

# Modeling Rabbit Temporomandibular Joint Torques During a Power Stroke

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**Abstract:** Little information exists regarding the effects of changes in mandibular form as a result of orthognathic surgery on torques produced about the temporomandibular joint (TMJ). In this study, we have modeled torques produced about the working side TMJ by selected compartments of the rabbit masseter muscle based on published electromyographic activity. The masseter muscle is composed of multiple subregions or compartments that have unique mechanical actions. In a previous study, forces were elicited by electrical stimulation of each compartment and were recorded by a multiaxis force transducer attached to the anterior mandible. Torques were calculated using mandibular lever arms measured from the center of the TMJ. We have extended this modeling to include variations in mandibular width, length, or height to determine the torques that would be generated with variations in mandibular form. Three superficial masseter compartments on the working side and one posterior deep compartment from the balancing side masseter were examined using data collected from a companion study. It was found that the working and balancing side compartments were synergists for pitch torque components but were antagonists for roll and yaw. In modeling an increase of each mandibular dimension by 20%, nonuniform changes in compartment-generated torques were found. The largest increase was found for the posterior superficial masseter yaw torque component. The effects of changing mandibular form on torques produced about the TMJ may be greater than predicted by previous models that assumed a single line of force produced by each jaw muscle. (*Angle Orthod* 2002;72:331–337.)

**Key Words:** Temporomandibular joint; Torques; Masseter muscle; Compartments

## INTRODUCTION

The role of muscle function during mastication and the torques they produce about the temporomandibular joint (TMJ) have been topics of interest for many years.<sup>1–3</sup> It has been traditionally accepted that muscle recruitment involves activation of the whole muscle (defined by its general anatomy). However, this view has changed over the past two decades and there is now good evidence that many muscles, including the masticatory muscles, are compartmentalized.

Much can be gained in understanding the forces produced by human muscle compartments during function and the resulting torques about a joint through the use and manipulation of an animal model that has similar muscle architecture and motor control mechanisms. The rabbit masticatory system provides an excellent model for human jaw muscle function in that rabbit masseter has similar muscle architecture and activity. Both human and rabbit masseter muscles consist of superficial, intermediate, and deep layers.<sup>4,5</sup> Although the angle of pinnation of muscle fibers in these layers may be less in the human masseter, the relative orientations are similar (ie, the superficial layer has muscle fibers oriented toward the anterior while the deep layer has muscle fibers oriented toward the posterior). Another similarity between human and rabbit masticatory systems is the chewing pattern that incorporates working and balancing side movements during reduction of the bolus of food.<sup>2</sup> The rabbit also has jaw motor-control mechanisms that are similar to those observed in the human and has been extensively studied.<sup>6,7</sup> These similarities qualify the rabbit as one of the best animal models for studying the human masticatory system.

In human jaw muscles, the anterior and posterior temporalis muscle,<sup>8,9</sup> superficial and deep masseter muscle,<sup>10,11</sup>

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and superior and inferior heads of the lateral pterygoid<sup>12,13</sup> have all been shown to vary in the intramuscle activity according to the specific masticatory task and to support a regionalization of muscle activation. The rabbit masseter muscle has multiple tendons of origin and insertion that further separate the three layers of the muscle into 12 anatomic partitions.<sup>14</sup> In addition, each anatomic partition may be composed of one or more compartments. We have shown that the most superficial partition has at least two compartments (anterior superficial masseter, posterior superficial masseter) that produce different torques about the TMJ.<sup>15</sup> The estimated number of distinct output elements composing the rabbit masseter may be as many as 20–25 compartments. These different regions or compartments are differentially activated during the production of different oral behaviors.<sup>16,17</sup>

In a previous study, we examined the torques produced about the TMJ by individual masseter muscle compartments.<sup>17</sup> We found that each compartment produced a unique torque vector, in terms of its magnitude and/or direction, about the TMJ. These mechanical differences qualified each compartment as an output element. Once these fundamental output elements were identified, the effects of combinations of elements during the power stroke could be examined to understand the diversity of mechanical actions that can be generated by a single muscle. These findings serve as a foundation for the modeling used in this study, in which we changed lever arms representing mandibular width, length, or height and studied the changes this produced in torques about the TMJ.

