respect to the center of gravity which was located between the apices of the second molars (Koolstra and van Eijden, 1995).

Anterior slope of the articular eminence

The shape of the glenoid fossa and articular eminence perpendicular to the condylar axis was defined by a fifth-order polynomial. This allowed determining the angle of the anterior slope with respect to the occlusal plane independent of the posterior angle. The coefficients of the polynomial were chosen in such a way that only the anterior slope was altered. The angle of its steepest part was gradually changed from 40 degrees (the reference) to 25 degrees or 55 degrees in steps of five degrees.

Orientation of jaw closers

The working lines of all jaw closers were altered by rotating them about a transverse (left/right) axis through their mandibular insertions. They were rotated in the anterior direction (rotation angles were +5, +10, and +15 degrees) and posterior direction (-5, -10, -15 degrees) (Fig. 1), with respect to their reference orientation.

Simulation procedure

For each combination of anterior slope angle and jaw closer orientation, a symmetrical open and close movement was simulated with a time step of $1.0*10^{-4}$ seconds. Simulations started with a closed mouth and bilateral molar contact. The jaw openers were activated up to their maximum to simulate an open-lock-provoking movement. Thereafter, the jaw closers were activated to 4% of their maximum to close the mouth. The applied muscle activation pattern was averaged from EMG measurements during mastication (Møller, 1966). All muscle forces and bilateral reaction forces from ligaments and joints were predicted. Also the moments resulting from these forces were calculated with respect to the center of gravity of the lower jaw. From the predicted translations and rotations of the lower jaw, the condylar travel was quantified by the instantaneous horizontal distance between the condylar center and the apex of the eminence.

Results

At the start of the simulation, the mandibular condyles were located in the mandibular fossae, 8 mm posterior of the apex of the articular eminences (Fig. 2A, Time = 0.0 s). In the reference configuration, the mandibular condyles traveled up to 5 mm in front of the apex, upon activation of the jaw openers (Fig. 2A, Time = 0.25 s) and returned to their initial position at the end of the simulation, after the jaw-closing muscles had been activated (Fig. 2A, Time = 0.8 s). With smaller anterior slope angles (-5 to -15 degrees), the condyles also returned to the fossae. However, with a steeper anterior slope angle (+5 to +15 degrees), the condyles could not return to the mandibular fossae. Instead, they traveled an additional 5 mm in the anterior direction along the anterior slope, creating an open lock situation. This is also illustrated by the opening angle of the lower jaw, which stayed above 20 degrees for anterior slope angles of +5 to +15 degrees (Fig. 2B).

The anterior/posterior position of the center of the condyles at the end of simulation time is shown in Table 1. It illustrates that a steep anterior slope angle of the eminences not necessarily makes the system vulnerable to end up in an open lock, provided that the jaw closers are sufficiently directed backwards. With a backward orientation of -5 to -15 degrees, the jaw closers could guide the condyles back into the mandibular fossae with anterior slope angles up to +10 degrees. On the other hand, a +5 to +15 degrees forward inclination of the jaw closers contributed increasingly to the susceptibility of an open lock (Table 1).

Discussion

In the present study, we numerically investigated which relevant musculoskeletal aspects of the masticatory system provide conditions to reach an open lock after wide jaw opening. We qualitatively explored the combined effect of the anterior slope angle of the articular eminence and the generalized orientation of the jaw closers. The model simulations indicated that combinations of a relatively steep anterior slope angle and relatively forward inclined lines of action of the jaw closers provide the conditions to end up in an open lock.

Assumptions were made for the anterior eminence angle and the orientation of jaw closers. Due to the absence of valid estimates, we presumed angles of 25 - 55 degrees for the anterior slope of the articular eminence based on anatomical atlases (e.g. Putz and Pabst, 1994) and dissecting experience. The orientation of the jaw closers was altered by rotating their working lines about the mandibular insertion. The rotation was limited to -15 and +15 degrees. Rotations of -10 to +10 degrees resulted in origins of the jaw closers within the range of biological variation (Van Eijden et al., 1997). Rotations beyond ±15 degrees were considered anatomically unrealistic. The chosen angles, therefore, are considered to be compliant with the considerable amount of variation in jaw muscle attachments.

To be certain to reach a maximum jaw opening, the jaw openers were activated up to their maximum force capacity. It provided the mandibular condyles to reach the anterior slope of the articular eminences close to its steepest part (within two degrees). This replicated the position of the mandibular condyles anterior of the eminences in maximum mouth opening.

The trajectory of the mandibular condyles was not entirely smooth, illustrated by a slight movement of the condyles back and forth along the articular eminences at the transfer between opening and closing (Fig. 2a). We observed no medio-lateral translations nor instabilities during the simulations. The small anterior/posterior movement of condyle is due to the passive forces of the jaw-closing muscles overcoming the decreasing forces of the jaw openers before the actual jaw closing was initiated. The temporalis muscle became stretched during wide opening and produced a closing moment due to the force-length relationship as implemented in the Hill-type muscle model. The additional translation could have been corrected by application of a different muscle activation pattern. These were unavailable for the present movements. Therefore, the applied pattern was adapted from a study on chewing (Møller, 1966). The resulting movement illustrates the importance of subtle timing in activation patterns to enable smooth jaw movements (Weijs, 1980). The distinction between success and failure to close the jaw after being opened wide is in the instantaneous balance of forces and moments applied to the lower jaw. Relative to the center of gravity, the joint reaction forces provide the closing moment, while the net moment of the jaw closers is an opening one. In order to initiate jaw closing (Fig. 3a), the moment of the reaction forces has to be larger than that of the jaw closers. Since the magnitude of the reaction forces is less than the resultant muscle force, their moment arms must be considerably larger than that of the latter. When the mandibular condyles rest against the anterior slope of the articular eminences (Fig. 3b), the joint reaction forces are directed obliquely anterior. Therefore, with an increase of steepness their moment arms diminish and herewith the closing moment. At a certain instant it becomes insufficient to overcome the opening moment of the muscles.

Fig. 2 illustrates a clear distinction between the prerequisites for avoiding an open lock situation. For anterior slope angles up to the reference value, the mandibular condyles start to return to the fossa at t=0.30 s. This is the moment when deactivation of the jaw openers starts. For angles beyond the reference value, the condyles continue to travel anteriorly. Then, the balance between opening and closing moments has been tipped towards an open lock.

The present predictions may have some implications for patients suffering from open locks, and may support current conservative treatment. Generally, patients are taught to limit mouth opening (Okeson, 2003). Limitation of anterior travel of the mandibular condyles such that the steepest part of the anterior slope is not reached, can be achieved by activating the jaw openers less. Another option is to place a hand under the chin during yawning. Once confronted with a difficulty to close the mouth, some patients may have the ability to change the common recruitment pattern of the jaw closers in favor of backwardly inclined muscle portions. This may be successful if the backward inclination is sufficient.

Patients with severe complaints of habitual open locks may have an indication for surgical treatment. A possible working principle behind eminectomy (Undt et al., 1997) can be derived from the current series of simulations. When the anterior slope angle is decreased by the eminectomy, the closing moment of the joint reaction force is prevented to decrease so much that it becomes insufficient to overcome the jaw closers' opening moment. Eminectomy thereby may allow the mandibular condyles to pass below the eminences safely.

Conclusion

An open lock occurs when at a certain instant during the start of jaw closing the closing moment of the joint reaction forces starts to become insufficient to complete this movement. The interaction of anterior slope angle of the articular eminences and orientation of the jaw-closing muscles determines whether such insufficiency may occur. Various unfavorable combinations of these parameters may exist within normal morphological ranges. Whether patients suffering from open locks indeed have such unfavorable combinations needs to be confirmed in clinical studies.

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Figure 1. Graphical representation of the biomechical model of the human masticatory system. Right anterior view. Arrows indicate forces (right side only). F: fossa. C: mandibular condyle. E: articular eminence. JRF: joint reaction force. Jaw closers: TA: anterior temporalis, TP: posterior temporalis, MP: medial pterygoid (dotted to indicate it travels medially of the mandible), MA: masseter (three parts). Dashed arrows: rotated working line of jaw closers (15 degrees clockwise rotation and 15 degrees counter-clockwise rotation), applied to TA, as an example for all jaw-closing muscles. ASA: anterior slope angle of the articular eminence. ASA and the rotation of the jaw closers are referred to the sagittal plane.

Insert. dAP: horizontal distance in anterior/posterior direction between the centre of the condyle and the apex of the articular eminence.

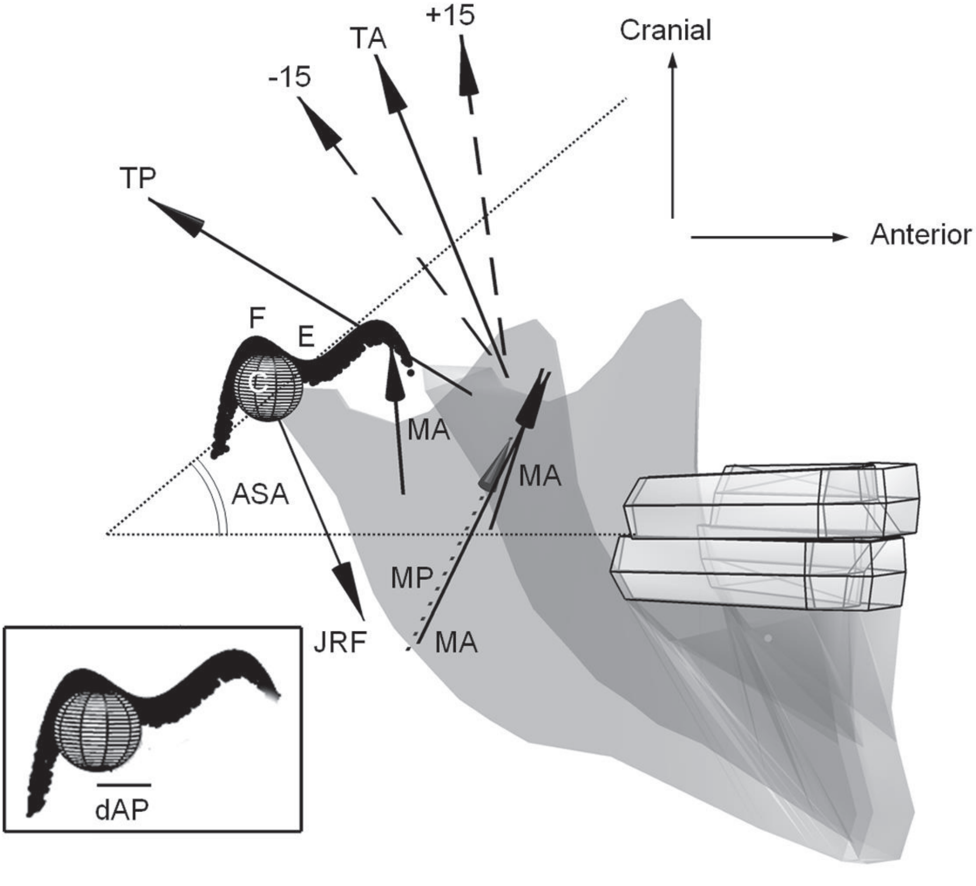

Figure 2. Mandibular movement upon jaw opening and -closing attempts as a function of the anterior slope angle (ASA), lower ASA's in darker shades of grey. A: The horizontal distance in the anterior/posterior direction (dAP in mm) between the centre of the condyle and the apex of the articular eminence with time. B: The opening angle of the lower jaw relative to the upper jaw (degrees) with time. C/D: Activation level with time.

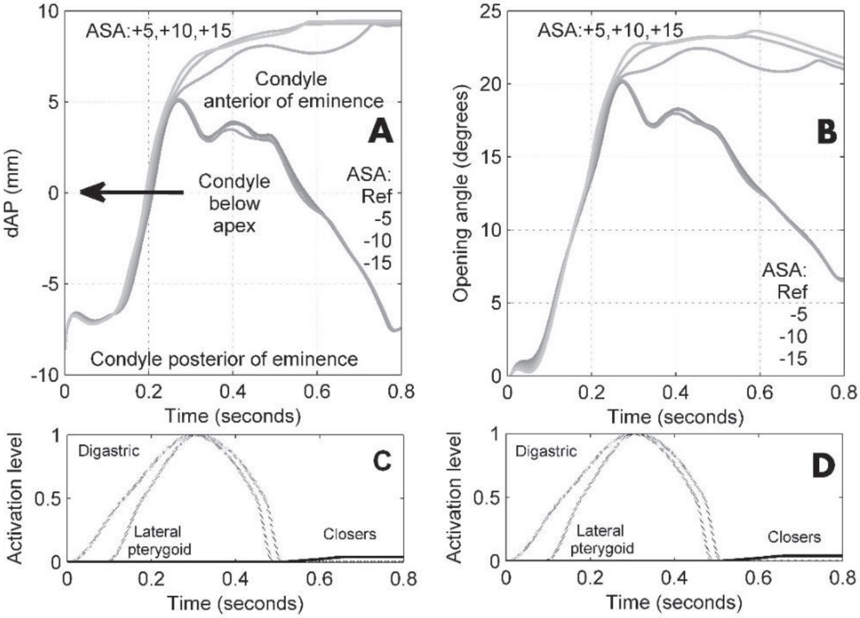

Figure 3. Free body diagram of the lower jaw seen from the right. The crosshairs indicate the centre of gravity of the lower jaw. A. Normal situation at wide open jaw. The jaw closing moment of the joint reaction forces exceeds the jaw opening moment of the resultant muscle forces. B. Situation at wide opening during open lock. The jaw opening moment of the resultant muscle forces exceeds the jaw closing moment of the joint reaction forces.

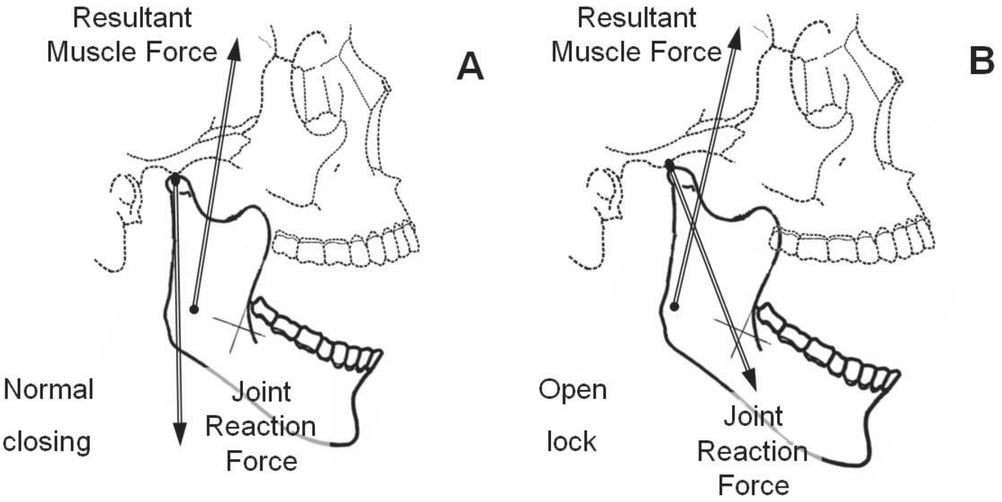

Table 1. Distance in the horizontal anterior/posterior direction (dAP in mm) between the centre of the condyle and apex of the articular eminence at the end of the simulations as a function of maximum anterior slope angle and rotation angle of the jaw closers.

Ref indicates the reference simulation with a 40 degree anterior slope angle and no rotation of the jaw closers. A positive number indicates that the condyle has become locked in front of the articular eminence at the end of the simulation (grey background). A negative number indicates that the condyle has returned posteriorly to the apex (white background).

