Original Paper

Function of digastric muscle as regards the controllability of temporomandibular joint loading: A static 2-D analysis using a rigid-body spring model

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[Received: August 29, 2002.]

Key Word: temporomandibular joint (TMJ) loading, bite force, static analysis, rigid-body spring model, digastric

Abstract: In order to clarify the control mechanisms of temporomandibular joint (TMJ) loading during a static bilateral bite, we have been numerically analyzing the controllability of TMJ loading through coordinative activities of the masticatory muscles, employing a static two-dimensional (2-D) jaw model, which consists of a rigid-body model of the jaws with a rigid-body spring model of the TMJ and masticatory muscles, such as the masseter, the anterior portion of the temporalis and the lateral pterygoid. These muscles were all simulated as force vectors applied to the mandible. Bite force was applied to a single point on the lower first molar, and its direction was set so as to be perpendicular to the occlusal plane. Numerical simulations verified that TMJ loading can be minimized by simply adjusting the activities of the masseter and temporalis muscles. The direction of the minimum TMJ-loading vector nearly agrees with the direction from the intermediate zone of the articular disk to the condylar center. Our previous model, however, neglected the digastric muscle, even though it functions during a bilateral bite. This paper then attempts to analyze the effects of the digastric force on the afore-mentioned controllability of TMJ loading, employing an updated jaw-model that includes the digastric muscle. Through numerical experiments, the activation of this muscle was verified to slightly increase the minimum TMJ-loading and to be completely independent of the direction of the minimum TMJ-loading vector. Thus, the digastric muscle is believed to play no significant role in the control of TMJ loading, and its activation had no discernible effect on our previous findings, with respect to the minimization of TMJ loading.

I. Introduction

Previous papers¹⁻¹⁴⁾ have discussed the static analysis of TMJ loading. These have focused primarily on the magnitude of the joint reaction force and the distribution of compressive stress within the articular disk. Previously reported TMJ loading values differed significantly with each other, probably because masticatory muscle forces and the elastic modules of the bone and articular disk that were used in the static jaw model included a large degree of error. In order to escape such a vicious circle, we discarded the estimation of the 'absolute value' of TMJ loading, and then undertook the analysis of its 'controllability' which is achieved by the coordinated activities of the masticatory muscles. Subsequently, we revealed that the magnitude of a TMJ loading vector can be minimized by coordinating masseter and temporalis activities. The minimized loading vector pointed in the general direction of the intermediate zone of the disk¹⁵⁻¹⁷⁾.

Pruim¹⁸⁾ reported that a strong bilateral bite brought about a marked increase in the electromyographic activities of the anterior portion of the digastric muscle, as well as the masseter and temporalis muscles. Taking the activity of the digastric muscle into consideration, we incorporated it into our previous jaw model^{16, 17)}. The aim of this paper, then, is to theoretically analyze the role of digastric muscle activity in the control of TMJ loading during a bilateral bite, using our static 2-D jaw model with a rigid-body spring model of TMJ¹⁷⁾.

[Nomenclature]

- f_m : magnitude of masseter force
- ϕ_m : direction of masseter force
- f_t : magnitude of temporalis force
- ϕ_t : direction of temporalis force
- f_l : magnitude of lateral pterygoid force
- ϕ_l : direction of lateral pterygoid force
- f_d : magnitude of digastric force
- ϕ_d : direction of digastric force
- f_o : magnitude of bite force
- ϕ_o : direction of bite force
- f_j : magnitude of TMJ loading
- ϕ_j : direction of TMJ loading
- (x_m, z_m) : point of application of masseter force (initial position)
- (x_{ma}, z_{ma}) : point of application of masseter force (displaced position)