Similar changes in mandibular length occur after orthognathic surgery, but little is known about their mechanical consequences or how this might impact on TMJ form and function. Skeletal malocclusions are many times treated using mandibular advancement or mandibular retraction procedures such as the bilateral sagittal split ramus osteotomy.<sup>18</sup> These procedures change the position of the mandibular teeth in the anterior–posterior dimension while not affecting the attachment of the masticatory muscles. It is known from a recent study that the bite force of orthognathic surgery patients meets or exceeds presurgical levels within one year after the surgery.<sup>19</sup> Thus, even with altered mandibular length, the incising and crushing forces necessary to support a normal diet are achieved. Thus, it is reasonable to assume that an increase in torques about the TMJ occurs since the same or higher bite force is applied but with a longer lever arm if the surgery was correcting a Class II deficiency.

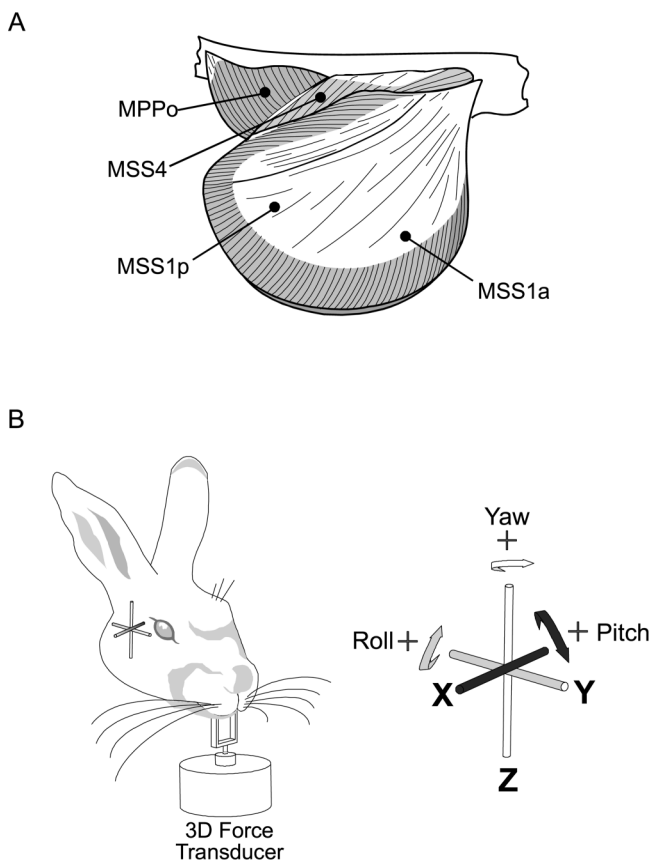
The purpose of this study was to model the torques produced about the rabbit temporomandibular joint as a function of changes in the length, width, and height of the mandible. In addition, modeling activity of specific masseter compartments rather than the whole muscle during a power stroke may provide insight into potential torques about the human TMJ that previously had not been considered.

## MATERIAL AND METHODS

Data forming the basis for this study were taken from our recent measurements of the torques produced by electrically stimulating different masseter muscle compartments in the rabbit. Details of the methodology of data acquisition can be found elsewhere and will be described here briefly.<sup>15</sup>

Four adult male and one adult female New Zealand white rabbits were used to generate the primary data utilized in our simulations. All experiments were conducted in accordance with institutional guidelines governing the use of laboratory animals. The right masseter was surgically exposed to reveal the entire rostral to caudal extent of the muscle. Bipolar fine wire EMG electrodes were implanted into six defined sites (MSS1a, anterior superficial masseter; MSS1p, posterior superficial masseter; MSPR, pars reflexa of the superficial masseter; MSS3 and MSS4, two caudal superficial compartments; and MPPo, posterior deep masseter) near the endplates on the surface of the compartment (Figure 1A).<sup>14</sup> Four of these compartments (MSS1a, MSS1p, MSS4, and MPPo) were used in the modeling study because published EMG data are available to document their participation during the power stroke. A stainless steel clamp was attached to the mandible bilaterally just posterior to the mental foramina, and this clamp was attached to the surface of a multiaxis force/torque transducer (Gamma 65/5, ATI) to record mandibular forces. Compartments were stimulated with a constant voltage at an intensity (2T) that elicited a very localized muscle contraction that was visible in the muscle and was confirmed to be localized as an EMG potential in one of the six compartment EMG recordings.

