

## THE EFFECTS OF PAIN FROM THE MANDIBULAR JOINT AND MUSCLES ON MASTICATORY MOTOR BEHAVIOUR IN MAN

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**Summary**—Habitual chewing of a coherent bolus was studied in 12 dentate subjects with painful mandibular-joint disorders and 12 healthy, dentate controls. Bilateral electromyograms of jaw elevators, and jaw movement, were recorded for three complete masticatory sequences. Computer analysis was used to classify chewing movements as continuous or discontinuous. Root-mean-square (r.m.s.), myoelectric signal amplitudes were computed for each of four jaw elevators. Although discontinuous chewing cycles were significantly more frequent in painful function ( $p = 0.001$ ), they also occurred in pain-free function, a finding which reduces their diagnostic significance. During painless and painful function, r.m.s. activities did not differ statistically when elevators acted as agonists on both the dominant and non-dominant chewing side ( $p > 0.1$ ). When used as antagonists, such as during jaw opening, the elevators had greater mean peak activities during painful than painless function ( $p = 0.0001$ ). Variability in maximum gape was greater during painful than painless function ( $p = 0.001$ ), but peak maximum gapes in complete masticatory sequences were not affected by pain, and neither were minimum interocclusal gapes. More frequent reshaping and repositioning of the bolus in the presence of pain could explain these differences between painful and pain-free function.

### INTRODUCTION

There are numerous descriptions of normal mastication in man (Hildebrand, 1931; Atkinson and Shepherd, 1967; Ahlgren, 1967, 1976; Gillings, Graham and Duckmanton, 1973; Goodson and Johansen, 1975; Hannam *et al.*, 1977; Gibbs and Lundeen, 1982), which emphasise the regular pattern of jaw movement. Few attempts to quantify any irregularities of mandibular movement have been made, yet such irregularity is significant because the degree of fluctuation in vertical jaw velocity may be a measure of painful mandibular dysfunction (McCall, Bailey and Ash, 1976). In McCall's study, a curve-fitting algorithm was used to quantify irregular mandibular movements during a voluntary, empty open-close cycle; the error between the plot of jaw position versus velocity (called phase plane) and the best-fit parabolic model for data plotted in this fashion were then expressed in statistical terms. However, experiments by Naeije and Honee (1979, 1980) raise concern about the reproducibility of measurements of movement and the application of phase-plane modelling for diagnostic purposes. There is no objective scheme available for classifying the movement characteristics of mastication, one or several of which could be significantly associated with painful function.

Our research was undertaken (a) to classify mandibular chewing movements by computer analysis; (b) to investigate if painful function affects the frequency of the classified chewing movements; and (c) to study muscle use in painful function with electromyography. In our analysis, we adopted the hypothesis that mandibular chewing movements are made up of three components with the rhythmic open-close movements the most dominant. Embedded in this larger pattern are other components, such as the

events which occur during tooth-food-tooth (TFT) contact, and movements which may be related to patterns for escaping an unfavourable jaw relationship, coping with pain, and escaping or avoiding pain.

### MATERIALS AND METHODS

#### *Subjects*

Experimental and control subjects had a full or almost full complement of teeth ( $\geq 26$ ). Malocclusions like crossbite (uni- or bilateral), balancing interferences, discrepancies between centric relation and centric occlusion of  $> 3$  mm horizontally, and/or deep overbite ( $> 3$  mm) were excluded because they were considered to be associated with specific motor strategies to cope with the local constraints. Overbites of  $> 3$  mm may cause the magnet of the jaw-tracking system cemented to the lower incisors to interfere with jaw closure.

*Experimental group.* The experimental group comprised 12 subjects, 1 male and 11 female, with painful mandibular-joint (MJ) disorders. Their ages ranged from 17 to 42 years; they had tenderness on palpation of the MJ and/or masticatory muscles, and limited jaw mobility because of pain. Maximum mouth opening (corrected for the amount of overbite) ranged between 28 and 38 mm (mean  $\pm$  SD:  $33.2 \pm 3.2$  mm). By Bell's (1983) classification of MJ disorders, they were diagnosed as suffering from acute masticatory-muscle disorder (8) and disc-interference disorder (4). Oral-facial pain was confirmed by verbal report at the time of recording. None had had occlusal treatment aimed at pain relief before the experiments.