- (x_t, z_t) : point of application of temporalis force (initial position)
- (x_{ta}, z_{ta}) : point of application of temporalis force (displaced position)
- (x_l, z_l) : point of application of lateral pterygoid force (initial position)
- (x_{la}, z_{la}) : point of application of lateral pterygoid force (displaced position)
- (x_d, z_d) : point of application of digastric force (initial position)
- (x_{da}, z_{da}) : point of application of digastric force (displaced position)
- (x_o, z_o) : point of application of bite force (initial position)
- (x_{oa}, z_{oa}) : point of application of bite force (displaced position)
- (x_j, z_j) : point of application of TMJ loading (initial position)
- (x_{ja}, z_{ja}) : point of application of TMJ loading (displaced position)
- $(x_{p,i}, z_{p,i})$: point of application of each spring tension on the condyle (initial position)
- $(x_{pa,i}, z_{pa,i})$: point of application of each spring tension on the condyle (displaced position)
- $(x_{q,i}, z_{q,i})$: point of application of each spring tension on the fossa (initial position)
- (x_g, z_g) : bite point (initial position)
- α : inclination of the occlusal plane

II. Two-dimensional model of the jaws

Figure 1 illustrates a 2-D rigid-body spring model of TMJ. The mandibular condyle and the articular fossa were both

Fig. 1 A rigid-body spring model of the temporomandibular joint (TMJ)

Table 1 Relationship between spring number and anatomy part

Spring	Anatomy part
1-13	retrodiscal connective tissue
14-21	posterior band TMJ disk
22-29	intermediate zone of TMJ disk
30-37	anterior band of TMJ disk

assumed to be rigid bodies. Their contours were determined by referring to a report by Oishi¹⁹⁾. The TMJ disk and its retrodiscal connective tissue were implemented in the model, using a series of 37 different springs¹³⁾. The springs simulating the disk were assumed to resist the compressive forces alone, while those simulating the connective tissue were assumed to resist neither compressive nor tractional forces. Each spring of the model was positioned so as to coincide with its corresponding portion of the disk or the connective tissue (Table 1). These springs (1-37) were arranged radially between the mandibular condyle and the fossa at an interval of 5 degrees¹⁷⁾ (Fig. 1). The constant for each spring in the model is denoted by $\{k_i\}$:

$$k_i = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)h_i} \times (\text{unit area}), \quad (1)$$

where E , ν , h_i and (unit area) were Young's modulus, Poisson's ratio, the length and the contact area of the spring, respectively^{14, 17, 19, 20)} (Table.2).

Figure 2 demonstrates the 2-D static model of the jaws employed in our previous papers^{16, 17)}. Let O - XZ be a reference coordinate system, which we assign to the maxilla, where the X -axis is set parallel to the Frankfort horizontal plane. Our jaw model incorporated masticatory muscles such as the masseter, the medial pterygoid and the anterior portion of the temporalis, as well as the digastric muscle, where the masseter and the medial pterygoid were united as one muscular bundle, due to their shared position and orientation within the 2-D model.

The bite-force vector was determined, based upon its point of application, located at the first molar on the occlusal plane; its direction lay perpendicular to that plane (Fig. 2); the said plain inclined anteriorly from the Frankfort horizontal plane by 10° , i.e., $\alpha = 10^\circ$. The mandible was assumed to be able to

Table 2 Mechanical properties of TMJ disk used for determining spring constant k_i for each spring

TMJ disk	
Young's modulus E [MPa]	Poisson's ratio ν
10.00	0.40

Fig. 2 A two-dimensional static jaw model

rotate at the bite point and to translate along the occlusal plane, frictionlessly. Thus, the bite point functioned in the capacity of the mandible's moving pivot, on the occlusal plane.

The point of application and the direction of the masticatory-muscle, bite-force and TMJ-loading vectors were determined, using geometric data supplied by Sinozaki¹³⁾, while those of the digastric force vector were determined from Trainor's data¹¹⁾ (numerical data, Tables 3 and 4).

The direction of each force vector was measured counter-clockwise from the X -axis. The magnitude of each muscle vector was calculated, using the method reported by Koriath¹⁰⁾. Table 5 lists the estimated values of the muscle forces^{16, 17)}, which we term 'reference values' in the remainder of this paper.