Orientation of jaw closers (degrees)	Anterior slope angle (degrees)						
	-15	-10	-5	**Ref**	+5	+10	+15
+15	-7	-2	9	9	9	9	10
+10	-7	-5	-2	9	9	9	10
+5	-7	-7	-7	9	9	9	10
Ref	-7	-7	-7	-7	9	9	9
-5	-7	-7	-7	-7	-7	9	9
-10	-7	-7	-7	-7	-7	-7	9
-15	-7	-7	-7	-7	-7	-7	9

Chapter IV

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.

Keywords: 3D mathematical modelling; Anatomy; Dislocations; Jaw biomechanics; Temporomandibular disorders

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 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.

Materials and 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).

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 (Figure 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, 1980; 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 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).

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 1.0Ns/cm for translations and 1.0Ns/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 0.44kg to the lower jaw.

All moments (i.e. roll, pitch, and yaw, see Figure 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 centre of the condyles and the apex of the articular eminence (dAP in mm), muscle forces, and joint forces) and closing moment (pitch).

Simulations

The forward dynamic simulations started with a closed mouth and bilateral molar contact. The top of the mandibular condyle was located against the roof of the fossa. The jaw was opened by maximally activating the jaw openers to achieve a position of the mandibular condyle anterior of the eminence. As the jaw closing movement in patients is hampered, different closing strategies were applied. Jaw closing was attempted directly in the reference simulation, or by applying the relaxation strategy, or the laterotrusion strategy.

The relaxation strategy consisted of a relaxation phase of 0.5s preceding the closing phase. During this relaxation phase jaw openers and jaw closers were deactivated completely (Figure 2).

The laterotrusion strategy tried to achieve a consecutive return of the mandibular condyles. Therefore, the closing phase was preceded by a yaw phase in which laterotrusion was attempted. This yaw phase was preceded by a roll phase to facilitate the yaw movement by unloading the right joint. The muscles with the highest potential to produce a roll or yaw moment were selected at maximum mouth opening. They were activated for 0.5s to 10% of their maximum (Figure 3).

To compare the potential of both strategies to resolve an open lock, the angle of the anterior slope of the articular eminence (ASA) was increased with 5°. This was repeated until one strategy was still able to resolve the open lock while the other wasn’t, given the same ASA..

The simulations were performed with a time step of $1.0*10^{-4}$ seconds and could be terminated when the condyles had returned to the fossa, with or without tooth contact.

Results

Reference simulation

In the reference simulation, the mandibular condyles remained in front of the articular eminence (dAP=9-10mm) (Figure 4A). Despite the fact that the lower jaw made a slow closing movement, the condyles did not return to the glenoid fossae. The lower jaw maintained an inter-incisor distance of 1.5cm in a protruded position (see also Online Resource 1: ref_asa_45_movie_1).

During the closing phase, the muscles produced a negligible force in the anterior/posterior (AP) direction, and an average opening moment of 95Ncm (Figure 5A). The joint reaction forces produced a closing moment which exceeded the opening muscle moment slightly (Figure 5B), leading to a small net closing moment (Figure 5C). This explains the reduced mouth opening at the end of this simulation. The net joint reaction force was about 20N in anterior direction (Figure 5B), preventing the condyles to move backwards.

Relaxation strategy

The relaxation strategy successfully resolved the open lock of the reference configuration (ASA = 45°). During the relaxation phase, the mandibular condyles travelled posteriorly for 8-9mm. During the closing phase, they returned to the glenoid fossa and the mouth closed properly (Figure 4B: Online Resource 2: relax_asa_45_movie_2). The passive forces of the relaxed jaw-closing muscles were directed posteriorly and provided initially a closing moment of 50Ncm. This moment decreased during the relaxation phase and turned into a small opening moment (Figure 5D). The anterior component of the joint reaction force disappeared during the relaxation phase, and its moment changed from opening to closing (Figure 5E). Note that half way the relaxation phase the net moment subsided (Figure 5F), which explains a pause of the movement at t=0.8s (Online Resource 2: relax_asa_45_movie_2: Figure 4B). At the start of the closing phase the condyle rested below the eminence. Next, the net moment was largely closing (Figure 5F) causing the mouth to close properly.

When the ASA was increased to 50°, the mandibular condyles failed to move towards the glenoid fossa upon relaxation. The lower jaw ended in the same protruded position as in the reference simulation (Figure 4C: Online Resource 2: relax_asa_50_movie_3). During this closing attempt, the posterior component of the muscle force (Figure 5G) was not able to overcome the anterior component of the joint reaction force (Figure 5H), leading to a net anterior force throughout both phases (Figure 5I). The muscles’ closing moment of 50 Ncm (Figure 5G, 5I) was opposed by a slightly smaller opening moment of the joint reaction forces (Figure 5H), resulting in a small closing moment (Figure 5I).

Laterotrusion strategy

Contrary to the reference simulation (Figure 6A), the laterotrusion strategy was successful in obtaining full closure of the mouth for a configuration with an ASA of 45°, by retrieving the mandibular condyles to the glenoid fossa one at a time. The right mandibular condyle travelled posteriorly for 5mm in the roll phase and returned to the fossa early in the yaw phase. The left condyle trailed by 0.5s and returned to the fossa 0.2s into the closing phase (Figure 6B: Online Resource 4: laterotrusion _asa_45_movie_4: Online Resource 5: laterotrusion_asa_45_frontal_movie_5).

In the roll and especially the yaw phase, the muscles produced a posteriorly directed force component (Figure 7D). During the roll phase, this led to a substantially smaller opening moment (Figure 7D) than during symmetrical closing in the reference simulation (Figure 7A). During the yaw phase, the muscles produced a closing moment of about 50Ncm. This diminished during the symmetrical closing phase.

The resultant joint reaction force maintained an anteriorly directed component throughout the roll and yaw phase, (Figure 7E). They provided a net jaw-closing moment during both phases (Figure 7E), which was smaller than in the closing phase of the reference simulation (Figure 7B). This continued during the closing phase.

At the start of the yaw phase, the net force had a posteriorly directed component (Figure 7F) explaining the swift return of the right condyle (Figure 6B). Overall, the net moment during both the roll and yaw phases was a closing one (Figure 7F). During the closing phase, the joint reaction forces added to the net closing moment. When both condyles had returned to the fossae at 1.7s, the simulation was terminated.

Contrary to the relaxation strategy, the laterotrusion strategy was able to retrieve the condyles when the ASA was increased to 50° (Figure 6C). The results for both ASA values were similar. The most notable difference was that during the yaw phase the build-up of a posteriorly directed net force and a net closing moment took about 0.3s longer (Figure 7F, Figure 7I), explaining the delayed return of the right mandibular condyle to the mandibular fossa (Figure 6B, Figure 6C, Online Resource: laterotrusion_asa_50_movie_6, Online Resource: laterotrusion_asa_50_ frontal_movie_7).

Discussion

With a forward dynamics approach, we assessed the effect of relaxation and laterotrusion strategies on the muscle and joint reaction forces and their moments in an open lock configuration of the temporomandibular joint. We showed that both strategies were successful in accomplishing jaw closure for a configuration with an anterior slope angle that would otherwise lead to an open lock (Tuijt et al., 2012). When this slope became steeper, the relaxation strategy failed to resolve an open lock, while the laterotrusion strategy remained effective.

Relaxation strategy

The relaxation strategy was successful in resolving an open lock for a joint with an ASA of 45°. Compared with direct closing, the anterior component of the joint reaction forces markedly decreased (Figure 5E). Herewith, the larger posterior muscle force components could retrieve the condyles to the glenoid fossa. Also, the net closing moment successfully closed the mouth.

Inspection of the individual contributions to the net forces and moments revealed that the temporalis muscles provided a larger passive force than the masseter and medial pterygoid, at the start of the relaxation phase. Simultaneously, the temporalis muscle forces provided a closing moment. This might also have been achieved by predominantly activating the temporalis muscle, but it is not known, whether the brain can selectively activate this muscle in favour of the masseter and medial pterygoid muscles.

For a steeper ASA, the more anterior direction of the joint reaction force could not be overcome by the passive muscle forces of the temporalis muscles. However, a small net moment slightly closed the jaw.

Laterotrusion strategy

The laterotrusion strategy could resolve an open lock an ASA up to 50º. Similarly to the passive forces during relaxation, the active forces of the dorsally oriented parts of the temporalis muscle provided the necessary force and moment to retrieve both condyles (cranio-dorsally force of 20N and a pitch moment of 60Ncm).

The one-by-one retrieval of the condyles was facilitated by the unloading of the right joint during the roll phase. Its reaction force was half that of the left one. At the start of the subsequent yaw phase, the right joint was loaded less, which can be seen in the decrease of the anterior component of the joint reaction force (Figure 7E). While the right condyle travelled posteriorly for 5mm (Figure 6B), its moment changed from opening to closing, augmenting the net closing moment.

The result of the roll and yaw moments was a laterotrusion with a 10mm sideways excursion of the interincisal point (Figure 8A). This resembles the movements of patients with symptomatic hypermobility (Kalaykova et al., 2006a) (Figure 8B). However, it is not known whether the patients' movement is caused by an activation strategy like the present laterotrusion strategy, or by asymmetric bony morphology.

Assumptions/limitations

Since habitual muscle activation patterns for the requested roll and yaw movements were not available, arbitrary patterns were applied that included instantaneous activation. Although the choice of block pulses is not very lifelike, the muscle forces were not applied instantaneously. The Hill-type muscle model incorporated an electromechanical delay of 0.045s for activation and 0.075s for de-activation (Winters and Stark, 1987), creating a more gradual change in muscle forces.

For achieving maximum mouth opening, we increased the activation level of the jaw openers to 100%. This didn’t lead to higher joint reaction forces during jaw opening. The same peak occurred during opening when the condyle had to overcome the posterior slope of the eminence. The magnitude of the estimated joint reaction forces was in the same range as other model studies (e.g. Langenbach and Hannam, 1999) and within the physiological range reported in primate studies (e.g. Boyd et al., 1990).

For the roll and yaw phases, the muscles were selected on their potential of producing the required moments in a wide open jaw position. The resulting roll moment was 145Ncm (right condyle moves caudally) and the yaw moment amounted to -70Ncm (right condyle moves posteriorly). Despite the fact that it is not known whether these muscles are active in this combination, the central nervous system has a large number of muscles *and* activation levels to choose from (Latash, 2012). Therefore, the applied strategy could be part of a wider range of solutions.

In the maximum mouth opening, it is likely that the ligaments will start to limit the excursion of the mandibular condyle. During the reference simulation and relaxation simulation, the lateral ligament did not produce any force. Only shortly during laterotrusion, the lateral ligament showed short bursts of force. However, they did not contribute to posterior translation of the jaw.

To identify successful variations of the proposed activation strategies, inverse, optimization modelling could be performed. This kind of analysis has already been performed in a closed position(Trainor et al., 1995; Schindler et al., 2007). At wide mouth opening, the objective function could maximize the net posterior force combined with a net jaw closing moment.

During the final part of closing, the contact between the condyle and the fossa was lost. Thus, no joint reaction force was produced. This coincided with a quick posterior translation of the condyle (Figures 2B, 4B, 4C). Subsequently, a peak joint moment was produced (Figure 3E), when the condyle contacted the posterior aspect of the temporal surface. Although this may have caused a slightly unrealistic movement, this occurred *after* the open lock had been resolved.

Despite maximally activating the jaw openers, the maximum distance between the bite-plane and interincisal point did not exceed 3cm. Clinically, this would be interpreted as limited, since maximum interincisal distances average 45mm for women and 54 mm for men (Mapelli et al., 2009). Presently, both the hyoid bone and the cranium are fixed to the reference frame. Normally, the cervical spine extends 15° during maximal mouth opening (Muto and Kanazawa, 1994; Kohno et al., 2001) and the hyoid translates caudally and dorsally for 4-5 mm (Pancherz et al., 1986). These movements could enlarge maximum mouth opening by enabling the jaw openers to produce more force and a larger opening moment (Koolstra and Van Eijden, 2004). On the other hand, these movements would also facilitate an open lock. Therefore, the present simulations can be seen as conservative estimations of open locks.

In our model, the muscles were defined as a line from origin to insertion, except the superior head of the lateral pterygoid. To describe the muscle fibre orientation more precisely, muscle wrapping (e.g. Desailly et al., 2010; Favre et al., 2010) seems to be a promising approach, especially for the curve of the temporalis muscle along the skull (Liu et al., 2012).

Clinical implications

After opening wide with an ASA of 45°, direct symmetrical jaw closing would have resulted in locking of the jaw (Tuijt et al., 2012). Applying a relaxation strategy would have resolved this. Therefore, our results provide support for clinical advice of trying to relax the jaw muscles after being locked in an open position (de Leeuw, 2008).

For joints with a steeper ASA, the laterotrusion strategy may have more potential for resolving open locks and may complement non-invasive interventions. Physical therapists, dentists, or other health care professionals could teach patients to attempt a laterotrusion movement when an open lock occurs. Also, the manual repositioning of an open lock could be attempted with a similar laterotrusion strategy. Finally, cervical extension might facilitate an open lock. Therefore, it seems well advised to teach patients to limit neck extension during yawning or laughing.

Conclusion

Open locks of the temporomandibular joint may be solved by strategies targeted at the activation dynamics of the jaw closers. It seems that performing a laterotrusion movement from an open lock position has a larger potential to resolve the open lock than relaxing the jaw closers. Herewith, we rejected our null-hypothesis that both strategies are equally capable of resolving open locks. 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. The temporalis muscle appeared to be crucial to retrieve the mandibular condyles to the glenoid fossa, due to its’ more posterior orientation.

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Figure 1. Right anterior view of the 3D-biomechical 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.

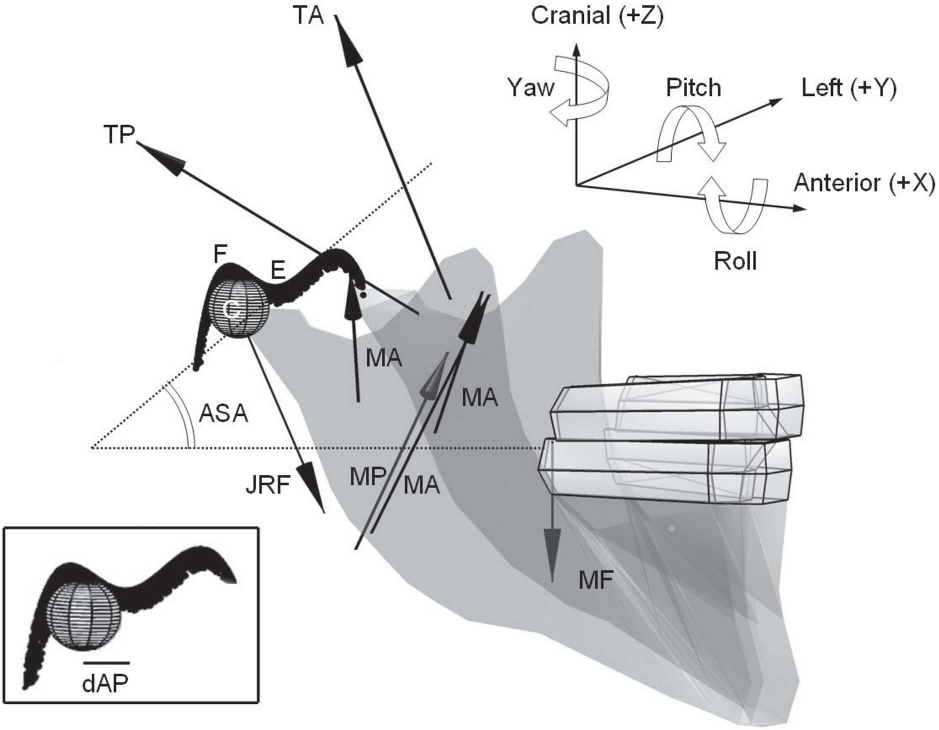


Figure 2. Activation scheme for the relaxation strategy. For the opening and closing phase, the active muscles are indicated. In the lower cell, the activation level with time is displayed.