*Control group.* Twelve adult, dentate volunteers, 7 male and 5 female, aged 22-38 years were used as

controls. None gave a history of functional disturbances of the masticatory system or had signs and symptoms of MJ disorder. None had teeth sensitive to percussion, clinically overt increased tooth mobility or discomfort during chewing. Maximum mouth opening (corrected for the amount of overbite) ranged between 47 and 56 mm (mean  $\pm$  SD:  $50.8 \pm 3.1$  mm).

#### Experimental procedure

Experiments were performed in a radio-frequency shielded room which was shown to the subjects approximately one week before the recordings were made. Subjects were unobserved during the tests. They were seated upright against a comfortably adjusted back-rest; drinking water was supplied. They were requested to chew in their habitual manner a standardized piece of beef (Beefstick, Frito-lay, Inc., Dallas, TX 75325, U.S.A.); this is of medium-soft consistency and offers a coherent bolus. Three complete masticatory sequences were recorded. A masticatory sequence included all actions from the intake of food to those immediately before swallowing; it comprised  $34 \pm 10$  chewing cycles (range 17–59) in the experimental group and  $30 \pm 8$  chewing cycles (range 20–59) in the controls. After recording these three masticatory sequences, tooth-guided excursions from maximum intercuspation to the left and right were recorded to determine the pattern of the cuspal inclines on either side. These were used to analyse bolus placement on either the left or right side.

#### Recording techniques

A bipolar, surface electromyographic technique was used to record the elevator activities of the right and left masseter (RM, LM), and anterior temporal muscles (RAT, LAT). The Ag/AgCl disc electrodes,

diameter 9 mm each, were spaced 20 mm apart from centre-to-centre, giving a distance of approx. 10 mm between discs. Noise levels (root mean square; r.m.s.) in the four amplifying systems, determined by shortening and grounding the input and by setting the 30 Hz high-pass filter, ranged between 0.35 and  $0.85 \mu\text{V}$ . Electrode impedance was checked (Grass Impedance Meter EZM, Grass, Inc., Quincy, MA 02169, U.S.A.) and values  $\leq 2 \text{ k}\Omega$  were accepted. A Mandibular Kinesiograph (MKG-5 Research, Myotronics, Inc., Seattle, WA 98101, U.S.A.) was used to track the movement of the incisal point. The detailed procedure for obtaining a simultaneous record of the incisal-point movement and the corresponding jaw-elevator electromyograms has been described by Stohler (1986). Analogue data from a complete masticatory sequence were digitized through a digital converter with shift-programmed, successive-approximation architecture and 12-bit resolution. The sampling rate was either 500 Hz for vertical jaw-movement data, which were then used for computer analysis, or 2500 Hz per data channel when sequential quantification of both myoelectric and kinesiometric data was required to analyse the action of muscles in the presence and absence of pain.

#### Analysis

*Classification of jaw-movement data.* Computer analysis was used to recognize any defined discontinuities in the rhythmic chewing movement. Because there are large variations in the amplitude and duration of the human chewing cycle, both within and between subjects (Bates, Stafford and Harrison, 1975a), it was necessary to design an analytical routine that would be independent of this inherent variance. Masticatory sequences were first divided into individual chewing cycles (Fig. 1); this led to a

