Published in final edited form as:

J Biomech. 2018 October 05; 79: 119–128. doi:10.1016/j.jbiomech.2018.08.010.

Three-Dimensional Temporomandibular Joint Muscle Attachment Morphometry and Its Impacts on Musculoskeletal Modeling

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Abstract

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 coregistering 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

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CONFLICT OF INTEREST None of the authors of this paper has a conflict of interest that might be construed as affecting the conduct or reporting of the work presented.

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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.

Keywords

Temporomandibular joint; Musculoskeletal modeling; Muscle attachment; 3D morphometry; Moment arm

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; 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; Goto et al., 2006; Hannam and Wood 1989; Koolstra 2002; Raadsheer et al., 1994; Sasaki et al., 1989; Van Spronsen et al., 1989; Van Spronsen et al., 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; van Eijden et al., 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.

METHODS

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 $0.2 \times 0.2 \times 0.2 \text{ mm}^3$. A more detailed description of the following experiment and analysis protocols is presented in the Supplementary Materials.

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) (9.5mm markers, NaturalPoint, Corvallis, OR) was developed to determine the continuous spatial coordinates of the TMJ muscle attachment boundaries (Figure 1A and 1B). 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 (Figure 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.

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).

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 (Figure 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 (Figure 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 (Figure 6A). Muscle lengths were determined as the length of the corresponding muscle force vectors from origin to insertion, including tendon length between muscle and bone. Muscle moment arms were determined by the perpendicular distance between the sagittal projections of the muscle force vectors and transverse axis

connecting lateral poles of the mandibular condyles, as previously described (van Eijden et al., 1997).

TMJMusculoskeletal Modeling

To assess the impact of 3D muscle attachment morphometry in the ‘Distributed model’ compared to the centroid-to-centroid muscle model on joint mechanics, inverse dynamics models of the mandible were developed to estimate muscle length change, forces, moments, and joint reaction forces during mandible maximal open-close (de Zee et al., 2007). With institutional approval, a 3D solid model of the skull and mandible was obtained from a CBCT scan of a 29-year old male with normal skeletal anatomy and no known history of TMJ disorders. The subject was selected to approximate the average skull size of the cadaveric specimens. Muscle attachment morphometry of the live subject was achieved by co-registering the 3D solid model with digitized muscle attachment boundaries of the median-sized cadaver specimen through point-based registration and ICP techniques (Pellikaan et al., 2014). Two TMJ computational models, consisting of the skull, mandible, temporalis, masseter, lateral pterygoid, and medial pterygoid, were then constructed: 1) a ‘Distributed model’ including distributed muscle force vectors for temporalis (Figure 5A) and masseter (Figure 6A) muscles, which have broad attachments; and 2) a ‘Centroid model’ replacing the distributed temporalis muscle forces with centroid-to-centroid force vectors. Dynamic stereometry (Palla et al., 2003) recorded jaw movement with custom tracking devices (Figure 7A). Bilateral temporalis and masseter muscle EMG activities were recorded with surface electrodes (Biometrics, Newport, UK). The relative movement of the lower jaw with respect to the skull was calculated using a coordinates transformation method (Spoor and Veldpaus, 1980). Anterior-posterior translation of the condylar center was calculated, to determine the position and timing of mandible open-close (Tuijt et al., 2010). The obtained mandible kinematics and EMGs were input into the two computational models to calculate instantaneous muscle length, velocity, and moment arm, as well as muscle forces and joint reaction force, during jaw open-close (Buchanan et al., 2004).

The results of temporalis muscle length change, temporalis muscle forces, moments, and joint reaction forces were compared between the ‘Distributed model’ and ‘Centroid model’.

Statistical Analysis

A repeated measures general linear model, with skull side as a within-subject factor and age as the covariate, was used to test symmetry between left and right hemispheres in the muscle attachment morphometry of cadaveric specimens. A one-way ANOVA with Turkey’s post hoc tests was performed on the muscle lengths and moment arms to determine the differences between the centroid-to-centroid force vectors and distributed force vectors within the temporalis and masseter muscles. Descriptive statistics were reported as mean $\pm$ standard deviation. Statistically significant differences were reported at $p < 0.05$. Statistical analysis was performed using SPSS (Version 24.0, IBM Corp., Armonk, NY).