III. Equations of static equilibrium

Static equilibrium requires three conditions regarding forces and moments: 1) the sums of both X - and Z -components of all forces equal zero; and 2) the sum of the moments

Table 3 Points of application of muscle forces, bite force and TMJ loading

Muscle forces, bite force and TMJ loading	Point of application (x, z)[mm]
Masseter	(x _m , z _m) = (53.5, 94.5)
Temporalis	(x _t , z _t) = (80.5, 144.0)
Lateral pterygoid	(x _l , z _l) = (53.0, 154.5)
Digastric	(x _d , z _d) = (110.2, 62.0)
Bite force (first molar)	(x _o , z _o) = (100.0, 100.0)
TMJ loading	(x _j , z _j) = (46.5, 156.5)

Table 4 Direction angles of muscle forces and bite force

Muscle forces, bite force	Direction angle [deg]
Masseter	φ _m = 54.1
Temporalis	φ _t = 89.5
Lateral pterygoid	φ _m = -10.0
Digastric	φ _d = 170.0
Bite force (first molar)	φ _o = -100.0

around any axis point also equals zero. Applying these conditions to our model, we arrive at three equations of equilibrium:

$$f_m \cos \phi_m + f_t \cos \phi_t + f_l \cos \phi_l + f_o \cos \phi_o + f_d \cos \phi_d + \sum_{i=1}^n (f_{p,i} \cos \phi_{p,i}) = 0, \quad (2)$$

$$f_m \sin \phi_m + f_t \sin \phi_t + f_l \sin \phi_l + f_o \sin \phi_o + f_d \sin \phi_d + \sum_{i=1}^n (f_{p,i} \sin \phi_{p,i}) = 0, \quad (3)$$

$$f_m(z_{ma} \cos \phi_m - x_{ma} \sin \phi_m) + f_t(z_{ta} \cos \phi_t - x_{ta} \sin \phi_t) + f_l(z_{la} \cos \phi_l - x_{la} \sin \phi_l) + f_o(z_{oa} \cos \phi_o - x_{oa} \sin \phi_o) + f_d(z_{da} \cos \phi_d - x_{da} \sin \phi_d) + \sum_{i=1}^n f_{p,i}(z_{pa,i} \cos \phi_{p,i} - x_{pa,i} \sin \phi_{p,i}) = 0, \quad (4)$$

where the moment (4) was calculated around origin O. During a bite, the mandible rotates and translates infinitesimally. The points of application of muscle force vectors and spring tensile forces then also become dislocated, to a slight

degree. Letting θ and u be the rotation angle and the magnitude of translation of the mandible relative to the maxilla, respectively, the displaced positions of the points of application are described as:

$$\begin{aligned} \begin{bmatrix} x_{ma} \\ z_{ma} \end{bmatrix} &= \begin{bmatrix} x_m \\ z_m \end{bmatrix} + \begin{bmatrix} \cos \alpha & -(z_m - z_g) \\ \sin \alpha & x_m - x_g \end{bmatrix} \begin{bmatrix} u \\ \theta \end{bmatrix}, \\ \begin{bmatrix} x_{ta} \\ z_{ta} \end{bmatrix} &= \begin{bmatrix} x_t \\ z_t \end{bmatrix} + \begin{bmatrix} \cos \alpha & -(z_t - z_g) \\ \sin \alpha & x_t - x_g \end{bmatrix} \begin{bmatrix} u \\ \theta \end{bmatrix}, \\ \begin{bmatrix} x_{la} \\ z_{la} \end{bmatrix} &= \begin{bmatrix} x_l \\ z_l \end{bmatrix} + \begin{bmatrix} \cos \alpha & -(z_l - z_g) \\ \sin \alpha & x_l - x_g \end{bmatrix} \begin{bmatrix} u \\ \theta \end{bmatrix}, \\ \begin{bmatrix} x_{oa} \\ z_{oa} \end{bmatrix} &= \begin{bmatrix} x_o \\ z_o \end{bmatrix} + \begin{bmatrix} \cos \alpha & -(z_o - z_g) \\ \sin \alpha & x_o - x_g \end{bmatrix} \begin{bmatrix} u \\ \theta \end{bmatrix}, \\ \begin{bmatrix} x_{da} \\ z_{da} \end{bmatrix} &= \begin{bmatrix} x_d \\ z_d \end{bmatrix} + \begin{bmatrix} \cos \alpha & -(z_d - z_g) \\ \sin \alpha & x_d - x_g \end{bmatrix} \begin{bmatrix} u \\ \theta \end{bmatrix}, \\ \begin{bmatrix} x_{pa,i} \\ z_{pa,i} \end{bmatrix} &= \begin{bmatrix} x_{p,i} \\ z_{p,i} \end{bmatrix} + \begin{bmatrix} \cos \alpha & -(z_{p,i} - z_g) \\ \sin \alpha & x_{p,i} - x_g \end{bmatrix} \begin{bmatrix} u \\ \theta \end{bmatrix}. \end{aligned} \quad (5)$$