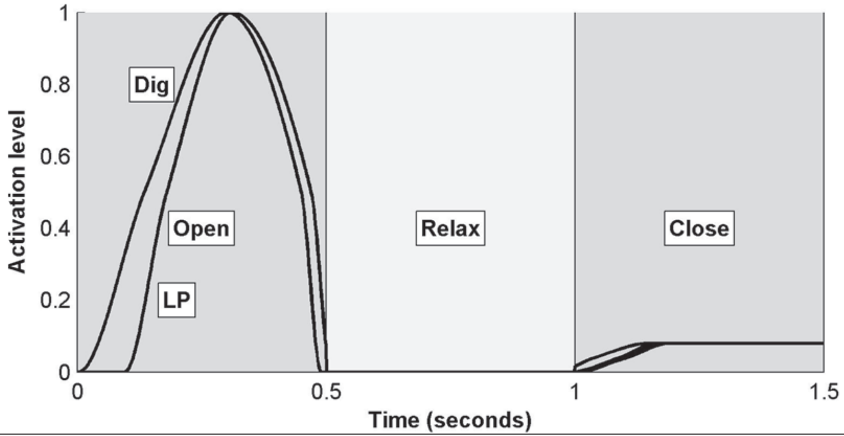
<table>
<tr><th>Opening phase</th><th>Relaxation</th><th>Closing phase</th></tr>
<tr><td>- superior belly of lateral pterygoid (LP)
- inferior belly of lateral pterygoid
- mylohyoid (anterior part)
- mylohyoid (posterior part)
- anterior belly of digastric (Dig)
- geniohyoid</td><td>-</td><td>- superficial masseter
- deep masseter anterior
- deep masseter posterior
- medial pterygoid
- anterior temporalis
- posterior temporalis</td></tr>
<tr><td colspan="3">
</td></tr>
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Figure 3. Activation scheme for the laterotrusion strategy. For the opening phase, roll phase, yaw phase, and closing phase, the active muscles are indicated. In the lower cell, the activation level with time is displayed.

Opening phase	Roll phase	Yaw phase	Close phase
- lateral pterygoid superior belly (LP) - lateral pterygoid inferior belly - mylohyoid - anterior belly of digastric (Dig) - geniohyoid	- medial pterygoid left - superficial masseter left - temporalis anterior left - lateral pterygoid left both bellies	- anterior temporalis right - posterior temporalis right - digastric right	- superficial masseter - deep masseter - medial pterygoid - anterior temporalis - posterior temporalis

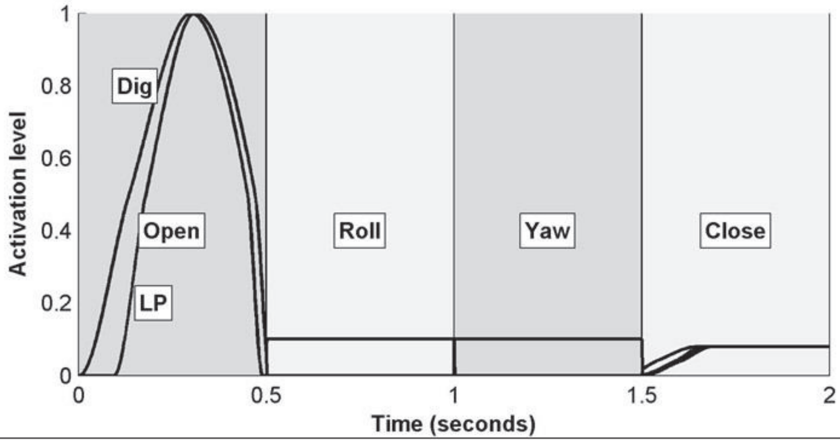


Figure 4. Influence of the relaxation strategy on the horizontal distance in the anterior/posterior direction (dAP in mm) between the centre of the mandibular condyle and the apex of the articular eminence with time (s). Positive in anterior direction. A: Reference simulation for anterior slope angle (ASA) of 45°, opening immediately followed by closing. B: Relaxation strategy and an ASA of 45°. C. Relaxation strategy and an ASA of 50°.

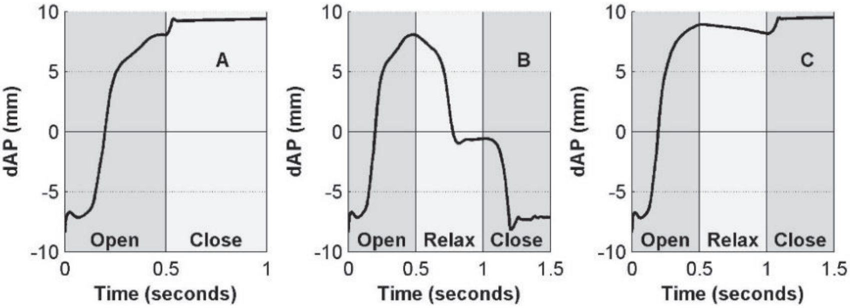


Figure 5. Influence of relaxation strategy on summed muscle force and summed muscle moment (top row), joint reaction force (JRF) and moment (middle row) and net force and moment (bottom row) in N (right axis) and for pitch in Ncm (left axis) with time(s) for the relaxation strategy.
A, B, C: Reference simulation for anterior slope angle (ASA) of 45°, opening immediately followed by closing. D, E, F: Relaxation strategy and an ASA of 45°. G,H,I: Relaxation strategy and an ASA of 50°.
Dashed lines: forces, positive in anterior direction. Solid lines: net pitch moment, positive in opening direction.

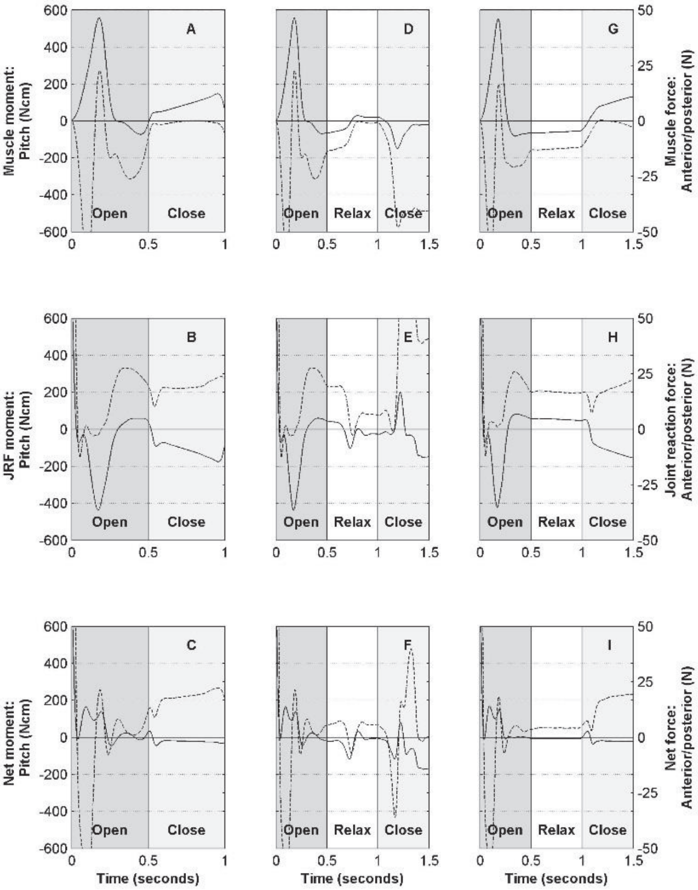


Figure 6. Influence of the laterotrusion strategy on the horizontal distance in the anterior/posterior direction (dAP in mm) between the centre of the mandibular condyle and the apex of the articular eminence with time (s). Positive in anterior direction. A: Reference simulation for anterior slope angle (ASA) of 45°, opening immediately followed by closing. B: Laterotrusion strategy and an ASA of 45°. C. Laterotrusion strategy and an ASA of 50°. Grey line indicates left condyle. Black line indicates right condyle.

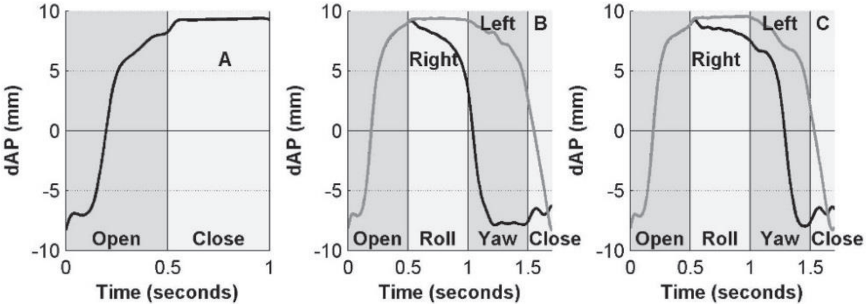


Figure 7. Influence of the laterotrusion strategy on muscle force and moment (top row), joint reaction force (JRF) and moment (middle row) and net force and moment (bottom row) in N (right axis) and for pitch in Ncm (left axis) with time(s) for the laterotrusion strategy.
A, B, C: Reference simulation for anterior slope angle (ASA) of 45°, opening immediately followed by closing. D, E, F: Laterotrusion strategy and an ASA of 45°. G,H,I: Laterotrusion strategy and an ASA of 50°.
Dashed lines: forces, positive in anterior direction. Solid lines: pitch moment, positive in opening direction.

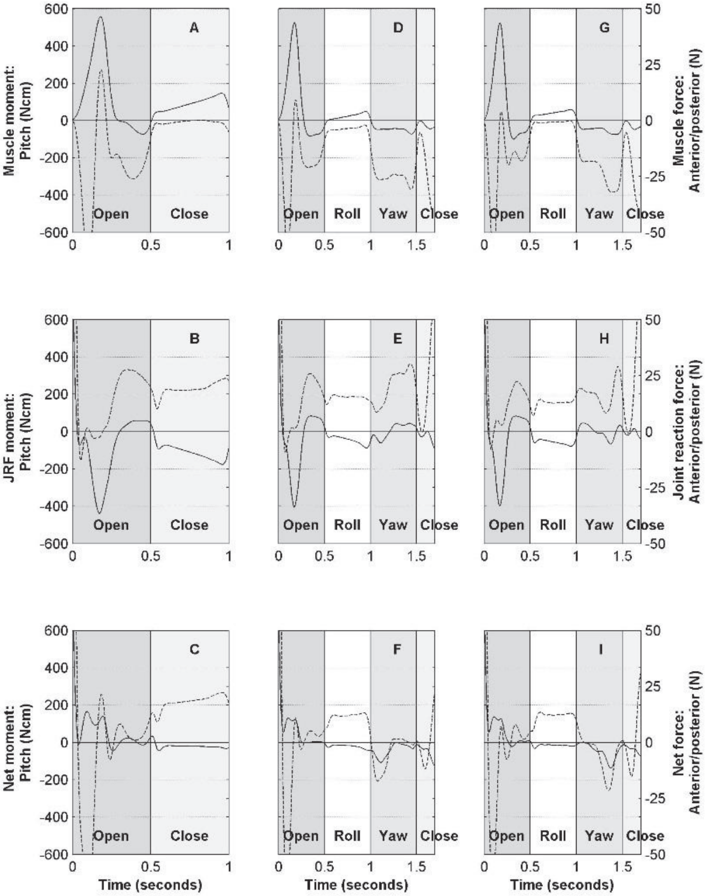
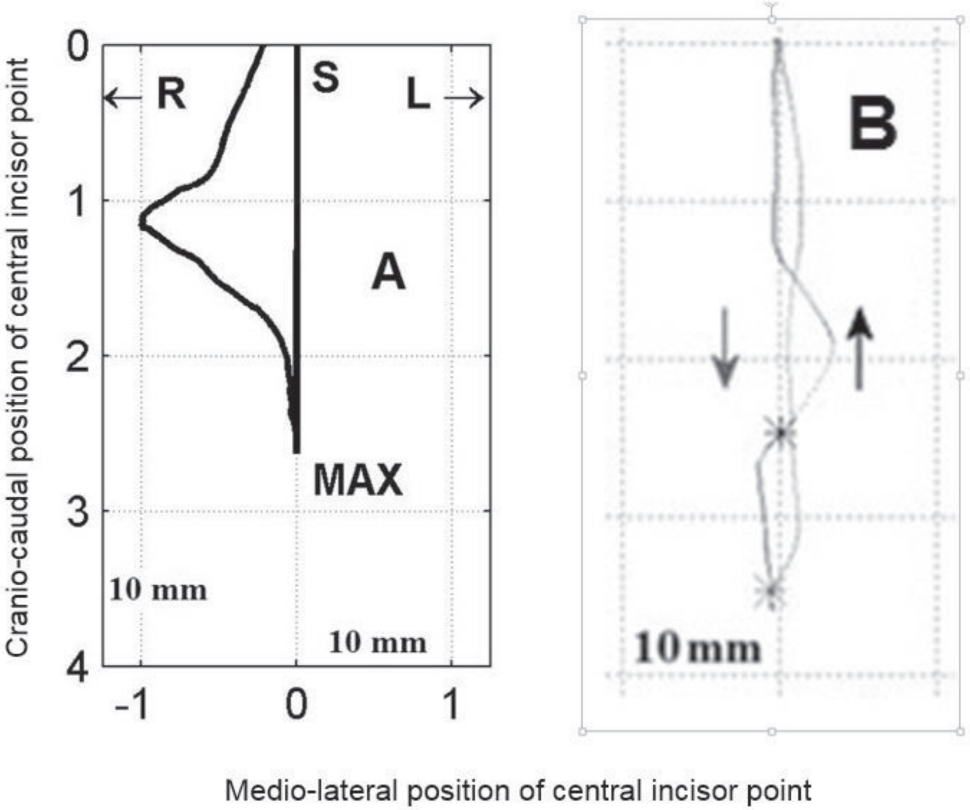


Figure 8. Laterotrusive movements of the interincisor point of the lower jaw in the frontal plane.

A. Predicted trace for the laterotrusion strategy. Distances in cm. S: start of simulation in occlusion. L: left. R: right. MAX: maximum opening.

B. Measured trace with motion capture system during an opening and closing movement of a symptomatic hypermobile patient (reprint with permission).



Chapter V

Human jaw-joint hypermobility: diagnosis and biomechanical modelling

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Abstract

Patients with hypermobility disorders of the jaw joint experience joint sounds and jerky movements of the mandibular condyle. In severe cases, a subluxation or luxation can occur. Clinically, hypermobility disorders should be differentiated from disc displacements. However, joint shape and muscle function are difficult to assess. With biomechanical modeling, we previously identified the anterior slope angle of the eminence and the orientation of the working lines of the jaw closers to potentially contribute to hypermobility disorders. Using cone-beam computed tomography (CBCT), we can construct patient-specific models of the masticatory system to incorporate these aspects. It is not known whether the clinical diagnosis of hypermobility disorders is associated with the prediction of hypermobility by a patient-specific biomechanical model. Fifteen patients and eleven controls, matched for gender and age, enrolled in the study. Clinical diagnosis (gold standard) was performed according to the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) and additional testing to differentiate hypermobility from disc displacements. Patient-specific biomechanical models were constructed based on CBCT. A forward simulation of maximum opening and subsequent closing movement of the lower jaw was performed. This predicted a hypermobility disorder, indicated by a luxation, or a control, indicated by normal closing. We found no association between the clinical gold standard and model predictions of hypermobility disorders. The biomechanical models overestimated the number of patients, yielding a low specificity. The role of the collagenous structures remains unclear; therefore, the articular disc and the ligaments should be modeled in greater detail. This also holds for the fanned shape of the temporalis muscle. However, for the osseous structures, we determined post hoc that the anterior slope angle of the articular eminence is steeper in patients than in controls.

