Temporomandibular joint loads in subjects with and without disc displacement

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Abstract

The likelihood of development of degenerative joint disease (DJD) of the temporomandibular joint (TMJ) is related to the integrity of the TMJ disc. Predilection for mechanical failure of the TMJ disc may reflect inter-individual differences in TMJ loads. Nine females and eight males in each of normal TMJ disc position and bilateral disc displacement diagnostic groups consented to participate in our study. Disc position was determined by bilateral magnetic resonance images of the joints. Three-dimensional (3D) anatomical geometry of each subject was used in a validated computer-assisted numerical model to calculate ipsilateral and contralateral TMJ loads for a range of biting positions (incisor, canine, molar) and angles (1-13). Each TMJ load was a resultant vector at the anterosuperior-most mediolateral midpoint on the condyle and characterized in terms of magnitude and 3D orientation. Analysis of variance (ANOVA) was used to test for effects of biting position and angle on TMJ loads. Mean TMJ loads in subjects with disc displacement were 9.5-69% higher than in subjects with normal disc position. During canine biting, TMJ loads in subjects with disc displacement were 43% (ipsilateral condyle, p=0.029) and 49% (contralateral condyle, p=0.015) higher on average than in subjects with normal disc position. Biting angle effects showed that laterally directed forces on the dentition produced ipsilateral joint loads, which on average were 69% higher (p=0.002) compared to individuals with normal TMJ disc position. The data reported here describe large differences in TMJ loads between individuals with disc displacement and normal disc position. The results support future investigations of inter-individual differences in joint mechanics as a variable in the development of DJD of the TMJ.

Introduction

Degenerative changes of the human temporomandibular joint (TMJ) are evident in 3-29% of the population aged 19-40 years.[1] Although degenerative joint disease (DJD) is common in the human TMJ, the pathomechanics are poorly understood. The mean age of onset of DJD of the human TMJ is between 25 and 35 years[1-9] and approximately 20 years earlier than reported for the hip.[10-12] Therapeutic interventions to ameliorate the effects of DJD in the TMJ, like other synovial joints, have not been predictably successful.[13] The intra-articular disc is the main mechanism of load distribution and lubrication in the TMJ.[14-18] Although the high prevalence of disc displacement in otherwise asymptomatic adults has led some researchers to propose that it is a non-pathological variation of anatomy,[19,20] disc displacement is absent mostly in the young, increases with time through adolescence and early adulthood, and thus precedes the precocious time-line of DJD in the TMJ.[21-23] It has been postulated that the propensity to develop DJD of the TMJ depends on the health of the disc,[22] which is anisotropic with respect to mechanical fatigue.[24]

The objective of our study was to use a numerical modeling approach[25-27] to test the hypothesis that TMJ loads during static biting are larger in subjects with TMJ disc displacement compared to subjects with normal disc position.

Materials and Methods

Thirty-four subjects gave informed consent to participate. The study protocol was approved by Institutional Review Boards. Subjects had generally intact dentitions, and did not report or exhibit postcranial DJD, orofacial pain, gross asymmetries in craniomandibular anatomy as determined by examination, and were not pregnant as determined by medical history. Diagnostic classification was established by a clinical examiner using research diagnostic criteria for temporomandibular disorders[28] and a radiologist using magnetic resonance imaging and three-dimensional (3D) computed tomography.[29] The subjects, 18 females and 16 males, were divided evenly into two diagnostic groups (Table 1). Mean ages (SD) were 35 (14) and 34 (15) years for disc displacement and normal disc position groups, respectively.

A geometry file was created for each subject that described positions of the mandibular condyles, teeth, and five pairs of masticatory muscles (masseter, anterior temporalis, medial pterygoid, lateral pterygoid, anterior digastric), determined from standardized lateral and posteroanterior cephalographs according to a 3D coordinate system[25,27] (Figure 1). Geometry files

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Table 1. Subjects in two diagnostic groups.

