Masticatory Strains on Osseous and Ligamentous Components of the Temporomandibular Joint in Miniature Pigs

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Aims: *An animal study of functional biomechanics was undertaken to understand normal loading of the temporomandibular joint (TMJ) and to provide insight into the pathogenesis of TMJ disorders.* **Methods:** *Bone strain and ligamentous deformation were measured during mastication in 26 10-month-old minipigs. Half the subjects had undergone a surgical disruption of the left lateral capsular and disc attachments to the condyle 5 to 6 weeks previously. Rosette strain gauges were bonded to the left lateral surfaces of the squamosal bone near the TMJ, the condylar neck, and the mandibular corpus below the molar region. Differential variable reluctance transducers (DVRTs) were placed bilaterally in the lateral capsular tissue of the joints. Bone strains, ligamentous deformations, and the electromyographic activities of the masseters and lateral pterygoids were recorded during natural mastication.* **Results:** *In all animals on both working and balancing sides, mastication caused bone strains that were dominated by tension in the squamosal bone site and by compression in the other sites. Measurements from the DVRT revealed elongation of the lateral capsular tissue in the last phase of the power stroke and shortening in the initial phase of opening, which was almost simultaneous with the development of bone strain. Strain in the capsule ranged from 3 to 25%, with the strain of the balancing side exceeding that of the working side. The surgical disruption did not alter chewing side preference or bone strain, but a tendency toward more extensive ligamentous deformation on the intact side was observed. Furthermore, the ratio of masseter to lateral pterygoid activity was smaller on the disrupted side and larger on the intact side, in comparison to control pigs.* **Conclusion:** *Both osseous and ligamentous components of the TMJ are strained during mastication, and the latter are more deformed on the balancing side. Disruption of the lateral attachment had little effect on strain in the osseous components but appeared to increase strain in the capsule and to modify the balance of masticatory muscle activity.*

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Key words: temporomandibular joint, masticatory muscles, ligaments, electromyography

Temporomandibular joint (TMJ) disorders have been attributed, usually without proof, to many biomechanical causes, including trauma, loose capsules, ruptured disc attachments, abnormal articular shapes and surfaces, occlusal factors, and muscular (particularly lateral pterygoid) dysfunction. Treatment based on these supposed etiologies has been rendered to innumerable patients, with little evidence of success and some documented harm.[1] The need for validated animal models to study normal and abnormal TMJ functions is a recurrent theme in the literature.[2] Although no animal can exactly duplicate the human condition, the pig has been proposed as a reasonable substitute on both anatomic[3,4] and functional[5] grounds.

The present study was undertaken as part of the process of characterizing the biomechanics of the pig TMJ under normal conditions and in response to minor injury. A previous report[6] focused on bone strain and pressure produced by the masseter and lateral pterygoid muscles when contracted in isolation in anesthetized animals. Although that study clarified the different roles of the 2 muscles in loading the TMJ, it did not deal with the more complicated in vivo condition, in which muscles interact to produce the forces and movements of various oral functions. The present paper remedies this lack by concentrating on natural mastication. Using the same sample as before, the authors now report on functional bone strains from the condylar and squamosal elements near the TMJ and from the mandibular body. In addition to recording strains from osseous components, the authors simultaneously measured linear deformation of the lateral ligamentous component of the TMJ.

Previous in vivo studies of the TMJ have emphasized the mandibular condyle, which is generally agreed to be under compressive loading in both pigs and primates.[7–10] Loading conditions on the squamosal part of the zygomatic arch involve substantial amounts of bending and torsion in both pigs and monkeys.[11,12] Although no functional data are available for the area adjacent to the TMJ, studies of anesthetized dogs[13] and pigs[6] also indicate bending and torsion.

In contrast to the osseous components, nothing is known about in vivo strains of ligamentous structures around the TMJ. In humans, the lateral capsule of the TMJ is thickened to form the temporomandibular ligament, which arises from the articular tubercle and the zygomatic arch of the temporal bone just lateral to the articular eminence, attaches to the posterolateral neck of the condyle (oblique part), and attaches, with the disc, to the lateral pole of condyle (horizontal part).[14] This complex is considered to be important for suspending and stabilizing the TMJ and for regulating and restraining functional jaw movements.[15–17] Although the capsule of pigs is thinner than a human capsule, the attachments are the same.

Ligaments can bear tensile loads and are stretched when loaded under tension (tensile strain). An in vitro tensile test of the lateral disc attachment in humans estimated tensile strength at 28.8 to 55.8 N.[17] Both electromyographic (EMG) and bone strain studies have suggested that certain functional condylar movements could put the TMJ capsule under tension,[13,18] but direct measurements of deformation in this critical structure during function have never been attempted.

In recent years, an arthroscopically implantable transducer suitable for soft tissues, the differential variable reluctance transducer (DVRT), has been used to explore the functional deformations of the anterior cruciate ligament of the knee,[19–21] the syndesmotic ligaments of the ankle,[22] and the volar carpal ligaments,[23] both in vivo and in vitro. In the present study this device was employed on the lateral capsule of the pig TMJ.

Clinically, disc displacement is one of the most common of the TMJ arthropathies. Malposition of the disc is most often in an anterior or anteromedial location in relation to the condyle,[24] implying that damage has occurred in the lateral and/or posterior discal attachments. Conceivably, this area may bear relatively large loads or may be a zone of weakness. In any case, it is necessary to understand the normal loading regime in this area and the possible effects of pathologic interference on loading. Therefore, the authors also investigated masticatory biomechanics after surgery was performed to damage the attachments of the disc and capsule to the lateral pole of the condyle.

