Human Movement Science 49 (2016) 132–140

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Full Length Article

The influence of the human TMJ eminence inclination on predicted masticatory muscle forces

Michala Marková [a,b,*], Luigi M. Gallo [a]

[a] Clinic of Masticatory Disorders, Removable Prosthodontics, Geriatric and Special Care Dentistry, University of Zürich, Plattenstrasse 11, 8032 Zürich, Switzerland
[b] Laboratory of Biomechanics, Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 16607 Prague 6, Czech Republic

ARTICLE INFO

Article history:
Received 18 November 2015
Revised 9 May 2016
Accepted 23 June 2016

PsycINFO classification:
2227 Educational Measurement
2260 Research Methods & Experimental Design

Keywords:
Temporomandibular joint
Masticatory muscles
Masticatory force
Theoretical models
AnyBody™

ABSTRACT

Aim of this paper was to investigate the change in masticatory muscle forces and temporomandibular joint (TMJ) reaction forces simulated by inverse dynamics when the steepness of the anterior fossa slope was varied. We used the model by de Zee et al. (2007) created in AnyBody™. The model was equipped with 24 musculotendon actuators. Mandibular movement was governed by the trajectory of the incisal point. The TMJ was modelled as a planar constraint canted 5° medially and the caudal inclination relative to the occlusal plane was varied from 10° to 70°. Our models showed that for the two simulated movements (empty chewing and unilateral clenching) the joint reaction forces were smallest for the eminence inclination of 30° and 40° and highest for 70°. The muscle forces were relatively insensitive to change of the eminence inclination for the angles between 20° and 50°. This did not hold for the pterygoid muscle, for which the muscle forces increased continually with increasing fossa inclination. For empty chewing the muscle force reached smaller values than for clenching. During clenching, the muscle forces changed by up to 200 N.

1. Introduction

Musculoskeletal mathematical models provide – through computer simulation – insight into biomechanical variables that are difficult or impossible to measure directly, such as muscle forces or joint reaction forces (Peck & Hannam, 2007). Inverse dynamic modelling is a valuable method that helps back-calculating the activation of complex muscle systems starting from kinematic and anatomical data and is useful in several fields, such as sports training, ergonomics, dentistry. A major prerequisite for the use of a mathematical model is that it is verified, i.e. that its concept is correctly implemented without any mathematical errors, and validated, i.e. that it yields an accurate representation of the real system when its results are in agreement with experimental data (Anderson, Ellis, & Weiss, 2007; Hannam, 2011; Sargent, 2011; Hicks, Uchida, Seth, Rajagopal, & Delp, 2015; Lund, de Zee, Andersen, & Rasmussen, 2012). A verified and validated musculoskeletal model is therefore a valuable tool to analyse and simulate the impact of everyday movement patterns, a specific treatment or an operation. In the process of validation, sensitivity analysis should be held in order to determine the relative significance of the input parameters and their influence on the output (Hannam, 2011; Weiss, Gardiner, Ellis, Lujan, & Phatak, 2005). It is critical

* Corresponding author at: Clinic of Masticatory Disorders, Removable Prosthodontics, Geriatric and Special Care Dentistry, University of Zürich, Plattenstrasse 11, 8032 Zürich, Switzerland.

E-mail addresses: Michala.Markova@zzm.uzh.ch (M. Marková), luigi.gallo@zzm.uzh.ch (L.M. Gallo).

http://dx.doi.org/10.1016/j.humov.2016.06.012
0167-9457/

to determine the sensitivity of a biomechanical model to its input parameters in systems where material properties are not well characterized or where complex loading patterns occur (Hannam, 2011). Indeed, sensitivity analysis is paramount for validation, since it helps understanding how errors are propagated and yields the data range in which the model behaves which has to be consistent with the range of experimental data. Sensitivity studies may be also used to conduct virtual experiments or parameter optimizations without having to work on large experimental samples (Anderson et al., 2007).