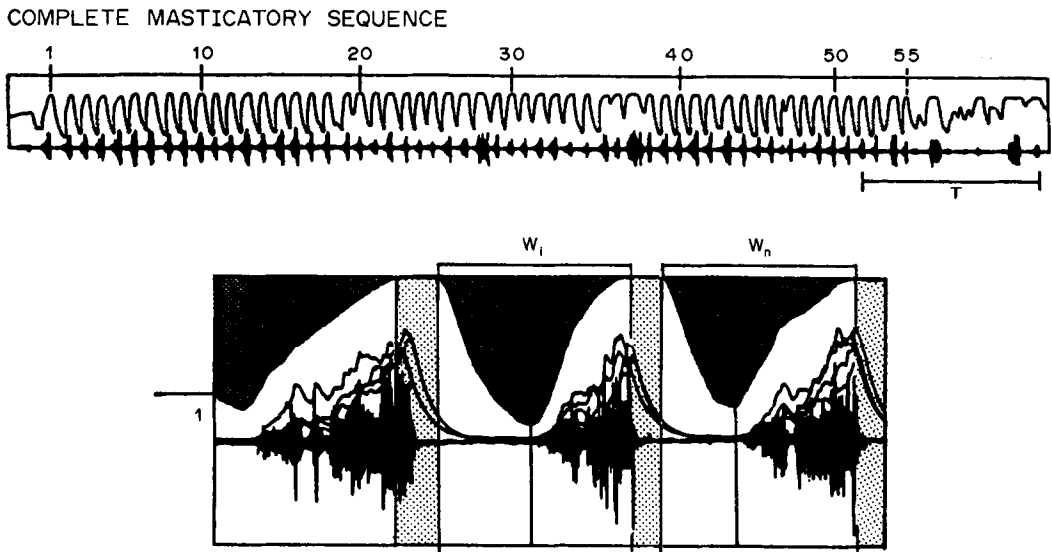


Fig. 1. Editing of data: complete masticatory sequences were divided into individual chewing cycles. Top: vertical jaw-movement trace and corresponding masseter electromyogram of a complete masticatory sequence of 55 chewing cycles. Bottom: plot, illustrating the division of the jaw-movement data into individual chewing cycles ( $W_1$ ,  $W_n$ ) and the raw and r.m.s. electromyograms of the jaw elevators. T corresponds to 10 s.

favourable condition in which the jaw-movement trace decayed to zero (or close to zero in an occlusal-stopped position with minimal food between the teeth) at both ends of the sample range. In this edited form, the chewing cycle started with the jaw opening that followed the occlusal-stopped position of the previous cycle, and ended with the next occlusal-stopped position, within a defined range of 0.0–1.0 mm minimal, cranio-caudal displacement. Because the first chewing cycle did not have this defined starting point, it was not analysed. Jaw-movement data within each sample range were differentiated by interpolating a fourth degree polynomial through five consecutive data points, and then computing its second derivative. The result of this was then subjected to digital filtering in order to identify the grossly discontinuous portion of the signal; signal components which were linked to the events at TFT contact were ignored. The chosen position of this smoothing procedure was based on extensive analysis of our data-base recordings of chewing a beefstick bolus. Because events at TFT contact constituted the high-frequency element in the trace, low-pass filtering was implemented using the inverse Fourier transformation of the Blackman window for convolution weights, with weights adjusted at the beginning and end of the data array to avoid so-called edge effects (Taylor, 1983). The more serious the distortions, however, the less likely is it that a smoothing of the data array will occur. Although this filtering technique was tailored to attenuate the natural noise-like components at TFT contact, it also tended to smooth opening movements more than was desirable. To alleviate this, different filter characteristics were used for jaw opening and closing. To avoid the problem of edge effects associated with the use of different filters on subsamples of the full sample range, the original data array was also subjected to a digital low-pass filter with different characteristics. This provided the desired signal conditioning for the opening movement.

The recognition of gross discontinuities was made by a simple operational definition. Chewing cycles or their respective sub-cycles were termed continuous if the conditioned second derivative crossed the zero line once both in opening or closing, and discon-

tinuous if more than one zero crossing occurred in either phase of the chewing cycle. Thus the signal was placed into one of two classes, continuous or discontinuous chewing cycles. The quotient of the number of discontinuous cycles divided by the total number of cycles within a masticatory sequence provided a descriptor of the stability of masticatory function, expressing the probability of grossly discontinuous chewing movements within a sequence. The two-sided Mann-Whitney *U*-test was used for comparative analysis of movement data from painless and painful function. In addition, maximum gape in chewing cycles and in complete masticatory sequences of painful and pain-free function were examined for equality of means and variances by analysis of variance (ANOVA).

*Muscle use in painless and painful function.* R.m.s. voltage traces were computed after digitizing and full-wave rectification of raw electromyographic data streams. Electromyographic features, such as peak agonistic activity and peak antagonistic activity, were determined to define the use of the jaw-elevator muscles in the presence and absence of pain (Fig. 2). As the electromyographic response of the jaw elevators is dependent on bolus placement, data were grouped in relation to the dominant or non-dominant chewing side. The working side was defined as the side (left or right) from which the incisal point approached the occlusal-stopped position in the most cranially directed part of the pathway of closure during chewing (Stohler, 1986). Mean peak muscle activities of the four jaw elevators in painless and painful function as agonists or antagonists were compared by the Mann-Whitney *U*-test. For the elevators, agonist function referred to activities during jaw closing, and antagonist function to activities during jaw opening.