Materials and Methods

Animals

Twenty-six Hanford miniature pigs (*Sus scrofa,* 13 males and 13 females) were supplied (Charles River, Inc) at the age of 8 months. All pigs were trained to feed while connected to recording equipment. Six males and 7 females received minor surgery to disrupt the lateral attachments of the TMJ. The remaining 13 animals constituted the control group. Recordings were performed 5 to 6 weeks postsurgery, when the pigs were 10 to 11 months old. Following completion of the measurements described in this paper, the pigs were anesthetized, and muscle stimulations were performed as reported previously.[6] The animal use protocol was reviewed and approved by the University of Washington Animal Care Committee.

Surgical Disruption

As described previously,[6] surgery was carried out under aseptic conditions 5 to 6 weeks before the experimental observations. Pigs of the surgery

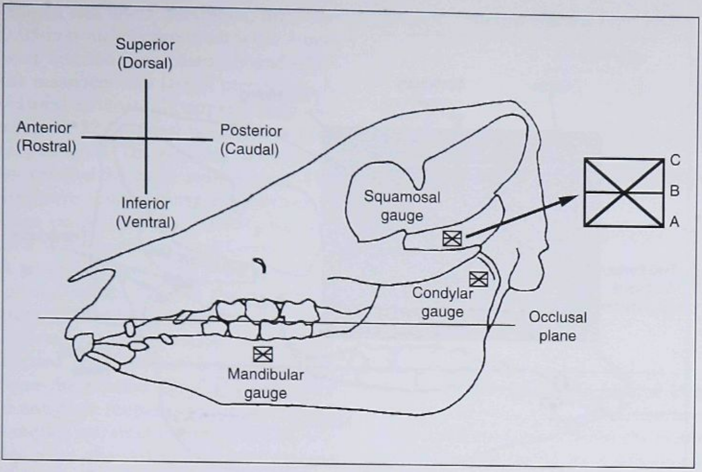

Fig 1 Left side of miniature pig skull showing the placement of 3 stacked rosette gauges on the lateral surface of the squamosal bone at the level of the articular eminence, the lateral surface of the condylar neck, and the lateral surface of the mandibular corpus. A, B, and C in the enlargement represent the 3 elements of each gauge. The coordinate system at the upper left indicates the anatomic nomenclature used in the article. Superior-to-inferior and anterior-to-posterior represent the vertical and the horizontal planes, respectively.

group (n = 13, as described above) were anesthetized with isoflurane. The left TMJ area was exposed, and the overlying posterosuperior fibers of the masseter were reflected from their insertion behind the condyle. The attachments of the capsule to the lateral side of the condyle were stripped with a curette, and the stripped region was then enlarged to include the lateral pole of the condyle to detach the major part of the lateral discal attachment. The synovial membrane remained intact. The reflected masseteric fibers were replaced and the incision was closed. An oral antibiotic (Clavamox 500 mg, twice daily; Pfizer) was administered for 3 days after the surgery.

Installation of Strain Gauges

The installation and calibration of strain gauges have been reported elsewhere.[6] In brief, on the day of the recordings, pigs were anesthetized with halothane/nitrous oxide and 2 incisions were made to expose the 3 gauge sites. Over each gauge site, the periosteum was reflected, and the bone surface was prepared by cauterization, scraping, degreasing, neutralization, and drying. Three-element 45-degree stacked rosette strain gauges (SK-06-030WR-120, Measurements Group Inc) were bonded to the lateral surface of the left squamosal bone at the level of the articular eminence, the lateral surface of the left condylar neck, and the lateral aspect of the left mandibular corpus below the first molariform tooth (Fig 1). These locations were chosen because the squamosal and condylar sites are the bony surfaces closest to the TMJ that can be approached surgically without disrupting the capsule, and the location below the molars may reflect bite force. The strain gauge outputs were calibrated so that 1.0 V of output was equal to 1,000 $\mu\epsilon$ at a bridge excitation of 2.0 V DC. During muscle stimulations, strain gauge outputs showed roughly linear relationships to both stimulation voltage and bite force.[6]

Calibration and Implantation of Transducers

The 1.5-mm-diameter, 13-mm-long DVRTs comprise a stationary and a free sliding coil, each secured in the tissue by a barb, plus a magnetically permeable core (Fig 2 inset). The position of the core is detected by measuring the coils' differential

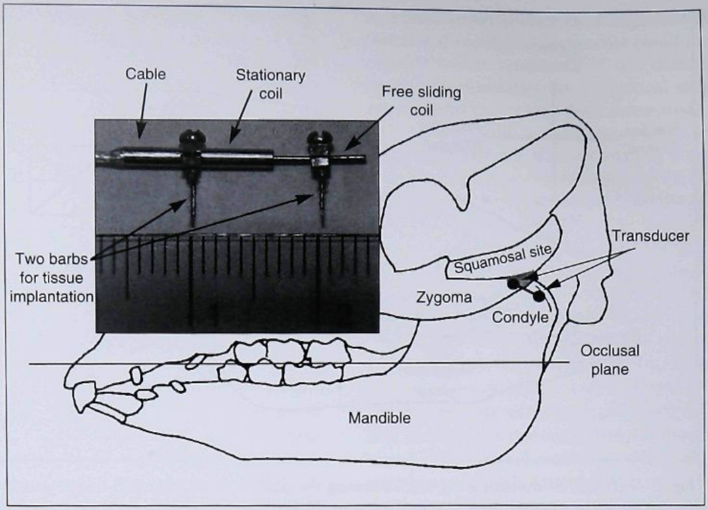

Fig 2 Implantation of the differential variable reluctance transducer (DVRT) was facilitated by removing the caudal tip of the zygomatic bone (shaded). The inset illustrates the DVRT, which was fixed in the joint capsule by 2 short barbs. The initial distance between the centers of the 2 barbs was 8 to 12 mm along the collagen fiber axis.

reluctance with a sine wave excitation and synchronous demodulator (MicroStrain Inc). According to the manufacturer, frequency response is 7,000 Hz with a signal-noise ratio of 600:1 and a sensitivity of ± 1 µm.

