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What is This?
Loading of a Unilateral Temporomandibular Joint Prosthesis: A Three-dimensional Mathematical Study

J.-P. van Loon¹*, E. Otten², C.H. Falkenström¹, L.G.M. de Bont¹, and G.J. Verkerke³

¹TMJ Research Group, Department of Oral and Maxillofacial Surgery, University Hospital Groningen, PO Box 30.001, 9700 RB Groningen, The Netherlands; ²Department of Medical Physiology, University of Groningen; and ³Center for BioMedical Technology, University of Groningen; *to whom correspondence should be addressed

Abstract. The load on the prosthetic side and the influence of the design on the remaining natural contralateral TMJ must be known before a unilateral temporomandibular joint (TMJ) prosthesis can be developed. The aim of the present study was to determine the maximum loading of the TMJ prosthetic side and the natural contralateral TMJ and to investigate the influence of the location of the center of rotation of the prosthesis on the maximum loading. For this purpose, a mathematical model of the mandible with a unilateral TMJ prosthesis with a fixed center of rotation (CR) was developed. The location of the CR of the TMJ prosthesis was varied from the middle of the natural mandibular condyle to 15 mm inferior to this location. Although the maximum joint reaction forces changed as a result of a unilateral TMJ prosthesis, the trend of the loading curves was similar to that of an intact mandible. A unilateral TMJ prosthesis resulted in a 50% higher loading of the prosthetic side, while the load on the natural contralateral TMJ remained within normal limits. The maximum load on the prosthetic side occurred during molar bites and could reach 100 N in the cranial direction, 30 N in the ventral direction, and 25 N in the medio-lateral direction. The location of the CR did not have a significant influence on the loading of the TMJ prosthesis and the natural contralateral TMJ.

Key words: temporomandibular joint, temporomandibular joint prosthesis, models, biomechanics, bite force, computer simulation.

Introduction

Before a temporomandibular joint (TMJ) prosthesis can be designed, the magnitude and direction of the loads on the TMJ prosthesis must be known. In addition, if one TMJ is replaced by a prosthesis, its influence on the remaining natural contralateral TMJ (CTMJ) must be determined. Because both TMJs are connected, the functioning of the prosthetic side directly influences CTMJ movements and possibly changes the loads on the CTMJ (van Loon et al., 1995). Both effects may affect the remaining CTMJ, which might eventually lead to its prosthetic replacement as well.

When a TMJ prosthesis is inserted, the mandibular condyle is removed together with the remnants of the articular disc, the capsule, and its ligaments. Consequently, the lateral pterygoid muscle is detached on the side of the TMJ prosthesis. We assume that lack of lateral pterygoid muscle function, in combination with a unilateral TMJ prosthesis, results in a different, probably compensatory, muscle recruitment. This would also change the distribution of the loads over both the prosthetic side and the CTMJ.

Several investigators studied the mechanical loads to which the mandible is subjected in the natural situation (Pruim et al., 1980; Osborn and Baragar, 1985; Smith et al., 1986; Baragar and Osborn, 1987; Koolstra et al., 1988). However, these studies did not predict the loads on a TMJ prosthesis. Although a few TMJ prostheses have been designed and applied, none of them addressed the problem of the possible influence of a TMJ prosthesis on the loads at both the prosthetic side and the CTMJ. The aim of this study was to determine the maximum loading of the TMJ prosthetic side and the CTMJ. In a previous study, it was shown that the functioning of the CTMJ improves when the center of rotation (CR) of the TMJ prosthesis is located inferiorly to the (former) center of the replaced natural mandibular condyle (van Loon et al., 1998). However, the influence of such a position of the CR on the loads at both joints is unknown. For this reason, our second aim was to
investigate the influence of the location of the CR on the maximum loading of the TMJ prosthetic side and the CTMJ.

