Individual Variations in Numerically Modeled Human Muscle and Temporomandibular Joint Forces During Static Biting

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Some of the data presented in this article were presented previously at the annual meeting of the American Association for Dental Research in Chicago in March 2001 and at the annual meeting of the International Association for Dental Research in Chiba, Japan, in June 2001.

Aims: *To test the effects of occlusal force (OF) angle on the variations in predicted muscle and temporomandibular joint (TMJ) forces during unilateral molar bites.* ***Methods:*** *The craniomandibular (CM) geometries of 21 individuals were determined from lateral and posteroanterior cephalometric radiographs. These geometries were used in a numerical model based on minimization of muscle effort. This model was previously validated for this subject group through the use of jaw tracking and electromyographic data. The model predicted muscle and TMJ forces associated with static OFs on the right mandibular first molar. OF angle was varied from vertical to 40 degrees in the buccal and lingual directions, in increments of 10 degrees.* ***Results:*** *Intra- and intersubject variations in predicted muscle and TMJ forces for unilateral molar biting were dependent on OF angle and CM geometry. Nonvertical OFs were associated with either large anterior temporalis muscle forces (> 100% of applied OF in 3 subjects) or large inferior lateral pterygoid muscle forces (> 90% of applied OF in 3 subjects). On average, vertically and buccally directed OFs were associated with higher mean contralateral TMJ forces (60% of applied OF, SD 12%). Two subjects had large ipsilateral or contralateral TMJ forces (> 90% of applied OF).* ***Conclusion:*** *In a group of healthy subjects, depending on the individual CM geometry, large muscle and/or TMJ forces were predicted to be associated with specific unilateral molar OF angles. Propensities to increased muscle or joint forces may be predisposing factors in the development of myofascial pain or intracapsular disease. The results may explain, in part, the variation in location of symptoms in individuals who first present with temporomandibular disorders.* J OROFAC PAIN 2004;18:235–245

Key words: biting, modeling, muscles, occlusal forces, temporomandibular joint

Many human anatomic features have been considered as predisposing factors in the development of masticatory muscle pain and/or temporomandibular joint (TMJ) degeneration.[1,2] Traditional descriptive analyses of the occlusion and cephalometric relationships have been unsuccessful in predicting which individuals, and which structures, are predisposed to dysfunction.[3–8] A better understanding of the physics of the individual craniomandibular apparatus and the objectives for neuromuscular control in this system may elucidate the observed variability among individuals with respect to the apportionment of muscle and joint forces during loading of the mandible. This in turn may account for whether and where symptoms occur in certain individuals and specific structures.

Computer-generated models based on human anatomy offer a method of studying muscle and TMJ forces in response to applied mandibular loads. Computer models have been used to study other joint systems[9] such as the wrist,[10] knee,[11,12] shoulder,[13] hip,[14] and spine.[15] These joint systems, as well as the craniomandibular system, are mechanically indeterminate, since there are a number of reasonable muscle and joint force solutions that could stabilize a given static load applied to the system. One approach to address the problem of indeterminacy has been to simulate the system by using specific assumptions to render a unique solution for static equilibrium. Such assumptions have included assignment of muscle forces, based on muscle cross-sectional area and averaged electromyographic (EMG) data,[16–19] and constraint of the direction of condylar loading.[20–24] The fidelity of a simulation model to the in vivo condition lies in the accuracy of using pooled data from which averages are derived and assumed to be applicable to the individual. The solutions rendered by simulation models are exceedingly difficult to validate because in vivo data to test the model results usually cannot be measured from living humans.

In contrast to simulation models, computer models have been developed that do not rely on large amounts of averaged or assumed data but rather render solutions for muscle and joint forces based on an optimal strategy or an objective function that is of biological importance. The objective function represents a theory of underlying neuromuscular control.[9,25–29] Examples of optimal strategies or objective functions include minimization of joint loads or minimization of the square of muscle force (muscle effort). This type of computer modeling uses an iterative or "trial and error" technique in which muscle and joint forces are varied in order to produce static equilibrium while meeting the requirements of a particular objective function. Features that distinguish objective-function-based models are the number of independent muscles or parts of muscles, the formulation of the joint loads, and the specific objective function. This strategy-dependent numerical modeling has been used to study the development of the immature[30,31] and mature[32–35] TMJ eminence and the muscle and TMJ forces associated with intraoral and extraoral loading of the mandible.[32–35] Trainor et al have provided detailed descriptions of nonlinear numerical methods in modeling of mandibular muscle forces and TMJ loads during static loading of the mandible.[26,36] The validity of this type of theoretical model can be determined by testing its predictive value for an individual against experimental data derived from the same individual.[32–35]

Previous studies have validated a set of objective function numerical models of the TMJ for a group of subjects.[32–34] The aim of this study was to apply these validated models to test the effects of mediolateral occlusal force (OF) angle on the variations in muscle and TMJ forces during unilateral molar biting. The long-term objectives of this work are to develop numerical models that will aid the diagnosis and prevention of temporomandibular disorders (TMD) and the development of biophysically sound methods of treating intracapsular disease.