Prior to each recording, each DVRT was calibrated with an automatic displacement sensor system provided by the manufacturer. Plots of DVRT output against micrometer position produced highly linear correlations for both shortening and elongation ($r^2 = 0.99$ or better) for a range of 6 mm (–3 to +3). The instrument can sense changes in axial distance only (sliding) between the 2 coils, not rotation.

After the strain gauges were bonded as described above, DVRTs were secured in the lateral ligament of each TMJ capsule by the 2 barbs. Because the caudal end of the zygomatic bone overlies the lateral aspect of the condyle, this portion (about 5 mm long) with attached masseteric fibers was removed by a rongeur to place the DVRT (Fig 2). A previous pilot study demonstrated that this minor removal does not cause abnormal function in the animals (Artese and Herring, unpublished data, 1996). In occlusion, the distance between the barbs was 8 to 12 mm ("initial length"). The long axis of each DVRT was oriented along the collagen fiber axis (about 20 to 30 degrees oblique to the occlusal plane; see Fig 2). The jaw was manipulated to verify that the DVRT was correctly situated and freely movable. At the same time, voltage outputs were checked for consistency with the calibration. Voltage increased when the DVRT elongated during closing, retrusion, and ipsilateral shifts, and voltage decreases accompanied shortening during opening, protrusion, and contralateral shifts. The range of motion was less than 5 mm in all manipulated jaw movements.

Recording Procedures

After the experimenters verified that all the devices were operational during jaw manipulation, the periosteum, fascia, and skin were sutured separately. The lead wires with attached plugs were exited from the incision and secured to a collar around the neck. The strain gauges were connected to conditioner/amplifiers (Model 2120A, Measurements Group), and the DVRTs were connected to a demodulator (MicroStrain Inc).

With the animal still under anesthesia, fine-wire electrodes (0.05-mm nickel-chromium wire, 1-mm bared tips) were inserted percutaneously and bilaterally into the masseters and lateral pterygoids. A posterior (caudal to rostral) approach to the condylar neck with 22-G spinal needles was used for the lateral pterygoid. The accuracy of electrode position was verified by back stimulation. The electrode wires were connected via steel springs to high-impedance probes (Model 7HIP5G, Grass), which in turn were connected to Grass 7P3C amplifiers. A ground electrode (50 × 25 mm metal plate) was placed on the back of the pig's neck with conductive gel (Burdick, Inc).

A topical anesthetic (2% procaine hydrochloride) was drizzled onto the incisions. After they recovered from the general anesthetic and were administered analgesic (buprenorphine hydrochloride, 0.005 mg/kg intramuscularly, Reckitt and Colman), pigs were allowed to feed unrestrained on the feeding table. Pig chow pellets were offered first, sometimes followed by cookies and biscuits. Three surgery animals refused food but did chew on rubber tubing or tongue depressors.

While pigs were chewing, the amplified signals of bone strain, DVRT displacement and EMG activity were sampled at 500 Hz and input into a Power Macintosh (Apple Computer) running AcqKnowledge III (MP100, Biopac Systems, Inc). Each recording session lasted 20 to 40 minutes. At the end of the session, animals were anesthetized for other procedures, after which they were sacrificed. Gauge sites, attachments, and orientations were inspected for any flaws and for standardization of strain orientation, and DVRTs were checked for placement and responses.

Data Processing and Statistical Analysis

The digitized signals were analyzed with AcqKnowledge III. For all channels except EMG recordings, baseline values were subtracted from peak values for each chewing cycle. The means of all variables were calculated from 5 to 10 stable and consecutive chewing cycles for each animal. Principal strains (tension and compression), shear strain (sum of absolute values of principal strains), and the orientation of tensile strain relative to the occlusal plane (see anatomic nomenclature in Fig 1) were calculated according to standard formulae.[25] According to convention, tensile and compressive strains are expressed as positive and negative values, respectively. DVRT displacements were calculated with the calibration regression equation, and DVRT strain was calculated as displacement divided by the original length in occlusion, ie, $(L - L_{(0)})/L_{(0)}$. The frequency of chewing cycles and the ratio between the numbers of right- and left-sided cycles were calculated from measurements of 20 to 50 consecutive cycles of EMG activation. The working side was identified by comparing the timing and amplitude of EMG activity in the 2 masseters[26] and referring to the pattern of activation of the lateral pterygoid muscle (see Results). AcqKnowledge III was used to calculate EMG burst duration and activity level (integrated and mean activities), and then ipsilateral masseter/lateral pterygoid muscle activity ratios were computed. Table 1 summarizes the successfully recorded sample sizes. Missing data are a result of transducer failures and the limited number of channels available for simultaneous recording in the earlier experiments.

Table 1 Sample Size for Each Transducer

	Control pigs		Surgery pigs	
	Left	Right	Left	Right
Strain gauge				
Squamosal site	12	0	11	0
Condylar site	12	0	9	0
Mandibular site	4	0	6	0
DVRT	6	6	7	4
EMG activity				
Masseter	7	9	8	8
Lateral pterygoid	7	6	8	3

DVRT = differential variable reluctance transducer; EMG = electromyographic.