When the disk is compressed, each spring exerts the compressive force, denoted by $f_{p,i}$, which can be described by Hooke's law as:

$$f_{p,i} = \begin{cases} k_i \cdot d_i & (d_i > 0) \\ 0 & (d_i \leq 0) \end{cases}, \quad (6)$$

where d_i can be expressed approximately, due to the very slight amount of displacement, as:

$$d_i = \sqrt{(x_{p,i} - x_{q,i})^2 + (z_{p,i} - z_{q,i})^2} - \sqrt{(x_{pa,i} - x_{qa,i})^2 + (z_{pa,i} - z_{qa,i})^2} \quad (7)$$

The direction of the spring-force vector, denoted by $\phi_{p,i}$, is

$$\phi_{p,i} = \tan^{-1} \left(\frac{z_{pa,i} - z_{qa,i}}{x_{pa,i} - x_{qa,i}} \right) \quad (8)$$

The TMJ-loading vector, denoted by $\mathbf{f}_j \equiv (f_{jx}, f_{jz})^T$ is given as that force which results from compressive forces $\{f_{p,i}\}$ as follows:

$$f_{jx} = \sum_{i=1}^n (f_{p,i} \cos \phi_{p,i}), \quad (9)$$

$$f_{jz} = \sum_{i=1}^n (f_{p,i} \sin \phi_{p,i}). \quad (10)$$

The direction of $\mathbf{f}_j$ is expressed as:

$$\phi_j = \tan^{-1} \left(\frac{f_{jz}}{f_{jx}} \right). \quad (11)$$

Table 5 Reference values of muscle forces

Masseter	Temporalis	Lateral pterygoid	Digastric
f_m [N]	f_t [N]	f_l [N]	f_d [N]
142.98	58.40	23.90	18.00

Equations (2)-(4) and (5) contain three unknown variables: 1) u ; 2) θ ; and 3) the magnitude of the bite-force vector, denoted by f_o . By solving simultaneous equations (2)-(11) numerically, bite-force magnitude f_o and TMJ-loading vector $\mathbf{f}_j$ can be obtained ¹⁷⁾.

IV. Materials and Methods

In order to analyze functions of digastric muscle activation during a bilateral bite in the control of TMJ loading, we calculated TMJ-loading vectors under widely various conditions with regard to the activation of the digastric muscle. Setting digastric force (f_d) to "zero", we calculated the value of u , θ and f_o by solving the static equilibrium equations mentioned in the previous section. The value of bite force f_o was 128.34 [N], which we refer to, throughout this work, as the 'reference value' of bite force ($f_{o,ref}$). We carried out two different experiments as follows: 1) to obtain bite forces and TMJ-loading vectors with and without digastric muscle activation; and 2) to obtain TMJ-loading vectors and temporalis forces under the reference bite condition ($f_{o,ref}$) by changing digastric force (f_d).

In the first experiment, we calculated unknown parameters $\{u, \theta, \text{ and } f_o\}$ and the TMJ-loading vector ($\mathbf{f}_j$), under condition that f_d is zero or the reference value (see Table 5), by solving the static equilibrium equations (2)-(11). In the second experiments, we always fixed parameters such as the force of the lateral pterygoid force (f_l) and the bite force (f_o) at the corresponding reference value. Digastric force (f_d) and masseter force (f_m) were dealt with as parameters, while the temporalis force (f_t) and the magnitude and direction of the TMJ-loading vector (f_j and ϕ_j) were computed. Digastric force (f_d) was adjusted, at 10% intervals, all the way from 0% to 100% of its reference value ($f_d=18$ [N]). For each adjusted value of f_d , unknown variables f_i , f_j and ϕ_j were computed by setting masseter force (f_m) at various values ranging from 30% to 130% of its reference value ($f_m=142.98$ [N]) at 1% intervals.