Materials and Methods

Subjects

The subjects were 21 adults (10 men and 11 women, mean age 24 ± 4 years) invited to participate in the model validation studies from a pool of patients before or after orthodontic treatment.[32–34] These individuals were free of symptoms of TMD, a history of TMD, or TMJ trauma, and all exhibited symmetrical dentofacial features. Each subject gave informed consent, and the study protocol was approved by the University of Nebraska Medical Center Institutional Review Board.

Craniomandibular Geometry

A 3-dimensional geometry file for each individual was developed using standardized lateral and posteroanterior cephalometric radiographs to determine the positions of the muscles of mastication, condyles, and tooth row according to a coordinate system (Fig 1). Preliminary studies were conducted using a set of adult male human skulls (mean age 39 ± 10 years) to develop a technique to identify reliably the areas of attachment of the muscles of mastication from standardized cephalometric radiographs.[37] The x, y, and z coordinates were determined for the centroids of the origins and insertions of 5 muscle pairs (superficial masseter, anterior temporalis, medial pterygoid, inferior head of lateral pterygoid, and anterior digastric muscles), the superoanterior-most point on the mandibular condyles, and the positions of the mandibular central incisors, canines, and first permanent molars. Serial tracings of x, y, and z coordinates for individual landmarks indicated that the maximum tracing errors were ± 3.5 mm. Error studies showed that this range of tracing errors produced less than 5% variance in predicted muscle or TMJ forces.

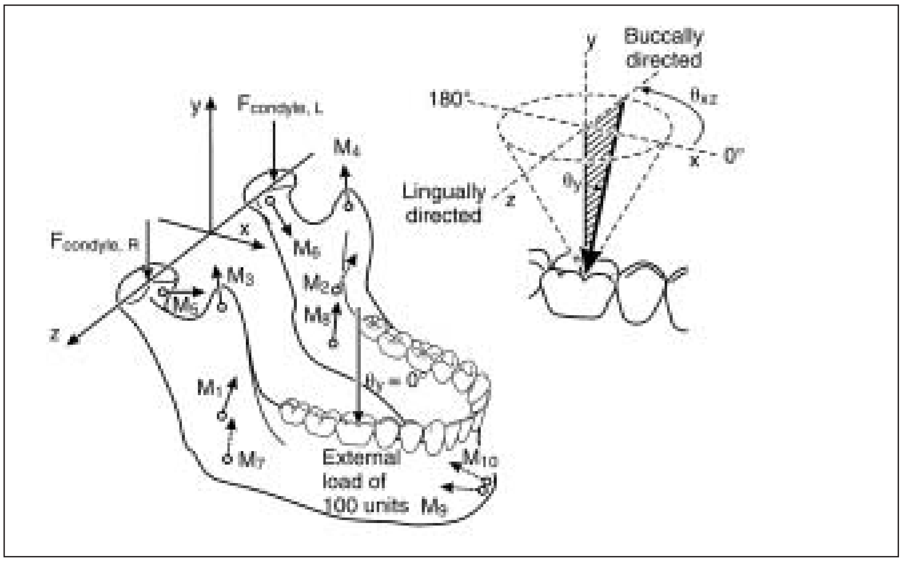


Fig 1 Orthogonal axis system used by the numerical models showing the force vectors involved in numerical models of isometric mandibular loading in humans. Forces on the mandible (eg, external load), at the joints ($F_{condyle}$, R = right, L = left), and representing 5 muscle pairs ($M_{1,2}$ = masseter, $M_{3,4}$ = temporalis, $M_{5,6}$ = lateral pterygoid, $M_{7,8}$ = medial pterygoid, $M_{9,10}$ = anterior digastric) are illustrated. The axis system used to characterize the relative positions of the condyles, the teeth, and the muscle vectors, based on an individual's anatomy, is also shown. Note that the x and z axes are parallel to the occlusal plane. Predicted force magnitudes were expressed as a percentage of the applied OF. This OF (external load) of 100 units was applied at the right first molar, at angles ranging from 0 to 40 degrees for θ_y and from –90 degrees (buccally directed) to 90 degrees (lingually directed) for θ_{xz}. The main diagram illustrates a vertical OF (θ_y = 0 degrees), while the insert illustrates a buccally directed OF (Modified from Smith et al[25]).

Validation Studies

The effective sagittal TMJ eminence morphology was defined by the shape of hard and soft tissue structures articulating with the mandibular condyle in lateral view. This morphology represented the sagittal plane projection of the trajectory of the intracapsular stress field during centered protrusion and retrusion of the mandibular condyle.[38] In each of the 21 subjects, jaw tracking was performed to measure the effective sagittal TMJ eminence morphology for comparison with numerical model predictions of this morphology. This method of jaw tracking has been described previously.[32–34] In brief, this method involved a custom-made mandibular removable appliance, similar to an orthodontic retainer, with a facebow attached. The positions of the right and left mandibular condyles were identified by palpation, and markers on the right and left ends of the facebow were adjusted to lie just lateral to these positions. The occlusal plane was identified with a metal guide and was drawn temporarily on the right and left cheeks. Each subject performed a set of 10 centered protrusive and retrusive movements of the mandible, with the teeth minimally separated, and the appliance, facebow, and a metric grid in place. This was recorded with video cameras positioned directly lateral to the subject on the right and left sides. The same movements were recorded at a second session on another day. The recordings from each side were viewed frame by frame and the condylar marker position relative to the occlusal plane was traced on acetate affixed to a video screen. The path of the marker was quantified in 2 dimensions with the occlusal plane and a perpendicular line as axes. A custom-made computer program was used to record the horizontal and vertical coordinates, correct for scale according to the metric grid, and calculate a best-fit cubic polynomial that represented the experimentally determined effective eminence shape. Results from each side and recording session were averaged and compared for symmetry and consistency. Combined intra- and intersession variability was on average a maximum of ± 0.4 mm, or ± 10% of full scale.