Differences between the 2 groups and between the working and balancing sides of each group were examined with 2-sample and paired *t* tests, respectively. Analysis of variance and the Student-Newman-Keul multiple-comparison test (SNK) were performed to elucidate the differences among the 3 strain gauge sites of each group.

Results

General Behavior and Performance of Mastication

Generally, pigs awoke from anesthesia and began to eat in less than 30 minutes. For the first 5 to 10 minutes, help from the examiner(s) was necessary to steady the groggy animals. Then, animals usually stood and ate food from the dish as usual.

Chewing frequency ranged from 1.5 to 2.2 Hz (average 1.9 ± 0.2), with no significant difference

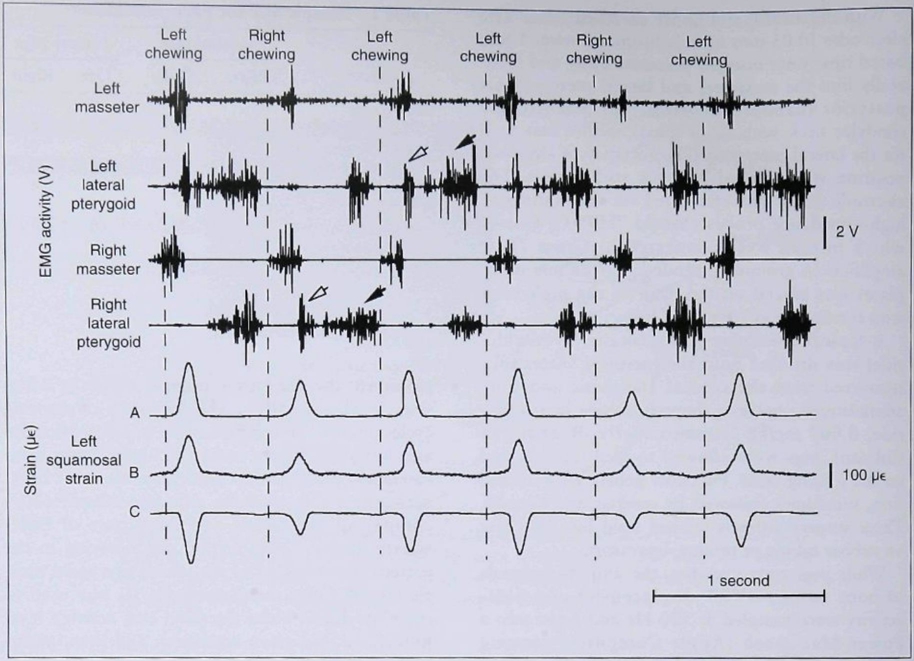

Fig 3 Raw EMG tracings and squamosal strain recordings of the masseter and lateral pterygoid muscles. When the working side is on the left (*left chewing*), the mandible moves to the right during the power stroke. The onset of the masseter burst is taken as the starting point of a chewing cycle (*dashed lines*). The working-side masseter, which moves the mandible toward the balancing side, typically begins and ends later than does the balancing-side masseter. The lateral pterygoid muscles showed the 2-phase firing pattern; the first phase (*open arrows*) started at the final stage of the masseter burst, and the second phase (*solid arrows*) started after the offset of the masseter burst and lasted longer than the first phase. The balancing-side lateral pterygoid muscle showed relatively low activity in the first phase and an obvious pause of activity between the 2 phases, compared to the working-side muscle. Left squamosal strains are higher when the left side is the working side.

between the 2 groups. As is typical for pigs, the animals alternated the working side and used both sides almost equally during a sequence of consecutive chewing. Neither control nor surgery pigs showed a preferred chewing side (control, 48.1% left side; surgery, 50.1% left side).

Muscle Activity Patterns

Figure 3 illustrates a typical recording of bilateral masseter and lateral pterygoid muscles with squamosal strains. The activity pattern of the masseter muscle was identical to that reported previously.[27] The lateral pterygoid muscle showed either a 2-phase activity pattern (62.5%, 15 of 24 muscles), a 1-phase pattern (20.8%, 5 of 24 muscles), or a mixed 1- and 2-phase pattern (16.7%, 4 of 24 muscles). The activity of the lateral pterygoid muscle was defined as 1 burst regardless of whether it showed 1 or 2 phases. No preference was found in either group. Generally, the first phase started at the final stage of the masseter burst (power stroke of mastication), and the second, longer phase followed after 80 to 150 ms. The lateral pterygoid on the working side exhibited stronger and longer firing in both phases than the balancing side muscle.

Table 2 summarizes the EMG parameters. Lateral pterygoid bursts were always longer than

Table 2 EMG Activity (Mean ± SD) During Mastication

	Left working side		Right working side	
	Masseter	Lateral pterygoid	Masseter	Lateral pterygoid
Control pigs				
Left muscle				
n	7	7	7	7
Duration (ms)	196 ± 49	260 ± 50	173 ± 26	322 ± 83
Integrated EMG (mV.s)	133 ± 125	140 ± 137	68 ± 64	150 ± 145
Mean EMG (mV)	690 ± 665	542 ± 525	375 ± 334	470 ± 445
Right muscle				
n	9	6	9	6
Duration (ms)	166 ± 39	355 ± 105	196 ± 43	280 ± 120
Integrated EMG (mV.s)	80 ± 78	231 ± 221	270 ± 253	190 ± 178
Mean EMG (mV)	540 ± 510	670 ± 646	1420 ± 650	675 ± 605
Surgery pigs				
Left muscle				
n	8	8	8	8
Duration (ms)	196 ± 53	292 ± 81	174 ± 34	309 ± 81
Integrated EMG (mV.s)	54 ± 36	177 ± 158	39 ± 30	256 ± 223
Mean EMG (mV)	287 ± 213	515 ± 381	235 ± 194	505 ± 395
Right muscle				
n	8	3	8	3
Duration (ms)	176 ± 36	317 ± 143	189 ± 42	279 ± 105
Integrated EMG (mV.s)	119 ± 109	35 ± 15	170 ± 155	20 ± 15
Mean EMG (mV)	760 ± 630	120 ± 43	701 ± 629	82 ± 33

