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A COMPARATIVE ELECTROMYOGRAPHIC AND KINESIOGRAPHIC STUDY OF DELIBERATE AND HABITUAL MASTICATION IN MAN

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Summary—Twelve healthy, fully-dentate subjects participated in experiments which included the continuous recording of surface electromyography and jaw movement during habitual and deliberate right-sided or left-sided chewing of a coherent bolus. Analogue data streams were converted to digital values. Root-mean-square (r.m.s.) muscle-activity traces were computed from raw electromyographic data. The working side was defined as the side from which the mandible approached the position of occlusal stoppage when in the most cranially directed part of the chewing cycle. In any given muscle, greater mean peak r.m.s. activities were found with ipsilateral than contralateral bolus replacement ($p < 0.01$, s); such differences were more pronounced for the masseter than the anterior temporal muscles. During habitual chewing, mean peak r.m.s. activities exceeded the value established by deliberate mastication with ipsilateral bolus placement in 27 of 48 muscles; this may be because of more vigorous chewing during habitual performance. No subject was strictly unilateral in their preference for bolus placement and in 6 of the 12 subjects, there was a timed side-switching of the bolus within the masticatory sequence. The results also indicated that any averaging of data based upon time-amplitude alone would be inappropriate for habitual chewing because of the call for different working sides within a particular masticatory sequence. Thus a new data format based upon numerical representation of the electromyographic activity against time was introduced.

INTRODUCTION

Natural chewing patterns are characteristic for each individual (Beyron, 1964; Murphy, 1965; Ahlgren, 1976); few subjects with normal occlusion show a strictly unilateral pattern of mastication and indeed, most seem to chew alternately on the left or right side(Hedegard, Lundberg and Wictorin, 1967; Wictorin, Hedegard and Lundberg, 1968, 1971). Cinefluorographic observation of bolus placement during habitual chewing showed that only 7 of 25 subjects with a natural dentition had a preference for chewing on one side only (Sheppard, Rakoff and Sheppard, 1968).

In research on mastication there is a need to distinguish between habitual (preferred) and deliberate unilateral (forced) chewing. Deliberate unilateral chewing is the accepted model for study of the influence of a specific factor upon mastication. Hannam *et al.* (1977a) used this model to demonstrate the relationship between the occlusion, the timing of muscle activity and the associated jaw movements.

In a laboratory environment, the subject's motivation is important (Rugh, 1971, 1972); habitual chewing is recorded when a subject can select a preferred and comfortable chewing pattern with the minimum of conscious involvement. Such chewing has been described as a series of unilateral strokes in which the bolus is shifted at random between the right and left side (Møller, 1976). However, it is not known whether this bolus shift follows a random pattern or some internal constraints of timing. To investigate this not just a small number of chewing cycles but complete masticatory sequences need to be recorded and analysed. There is a substantial body of information about deliberate unilateral chewing in man (e.g. Møller, 1966, 1974), but less about the complete masticatory sequences of habitual chewing. Significant technological progress has been made in combining the records of jaw movement and electromyography during chewing (Hannam *et al.* 1977b). The measurement of jaw movement during habitual mastication is important as the electromyographic pattern may vary with bolus placement. I have compared complete masticatory sequences of habitual and deliberate unilateral chewing by analysis of both jaw movement and electromyography.

MATERIALS AND METHODS

Subjects

Twelve dentate subjects, 7 male and 5 female, aged between 22 and 38 years, were asked to participate. None had a history of functional disturbances of the masticatory system, or signs and symptoms, such as limited mouth opening (less than 45 mm) and tenderness to palpation of the temporomandibular joints and masticatory muscles. They reported no discomfort during chewing; none had balancing tooth contacts or interferences as revealed by shim stock foil placed between opposing teeth during tooth-guided lateral excursions of the mandible. No subject had an overbite of more than 3 mm; this allowed easy cementing of the magnet of the jaw-tracking system to the labial surface of the lower incisors.

