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Three-dimensional temporomandibular joint muscle attachment morphometry and its impacts on musculoskeletal modeling

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A B S T R A C T

In musculoskeletal models of the human temporomandibular joint (TMJ), muscles are typically represented by force vectors that connect approximate muscle origin and insertion centroids (centroid-to-centroid force vectors). This simplification assumes equivalent moment arms and muscle lengths for all fibers within a muscle even with complex geometry and may result in inaccurate estimations of muscle force and joint loading. The objectives of this study were to quantify the three-dimensional (3D) human TMJ muscle attachment morphometry and examine its impact on TMJ mechanics. 3D muscle attachment surfaces of temporalis, masseter, lateral pterygoid, and medial pterygoid muscles of human cadaveric heads were generated by co-registering measured attachment boundaries with underlying skull models created from cone-beam computerized tomography (CBCT) images. A bounding box technique was used to quantify 3D muscle attachment size, shape, location, and orientation. Musculoskeletal models of the mandible were then developed and validated to assess the impact of 3D muscle attachment morphometry on joint loading during jaw maximal open-close. The 3D morphometry revealed that muscle lengths and moment arms of temporalis and masseter muscles varied substantially among muscle fibers. The values calculated from the centroid-to-centroid model were significantly different from those calculated using the 'Distributed model', which considered crucial 3D muscle attachment morphometry. Consequently, joint loading was underestimated by more than 50% in the centroid-to-centroid model. Therefore, it is necessary to consider 3D muscle attachment morphometry, especially for muscles with broad attachments, in TMJ musculoskeletal models to precisely quantify the joint mechanical environment critical for understanding TMJ function and mechanobiology.

1. Introduction

Temporomandibular joint (TMJ) disorders affect 5–12% of Americans, with an estimated annual economic cost of $4 billion (Stowell et al., 2007). The TMJ is a load-bearing joint, and its tissue homeostasis is sensitive to the joint mechanical environment (Nickel et al., 2018). The development and progression of TMJ disorders are likely associated with pathological change in the TMJ loading environment. (Beek et al., 2000; Donzelli et al., 2004; Nickel et al., 2003). Human TMJ muscles, primarily the temporalis, masseter, lateral pterygoid, and medial pterygoid, drive jaw movement to accomplish various oral tasks, and the loading environment is mainly regulated by forces exerted by those muscles on the mandible (Koolstra and van Eijden, 2005; Throckmorton et al., 1990; Trainor et al., 1995). Therefore, functional characterization of TMJ muscles, including muscle morphometry, is important for accurately determining the TMJ loading environment to achieve a better understanding of TMJ biomechanics and pathophysiology.

Due to the difficulty of directly measuring joint loading in humans, musculoskeletal models, such as inverse or forward dynamics models, are commonly used to determine the relationships between joint forces and motions in the knee and spine, as well as in TMJ (Buchanan et al., 2004; de Zee et al., 2007;

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Vasavada et al., 1998). In current human TMJ musculoskeletal models, TMJ muscle effective lines of action are represented by centroid-to-centroid force vectors connecting the approximated centers of each muscle attachment (de Zee et al., 2007; Hannam et al., 2008; Koolstra and van Eijden, 1997, 2005; Trainor et al., 1995). This simplification assumes equivalent muscle lengths and moment arms for all fibers within a muscle (May et al., 2001; Trainor et al., 1995). However, the centroid-to-centroid approximation is not always satisfied, where variations in the length and moment arm among human rectus femoris fibers, due to its complex geometry and broad attachment, have great influence on muscle force generation capacity in human knees (Herzog and ter Keurs, 1988). In regards to the TMJ, it still remains unknown how three-dimensional (3D) muscle attachment morphometry affects muscle force generation and joint mechanical loading, especially for the temporalis and masseter muscles with even broader attachments compared to the rectus femoris muscle.

Although many studies have been reported to elucidate the relationship between morphology and biomechanics of the masticatory muscles (Boom et al., 2008; Goto et al., 2002, 2006; Hannam and Wood, 1989; Koolstra, 2002; Raadsheer et al., 1994; Sasaki et al., 1989; Van Spronsen et al., 1989, 1992), quantitative analysis of masticatory muscle attachments is limited in the literature. To our knowledge, only one set of studies quantifying human TMJ muscle attachment morphometry exists in the literature (van Eijden et al., 1995, 1996, 1997). In these reports, the centroids of the temporalis, masseter, lateral pterygoid, and medial pterygoid muscle attachments were approximated by averaging coordinates of a discrete number of points along muscle attachment boundaries. Although these studies provided valuable morphometric baseline data for current musculoskeletal models of the human TMJ, these reports are limited by their inability to physiologically represent the entire 3D structure of the human TMJ muscle attachment surface. There is no pre-existing approach for quantitatively determining 3D TMJ muscle attachment morphometry. Consequently, the accuracy of current TMJ musculoskeletal models utilizing centroid-to-centroid muscle models in predicting joint mechanical loading is uncertain.