RESULTS

3D Muscle Attachment Morphometry

3D shapes of human TMJ muscle attachments for each cadaveric specimen were shown in Figures 3 and 4. The temporalis muscle origin was observed to have a large ‘shell’ shape, with a convex curvature, while the temporalis insertion had an approximately planar and triangular shape. The masseter muscle origin followed a thin arched shape running anterior-posteriorly with a large radius of curvature in the medial-lateral direction, while the masseter insertion was approximately planar and elliptical in shape. The superior origin of the lateral pterygoid muscle occupied a very limited area, which was simplified as a point. The inferior origin of the lateral pterygoid muscle was flat and rectangular in shape, while the lateral pterygoid muscle insertion was trapezoidal in shape. The medial pterygoid muscle origin and the inferior origin of the lateral pterygoid muscle were both located on the medial-lateral side of the lateral pterygoid plate and considered to be co-localized and similarly shaped. The medial pterygoid muscle insertion was observed to be oval in shape.

The 3D morphometry of TMJ muscle origins and insertions was quantified by 3D bounding box technique (Figure 2). Muscle attachment sizes (Length, Width, Thickness, and Area), spatial locations (x, y, and z), and spatial orientations (SA, FA, FHA), as well as muscle volumes, were determined and listed in Tables 1 and 2. Statistical results indicated that skull side was not a significant factor in determining TMJ muscle attachment morphometry; therefore, bilateral average muscle lengths and moment arms across the entire 3D shape of the muscle attachment were shown in Figure 5 for temporalis muscle and Figure 6 for masseter muscle, respectively. Temporalis muscle fiber lengths ranged from 30.7 ± 3.2 mm (‘Inferior’) to 117.9 ± 12.9 mm (‘Superior’), with muscle length significantly longer for ‘Superior’ ($p < 0.001$) and ‘Posterior’ ($p < 0.001$), and smaller for ‘Inferior’ ($p < 0.001$) force vectors, compared to the ‘Centroid’ force vector. Moment arms for temporalis muscle fibers ranged from 4.5 ± 2.5 mm (‘Posterior’) to 28.6 ± 3.0 mm (‘Anterior’), with moment arms significantly larger for ‘Anterior’ ($p < 0.001$) and smaller for ‘Posterior’ ($p < 0.001$) force vectors, compared to the ‘Centroid’ force vector. Masseter muscle fiber lengths ranged from 39.8 ± 6.0 mm (‘Lateral.1’) to 63.3 ± 6.0 mm (‘Anterior.2’), with ‘Anterior.2’ ($p < 0.001$) and ‘Lateral.2’ ($p = 0.047$) lengths significantly larger compared to the ‘Centroid’ force vector. The moment arms for masseter muscle fibers ranged from 7.8 ± 3.8 mm (‘Posterior’) to 48.3 ± 3.2 mm (‘Anterior.2’), with ‘Anterior.1’ ($p < 0.001$) and ‘Anterior.2’ ($p < 0.001$) significantly larger, and ‘Lateral.1’ ($p = 0.025$) and ‘Posterior’ ($p < 0.001$) smaller, compared to the ‘Centroid’ force vector.

Impacts of 3D Muscle Attachment Morphometry on TMJ Mechanics

Large differences were found in temporalis muscle length change, forces, moments, and TMJ reaction forces between the ‘Distributed model’ and ‘Centroid model’ of a live subject during mandible maximal open-close motion (Figure 7). Bilateral average ratio of temporalis muscle length changes (with respect to the initial length at the mouth close position) for ‘T₂ Distributed’ force vector in the ‘Distributed model’ was nearly two times that of the centroid-to-centroid force vector (‘T Centroid’) in the ‘Centroid model’. Consequently, the muscle force magnitude of the ‘T₂ Distributed’ force vector increased more sharply during

the initial opening phase, compared to the 'T Centroid' force vector. Throughout the mandible open-close motion, the total temporalis muscle force ('T Distributed', blue solid line) predicted in the 'Distributed model' was markedly larger than that ('T Centroid', red solid line) predicted in the 'Centroid model'. Temporalis muscle moment in the medial-lateral direction (major rotation axis) predicted from the 'Distributed model' ('T_X Distributed', blue solid line), was also larger than that ('T_X Centroid', red solid line) predicted from the 'Centroid model' during the entire open- close motion. Peak joint reaction force predicted from the 'Distributed model' was 48.8 N, while the peak joint reaction force predicted from the 'Centroid model' was only 38.8 N. Throughout the entire mandible open-close motion, the 'Centroid model' (red solid line) constantly underestimated the joint reaction forces, compared to the 'Distributed model' (blue solid line), with a maximum difference of 21.0 N (i.e., 54% of the peak joint reaction force predicted from the 'Centroid model') at both the mid-point of jaw open or close phase.