## RESULTS

A total of 1092 chewing cycles from healthy subjects and 1249 from subjects with painful function were analysed. For all subjects, chewing frequencies ranged between 0.95 and 1.36 Hz, as determined by the quotient of the number of chewing cycles in a masticatory sequence and the time used for it. Intrinsic

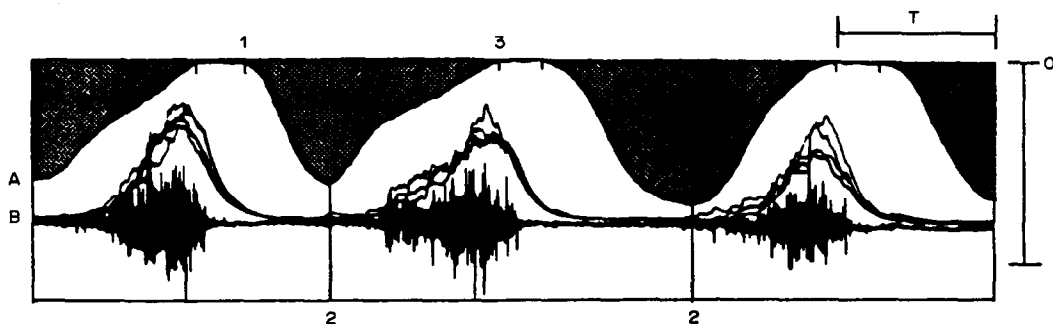


Fig. 2. Plot of the vertical jaw movement, and the raw and r.m.s. electromyograms of the jaw elevators versus time. 1 = Onset of jaw opening, 2 = max. opening, 3 = onset of occlusal phase. R.m.s. voltage traces were scanned for the peak voltage during the jaw closing and occlusal phase (agonistic peak activity), and during jaw opening (antagonistic peak activity). T corresponds to 500 ms. 0 refers to the closed position; the vertical bar represents 25 mm vertical gape.

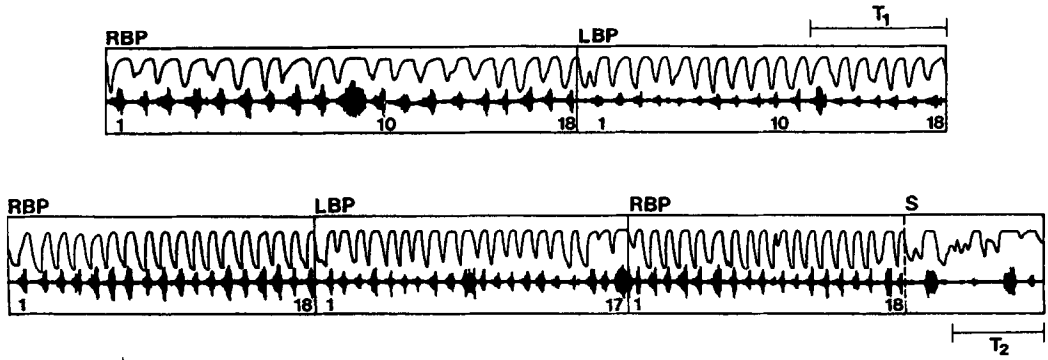


Fig. 3. Plots of vertical jaw movement and the corresponding masseter electromyogram. RBP = right, LBP = left bolus placement. The definition of the working side was based upon the approach angle of the incisal point in the final part of the closing phase as determined by the frontal-plane projection of the incisal-point movement. Top: sequence shows a difference in chewing frequency ( $>0.15$  Hz) between the subsequence with left or right bolus placement. Bottom: subsequences show minimal differences in chewing frequency ( $<0.15$  Hz).  $T_1$ ,  $T_2$  refer to 5 s.

sic variation ( $>0.15$  Hz) of the chewing frequency as a function of the working side occurred in only three out of 24 subjects so, in most subjects, chewing rhythm was not affected by the side of bolus placement (Fig. 3).