The primary objective of this study was to develop a co-registered 3D digitization and imaging-based method to quantify the 3D human TMJ muscle attachment morphometry through cadaver dissection. The secondary goal was to develop musculoskeletal models of a live subject to assess the impact of 3D muscle attachment morphometry on muscle force, moment, and joint loading during mandible movement. Specifically, muscle attachments (origin and insertion) were quantified by size, shape, location, and orientation for the temporalis, masseter, lateral pterygoid, and medial pterygoid muscles using a 3D bounding box technique. The distribution of muscle lengths and moment arms across entire attachment regions were determined for the temporalis and masseter, compared to centroid-to-centroid models. Furthermore, the impact of 3D muscle attachment morphometry on muscle force, moment, and joint loading during mandible maximum open-close movement were assessed through two TMJ musculoskeletal models, considering distributed and centroid-to-centroid temporalis muscle force vectors, respectively. It was hypothesized that human TMJ muscle lengths and moment arms across the entire 3D muscle attachment surface, and the resultant joint loadings, differ significantly from those determined from the centroid-to-centroid model.

2. Methods

2.1. Specimen preparation and CBCT imaging

Twenty-two male human cadaveric heads were screened, of which nine (76.8 ± 8.2 years) morphologically normal specimens without craniofacial deformity and TMJ degeneration were included in this study, with appropriate institutional approval. Each mandible was fixed to the maxilla with a custom plastic bracket, with the mouth in the closed position. Donor heads were scanned using a cone-beam computerized tomography (CBCT) scanner (Planmeca3DMax, Planmeca USA, Roselle, IL) with voxel dimensions of $0.2 \times 0.2 \times 0.2\ mm^3$. A more detailed description of the following experiment and analysis protocols is presented in the Supplementary Materials.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2018.08.010.

2.2. Sequential muscle dissection and muscle attachment digitization

A custom tracking probe with four fiducial passive reflective markers (M_1, M_2, M_3, and M_4) (9.5 mm markers, NaturalPoint, Corvallis, OR) was developed to determine the continuous spatial coordinates of the TMJ muscle attachment boundaries (Fig. 1A and B). Change in the 3D spatial coordinates of attached fiducial markers was tracked by a three-camera motion capture system (Prime 13, NaturalPoint, Corvallis, OR). Cameras were calibrated with a sampling frequency of 200 Hz and spatial precision of 0.2 mm.

A sequential dissection was conducted bilaterally on each human cadaveric cephalad, in order of masseter, temporalis, lateral pterygoid and medial pterygoid. Following dissection, the origin and insertion boundaries of each muscle attachment, where muscle is attached to bone via tendon (Benjamin et al., 2006), were outlined and digitized (Fig. 1C). In addition, nine feature landmarks on the custom plastic brackets fixing the mandible and maxilla, and four anatomical landmarks on the skull and mandible were also digitized for co-registering CBCT images with the digitized TMJ muscle attachment boundaries.

2.3. Image co-registration

3D solid models from the CBCT scans of each head were segmented in Amira (Amira 5.4, Hillsboro, OR). For each human head, 3D solid models of the bony surfaces were co-registered with the digitized muscle attachment boundaries by aligning the nine feature landmarks on the custom plastic bracket and four anatomical landmarks, using point-based registration methods (Fitzpatrick et al., 1998). Co-registration was further refined via iterative closest-point (ICP) techniques (Besl and McKay, 1992; Fitzpatrick and West, 2001). All algorithms used custom MATLAB programs (R2016b, The MathWorks, Inc., Natick, MA).

2.4. Morphometric analysis

Following muscle attachment boundary and skull surface co-registration, 3D muscle attachment surfaces were isolated (Geomagic Studio, Cary, NC). Each 3D muscle attachment surface (origin or insertion) underwent morphometric analysis, using a 3D bounding box technique to quantify muscle attachment size, shape, location, and orientation, with a defined skull-based coordinate system (Fig. 2) (Cassidy, 1993; Ohba, 1985; Weisl, 1954). Distributions of muscle lengths and moment arms across the entire attachment region were determined for the temporalis and masseter. For the temporalis muscle, five distributed force vectors were defined (Fig. 5A), including centroid-to-centroid force vectors (in blue) connecting temporalis origin and insertion centroids. For the masseter muscle, to reflect its layered anatomical structure (Tuijt et al., 2010; Van der Helm et al., 1992), the superficial and deep masseter muscles were represented by two (in red) and three (in black) distributed force vectors respectively (Fig. 6A). Muscle lengths were determined as the length of the corresponding muscle force vectors from origin to insertion, including tendon length