



IN VITRO STRAIN MEASUREMENTS IN THE CONDYLAR PROCESS OF THE HUMAN MANDIBLE

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Summary—Although there have been a number of experimental studies of temporomandibular joint loading, the precise relation between condylar load and condylar strain is incompletely understood. This *in vitro* study determined the magnitudes and directions of the principal components of strain on the four surfaces of the condylar process of human cadaver mandibles during loading with selected simulated muscle forces, with simultaneous measurement of occlusal and joint forces. Rosette strain gauges were placed on each of the four surfaces and the mandibles were loaded by a load cell to simulate the action of the masseter and medial pterygoid muscles. Force and strain values were measured at five different bite positions and nine different positions of the resultant muscle force. Forces and strain values were highest when the resultant muscle force was closest to the joint and the bite position was furthest from the joint. The ratios of bite force to joint force and the ratios of forces between the two joints conformed to theoretical predictions of many previous models, with the balancing-side joint being loaded more heavily than the working-side joint. At all gauge positions the maximum principal strain was tensile, the minimum principal strain was compressive, and the absolute strain values were correlated with the magnitude of the force on the condyle. However, under the chosen loading regimen, the ratio of compressive to tensile strain differed among the four surfaces. The highest levels of tensile strain occurred on the anterior and lateral surfaces and the highest compressive strain occurred on the posterior surface. It was not possible to detect significant changes in strain patterns due to bite position or muscle force position, that were independent of the force magnitudes.

Key words: temporomandibular joint, biomechanics, bone strain.

INTRODUCTION

Several factors make loads on the condylar process of the human mandible important. The form of the mandibular condyle and other elements of the temporomandibular joint depend upon the level of functional loading (Watt and Williams, 1951; Simon, 1977; McNamara and Carlson, 1979; Bouvier and Hylander, 1982; Hinton, 1983). Fractures commonly occur in the condylar process and the success of their treatment may depend upon the forces encountered during function (Ekholm, 1961; Schuchardt and Metz, 1966; Rowe and Killey, 1968).

Severely diseased temporomandibular joints must occasionally be replaced by total prostheses or by various types of autogenous grafts whose success may also depend upon the loading patterns at the joint. However, temporomandibular joint loads change dynamically with varying muscular effort and occlusal forces. Therefore, relevant condylar loading patterns must be determined under a variety of conditions. Unfortunately, prosthetic implants used in human temporomandibular joints have not always been designed to withstand these loading patterns (Fontenot and Kent, 1992).

Remodelling and growth of bone depend, in part, upon the magnitude and direction of its deformation

under load (Lanyon, Magee and Baggott, 1979; Bouvier and Hylander, 1981). The degree of deformation (strain) depends upon the shape of the bone, its mechanical properties, and the magnitude, direction and point of application of the applied load (Bassett and Becker, 1962; Epker and Frost, 1965).

The magnitude of condylar loads in non-human primates has been measured during function and following stimulation of the jaw muscles (Brehnan *et al.*, 1981; Hohl and Tucek, 1982; Boyd *et al.*, 1990). However, magnitude of the load alone does not indicate the strain pattern within the condylar process under those loads. Photo-elastic plastic models of the human mandible have been used to investigate the relation between strain and condylar shape (Standlee and Caputo, 1977; Standlee, Caputo and Ralph 1981). Unfortunately, the mechanical properties of their models' plastic differ substantially from those of human bone.

In vivo measurements of condylar strain have used macaques, but because of the difficult surgical approach, have been limited to strain measurements from the lateral surface of the condylar process during mastication and biting (Hylander, 1979; Hylander and Bays, 1979). Although these studies established that strains occur in the condylar process during normal function, the results were mostly qualitative, owing to the difficulties of obtaining the applied muscle forces and resulting occlusal forces.

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In vitro measurements of condylar strain in human cadaver mandibles have been limited to the posterior surface of the condylar process (Mongini *et al.*, 1981). Therefore, the precise relation between strain and forces at the human condyle remains unknown. Finite-element analyses of strain patterns in the condylar process can establish a precise relation, but must be validated with force and strain measurements from precisely controlled experiments (Hart *et al.*, 1992; Koolstra and Van Eijden, 1992; Korioto, Romilly and Hannam, 1992).

In summary, we lack measurements of strain on all four surfaces of the condyle with simultaneous force measurements at the condyle and the teeth. Therefore, our understanding of how the condylar process responds to various loading patterns remains incomplete. We do not know the degree and direction of possible bending of the condylar processes under load, or how changes in position of the bite along the tooth row and changes in relative muscle forces alter the condylar loads.

Ideally, an accurate simulation of normal condylar forces would use precise values for the magnitudes and directions of all of the jaw adductor muscles. Unfortunately, these values are not yet known precisely enough to allow complete simulation of *in vitro* conditions (Throckmorton, 1989). Therefore, no *in vitro* loading of the mandible can be expected to exactly mimic *in vivo* conditions. However, information from more limited experiments can still be useful. Even an incomplete analysis of strain patterns on all four surfaces could supply important mechanical information for evaluation of temporomandibular joint prostheses and surgical operations, as these surgical procedures often eliminate the action of the lateral pterygoids at the condyle. In addition, finite-element models can use the measured force values from these limited experiments. Although, these conditions do not precisely mimic *in vivo* conditions, comparison of the model's predicted strains to experimentally measured strains can still help to validate the finite-element models.

We have now quantified the relative static magnitudes and the directions of the principal components of strain on each of the four surfaces of the condylar process (anterior, posterior, medial, lateral) of cadaver mandibles during loading with simulated masseter and medial pterygoid forces and simultaneously measured the occlusal and joint forces. In addition, we have looked for changes in the relative strain patterns with changes in position of the simulated resultant muscle force and the position of the load along the tooth row.

MATERIALS AND METHODS

The mandibles

Five unembalmed human mandibles were removed from cadavers donated to the Willed Body Program of the University of Texas Southwestern Medical Center. All of the cadavers had been placed in cold storage rooms within 24 h of death, and the heads frozen within 48 h of death. The heads were later thawed and the mandibles removed by dissection. The articular discs were removed from the condyles and the mandibles were thoroughly cleaned of all

muscle and periosteum. The gingiva surrounding the teeth was left intact. The mandibles were then wrapped in moist paper towels and refrozen until the time of instrumentation and testing.

All specimens had intact lower incisors, premolars and first molars. In three specimens, second molars were also present. Four of the mandibles were from males (20–57 yr) and one was from a 68-yr-old female.

Instrumentation of the mandibles

At the time of testing each mandible was thawed and the four surfaces of the right condylar process were thoroughly degreased and cleaned with CSM-1, M-Prep Conditioner, and M-Prep Neutralizer (Measurements Group Inc., Raleigh, NC). A stacked delta-rosette strain gauge (Model NO. WA-06 030 WR-120, Micromasurements Group Inc., Raleigh, NC) was then bonded to each surface with methyl-methacrylate (Loctite 410, Loctite Corp, Newington, CT; Fig. 1). The anterior and posterior gauges were placed on flattened areas just below the articular cartilage. Because of the medial and lateral condylar ridges, the medial and lateral gauges had to be placed more inferiorly, approx. 1 cm below the condylar head. Thus, the anterior and posterior gauges were at the same level and opposite to each other on the condylar process, and the same was true for the medial and lateral gauges. The central element of the lateral and medial gauges was visually aligned parallel to the posterior edge of the condylar process and placed in the centre of the condylar shaft. The anterior and posterior gauges were placed in a wider area of the condylar neck, and therefore exact alignment was more difficult. The central element was visually aligned with the medial and lateral margins of the central shaft of the condylar process.