Gender	Number of subjects with normal disc position bilaterally	Number of subjects with disc displacement (II) according to RDC/TMD categories (a, b, c): IIa	IIb	IIc
Female	9	6	1	2
Male	8	6	1	1

Where: IIa = disc displacement with reduction, IIb = disc displacement without reduction with limited opening, IIc = disc displacement without reduction without limited opening (more complete criteria and definitions have been published previously [28,29]).

were used in a previously described numerical model,[30] first to validate the accuracy of the model in predicting data in each subject, and then to investigate inter-group differences in magnitudes of TMJ loads. Model-predicted ipsilateral and contralateral TMJ loads for a given static mandibular loading situation were resultant vectors at the anterosuperior-most mediolateral midpoint on the corresponding condyle and characterized in terms of magnitude and 3D orientation.

Model validation was determined by the ability to predict right and/or left sagittal plane projections of the TMJ stress-field trajectory in each subject[31] during symmetrical protrusion and retrusion of the mandible. That is, model-predicted orientations of TMJ loads were used as described previously and compared to individual-specific jaw tracking data measured *in vivo*.[25,27,32,33] Accuracy between model-predicted and measured data was deemed to be acceptable based on average errors of 16% (Iwasaki *et al.*, personal communication). Then the validated model was used to predict magnitudes of TMJ forces per unit biting force (BF) using an objective function of minimization of muscle effort (MME).[26,34] The MME model calculated joint forces for biting on incisor, canine, and molar teeth, at a variety of angles (Tables 2, 3). Data were pooled and averaged by group. Analysis of variance (ANOVA) was used to test for significant differences between groups for magnitudes of TMJ loads during biting on incisors, canines, and molars at 13 angles.

Results

Among all biting positions and angles, mean predicted TMJ loads were 9.5-69% higher in subjects with disc displacement compared to subjects with normal disc position. The highest mean predicted TMJ loads occurred during canine biting in subjects with disc displacement (Table 2), where mean contralateral joint loads were 138% of the BF. During canine biting, between-group differences in mean TMJ loads of 43% (ipsilateral, p=0.029) and 49% (contralateral, p=0.015) were statistically significant (Figure 2).

With respect to the effects of biting angle, vertical and laterally-directed BF produced significant differences in joint loads between the two diagnostic groups. In all cases, ipsilateral and contralateral joint loads in the subjects with disc displacement were higher, with statistically significant differences (all p<0.05) occurring during vertical (biting angle 1), laterally-directed (biting angles 2, 3), and anterolaterally-directed biting (biting angle 12; Figure 3; Table 3 a,b).

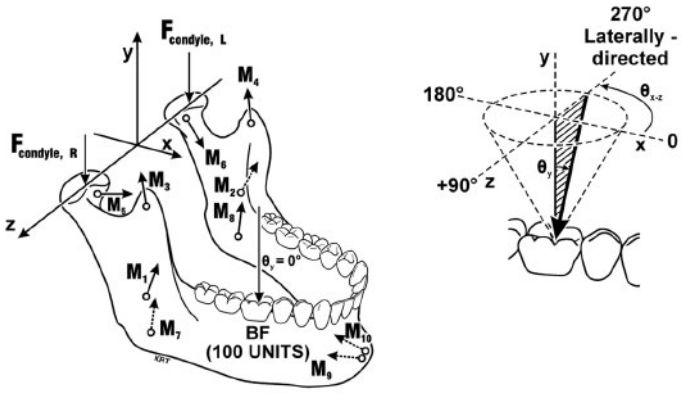

Figure 1. Force vectors involved in numerical models of isometric biting in humans. Forces of biting (BF, 100 units), at the joints ($F_{condyle}$), and representing five muscle pairs ($M_{1,2}$=masseter, $M_{3,4}$=anterior temporalis, $M_{5,6}$= lateral pterygoid, $M_{7,8}$= medial pterygoid, $M_{9,10}$=anterior digastric muscles) are illustrated. The axis system used to characterize the relative positions of the condyles, teeth, and muscle vectors, based on an individual's anatomy, is shown also. Force magnitudes were expressed as percentages of BF. Enlargement (upper right) shows the azimuth angle (θ_{xz}°), measured parallel to the occlusal plane, which varies between 0 and 359°, and the vertical angle (θ_y°) where θ_y=0° is normal to the occlusal plane. For example, laterally-directed molar BFs had θ_{xz}=270° and θ_y=20°, 40°, and were biting angles 2, 3, respectively. (Modified from previous work.[26])