A numerical modeling program using optimization based on unconstrained minimization of joint loads (MJL) and the subject's geometry file were employed to predict a unique effective sagittal TMJ eminence morphology.[26] Joint force directions were calculated for a series of symmetrical, bilateral vertical OFs applied from first molars to central incisors in 20 steps. At each step, the mandible was anteriorly repositioned by the computer program to be consistent with the bilateral bite position, and changes in muscle orientation were then incorporated before calculating the direction of joint loading. For equilibrium, each joint force was expected to be directed perpendicular to the effective eminence. Therefore, the effective eminence shape was delineated by a series of short lines representing surfaces perpendicular to predicted joint force directions for the series of bilateral vertical bite forces with corresponding posteroanterior condylar positions. The short lines were joined end to end and smoothed to generate a curve. The shape of the curve was stored as a cubic polynomial and compared metrically, using linear regression analysis, to the shape of the average effective eminence morphology measured by jaw tracking. The results validated the use of the model to predict effective sagittal TMJ eminence morphology in each subject.[32–34]

Two 3-dimensional models with different objective functions, *(a)* minimization and equalization of right and left TMJ loads (MJL), and *(b)* minimization of muscle effort (MME, minimization of the sum of squared muscle forces), and the individual craniomandibular geometries were used to predict muscle forces. In both models, the effective sagittal TMJ eminence shape was determined using the 2-dimensional MJL model described above. Three-dimensional joint force directions were then formulated to constrain the sagittal component in a direction perpendicular to the predicted eminence while maintaining an independent mediolateral component. An optimization strategy of either MJL or MME was chosen, and muscle forces were calculated for a given geometry and any prescribed mandibular position and force applied to the mandible. For this, a single-stage algorithm[36] was designed to operate directly in 3 dimensions and satisfy the constraint equations at all times. MJL or MME were nonlinear programming problems and, therefore, more complex optimizations. However, these problems were amenable to analysis using quadratic programming.[36] The algorithm performed an incremental "shakedown" of muscle force patterns in order to achieve MJL or MME.[26]

Bipolar EMG recordings were used to measure muscle activity as a surrogate for force during static mandibular loading tasks in each of the 21 subjects. These data were then used for comparison with individual numerical model predictions for muscle forces during the same static tasks. The in vivo and modeled tasks involved static chin loading,[34] vertical molar biting,[32,33] and molar biting with known buccal and lingual crown moments.[33] The EMG activities of the medial pterygoid and inferior head of the lateral pterygoid were recorded by indwelling intramuscular electrodes, as recently described.[35] The EMG activities of the right and left sides of the superficial masseter, anterior temporalis, and anterior digastric muscles were recorded with conventional surface recording methods that have been described previously.[32–34] In brief, for each muscle, paired surface electrodes approximately 23 mm apart were placed parallel to the direction of muscle action, over the middle of the muscle bulk, and a single ground electrode was affixed to the ear lobe. Impedances were below 30 kΩ. The electrical signals from the muscles were amplified (P511AC Grass Preamplifiers; Astro-Med) approximately 2,000 times. Amplifier input impedance was 20 MΩ and bandwidth was 0.1 to 3 kHz. Signals were viewed in real time using commercial software (PCscan MKII PCIF250NI Real-time Data Transfer System, Sony Magnescale America), and stored digitally (Sony PC-216A 16-Channel Digital Recorder, Spectris Technologies) on cassette tape. Signal-to-noise ratios were greater than 8 to 1.

Analysis of covariance and linear regression analyses were used to test for differences between model-predicted muscle forces and bilateral EMG data from the masticatory muscles. The validation studies involving molar biting,[32,33] demonstrated in 15 subjects that the model based on MME matched best overall with in vivo data.