Materials and methods

Geometric data of the mandible

A digitized three-dimensional shape of a “common looking” young adult human mandible with complete dentition was used, as described by Rozema et al. (Rozema et al., 1992). The center points of origins and insertions, defining the directions of muscle-working vectors, were estimated based on 3-D data described in literature (McMinn and Hutchings, 1977) (Fig. 1A). Further, the physiological cross-sectional area of muscles and the intrinsic strength of muscle fibers were adapted from literature (Weijs and Hillen, 1985; Koolstra et al., 1988), as was the point of application of the CTMJ reaction force (Koolstra et al., 1988). The x-axis runs parallel to the intercondylar axis. The x,z-plane is determined by the inferior border of the mandible that deviates by an angle of 9° from the occlusal plane (Fig. 1A). The y-axis runs perpendicular to the x,z-plane, in the cranial direction.

Mathematical model

The mathematical model simulates static bite situations with the mandible in occlusion (Fig. 1A). The unilateral TMJ prosthesis is modeled as a ball-and-socket joint with a fixed center of rotation (CR). The point of application of the prosthesis force vector is considered to be the location of the center of rotation (CR). Based on the assumption that any frictional force in a healthy TMJ can be neglected, the CTMJ reaction force vector is assumed to be perpendicular to the slope of the articular eminence (Koolstra et al., 1988). This direction is defined as the natural direction of the joint reaction force. The lateral pterygoid muscle is considered to be functional only for the CTMJ. The bite force is assumed to be perpendicular to the occlusal plane. For reference simulations, the TMJ prosthetic side can be exchanged for a TMJ with the same properties as the CTMJ, resulting in an intact mandible. With the model, the following parameters can be calculated:

- bite force \( F_{bc} \)
- static muscle forces \( \mathbf{F}_i \) of the masticatory muscles involved;
- the prosthesis reaction force \( \mathbf{F}_p \) and the CTMJ force \( \mathbf{F}_{jc} \), in a mandible with a unilateral TMJ prosthesis; and
- both TMJ reaction forces (left, \( \mathbf{F}_{pl} \); right, \( \mathbf{F}_{pr} \)), in normal bite simulations.

The number of variables exceeds the six equilibrium equations for static conditions, so a unique solution can be found only by means of an optimization criterion. The model uses an optimization criterion that results in a proportional relationship between the recruitment pattern and bite force magnitude for a particular bite force direction, as defined by Koolstra et al. (1988). This optimization criterion recruits the muscles in such a way that the relative activity of the most active muscle is as small as possible. This ensures a recruitment pattern that balances the mandible and provides the highest possible bite force. The calculated joint reaction forces and muscle forces are linearly proportional to the calculated bite force.

Methods

The direction of the prosthesis force vector was varied over half a sphere in steps of 10°, resulting in (9*36) + 1 = 325 directions of the force vector (Fig. 1B). Therefore, every bite point position resulted in 325 3-D prosthesis reaction force vectors, each vector accompanied by the corresponding CTMJ force magnitude, maximum bite force, and muscle recruitment pattern. From the 325 prosthesis force vectors, the maximum prosthesis reaction...
force was determined, with the corresponding CTMJ reaction force and bite force. As a reference, the TMJ reaction forces and corresponding bite force were calculated for the intact mandible. The bite force was varied over all dental elements, except for the two central incisor elements that were taken as one bite point, resulting in 13 bite point locations (Fig. 1C).

To study the influence of the location of the CR of the prosthesis, we varied the location from 0 mm to 15 mm inferiorly to the center of the removed condyle in steps of 5 mm, indicated as locations 0, 5, 10, and 15 (Fig. 2).

The direction of the natural CTMJ force vector was assumed to be identical to the natural direction. To determine the sensitivity of the model to this assumption, we performed additional simulations with the CTMJ force direction varying $10^\circ$ to medial, lateral, ventral, and dorsal, for every location of the CR.