Keywords: temporomandibular joint, hypermobility, luxation, clinical protocols, computer simulation, radiography, biomechanical phenomena, validity

Introduction

Hypermobility disorders of the human jaw joint can be subdivided into different levels of severity. The recently published and expanded DC/TMD (Peck et al., 2014; Schiffman et al., 2014) differentiates between subluxations and luxations. Patients with a subluxation are able to close their mouth themselves by relaxing the masticatory muscles. Alternatively, sideways movements or self-manipulations can aid to the return of the mandibular condyles to the glenoid fossae (de Leeuw, 2008; Tuijt et al., 2016). Clinically, symptomatic hypermobility of the jaw joint is used as a mild subdivision of subluxations. These patients often report clicking joint sounds and jerky movements of the lower jaw during wide opening and closing of the mouth (August et al., 2004; Huddleston Slater et al., 2004b; Kalaykova et al., 2006). Patients suffering from a luxation are not capable of reducing the luxation themselves. This is only possible by someone else, e.g., a relative or a clinician. When a clinician performs the procedure, this may be combined with a complete sedation of the patient (August et al. 2004). In clinic, luxations are also referred to as open locks (Shorey and Campbell, 2000b). For differential diagnosis in the DC/TMD, a history suffices to discriminate between subluxations and luxations, based on the ability of the patient to self-reduce the anteriorly displaced mandibular condyles.

In the clinical setting, clicks due to hypermobility can be distinguished from those due to anterior disc displacement by their timing during opening and closing. Clicks at the end of wide opening and at the beginning of closing suggest hypermobility, while clicks at any point during opening and at the end of closing suggest an anterior disc displacement (Huddleston Slater et al., 2004b; Huddleston Slater et al., 2007). In addition, if the clicks remain palpable or audible during protrusive open/close movements, (mild) subluxation is diagnosed. A luxation is only diagnosed when reproduced during the actual testing. As this additional testing can adequately differentiate between hypermobility disorders and disc displacements

(Huddleston Slater et al., 2004b; Marpaung et al., 2014), it is considered the gold standard.

We also approached the problem of hypermobility disorders biomechanically, by means of a model study (Tuijt et al., 2012). We identified two possible morphological aspects of the masticatory system that could contribute to luxations. First, for the angle of the anterior aspect of the articular eminence, the models predicted that steeper anterior slope angles were more likely to cause a luxation. Secondly, the models showed that a more forwardly inclined working line of the jaw closers could contribute to luxations. The addition of masticatory muscle forces and joint reaction forces resulted in a net anterior translation of the mandibular condyle, resulting in a luxation. These two factors showed an interaction, such that less steep slope angles could compensate for more anteriorly directed jaw closers and that steeper anterior slope angles could be compensated for by more posteriorly directed jaw closers. Subsequently, we showed that different activation schemes for the jaw closers were able to reduce a luxation compared with direct closing activation (Tuijt et al., 2016). Activation schemes of the jaw closers consisting of relaxation or inducing a lateral movement of the lower jaw could resolve a luxation, thus mimicking the clinical situation of subluxation.

From a translational viewpoint, it is not known whether the predictions from our biomechanical model correspond with the gold standard of the clinical diagnosis. To this end, the generic biomechanical model should be altered to meet the anterior slope angle and the working line of the jaw closers at an individual level. Cone-beam computed tomography (CBCT) can provide these three-dimensional data with suitable resolution for diagnostics and treatment planning (Oliveira et al., 2013; Parsa et al., 2013). The use of CBCT in the field of oral and maxillofacial imaging is currently widely accepted, due to advantages over computed tomography like lower cost and dose (Parsa et al., 2015). It has also been shown that CBCT has high diagnostic accuracy in assessment of osseous TMJ structures (Honey et al., 2007). In our aim to predict hypermobility disorders at an individual level, we use these CBCT scans that provide the morphological input to adjust the generic biomechanical model into a patient-specific biomechanical model. These predictions will be compared with the clinical diagnosis (gold standard). We hypothesized that the clinical diagnosis (gold standard) of hypermobility disorders is associated with the prediction of hypermobility disorders by patient-specific musculoskeletal models of the masticatory system.

Material and methods

Patients and controls

Patients were recruited through advertisement via the computer screens in the General Dentistry Department of the Academic Centre for Dentistry Amsterdam (ACTA), by an announcement of the protocol on ACTA's patient website, and from acquaintances, ACTA students, and colleagues. Two patients were referred by maxillo-facial surgeons from the Emergency Department of the Academic Medical Centre (AMC), Amsterdam.

We included patients between 18 and 65 years old with a report of hypermobility disorders of the jaw joint (subluxations (including symptomatic hypermobility), or luxations). Patients were excluded for serious general health impairments, complicated dental abnormalities, osteoarthritis of the jaw joint, or pregnancy. This exclusion was based on a short telephonic history, prior to enrollment in the study. We approached controls, matched for age and gender. Care was taken to limit differences between patient and control in terms of long face or short face physionomy. Power-analysis showed that a sample size of fifteen participants per group would be sufficient (Hoozemans et al., 2001). In total, fifteen patients and eleven matched controls enrolled in the study (eight males [four patients], eighteen females [eleven patients], mean±SD age = 33.5±11.0 years).

Ethics

The research protocol was designed according to the Helsinki declaration and was approved by the Medical Ethical Committee of the Vrije Universiteit medical center (VUmc), Amsterdam, protocol number NL18726.029.07. Upon entry in the clinic, participants received additional explanation of the protocol and an information sheet about the study. After reading this and agreeing to participate, participants signed an informed consent.

Data acquisition: clinical assessment

Upon entry in the Clinic of Orofacial Pain and Dysfunction of ACTA, a short history was taken, followed by a clinical examination by one of two trained and calibrated clinicians (MK, FL) who were blinded to the category of recruitment (patient, control). Clinical examination was performed according to the clinical tests described by Huddleston Slater et al. (2004a, 2007) and the expanded DC/TMD diagnostic rules described by Peck et al. (2014). The main diagnostic aim was to differentiate between hypermobility disorders, anterior disc displacement, and controls.

Data acquisition: radiology

CBCT scans were performed using NewTom 5G (QR Verona, Verona, Italy) at the Department of Oral Radiology of ACTA. The occlusal plane of each participant was set perpendicular to the floor. Scan settings were: 110 kVp, 38.25 (range 22.35 - 55.76) mAs (3.6 s exposure time), and field of view of 18x12 cm. All CBCT data sets were converted to Digital Imaging and Communication in Medicine (DICOM) format, with isotropic voxel size of 0.3 mm.

Data analysis: joint shape and muscle orientation

In the sagittal view of the DICOM-images, bilateral glenoid fossa and eminence shape were determined in the slice midway between the condylar poles (3Diagnosys 3.1, 3Diemme, Cantu, Italy). Based on manual, graphical input of the bony outline of the glenoid fossa and eminence, a spline definition was made to fit these structures (Curve Fitting Toolbox, MatLab, R2014b, The MathWorks Inc., Natick, MA, USA). The medio-lateral radius of the condyle was determined from half the distance between medial and lateral pole of the condyle. In an oblique slice, perpendicular to the medio-lateral radius, the inferior/superior radius and anterior/posterior radius of the condyle were also determined. (For details of the DICOM-images, the spline definition, and assessment of the radii of the condyle, please refer to the online supplemental material.)

The working lines of the left and right jaw closers (masseter, temporalis, and medial pterygoid muscle) were derived from the DICOM-images, based on assessment of their attachment sites. Origin and insertion of the jaw closers were determined according to Baron and Debussy (1979). The working line was subsequently defined with respect to the participant’s bite plane.

Data analysis: adapting biomechanical model to the participant

Our biomechanical model (Tuijt et al., 2010) was adapted to fit the musculoskeletal parameters of each participant (Figure 1). The working lines of the jaw closers of the model (which were originally based on a cadaver study (van Eijden et al., 1997) were adjusted to meet the muscle orientation from the CBCT-scan. To adequately describe the participant-specific joint morphology of the jaw joint, the spline shapes of the fossa/eminence were loaded into the model. Also, the radii of both mandibular condyles in the model were adapted to the participant’s dimensions.

Data analysis: simulations

From a closed mouth position, a forward dynamic simulation of a maximal mouth opening and closing movement was performed with MatLab (R2014b, The MathWorks Inc., Natick (MA), USA). Briefly, a forward simulation takes a pre-defined muscle activation pattern for the jaw openers and jaw closers. From the activation pattern, it calculates the produced muscle forces at each time step of the simulation. For each time step, the model also makes a prediction of joint reaction forces and ligament forces. These forces lead to the subsequent movement of the lower jaw in six degrees of freedom with respect to the skull. For in-depth modelling details, please refer to Tuijt et al. (2012). At the end of the simulation, the model predicted the mandibular condyle to either remain anterior of the articular eminence (hypermobility disorder), or return to the glenoid fossa (control).

Statistics

Various validity and predictive values for the diagnostic and the modelling approaches were calculated. First, recruitment based on self-report was compared with the gold standard diagnosis based on clinical examination. Subsequently, model predictions of hypermobility were cross-tabulated with, and tested against gold standard diagnosis of hypermobility disorders. We used a McNemar’s Chi-square test, with a significance level of 0.05 (Statistics Toolbox, MatLab, R2014b, The MathWorks Inc., Natick (MA), USA). This test was corrected for the relatively small sample size, with a mid-p calculation according to Fagerland, Lydersen, and Laake (2013).

Results

Comparison of recruitment with gold standard clinical diagnosis

From the participants, who were recruited as patients, eleven out of fifteen were diagnosed with hypermobility disorders according to the gold standard (Table 1). Also, one out of eleven controls was diagnosed as such. Therefore, the agreement was good as shown by a sensitivity of 0.73, a specificity of 0.91, and a kappa of 0.7. Overall, five participants were diagnosed differently from their recruitment. The differential diagnosis according to the clinical, gold standard was decisive, we therefore continued with twelve patients and fourteen controls.

Model predictions

For eighteen out of 28 participants, the predictions of our participant-specific biomechanical models resulted in a condyle position anterior of the eminence, either unilateral or bilateral, indicating a hypermobility disorder. Simulations of both conditions are reported in the supplemental material. For comparison, a simulation of a normal closing movement was added (Supplemental material Movie I: normal opening and closing; Movie II: unilateral luxation; Movie III: bilateral luxation).

Comparison of gold standard clinical diagnosis and model predictions

In nine out of the twelve patients, diagnosed according to the gold standard, both methods agreed. This yielded a good sensitivity of 0.75. From the fourteen gold standard controls, five also led to normal simulated closing, herewith the specificity was low (0.36). Out of the eighteen hypermobility predictions of the biomechanical model, nine were also diagnosed clinically, leading to a positive predictive value of 0.5. The negative predictive value amounted to 0.63 (five out of eight controls). Overall results coincided in fourteen out of 26 participants, thus the accuracy was 0.54.

Furthermore, the prevalence according to clinical diagnosis was 0.46 (twelve out of 26 participants). The test statistic χ^2 for the mid-p McNemar test amounted to 1.91, with a p-value of 0.83. Therefore, the observed agreement was considered accidental.

Discussion

The observed amount of agreement between clinical diagnosis of hypermobility disorders and participant-specific biomechanical prediction of hypermobility disorders was considered accidental. Our hypothesis, that there was an association between these two methods, was therefore rejected.

Diagnostics of hypermobility disorders: recruitment compared with gold standard

We showed a small difference between the patient’s enrollment based on history and the clinical gold standard. Four out of fifteen participants, recruited as patients, were not diagnosed as such. It appears to be very hard for patients to fundamentally understand questions about the position of the luxated jaw, or about closing problems. Misunderstandings can also occur between luxations and opening problems from a closed mouth position. We have minimized this problem by history taken by telephone, prior to enrollment. However, experienced closing problems of the lower jaw could also be attributed to anterior disc displacements (ADD). Two participants, who enrolled as patients, were clinically diagnosed with ADD, and thus further excluded from the patient category. The additional testing, that we performed, thus appeared to be necessary for accurately diagnosing a hypermobility disorder.

Participant-specific modelling of hypermobility: morphology of the musculoskeletal system

The predictions of the model overestimated the number of participants with a hypermobility disorder. This is indicated by the high number of false positives (eight participants), yielding a low sensitivity. We took great care to accurately describe the morphology of the patients and controls for the bony and muscular aspects of the masticatory system. Due to lack of discriminative power between patients and controls, it appears that not all parts of the adapted morphology differentiate between patients and controls. We tested this post-hoc with an independent students t-test (IBM, SPSS Statistics, Version 23) and found that only the anterior slope angle differed between patients and controls (right anterior slope angle: t=2,38, p=0.026; left anterior slope angle: t=1.5, p=0.14, which can be considered a strong trend due to the small number of participants). We found no difference in the direction of the working lines of the jaw closers. The variation was high for the anterior slope angles (SD 14˚) as well as for the working line for the jaw closers (masseter (SD 10˚), temporalis (SD 14˚), medial pterygoid (SD 15˚)). However, the difference in variation between groups was not significant for anterior slope angles, nor for the working line of the muscles (Levene's test p>0.05). The large variations suggest that there might be subsets of patients with hypermobility disorders with steeper anterior slope angles, who run a greater risk of having a luxation.

Temporalis muscle: passive and active forces

The role of the temporalis muscle in hypermobility disorders deserves attention. The fanned shape of the temporalis allows for a multitude of working lines at the coronoid process. It appears that the passive stretch of the posterior part just above the ear is a strong contributor to the posterior force to limit anterior translation of the jaw and condyle. However, in our current model, this large variation in working lines has been simplified to two muscle slips. A more elaborate description of the temporalis (Desailly et al., 2010) could provide further insight in its role in luxations of the jaw. Also, activation patterns of the various temporalis parts are not known. Earlier activation of the posterior part of the temporalis could limit further anterior translation of the condyle along the anterior slope. It has been shown that the activation pattern of the temporalis can change according to task speed. Blanksma and Van Eijden (1995) showed that the temporalis muscle shifts from the last muscle to be activated during self-selected speed of opening and closing to the first muscle during fast opening and closing, from and to the intercuspal occlusal position. This nearly 200ms earlier activation could also be beneficial during fast opening in patients suffering from subluxations or luxations. However, it is not known how well this closing speed can be controlled by patients, thus making its possible role in the management of luxations questionable.

Model limitations and assumptions: posterior capsule

After assembling the participant's data sets, all preliminary test simulations ended in a condyle anterior of the articular eminence. The mandibular condyle slipped off the anterior slope at its most anterior aspect. In the previous version of our model, we already incorporated a lateral ligament, as this is the strongest part of the capsule. However, at maximum opening, this ligament did not become stretched during the simulations and did not limit anterior translation. This anterior translation of the condyle could be stopped by the posterior part of the capsule. In the previous version of the model, this was neglected, although it becomes taut at maximum opening. Therefore, we added the posterior part of the capsule to limit the anterior translation to one centimeter anterior of the apex of the articular eminence. The mandibular and cranial attachment sites were chosen based on the anatomical descriptions of the condylar neck just below the condyle and inferior of the external hearing canal.

Model limitations: articular disc/compression forces

The current version of our model contains a precise description of the bony contour of the fossa/eminence complex. The joint reaction forces are estimated by a penalty-type contact criterion, based on the amount of penetration of the mandibular condyle into this complex. This represents the deformation of the disc and superior articular cartilage layer during loading. The assumption of a homogenous layer of cartilage has the smallest influence of model predictions at maximum mouth opening, as the thinnest part of the disc, the intermediate zone, is compressed at the anterior position of the condyle at maximum opening. However, the disc can also have a displaced position. In the clinic, it is very important to assess whether the disc is anteriorly displaced and, if this is the case, whether the posterior band of the disc reduces at maximum mouth opening. As stated, the current version of the model does not contain a description of the shape of the disc, and therefore the influence of disc displacements cannot be investigated. In future studies, the addition of a finite element model of the disc would result in a hybrid rigid body-finite element model (Koolstra and van Eijden 2005). This could provide further insight in the role of the disc in anterior disc displacements and hypermobility disorders.