Modeling of Static Occlusal Loads on the Mandibular Right First Molar

The objective function model based on MME and validated by subject-specific experimentally measured data[32,33] was used to test the hypothesis that significant individual variation exists with respect to the muscle and TMJ forces required to stabilize a given static OF on the mandibular right first molar. This MME model was used with the geometry of each of the 21 subjects to calculate subject-specific muscle and joint forces in response to loading of 100 units on the mandibular right first molars at θ_y angles of 0 to 40 degrees from a vertical direction, and θ_{xz} from –90 degrees (buccally directed) to 90 degrees (lingually directed) (Fig 1). Means and standard deviations (SDs) of the results were calculated, and individuals with muscle or

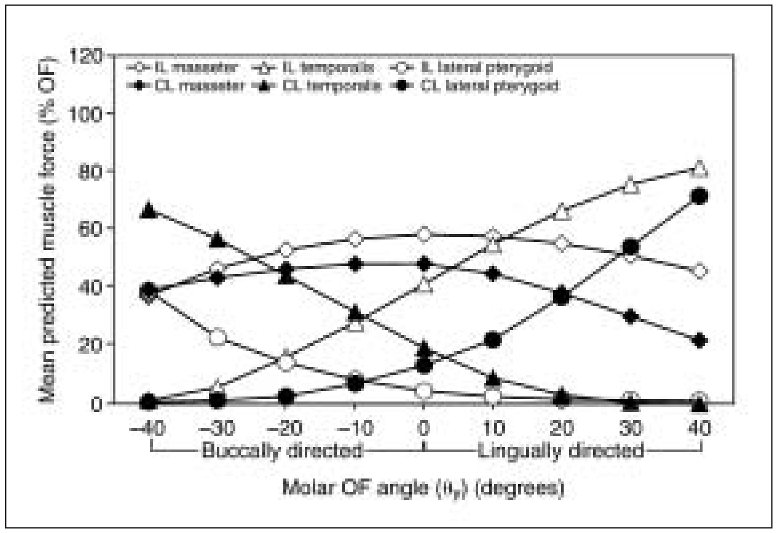


Fig 2 Mean predicted muscle forces for various molar OF angles. Mean results are from 21 subjects. Vertical OF angles are denoted as θ_y = 0 degrees, with buccally directed angles denoted as negative and lingually directed angles denoted as positive. Data from the medial pterygoid muscles are not shown but were similar to the data from the masseter muscle in these subjects. IL = ipsilateral; CL = contralateral.

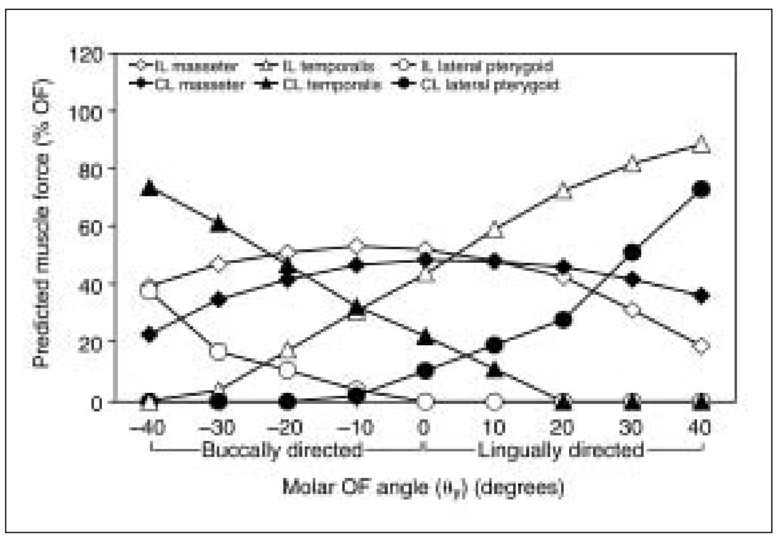


Fig 3 Predicted muscle forces for various molar OF angles for subject F9. Muscle forces are expressed as a percentage of the applied OF and vertical OF angles are denoted as θ_y = 0 degrees, with buccally directed angles denoted as negative and lingually directed angles denoted as positive. Data from the medial pterygoid muscles are not shown but were similar to the data from the masseter muscle in this subject. IL = ipsilateral; CL = contralateral.

TMJ forces much higher than the group means were identified. These individuals were identified in order to provide an estimate of the number of individuals in a clinically healthy population who manifest large muscle or joint forces, or both, and who therefore may have predisposing mechanical factors that influence the development of myofascial and/or intracapsular dysfunction.

Results

Predicted Muscle Forces for Various Molar OF Angles

Mean predicted muscle forces were investigated for a range of buccally directed, vertical, and lingually directed molar OF angles. These mean data showed general patterns of muscle force changes with OF angle change (Fig 2) that resembled data from some subjects (Fig 3), but individual variability in the patterns and the magnitudes of the predicted muscle forces were considerable. Mean results and individual results demonstrating the range of subject variability for each muscle are presented in the following sections.

Masseter Muscle (Superficial). Mean predicted ipsilateral masseter muscle forces were greater than mean predicted contralateral masseter muscle forces for the molar OF angles investigated in the 21 subjects except for the extremely buccally directed forces (Fig 4). Average SDs for the means for predicted ipsilateral and contralateral masseter muscle forces were 16% and 12% of the applied OF, respectively.