DISCUSSION

The objectives of this study were to develop a co-registered 3D digitization and imaging-based method to quantify 3D human TMJ muscle attachment morphometry, and to determine the impact of the muscle attachment morphometry on predicting muscle lengths, moment arms, and moment, and joint loading through musculoskeletal modeling. TMJ muscle attachments were quantified by muscle origin and insertion size, shape, location, and orientation for the temporalis, masseter, lateral pterygoid, and medial pterygoid using a 3D bounding box method. By considering 3D muscle attachment morphometry, muscle lengths, and moment arms varied significantly across the attachment region for temporalis and masseter muscles. These results suggest the assumptions required by centroid-to-centroid muscle models, wherein all muscle fibers have the same lengths and excursions, may not be valid, especially for muscles with broad attachment sites. Furthermore, through musculoskeletal modeling of maximum mandible open- close motion, the 'Centroid model' was shown to underestimate muscle length changes, forces, moments, and joint reaction forces compared to the 'Distributed model', which incorporated vital 3D muscle attachment morphology.

The 3D bounding box morphometric analysis in this study adopted ideas from previous studies that utilized a 2D bounding box to define the length and width of the articular surfaces of the sacroiliac joint (Cassidy, 1993; Ohba, 1985; Weisl, 1954). The 3D surface of human TMJ muscle attachments are irregularly shaped; thus, by applying the 3D bounding box, which reduces the complexity of 3D surface analysis while preserving key characteristics of TMJ muscle morphology, 3D TMJ muscle attachment morphometry could be quantified, and left-right asymmetry assessed. The resulting left-right asymmetry of TMJ muscle attachment morphometry proved to be not statistically significant in this study, given donor populations were selected with normal skeletal and musculature anatomy for a baseline measurement.

The size and orientation of TMJ muscle attachments significantly affected TMJ muscle biomechanics, especially for muscles with broad attachments. For example, the area of the temporalis origin was almost 22 times bigger than the temporalis insertion; thus, the

temporalis muscle should be modeled with multiple force vectors initiating from the temporalis origin and converging inferiorly at a single point at its insertion. As shown in Figure 5, the moment arms and lengths of these vectors were significantly different from the centroid-to-centroid force vector. The significant variation in moment arms among the seforcev ectors could be attributed to the large ‘Length’ (113.3 ± 11.8 mm) of the temporalis origin 3D surface defined in the bounding box (anterior-posterior). In contrast, temporalis muscle fiber lengths associated with each force vector varied significantly because of the large ‘Width’ (85.1 ± 10.2 mm) of the temporalis muscle bounding box (superior-inferior). A similar situation for muscle length and moment arm also arose in the masseter muscle, which has a broad attachment, as shown in Figure 6. Furthermore, unlike other TMJ muscle attachments, which are predominately parallel or perpendicular to an anatomic plane, the masseter origin tilted largely with respect to both the Sagittal plane ($SA = 66.2 \pm 8.2$ degree) and Frankfurt plane ($FHA = 34.3 \pm 7.1$ degree), consistent with its role in producing versatile biting forces (Hannam and Wood, 1989).