Force records were simultaneously obtained in three dimensions from single stimuli. All records were repeated six times. The axes were orientated such that working–balancing forces were in the *X* plane, protrusion–retrusion forces were in the *Y* plane, and jaw opening–closing forces were in the *Z* plane (Figure 1B). Lever arms used in torque calculations were measured from the center of the temporomandibular joint to the center of the transducer in each of the three dimensions. These three measures form the components of a position vector. Torque vectors were calculated as the cross-product of this position vector and the force vector measured in response to electrical stimulation. Each vector consists of three components, ie, pitch, roll, and yaw, as moments around the *X*, *Y*, and *Z* axes, respectively. Defined with respect to the anatomy, pitch is the jaw opening–closing torque and, by convention, jaw opening is positive while jaw closing is negative. Yaw is the working–balancing torque, and the balancing side is positive while the working side is negative. Roll is the torque component about the anteroposterior axis, with the rotation of the teeth toward the buccal is positive while rotation toward the lingual is negative. We determined the torques applied to the mandible about the ipsilateral (right) TMJ by the working



**FIGURE 1.** (A) Lateral view of the rabbit masseter with the stimulating locations designated for the four different compartments that were evaluated in this study. (B) The multiaxis force/torque transducer was attached to the mandible posterior to the mental foramen bilaterally by screws and the head was stabilized in a fixed headholder. The axes in the X, Y, and Z directions form the three-dimensional reference frame. The torque about these axes is shown with the arrows designating the positive torque direction for pitch, roll, and yaw components.

side superficial compartments (MSS1a, MSS1p, MSS4) and by the balancing side deep masseter compartment (MPPo).

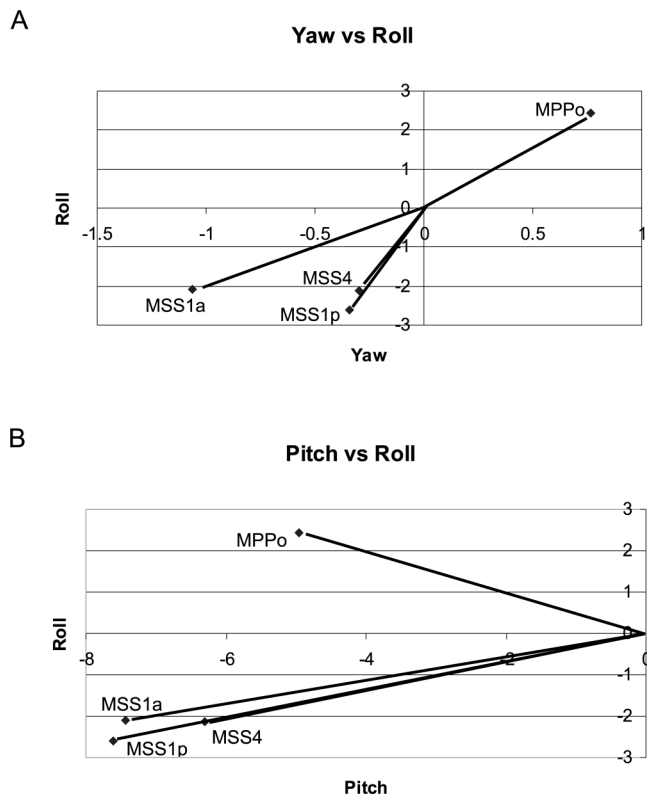
Modeling the torques about the working temporomandibular joint during the power stroke was the focus of this study. The power stroke in the rabbit consists of movement of the mandible from a lateral interocclusal position on the working side back toward the midline while maintaining tooth contact.<sup>20</sup> The four compartments studied (MSS1a, MSS1p, MSS4, MPPo) were selected because they are active during the power stroke. Weijs and Dantuma<sup>16</sup> showed that the superficial masseter (MSS1a, MSS1p, MSS4) was recruited on the working side at the same time that the deep masseter (MPPo) was active on the balancing side. Since all recorded forces used in our model were obtained from recordings made in response to stimulation of the working side masseter, we reversed the sign of the MPPo force in the X dimension (medial–lateral) in order to transpose the force to the balancing side. The change of sign of the MPPo force subsequently has been validated during bilateral elec-

trical stimulation (unpublished observations). The components of the force vector in the Y and Z planes were assumed to be the same for both the working and balancing side masseters.