Lead wires from each element of each strain gauge were connected to a separate signal-conditioner amplifier (Micromasurements Model 2120) for amplification and recording of changes in strain-gauge voltages. All strain-gauge amplifiers were balanced with the loading beam resting on the mandible but

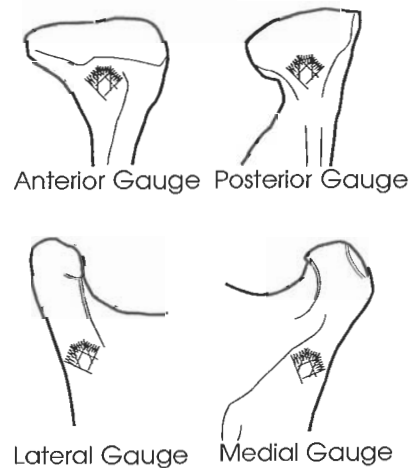


Fig. 1. Diagrammatic representation of location of the rosette strain gauges on each surface of the human condylar process.

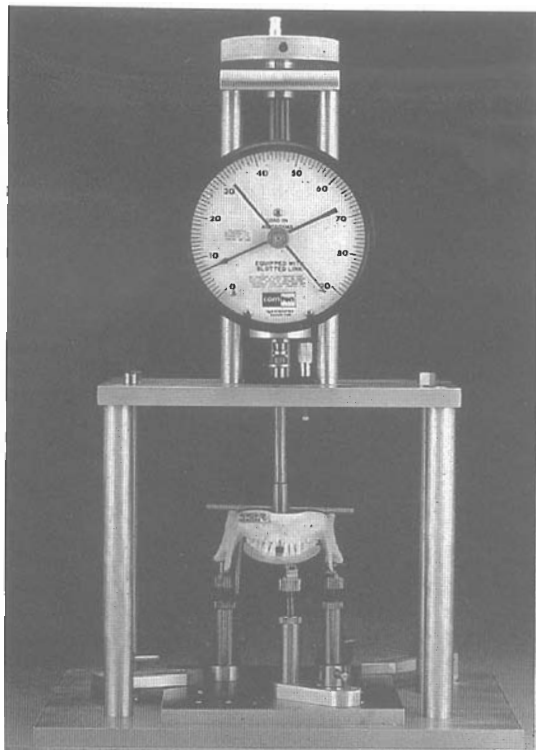


Fig. 2. Photograph of the mandibular compression tester with a mandible in place. The mandible is supported at the teeth and condyles by three dual-beam transducers. The load cell supplies simulated muscle force. The mandible, shown here with a bone plate and splint, is from a pilot study. The mandibles used in the current study had intact dentitions, no bone plate and no splints. From Throckmorton *et al.* (1992) with permission.

the load cell set at zero. The initial voltages for each gauge element were then sampled 100 times at 1500 samples/s (Model DT2821 A/D Converter, Data Translation, Marlboro, MA) and stored in an array in the computer (Compaq 386/20). A load of approx. 600 N was then applied by the load cell and the final voltages for each gauge element were sampled and recorded as before. A custom program written in ASYST software (Software Technologies Inc., Rochester, NY) calculated the magnitude and direction of the change in principal strain at each of the four gauges from the difference between the initial and final voltages. This procedure was repeated for 15 trials to give average values for the principal strains for each of the four gauges at each stable mandibular position.

Use of rosette strain gauges allowed the determination of the magnitude and direction of the maximum and minimum principal strain, with directions at right angles to each other and units in microstrain. Tensile strain has a positive value and compressive strain has a negative value. Depending upon the way a surface is deformed under load, each principal strain can be either tensile or compressive.

The compression device

Following instrumentation, each mandible was inverted and placed in a specially designed compression

device (Fig. 2), as described by Throckmorton *et al.* (1992). The device supported the mandible with three dual-beam transducers, one at the selected tooth position and one at each condyle. Each transducer's upper surface had a machined depression to receive the teeth and condyles, but the mandible was free to move within these depressions to its most stable position when load was applied. The transducers were calibrated with a series of known weights, giving a linear response up to their maximum deflection of approx. 360 N. These transducers measured the reaction forces at the teeth and each condyle. Repositioning of the transducers in three dimensions adjusted for the intercondylar distance of each mandible and for the different positions of the teeth.

The 600-N simulated muscle force was transmitted from the load cell down a central shaft to a loading beam lying across each mandibular body. The force stimulates the action of the superficial masseter and medial pterygoid muscles. The directions of this simulated muscle force relative to the occlusal plane and their distances anterior and medial to the right condyle for each mandible are listed in Table 1. No attempt was made to simulate the action of the temporalis or lateral pterygoid. Because the 600-N simulated muscle force was divided among three transducers (bite and right and left joint transducers), no single transducer experienced a load greater than its maximum capacity of 360 N. The entire mandible and supporting transducers could be moved relative to the load cell in order to simulate mediolateral and anteroposterior shifts of the resultant muscle force.

Testing conditions

Static strain measurements were recorded with five different bite positions (right central incisor, right and left first premolar, and right and left first molar; Fig. 3, Table 1). At each bite position strains were measured with the position of the resultant muscle force in up to nine different positions, three mediolateral (right, midline, left) and three anteroposterior (posterior, middle, anterior). At the midline positions the central shaft of the load cell was midway between the points where the loading beam touched the right and left mandibular rami. At the right and left positions the centre of the central shaft was located 20 mm from the respective mandibular ramus. In the posterior position the loading beam was at the angle of the mandible. At the middle and anterior positions the loading beam was anterior to the initial point by 10 and 20 mm, respectively. For each bite position the directions of the resultant muscle force relative to the occlusal plane are listed in Table 1.

Some of these positions were unstable, for example, posterior tooth positions, with the resultant muscle force located anteriorly and opposite to the biting side. Either no compressive load was produced at the right condyle or the unrestrained mandible was not stable under load. Whenever either of these conditions occurred, no data were recorded. Inadvertently, data for mandible No. 4 were not recorded during right premolar bites.

Each test required approx. 30 min to run. Thus, each mandible was in the testing device for up to 8 h per day over several days. Between days the mandible

was wrapped in moist paper towels and refrozen. During the 8 h that the mandible was in the testing device efforts were made to keep the surface of the bone moist, but some drying may have occurred.

Statistical analysis

The effects of drying were examined by comparing initial and final force and strain values with paired *t*-tests. Correlations between strain and force were tested with the Pearson correlation. Comparisons of relative strain magnitude among the four surfaces and the effects of bite position and muscle position on strain values were made using one-way analysis of variance.

RESULTS

Force measurements

Reproducibility of force measurements. The dependence of strain values upon the stress being applied to the mandible makes the extent of variance of the applied forces important. Ideally, the force generated by the load cell should equal the sum of the forces recorded at the three beam transducers. However, some of the force will be dissipated by compliance within the compressive device. Comparison of the load-cell value to the sum of forces measured at the bite and condyle transducers indicated a loss of about 10% of the force from compliance within the compression device. Although this meant that the actual load was less than 600 N, the distribution of forces to the transducers was not affected.

In addition to compliance in the system there were errors in reproducing the loads on the mandible. Comparison of the sum of forces across all experiments indicated a coefficient of variance of about 4% for reproducing the load on the mandible. Finally, within each experiment, slight shifting of the mandible between trials and differences in the load-cell setting could produce changes in the force measured at each transducer. The coefficients of variance among the 15 trials at each experimental setting ranged from about 4% for incisor bites to about 12% for molar bites. The higher variance during molar bites resulted from the mandible being less stable and thus more likely to shift.

Effect of drying on force measurements. Changes in the mechanical properties of the mandible due to drying were examined by comparing the first five sum-of-forces measurements for each mandible with the last five using a paired *t*-test. Four of the mandibles had slightly decreased sums of forces but the changes were not statistically significant.