The 3D muscle attachment morphometry affected TMJ mechanical loading predictions through musculoskeletal modeling. It was observed during mandible maximum open-close, that large variations in muscle length changes were present among distributed temporalis muscle fibers (Figure 7B), indicating the existence of diverse mechanical actions of muscle fibers within temporalis muscle. For example, the ‘T₂ Distributed’ (inferior) temporalis muscle fiber had a much shorter length and a larger ratio of length changes (nearly 2 times more) during the open- close motion compared to the centroid-to-centroid temporalis muscle fiber. These results suggest that a larger passive force could be generated in the ‘T₂ Distributed’ fiber during mandible opening because of an exponential increase of passive force as the muscle fiber is stretched beyond its optimum length (Van Ruijven and Weijs, 1990). It has been shown the passive forces of jaw-closing muscles, such as temporalis and masseter, are determinant joint forces during maximum jaw opening (Langenbach and Hannam, 1999; Peck et al., 2000; Weijs et al., 1989). Thus, compared to the “Centroid model”, it was anticipated from the “Distributed model” that the force magnitude of the ‘T₂ Distributed’ temporalis muscle fiber, as well as the overall temporalis muscle, increased more sharply and reached a higher level during the mandible opening phase (Figure 7C). Consequently, the temporalis muscle moment (Figure 7D) and TMJ reaction force (Figure 7E), which balances the muscle forces, were largely underestimated in the centroid-to-centroid muscle modeling (about 54% lower for joint reaction force). Accurate quantification of joint mechanical loading environment is critical in TMJ disorder diagnosis and treatment. It has been shown that mechanical work deposited on the TMJ disc was significantly higher in subjects with disc displacement than healthy individuals (Gallo et al., 2015). Determination of joint loading is the first step towards understanding TMJ disorder etiology and mechanobiology (Nickel et al., 2018). Musculoskeletal models can also be a powerful tool for the evaluation of TMJ implant design (Ackland et al., 2015) and treatment planning (de Zee et al., 2007). Thus, 3D muscle attachment morphometry needs to be considered in musculoskeletal models to precisely estimate TMJ muscle forces and joint reaction forces.

Limitations of this study include a relatively small size ($N=9$) of cadaveric samples. Given the well-controlled donor populations with normal musculoskeletal anatomy, the statistically

significant effect of the 3D muscle attachment morphometry on TMJ biomechanics was successfully demonstrated under the current sample size. It is worth noting that previous studies (van Eijden et al., 1995, 1996; van Eijden et al., 1997) successfully measured masticatory muscle architecture with a similar sample size of eight. Additionally, musculoskeletal models studying the impact of 3D muscle attachment morphometry on TMJ mechanics were developed based on one live subject. Considering the purpose of building a generic mandible model for TMJ biomechanics, the live subject was representative of the average size of the cadaveric samples. Furthermore, instead of direct measurement of joint reaction forces, the dynamics model was validated by comparing the predicted muscle forces against measured muscle EMG activity, which is commonly used in TMJ and knee musculoskeletal models (Supplementary Figure 5) (Erdemir et al., 2007).

In conclusion, this study quantified the 3D size, shape, location, and orientation of human TMJ muscle attachments by co-registering TMJ muscle attachment boundary digitization with CBCT skull images. Significant variations of moment arms and muscle lengths were found within temporalis and masseter muscles. The values calculated from the 'Centroid model' were significantly different from those calculated using the 'Distributed model', which considered crucial 3D muscle attachment morphometry. Consequently, joint loading was underestimated in the 'Centroid model'. This study demonstrated 3D muscle attachment morphometry should be considered in TMJ musculoskeletal models to precisely quantify the joint mechanical environment critical for understanding TMJ function and mechanobiology.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGEMENTS

This project was supported by NIH grants DE018741 and DE021134, a NIH T32 postdoctoral fellowship DE017551 and a NIH F32 post-doctoral fellowship DE027864 to MCC, and an International Research Collaboration grant to XC.

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Figure 1:

(A) A custom tracking probe was developed to digitize the human TMJ attachment boundaries, where red curves represent a contour of the digitized muscle attachment boundary. Position vectors of the marker probe's tip in the GCS were calculated from four fiducial reflective markers (M_1 , M_2 , M_3 , and M_4). (B) The custom tracking probe with fiducial markers was designed with interchangeable tips to facilitate measuring of muscle attachment locations, which could be interior to the bony surfaces of the skull or mandible. A reference marker set was attached to the skull during dissection to determine its instantaneous position. (C) TMJ muscles were dissected sequentially by oral and maxillofacial surgeons who outlined each TMJ muscle attachment origin and insertion boundary for digitization after removing muscle.

Figure 2:

The size of the 3D surface of each TMJ muscle attachment (temporalis origin illustrated as an example) was represented by the Length, Width, and Thickness of a 3D bounding box (black bold frame). A skull-based coordinate system was established to determine the Centroid (C) coordinates (x, y, and z) of each muscle attachment for its location, and the angles between 'Box Plane' and Sagittal plane (SA), Frontal plane (FA), and Frankfurt plane (FHA) respectively for its orientation.

Figure 3: Morphology of Temporalis and Masseter muscle attachments (N=9), where the red curve on each skull indicates a representative digitization of the muscle attachment boundaries. TO is Temporalis Origin; TI is Temporalis Insertion; MO is Masseter Origin; MI is Masseter Insertion. A and P stand for the anterior and posterior directions. These images do not reflect the relative size of the muscle attachments between muscle groups (see Table 1), but do represent the relative size within a muscle group.