To model the effects of altering mandibular form, we simulated changes in mandibular width, length, or height by  $\pm 20\%$ . We assumed that the forces at the transducer would remain constant since the forces necessary to penetrate and break down the foodstuff would be the same regardless of the mandibular form, and this assumption has been supported by the results from a recent study of orthognathic surgery patients.<sup>19</sup> The simulated changes in mandibular form were expressed as changes in the lever arms (position vector) used to compute the torques. The pitch, roll, and yaw components of the torque vectors produced by each compartment about the working TMJ were calculated using these modified lever arms, and these were compared with the torques computed using the original lever arms. A summed torque vector representing the contributions of the four masseter compartments was also calculated for each modeling parameter and analyzed similarly. Differences in calculated torques resulting from the changes in lever arm lengths were expressed as a percent change for each compartment. These differences were analyzed using a Friedman ANOVA followed by Wilcoxin matched pair signed rank tests for multiple comparisons using a probability level of .05. Nonparametric statistics were used because the requirements for use of parametric methods could not be met, probably due to the small number of samples (five rabbits).

## RESULTS

The torques about the working side TMJ produced by activating the four masseter compartments differ from one another in both magnitude and direction. In Figure 2, the three rectilinear components of the torque vector, pitch, roll, and yaw, determined for each compartment are graphed against one another in two bivariate scatterplots. Solid lines connect each point with the origin. The magnitude of each vector is proportional to the length of this line. The orientation of each line in space describes the direction of the torque vector. Note that all four compartments studied produce negative pitch, indicating that they produce a jaw-closing torque. In contrast with this synergism in jaw closing, the three compartments from the masseter muscle on the working side antagonize both the yaw and roll components of the torque vector produced by the balancing side posterior deep masseter (MPPo). When the four torque vectors produced by the different compartments are summed, the single vector that results contains a very strong jaw-closing component that reflects the synergy about that axis and smaller yaw and roll components that reflect the antagonism of the compartments about those axes. Such a



**FIGURE 2.** Mean compartment torque components plotted as yaw and roll (A) or pitch and roll (B). Torques are expressed as cm-N. Note that MPPo has yaw and roll components that are nearly opposite to the superficial compartments while all compartments contribute a negative pitch equivalent to a jaw closing rotation.

summed effect would be expected during the power stroke of chewing.

When we changed lever arm dimensions to simulate variation in mandibular form, a differential effect on the torques generated by each compartment was observed. In the formulas for calculating torque vector components, each of the three components of the position vector used (lever arms) contributes to two torque vector components. For example, mandibular length is used in the calculation of the pitch and yaw components of the torque vector but not the roll component. Changes in mandibular length would be expected to influence pitch and yaw but not roll. Similarly, changes in mandibular width would be expected to change yaw and roll but not pitch and changes in mandibular height would influence pitch and roll but not yaw. Changes in the torque vectors produced by each of the four masseter compartments studied associated with simulated increases in different aspects of mandibular form are shown in Figure 3A. Changes in the vector produced by summing the vectors for all four compartments are shown in Figure 3B. In all cases, significant changes in all components of the vector were found by changing mandibular form, but the most striking effect was on the yaw component.

The net effect of a 20% decrease in each of the *X*, *Y*,

and *Z* dimensions is shown for the summed vectors in Figure 3B. A simulated 20% decrease of the mandibular dimensions of width, length, and height resulted in a change in the individual torque magnitudes that were roughly equal in magnitude and opposite in direction when compared with the effect of the 20% increases in mandibular form described above. For example, decreasing mandibular width by 20% produces a simulated *reduction* in the roll component of the torque vector that is comparable with the increase in roll produced by an *increase* in mandibular width by 20%. Similarly, decreasing mandibular length results in an increase in the yaw component of the TMJ torque vector, the magnitude of which is comparable with the decrease in yaw resulting from increasing mandibular length by 20%.