Effect of tooth position on force measurements. The average joint force on the instrumented right condyle ranged from a high of 210 N during a contralateral premolar bite with a posteriorly placed, ipsilateral, resultant muscle force to a low of 0 N during an ipsilateral molar bite with a contralateral, anteriorly placed, resultant muscle force [Fig. 4(a)]. If the contralateral molar bite position had been stable, presumably it would have generated an even higher joint force. Joint force was lowest at the ipsilateral molar position and gradually increased as the bite

Table 1. Bite-force positions relative to the right condyle and resultant muscle-force directions relative to the occlusal plane

	Mandible 1	Mandible 2	Mandible 3	Mandible 4	Mandible 5
Incisor					
Mus. Dir.	65.7 ± 1.65	70.8 ± 2.03	72.6 ± 1.18	61.4 ± 6.05	63.9 ± 3.04
Bite X	4.56 ± 0.152	5.04 ± 0.098	4.83 ± 0.082	5.22 ± 0.053	5.20 ± 0.103
Bite Y	9.01 ± 0.158	8.86 ± 0.068	9.56 ± 0.058	8.14 ± 0.052	8.67 ± 0.173
Left pre.					
Mus. Dir.	69.6 ± 0.68	70.3 ± 0.88	81.0 ± 1.24	—	62.3 ± 0.79
Bite X	6.88 ± 0.025	7.03 ± 0.040	7.09 ± 0.116	—	7.03 ± 0.055
Bite Y	7.31 ± 0.041	7.66 ± 0.037	7.82 ± 0.056	—	8.22 ± 0.103
Right pre.					
Mus. Dir.	69.7 ± 1.24	70.4 ± 2.97	81.0 ± 0.73	59.6 ± 0.57	57.6 ± 2.98
Bite X	2.62 ± 0.055	3.13 ± 0.069	2.61 ± 0.070	3.61 ± 0.179	2.94 ± 0.193
Bite Y	7.31 ± 0.034	7.78 ± 0.038	7.83 ± 0.041	7.52 ± 0.228	7.89 ± 0.399
Left mol.					
Mus. Dir.	68.2 ± 0.59	69.3 ± 0.59	79.0 ± 0.50	68.4 ± 17.46	56.7 ± 7.07
Bite X	7.22 ± 0.085	7.31 ± 0.022	7.10 ± 0.173	7.14 ± 0.086	7.62 ± 0.272
Bite Y	6.02 ± 0.062	6.90 ± 0.035	7.06 ± 0.074	6.46 ± 0.037	7.32 ± 0.085
Right mol.					
Mus. Dir.	69.2 ± 0.27	68.0 ± 0.95	77.9 ± 1.57	57.4 ± 2.19	59.0 ± 2.14
Bite X	2.17 ± 0.062	2.67 ± 0.024	2.33 ± 0.241	3.06 ± 0.096	2.60 ± 0.108
Bite Y	5.80 ± 0.041	7.17 ± 0.024	7.23 ± 0.107	6.68 ± 0.130	7.10 ± 0.108
Muscle pos					
Posterior Y	3.61 ± 0.314	3.70 ± 0.259	2.53 ± 0.258	4.25 ± 0.139	4.98 ± 0.256
Middle Y	4.92 ± 0.517	5.06 ± 0.256	3.45 ± 0.257	4.95 ± 0.100	6.03 ± 0.229
Anterior Y	6.71 ± 0.517	6.42 ± 0.058	4.12 ± 0.399	5.94 ± 0.179	6.88 ± 0.104
Right X	6.15 ± 0.472	6.33 ± 0.152	6.47 ± 0.276	6.70 ± 0.286	6.66 ± 0.378
Midline X	4.66 ± 0.287	4.73 ± 0.083	4.47 ± 0.135	5.25 ± 0.249	5.17 ± 0.148
Left X	3.44 ± 0.541	3.19 ± 0.198	2.75 ± 0.275	3.52 ± 0.236	3.79 ± 0.294

Results shown are the means and SD for resultant muscle force directions, resultant muscle-force positions, and bite-force positions. Mus. Dir, direction of the simulated resultant muscle force relative to the occlusal plane. Zero degrees is parallel to the occlusal plane and anteriorly directed. X, the medial distance from the right condyle as indicated in Fig. 3. Y, the anterior distance from the right condyle as indicated in Fig. 3.

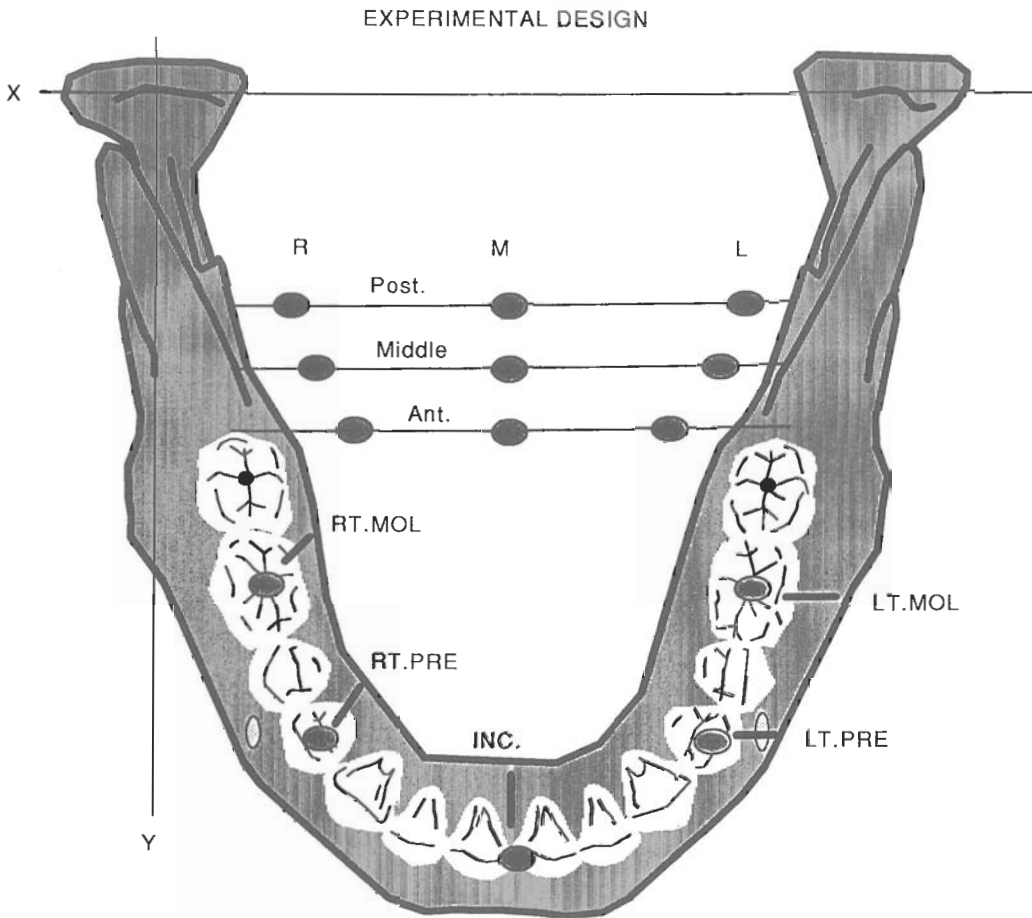


Fig. 3. Diagrammatic representation of the experimental design. Grey ellipses represent the bite positions used right molar (RT.MOL), right premolar (RT.PRE), incisor (INC), left premolar (LT.PRE) and left molar (LT.MOL) and the positions of the resultant muscle forces.

position moved toward the contralateral molar position. The joint force for an ipsilateral molar bite was approximately half that for a contralateral molar bite [Fig. 4(a)].

The average ratios of bite force to joint force are given in Table 2 and Fig. 4(b). The absolute value of the ratios varied depending upon the morphology of each mandible. The relation between the ratios and tooth position was best seen with the resultant muscle vector in the most posterior position at the midline, where values were available for all five tooth positions. The ratio was lowest at the incisor position and highest at the ipsilateral molar position. The bite/joint force ratio increased as bite position moved posteriorly along the tooth row, with a greater rate of increase on the ipsilateral side. As the bite position moved posteriorly, more of the muscle force produced bite force and less produced joint force.