The changes in predicted masseter muscle forces with respect to OF angle and predominance of ipsilateral or contralateral masseter muscle force depended on the subject. Model predictions for

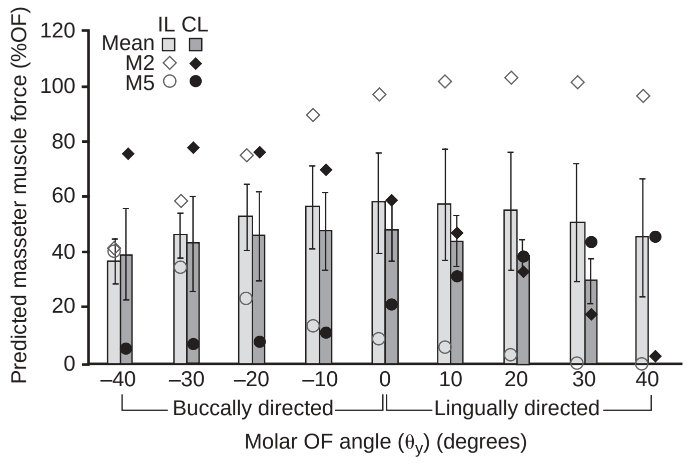


Fig 4 Predicted masseter muscle forces for various molar OF angles. Mean results for 21 subjects as well as individual results for subjects M2 and M5 are shown. Muscle forces are expressed as a percentage of the applied OF, and vertical OF angles are denoted as θ_y = 0 degrees, with buccally directed angles denoted as negative and lingually directed angles denoted as positive. SDs are indicated by vertical lines. IL = ipsilateral; CL = contralateral.

subjects M2 and M5 showed ipsilateral versus contralateral masseter muscle force relationships that changed in opposite directions for the same change in OF angle (Fig 4). The highest predictions were for subject M2. For this subject, ipsilateral masseter muscle force predictions surpassed the group means by between 22% and 51% of applied OF for buccally directed OF angles of ≤ 20 degrees. For lingually directed OF angles, contralateral masseter muscle force predictions were between 22% and 37% greater than the group means (Fig 4).

Temporalis Muscle (Anterior). Predicted ipsilateral temporalis muscle forces increased with lingually directed OF angle, while predicted contralateral temporalis muscle forces increased with buccally directed OF angle (Fig 5a). Average SDs for the mean predicted ipsilateral and contralateral temporalis muscle forces were 14% and 13% of the applied OF, respectively.

The pattern of predicted ipsilateral and contralateral temporalis muscle force change with molar OF angle change varied between subjects, but not as dramatically as for other muscles. For example, for subject F2, the crossover point between ipsilateral and contralateral temporalis muscle forces occurred approximately at vertical biting (Fig 5a). Other subjects showed a similar pattern; however, there was variation in the predicted magnitudes of temporalis muscle force and the crossover point. Predictions for 3 subjects (M1, F1, M5) showed ipsilateral temporalis muscle forces greater than the group means, particularly for lingually directed molar OF angles (Fig 5b). Predictions for 3 subjects (M1, F1, F2) showed contralateral temporalis muscle forces greater than the group means for buccally directed molar OF angles (Fig 5c).

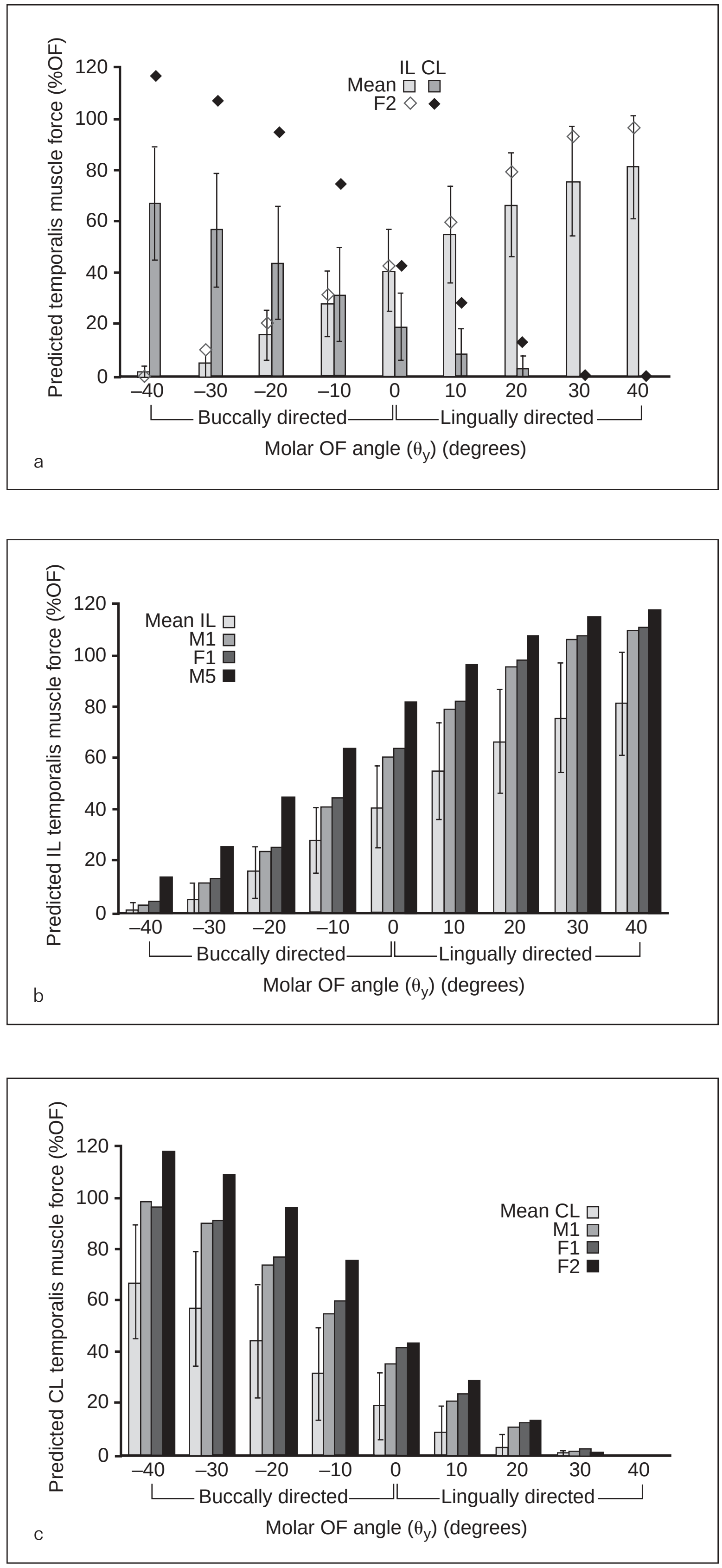
Lateral Pterygoid Muscle (Inferior Head). The overall pattern of mean predicted lateral pterygoid muscle forces (Fig 6a) was generally opposite of that seen for mean predicted temporalis muscle forces. Mean predicted ipsilateral lateral pterygoid muscle forces increased with buccally directed OF angles, while mean predicted contralateral lateral pterygoid muscle forces increased with lingually directed OF angles. Average SDs of the means for predicted ipsilateral and contralateral lateral pterygoid muscle forces were 10% and 13% of the applied OF, respectively. However, SDs varied considerably (± 3% to 22% of applied OF) depending on OF angle (Fig 6a).