Brackets indicate significant differences between right and left muscles (* $P < 0.05$; † $P < 0.01$).

those of the masseter muscle. In the control pigs, both integrated and mean EMG activities of the working-side masseter muscle were usually larger than those on the balancing side, whereas working- and balancing-side values were similar for the lateral pterygoid muscle. No statistically significant difference was found between the 2 groups for individual EMG parameters, but the surgery pigs were strikingly different from the controls in the low activity seen in the left masseter and the right lateral pterygoid muscles, regardless of chewing side. Because of these changes, the ratio of ipsilateral masseter to lateral pterygoid activity was very different in the 2 sides of the surgery pigs (Fig 4). In the control pigs, this ratio was typically between 1 and 2. However, for the surgery pigs, the ratio was always less than 1 on the left (disrupted) side and always greater than 3 on the right (intact) side.

Bone Surface Strains

Table 3 and Fig 5 summarize bone strain magnitudes and orientations during mastication. Regardless of chewing side, larger principal tensions than compressions were found at the squamosal site, with the tension oriented superiorly and slightly posteriorly, almost perpendicular to the occlusal plane. In contrast, larger compressive than tensile strains were common in the condylar site. In control pigs, the direction of tension was about 135 degrees, and thus the compressive axis (90 degrees from tension) was oriented about 45 degrees anterosuperiorly from the occlusal plane. At the mandibular site, compressive strain was usually comparable to tensile strain, and orientation was similar to the squamosal location. No significant differences were found between working and balancing sides for any site. Comparisons among the 3 locations indicated that compressive strain was greatest in the condyle. Principal strains were generally smallest at the mandibular site.

Surgery and control pigs showed similar strain patterns at all 3 sites. However, the orientation of tension at the condylar site in the surgery pigs tended to be more vertical, especially on the working side ($P = 0.051$), which resulted in compression oriented almost parallel to the occlusal plane. There was also a suggestion of a working/balancing side difference at the mandibular site (Fig 5), but it was not statistically significant. Differences in strain amplitudes among the 3 sites in surgery pigs were not as obvious as in the control pigs.

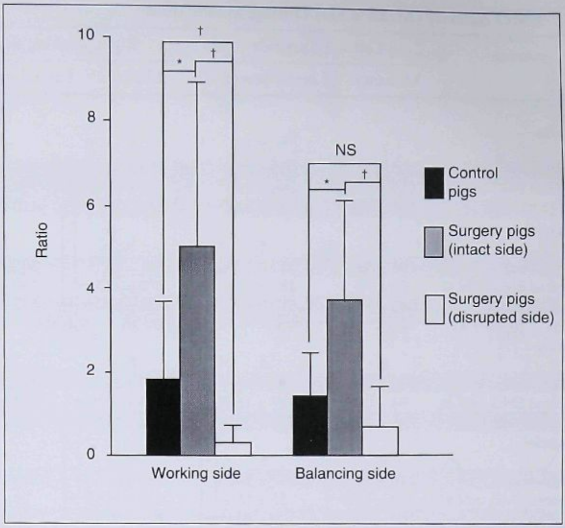

Fig 4 Mean activity ratios (means and standard deviations) of ipsilateral masseter to lateral pterygoid muscles. Compared to control pigs, the ratios for the intact side were larger and for the disrupted side were smaller in surgery pigs, regardless of chewing side. $*P < 0.05$; $^{\dagger}P < 0.01$.

Table 3 Peak Principal Bone Strains (Mean ± SD, in µϵ) During Mastication

	Working side				Balancing side			
	Max	Min	Shear	Dir	Max	Min	Shear	Dir
Squamosal site (SQ)								
Control (n = 12)	211 ± 90	−59 ± 69	270 ± 122	104 ± 31	213 ± 138	−84 ± 76	297 ± 188	110 ± 29
Surgery (n = 11)	215 ± 104	−73 ± 55	288 ± 133	101 ± 35	189 ± 106	−60 ± 55	255 ± 136	96 ± 40
Condylar site (CD)								
Control (n = 12)	165 ± 113	−230 ± 164	395 ± 260	133 ± 44	127 ± 75	−195 ± 136	322 ± 197	138 ± 41
Surgery (n = 9)	164 ± 148	−256 ± 220	420 ± 257	99 ± 25	118 ± 42	−190 ± 172	308 ± 218	110 ± 51
Mandibular site (MD)								
Control (n = 4)	77 ± 32	−136 ± 100	213 ± 127	104 ± 48	86 ± 12	−125 ± 84	211 ± 91	100 ± 36
Surgery (n = 6)	135 ± 116	−148 ± 98	283 ± 160	102 ± 50	100 ± 24	−82 ± 91	182 ± 93	71 ± 45
P values*								
Control	0.02† SQ > MD CD > MD	0.01‡ CD > SQ CD > MD	0.13	0.18	0.06	0.05† CD > SQ	0.56	0.09
Surgery	0.46	0.04† CD > SQ CD > MD	0.54	0.91	0.12	0.04† CD > SQ	0.29	0.20

Max = tension; Min = compression; Shear = Max + Min (absolute value); Dir = direction of tension relative to the occlusal plane (angle in degrees).
*ANOVA (gauge-site test). $^{\dagger}P < 0.05$; $^{\ddagger}P < 0.01$.