Effect of muscle position on joint force measurements. The importance of the mediolateral position of the resultant muscle force was best seen when the resultant muscle force was located posteriorly, as this was the most stable position for the mandible. The highest joint forces occurred when the resultant muscle force was ipsilateral to that joint [Fig. 4(a)].

At any given bite position the bite/joint force ratio increased as the resultant muscle vector moved from the ipsilateral to the contralateral side [Table 1, Fig. 4(b)]. When the resultant muscle vector was on the same side as the joint, the ranking of bite/joint ratios shifted so that the lowest ratio was during contralateral premolar bites instead of incisor bites. With the muscle in this position, the ratio might have been even lower at the contralateral molar position but the mandibles were not stable enough for taking force measurements.

Joint forces were also highest when the resultant muscle force was at its most posterior position and became progressively lower as the resultant muscle force moved anteriorly. The bite/joint force ratios also increased as the resultant muscle vector moved from its most posterior position to its most anterior position. This was most clear at the incisor bite position [Fig. 4(b)], where values were available for all nine muscle positions. In summary, the forces in a temporomandibular joint were highest when the resultant force was closest to the joint and the bite position was furthest around the tooth row from the joint.

The relative magnitudes between the two tempo-

mandibular joints also conformed to theoretical predictions (Fig. 5). The ratio of the two joint forces depends upon a specific relation between the bite position along the tooth row and the position of the resultant muscle force (Greaves, 1983). The simplest

case is a bite located over both central incisors with the resultant muscle force located in the midline [Fig. 5(a)]. A line connecting the position of these two vectors intersects the intercondylar line in the midline, and the ratio of the two joint forces should be

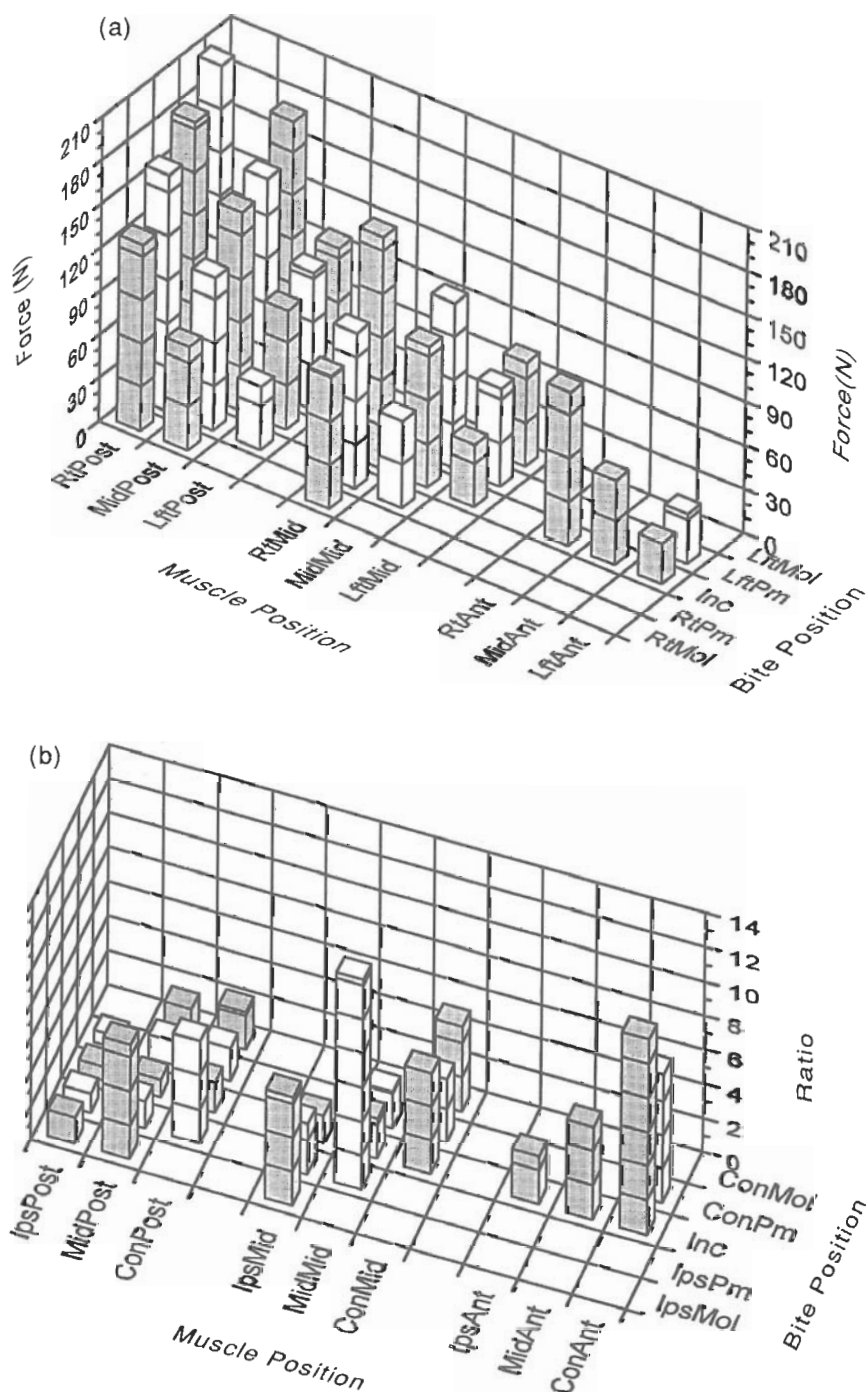


Fig. 4. (a) Mean joint forces, in Newtons, at the instrumental right condyles for various bite and resultant muscle force positions. Stippled bars represent mean joint forces at the molar and incisor bite positions; open bars represent mean joint forces at premolar bite positions. (b) Bite-force/joint-force ratios. Stippled bars represent mean ratios at molar and incisor positions; open bars represent mean ratios at premolar bite positions. Zero ratios indicate unstable experimental positions.

Table 2. Bite/joint-force ratios

Muscle position	Ips-Molar	Ips-Premolar	Incisor	Cont-Premolar	Cont-Molar
Posterior					
Ipsilateral	1.544	1.111	0.808	0.740	—
Midline	6.719	1.595	0.999	1.138	1.492
Contralateral	—	6.022	1.736	1.910	2.220
Middle					
Ipsilateral	6.388	3.011	1.628	—	—
Midline	—	12.328	2.376	2.089	—
Contralateral	—	—	5.889	3.739	4.983
Anterior					
Ipsilateral	—	—	2.792	—	—
Midline	—	—	5.426	—	—
Contralateral	—	—	11.449	8.496	—

Matrix of bite-force ratios for various bite positions of the resultant muscle force. Ips, indicates a bite position on the same side as the instrumented joint; Cont, indicates a bite position on the side opposite to the instrumented joint. Missing values indicate unstable combinations of bite and muscle positions.

1.0. In our experiments, the bite-force transducer was placed over the right central incisor, slightly off the midline, and the resulting joint force ratio was significantly less than 1.0.

If the resultant muscle force is now moved toward the joint [Fig. 5(b)], the intersection point also moves toward the joint, and the relative joint loads will be inversely proportional to the lengths of each line segment from the intersection point to the respective joint (Greaves, 1983). Therefore, the ratio of the ipsilateral/contralateral joint force is predicted to be greater than 1.0. In our experiments the ratio was more than 3.0 when the simulated muscle force was positioned toward the joint.