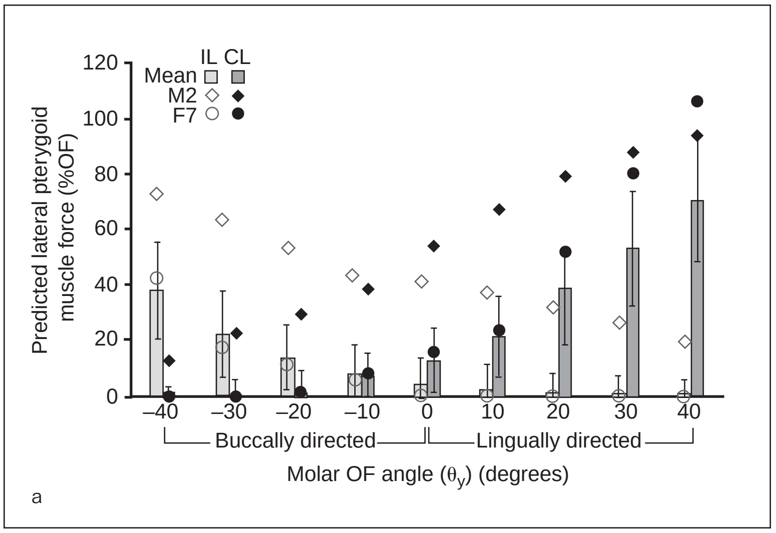
Model predictions for subject M2 showed that ipsilateral and contralateral lateral pterygoid muscle forces existed for all molar OF angles investigated, and that these were all high relative to the group means (Fig 6a). In contrast, results for the rest of the subjects (eg, subject F7, Fig 6a) showed no ipsilateral lateral pterygoid muscle forces for vertical and lingually directed OF angles.

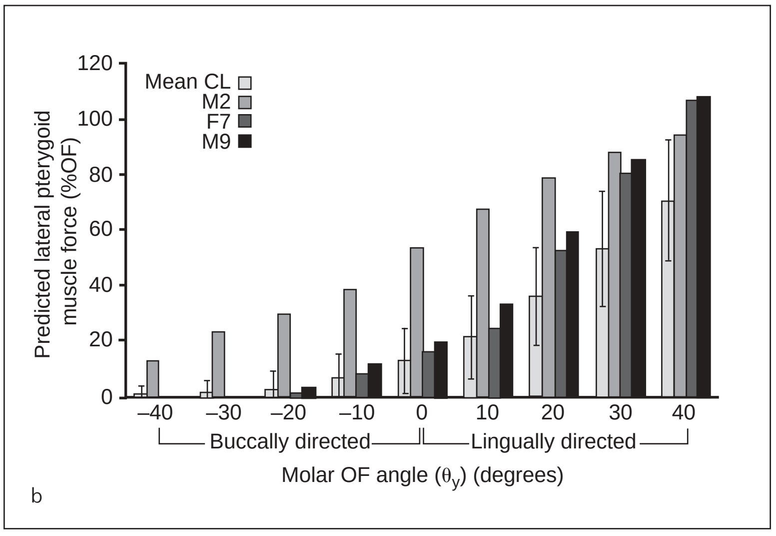
Predictions for 3 subjects (M2, F7, and M9) showed contralateral lateral pterygoid muscle forces greater than the group means for lingually directed OF angles (Fig 6b). For buccally directed OF angles, predictions for subjects M2 and M9 were higher than the group means, M2 by 11% to 35% of applied OF.