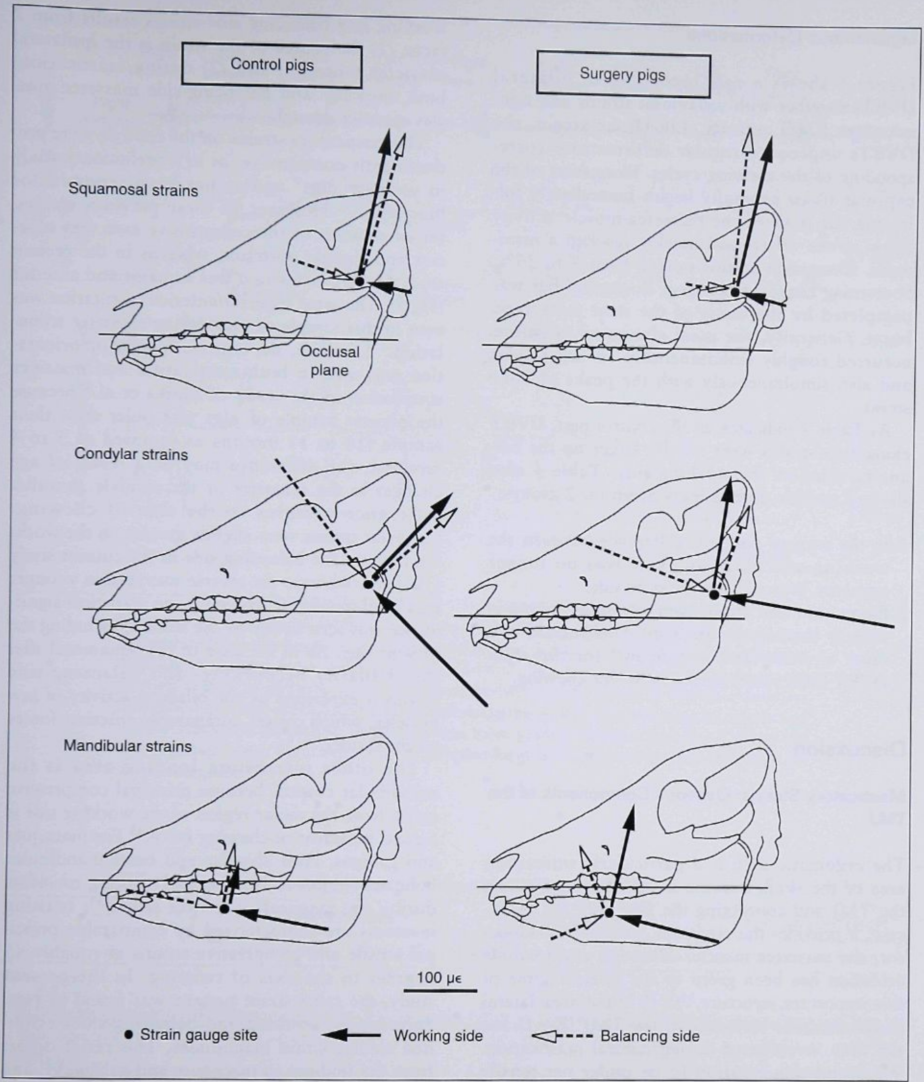

Fig 5 Average principal strains for 3 gauge sites during mastication in control and surgery pigs (data and standard deviations are shown in Table 3). Arrows heading toward the gauge site indicate compressive strain; arrows heading away from the gauge site indicate tensile strain. Solid lines and arrows indicate the strains during left-side chewing (gauge sites on the working side). Dashed lines and open arrows indicate the strains during right-side chewing (gauge sites on the balancing side). The squamosal site showed larger tensile than compressive strains, with the direction of tension posteriorly vertical to the occlusal plane. The condylar site showed larger compressive than tensile strains, with the direction of compression oblique to the occlusal plane anterosuperiorly. At the mandibular site, the tensile and compressive strains tended to be comparable, and strains were significantly smaller than those at the squamosal and condylar sites. The directions of the principal strains were similar to those of the squamosal strains. The differences between chewing sides and between surgery and control pigs were not statistically significant.

Ligamentous Deformations

Figure 6 shows a raw recording of bilateral DVRTs together with squamosal strains and right masseter EMG activity. Like bone strain, the DVRTs underwent regular deformations corresponding to the chewing cycles. Elongation of the capsular tissue generally began immediately following the peak of the masseter muscle activity (close to the offset) and quickly reached a maximum. Elongation strains ranged from 3 to 25%. Shortening lasted longer than elongation but was completed by the onset of the next masseteric burst. Generally, the most elongated positions occurred roughly simultaneously on the 2 sides and also simultaneously with the peaks of bone strain.

As Table 4 indicates, in the control pigs, DVRT elongation strains were usually larger on the balancing than on the working side. Table 4 also shows 2 notable differences between the 2 groups:

1. In the surgery pigs, the difference between the working and balancing side was no longer apparent, especially on the right side.
2. Elongation and strain were generally larger in surgery than in control pigs. This feature was most obvious (and significant) for the right DVRT (intact side) during right-side chewing.