Similar predictions can be made at other bite and muscle positions. At premolar and molar bite positions [Fig. 5(c)] the ratio should be less than 1.0 when the resultant muscle force is in the midline. Experimental ratios were 0.58 and 0.46 for premolar and molar bites, respectively. When the resultant muscle force moves ipsilaterally [Fig. 5(d)], the joint force ratio should be greater than the ratio at the midline. Experimental values were 1.78 and 1.59 for premolar and molar bites, respectively, approximately three times higher than the midline values. Conversely, when the resultant muscle force moves contralaterally [Fig. 5(e)], the joint force ratio should be less than the ratio at the midline. Here, because of instability of the mandible at these positions, the number of experimental values was more limited but the observed ratios were 0.24 and 0.13 for the premolar and molars, respectively, less than half the midline values.

Strain measurements

Reproducibility of strain measurements. As was the case for force measurements, the variability of strain measurements, at each position, was strongly dependent upon the stability of the loaded mandible. Loading the two joints approximately equally was most stable, for example, at the incisor bite position with the resultant muscle force in the midline, or a molar bite position with the resultant muscle force at the ipsilateral position. Under these conditions the SD was 1–4% of the mean, the same as the variability of the force measurements. At more unstable positions, for example the molar bite positions with the

resultant muscle force in the contralateral position, the SD was 20–40% of the mean, higher than the variability of the force measurements. Under these less stable conditions, small, unintentional changes in mandible and load positions had large effects on the strain values.

At any given position, absolute strain values differed substantially among the five mandibles, reflecting morphological differences. The mandibles differed in the curvature of their condylar surfaces and the relative distances between the positions of the teeth, angle of the mandible, and position of the condylar heads. Although we did not measure these morphological differences, we believe they contributed significantly to the intermandibular variance in strain patterns.

Correlation of strain and force measurements. In general, maximum principal strain magnitudes correlated positively (Pearson correlation) with force at the condyle and minimum principal strain correlated negatively (Table 3). The absolute magnitude of both components of principal strain increased with increasing force. However, for the medial and posterior gauges the correlations between force and tensile-strain magnitude were not significant. These two gauges had the lowest values for tensile strain at each bite/muscle position.

Effect of drying on strain measurements. Although it has been established that drying increases the stiffness of small, homogenous bone samples (Sedlin and Hirsch, 1966), the effect of limited drying on a complex structure like the dentate mandible is not clear. Our specimens were exposed to air for up to 24 h during the course of our study, although efforts were made to keep the surfaces of the bone hydrated. Despite these precautions we looked for changes in mandibular stiffness over the experimental period, expressed as the average strain value divided by the load at the condyle. An increase in mandibular stiffness should result in a decrease of the ratio of strain to applied force. We found no consistent evidence of increased stiffness in our mandibles from the first experiment to the last. Initial strain/force ratios did not differ in a consistent direction from final strain/force ratios and the direction of the change differed among the mandibles and gauge

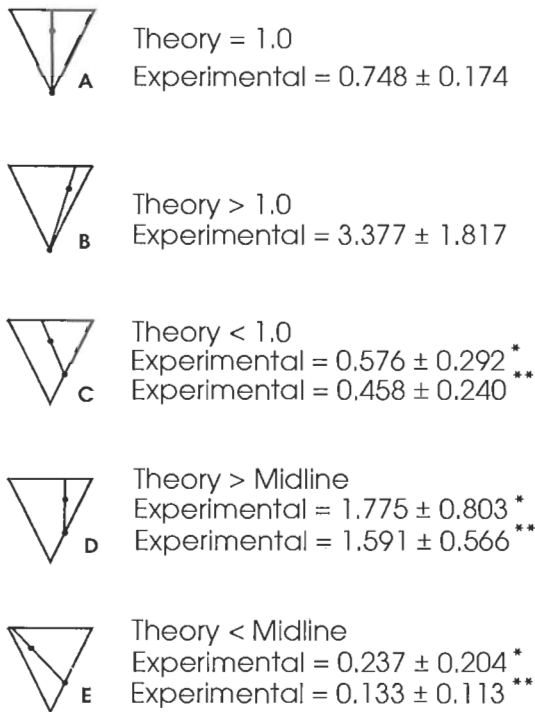


Fig. 5. Theoretical versus experimental ratios of forces at the working and balancing joints. The diagrams indicate the relative positions of the bite and resultant muscle forces. The two condyles are located at the corners of the base of the triangle and the incisor position is at its apex. (a) Bite position at central incisors, resultant muscle force in the midline. (b) Bite position at central incisors, resultant muscle force at 'working' side joint. (c) Bite position at a posterior tooth, resultant muscle force in the midline; *experimental values at premolar positions, **experimental values at molar positions. (d) Bite position at a posterior tooth, resultant muscle force toward the working side joint; *experimental values at premolar positions, **experimental values at molar positions. (e) Bite position at a posterior tooth, resultant muscle force toward the balancing side joint; *experimental values at premolar positions, **experimental values at molar positions.

positions. At the anterior gauge position, four mandibles had an increased ratio and one had a decreased ratio. At the posterior gauge position, four mandibles had decreased ratios and one had an increase. At the lateral and medial gauge, some ratios increased, some decreased, and some did not change.

Relative strain magnitudes among the four condylar surfaces. At all gauge positions the maximum principal strain was tensile, the minimum principal strain was compressive, and the absolute strain values followed the pattern of force measurements at the condyle. At the anterior gauge position [Fig. 6(a and b)] the absolute magnitude of the compressive com-

ponent of strain is higher than tensile-strain component. The ratio of the absolute magnitude of compressive to tensile strain ranged from 1.41 to 2.55 (Mean = 2.04 ± 0.300). In contrast, at the posterior gauge position [Fig. 6(c and d)], compressive strain was almost six times higher than the tensile component, ranging from 3.32 to 10.10 (Mean = 5.80 ± 1.70). At the lateral gauge position [Fig. 7(a and b)] the tensile component was often higher than the compressive component, with the ratio ranging from 0.17 to 1.67 (Mean = 0.851 ± 0.455). At the medial gauge position [Fig. 7(c and d)], strain patterns were similar to those of the posterior gauge position. The compressive to tensile ratio ranged from 2.57 to 7.61 (Mean = 5.25 ± 1.48).

Effect of bite position on strain. Generally, for any given resultant muscle force position, both the maximum and minimum principal strains were least during ipsilateral molar bites. However, when the resultant muscle force was located posteriorly, the medial gauge tended to have the lowest maximum (tensile) strains at the incisor rather than the right molar position [Fig. 7(c)]. These differences were not statistically significant. Generally, the maximum and minimum principal strains were greatest when biting on the most posterior contralateral tooth (either premolar or molar). However, for the posterior gauge, slightly higher strains tended to occur at the incisor position when the resultant muscle force was away from the midline [Fig. 6(c and d)]. The differences were not statistically significant.

Effect of muscle position on strain. The patterns of strain with changing muscle position were essentially the same as the patterns of joint force. At each bite position, strain values generally decreased as the muscle force moved from ipsilateral to contralateral to the joint, and also decreased as the muscle force moved anteriorly.

Directions of principal strain components. On the anterior, posterior, and medial surfaces the directions of compressive strain centred around the long axis of the condylar process. The average directions were within $\pm 25^\circ$ of parallel to the shaft. On the lateral surface the direction of compressive strain tended to be more posteriorly orientated, but was not significantly different from the directions on the other surfaces. Although there were differences among mean directions at different bite and resultant muscle-force positions, the differences were much smaller than the SDs and none as significantly different from directions parallel to the shaft.