V. Results

The TMJ-loading vectors and bite forces obtained in the first experiment were $\{f_j=96.10$ [N], $\phi_j=152.96$ [deg] $\}$ and $f_o=128.34$ [N], respectively, when $f_d=0$ [N], and $\{f_j=100.45$ [N], $\phi_j=135.77$ [deg] $\}$ and $f_o=104.72$ [N], respectively, when $f_d=18.0$ [N]. Figure 3 visualizes these TMJ-loading vectors.

Figure 4 shows the relationship between masseter force f_m and TMJ-loading vector $\mathbf{f}_j$ under digastric force conditions, where $f_d=0\%$, 50% and 100%, respectively. Figure 4(a) demonstrates that when f_d was fixed at any value, f_j was minimized at a certain masseter force (f_m), and when f_m is fixed, f_j varied with the increase of digastric force (f_d). Figure 4(b) demonstrates that when f_d was fixed, ϕ_j increased roughly in proportion to f_m , and when f_m is fixed, ϕ_j varied inversely with the increase of f_d . The minimized TMJ-loading increased in proportion to f_d (broken line, Fig. 4(a)), while ϕ_j remained stable, even if we modified the value of f_d (broken line, Fig. 4(b)).

In our previous paper ¹⁶⁾ (Itoh, 1997), we demonstrated that the variation of muscle forces f_m and f_t brings about a linear trajectory of TMJ-loading vector $\mathbf{f}_j$, when f_l and f_o are both fixed. The same visualization was employed in Fig. 5, which depicts the two linear trajectories of $\mathbf{f}_j$, with respect to 0% and 100% of the reference value of f_d (18[N]). These trajectories demonstrate that when $\mathbf{f}_j$ is perpendicular to the trajectory, its norm is minimized. Such a minimized vector is referred to as a 'minimum TMJ loading', denoted by $\mathbf{f}_{j,min}$. The magnitude and direction of $\mathbf{f}_{j,min}$ are denoted by $f_{j,min}$ and $\phi_{j,min}$, respectively. The alteration of f_d brought about the translation of the trajectory, but this in no way affected its inclination. Thus,

Fig. 3 TMJ-loading vectors, when $f_d=0$ [N] or 18[N]

Fig. 4 Relationship between masseter force f_m and TMJ-loading vector f_j at three different values of digastric force f_d , represented as the ratio to its reference value, 0%, 50% and 100% (bite force and lateral pterygoid force are both fixed at reference values).

Fig. 5 Linear trajectories of TMJ-loading vector f_j at two different values of digastric force f_d , represented as the ratio to its reference value, 0% and 100%.

Fig. 6 Influence of digastric force f_d on the ratio of the minimum TMJ loading to the reference bite force, $f_{j,min}/f_{o,ref}$, and the force ratio of the masseter to the temporalis, f_m/f_t ; digastric force f_d is represented as the ratio to its reference value.

direction $\phi_{j,min}$ of $f_{j,min}$ is completely independent of f_d (Fig. 5).

Figure 6 shows the effects of digastric force f_d on the minimum TMJ-loading/reference bite-force ratio ($f_{j,min}/f_{o,ref}$), as well as the masseter/temporalis force ratio (f_m/f_t). Values of $f_{j,min}/f_{o,ref}$ and f_m/f_t varied with the increase of f_d . Thus, the increase of f_d resulted in an increase of minimum TMJ-loading relative to the bite force, as well as an increase of masseter force (f_m) relative to temporalis force (f_t), under minimal TMJ loading.

VI. Discussion

Our previous papers¹⁵⁻¹⁷⁾ described that when bite force and lateral pterygoid force are both fixed, TMJ loading can be minimized by coordinating the activities of the masseter muscle with those of the anterior portion of the temporalis muscle¹⁵⁾. Its mechanism was subsequently analyzed from the perspective of loading vector's trajectory¹⁶⁾, as shown in Fig. 5. Remarkably, the direction of the minimized loading vector ($\phi_{j,min}$) agreed well with the direction from the intermediate zone of the disk to the condylar center. Of utmost importance is the fact that $\phi_{j,min}$ is determined from individual morphological factors, independent of: 1) any specific point to which bite force might be applied, 2) bite-force direction; and 3) lateral-ptyergoid force.