To verify the idea that lack of lateral pterygoid muscle function on the prosthetic side changes the loading of both the prosthetic and the CTMJ side, we performed an additional simulation with the lateral pterygoid muscle on the prosthetic side functioning, for CR = 0.

Finally, the maximum loading on the TMJ prosthesis and the CTMJ was calculated as a percentage of the maximum possible bite force.

### Results

#### Intact mandible

For an intact mandible, left and right sides are symmetrical, and thus the graph of the TMJ reaction forces is symmetrical (Fig. 3). The left and right TMJ forces ($F_{JR}, F_{JR}$) were maximal for contralateral premolar bite locations (340 N) and minimal for ipsilateral second molar bite locations (0 N). The maximum bite force (900 N) occurred for contralateral first molar bite locations.

#### Mandible with unilateral TMJ prosthesis

To visualize the relation between the prosthesis reaction force and its direction, we connected the far ends of the calculated prosthesis reaction force vectors, resulting in force vector envelopes (Fig. 4). The outer surface of the envelope showed the force magnitude of the prosthesis reaction force that corresponds to the direction of the force vector. For the CTMJ reaction force, we fabricated an envelope by pointing the magnitude of the CTMJ reaction force in the direction of the prosthesis force direction. Only the frontal views of the envelopes are shown, because the lateral views showed similar global shapes and dimensions. Only the envelopes for CR = 15 are shown, because the envelopes for the other locations of the CR were very similar. For all locations of the CR, the maximum prosthesis force was smallest for ipsilateral second molar bite locations, increasing to a maximum for contralateral canine and first premolar bite locations, followed by a decrease to a moderate level for contralateral second molar bite location. For the ipsilateral second molar bite location, the maximum of the (relatively small) prosthesis force was directed in the horizontal plane. For other bite locations, the prosthesis reaction force was directed more cranially. Contrary to the prosthesis force envelopes, no clear trend of the CTMJ force envelope could be noticed, except that the envelopes were smallest for both second molar bite locations.

From the force envelopes, the maximum prosthesis reaction

![Figure 2. The four studied locations of the prosthetic CR, indicated by a dot. CR = 0 is located in the middle of the mandibular condyle. CR = 5, CR = 10, and CR = 15 are located 5 mm, 10 mm, and 15 mm, respectively, inferior to the middle of the condyle.](image)

![Figure 3. Maximum bite force ($F_B$) and corresponding TMJ reaction forces as a function of bite location for an intact mandible ($F_{JR}, F_{JR}$) and for a unilateral TMJ prosthesis ($F_p, F_{JC}$) with CR = 15.](image)
force and the corresponding bite and CTMJ force were determined. Compared with the natural situation, the graph had become very asymmetrical (Figs. 3, 5). The TMJ prosthesis increased the maximum joint reaction force on the prosthetic side by 50% (510 N vs. 340 N), while the corresponding maximum CTMJ reaction force decreased by 25% (250 N vs. 340 N). The maximum bite force with TMJ prosthesis (900 N) was in the same range as for an intact mandible. Except for the ipsilateral second premolar bite location, the maximum prosthesis reaction force was directed mainly in the y-direction (Table 1). From the prosthesis reaction force envelopes, it followed that the reaction force component in the x,z-plane could become approximately 25% of the maximum prosthesis reaction force (Fig. 4).

The location of the CR did not have a significant influence on the maximum force magnitudes (Fig. 5). The direction of the maximum prosthesis force was significantly influenced by the location of the CR only for the ipsilateral second premolar bite location (Table 2).

Varying the direction of the CTMJ reaction force vector especially influenced the magnitude of the CTMJ reaction force (Fig. 6). Although the pattern of the CTMJ reaction force changed, the maximum CTMJ reaction force remained in the natural range. The maximum bite force and the maximum prosthesis reaction force showed only small changes.