Experimental procedure

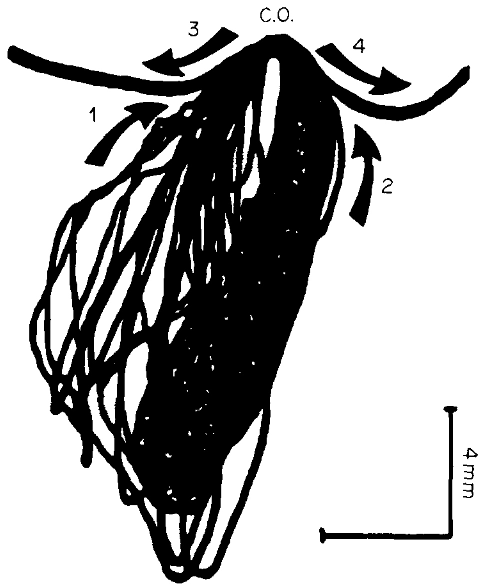
Experiments were performed in an electrically shielded and air-conditioned environment, which has been shown to the subjects approx. 1 week before the recordings were made. Subjects were unobserved during the tests; they were seated upright against a comfortably adjusted back-rest with the head positioned so that the Frankfurt Plane was parallel to the floor. Drinking water was supplied and standardized pieces of beef (Beefstick, Frito-Lay Inc., Dallas, TX 75235, U.S.A.) given to chew; these are of medium consistency and provide a coherent bolus. A masticatory sequence included all actions from intake of food to those immediately prior to swallowing and comprised 30 ± 8 chewing cycles. Subjects were first requested to chew habitually; after recording three complete masticatory sequences, they were then asked to chew strictly on the left or right, and three more masticatory sequences were recorded for each side. Finally tooth-guided excursions from maximum intercuspation to the left and right were recorded to determine the pattern of the cuspal inclines on either side.

Recording techniques

With a bipolar recording technique, interference pattern electromyograms of both left and right anterior temporal (LAT, RAT) and masseter muscles (LM, RM) were obtained via surface-type, Ag/AgCl disc electrodes (Mod. E4, Grass Inc., Quincy, MA 02169, U.S.A.). An electrode (E34S, Grass Inc.) clipped to the right ear lobe was the ground reference. Electrode placements and gain settings remained unchanged for the three experiments. Signals were bandwidth limited (−3dB down at 14 and 560 Hz) after amplification through standard neurophysiological amplifiers. The Mandibular Kinesiograph (MKG-5Research, Myo-tronics Research, Seattle, WA 98101, U.S.A.) was used for tracking incisal point movement during chewing. A gauge, separating the upper and lower incisors by 25 mm (corrected for the amount of vertical overbite) was used for calibration. Low-pass filtering (−3dB down at 45 Hz) was applied to all three kinesiometric channels. Electromyographic and kinesiometric data were recorded with an FM tape recorder. Polygraphic hard copies were generated from playback of recorded signals. Analogue data streams from the recorded sequences were digitized with 12-bit resolution at a rate of 3500 samples per second per channel, and stored on hard disk. Programmed examination of the data files gave the number of values in the file, the largest and smallest value within each channel, and the largest differences between successive values; the places in the file where these values occurred were also reported, and a warning was printed if the 12-bit limit of the converters was exceeded. Another program displayed a series of data points on an oscilloscope by means of a two-channel digital-to-analogue (D/A) converter which allowed editing and sorting of data. Electromyographic data streams were corrected for d.c. offset.

Analysis

Definition of working side. This was 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 jaw closure during chewing. The definition was based upon the reading of the frontal-plane projection of the incisal-point movement (Fig. 1). For enforced bolus placement on either side, this criterion served as a control for comparison with the subject's performance. An index, RWP (right working preference), was used to indicate the probability of right-sided bolus placement; it was the quotient derived from the number of chewing cycles with right-side working movement divided by the total number of chewing cycles per masticatory sequence. Mean RWP index was calculated from the three recorded masticatory sequences; an index of 1.0 would indicate strictly right-sided chewing and 0.0 left-sided chewing.



Habitual bolus placement

Fig. 1. Display of mandibular movement during habitual mastication as seen in the frontal plane. Working side was defined as that side (left or right) from which the incisal point approached occlusal stoppage in the most cranial part of the closing path when chewing a coherent bolus. Arrows refer to 1—right, and 2—left-closing path; 3—empty, tooth-guided movement from maximum intercuspation (C.O.) to the right; 4—to the left side.