Figure 4: Morphology of Pterygoid muscle attachments (N=9), where the red curve on each skull indicates a representative digitization of the muscle attachments. LPO is Inferior Lateral Pterygoid Origin; LPI and MPI are Lateral and Medial Pterygoid Insertions, respectively. A, P, M, and L stand for the anterior, posterior, medial and lateral directions. These images do not reflect the relative size of the muscle attachments between muscle groups (see Table 1), but do represent the relative sizes within a muscle group.

Figure 5:

(A) Five force vectors of temporalis muscle were defined, with the four black arrows indicating the 'Anterior', 'Posterior', 'Superior', and 'Inferior' force vectors, and the blue arrows ('Centroid') representing the centroid-to-centroid force vector. (B) Bilateral average muscle lengths and moment arms of the 5 representative force vectors of temporalis muscle (N=9). Muscle length was significantly larger for 'Superior' and 'Posterior', and smaller for 'Inferior' force vectors, compared to that of the centroid-to-centroid force vector. Moment arms of the 'Anterior' force vector was significantly larger than that of the centroid-to-centroid force vector; moment arms of the 'Posterior' force vector were significantly smaller than that of the centroid- to-centroid force vector. **: ANOVA, $p < 0.001$

Figure 6:

(A) Six force vectors of masseter muscle were defined, with the three black arrows indicating 'Anterior.1', 'Lateral.1' and 'Posterior' force vectors for deep masseter, and two red arrows indicating 'Anterior.2' and 'Lateral.2' force vectors for superficial masseter, and the blue arrows ('Centroid') representing the centroid-to-centroid force vector. (B) Bilateral average muscle lengths and moment arms of the six representative force vectors of masseter muscle (N=9). Muscle length was significantly larger for 'Anterior.2' and 'Lateral.2' compared to that of the centroid-to-centroid force vector. Moment arms of 'Anterior.1' and 'Anterior.2' force vectors were significantly larger than that of the centroid-to-centroid force vector; moment arms of 'Lateral.1' and 'Posterior' force vectors were significantly smaller than that of the centroid-to-centroid force vector. *: ANOVA, $p < 0.05$; **: ANOVA $p < 0.001$

Figure 7:

(A) Custom tracking devices with fiducial markers, fixed rigidly to the skull ('Markers_1') and mandible ('Markers_2') respectively, were utilized to capture the motion during dynamic mandible maximal open-close. Surface electrodes were used for measuring bilateral EMG activities of human temporalis ('EMG_TL, R' at left/right side cephalad) and masseter ('EMG_ML, R' at left/right side cephalad) muscles. 3D solid models of the skull and mandible were created, with condylar center defined as approximate center of condylar head. (B) Bilateral average ratio of temporalis muscle length changes to initial length at mouth closing position. 'T_{1~5} Distributed' represented 'Superior', 'Inferior', 'Anterior', 'Posterior' and 'Centroid' temporalis forces in 'Distributed model'; 'T Centroid' represented centroid-to-centroid temporalis muscle force in 'Centroid model'. 'Displacement' referred to displacement of condylar center in anterior-posterior direction. (C) Bilateral average magnitude of temporalis muscle forces. 'T Distributed' was resultant force of 'T_{1~5} Distributed' in 'Distributed model'. (D) 'T_{x,y,z} Distributed' and 'T_{x,y,z} Centroid' were bilateral total temporalis muscle moments with respect to mandible mass center along the medial-lateral, anterior-posterior, and superior-inferior directions from 'Distributed model' and 'Centroid model' respectively. (E) Bilateral average magnitude of TMJ reaction forces and predicted difference between 'Distributed model' and 'Centroid model'.

Table 1:

Human TMJ muscle attachment size (Length, Width, Thickness of the bounding box, and Area of the 3D attachment surface) in addition to volume of each temporomandibular joint muscle (Volume), by left and right side. Origin* stands for inferior lateral pterygoid origin.