Our previous studies¹⁵⁻¹⁷⁾, however, neglected the digastric muscle, which is activated during a bilateral bite¹⁸⁾. We then analyzed the effects of the activation of the digastric muscle on the afore-mentioned findings, by employing a 2-D static

model of the jaws with a rigid-body spring model of the TMJ. Figure 5 demonstrates that the activation of the digastric muscle merely shifts the linear trajectory of TMJ loading-vector $\mathbf{f}_j$ antero-inferiorly. However, it in no way affects the inclination of the trajectory. Thus, the direction ($\phi_{j,\min}$) of minimum TMJ-loading vector $\mathbf{f}_{j,\min}$ was verified to be completely independent of the digastric force. With respect to the minimization of TMJ loading, the activation of the digastric muscle slightly increases the magnitude ($f_{j,\min}$) of $\mathbf{f}_{j,\min}$, while providing a boost to the masseter force relative to the temporalis force, as shown in Fig. 6.

A role of digastric muscle during a bite is believed to stabilize the mandible, relative to the maxilla, by antagonizing the activation of the jaw-closing muscles^{21, 22)}. When crushing food between opposing occlusal surfaces, such stabilization can reduce the displacement of the mandible, which occasionally results in unnecessary tooth contact. In order to certify such a stabilization function of the digastric muscle, we computed bite force (f_o) and TMJ-loading vector ($\mathbf{f}_j$) with and without digastric muscle activation in the first experiment. As expected, bite force (f_o) was reduced by 18.4% by digastric muscle activation, certifying an antagonistic role of the digastric muscle against the jaw-closing muscles. Additionally, digastric force was verified to possess a function of rotating $\mathbf{f}_j$ counterclockwise, with a slight increase of its magnitude.

The second experiments revealed that when the digastric muscle is activated, the minimization of TMJ loading is achieved by increasing the masseter/temporalis force ratio (f_m/f_t) (see Figs. 5 and 6). With respect to the minimum TMJ-loading vector ($\mathbf{f}_{j,\min}$), the digastric force merely causes a slight increase in magnitude $f_{j,\min}$ of $\mathbf{f}_{j,\min}$, and in no way affects direction $\phi_{j,\min}$ of $\mathbf{f}_{j,\min}$. In this respect, the activation of the digastric muscle seems to possess no significant function as regards the controllability of TMJ loading. From the perspective of entire jaw kinetics, however, it seems to play an 'indirect' role in the control of TMJ loading during a relatively strong bite. When crushing hard food, the masseter muscle is activated significantly so as to generate a strong bite force, possibly increasing masseter/temporalis force ratio (f_m/f_t). Figure 6 demonstrates that (f_m/f_t) in the minimum TMJ-loading increases when the digastric muscle is activated. In this respect, the digastric muscle activation during a strong bite indirectly contributes to prevent a drastic increase of TMJ loading.

VI. Conclusion

This study employed a static 2-D jaw model with a rigid-body spring model of the TMJ in order to theoretically analyze the functions of the digastric muscle, as they relate to the control of TMJ loading during the application of a bilateral bite force. The results of the first experiments were as follows: a simple addition of the digastric muscle force into the previous model yielded 1) the decrease of bite force; 2) a slight increase of TMJ loading; and 3) a counterclockwise rotation of the TMJ-loading vector. The results of the second experiments were summarized as follows: when the digastric muscle was activated under a fixed bite condition, 1) the trajectory of the TMJ-loading vector was translated antero-inferiorly; 2) the magnitude of the minimum TMJ-loading vector increased slightly, but its direction was unchanged; and 3) the minimization of TMJ loading brought about an increase in the force ratio of the masseter relative to the temporalis. Consequently, the digastric muscle antagonizing the jaw-closing muscle plays no direct role as regards the controllability of TMJ loading, and has no effects on our previous findings^{15, 16)}, that TMJ loading can be minimized by merely adjusting the activities of the masseter and temporalis muscles.

Acknowledgements

The authors wish to thank Prof. Shoji Kohno, DDS, Ph.D., as well as Raul U. Medina, DDS, Ph.D., Graduate School of Medical and Dental Sciences, Niigata University, for helpful advice.

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