Digital data processing. This used the UM public library of software, subroutines from International Mathematical and Statistical Libraries, Inc. (IMSL), and program packages of the UM Statistical Research Laboratory available on the Computing System of the University of Michigan.

Time-independent analysis: Full-wave rectification and the computation of the root mean square (r.m.s.) voltage traces was made via appropriate software. The peak electromyographic response per cycle and muscle was used for the comparison of deliberate unilateral and habitual chewing because it is independent of time and may therefore be averaged. Paired t-tests were used to analyse differences between the working- (with ipsilateral bolus placement) and non-working side (with contralateral bolus placement) activity of a given muscle. Mean peak r.m.s. muscle activity, calculated on the basis of all chewing cycles of a masticatory sequence of a given muscle during contralateral bolus placement, as well as during habitual performance, were compared to the corresponding value observed during ipsilateral bolus placement. Statistics was based on the mean value of the three masticatory sequences recorded for each condition.

Time-dependent analysis: Root mean square voltage traces of each chewing cycle of a masticatory sequence were sorted using the onset of jaw closing in each cycle as common point of reference (Fig. 2). Each trace, comprising equally spaced points in time, was entered into a data file where the line number indicated the position of that chewing cycle within the masticatory sequence. A cluster of data points which showed the distribution of data in the sample was then generated to confirm the validity of input loading. A grid was then computed to represent the numerical r.m.s. activities of a given muscle during a complete masticatory sequence; grid matrices were written onto tape file. The software allowed further processing of information contained in more than one grid. The grid was then drawn in computergraphic perspective with each node offset vertically by an amount proportional to the r.m.s. value at the particular location. This gave a graphical representation of time and amplitude data for a complete masticatory sequence. To provide satisfactory representation of the original data in this profile map, data points which differed by more than ± 1 SD of the standardized difference were indicated in the lineprinter output.

RESULTS

Figure 3 gives an example of the raw electromyographic and kinesiographic data. Gain settings remained unchanged for any given channel under the three experimental conditions, which allowed direct comparison of data within each channel. A summary of mean peak r.m.s. muscle activities for a given muscle in each of the conditions is presented in Table 1 for habitual mastication, in Table 2 for right-sided chewing and in Table 3 for left-sided chewing.

Deliberate, unilateral chewing

Mean peak r.m.s. muscle activity on the balancing side was consistently smaller than the same muscle during ipsilateral bolus placement in all subjects. The difference in muscle activity during ipsilateral and