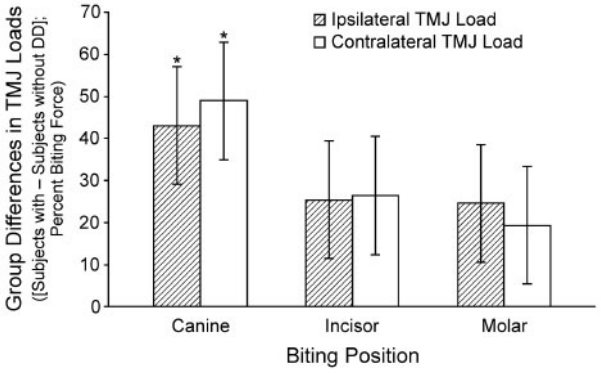

Figure 2. Between-group differences (disc displacement group - normal disc position group) in mean ipsilateral and contralateral TMJ loads for three biting positions. Mean differences between disc displacement (DD, n=17) and normal disc position (n=17) groups in ipsilateral and contralateral TMJ loads are plotted on the vertical axis for three biting positions (canines, incisors, molars) along the horizontal axis. Differences in TMJ loads were expressed as a percentage of the applied bite force. For all biting positions, subjects with TMJ disc displacement had higher joint loads. *indicates p<0.05.

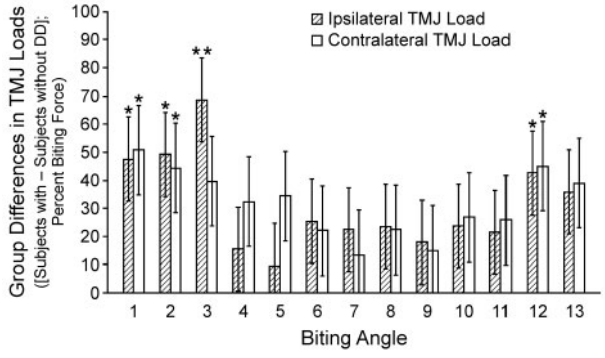

Figure 3. Between-group differences (disc displacement group – normal disc position group) in mean ipsilateral and contralateral TMJ loads for 13 biting angles. Mean differences between disc displacement (DD, n= 17) and normal disc position (n= 17) groups in ipsilateral and contralateral TMJ loads are plotted on the vertical axis for 13 biting angles (see Table 2 for descriptions) along the horizontal axis. Differences in TMJ loads were expressed as a percentage of the applied bite force. For all biting angles, subjects with TMJ disc displacement had higher joint loads. *indicates p<0.05, **indicates p<0.005.

Table 2. Mean (SD) TMJ loads for three biting positions in two diagnostic groups.

Biting position	Displaced TMJ disc group Ipsilateral TMJ Load (% BF) Mean (SD)	Displaced TMJ disc group Contralateral TMJ Load (% BF) Mean (SD)	Normal TMJ disc position group Ipsilateral TMJ Load (% BF) Mean (SD)	Normal TMJ disc position group Contralateral TMJ Load (% BF) Mean (SD)
Canines	124[a] (14)	138[b] (14)	81[a] (13)	89[b] (14)
Incisors	119 (14)	118 (14)	94 (13)	92 (14)
Molars	76 (14)	87 (14)	52 (13)	67 (14)

Where similar superscript letters indicate significant differences, $p<0.05$.