DISCUSSION

This *in vitro* simulation was limited by a number of factors. First, only static forces in a vertical direction were applied to the mandible. During normal mastication, force levels change quickly and their direc-

Table 3. Condylar force versus principal strain (Pearson correlation)

	Anterior		Posterior		Lateral		Medial	
	r^2	p	r^2	p	r^2	p	r^2	p
Tensile	0.716	<0.001	0.006	1.000	0.587	<0.001	0.134	1.000
Compressive	-0.614	<0.001	-0.754	<0.001	-0.330	0.004	-0.471	<0.001

tions differ from vertical in the sagittal plane (Hylland, 1978; Van Eijden *et al.*, 1988, 1990; Koolstra and Van Eijden, 1992). Second, the simulated muscle forces were applied only at the angle of the mandible, representing only the masseter/medial pterygoid complex. Actions of muscles not included—the temporalis at the coronoid process and the lateral pterygoid at the condylar neck—might alter the relative strain patterns of the four condylar surfaces. In addition, it is not

known how closely the simulated resultant muscle-force positions correspond to the position of the resultant muscle-force vector during normal function. Each of the jaw adductor muscles inserts over a broad area of the mandible, yet in these simulations the resultant muscle force was applied at only two points. Therefore, strain patterns found within the human condylar process during normal function may differ substantially from those reported in our simulation.

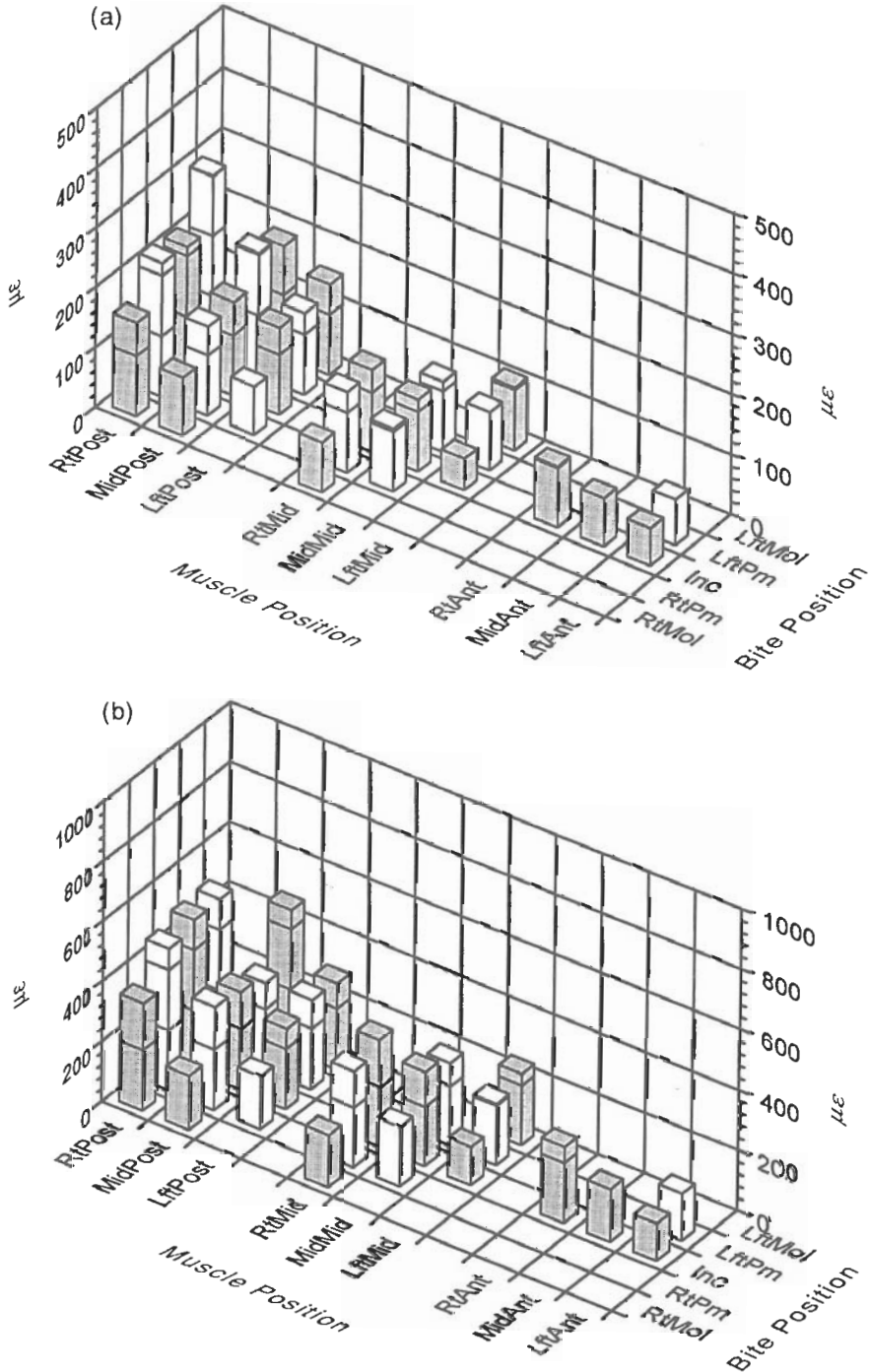


Fig. 6(a and b)—legend overleaf.

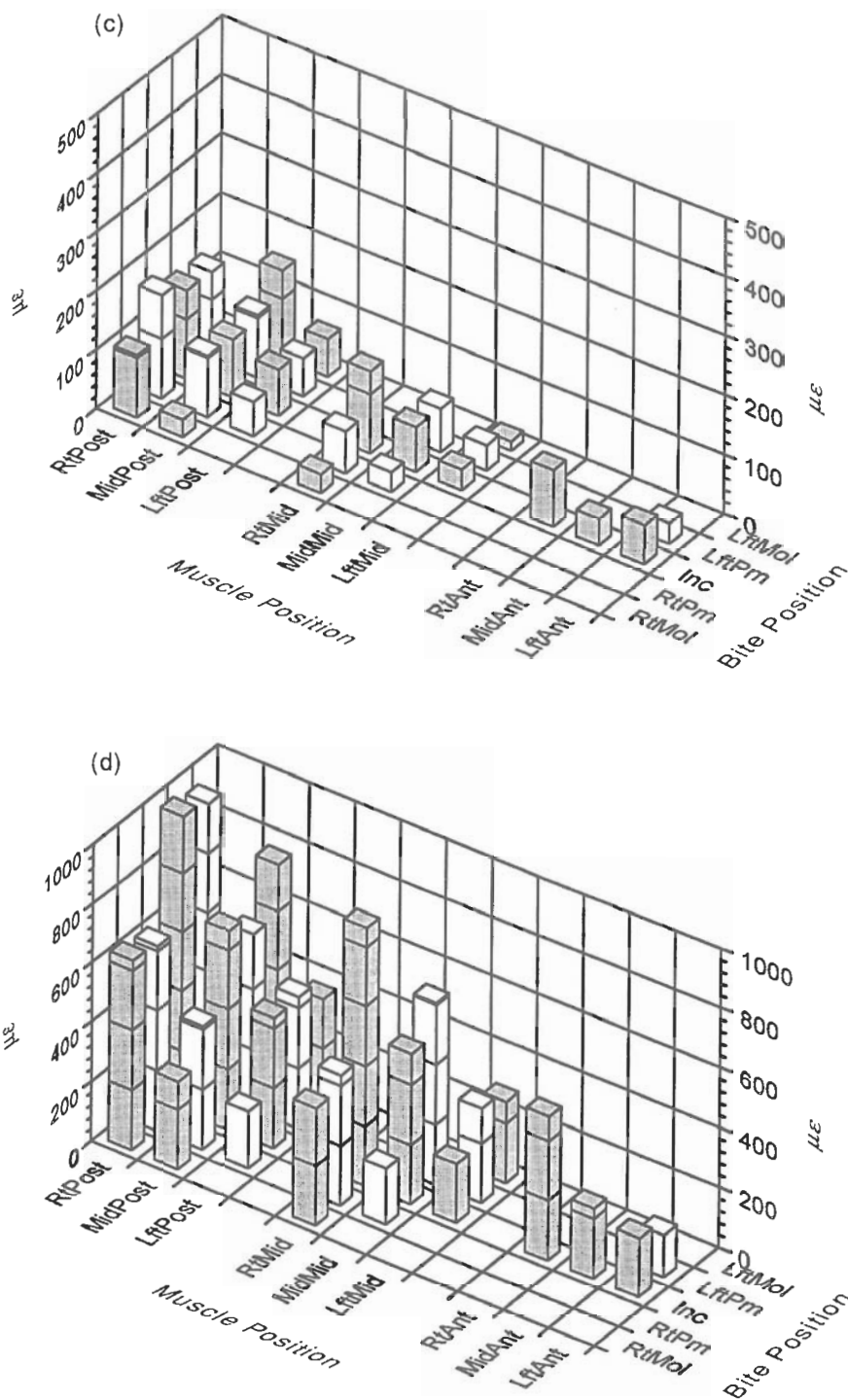


Fig. 6(c and d).