A sample of typical gape-time plots of chewing movements is given in Fig. 4. Fluctuations in the smooth course of movement were linked to the events at TFT contact, affecting the vertical jaw-movement trace in the closing phase. This modulation of the dominant open-close movement was an intrinsic component of chewing both in pain and in its absence. Without pain, a relatively stable open-close rhythm with little variation in maximum gape and cycle duration was found. Minimum interocclusal gaps ranged from 0.00 to 0.85 mm and were not influenced by painful function. Maximum gape in chewing cycles ranged from 9.0–23.1 mm in painless function, and from 7.4–22.6 mm for painful function. The variability of the maximum gape in chewing cycles was significantly greater during painful than pain-free function (ANOVA:  $p = 0.001$ ). Maximum gapes in complete masticatory sequences were not affected by pain.

Examples of vertical jaw-movement data from complete masticatory sequences of painless and painful chewing are given in Fig. 5. Maximum vertical gape was more predictable in the absence of pain than

during painful function in all subjects. A medium frequency modulation, lying between that of underlying open-close rhythm and the modulation movement at TFT contact was noticed in pain function, and this required further analysis.

An example of the computational results of cl:

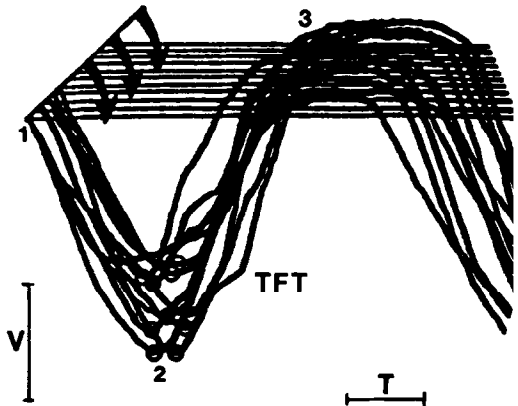


Fig. 4. Typical gape-time plots of mandibular chewing movements. 1 = Onset of opening movement, 2 = maximum gape, 3 = onset of occlusal phase, TFT = tooth-food-tooth contact. Calibrations:  $V = 10$  mm vertical incisal-point placement,  $T = 200$  ms.

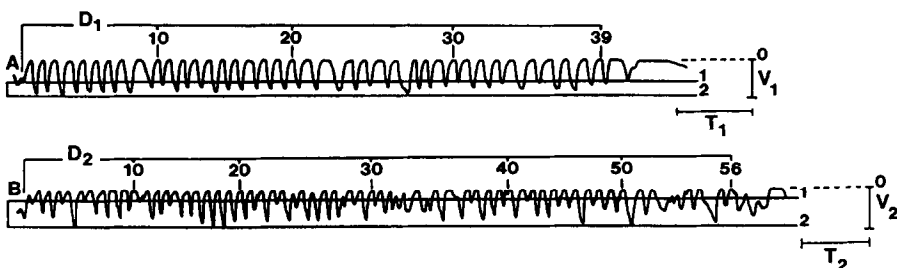


Fig. 5. Plots of vertical jaw-movement data from complete masticatory sequences of painless (top) and painful function (bottom). Sequences included 39 or 56 chewing cycles. Cycle-related maximum gapes occurred within the range described by the horizontal lines, indicated by 1 and 2. 0 refers to the closed position;  $V_1$ ,  $V_2$  represents 25 mm vertical gape of the incisal point.  $T_1$ ,  $T_2$  refer to 5 s.