A TMJ prosthesis with functioning lateral pterygoid muscle resulted in a loading pattern very similar to the pattern without functioning lateral pterygoid muscle. With a functioning lateral pterygoid muscle, the maximum prosthesis reaction force and the maximum bite force were similar to the results without a functioning lateral pterygoid muscle.

### Table 1. Direction of the maximum prosthesis reaction force for all 13 bite point locations, represented by its unit vector (CR location = 15)

<table>
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<td>x</td>
<td>-1</td>
<td>0.59</td>
<td>0.47</td>
<td>0.34</td>
<td>0.17</td>
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<td>0.03</td>
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<tr>
<td>y</td>
<td>0</td>
<td>-0.64</td>
<td>-0.87</td>
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<td>-0.98</td>
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<td>z</td>
<td>0</td>
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The maximum CTMJ reaction force was increased by 15% (290 N vs. 250 N) (Fig. 7). The direction of the maximum joint reaction force at the prosthetic side was similar to the direction in a TMJ prosthesis lacking the lateral pterygoid muscle. The prosthesis reaction force was maximal for the first premolar bite location. For this bite location, both heads of the lateral pterygoid muscle were maximally activated. On the CTMJ side, the superior head of the lateral pterygoid muscle was not activated, while the inferior head of the lateral pterygoid muscle was maximally activated.

Dividing the maximum joint reaction force by the maximum possible bite force showed a difference in load transfer to the prosthetic side and CTMJ (Fig. 8). The prosthetic side was loaded maximally with 80% of the bite force (incisor bite location), while the CTMJ reached a maximum of 40% of the bite force (contralateral canine bite location). For the ipsilateral molar bite locations, the prosthetic side was loaded with less than 30% of the bite force and approximately 50% for contralateral molar bite locations. The CTMJ was not loaded for ipsilateral molar bite locations, while for contralateral bite locations, it was loaded with approximately 30% of the bite force. Results are shown only for CR = 15; the other locations of the CR showed similar results.

Muscle recruitment

For an intact mandible, the masseter and the medial pterygoid muscles were generally maximally activated (Fig. 9). The anterior temporal muscles were maximally activated for ipsilateral bite locations and gradually decreased their activity toward contralateral bite locations. The left deep and posterior temporal muscles were activated only at the working side. The lateral pterygoid muscles were maximally recruited, except for molar bites.

Compared with the intact mandible, the muscle recruitment pattern for the maximum TMJ prosthesis force showed

| Table 2. Deviation of the direction of the maximum prosthesis reaction force for the CR locations 0, 5, and 10 compared with that of CR location 15, for all 13 bite point locations (in %) |
|---------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|
|                                | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 |
| CR = 0º                        | 0  | 9  | 55 | 0  | 2  | 0  | 0  | 0  | 0  | 15 | 0  | 0  | 0  |
| CR = 5                         | 0  | 7  | 55 | 0  | 2  | 0  | 0  | 0  | 0  | 2  | 0  | 0  | 0  |
| CR = 10                        | 0  | 7  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |

* The CTMJ reaction force is directed in the natural direction.
The recruitment patterns were very similar (Fig. 9). For both patterns, the left temporal muscle components were maximally activated for all bite point locations except for the second premolar bite location. The right temporal muscle components were activated for bite locations on the right (CTMJ) side and for the second molar location on the left side. Both heads of the right lateral pterygoid muscle were activated in only a few bite locations, predominantly molar bite locations on the prosthetic side, but not for incisor bite locations.

**Discussion**

The loads on the TMJ cannot be determined experimentally. Therefore, the TMJ reaction force must be estimated with the help of mathematical models. The results can be verified only indirectly, by experimental bite force measurements and electromyographic (EMG) measurements of the activity of the masticatory muscles. In TMJ prostheses, neither bite force nor EMG measurements have been performed. Therefore, the results of the present study can be compared only with experimental and mathematical studies of an intact mandible. For the intact mandible, the calculated maximum bite forces for the molar region are in the same range as experimental results, while for incisive and premolar bite locations, the calculated bite forces were higher than experimentally measured (Mansour and Reynik, 1975; Craig, 1985; van Eijden et al., 1988). The results for an intact mandible agree well with a mathematical study that used the same optimization criterion (Koolstra et al., 1988).