Fig. 6. Mean strain values in the right condylar process (in microstrain) for the anterior gauge and posterior gauges. Stippled bars represent mean strain values at molar and incisor bite positions; open bars represent mean strain values at premolar bite positions. (a) Maximum principal strain (Tension) at the anterior gauge. (b) Minimum principal strain (Compression) at the anterior gauge. Mean compressive strain is shown as the absolute magnitude of the minimum principal strain. (c) Maximum principal strain (tension) at the posterior gauge. (d) Minimum principal strain (compression) at the posterior gauge. Mean compressive strain is shown as the absolute magnitude of the minimum principal strain.

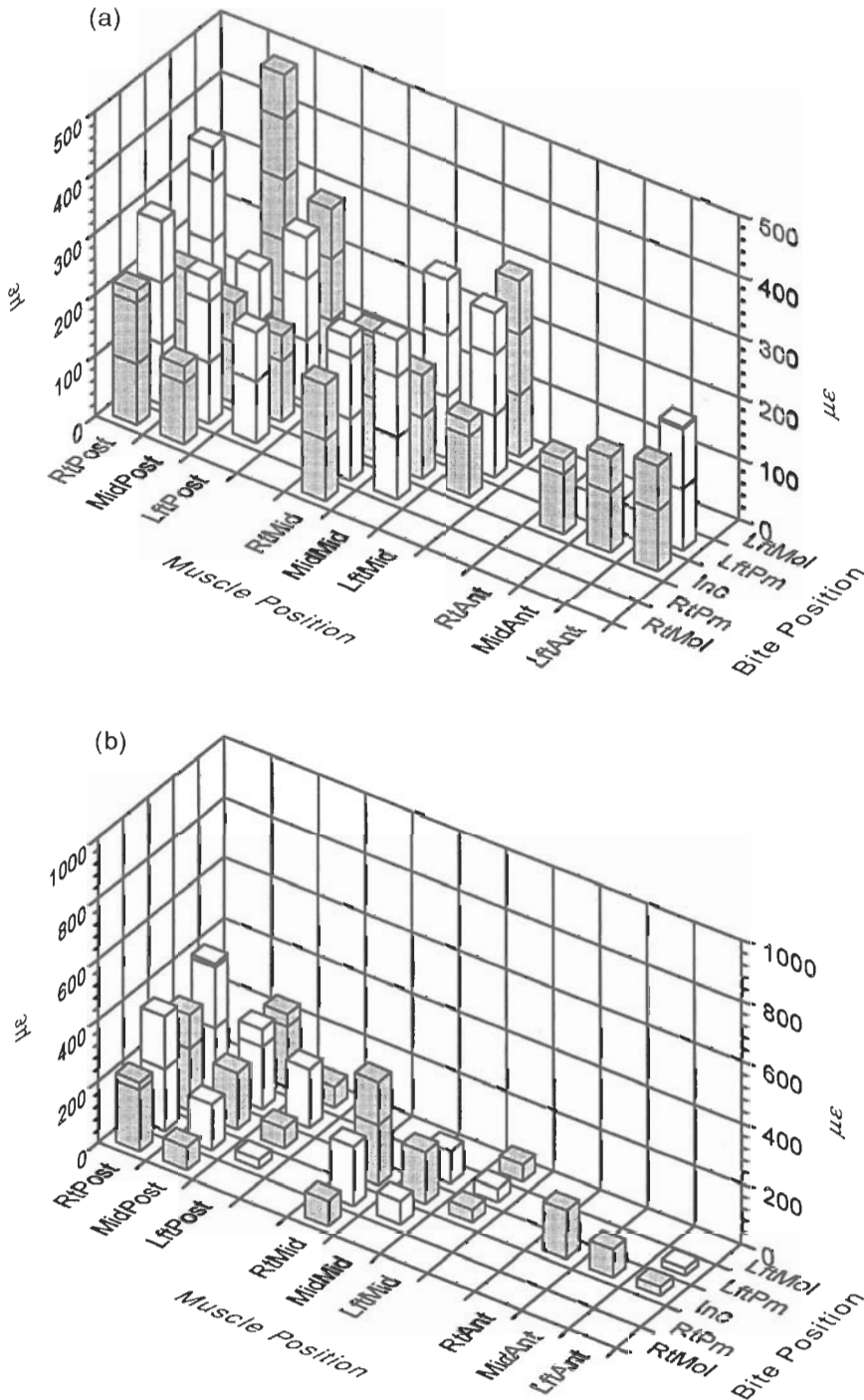


Fig. 7(a and b)—legend overleaf.

However, the *in vitro* simulation did produce a distribution of forces between the two condyles that was similar to that predicted in many previous biomechanical studies (Gysi, 1921; Greaves, 1983; see Hylander, 1985 for a review of others). During unilateral bites the balancing-side condyle was more heavily loaded than the working side condyle. Basically, joint load increased as the resultant muscle

force moved towards the joint. Therefore, for any given bite position, joint force increased at more posterior and more ipsilateral positions of the resultant muscle force. Conversely, for any given position of the resultant muscle force, the joint force increased as the bite position moved around the tooth row away from the joint.