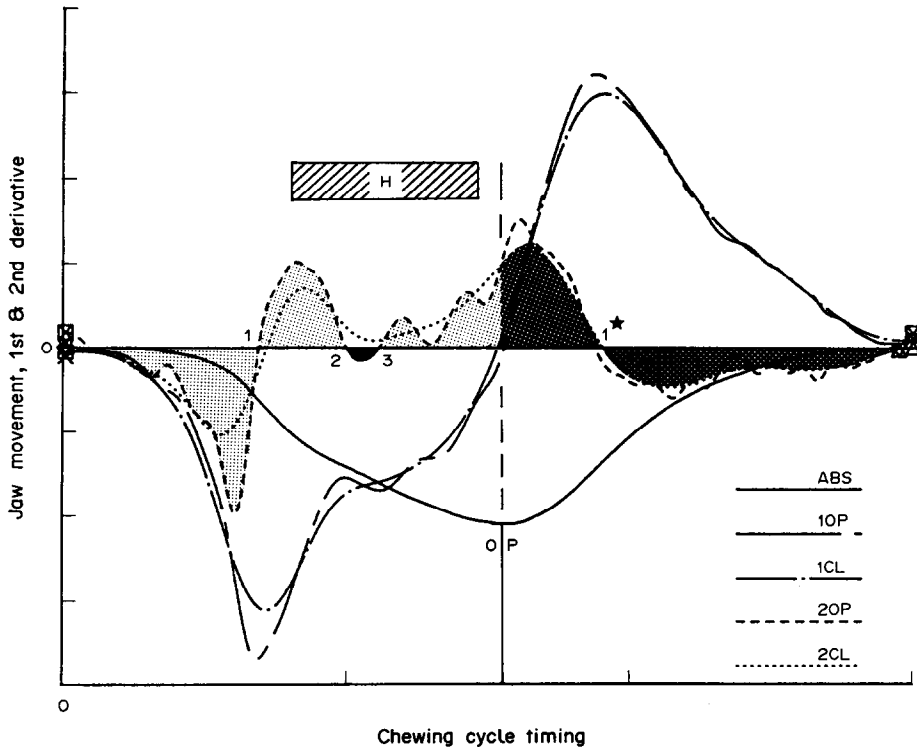


Fig. 6. Computational steps for classification of chewing movements. ABS refers to raw-movement data, its first derivative is indicated by 1OP and 1CL (smoother to remove the distortions of movement at TFT contact); 2OP and 2CL refer to the second derivative. Note that 2OP shows three zero crossings during opening and 2CL one zero crossing (1\*) during closing. OP represents maximum opening, H refers to a hesitation during jaw opening as judged by electromyographic evidence.

fyng mandibular movements into two categories is given in Fig. 6. Filtration of the first and second derivative of the jaw-closing movement aimed at eliminating the natural noise-like modulation at TFT contact, present in painless, as well as painful, function. The cut-off frequency for the Blackman window was set at 1/20 cycles per data point, so that all frequencies with periods shorter than 20 data points were eliminated. By using an optimal filter cut-off frequency, gross-movement discontinuities were preserved by this filtering. Gross-movement irregularities were especially marked during the jaw-opening phase of chewing, and the high-frequency modulation was primarily related to sudden changes in velocity during the closing phase. However, the filter used to attenuate the events at TFT contact also tended to attenuate movement discontinuities of interest during the opening phase. To avoid this, an independent analysis of the jaw-opening phase was performed with a low-pass filter eliminating all frequencies with periods shorter than 6.6 data points (cut-off frequency for the Blackman window: 0.15 cycles per data point).

The results of the computer analysis to classify the total output from both painless and painful function, expressed in terms of the probability of discontinuous cycles among all cycles of a masticatory sequence, are given in Fig. 7. Statistical analysis indicated that discontinuous cycles were significantly more frequent in painful function (Mann-Whitney:  $p = 0.001$ );

however, their presence was not a reliable indicator of pain. In fact, four healthy subjects scored in the range within which which painful function occurred. Thus grossly discontinuous movements were not unique to painful function.

The results of electromyographic analysis of the jaw elevators during painless and painful function as agonists are given in Table 1. For the given food, peak-activity levels did not differ statistically between function with or without pain for any of the muscles

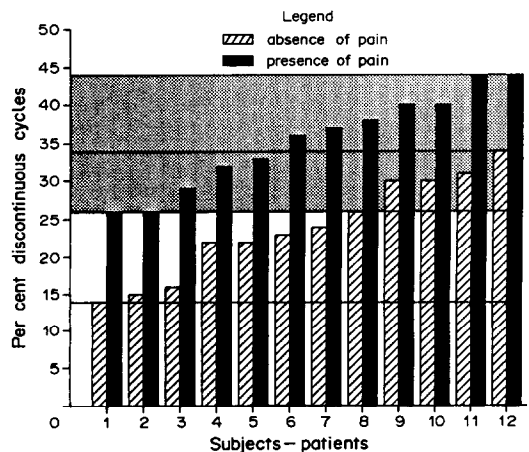


Fig. 7. Percentage of discontinuous chewing cycles in painless and painful function.