Discussion

Masticatory Strains: Osseous Components of the TMJ

The zygomatic arch is a particularly interesting area of the skull, because in addition to forming the TMJ and connecting the face with the braincase, it provides the origin for a major jaw adductor, the masseter muscle. Although considerable attention has been given to the strain regime of this important structure,[11,12,28–30] the area lateral to the articular eminence of the TMJ (Fig 1) has not been investigated during natural mastication. We found this location to be under net tensile strain, similar to the pattern of more anterior squamosal locations, but with a slightly more vertical orientation of the tensile axis (103 degrees, as opposed to 126 degrees, as reported by Herring et al[11]; see Table 4 and Fig 5). Masticatory strains lateral to the articular eminence of the TMJ were very similar to those produced by stimulation of the ipsilateral masseter muscle[6] but were about one-third smaller in magnitude. The similarity of working and balancing side strains results from 2 facts: *(1)* the source of the strain is the ipsilateral masseter muscle[11]; and *(2)* during mastication, both working- and balancing-side masseter muscles contract strongly.

The masticatory strains on the condyle were predominantly compressive, as in a preliminary study in younger pigs[9] and as has been reported for monkeys.[7,31] However, in these previous studies, the orientation of the compressive axis was superior and slightly posterior, whereas in the present study compressive strain was superior and anterior (Fig 5). The same superior/anterior orientation was seen in this sample of pigs during masseter stimulation.[6] Likewise, the superior/posterior orientation was seen in both mastication and masseter stimulation in the study of Marks et al.[9] Because the present sample of pigs was older than their sample (10 to 11 months as opposed to 3 to 4 months), the difference may be a result of age changes in the masseter or the condyle. Another difference pertains to the side of chewing. Condylar strains were slightly greater on the working than on the balancing side in the current study (Table 3), whereas the reverse was seen in younger pigs[9] and monkeys.[7] However, no statistical significance was seen in any of the studies, including the present one. As in the case of the squamosal site, the similarity of working- and balancing-side strains is explained by the bilateral activity of jaw muscles, which causes comparable reaction forces on the 2 sides.[32]

The other interesting loading area is the mandibular corpus, because principal compressive strain from the molar region of the working side is a good indicator of chewing force.[33] For macaques and galagos, both alveolar and basal mandibular bone are subject to bending and twisting moments during the masticatory power stroke[34]; twisting moments are characterized by comparable principal tensile and compressive strains at roughly 45 degrees to the axis of twisting. In the present study, the same strain pattern was found in pigs. Surprisingly, working and balancing sides exhibited similar strain magnitudes. This result differs from the findings in macaques and galagos[8,35] and rabbits,[36] where the working side was more heavily strained. The explanation for the even distribution of strain in pigs may lie in their occlusion and masticatory pattern. Unlike the other species studied, the pig has nearly isognathous jaws, and both the initial closing stroke and power stroke of mastication are probably bilateral.[37] Although the working side can be identified by the direction of jaw movement during the power stroke (toward

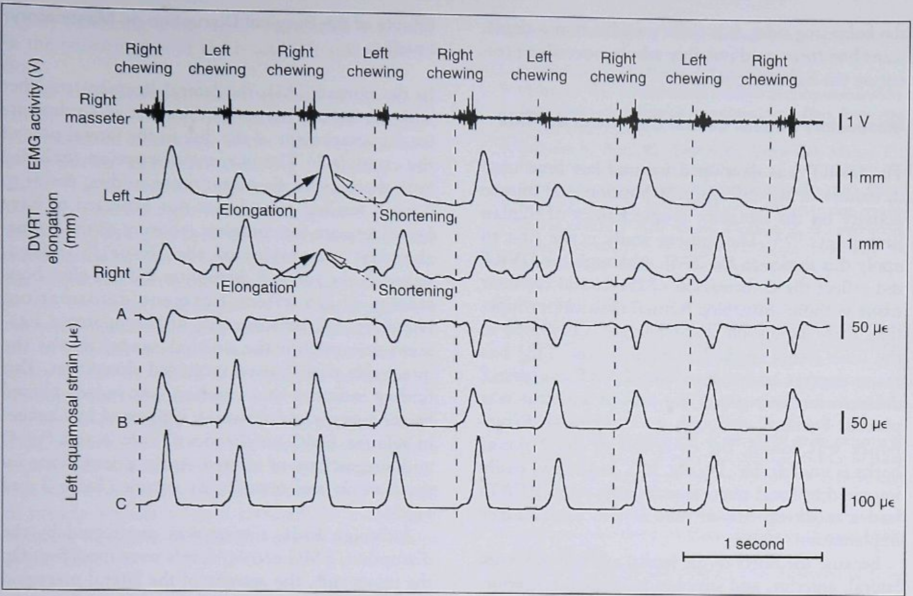

Fig 6 Raw tracings of DVRTs, squamosal strains, and right masseter EMG activity. Upward deflection indicates elongation (*solid arrows and lines*), and downward deflection indicates shortening (*open arrows and dotted lines*). The dashed vertical lines indicate the starting points of chewing cycles, as characterized by the onset of masseter activity. Elongation generally started immediately following the peak of masseter muscle activity and quickly reached a maximum. Shortening was more gradual but was completed before the next masseter burst. The range of DVRT displacement was larger on the balancing than on the working side.