Table 3a. Mean (SE) ipsilateral TMJ loads for thirteen biting angles in two diagnostic groups.

Unilateral right biting angle (Description)	BF directions (°) θ_{xz}	BF directions (°) θ_y	Mean ipsilateral TMJ load (% of BF) Displaced TMJ disc group (SE = 15)	Mean ipsilateral TMJ load (% of BF) Normal TMJ disc position group (SE = 15)	*p*
1 (Vertical)	90	0	116	69	0.028
2 (Laterally-directed)	270	20	91	42	0.023
3 (Laterally-directed)	270	40	113	44	0.002
4 (Medially-directed)	90	20	115	100	0.469
5 (Medially-directed)	90	40	131	121	0.655
6 (Posterolaterally-directed)	355	20	103	77	0.237
7 (Posterolaterally-directed)	355	40	107	85	0.293
8 (Posteromedially-directed)	5	20	104	81	0.273
9 (Posteromedially-directed)	5	40	107	89	0.400
10 (Anteromedially-directed)	175	20	94	70	0.268
11 (Anteromedially-directed)	175	40	94	73	0.314
12 (Anterolaterally-directed)	185	20	108	66	0.049
13 (Anterolaterally-directed)	185	40	101	65	0.096

Table 3b. Mean (SE) contralateral TMJ loads for thirteen biting angles in two diagnostic groups.

Unilateral right biting angle (Description)	BF directions (°) θ_{xz}	BF directions (°) θ_y	Mean contralateral TMJ load (% of BF) Displaced TMJ disc group (SE = 16)	Mean contralateral TMJ load (% of BF) Normal TMJ disc position group (SE = 15)	*p*
1 (Vertical)	90	0	127	76	0.023
2 (Laterally-directed)	270	20	150	105	0.047
3 (Laterally-directed)	270	40	160	121	0.074
4 (Medially-directed)	90	20	86	54	0.144
5 (Medially-directed)	90	40	84	50	0.120
6 (Posterolaterally-directed)	355	20	122	100	0.319
7 (Posterolaterally-directed)	355	40	127	114	0.545
8 (Posteromedially-directed)	5	20	119	97	0.309
9 (Posteromedially-directed)	5	40	122	108	0.500
10 (Anteromedially-directed)	175	20	91	64	0.224
11 (Anteromedially-directed)	175	40	80	54	0.242
12 (Anterolaterally-directed)	185	20	114	69	0.043
13 (Anterolaterally-directed)	185	40	101	62	0.079

Discussion

The data presented here are the first to imply that subjects with TMJ disc displacement have higher joint loads compared to subjects with normal disc position. During daily activities, subjects with disc displacement were capable of producing TMJ loads >60% higher than control subjects. TMJ loads predicted by validated computer modeling showed inter-group differences and suggest that inter-individual differences in joint mechanics are potential variables in DJD of the TMJ.

The numerical modeling approach has limitations that have been discussed in detail previously.[28] One of these limitations is the simplified representation of joint and muscle forces. The model predicts magnitudes of these forces and also the direction of joint forces based on individual-specific anatomical data that include the position and direction of masticatory muscle forces. The area of joint loading in the individual is an important variable and should be investigated in future studies; for example, through dynamic stereometry.[31] Furthermore, the muscles of mastication are multi-pennate muscles and, theoretically, each anatomical portion of a muscle can be represented by a vector. These vectors can be summed to produce a single unit vector. Variation in the direction of this unit vector depends on whether or not discrete areas of a muscle can be differentially activated. Contrary to reported conclusions, documented data for the masseter and temporalis muscles fail to show discrete differential activation of portions of muscles except with cortical feedback. That is, for the masseter muscle no single portion was solely active for a variety of tasks performed[35] and near absence of differential activation was shown for most biting loads.[36] The posterior deep portion behaved most differently from the rest of the masseter muscle, but behaved similarly to the neighboring temporalis muscle,[37] which may indicate cross-talk from the latter muscle. Similarly all portions of the temporalis muscle were active during biting tasks and extremes of unit vector orientation were relatively inconsequential (<10°).[37] These findings sup-

port the use of a unit vector as a reasonable first approximation of the force vector. Another limitation is the 2D validation currently used; however, capabilities for 3D validation using dynamic stereometry should be possible in future. In addition, further validation of muscle force magnitudes during modeled jaw tasks using EMG data recorded *in vivo* during similar tasks should be carried out in future.