		Side	Length (mm)	Width (mm)	Thickness (mm)	Area (cm ²)	Volume (cm ³)
Temporalis	Origin	Left	111.0±13.4	82.1±11.3	21.7±2.9	75.0±16.0	27.3±7.0 (L)
		Right	115.7±10.9	88.1±10.8	23.7±3.6	79.0±16.0	
	Insertion	Left	26.9±5.22	24.5±7.1	3.0±1.1	3.7±1.2	25.9±7.1 (R)
		Right	28.7±5.2	21.0±5.2	2.4±0.4	3.2±1.1	
Masseter	Origin	Left	45.3±4.5	4.2±1.8	8.9±3.6	-	15.7±4.3 (L)
		Right	50.8±8.4	5.3±1.5	12.1±4.4	-	
	Insertion	Left	30.9±6.42	33.1±4.1	4.6±1.3	7.9±2.5	15.7±5.1 (R)
		Right	31.8±7.6	32.1±5.8	3.6±1.0	7.5±2.2	
Lateral Pterygoid	Origin*	Left	13.7±2.5	26.2±3.1	4.5±1.3	3.0±0.9	5.5±1.3 (L)
		Right	15.0±2.7	27.2±2.4	4.7±0.8	3.0±0.6	
	Insertion	Left	3.9±0.82	11.6±1.5	14.5±1.7	1.4±0.2	5.2±1.0 (R)
		Right	4.0±0.8	11.5±2.0	14.3±2.1	1.4±0.3	
Medial Pterygoid	Origin	Left	13.7±2.5	26.2±3.1	4.5±1.3	3.0±0.9	6.8±0.9 (L)
		Right	15.0±2.7	27.2±2.4	4.7±0.8	3.0±0.6	
	Insertion	Left	25.1±3.72	26.9±4.7	3.9±0.8	4.5±1.0	7.2±0.9 (R)
		Right	26.0±6.4	27.3±5.0	4.0±0.5	4.6±1.0	

Table 2:

Human TMJ muscle attachment spatial location (x, y, and z) and spatial orientation (SA, FA, FHA), by left and right side. Origin# stands for superior lateral pterygoid origin and Origin* stands for inferior lateral pterygoid origin.

		Side	x (mm)	y (mm)	z (mm)	SA (°)	FA (°)	FHA (°)
Temporalis	Origin	Left	-60.2±2.6	20.2±5.3	35.9±8.1	16.6±5.0	77.2±3.4	80.5±5.5
		Right	59.7±2.0	14.2±4.7	40.4±7.4	11.2±3.2	81.2±2.6	83.8±3.4
	Insertion	Left	-43.3±1.6	35.2±5.3	-34.0±5.4	17.7±3.8	83.7±4.1	73.9±3.1
		Right	46.6±2.5	35.1±3.9	-30.2±3.5	14.2±3.0	83.7±4.2	77.7±1.9
Masseter	Origin	Left	-54.4±2.6	45.2±3.0	-18.9±3.1	68.4±15.7	68.5±10.2	34.7±14.0
		Right	55.3±1.8	44.3±6.6	-16.0±2.4	64.0±11.6	72.8±7.3	34.0±5.6
	Insertion	Left	-43.7±2.4	17.6±5.9	-57.8±4.6	18.8±5.6	72.9±6.6	83.4±2.4
		Right	48.1±3.3	17.4±4.8	-54.8±2.4	18.1±4.2	73.1±4.3	84.7±3.3
Lateral Pterygoid	Origin*	Left	-26.8±4.8	38.2±3.5	-4.2±5.2	-	-	-
		Right	25.3±4.8	35.7±3.8	-1.7±3.0	-	-	-
	Origin#	Left	-21.9±2.3	33.0±1.6	-22.2±2.5	22.6±5.5	72.6±5.0	77.4±6.4
		Right	23.2±1.9	32.7±1.8	-20.2±3.1	26.3±3.8	70.9±5.7	73.7±4.4
	Insertion	Left	-47.8±3.7	12.3±1.9	-13.3±2.3	58.6±10.0	33.4±8.7	82.5±5.8
		Right	49.0±2.4	12.5±2.6	-9.6±3.2	60.1±7.0	30.8±7.3	84.3±4.0
	Origin	Left	-21.9±2.3	33.0±1.6	-22.2±2.5	22.6±5.5	72.6±5.0	77.4±6.4
		Right	23.2±1.9	32.7±1.8	-20.2±3.1	26.3±3.8	70.9±5.7	73.7±4.4
Medial Pterygoid	Insertion	Left	-40.1±2.6	12.7±6.5	-60.3±5.4	22.6±7.7	69.3±9.4	83.4±3.4
		Right	45.2±2.9	11.7±5.8	-57.2±3.1	21.3±5.1	69.6±5.5	85.5±3.7