Table 4 DVRT Elongation and Strain During Mastication (Mean ± SD)

	Working side		Balancing side		Chewing-side test (*P*)	
	Elongation (mm)	Strain (%)	Elongation (mm)	Strain (%)	Elongation	Strain
Control pigs						
Left DVRT (n = 7)	0.78 ± 0.54	9.4 ± 7.0	1.45 ± 0.96	16.9 ± 10.0	0.02*	0.01†
Right DVRT (n = 4)	0.60 ± 0.41	7.8 ± 5.4	1.18 ± 0.93	11.4 ± 10.3	0.07	0.23
Both sides (n = 11)	0.69 ± 0.47	8.7 ± 6.1	1.34 ± 0.90	15.4 ± 9.2	0.00†	0.00†
Surgery pigs						
Left DVRT (n = 7)	1.25 ± 0.63	12.8 ± 5.6	1.62 ± 0.69	18.4 ± 5.9	0.19	0.10
Right DVRT (n = 4)	0.91 ± 0.28	14.5 ± 1.3	1.04 ± 0.19	16.2 ± 5.1	0.29	0.66
Inter-group test *P* values						
Left DVRT	0.25	0.29	0.85	0.89		
Right DVRT	0.05*	0.05*	0.42	0.46		

*$P < 0.05$; †$P < 0.01$.

the balancing side), it is quite possible that a significant bite force, and possibly a bolus, are also present on the balancing side.

Masticatory Strains: Lateral Capsule of the TMJ

The DVRT was developed for and has been used in studies of the influence of position and muscle activity on the ligament biomechanics of human limb joints.[19–23] The present study is the first to apply this device to the TMJ. Although the DVRT did reflect the deformation of the lateral capsular tissue without disturbing normal masticatory function, there were some disadvantages. Compared to the limb joints studied previously, the TMJ has many degrees of freedom. The DVRT can detect deformation only along the axis in which it was placed. Further, although no functional disturbance was found, the insertion of the 2 metal barbs is undesirable. Finally, this device was easily impaired by local tissue interference; most DVRTs had a working life of just 2 to 3 hours after implantation.

Because the fibers of the lateral capsule run from lateral, anterior, and superior to medial, posterior, and inferior, the DVRTs were implanted along this orientation. This part of the capsule is probably slack in some jaw positions, accounting for the fact that the observed strains (3% to 25%) were larger than those typically reported from the cruciate ligaments (1.7% to 3.6%).[20] Manipulation of anesthetized animals verified that elongation (presumably stretching) accompanied all movements with a retrusive component, ie, retrusion, closing, and ipsilateral deviation. During mastication, elongation occurred only during the power stroke (Fig 6). Although both condyles probably retrude during the power stroke, the balancing side has much farther to go, because the mandible is moving toward the balancing side. Thus, capsular strain is significantly larger on the balancing side. This abrupt and substantial elongation suggests that the capsular ligament may bear a tensile load during the power stroke, although this speculation requires knowledge of the resting length of the capsular ligamentous fibers that we do not yet have. On the other hand, shortening of the capsular ligament occurred in the initial phase of opening (Fig 6). Thus, capsular shortening must accompany the protrusive component movement, which presages opening rather than opening itself.[26] In summary, we may conclude that load-bearing by the ligamentous components of the TMJ is most likely to occur during the power stroke and to be higher on the balancing side than on the working side.

Effects of the Surgical Disruption on Masticatory Loads

In the human TMJ, the lateral ligament together with the capsule may sometimes act as a substitute for the attachment of the disc to the lateral pole of the condyle.[17] The current disruption included both these areas. Based on other studies, the 5- to 6-week healing period was not expected to have been adequate for complete recovery of the biomechanical properties of the tissue.[38] Indeed, although the surgical disruption did not alter bone strain, it did affect ligament deformation. However, the performance of the operated ligament was within the normal range; it was the intact side that showed increased elongation. This finding indicates that chewing was indeed altered by the surgery, a conclusion supported by changes in relative EMG amplitudes (Table 2 and Fig 4) and suggestions of altered strain orientations on the condyle and mandibular corpus (Table 3 and Fig 5).

Although EMG timing was unaffected by the disruption, EMG activity levels were modified. On the intact side, the activity of the lateral pterygoid muscles became significantly weaker, while on the disrupted side the masseter was weakened. It is conceivable that surgical trauma to the left side damaged the left masseter. The left masseter acts to deviate the mandible to the right and hence is the antagonist of the right lateral pterygoid, which deviates the mandible to the left. The weak activity in the right lateral pterygoid could then be interpreted as an adaptation to avoid overdeviation to the left. Alternatively, the change in muscle activity might not have been a result of muscle injury but of destabilization of the TMJ. In this view, the limitation of leftward deviation could be an attempt to splint an unstable joint. Whatever its cause, the change in relative muscle activity in the surgery pigs had sequelae for the TMJ. Although only marginally statistically significant ($P = 0.051$), compressive strain on the left (disrupted side) condyle was 30 to 40 degrees more horizontally oriented than in controls (Table 3 and Fig 5); this suggests there was a possible change in the recruitment pattern of masseter muscle fibers such that the action line of the masseter became more horizontal. Such a change could result from inactivity of the anteriorly placed vertical fibers of the left masseter,[39] which would also account for the reduced EMG activity (Table 2 and Fig 4). Surgery pigs also tended to have reoriented left mandibular corpus strain when they were chewing on the right (Table 3 and

Fig 5, balancing side), again suggesting a change in the performance of right- and left-side mastication.

The clearest functional correlate of the EMG changes in the surgery pigs is the DVRT findings. The increased elongation of the right capsular ligament during right-side chewing (working side, Table 4) indicates relatively more retrusion on this side. Because the right lateral pterygoid is the primary protrusor, its lack of activity could be the direct cause of this relatively increased retrusion. An additional cause of right-side retrusion would be the more horizontal pull of the weakened left masseter muscle discussed above. The anterior vector of the left masseter would increase the tendency of this muscle to move the jaw to the right, retruding the right condyle.

The minor surgery to the lateral capsule of the TMJ apparently did not prevent the tissue from undergoing normal changes in length, but mastication was nevertheless altered. The changed balance of muscle activity in turn affected the loading of both the ligamentous and the osseous components of the TMJ.

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