Although Boyd *et al.* (1990) reported higher joint

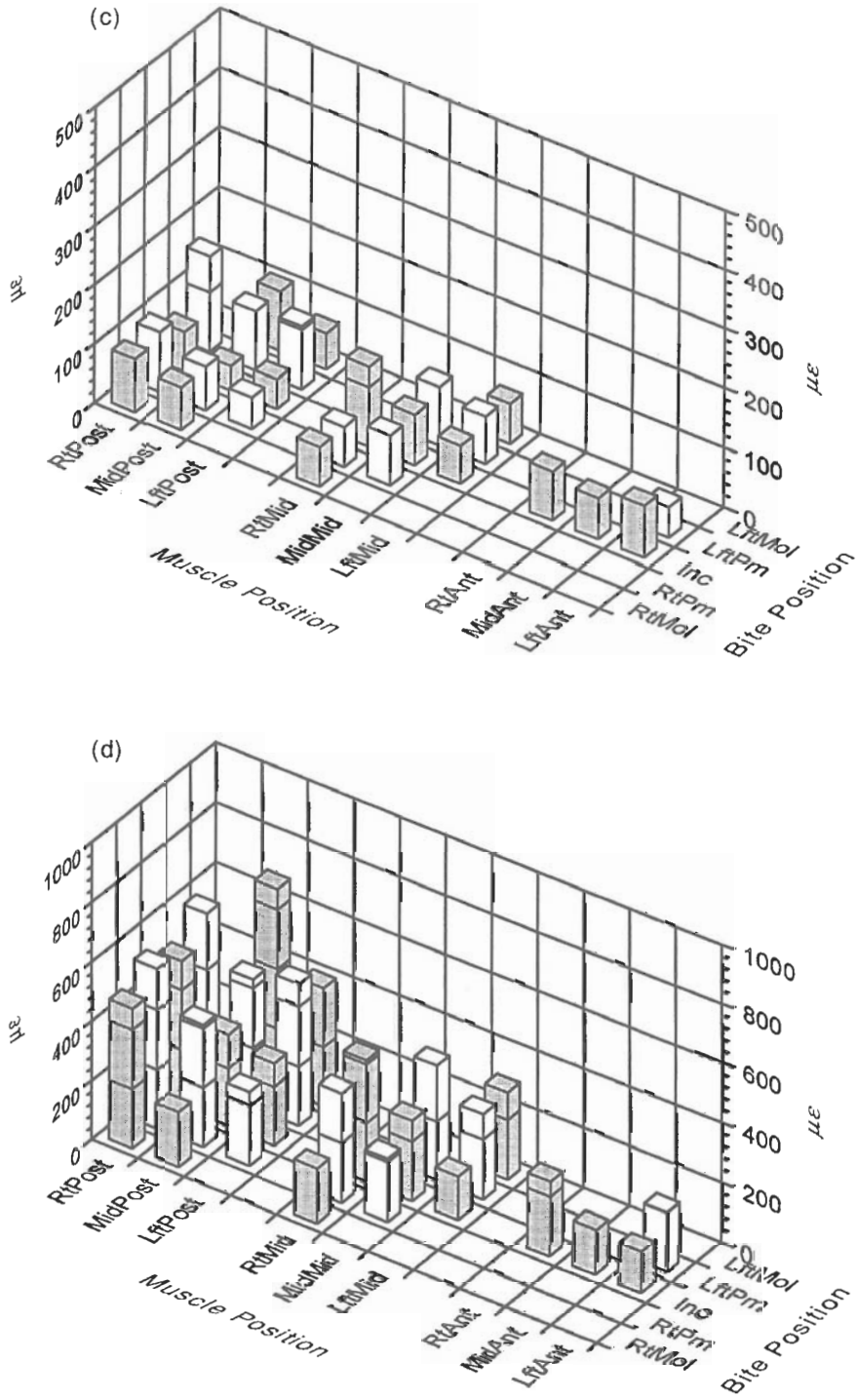


Fig. 7(c and d).

Fig. 7. Mean strain values in the right condylar process (in microstrain) for the lateral gauge and medial gauges. Stippled bars represent mean strain values at molar and incisor bite positions; open bars represent mean strain values at premolar bite positions. (a) Maximum principal strain (tension) at the lateral gauge. (b) Minimum principal strain (compression) at the lateral gauge. Mean compressive strain is shown as the absolute magnitude of the minimum principal strain. (c) Maximum principal strain (tension) at the medial gauge. (d) Minimum principal strain (compression) at the medial gauge. Mean compressive strain is shown as the absolute magnitude of the minimum principal strain.

loads at bite positions closer to the joint, they measured forces at only one joint and occlusal forces were not controlled. Lower occlusal forces when chewing on the side opposite the instrumented joint could result in lower joint forces than when chewing on the same side with high occlusal forces. Such a protective response might be expected following surgical invasion of the joint with disruption of normal sensation from the joint and surrounding tissues.

Our patterns of joint-force magnitudes are in close agreement with most theoretical models of temporomandibular forces. We found the largest joint forces during contralateral bites on more posterior teeth, with a resultant muscle force placed posteriorly and on the same side as the joint. These results conform to the theoretical predictions of Smith, McLachlan and McCall (1986). We found that as the bite position moves posteriorly the jaw muscles contribute proportionally more force to the joint and less to the bite, equivalent to the results of Gysi (1921) and the predictions of Smith (1978). The highest joint forces occurred when the resultant muscle force was ipsilateral to that joint, as predicted by the theoretical modelling of Hart *et al.* (1992). The joint forces were highest when the resultant muscle force was closest to the joint and the bite position furthest around the tooth row from the joint, conforming to theoretical predictions (Smith, 1978; Greaves 1983, 1988). And finally, our results are the first experimental confirmation that predicted ratios of the two joint forces follow a relation between bite position and resultant muscle-force position, as outlined by Greaves (1983).

The directions of the compressive strain on each of the four surfaces varied a great deal between bite and muscle positions for any mandible and between mandibles for any bite and muscle position. An average direction parallel to the long axis of the condylar process (with 1 SD of $\pm 25^\circ$) is consistent with results from *in vivo* macaque experiments (Hylander, 1979) and from finite-element models of human mandibles (Korioth *et al.*, 1992). However, the precision of our experiments was not high enough to confirm the suggestion of Korioth *et al.* (1992) that the direction of compressive strain is more vertically orientated in the balancing-side condylar process.

Our limited study addressed two questions concerning surface strain in the condylar process. (1) Do each of the four surfaces experience the same magnitudes of strain? Distinct strain patterns were observed for each of the four surfaces of the condylar process. The highest levels of tensile strain occurred on the anterior and lateral surfaces while the medial surface had the lowest level of tensile strain. The highest compressive-strain levels were on the posterior surface and the lateral surface had the lowest levels of compressive strain.

What do these strain differences mean? Strain gauges measure the change in shape (strain) of bone surfaces when a load is applied. The amount of observed strain depends both upon the amount of force applied to the bone and the bone's ability to resist a change in shape. The bones resistance to shape change is expressed by mechanical properties

such as Young's modulus and the shear modulus. The different observed strain levels on the four surfaces of the condylar process could be due to differences in distribution of force to each of the surfaces or to differences in mechanical properties of the bone at each of the four surfaces, or both.

The shape of the condyle and condylar process could result in an uneven distribution of force among the four surfaces. Standlee and Caputo (1977) and Standlee *et al.* (1981) reported strain differences between the anterior and posterior borders of the condylar neck even though their photo-elastic resin model had homogenous mechanical properties. In addition, the mechanical properties of bone from various parts of the condylar process do not apparently differ (Schwartz-Dabny and Dechow, 1993). Therefore, observed differences in strain presumably reflect some bending of the condylar process under load. Our results suggest that the condylar process bend medially and posteriorly when loaded under our experimental conditions.

A number of studies have suggested that the lateral aspect of the balancing-side joint is normally more heavily stressed than its medial aspect (Hylander, 1979; Hylander, Johnson and Crompton, 1987; Korioth and Hannam, 1990). Therefore, one would expect higher compressive strain on the lateral condylar surface than on the medial. In contrast, our *in vitro* study found that the lateral surface experienced higher tensile strain than the medial surface, but the opposite was true for compressive strain. The difference, presumably, was a more centrally loaded condyle in our study than in previous monkey and modelling studies. However, we were unable to determine the distribution of forces on the condyle during normal function.

(2) Do the strain patterns at the four surfaces change with changing position of the bite and resultant muscle forces? In general, the changes in absolute strain followed closely the changes in magnitude of force on the condyle. There was a tendency in all gauges for the ratio of compressive to tensile strain to decrease as the resultant muscle force moved from the ipsilateral to the contralateral side. This effect was most noticeable in the medial and lateral gauges. Although the differences were not significant in this small number of mandibles, the results do suggest that bending of the condylar process is reduced by moving the resultant muscle force toward the opposite side.

This study was unable to detect changes in relative strain patterns that significantly correlated with bite position or the anterior-posterior position of the resultant muscle force. Standlee and Caputo (1977) found changes in strain patterns in the condylar head at different bite positions but not in the condylar process. However, because of the high variability among mandibles, we cannot rule out that changing bite or anterior-posterior resultant muscle-force position does not also change relative strain values.

This study emphasises again the difficulty of recording forces and strains in the temporomandibular joint. In spite of the rigorous controls possible in an *in vitro* experiment, differences in morphology and mechanical properties among human mandibles produced high levels of variation. Consistent and

expected patterns of changing condylar loads were observed with different bite- and muscle-free combinations. Strain values are not identical for the four surfaces of the condylar process, and the results suggest bending or possibly torsion of the condylar process under unrestrained loading. The importance of joint-force direction to condylar strain remains unresolved.

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