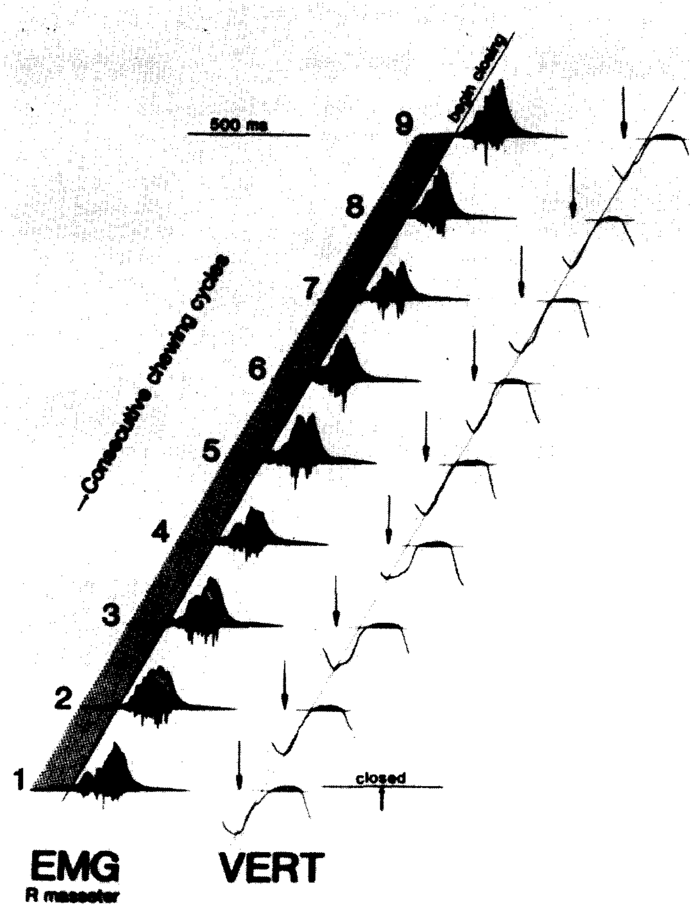


Fig. 2. Schematic illustration of the sampling and sorting of the electromyographic data streams. The onset of jaw closing was used as common point of reference. A matrix, representing the numerical value of r.m.s. voltages in time was computed on the basis of the sorted data. EMG refers to sorted raw and r.m.s. electromyograms of consecutive chewing cycles, VERT to the corresponding jaw movement trace versus time with arrows pointing to the onset of jaw closing.