Table 1. Mean peak r.m.s. muscle activities of jaw elevators (in  $\mu\text{V}$ ) during painless and painful function as agonists

	Painless <i>N</i> = 12 r.m.s. activity in $\mu\text{V}$	Painful <i>N</i> = 12 r.m.s. activity in $\mu\text{V}$	
<i>Anterior temporal m.</i>			
Dominant side:			
Group mean $\pm$ SD	187 $\pm$ 19	174 $\pm$ 16	<i>p</i> = 0.1931, n.s.*
Min-Max	163-221	144-202	
Non-dominant side:			
Group mean $\pm$ SD	164 $\pm$ 18	154 $\pm$ 13	<i>p</i> = 0.1118, n.s.*
Min-Max	129-192	135-175	
<i>Masseter m.</i>			
Dominant side:			
Group mean $\pm$ SD	146 $\pm$ 15	149 $\pm$ 10	<i>p</i> = 0.4183, n.s.*
Min-Max	121-174	138-165	
Non-dominant side:			
Group mean $\pm$ SD	104 $\pm$ 25	108 $\pm$ 25	<i>p</i> = 0.6440, n.s.*
Min-Max	70-142	74-151	

\*Mann-Whitney *U*-test; n.s. = statistically not significant.

studied on both the dominant and non-dominant chewing side. During antagonist function, however, the elevators had greater mean peak activities in the presence of pain than in its absence (Table 2).

#### DISCUSSION

Chewing involves the generation of rhythmic motor patterns in which appropriate muscles are recruited with adequate excitation and in proper spatio-temporal sequence relative to each other. Our findings suggest that the predominant low-frequency component of jaw movement is essential to the smoothness and periodicity of movement during chewing. There is evidence that this basic, low-frequency component is largely pre-programmed (Dellow and Lund, 1971; Lund, 1976; reviewed by Luschei and Goldberg, 1981), but not beyond modulation by peripheral perturbations. In fact, the act of chewing is considered to be flexible enough to accom-

modate a range of central and peripheral perturbations, whether these be transient or permanent (Hannam, 1979).

Neural control of mastication in the presence of pain should include mechanisms for coping with the impaired system as well as for escaping a sudden, noxious incident. The role of feedback during painful function is of interest in the context of our research. Background discharges occur more frequently and at higher rates in fine afferent nerves from the joint following experimentally induced inflammation in the knee (Coggeshall *et al.*, 1983). Handwriting is profoundly altered by artificially-induced pain in handwriting muscles (Gellhorn and Thompson, 1944). Irregularly-shaped chewing cycles have been observed in the presence of MJ pain (Shepherd, 1960; Atkinson and Shepherd, 1961). In man, transient electrical stimulation within the mouth during the closing phase of chewing prolongs the mean length of the masticatory cycle (Hannam and Lund, 1981). We

Table 2. Mean peak r.m.s. muscle activities of jaw elevators (in  $\mu\text{V}$ ) during painless and painful function as antagonists

	Painless <i>N</i> = 12 r.m.s. activity in $\mu\text{V}$	Painful <i>N</i> = 12 r.m.s. activity in $\mu\text{V}$	
LAT			
Mean $\pm$ SD	1.9 $\pm$ 0.5	5.5 $\pm$ 1.0	<i>p</i> = 0.0000, s.*
Min-Max	1.2-2.8	3.9-7.1	
RAT			
Mean $\pm$ SD	1.9 $\pm$ 0.5	4.9 $\pm$ 0.8	<i>p</i> = 0.0000, s.*
Min-Max	1.4-3.1	3.6-6.1	
LM			
Mean $\pm$ SD	3.3 $\pm$ 0.7	5.4 $\pm$ 1.1	<i>p</i> = 0.0001, s.*
Min-Max	2.3-4.4	4.2-8.3	
RM			
Mean $\pm$ SD	3.6 $\pm$ 0.6	5.0 $\pm$ 0.9	<i>p</i> = 0.0001, s.*
Min-Max	3.1-4.2	4.0-7.5	

\*Mann-Whitney *U*-test, s. = statistically significant.

LAT = left, RAT = right anterior temporal muscle, LM = left, RM = right masseter muscle.

now show that pain degrades the smoothness of the basic open-close rhythm. Discontinuous patterns, clearly distinct from those irregularities of movement found at TFT contact, were significantly associated with painful function, particularly in the jaw-opening phase. As a strategy for the masticatory system, frequent reshaping and repositioning of the bolus may be needed to prevent unfavourable loading of the affected tissues, thus giving rise to irregular jaw movement.