**Directions of muscle force vectors and bite force**

The working line of a muscle was assumed to be the line connecting origin and insertion, neglecting variation in muscle density and structure. In reality, the working line may change during activation.

different patterns. For different locations of the CR, the recruitment patterns were very similar (Fig. 9). For both sides, the superficial and deep masseter muscles were maximally activated except for second molar bite locations. The left medial pterygoid muscle was maximally activated for almost all bite locations, while the right medial pterygoid muscle was activated to a much smaller extent. The left temporal muscle components were maximally activated for all bite point locations except for the second premolar bite location. The right temporal muscle components were activated for bite locations on the right (CTMJ) side and for the second molar location on the left side. Both heads of the right lateral pterygoid muscle were activated in only a few bite locations, predominantly molar bite locations on the prosthetic side, but not for incisor bite locations.
The muscle force direction may have a significant influence on the performance of the chewing system (Throckmorton, 1985; Koolstra et al., 1988). However, for comparing the loading of the TMJ with and without a unilateral TMJ prosthesis, the model is thought to be sufficient.

In the model, it was assumed that the bite force is directed perpendicular to the occlusal plane. It has been shown with a mathematical model as well as experimentally that the maximal possible bite force is not directed perpendicular to the occlusal plane, but more anteriorly and medially (Koolstra and van Eijden, 1992). However, for a chosen value of the bite force, the resulting joint reaction force is higher for a bite force direction perpendicular to the occlusal plane than for a more anteriorly and medially directed bite force (Koolstra and van Eijden, 1992). We therefore consider it acceptable to apply vertically directed bite forces only.

**Direction of the CTMJ reaction force vector**

The direction of the CTMJ force vector was assumed to be perpendicular to the slope of the articular eminence, indicated as the natural direction of the joint reaction force. Variation of the direction of the CTMJ force vector by 10° laterally, medially, ventrally, and dorsally mainly influenced the magnitude of the CTMJ reaction force itself. However, the magnitude of the CTMJ force magnitude was still in the natural range. Therefore, the direction of the CTMJ force is considered to be of minor importance.

**Muscle recruitment**

It appears that the applied optimization criterion predicts maximal activation of muscles that largely contribute to the bite force magnitude, and partly activates three muscles for balancing the mandible, while completely switching off remaining muscles. In nature, muscles show graded activation: They are not completely switched on and off abruptly during chewing and biting (Møller, 1966; Ahlgren and Owall, 1970; Pruim et al., 1978). However, any other recruitment pattern results in smaller bite forces, so the worst-case loading pattern is predicted.

For the TMJ prosthesis side, it was assumed that the lateral pterygoid muscle was no longer functional. This resulted in a more cranially directed prosthesis reaction.
force. However, when the lateral pterygoid muscle on the prosthetic side was made functional again, the loading pattern and the direction of the maximum prosthesis reaction force were almost identical to the results without the functioning lateral pterygoid muscle. This indicates that it is not the lack of the lateral pterygoid muscle but the direction of the prosthesis reaction force that causes the differences between the loading patterns of an intact mandible and a mandible with unilateral TMJ prosthesis.

The more cranially directed joint forces resulted in a 50% increased prosthesis reaction force, supplied by an increase of muscle activity at the prosthetic side. It is questionable whether this effect will occur in patients. Especially the temporal muscles were activated maximally for almost all bite locations, while for the natural situation they were activated only at the working side. So, for a cranially directed joint reaction force, the model used all muscle components with cranially directed working lines, while for the natural direction of the joint reaction force, these muscle components were not used. However, it is more likely that a more natural muscle recruitment pattern will occur, which would result in a lower bite force and lower prosthesis reaction force. Therefore, the predicted situation is a worst-case model.