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Figure 1. Graphical representation of the biomechanical model of the human masticatory system. Right anterior view. Arrows indicate forces (right side only). Anterior slope angle of the articular eminence (ASA). Working line of the jaw closers. More forward inclination (+15) depicted only for anterior aspect of temporalis muscle (TA). TP: posterior temporalis, MP: medial pterygoid, MA: masseter (three parts). JRF: joint reaction force. C: mandibular condyle. E: articular eminence.

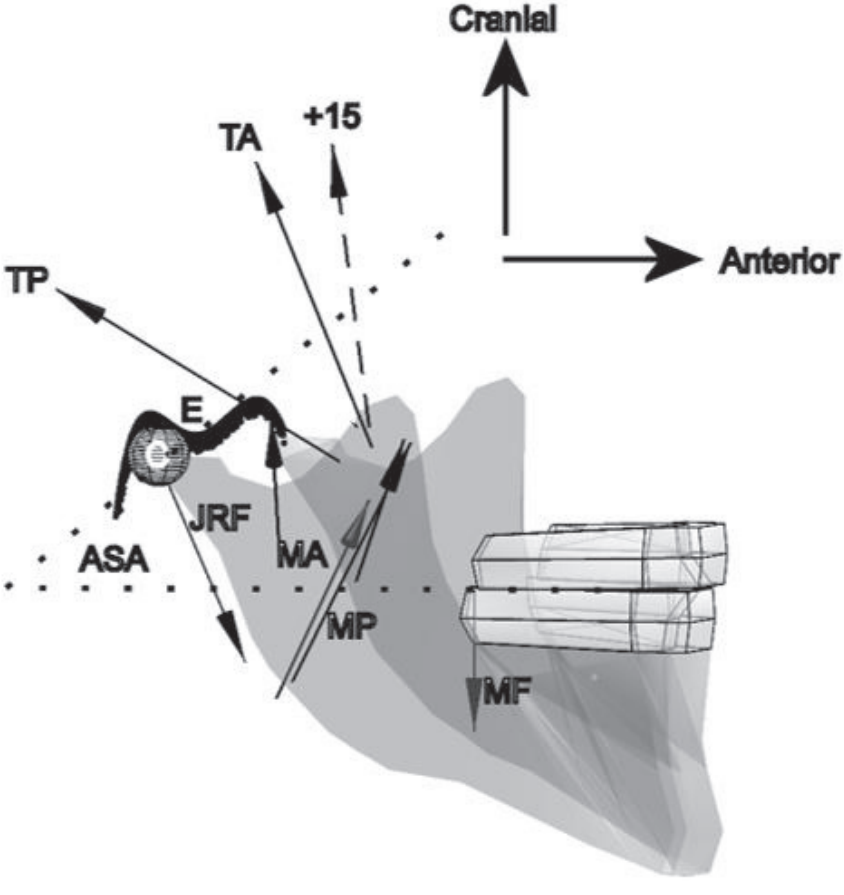

Figure 2. Sagittal mid condylar slice. E: articular eminence. C: mandibular condyle. MA: meatus acousticus. The hourglasses indicate the manual, graphical input points across the bony outline of the glenoid fossa and articular eminence. The solid black line represents the spline definition fitting the bony outline of these bony structures.

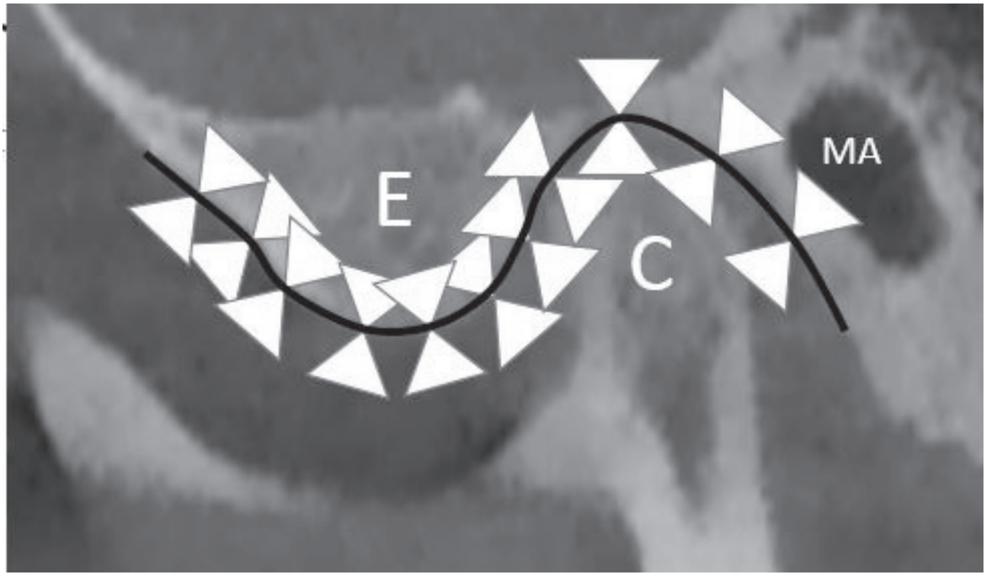

Figure 3. Three radii describing the mandibular condyle.
A. Distance between medial and lateral pole of the mandibular condyle. The radius amounts to half of this medio-lateral distance.
B. Inferior-superior radius of the mandibular condyle. Dotted line runs through the anterior most point of the condyle.
C. Anterior-posterior radius of the mandibular condyle. Dotted line runs through the superior most point of the condyle.

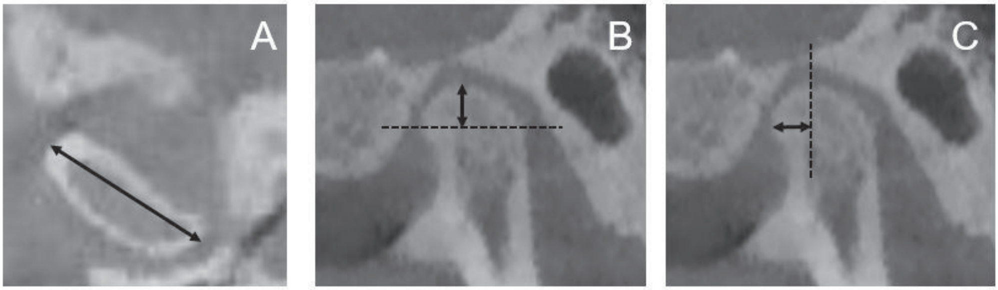

Table 1. Crosstab of recruitment of hypermobility disorders versus gold standard diagnosis of hypermobility disorders.

		Recruitment: Hypermobility disorders		
		+	**-**	**Total**
Diagnosis: Hypermobility disorders	**+**	**11**	**1**	**12**
	-	**4**	**10**	**14**
	Total	**15**	**11**	**26**

Table 2. Crosstab of gold standard diagnosis of hypermobility disorders versus simulation results of hypermobility disorders.

		Diagnosis: Hypermobility disorders		
		+	-	Total
Simulation results: Hypermobility disorders	+	9	9	18
	-	3	5	8
	Total	12	14	26

Supplemental material:

Movie I: Graphical representation of the movement of the lower jaw during a simulation of a normal maximum opening and closing of the jaw.
Left pane: sagittal view from right. Right top pane: transverse view in caudal direction. Bottom right pane: frontal view.
Green point cloud: left fossa. Green sphere: left condyle. Red point cloud: right fossa. Red sphere: right condyle. Blue asterisks: origins of jaw closers on cranium, and origins of jaw openers on hyoid. Red asterisks: insertions of jaw openers and closers on lower jaw. Light blue lines: working line of jaw openers and jaw closers. When muscles are active, muscle forces are indicated by yellow, scaled to maximum muscle force. Yellow asterisks: attachments of ligaments. Dark yellow lines: line of ligaments. Red arrows: joint reaction forces.

Movie II: Graphical representation of the movement of the lower jaw during a simulation of a maximum opening and closing attempt of the jaw, resulting in a unilateral luxation.
Left pane: sagittal view from right. Top right pane: transverse view in caudal direction. Bottom right pane: frontal view.
Green point cloud: left fossa. Green sphere: left condyle. Red point cloud: right fossa. Red sphere: right condyle. Blue asterisks: origins of jaw closers on cranium, and origins of jaw openers on hyoid. Red asterisks: insertions of jaw openers and closers on lower jaw. Light blue lines: working line of jaw openers and jaw closers. When muscles are active, muscle forces are indicated by yellow, scaled to maximum muscle force. Yellow asterisks: attachments of ligaments. Dark yellow lines: line of ligaments. Red arrows: joint reaction forces.

Movie III: Graphical representation of the movement of the lower jaw during a simulation of a maximum opening and closing attempt of the jaw, resulting in a bilateral luxation.
Left pane: sagittal view from right. Top right pane: transverse view in caudal direction. Bottom right pane: frontal view.
Green point cloud: left fossa. Green sphere: left condyle. Red point cloud: right fossa. Red sphere: right condyle. Blue asterisks: origins of jaw closers on cranium, and origins of jaw openers on hyoid. Red asterisks: insertions of jaw openers and closers on lower jaw. Light blue lines: working line of jaw openers and jaw closers. When muscles are active, muscle forces are indicated by yellow, scaled to maximum muscle force. Yellow asterisks: attachments of ligaments. Dark yellow lines: line of ligaments. Red arrows: joint reaction forces.

Chapter VI

General discussion

General Discussion

A theoretical perspective on open locks of the temporomandibular joint

On a cigar box, the problem of an open lock of the temporomandibular joint could be drawn (Figure 1). As the opening and closing movements of the lower jaw are combined translatory and rotatory movements, both forces and moments acting on the jaw could play a role in the failure to close the mouth after wide opening. A distorted balance of forces and/or moments should exist to explain the end position during an open lock. When focussing on the forces in the sagittal plane, the direction of the net force of bony, muscular, and ligamentous structures has to be ventrally oriented. This would obstruct the posterior travel of the mandibular condyle.

Several structures, that could contribute to an open lock have been discussed in the literature. For instance, the ligaments were suggested to guide the movements of the lower jaw during opening, closing, and mastication (Osborn, 1995). Also, the anterior band of the joint disc has been suggested to obstruct the closing path of the mandibular condyle (Westesson 1983; Kai et al., 1992; Nitzan 2002). In a normal synovial joint, the friction in joint compartments is very low (Tanaka et al., 2004). If the anterior band were to prevent the posterior translation of the mandibular condyle, this could only be explained in the presence of highly increased friction in the upper and/or lower joint compartment. In that case, the large anterior translation would already be restricted. With respect to overly loose ligaments, the risk factor of generalized joint hypermobility was identified for open locks (de Coster, 2005).

The jaw muscles have also been designated to play a role in open locks. In her thesis (2010), Kalaykova suggested that an unfavorable pulling direction of the jaw closers exists in patient with open locks. Furthermore, she pointed out that muscle control could have disadvantageous effects upon condylar movement around the eminence and proposed to model jaw motions in order to identify these activation patterns.

The joint reaction forces, acting between the mandibular condyle and the glenoid fossa/articular eminence complex, play a key role as well. In figure 1, the vector of the joint reaction forces travels closely to the centre of mass of the lower jaw. The direction of this vector is determined by the bony outline of the fossa and eminence, and small translations of the condyle in the anterior-posterior direction are likely to have a big effect of the moment arm of the joint reaction forces. As joint reaction forces in the human temporomandibular joint are currently not measurable, a computational modelling approach to the problem of open locks is justifiable. This could also provide further insight in the complex interactions of ligaments, joint shape, the orientation of the jaw muscles, and the control of these muscles.

A biomechanical perspective on open locks of the temporomandibular joint

We set out to increase the understanding of the biomechanics behind open locks of the temporomandibular joint. With a biomechanical model of the masticatory system, incorporating joint shape and adjustable muscle lines of actions, the complex interactions of muscle and joint forces can be unraveled. This is the first attempt at modelling the maximum opening movements of the lower jaw, reaching full activation of the jaw openers. More importantly, the subsequent closing movement, which is the problematic movement for patients suffering from open locks, was modelled. The biomechanical model provides estimations of the net effect of the acting ligament forces, muscle forces, and joint reaction forces on the occurrence of open locks.

In normal opening and closing, we showed that the joint reaction forces are larger during opening than during closing of the jaw (Chapter 2). The condyle translated anteriorly for one centimeter, just below the articular eminence, when the jaw openers were activated up to 50% of their maximum. By increasing the activation level up to the maximum, the condyle reached a postion 5 mm anterior of the eminence (Chapter 3). For anterior slope angles (ASA’s) up to 40°, the condyle returned to the glenoid fossa. Steeper ASA’s resulted in an open lock position. For these steeper ASA’s, the decomposition of the joint reaction forces showed that an anterior component was present, which was not counteracted by a posterior component of the muscle forces. This is due to the anterior orientation of the line of action of the masseter muscle and the medial pterygoid muscle. Only the temporalis muscle, especially the posterior aspect, provided posteriorly oriented forces. This contradicts some textbook descriptions, in which contraction of the temporalis is primarily identified as responsible for open locks (e.g. Baart and van der Waal, 2009). The effect of the anterior orientation of the line of action of the masseter can also be illustrated from the fact that diurnal clenching is found to be a risk factor for intermittent (closed) locking (Kalaykova et al., 2011). Higher rest tension in the masseter muscle might result in higher forces produced during closing of the jaw. A higher force of the masseter will add to a larger anterior component of the net force, and thus to open locks. By identifying the steeper anterior slope angles of the articular eminence as potential bony structure to play a role in open locks, we also addressed our first aim to increase the understanding of the interplay of morphological aspects, such as joint shape and muscle orientation, in open locks of the human temporomandibular joint.

Large translations of the mandibular condyle during maximum opening and closing movements have to be considered as normal. Condylar positions anterior of the articular eminence were seen on X-ray and MRI in healthy populations (Wooten 1966; Kalaykova et al., 2010). In Chapter 3, the simulations predicted similar translations of the condyle anterior of the eminence. This illustrates that the joint capsule allows this anterior translation. Ultimately, the ligaments could only limit the endmost anterior translation of the mandibular condyle. However, incorporation of the lateral ligament in Chapter 3, which is the strongest component of the joint capsule, did not lead to force production of this ligament in symmetrical maximal opening. Herewith, it seems unnecessary to take the lateral ligament into account when addressing open locks

In Chapter 5, the posterior aspect of the joint capsule was incorporated into the biomechanical model, because our biomechanical model has no predefined spatial constraints and all subject-specific models of the anterior slope angle resulted in an open lock. With the incorporation of the posterior aspect of the capsule, the locking of all subject specific simulations was solved, which seems to underline the importance of this part of the capsule. The morphological parameters of this part of the capsule were scaled down from the thicker lateral ligament, and the attachment site were estimated from anatomical description. Currently, this pragmatic approach seems the best option as patient specific data of stiffness parameters cannot be derived from imaging.

We also studied the potential role of the muscle components of the masticatory system in open locks. Following the suggestion of Kalaykova (2010) of potentially unfavorable pulling directions of the jaw closers, we predicted in Chapter 3 that the anteriorly oriented lines of action of the jaw closers could indeed predispose for open locks. In her thesis, Kalaykova (2010) also suggested that modelling jaw motion could be helpful to identify jaw-muscle activation patterns that have disadvantageous effects upon condylar movement around the eminence. We used simplified activation patterns of normal opening and closing of the jaw (Møller, 1966). An increase of the maximum activation of jaw openers to 100% was already sufficient for the model to predict an open lock. Different activation patterns were therefore not further investigated.

We took the idea of muscle control one step further, and used it to simulate whether an open lock could be resolved. With postponing the activation of the jaw closers subsequent to maximum opening, we showed that such a relaxation strategy could solve an open lock (Chapter 4), given that the anterior slope angle was not too steep. Also, actively making a laterotrusion movement with the lower jaw could alleviate the open lock for slightly steeper ASA's (Chapter 4). These findings corroborate commonly given advise in the clinic to self-reduce the condyles when an open lock occurs.