Nevertheless, currently there are no other acceptable means known, besides the validated numerical modeling approach, to determine individual-specific TMJ forces during static or dynamic loading of the jaws. Additional future work should focus on diagnostic group differences in intracapsular mechanics and frequency of loading as variables associated with fatigue failure of the TMJ articulating tissues.

References

1. Pullinger AG, Seligman DA, Solberg WK. Temporomandibular disorders. Part I: Functional status, dentomorphologic features, and sex differences in a nonpatient population. J Prosthet Dent 1988;59:228-35.
2. Heloe B, Heloe LA. Characteristics of a group of patients with temporomandibular joint disorders. Community Dent Oral Epidemiol 1975;3:72-9.
3. Israel HA, Ramamurthy NS, Greenwald R, et al. The potential role of doxycycline in the treatment of osteoarthritis of the temporomandibular joint. Adv Dent Res 1998; 12:51-5.
4. Luder HU. Factors affecting degeneration in human temporomandibular joints as assessed histologically. Eur J Oral Sci 2002; 110:106-13.
5. Murakami KI, Shibata T, Kubota E, et al. Intra-articular levels of prostaglandin E2, hyaluronic acid, and chondroitin-4 and -6 sulfates in the temporomandibular joint synovial fluid of patients with internal derangement. J Oral Maxillofac Surg 1998; 56:199-203.
6. Nilner M. Prevalence of functional disturbances and diseases of the stomatognathic system in 15-18 year olds. Swed Dent J 1981;5:189-97.
7. Ong TK, Franklin CD. A clinical and histopathological study of osteoarthrosis of the temporomandibular joint. Br J Oral Maxillofac Surg 1996;34:186-92.
8. Solberg WK, Woo MW, Houston JB. Prevalence of mandibular dysfunction in young adults. J Am Dent Assoc 1979;98:25-34.
9. Stegenga B, De Bont LG, Boering G. A proposed classification of temporomandibular disorders based on synovial joint pathology. Cranio 1989;7:107-18.
10. Felson DT, Zhang Y, Hannan MT, et al. Risk factors for incident radiographic knee osteoarthritis in the elderly: the Framingham Study. Arthritis Rheum 1997;40: 728-33.
11. Lawrence RC, Hochberg MC, Kelsey JL, et al. Estimates of the prevalence of selected arthritic and musculoskeletal diseases in the United States. J Rheumatol 1989;16: 427-41.
12. Vingard E, Alfredsson L, Malchau H. Osteoarthrosis of the hip in women and its relation to physical load at work and in the home. Ann Rheum Dis 1997;56:293-8.
13. Brandt KD, Dieppe P, Radin EL. Etiopathogenesis of osteoarthritis. Rheum Dis Clin North Am 2008;34:531-59.
14. Beek M, Koolstra JH, van Eijden TM. Human temporomandibular joint disc cartilage as a poroelastic material. Clin Biomech (Bristol, Avon) 2003;18:69-76.
15. Nickel JC, Iwasaki LR, Beatty MW, et al. Static and dynamic loading effects on temporomandibular joint disc tractional forces. J Dent Res 2006;85:809-13.
16. Nickel JC, McLachlan KR. In vitro measurement of the stress-distribution properties of the pig temporomandibular joint disc. Arch Oral Biol 1994;39:439-48.
17. Nickel JC, McLachlan KR. In vitro measurement of the frictional properties of the temporomandibular joint disc. Arch Oral Biol 1994;39:323-31.
18. Spilker RL, Nickel JC, Iwasaki LR. A biphasic finite element model of in vitro plowing tests of the temporomandibular joint disc. Ann Biomed Eng 2009;37:1152-64.