We wished to determine whether irregularities in chewing could have some diagnostic significance. Such irregularities, however, were not exclusive to painful function, though they were clearly more frequent at the population level when pain was present. Four healthy subjects had irregularities in the range within which painful function also occurred, a false positive reading of 33 per cent as far as the diagnostic power of this classification is concerned. Clearly, movement irregularities alone are not enough to discriminate painful from pain-free subjects.

Neural control of mastication should also incorporate mechanisms for coping with benign influences (Hannam, 1979), particularly those events which occur at food or tooth contact (Thexton, 1976), which in our experiments were related to the high-frequency modulation of the jaw-closing movement. Initial fast closure quickly brings the mandible close to food impact; the subsequent course of movement is modified via both monosynaptic connections to motoneurons and open-loop control systems (reviewed by Sessle, 1981; Luschei and Goldberg, 1981). The high-frequency modulation of the basic chewing movement was owing to food or to structural interference. In earlier work, we documented silent periods in the electromyogram of the closing muscles which were associated with these mechanical events (Stohler and Ash, 1984).

Chewing cycles may not be abandoned in the presence of sudden pain during jaw closing, and instead an excitatory response of jaw elevators with significantly increased contraction times and amplitudes was found in those cycles which were indicated as painful above the level of any background pain (Stohler and Ash, 1986). This excitatory response was regarded as a strategy for overcoming a sudden noxious stimulus. With background pain, however, we have now demonstrated no significant differences in the peak electromyographic activities of the jaw elevators during painless and painful function as agonists. We did not record from other important muscles which may be painful in MJ disorders, so our findings should not be assumed to be of general application.

Tonic hyperactivity as a result of pain has been produced experimentally and identified by electromyography in limb muscles (Cobb *et al.*, 1975). Patients with MJ disorder have more postural activity of mandibular elevators than in controls (Møller, 1976). In painful MJ disorders, antagonistic co-contraction of the jaw elevators is found in the intermediate or even in the early opening phase of the empty, open-close cycle (Stohler, Yamada and Ash, 1985). In subjects with post-operative trismus, limitation of mouth opening is attributed to

co-contraction of jaw elevators during attempted opening (Greenfield and Moore, 1969). Similarly, during chewing, significantly increased intermediary activity has been observed between bursts from the jaw elevators (Møller, Sheikholeslam and Lous, 1984), and this was confirmed by our recordings.

We found significantly greater variability of maximum gape in chewing cycles during painful function. However, the range and, in particular, the maximum gape in complete masticatory sequences were not affected by pain. It appears that the chosen bolus size required the observed cranio-caudal range of movement in order to be prepared for swallowing. Neither the range of function, nor the excitation of the jaw elevators during jaw closing was influenced by pain. This implies that a given bolus demands a certain excitation level in order to be comminuted. The greater variability of maximum gape in chewing cycles where there was significantly increased activity in jaw elevators during function as antagonists can be explained by more frequent or careful reshaping and repositioning of the bolus in the presence of pain.

We sought to measure the motor behavioural strategies employed during painful function but, for simplification, complex three-dimensional jaw movement was reduced to observation of the cranio-caudal displacement of the incisal point. This is a reasonable approximation, but more subtle effects may be missed by this approach. Rather than enforce deliberate chewing on either side, we chose habitual chewing to measure the disease characteristics. In this free-wheeling condition, learned strategies to cope with pain or to escape a painful condition were considered to be operative.

Beef was chosen not because it offers a coherent, unbreakable bolus with a well-defined working side, but also because it is chewed slowly. The foodstuff is known to influence the chewing frequency (reviewed by Bates, Stafford and Harrison, 1975b; Hiiemae, 1978) as well as the level of excitation of the jaw elevators. Mean peak EMG for masseter and anterior temporal muscles are higher when chewing peanuts than with gum (Ahlgren, 1966), or with apple or bread (Haraldson and Ingervall, 1979). Chewing is also influenced by subject motivation (Rugh, 1972).

The operational classification of mandibular chewing movements was based upon the construction of the cranio-caudal movement signal within the sample range. Aside from counting the number of zero-crossings, frequency analysis could have been used to detect the medium frequency modulation in the movement signal. The chosen method was preferred because it allowed well-defined classification of chewing cycles into one or the other category. It should be emphasized that the filter characteristics required to eliminate the movement distortions at TFT contact were matched to the basic frequencies observed for habitual chewing of beef.

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