While we identified possible control strategies to solve open locks, we ignored the potential role of coordination with adjacent joints. The jaw moves simultaneously with the neck and hyoid. For instance, the cervical spine extends 15° during maximal mouth opening (Muto and Kanazawa, 1994; Kohno et al., 2001) while the hyoid translates caudally and dorsally for 4-5 mm (Pancherz et al., 1986). Both would have the effect of reducing the shortening of the jaw openers during maximum opening. Herewith, they keep the digastric muscle from becoming actively insufficient and opening would be further faciliated. By abstracting from both movements, we made conservative estimations of open locks.

As illustrated, a net anterior force exists during an open lock, therefore the primary problem of open locks is of translatory nature. However, the rotations of the lower jaw also deserve some attention. The end position of our simulations that ended with an open lock position (Chapter 3) shows an intra-incisal distance of three centimeters in a protruded position. This corresponds highly with the position of patients with open locks, as seen in the clinic for repositioning of their lower jaw. This could be interpreted as an ecological validation of the model, based on clinical observation. Furthermore, the modeled rotations of the lower jaw during laterotrusion (Chapter 4) show large resemblance with the movements patients seek actively to reposition the condyles into their fossa, be it actively or manually. The roll and yaw degrees of freedom of the lower jaw can be exploited to circumvent the disadventageous balance of forces in the sagittal plane. With a one-by-one retrieval of the mandibular condyles, the open lock can be resolved, because the joint reaction forces of the ipsilateral condyle are lower than the joint reaction forces on the contralateral condyle during the laterotrusion movement (Chapter 4).

Finally, the effect of the joint reaction forces during closing of the mouth deserves some attention. The net closing movement is provided by a net closing moment of joint reaction forces and jaw muscles. The jaw muscles are traditionally divided into openers and closers, which is inaccurate when regarding the moments they provide. Due to the anterior orientation of their lines of action, the masseter muscle and medial pterygoid provide an opening moment. Only the posterior temporalis provides a closing moment. The net closing moment is only achieved by the joint reaction force combined with its rather long moment arm, comprised of the mandibular neck to the centre of mass of the lower jaw. One could conclude that the joint reaction force is the strongest closer of the lower jaw.

A patient-specific biomechanical perspective on open locks of the temporomandibular joint

The final aim of this thesis was to improve the level of detail of the biomechanical model, to allow for tailor-made models at a patient level. This would make risk assessment for open locks possible at a subject level. The use of conebeam computed tomography provided fast and high resolution images of the bony outlines of the masticatory system of patients and controls (Chapter 5). This was done at relatively low radiation doses. Based on these scans, origins and insertions of temporalis, masseter, and medial pterygoid were incorporated into our biomechanical model. Furthermore, the bony contours of the condyle, and fossa/eminence complex were used in the model. Compared with gold standard, clinical diagnosis, the model overestimated the number of patients, predicting open locks for some of the control subjects (Chapter 5). This asks for further improvement of the model. The description of the fan-shape of the temporalis might improve predictions. Also, large unknowns exist about the shape, length, and plasticity of the joint capsule, which is the only ligamentous structure that could limit anterior translation of the mandibular condyle. However, retrieval of in vivo data of these structures is extremely hard, if not impossible.

In the process of model validation and verification, we predicted that steeper anterior slope angles of the articular eminence predisposed for open locks. This was corroborated *in vivo* in the patient study of Chapter 5. Also, in mid-condylar radiographs (Kai et al., 1992), the same typical steep anterior slope angle, that we found in patients with a history of open locks, can be seen (Chapter 5).

In Chapter 3, we predicted that the anteriorly oriented line of action of the jaw closers could predispose for open locks, as suggested by Kalaykova (2010). However, in the clinical study (Chapter 5), we did not find a difference between patients and controls in pulling direction of the masseter, medial pterygoid, or temporalis muscle.

One issue that warrants further discussion is the fact that we found a substantial difference in lines of action between the generic version of our model and the patient datasets. The scanning position is most probably not of influence. The data set of van Eijden et al. (1997) used eight cadavers in a supine lying position. The

CBCT-scans of all participants was also performed in a supine position with the Frankfurter plane directed vertically. However, the difference in age on one side, and embalmed specimens vs. alive patients on the other, may play a role. Lastly, there could have been differences in the protocols to determine the direction of pull relative to the Frankfurter horizontal or the bite plane. Especially, for the temporalis the lines of action are hard to assess, due to the fan shape of this muscle along the outside perimeter of the skull. We will address the temporalis muscle further in the last paragraph on future research directions.

Clinical perspectives on open locks of the temporomandibular joint

In the previous paragraphs, we have seen that various parts of the masticatory system play a role in the occurrence of open locks. First, the morphology of the joint and ligaments determines whether an open lock can occur. Secondly, the patients' control of the jaw muscles could resolve an open lock. Finally, the coordination of jaw movement relatively timed to cervical movement and hyoid movement could aggravate the occurrence of an open lock. As all these factors play a role, the classical distinction between articular and non-articular disorders (de Bont et al., 1997) does not justify the complexity of an open lock, as it relates to both categories. Also, the biomedical focus on merely bodily aspects is becoming increasingly outdated since Engel introduced the biopsychosocial model of disease (1977). To get a full picture of a patient suffering from open locks, we will discuss a case and relate this case to different diagnostic models. Also, interventions for open locks are discussed.

A case of open lock

In the text box below, a case is described. This text was translated from our previous publication in the Dutch professional dental journal Dental Quality Practice (Visscher et al., 2012). It elaborates on the clinical manifestation, diagnosis, and referral.

Miss X. (29 years old) was referred to a dentist specialized in TMD and Orofacial Pain of the department of Oral Kinesiology of the Academic Centre of Dentistry Amsterdam (ACTA). Since puberty, she has had complaints of jerky movements of the lower jaw, especially during the closing movement of the mouth. Lately, she has been suffering from a locking of the closing movement. This happens mostly after wide opening such as yawning, laughing out loud, or during dental treatment. The first time that she was unable to close her mouth is now four years ago. Her lower jaw was then repositioned at the ER of a hospital. Since then, the problem has recurred several times and most of the time she was unable to reposition her jaw herself. During an open lock, she suffers from pain pre-auriculary, which subsides quickly upon repositioning. Last month, she presented again at the ER and was referred to ACTA for further conservative treatment.

Based on a diagnostic questionnaire, she is in good general health, she has no parafunctions, nor is she anxious or depressed. She has developed fear of movement, as indicated by a high score on the Tampa Scale for Kinesiophobia for TMD (TSK-TMD,Visscher et al, 2010). This is also confirmed in the physical examination, where she fears opening widely. Upon encouragement, she displays an active mouth opening of 52 millimetres with 3 mm vertical overbite. Based on the history of open locks and the kinesiophobia, the dentist refrains from a further passive mouth opening. During closing of the mouth, bilateral snapping sounds are audible with auscultation. Palpation of the masseter muscles reveals a tenderness bilaterally Normally this is not a complaint for

Clinical framework: DC-TMD

For temporomandibular disorders (TMD), a framework has been developed in the nineties of the previous century (Dworkin and LeResche, 1992). These Research Diagnostic Criteria for Temporomandibular Disorders (RDC-TMD) are internationally used and translated into various languages. A distinction is made into the physical and psychological aspects of TMD. Focusing on the physical part or AXIS I, the diagnostic algorithms within the RDC-TMD allow for discriminating myofascial pain, various types of disc placements, arthralgia, osteoarthrosis, and osteoarthritis. However, the diagnostic algorithms did not include criteria for open locks of the TMJ. Consequently, miss X. could not be diagnosed with this system.

In 2014, an adaptation of the RDC was made and is now presented as DC-TMD (Schiffman et al., 2014). With these new DC-TMD, open locks were incorporated in the diagnostic schemes for joint disorders. The oral history of the patient determines the difference between subluxation and luxation, with the discriminating factor being whether the patient indicates whether he/she could reposition the lower jaw him /herself (subluxation) or he/she needed medical treatment for repositioning (luxation). According to the DC-TMD, miss B. was diagnosed with luxation of the temporomandibular joint.

In Chapter 3 and 4, we showed that there is a possibility that joint shape and muscle orientation could both contribute to the occurrence and resolving of open locks. The division of open locks amongst the joint disorders therefore represents a limited view of the clinical problem. The classical dichotomous division into arthogeneous and myogenous TMD, which can often be seen in clinical textbooks (e.g. Baart and van der Waal, 2009), is also an oversimplification. As such we need a broader view to incorporate all experienced problems of a patient. This is also the case for the psychological part or AXIS II assessing the personal factors with an influence on TMD.

With a focus on the personal factors only, however, the environment of the patient is not taken into account. In conclusion, to better understand the whole situation of a patient a broader view is needed. To this end, the model of the International Classification of Functioning, Disability and Health (ICF, 2001) will be introduced in the next section.

Clinical framework: ICF and RPS of open lock

The ICF is an extension of biopsychosocial model (Engel, 1977). The ICF was endorsed by the World Health Organization in 2001. Below a schematic drawing (Figure 2) is depicted of the International Classification of Functioning, Disability and Health (World Health Organization, 2001). At the top, the health condition is stated. . The model describes a patient at three different levels: function, activity, and participation and also takes personal and environmental factors into account. The first level is the function of all body parts (e.g. coordination) and their structure (e.g. joint shape, ligament length, muscle strength). The second level is that of activities the patients has to perform in daily living, such as speaking, eating, drinking, and caring for teeth. The third and highest level is the participation in daily life, which encompasses the roles the patient plays in life, such as relationships, care for relatives, sport and leisure, and work. Furthermore, the influence of the environment (e.g. support by relatives, or at work) on the health condition is taken into consideration, as well personal factors, such as stress or kinesiofobia.

The case of miss X. can be described within the ICF-framework. For this, her case was summarized by means of the Rehabilitation Problem Solving-form (RPS) (Figure X). The RPS was introduced by (Steiner et al., 2002), who based this form on the ICF, but also included the role of the health care professional. In this manner, the patient reported problems from the history (upper panels) and results from the physical examination (lower panels) can be integrated. Plausible and causative relations between results from the physical examination and the chief complaint are then drawn in the form.

In the RPS-form, the problems at participation level can be well understood (Figure 3). Arrow A and B give a plausible explanation for the complaints indicated in Circle 2. However a clear, causative explanation of the problems at the activity level in Circle 1 cannot be given based on history, nor on a diagnosis at the level of body structures and functions. In Chapter 3, we identified two possible factors, at the level of body structures, that could contribute to open locks. First, the anterior slope angle of the articular eminence might play a role based on biomechanical modelling of opening and closing movements of the lower jaw. Secondly, the direction in which the jaw closers pull, contributed to the susceptibility for an open lock. In Figure 4, these two factors were added to the RPS of Miss X. However, these predictions were based on biomechanical simulations of an average muscle morphology. Therefore, we investigated these predictions in Chapter 5 with subject-specific biomechanical models. In patients with open locks or suffering from symptomatic hypermobility (a milder problem occurring during the closing movement of the jaw, e.g. clicks or sideways movements during closing), we found indeed that the anterior slope angle is steeper than in age- and gender matched controls. On the other hand, we found no difference in the orientation of jaw closers between patients and controls. These results are incorporated into Figure 4. We now have identified one causative factor for open locks of the human temporomandibular joint. This new knowledge can be used for counseling of Miss X, and potentially be used in therapy.

Diagnostics and intervention of open locks

Surgical interventions are only used for open locks, when they become habitual and conservative treatment has failed. According to the treatment triangle (Shorey and Campbell, 2000), ligament, muscles, or bones are targeted during surgery. Examples of such interventions are plication of the lateral joint capsule, botox, temporalis tendon shortening, and down-fracturing according to Dautrey. Currently, eminectomy is most often performed for treating habitual open locks. To the best of our knowledge no randomized controlled clinical trials have been performed on treatment of open locks of the jaw joint. In their recent review of 2016, de Almeide et al. found a number of observational studies, either prospective or retrospective, with small sample sizes. They stated that based on clinical experience eminectomy is considered the last resort, but that this intervention is also very effective given the fact that up to three years post operatively no recurrences were reported. Eminectomy effectively results in a less protruding articular eminence by which both the posterior and anterior slope of the eminence decrease markedly. In Chapters 3 and 5, we showed that larger anterior slope angles could result in open locks. For smaller slope angles, open locks did not occur and therefore this can be interpreted to underpin the working principle of eminectomy. In the clinic of maxillo-facial surgery or dentistry, it could thus be worthwhile to assess the anterior slope angle of the articular eminence. As the articular eminence is the targeted structure for eminectomy, pre-surgical assessment of the anterior slope angle could be used to predict treatment outcome. It would also be possible to incorporate the desired shape of the eminence in the current model, and predict whether the eminectomy could be successful. When assessing the ASA, scanning procedures would have to be developed and diagnostic tests would have to be performed to asses inter- and intra- rater reliability for determining this angle.

Conservative treatment of open lock typically consists of counselling and physical therapy. Based on Chapter 3, the advice of relaxation of the jaw muscles is corroborated. The laterotrusion movement modelled in the same chapter serves as ground for the advice to make lateral movements to resolve the open locks, either actively or passively by manipulation. Patients should always be taught to limit neck extension during mouth opening. Yawning and laughing out loud should be performed with the chin close to the chest. Instructions should also be given to cut large foods like

Future research: model improvements

In a future version of the model presented in this thesis, it could be an improvement to add the anterior part of the capsule. As this anterior part becomes stretched around the condyle itself, it provides a posteriorly directed force. However, the attachment sites of this capsule are not well described and may vary at their cranial attachment between patients and controls. Also, its rest length and elasticity will ultimately determine the maximum anterior translation. These data are currently impossible to assess within a patient population.

The anterior band of the joint disc has been suggested to obstruct the closing path of the mandibular condyle (Kai et al., 1992). Currently, our biomechanical model (Chapter 2) does not incorporate a disc shape. Therefore, the mechanism of the anterior band preventing this posterior translation cannot be investigated. With an eloborate description of the disc, and it’s friction with the cranial bones we would be able to address the role of the disc in open locks.

As a final model improvement, the temporalis muscle should be described in more detail, while the model currently has two lines of action. Tractography in diffusion tensor imaging (DTI) is a very promising field, that could provide such an accurate description (Froeling, 2011; Figure 5). Especially, the posterior fibers above the ear, which become stretched at maximum mouth opening, could be incorporated in greater detail.

Future research: patient studies

Whether disadvantageous activation patterns of the jaw muscles occur in patients with open locks, needs further investigation. Multi-channel electromyography is currently available with sensor grids up to 128 electrodes (Staudenmann et al., 2005). Its use would be most interesting for the temporalis muscle, but will be acceptable in bald patients only. A combination of the sensor grid with a detailed description of the temporalis muscle based on DTI could be a meaningful contribution to investigation in its role in open locks. The timing of the temporalis muscle has been shown to change with closing speed (Blanksma et al., 1995). Potentially, delayed activation of the (posterior) temporalis in wide jaw opening could play a role in open locks of the temporomandibular joint. Whether this occurs in patients, could be further investigated.

Conclusions

In Chapter 5, we showed that patients, who experienced open locks, have steeper anterior slope angles than healthy, age-matched, and gender-matched controls. Radiologic assessment of this anterior slope angle might be meaningful in the diagnostic process in the clinic of maxillo-facial surgery or dentistry. Studies into inter-rater reliability would have to be performed, before such an implementation.

The commonly given advise to relax the jaw muscles was corroborated in Chapter 3. Moreover, model predictions showed that the laterotrusion movement was superior to relaxation, as it was capable of resolving open locks for steeper anterior slope angles.