Medial Pterygoid Muscle. The modeled results for the medial pterygoid muscle mimicked those for the masseter muscle, where marked variation in muscle force for OF angle was demonstrated. Average SDs of the means for predicted ipsilateral and contralateral medial pterygoid muscle forces were 7% and 5% of the applied OF, respectively.

Figs 5a to 5c Predicted temporalis muscle forces for various molar OF angles. Muscle forces are expressed as a percentage of the applied OF, and vertical OF angles are denoted as θ_y = 0 degrees, with buccally directed angles denoted as negative and lingually directed angles denoted as positive. SDs are indicated by vertical lines. *(a)* Mean results for 21 subjects as well as individual results for subject F2. *(b)* Predicted IL temporalis muscle forces for the group (mean IL) compared to predicted forces for subjects M1, F1, and M5. *(c)* Predicted contralateral temporalis muscle forces for the group (mean contralateral) compared to predicted forces for subjects M1, F1, and F2. IL = ipsilateral; CL = contralateral.







Figs 6a and 6b Predicted lateral pterygoid muscle forces for various molar OF angles. Muscle forces are expressed as a percentage of the applied OF, and vertical OF angles are denoted as θ_y = 0 degrees, with buccally directed angles denoted as negative and lingually directed angles denoted as positive. SDs are indicated by vertical lines. *(a)* Mean results for 21 subjects as well as individual results for subjects M2 and F7. *(b)* Predicted contralateral lateral pterygoid muscle forces for the group (mean contralateral) are compared to those for subjects M2, F7, and M9. IL = ipsilateral; CL = contralateral.

Predictions for subject M2 were the highest for the group. For ipsilateral medial pterygoid muscle forces and lingually directed OF angles, they surpassed the group means by 20% to 23% of the applied OF, and for contralateral medial pterygoid muscle forces and buccally directed OF angles, they surpassed the group means by 10% to 15% of applied OF.

Predicted TMJ Forces for Various Molar OF Angles

Mean predicted TMJ forces varied with molar OF angle in a fashion similar to the pattern seen with mean predicted temporalis muscle forces. Buccally directed and vertical molar OF angles resulted in higher mean contralateral TMJ forces (Fig 7). Mean predicted contralateral TMJ loads were more than 3.5 times greater than the mean ipsilateral loads for the buccally directed OF angles of –40 degrees. As the molar OF angle became lingually directed, mean predicted contralateral TMJ loads decreased, while ipsilateral TMJ loads more than doubled.

Predicted TMJ force patterns varied among subjects. For example, results for subject F7 showed higher contralateral TMJ forces than ipsilateral TMJ forces (Fig 7). In contrast, results for subject M2 showed that ipsilateral TMJ forces increased and contralateral TMJ forces decreased as the lingually directed OF angle increased, while contralateral TMJ forces increased and ipsilateral TMJ forces decreased as the buccally directed OF angle increased.

Average SDs of the means for ipsilateral and contralateral TMJ forces were 14% and 12% of applied OF, respectively. Based on the modeled TMJ forces, 2 individuals had potential for large

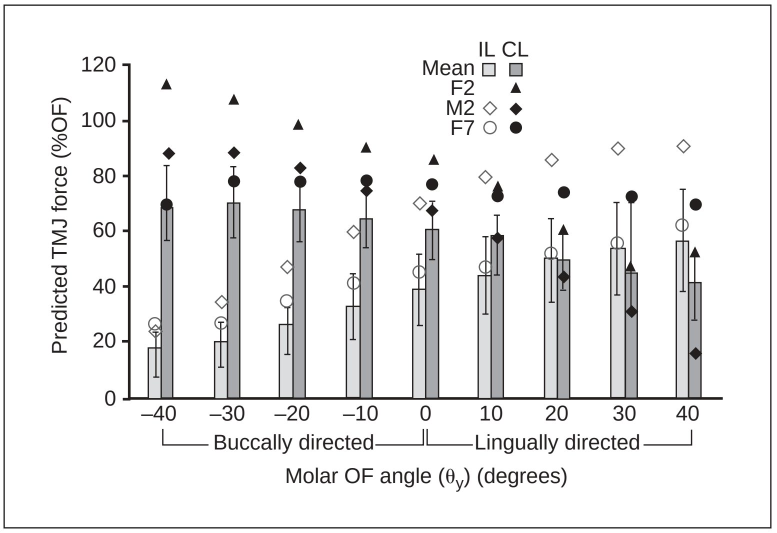


Fig 7 Predicted TMJ forces for various molar OF angles. Mean results for 21 subjects as well as individual results for subjects F2, M2, and F7 are shown. Muscle forces are expressed as a percentage of the applied OF, and vertical OF angles are denoted as θ_y = 0 degrees, with buccally directed angles denoted as negative and lingually directed angles denoted as positive. SDs are indicated by vertical lines. With respect to subject F2, the magnitudes of the ipsilateral TMJ loads and the changes in loads with changing OF angle were like those seen for subjects M2 and F7, so these data were not included in the figure. IL = ipsilateral; CL = contralateral.

condylar loads. Results for subject M2 showed ipsilateral TMJ forces that surpassed the group means for vertical and lingually directed OF angles by 33% to 35% of applied OF (Fig 7). Results for subject F2 showed contralateral TMJ forces that surpassed the group means for vertical and buccally directed OF angles by 26% to 44% of applied OF (Fig 7).