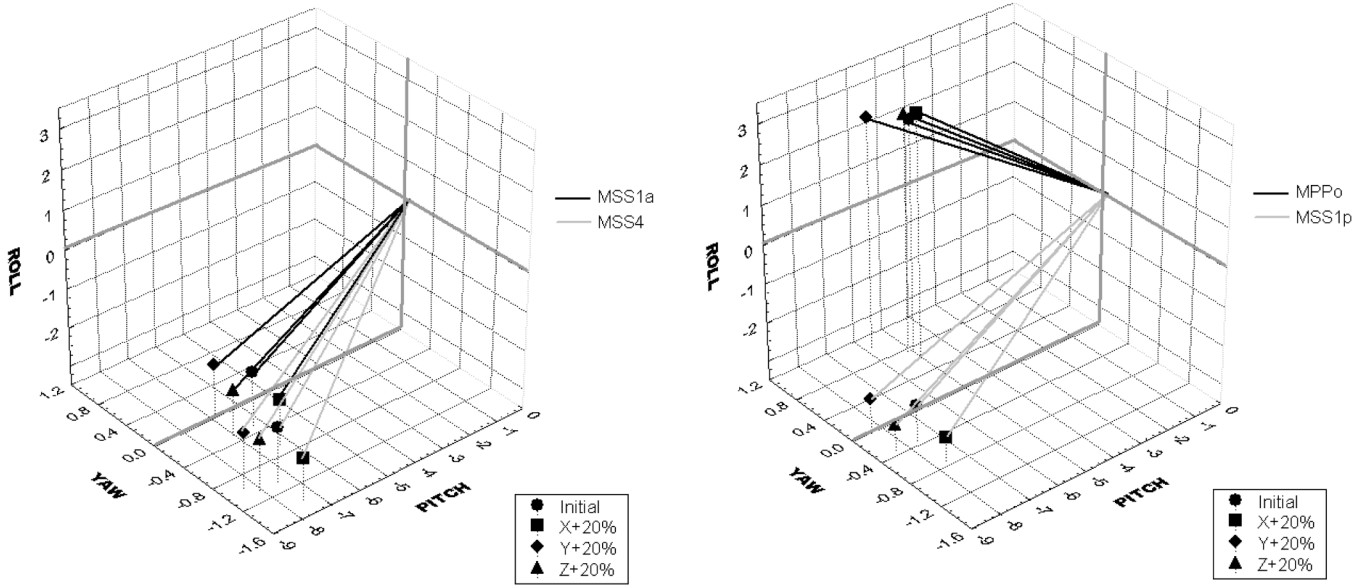
It is noteworthy that changes in mandibular form may have interacting effects. For example, decreasing mandibular width results in a simulated change in yaw that is comparable with the change produced by increasing mandibular length. Based on our simulations, we would anticipate that increasing both mandibular length and width would result in an approximate additive increase in pitch but little change in yaw.

The differential effect of changing mandibular form on the components of the working side TMJ torque vector is noted also if the change in each component is expressed as a percentage (Figure 4). Significant ( $P < .05$ ) changes in the magnitude of each of the three components of the torque vector were encountered with all changes in mandibular form, but the yaw component was most strikingly changed.