The fan-shape of the temporalis muscle is a key factor in providing posteriorly oriented forces to retrieve the mandibular condyle into the glenoid fossa. The timing of the temporalis in patients should be further investigated as well the level of detail with which this model is described in our computational model.

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Figure 1. Free body diagram lower jaw. Interplay of net muscle force and joint reaction force. The crosshairs indicate the centre of mass of the lower jaw.

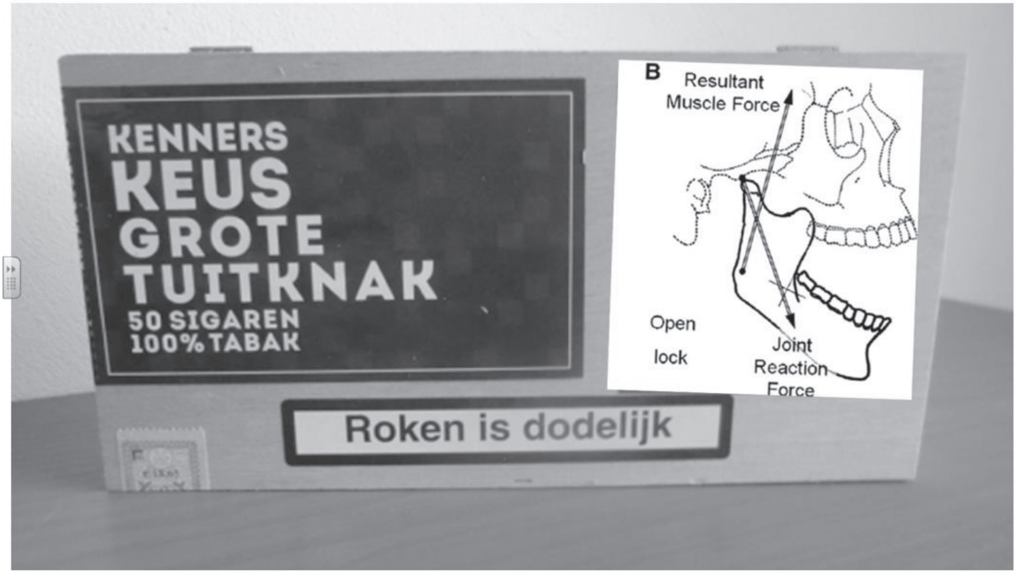


Figure 2. International Classification of Function, ICF (WHO 2002).

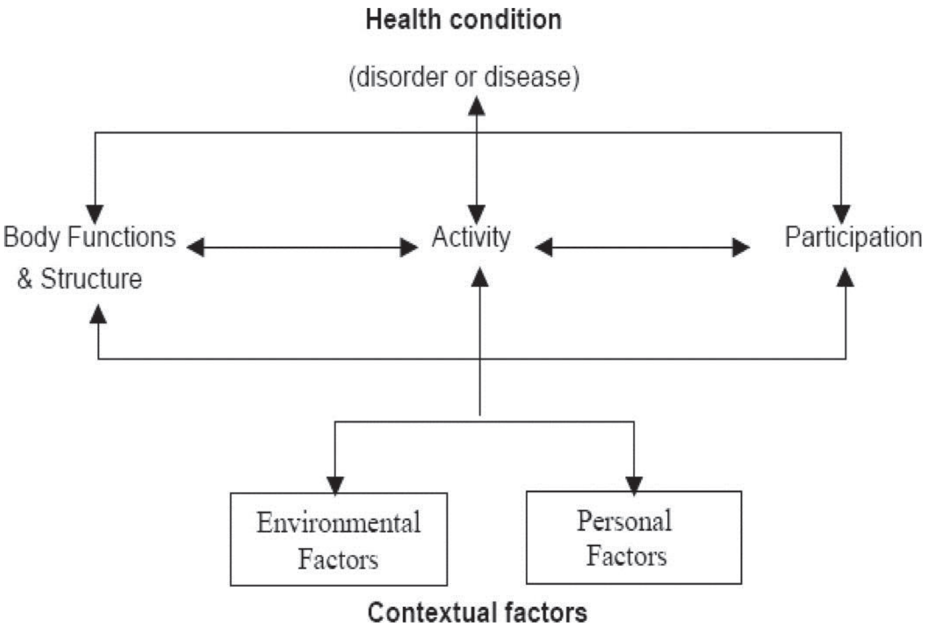
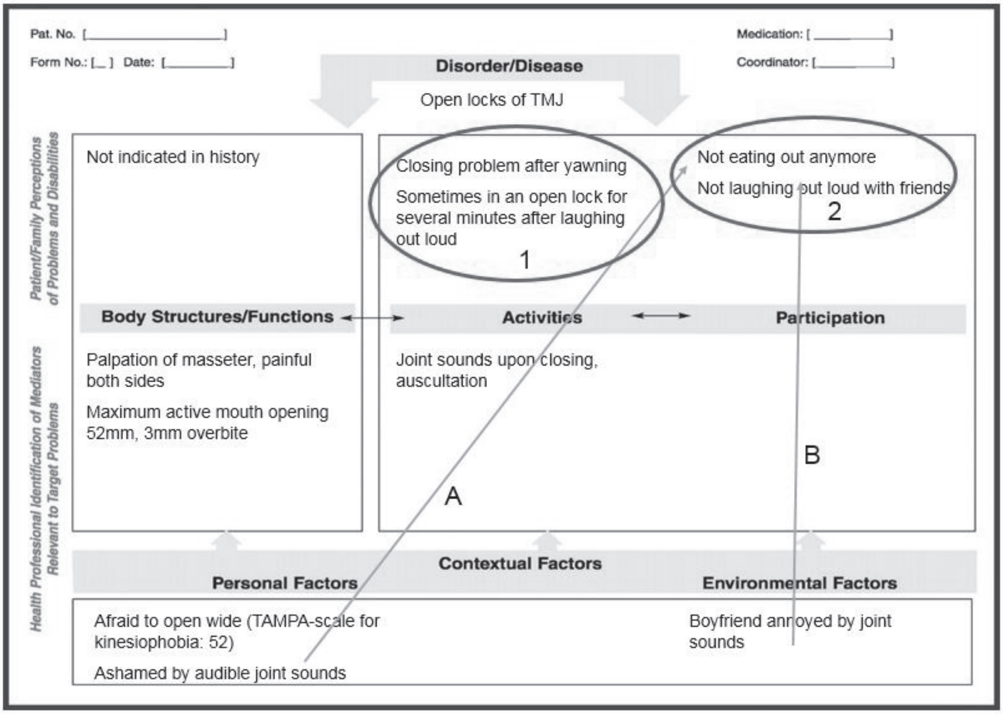


Figure 3. Rehabilitation Problem Solving-form (RPS) of Miss B. (29 years old), diagnosed with open locks of the TMJ.



Pat. No. [________________]

Form No.: [__] Date: [_________]

Medication: [__________]

Coordinator: [__________]

Disorder/Disease

Open locks of TMJ

Patient/Family Perceptions of Problems and Disabilities

Not indicated in history

Closing problem after yawning

Sometimes in an open lock for several minutes after laughing out loud

Not eating out anymore

Not laughing out loud with friends

Body Structures/Functions ↔ **Activities** ↔ **Participation**

Health Professional Identification of Mediators Relevant to Target Problems

Palpation of masseter, painful both sides

Maximum active mouth opening 52mm, 3mm overbite

Joint sounds upon closing, auscultation

Contextual Factors

Personal Factors

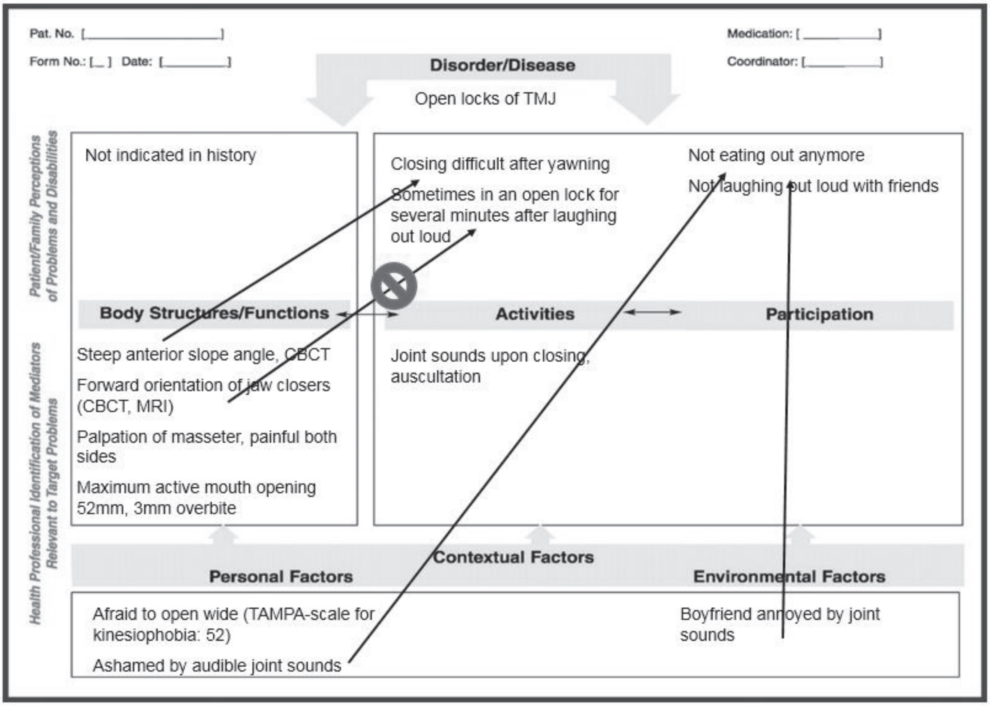
Afraid to open wide (TAMPA-scale for kinesiophobia: 52)

Ashamed by audible joint sounds

Environmental Factors

Boyfriend annoyed by joint sounds

Figure 4. Rehabilitation Problem Solving-form (RPS) of Miss B. (29 years old), diagnosed with open locks of the TMJ. Based on the results of Chapter 5, the top arrow of Body Structures was corroborated, the lower one was not.



Pat. No. [_______________]

Form No.: [__] Date: [________]

Medication: [__________]

Coordinator: [__________]

Disorder/Disease

Open locks of TMJ

Patient/Family Perceptions of Problems and Disabilities

Not indicated in history

Closing difficult after yawning

Sometimes in an open lock for several minutes after laughing out loud

Not eating out anymore

Not laughing out loud with friends

Body Structures/Functions

Activities

Participation

Health Professional Identification of Mediators Relevant to Target Problems

Steep anterior slope angle, CBCT

Forward orientation of jaw closers (CBCT, MRI)

Palpation of masseter, painful both sides

Maximum active mouth opening 52mm, 3mm overbite

Joint sounds upon closing, auscultation

Contextual Factors

Personal Factors

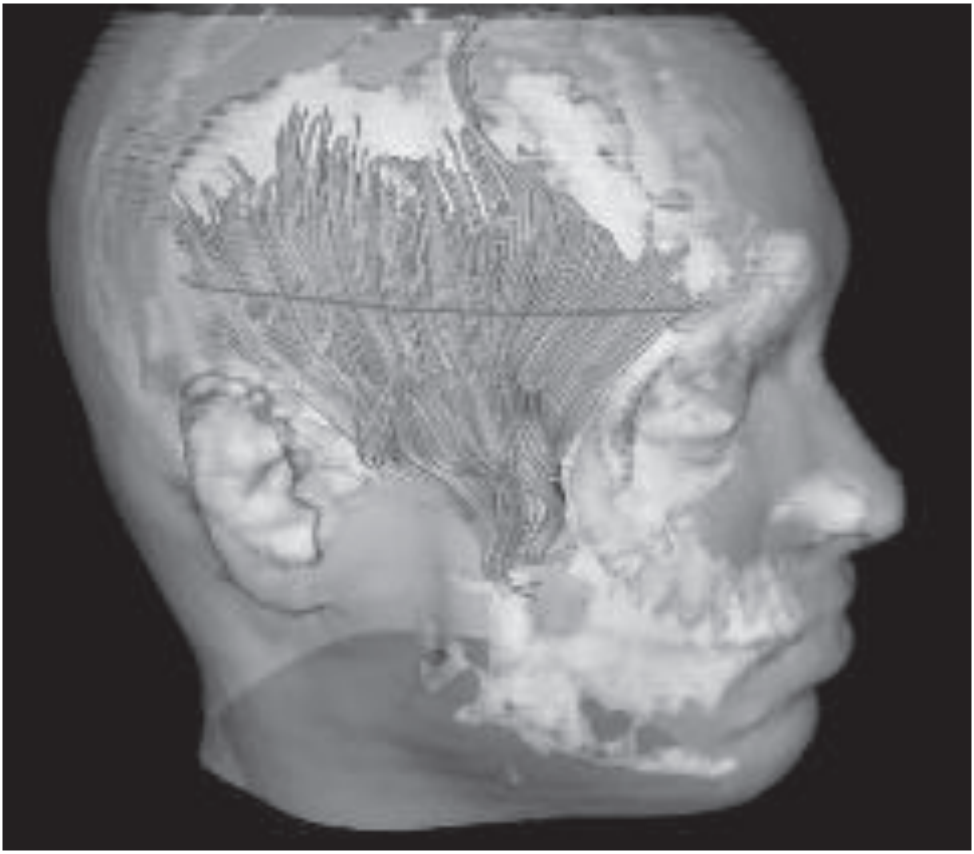
Environmental Factors

Afraid to open wide (TAMPA-scale for kinesiophobia: 52)

Ashamed by audible joint sounds

Boyfriend annoyed by joint sounds

Figure 5. Diffusion tensor imaging: tractography of the right temporalis muscle.
Courtesy of Martijn Froeling et al Proc. Intl. Soc. Mag. Reson. Med. 19 (2011)



Chapter VII

Summary

Summary

In the clinic, dentists can be confronted with patients with hypermobile temporomandibular joints. These patients may report dull clicks of the jaw joints, problems to close the jaw smoothly, or in the worst case the inability to close the mouth after opening widely. This latter condition is referred to as “open lock” or “luxation”. Patients with frequently occurring open locks may need treatment to prevent recurrence of this condition. Although many different treatments have been developed to address open locks, very little research has been performed to increase the knowledge about the role of morphology of the masticatory system in these locks. As in vivo research is largely restricted due to ethical considerations, we used biomechanical models of the masticatory system to study the interaction of joint shape and muscle orientation. By means of these models, a detailed study of the forces of the acting muscles could be performed. Also, the subsequent joint reaction forces were predicted, as well as the resulting moments of muscles and joint reaction forces. Furthermore, we increased the level of detail of the biomechanical model, to attain a model at patient level.

In Chapter 2, we first studied normal opening and closing of the jaw and focused on the differences in temporomandibular joint loading between opening and closing. Previous studies regarding the kinematics of the lower jaw provided conflicting evidence of the trajectory of the mandibular condyle. Therefore, we assessed the magnitude of the joint reaction forces acting on the temporomandibular joints during submaximal opening and subsequent closing. Model predictions showed that the joint reaction forces were markedly

higher during opening than during closing. The predicted opening trajectory of the centre of the mandibular condyle was located cranially of the closing trajectory. As one could argue that the activation level of the jaw muscle and the thickness of the joint cartilage layers are critical to these results, we performed a sensitivity analysis of these parameters on the basis of which we showed that our results were consistent for a large range of activation levels and cartilage thicknesses.

As the first aim of this thesis, we wanted to increase the understanding of the interplay of morphological aspects, such as joint shape and muscle orientation, relevant to open locks of the human temporomandibular joint. We addressed this by manipulating the anterior slope angle (ASA) of the temporomandibular joint and the orientation of the pulling direction of the jaw closers (Chapter 3). Results from the various forward dynamical models showed that combinations of relatively forward oriented jaw closers and a steep anterior slope caused the condyles to continue traveling anteriorly despite jaw-closing attempts, ending in an open lock position. It is of importance to note that these unfavorable combinations of jaw-closer orientation and anterior slope angle may exist within normal physiological ranges.