Although the generation of the maximum possible bite force may be one of the objectives of the chewing system, the recruitment pattern will also be determined by biological and physiological restrictions. For example, signals from receptors in the TMJ and mandible can inhibit muscle recruitment and thus limit the magnitude of the bite force, to prevent TMJ structures, the mandible, and the dentition from overloading. This phenomenon is best illustrated by incisive bites for which a maximal bite force of ± 600 N was predicted, with both TMJs loaded relatively high (Fig. 3). Experimental bite force measurements, however, showed lower bite force magnitudes for this bite location, up to 220 N (Mansour and Reynik, 1975; Craig, 1985). This biological inhibition is not represented in the model, so again the results represent a worst-case loading pattern.

Influence of the location of the CR of the TMJ prosthesis
The location of the CR had a minor influence on all force magnitudes and the prosthesis force direction. This can be explained by examination of the working lines of the muscle vectors that may be considered the largest contributor to the bite force, i.e., the masseter muscle. These working lines point in such a direction that a change in the location of the CR causes only minor changes in the muscle moment arm. To satisfy the equilibrium equations and the optimizing criterion, a similar pattern of muscle forces will be predicted, resulting in similar maximum bite forces and joint reaction forces for all examined locations.

Functional loading of the TMJ prosthesis and CTMJ
The functional loading of the TMJ prosthesis and the CTMJ depends on the magnitude of the applied bite force and the efficiency of the chewing apparatus to transfer muscle forces to the bite force. For a unilateral TMJ prosthesis, the prosthetic side was less efficient in transferring muscle forces to a bite force than the CTMJ, resulting in a relatively larger loading on the prosthetic side (Fig. 8). The prosthesis reaction force reached its maximum for contralateral bite locations (Fig. 3). These bite locations are used mainly during chewing. Experimental chewing force measurements showed that normal molar chewing forces of an adult are in the range of 200 N (Hylander, 1975; Gibbs et al., 1981; Proffit et al., 1983) and somewhat lower (150 N) for TMJ patients (Ow et al., 1989). For other bite point locations, the chewing forces are smaller. For a chewing force of 200 N, a TMJ prosthesis will be loaded by 100 N, in approximately a cranial direction. In the x,z-plane, a reaction force component of approximately 25% of the prosthesis force is possible. From this, it follows that the possible prosthesis reaction force in the medio-lateral direction is 25 N. Because the x,z-plane is rotated 9° relatively to the occlusal plane, the maximum load in the ventro-dorsal direction follows from a transformation of the force envelopes to the horizontal and coronal planes. The maximum possible prosthesis reaction force in the ventral direction then becomes 30 N and in the dorsal direction 10 N.

The CTMJ reaction force for ipsilateral molar bites was very small. For left molar bites, the reaction force became 30% of the bite force, resulting in a maximum load on the CTMJ of 60 N. For the incisive region, both the CTMJ and TMJ prosthesis were loaded relatively high, 40% and 80% of the bite force, respectively. Patients with a TMJ prosthesis should therefore avoid incisive bites.

The present study shows that a unilateral TMJ prosthesis increases the joint reaction force on the prosthetic side with 50%, while the load on the contralateral natural joint remains within normal ranges. The maximum load on the TMJ prosthesis occurs for molar bites and may reach 100 N in the vertical direction, 30 N in the ventral direction, and 25 N in the mediolateral direction. An inferiorly located center of rotation does not have a significant influence on the loading pattern of the TMJ prosthesis and the natural contralateral TMJ.

It is further concluded that a vertical direction of the joint reaction force reduces the efficiency of the force transfer from the masticatory muscles to the bite force compared with the natural situation. Since a unilateral TMJ prosthesis does not increase the loading of the contralateral natural TMJ, joint problems on the contralateral natural side are not likely to be the result of overloading.

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