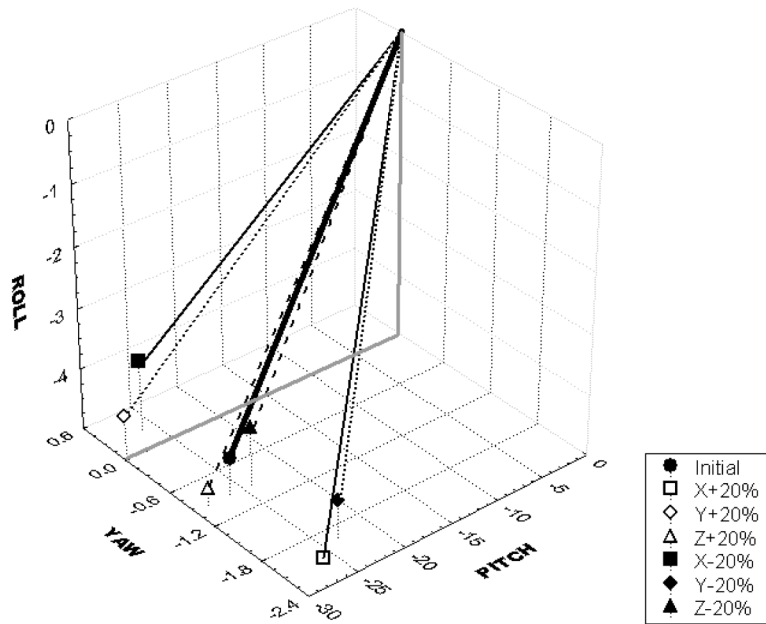
## DISCUSSION

Increasing the width, length, or height of the mandible by 20% did not have a uniform effect on the torque components produced about the TMJ by each masseter compartment. Instead, the greatest effect was on yaw, with an increase of over 240% produced by the posterior superficial masseter (MSS1p) while only affecting pitch and roll at levels of up to 20%. This differential effect can be explained by the relatively different components of the forces produced by these compartments in the *X*, *Y*, and *Z* axes. Although simulated changes in mandibular form resulted in hypothetical changes in the *magnitude* of masseter compartment torques about the TMJ that were significantly different, the net effect of this more robust effect on yaw is that the *direction* of the torque vector produced by each compartment is changed as well. Understanding the potential effect of changing mandibular form on torques produced about the temporomandibular joint is particularly important because these changes may occur subsequent to orthognathic surgery. For example, after the mandible is lengthened for correction of a Class II malocclusion, the patient regains normal bite force levels within a year.<sup>19</sup>

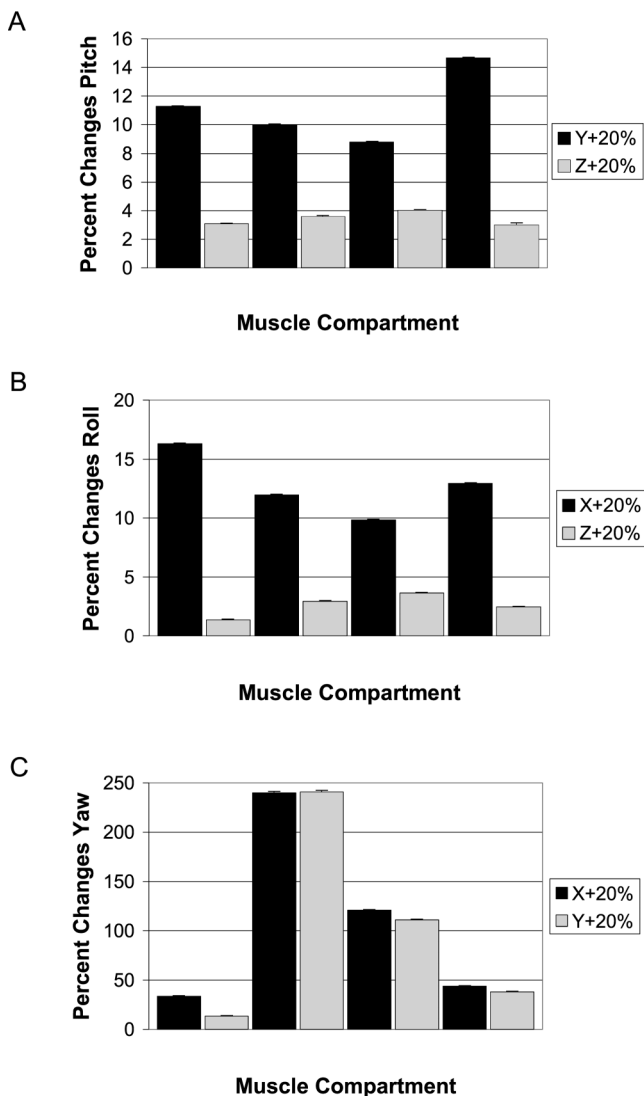
A



B



**FIGURE 3.** (A) Mean resultant torques shown as a three-dimensional plot produced by each compartment for the initial mandibular dimensions as well as 20% increased in width (X), length (Y), or height (Z) values. (B) Vectors representing the sum of the individual torques produced by each compartment for each condition including the initial mandibular dimensions, a 20% increase or 20% decrease in width, length, or height.