In Chapter 4, we addressed our second aim, which was to increase the understanding of the biomechanics behind open locks of the temporomandibular joint. We wanted to gain further insight into the net effect of the acting muscle forces and joint reaction forces and their resulting moments. Patients vulnerable to open locks try to relax the lower jaw and/or to actively make a lateral movement (laterotrusion), when the jaw is in an almost luxated position. We copied this idea into the activation patterns to forwardly drive our biomechanical model. Building from Chapter 3, we took a combination of a steep anterior slope angle (45 degrees) and normal orientation of the jaw closers, that had resulted in an open lock. When we applied a relaxation activation scheme, this open lock was resolved. Performing a laterotrusion movement was predicted to release an open lock for an even steeper anterior slope angle. The working principle behind both strategies is that they both 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.

The final aim of this thesis was to improve the level of detail of the biomechanical model, to allow for tailor-made models at a patient level. We addressed this in Chapter 5, where we constructed patient-specific biomechanical models based on cone-beam computed tomography (CBCT). The model was individualized with left and right anterior slope angles taken from the CBCT scans. Furthermore, the pulling direction of the jaw closers (temporalis muscle, medial pterygoid muscle, and masseter muscle) was adapted, based on bony landmarks. Although this already met our aim of an improved level of detail, we subsequently tested whether the predictions for open locks by the patient-specific models corresponded with the clinical diagnosis of these patients. Fifteen patients and eleven controls, matched for gender and age, enrolled in this study. Clinical diagnosis (gold standard) was performed according to the Diagnostic Criteria for Temporomandibular

Disorders (DC/TMD). This was applied among others to discriminate between hypermobility and other afflictions like disc displacements. A forward simulation of maximum opening and subsequent closing movement of the lower jaw was performed with the patient-specific models. We found no association between the clinical gold standard and model predictions of hypermobility disorders. The biomechanical models overestimated the number of patients, yielding a low specificity. However, for the bony structures, we determined post hoc that the anterior slope angle of the articular eminence is steeper in patients than in controls. It appears that in future research the fan-shape of the temporalis muscles should be modelled in greater detail. The temporalis muscle is the only jaw closer with posteriorly oriented muscle fibers and appears to be pivotal in the retrieval of the mandibular condyles after an open locks. Future expansions of our biomechanical model, which were discussed in Chapter 6, could incorporate recordings of the electromyographic activity of these muscle fibers, for forwardly driving these muscle fibers. The orientation and thickness (strength) of these fibers can be obtained from diffusion tensor imaging.

In Chapter 6, the broad clinical framework of the International Classification of Functioning, Disability, and Health (ICF; WHO, 2001) was applied to a case report of a patient suffering from open locks. The use of the Rehabilitation Problem Solving-form was illustrated with this case and the results of Chapters 3 and 5 from this thesis were incorporated. When a comparison is made between the DC/TMD and the ICF, the DC/TMD is more oriented toward the function level of the ICF. The DC/TMD also applies a distinction between arthogenous and myogenous disorders. Although these categories are clinically highly relevant for e.g. determining the source of nociception, this distinction is not applicable for open locks. For assessing the vulnerability for open locks, the complicated interaction between joint shape, muscle activation, and muscle morphology should be taken into account. In future versions of the DC/TMD, this could deserve further attention. Furthermore, it appears that the ICF takes a broader view by also incorporating environmental factors, and ultimately describing the most important aspect of this clinical framework, which is the participation to daily living by the patient.

Chapter VIII

Samenvatting

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In de tandheelkundige praktijk kunnen (tand)artsen geconfronteerd worden met patiënten met hypermobiele kaakgewrichten. Deze patiënten kunnen last hebben van doffe knappen of klikken in de kaakgewrichten. Ook rapporteren ze soms problemen met het soepel sluiten van hun mond of in het ergste geval kunnen ze hun mond helemaal niet meer sluiten *na* een maximale mondopening. Dit laatste geval wordt ook wel een “open lock” of “luxatie” genoemd. Patiënten met herhaaldelijk optredende open locks kunnen in aanmerking komen voor behandeling met als doel het terugkeren van deze aandoening te voorkomen. Hoewel er veel verschillende behandelingen zijn ontwikkeld voor open locks, is er weinig onderzoek gedaan om de kennis te vergroten over de rol van de bouw van het kauwstelsel in het optreden van open locks. Aangezien onderzoek in levende patiënten sterk beperkt is door ethische overwegingen, hebben we biomechanische computermodellen van het kauwstelsel gebruikt om de interactie tussen de vorm van het kaakgewricht en de trekrichting van kauwspieren te onderzoeken. Met deze modellen kan een gedetailleerde studie gemaakt worden van de krachten van actieve spieren. Verder kunnen de vervolgens optredende gewrichtsreactiekrachten voorspeld worden, net als de resulterende momenten van spierkrachten en gewrichtsreactiekrachten. Bovendien hebben we het detailniveau van het computermodel vergroot om patiënt specifieke modellen te kunnen maken.

In hoofdstuk 2, hebben we eerst een studie gedaan naar normaal openen en sluiten van de kaak. De nadruk lag daarbij op het verschil in belasting van het kaakgewricht tussen openen en sluiten van de mond. Uit eerder onderzoek van de bewegingen van de onderzoek kwam tegenstrijdig bewijs naar voren over de bewegingsbanen van de kaakkopjes. Daarom hebben we de grootte van de reactiekrachten op de kaakgewrichten geschat tijdens sub-maximaal openen en de volgende sluitbeweging van de kaak. De voorspellingen van het model lieten zien dat de reactiekrachten aanzienlijk groter waren tijdens openen dan tijdens sluiten. De voorspelde bewegingsbaan van het centrum van het kaakkopje tijdens openen lag ook boven de voorspelde bewegingsbaan van de sluitbeweging. Aangezien het activatie niveau van de kaakspieren en de dikte van het kraakbeen in het gewricht sterke invloed kunnen hebben op deze resultaten, hebben we een gevoeligheidsanalyse gedaan voor deze parameters. De resultaten hiervan lieten zien de resultaten steeds hetzelfde opleverden voor een groot bereik van zowel spieractivatieniveau als kraakbeendikte.

Als eerste doel van dit proefschrift hebben we gesteld om de interactie van vorm aspecten van het kauwstelsel, die relevant zijn voor open locks van het kaakgewricht, beter te begrijpen. Hierbij hebben we gekeken naar de vorm van het kaakgewricht en de oriëntatie van de spiervezels. Dit hebben we bekeken door de voorste hellingshoek van het kaakgewricht en de trekrichting van de kaaksluiters te manipuleren in het computermodel. De resultaten van diverse voorwaarts-dynamische simulaties demonstreerden dat combinaties van meer voorover georiënteerde kaaksluiters en steilere voorste hellingshoeken ervoor zorgden dat de kaakkopjes voorwaarts bleven bewegen, ondanks activatie van de kaaksluiters. Uiteindelijk kwamen de kaakkopjes hierdoor in een open lock positie terecht. Het is van belang hierbij aan te tekenen dat deze ongunstige combinaties van oriëntatie van kaaksluiters en voorste hellingshoek kunnen bestaan binnen normale fysiologische grenzen.

In hoofdstuk 4 hebben we ons gericht op het tweede doel van dit proefschrift, namelijk om het begrip te vergroten van de biomechanica achter open locks van het kaakgewricht. Hiertoe wilden we het inzicht vergroten op de gesommeerde spier- en gewrichtsreactiekrachten, alsmede hun resulterende momenten. Patiënten met een risico voor open lock proberen vaak hun onderkaak te ontspannen en/of maken een zijwaartse beweging (laterotrusie) met hun kaak, als de kaak bijna op slot schiet. Dit idee hebben we verwerkt in het aanpassen van de activatiepatronen, waarmee ons biomechanische model worden aangedreven. Voortbouwend op de resultaten van hoofdstuk 3, namen we een simulatie, die was geëindigd met een open lock, als uitgangspunt. Hierin was sprake van een voorste hellingshoek van 45 graden en een normale trekrichting van de kaaksluiters. Bij het gebruik van een activatie patroon, waarin ook ontspanning was opgenomen, lukte het om de open lock op te lossen. Dit lukte ook met een laterotrusie patroon. Het laterotrusie patroon was zelfs iets succesvoller, omdat dit ook nog een open lock kon oplossen van een steilere hellingshoek. Het principe achter beide strategieën bleek dat beide een netto kaak-sluitend moment produceren, maar dat alleen de laterotrusie strategie in staat bleek een netto kracht naar achteren te produceren voor de steilere hellingshoeken. In beide strategieën, lijkt de temporalis spier de kern te zijn om de kaakkopjes terug te krijgen naar de gewrichtskom. Dit komt doordat dit de enige kaaksluiter is met achterwaarts georiënteerde spiervezels.

Het laatste doel van dit proefschrift was om het detailniveau van het biomechanische model te verbeteren om te komen tot individuele modellen op maat. Dit hebben we uitgewerkt in Hoofdstuk 5, waarin we op basis van cone-beam computer tomografie (CBCT) patiënt-specifieke modellen hebben geconstrueerd. Hierin werden de linker- en rechter voorste hellingshoeken aangepast aan de hand van de CBCT-scans. Ook de trekrichting van de kaaksluiters (temporalis, mediale pterygoid en masseter) werk aangepast op grond van benige delen. Hoewel hiermee het doel van verbeterd detailniveau al was bereikt, hebben we vervolgens getest of de voorspellingen van het model voor open locks overeenstemden met de klinische diagnose van patiënten en controles. Vijftien patiënten en elf controles van gelijke leeftijd en geslacht namen deel aan deze studie. De klinische diagnose (gouden standaard) werd gesteld aan de hand van de Diagnostic Criteria for Temporomandibular Disorders (DC/TMD). Deze standaard werd onder andere gebruikt om te differentiëren tussen hypermobiliteit en discus verplaatsingen. Met de patiënt-specifieke modellen werd een voorwaartse simulatie gedaan van maximaal openen en de opeenvolgende sluit beweging. We hebben geen associatie gevonden tussen de klinische diagnose, volgens de gouden standaard (DC/TMD), en de voorspellingen van hypermobiliteit. De voorspellingen van de patient-specifieke modellen overschatten het aantal gevallen van hypermobiliteit, wat leidde tot een lage specificiteit (veel fout positieven). Echter hebben we wel vast kunnen stellen dat de voorste hellingshoek van het kaakgewricht bij patiënten steiler is dan bij controles. Het lijkt erop dat in de toekomstige modellen de waaiervorm van de temporalis spier met meer detail moet worden opgenomen, aangezien dit de enige kaaksluiter is met achterwaartse georiënteerde spiervezels. Hiermee is dat enige spier, die de kaakkopjes achterwaarts kan verplaatsen. Toekomstige uitbreidingen van ons biomechanische model, zoals besproken in Hoofdstuk 6, zouden ook kunnen bestaan uit metingen van electromyografische activiteit van deze spiervezels. Met deze metingen kunnen deze spiervezels in het model voorwaarts worden aangestuurd. De trekrichtingen en dikte (als voorspeller van de kracht van de spier) zouden kunnen worden bepaald met diffusie tensor beeldvorming, op basis van MRI.

In de algemene discussie in Hoofdstuk 6 werd de International Classification of Function, Disability, and Health (ICF) gebruikt. Dit veelomvattend klinische kader van de World Health Organization (WHO, 2001) werd toegepast op een casus van een patiënt met open locks. Aan de hand van deze casus werd het gebruik van het Rehabilitation Problem Solving-formulier inzichtelijk gemaakt en de resultaten van Hoofdstuk 3 en Hoofdstuk 5 werden hier direct in opgenomen. Als er een vergelijking gemaakt wordt tussen de DC/TMD en de ICF, dan valt op dat de DC/TMD de nadruk heeft op het functie niveau van de ICF. Ook gebruikt de DC/TMD een onderscheid tussen artrogene en myogene aandoeningen. Hoewel deze categorieën in de kliniek zeer relevant zijn voor bijvoorbeeld het bepalen van de bron van pijnbeleving, is dit onderscheid niet toepasbaar op open locks. Om het risico op open locks in kaart te brengen, zal er gekeken moeten worden naar de complexe interactie tussen gewrichtsvorm, spieractivatie en spiermorfologie. In toekomstige versies van de DC/TMD kan hieraan meer aandacht worden geschonken. Verder lijkt het erop dat de ICF ook een bredere klinische blik biedt door omgevingsfactoren op te nemen. Uiteindelijk omvat de ICF het belangrijkste deel van dit klinische kader en dat is het participatie niveau ofwel de deelname aan het dagelijks leven door de patiënt.

Author contributions

Author contributions

Contribution to manuscript	Chapter 2, 3, 4	Chapter 5
Study conception and design	MT, JHK, FL ,MN	MT, JHK, FL, EB
Acquisition of data	MT	MT, FL, AP, MK
Analysis and interpretation of data	MT, JHK, FL ,MN	MT, JHK, AP, FL
Drafting of manuscript	MT	MT
Critical revision	MT, JHK, FL ,MN	MT, JHK, AP, EB, MK, FL

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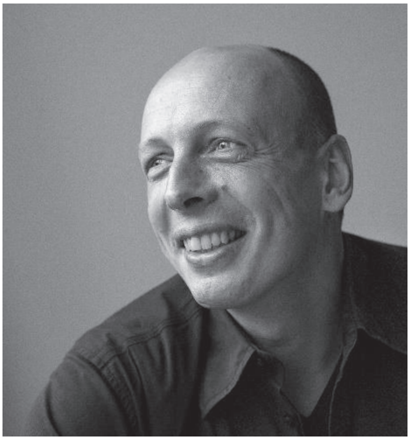
Curriculum vitae



Matthijs Tuijt was born on the 10th of October, 1974, in Hengelo (Ov.), The Netherlands. He finished pre-university secondary education in 1993 (De Grundel, Hengelo). After a sidestep at KPMG, Apeldoorn, he pursued his interest in human movement and motor learning and graduated as an exercise therapist (Cesar kinetics therapy) in 1999 at the Hogeschool Utrecht. After three years as a general therapist, he started as an occupational trainer with an emphasis on manual material handling and the associated musculoskeletal complaints. From 2002 onwards, he combined this work with the study of Human Movement Sciences at the VU, Amsterdam, where he graduated in 2006, specializing in ergonomics. While being an active dad, he delved further into the biomechanics of musculoskeletal systems. At the Move Research Institute, Amsterdam, he started a translational PhD on hypermobility disorders of the human jaw joint in 2007. The return in 2010 to the Hogeschool Utrecht as a teacher, meant an intricate juggle of teaching, parenting, and research tasks. Currently, Matthijs teaches in first and second year biomechanics and anatomy courses at the Cesar kinetics department, Institute for Movement Studies, HU University of applied sciences. He also coordinates the bachelor research thesis and supervises theses. Recently, Matthijs acquired a grant from the Cesar Development Fund to investigate the effect of exercise therapy on movement variability in patients with low back pain or complaints of arm, neck, and shoulder. The new movement laboratory of the Human Movement and Adaptation Research Group will be the playground to kick-start his research line on movement variability.

Publications

Publications: peer reviewed

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Congress visits

ESB, European Society of Biomechanics, Luzern, 2008, visiting

ESB, European Society of Biomechanics, Edinburgh, 2010, poster

IUTAM, International Union of Theoretical and applied Mechanics, Symposium Analysis and simulation of human motion, Leuven, 2010, poster

ISEK, International Society of Electromyography and Kinesiology, Brisbane, 2012, poster

IOT, Interuniversitair Onderzoekoverleg Tandheelkunde, Lunteren, 2006-2012, visiting

IOT, Interuniversitair Onderzoekoverleg Tandheelkunde, Lunteren, 2010, presenting

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