Discussion

An objective function numerical model was used to predict muscle and TMJ forces required to stabilize static OFs applied unilaterally at the first molar in a range of mediolaterally directed angles. The model results suggest that the mix of muscle and TMJ forces required depends on the anatomy of the subject and the specific angle of the applied OF.

Numerical Modeling and Human Craniomandibular Mechanics

Generally, the contralateral condyle is regarded as being loaded more than the ipsilateral condyle during unilateral biting.[39,40] For many of the biting conditions examined, the numerical models predicted this relationship. However, in specific individuals, the numerical models predicted larger ipsilateral than contralateral TMJ forces when the OF angles were more lingually directed. Ipsilateral TMJ forces greater than 80% of the applied OF were produced by lingually directed OF angles of 10 to 40 degrees from vertical (subject M2, Fig 7). The current study predicted that high ipsilateral or contralateral condyle loads were dependent on an individual's craniomandibular geometry and the direction of the OF.

The individual variability demonstrated relative to mean results for predicted muscle forces (eg, Figs 4 and 5), may explain, in part, the reported differences in muscle behavior during static biting. Other studies have shown that buccally directed OFs on the mandibular molar produced mean ipsilateral/contralateral masseter muscle ratios greater than 1.0.[41,42] In contrast, these same OFs produced mean ipsilateral/contralateral temporalis muscle ratios less than 1.0. When OFs were lingually directed, mean ipsilateral/contralateral masseter muscle ratios were less than 1.0, due to an increase in contralateral and a decrease in ipsilateral masseter muscle activities. Data from subject F9 (Fig 3) show similar patterns of predicted masseter muscle forces for various OF angles as reported in these studies.[41,42] In another study of unilateral molar biting at different angles in 5 subjects,[43] dissimilar results were found. That is, the mean ipsilateral/contralateral masseter muscle ratio was found to be greater than 1.0 for buccally directed OFs, and increased for lingually directed OFs. Subject M2 in the current study demonstrated a similar trend for the predicted masseter muscle force change for OF angle change (Fig 4). Mean ipsilateral/contralateral temporalis muscle ratios increased when the OF angles changed from buccally to lingually directed in the previous studies noted,[41–43] and for the predicted results in the current study (Fig 5a).

Previous work[32,33] suggested that for the group of subjects studied, MME was the neuromuscular objective employed to stabilize static loads applied to the mandibular right first molar. The mechanism of feedback and central pattern generator control of muscle recruitment probably relies on the periodontal ligament mechanoreceptors. These receptors are organized into fields that permit directional sensitivity.[44,45] It remains to be determined how these groups of receptors elicit muscle recruitment patterns that are consistent with a neuromuscular objective of MME. Studies using local anesthesia may be a practical method of testing whether these mechanoreceptors are the primary source of information upon which masticatory muscle recruitment is determined.

The previous validation studies[32–34] that were the basis of the current study had limitations in that in vivo data from only 3 of 5 masticatory muscles and from intraoral (biting) tasks in only 15 of the 21 subjects were measured. In only 1 of these validation studies[33] did the biting tasks mimic lingually and buccally directed OF angles ranging from 0 to 30 degrees. More recent tests of the objective function models involving other subjects have included indwelling electrodes to gather data from the lateral and medial pterygoid muscles in addition to surface EMG recording from the masseter, temporalis, and digastric muscles and have included a wider range of OF angles.[35] To date, all of the previous validation studies were limited in that tests of accuracy of modeled joint force direction were restricted to the sagittal plane (θ_{xy}). Future work should test modeled 3-dimensional loading of the human TMJ using computer-aided surface contact analysis of reconstructed 3-dimensional nuclear magnetic resonance images.

Variables Important to Craniomandibular Mechanics

Studies using objective function modeling have shown that certain anatomical features (eg, height of the condyle above the occlusal plane, anteroposterior position of the teeth, and angulation of the masseter, temporalis, and lateral pterygoid muscles relative to the occlusal plane) are particularly important to the mechanics of the craniomandibular system.[37] The relationships between important variables deserve attention in future studies. Objective-function-based numerical modeling provides a method to investigate these relationships systematically for the individual.

Acknowledgments

The authors wish to acknowledge the work and dedication of Drs Brian Baird, Robert Walker, and Ping Yao, who gathered in vivo data to test the models, and Mr Kim Theesen, who helped with the figures. Dr B. R. Thornton was supported by a University of Nebraska Medical Center College of Dentistry Student Summer Research Fellowship Award.

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