A large set of musculoskeletal models of different parts of the human body exists, but only few of these models describe the temporomandibular joint (TMJ) which is a bilateral articulation between the mandible and the temporal bone. The TMJ is composed of the articular surface of temporal bone, articular disc, mandibular condyle, capsule, ligaments, and lateral pterygoid muscle. The articular eminence forms the superoanterior part of the mandibular fossa of the temporal bone which is the part of the fossa most heavily travelled by the mandibular condyle. The TMJ grants a large mobility of the mandible, which is necessary for activities such as chewing and speaking. Even though the TMJ is a small joint, a diseased TMJ has a strong impact on mandibular function and consequently on the quality of life (Nickel et al., 2009; Spilker, Nickel, & Iwasaki, 2009). The masticatory system is anatomically and functionally complex, therefore its modelling and analysis is not straightforward (Koolstra, 2002; Peck & Hannam, 2007). Moreover, the variability of TMJ morphology and loading patterns is very large (Gallo, Brasi, Ernst, & Palla, 2006; Gallo, Nickel, Iwasaki, & Palla, 2000; Schilling et al., 2014). Nevertheless, researchers tend to model the TMJ in an overly simplified way, so that the condyles are represented by spheres, ellipsoids or even points, whereas the fossa-eminence complex is mostly modelled as a plane or set of planes or as a curvilinear constraint (Hannam, 2011). These models are still in use and few advances have occurred in the last years.

In an article previously published (de Zee et al., 2007), the guidance of the articular eminence was modelled as a planar constraint with five degrees of freedom. This means that the mandibular condyle during its movement followed a linear path. However, the literature as well as the body of data collected at the Center of Dental Medicine (ZZM, University of Zurich, Switzerland) shows that the condylar path is almost never linear (Gallo, Gossi, Colombo, & Palla, 2008; Merlini & Palla, 1988; Palla, Gallo, & Gossi, 2003; Salaorni & Palla, 1994). Moreover, the eminence slope ranges interindividually broadly between 10° and 70° (Baqaien, Al-Salti, & Muessig, 2007; Iwasaki et al., 2010; Lindblom, 1960). It has been shown previously that for healthy subjects the eminence shape is linked to the minimization of joint loads (Iwasaki, Petsche, McCall, Marx, & Nickel, 2003; Trainor, McLachlan, & McCall, 1995) and as was shown by Mark de Zee et al. (2009) also in patient before and after distraction osteogenesis was the eminence inclination consistent with minimization of joint loads.

Since the reference plane for the eminence inclination in that former study was based on literature and not on the CT scans used for the model of the skull and mandible (de Zee et al., 2007), we wondered how changes of this particular parameter can influence the results presented.

Aim of this paper was therefore to use the TMJ model formerly published and still present in a public accessible repository (de Zee et al., 2007) and to investigate how simulated bilateral masticatory muscle forces and joint reaction forces are sensitive to the eminence inclination.

2. Materials and methods

The three-dimensional musculo-skeletal model of the human mandible implemented in the AnyBody™ modelling system (AnyBody Technology A/S, Aalborg, Denmark, version 5.3.1.3556), stored in the AnyBody™ repository (version 1.6.3, www.anybodytech.com) and published previously, was used (de Zee et al., 2007). The anatomy was based on CT-scans of a cadaver of a 30-years old male. The x, y and z axes of the coordinate system were oriented dorso-ventrally, medio-laterally and caudo-cranially, respectively. The model consisted of two rigid bodies, the skull and the mandible. The mandibular fossa was modelled as a planar constraint, angled 30° downwards relative to the occlusal plane and canted 5° medially. A continuous contact between the condyle and the mandibular fossa was assumed, so that the condylar path followed the eminence inclination since the articular disc was not implemented. Each TMJ could rotate around three axes and translate in a plane, i.e. it had 5 degrees-of-freedom (DOF).

The movement of the mandible was governed by twelve pairs of musculotendon actuators (three-element Hill-type muscles; Cadova & Vilimek, 2009; Hill, 1938), i.e. bilaterally, the anterior mylohyoids, posterior mylohyoids, anterior digastrics, geniohyoids, superficial masseters, deep anterior masseters, deep posterior masseters, medial pterygoids, anterior temporalis, posterior temporalis, superior lateral pterygoids, and inferior lateral pterygoids. The hyoid bone was not included in the model; therefore, the mouth openers (hyoid muscles) were attached to a static fictive point. The attachment points of the muscles and their physiological properties were adopted from the literature (de Zee et al., 2007; Koolstra & van Eijden, 2005). Five movement/clenching tasks were recorded by de Zee et al. (2007). Two of them where used for the presented models: Task 2 – empty chewing movement, and Task 4 – unilateral clenching with the force transducer between the left first premolars (maximum value of 441 N). The movement was governed by the path of the lower incisal point, even though for the Task 4 only minor movements of the mandible occurred, since the teeth were in contact throughout the whole cycle.

The eminence inclination of the rigid-body model established above (with the 30° eminence inclination) was then altered according to data found in the literature and in our database (Tables 1 and 2). The medial eminence inclination was kept constant at the values of 5°. The slopes of both eminences relative to the occlusal plane were varied from 10° to 70° in 10° steps (Fig. 1).