**FIGURE 4.** Mean percent changes ( $\pm$ SE) for (A) pitch, (B) roll, and (C) yaw after a 20% increase in either of the two axes used to calculate the torque component produced by each compartment. All compartment value comparisons were statistically different for each dimensional change.

Based on the results of our simulations, we would predict that, because of the alteration in mandibular form, these patients would produce torques about the working side TMJ whose magnitudes were larger than normal and whose directions were different than before surgery. If comparable changes occur in humans after mandibular dimensional changes, the changes in TMJ torque, especially the dramatic change in yaw, may elicit adaptive changes. One such form of adaptation might be the recruitment of other compartments in the masseter (or other jaw muscles) to higher than normal levels in an effort to counteract the big change in yaw. Such muscle adaptations may result with a more pronounced loading of the TMJ during chewing. Indeed, evidence of adaptation or remodeling changes within the joint have been reported as new clicking or crepitus sounds in

patients after orthognathic surgery.<sup>21,22</sup> However, more extensive animal and human investigations are necessary to determine if these increased torques are produced at significant levels to cause bony and soft tissue changes within the TMJ.

During the rabbit power stroke, the activation of the working side superficial masseter and balancing side deep masseter has the net effect of producing a large closing pitch while at the same time decreasing the yaw and roll components about the working side temporomandibular joint. This outcome reduces off-sagittal torques about the joint during a heavy bite. However, based on the results of our modeling experiments, we anticipate that the off-sagittal torques of the working side TMJ torque vector will be most profoundly affected by changes in mandibular form. If these off-sagittal components of the TMJ torque become larger than normal, then structures such as the collateral ligaments that attach the disc to the condyle could become stressed and result in laxity of these ligaments and hypermobility of the disc.

Thus far, the discussion has focused on the changes of one of the dimensions of the mandible and the net biomechanical effects. However, in humans, the orthognathic surgical procedure to address mandibular retrognathism results in an increase in both mandibular length and a small increase in mandibular width. This is due to the reattachment of the distal segments of the mandible at a more posterior position that has a wider dimension due to the divergence of the mandible. In the rabbit, increasing both the mandibular length and width in the same proportions would have the net effect of a small increase in the pitch but very little change in the yaw and roll. Therefore, off-sagittal torques would be minimally affected when both length and width of the mandible are increased. However, if all three dimensions were increased, the result would generate an increase in the roll component, at least in the rabbit. It is important to limit the interpretations of these findings because it is unclear whether this same result would be found in the human jaw system since we do not have modeling data. Nevertheless, the potential for biomechanical changes in the TMJ should be recognized after mandibular surgery and understanding these changes may allow a more predictive surgical outcome.

This study is the first to model the torques about the temporomandibular joint using experimentally measured forces from different regions of the same muscle. Most models of masticatory muscles use estimates of fiber orientations measured from the centroid of serial magnetic resonance imaging (MRI) or computerized tomography (CT) muscle cross-sections and estimate the relative muscle force using the muscle cross-sectional area.<sup>23-26</sup> The advantage of the model in this study is that experimentally measured force magnitudes and directions in three dimensions were used as well as electromyographic evidence of the participation of these compartments during a limited portion of

the chewing cycle. Further studies are necessary to expand this model. Understanding the complexity of the force production from compartments within jaw muscles and their individual contributions to the chewing cycle will give us further insight into the effect that alterations of the anatomy can have on masticatory function.

### CONCLUSION

Based on a rabbit model of working side temporomandibular joint torques produced by regional activation of compartments of the working and balancing side masseter muscle, the net biomechanical effect seems to maximize the pitch torque components (jaw closing rotation) while minimizing the resulting yaw and roll torques. The regional compartments within the masseter produce different medial-lateral, anterior-posterior, and superior-inferior force components and therefore generate different torques about the joint. Modeling changes of mandibular width, length, or height was shown to affect the torques about the TMJ, with the greatest relative effect on the working-balancing axis of rotation of the condyle (yaw). The resulting changes of torques within the temporomandibular joint after surgical mandibular advancement or retraction should be recognized as a potential factor that requires adaptation by the patient.

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