19. Hellsing G, Holmlund A. Development of anterior disk displacement in the temporomandibular joint: an autopsy study. J Prosthet Dent 1985;53:397-401.
20. Stegenga B. Osteoarthritis of the temporomandibular joint organ and its relationship to disc displacement. J Orofac Pain 2001; 15:193-205.
21. Kurita H, Uehara S, Yokochi M, et al. A long-term follow-up study of radiographically evident degenerative changes in the temporomandibular joint with different conditions of disk displacement. Int J Oral Maxillofac Surg 2006;35:49-54.
22. Larheim TA. Role of magnetic resonance imaging in the clinical diagnosis of the temporomandibular joint. Cells Tissues Organs 2005;180:6-21.
23. Tanaka E, Detamore MS, Mercuri LG. Degenerative disorders of the temporomandibular joint: etiology, diagnosis, and treatment. J Dent Res 2008;87:296-307.
24. Beatty MW, Bruno MJ, Iwasaki LR, et al. Strain rate dependent orthotropic properties of pristine and impulsively loaded porcine temporomandibular joint disk. J Biomed Mater Res 2001;57:25-34.
25. Iwasaki LR, Petsche PE, McCall WD Jr, et al. Neuromuscular objectives of the human masticatory apparatus during static biting. Arch Oral Biol 2003;48:767-77.
26. Iwasaki LR, Thornton BR, McCall WD Jr, et al. Individual variations in numerically modeled human muscle and temporomandibular joint forces during static biting. J Orofac Pain 2004;18:235-45.
27. Nickel JC, Iwasaki LR, Walker RD, et al. Human masticatory muscle forces during static biting. J Dent Res 2003;82:212-7.
28. Dworkin SF, LeResche L. Research diagnostic criteria for temporomandibular disorders: review, criteria, examinations and specifications, critique. J Craniomandib Disord 1992;6:301-55.
29. Mansur A, Hollender L, Anderson Q, et al. Research diagnostic criteria for temporomandibular disorders (RDC/TMD): development of image analysis criteria and examiner reliability for image analysis. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2009;107:844-60.
30. Trainor PG, McLachlan KR, McCall WD. Modelling of forces in the human masticatory system with optimization of the angulations of the joint loads. J Biomech 1995; 28:829-43.
31. Gallo LM, Chiaravalloti G, Iwasaki LR, et al. Mechanical work during stress-field translation in the human. J Dent Res 2006; 85:1006-10.
32. Iwasaki LR, Baird BW, McCall WD Jr, et al. Muscle and temporomandibular joint forces associated with chincup loading predicted by numerical modeling. Am J Orthod Dentofacial Orthop 2003;124:530-40.
33. Nickel JC, Yao P, Spalding PM, et al. Validated numerical modeling of the effects of combined orthodontic and orthognathic surgical treatment on TMJ loads and muscle forces. Am J Orthod Dentofacial Orthop 2002;121:73-83.
34. Nickel JC, Iwasaki LR. In vivo tests of TMJ morphology and masticatory muscle forces predicted by computer-assisted models. In: Biological mechanisms of tooth movement and craniofacial adaptation. Davidovitch Z, Mah J, ed. Boston: Harvard Society for the Advancement of Orthodontics, 2004, pp 59-70.
35. McMillan AS, Hannam AG. Task dependence of human masseter motor unit reflex behaviour. Exp Brain Res 1992;88:443-6.
36. Blanksma NG, Van Eijden TM, Weijs WA. Electromyographic heterogeneity in the human masseter muscle. J Dent Res 1992; 71:47-52.
37. Blanksma NG, Van Eijden TM. Electromyographic heterogeneity in the human temporalis muscle. J Dent Res 1990;69:1686-90.