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Research Paper

Finite element analysis of the human mastication cycle

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ABSTRACT

The aim of this paper is to propose a biomechanical model that could serve as a tool to overcome some difficulties encountered in experimental studies of the mandible. One of these difficulties is the inaccessibility of the temporomandibular joint (TMJ) and the lateral pterygoid muscle. The focus of this model is to study the stresses in the joint and the influence of the lateral pterygoid muscle on the mandible movement. A finite element model of the mandible, including the TMJ, was built to simulate the process of unilateral mastication. Different activation patterns of the left and right pterygoid muscles were tried. The maximum stresses in the articular disc and in the whole mandible during a complete mastication cycle were reached during the instant of centric occlusion. The simulations show a great influence of the coordination of the right and left lateral pterygoid muscles on the movement of the jaw during mastication. An asynchronous activation of the lateral pterygoid muscles is needed to achieve a normal movement of the jaw during mastication.

1. Introduction

Biomechanical models of the human mandible have been extensively used to explore the functioning of dental implants (Huang et al., 2014; Holberg et al., 2013; Lan et al., 2012; Ojeda et al., 2011), other fixation devices (Huang et al., 2012; Bohluli et al., 2010), mandible reconstruction (Narra et al., 2014; Li et al., 2014), and temporomandibular disorders (Cheng et al., 2013; Commisso et al., 2014) among other problems. This paper uses a model of the mandible, including the temporomandibular joint (TMJ), to simulate the process of unilateral mastication. Two basic aspects of this process constitute the main focus of this study: the articular disc of the TMJ and the muscular activity, in particular that of the lateral pterygoid muscle.

The main component of the TMJ is the articular disc, a plate of fibrocartilage that facilitates the relative movement between the mandible and the temporal bone. The articular disc acts as a load absorber and distributes the loads over larger contact areas to prevent the damage of the articulating surfaces. In turn, damage of the articular disc can be one of the causes of temporomandibular disorders (TMD). Some researchers have shown that acute mechanical overloads in vivo can cause severe cartilage damage (Radin et al., 1984; Thompson et al., 1991). Particularly, shear stresses are believed to alter the cells in the tissue and might lay behind the damage in the cartilage (Smith et al., 2004). So, the

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analysis of the shear stresses in the disc during chewing can be of interest for a study of TMD.

The stresses and strains in the articular disc during loading are very difficult to measure experimentally. Therefore, several studies have investigated the stress and strain distribution in the TMJ during mastication by means of finite element (FE) models (see Beek et al., 2001; Koolstra and van Eijden, 2007, among others). To the authors' knowledge, only Koolstra and van Eijden (2007) studied a complete mastication cycle and considered the viscoelastic behaviour of the articular disc. However, the movement of the mandible was defined with a multibody model and the jaw was assumed as a rigid body, so that the stress distribution within the bone was not accessible. The present study tries to overcome that limitation by using a FE model of the mandible with a detailed treatment of the TMJ, including the ligaments and a viscoelastic model of the articular disc.

In regard to the second pillar of this study, the muscular activity during mastication, it must be noted that the human masticatory system has a very complex performance and requires the balanced and coordinated activities of the masticatory muscles on the left and right sides (Yamaguchi et al., 2011). In particular, the human lateral pterygoid muscle plays an important role in the control of the jaw movements (Murray, 2012) and stabilization of the TMJ (Murray et al., 1999). Nevertheless, there is very limited understanding on how it performs these functions. Furthermore, studies do not even agree on the specific functions of the two major bellies of the muscle (Murray et al., 1999): the superior and inferior heads. Only one thing seems to be clear: the inferior head is active in jaw-opening, jaw protrusion and contralateral jaw movements (Phanachet et al., 2001; Murray, 2012).

One of the main reasons for the lack of understanding of the function of this muscle is the difficulty of studying it with electromyography (EMG) recordings, arising from the deep location of the muscle, which can result in a misplacement of the electromyograph. Another reason is that the condylar movement should be simultaneously recorded with the lateral pterygoid activity. This is essential in this muscle, in light of the observations of several authors (Sessle and Gurza, 1982; Murray et al., 1999), who noticed that the position of the jaw is an important determinant of its EMG activity.

As an alternative to these EMG studies, some previous studies have simulated the mastication cycle to predict the activity of the lateral pterygoid from an inverse analysis. Hannam et al. (2008), Koolstra and van Eijden (2005) and de Zee et al. (2007) proposed multibody system models of the mandible and the muscles attached to it to simulate masticatory movements. They proposed an inverse analysis to fit the activity of the lateral pterygoid, such that it produced the normal movement of the jaw during mastication. This normal movement is characterized by a trajectory of the incisal edge with a "tear drop shape" when projected on a frontal plane (Buschang et al., 2000; Bhatka et al., 2004). However, those models contain simplifications with a major influence on the masticatory movement. Apart from the use of a multibody system model (rigid) for the mandible, the model of the TMJ was very simplified and the activities of the left and right lateral pterygoid muscles were synchronous (Koolstra and van Eijden, 2005) or nearly synchronous (Hannam et al., 2008). It will be shown here that synchronous activation patterns result in abnormal movements when the constraints imposed by the TMJ are more accurately modelled.

The lateral pterygoid muscle and its relationship with TMD have also been studied and reviewed extensively (Juniper, 1984; Widmalm et al., 1987; Hiraba et al., 2000; Fujita et al., 2001; Okeson, 2003; Desmons et al., 2007), though no consensus has been achieved to establish the origin of that relationship. In order to shed light on this matter it is essential to understand well its normal functioning.

In this work, a FE model of the mandible and TMJs is proposed to simulate a mastication cycle by applying the loads exerted by the jaw opening and jaw closing muscles during the cycle. A special treatment is given to the forces applied by the lateral pterygoid muscle. Since there is no agreement in defining the activity of that muscle, different temporal activation patterns were tried to analyse its influence on the jaw movement.

The main objective of this work is to propose a comprehensive biomechanical model of the masticatory system that allows the study of a mastication cycle and the stresses generated in the mandible and in the TMJ during it. Another objective is to check if the activity of the lateral pterygoid muscle has a significant influence on the movement of the jaw during chewing.

2. Materials and methods

2.1. Finite element model

A FE model of the mandible and TMJ was built using the commercial software Abaqus FEA® v6.10. The model was previously described in more detail in Commisso et al. (2014). The modelled parts of the joint were the articular disc, the collateral and temporomandibular (TML) ligaments and the posterior part of the articular capsule (see Fig. 1).

2.2. Muscle model

The estimation of the muscle forces was made using a Hill-like model (Hill, 1938; Thelen, 2003), with the force being applied by the muscle the sum of two terms: the active force, due to the contraction of the muscles fibres, and the passive force, due to the stiffness of the connective tissue:

$$\mathbf{F} = \mathbf{F}^A + \mathbf{F}^P \quad (1)$$

The active forces are generally expressed as a function of the maximum force in isometric contraction, $\mathbf{F}_0^M$, the length of the muscular-tendon unit, l, the contraction velocity, v, and the activation level, a. For example, in the Thelen (2003) model,

$$\mathbf{F}^A = a \cdot \mathbf{F}_0^M \cdot f_L(l) \cdot f_V(v) \quad (2)$$

where $f_L(l)$ and $f_V(v)$ describe the dependency on the length and the contraction velocity respectively and are dimensionless functions of the so-called optimal fibre length, l_0^M, among other variables. The function $f_L(l)$ has a maximum $f_L(l_0^M) = 1$. Besides, l_0^M was assumed to occur when the interincisal gap is 2 mm, like in Langenbach and Hannam (1999). Mouth opening during