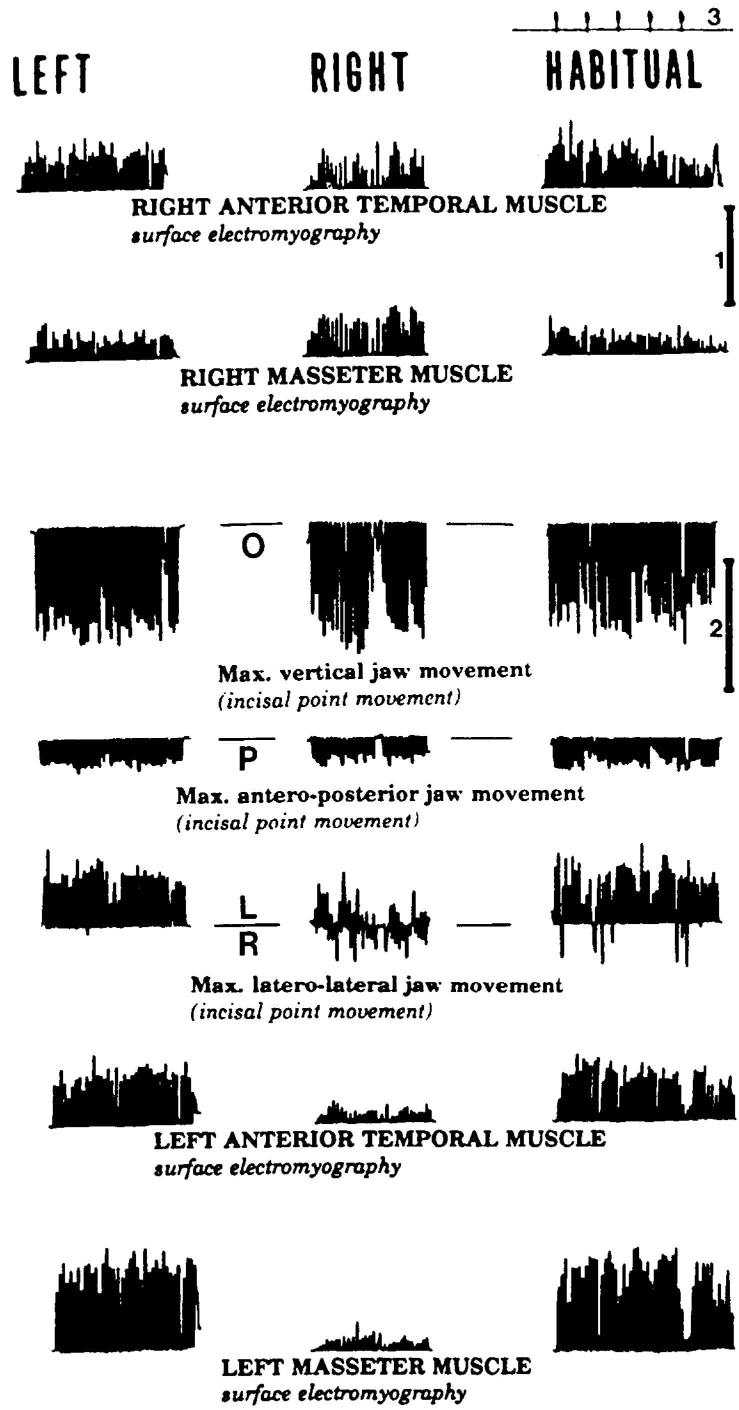


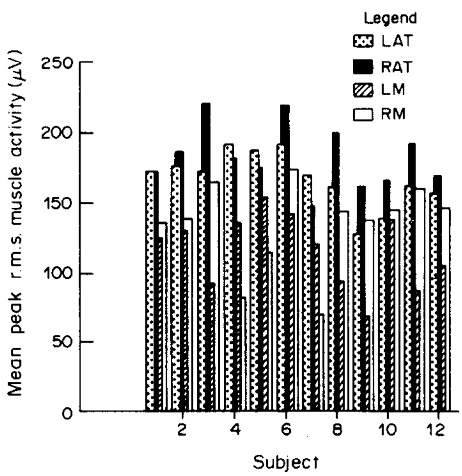
Fig. 3. Display of a subject's masticatory sequences with deliberate left-sided (LEFT), right-sided (RIGHT) or habitual (HABITUAL) bolus placement. Traces show chewing cycle related maximum r.m.s. muscle activities in the case of electromyographic data channels, and the corresponding maximum jaw displacements of the incisal point. Note the significant differences in the peak responses of the left elevators between ipsilateral and contralateral bolus placement. O—open; P—posterior; L/R—left, right; 1—200 μV; 2—25 mm; 3—7.5 s between tick marks.

contralateral bolus placement is best expressed in relative percentages (Fig. 4). The within-subject difference of mean peak r.m.s. voltage between working and balancing side function of a given muscle was statistically significant for all muscles (paired t-test: $p < 0.01$, s) with population means of the within-subject mean differences of 55 μV for the RAT, 39 μV for the LAT, 91 μV for the RM and 70 μV for

Table 1. Mean peak r.m.s. muscle activity during habitual mastication

Subject	RWP* (mean)	LAT† (μV)	RAT‡ (μV)	LM§ (μV)	RM¶ (μV)
1	0.57	171 ± 57	172 ± 60	125 ± 53	135 ± 61
2	0.70	176 ± 54	186 ± 56	130 ± 51	138 ± 54
3	0.96	172 ± 45	221 ± 42	92 ± 36	164 ± 42
4	0.03	191 ± 40	181 ± 38	136 ± 39	82 ± 28
5	0.31	187 ± 62	175 ± 59	153 ± 50	115 ± 48
6	0.75	192 ± 58	220 ± 63	142 ± 50	174 ± 52
7	0.11	170 ± 47	149 ± 36	121 ± 37	71 ± 32
8	0.85	162 ± 52	201 ± 63	95 ± 48	145 ± 50
9	0.96	129 ± 46	163 ± 43	70 ± 29	139 ± 43
10	0.59	141 ± 63	168 ± 60	140 ± 56	147 ± 58
11	0.89	164 ± 55	194 ± 56	89 ± 36	162 ± 47
12	0.89	159 ± 40	172 ± 44	108 ± 35	148 ± 30

*RWP = right working preference, see Materials and Methods.
†LAT = left anterior temporal muscle.
‡RAT = right anterior temporal muscle.
§LM = left masseter muscle.
¶RM = right masseter muscle.



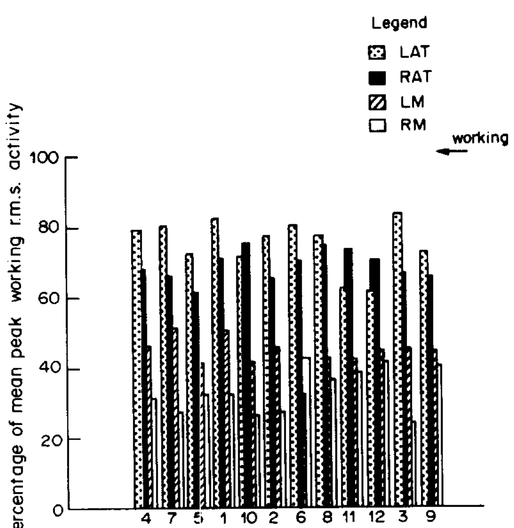


Fig. 4. Comparison of mean peak r.m.s. muscle activity between deliberate ipsilateral (working) and deliberate contralateral (non-working side) bolus placement. The within subject and muscle means during contralateral bolus placement where referenced (in per cent) to the corresponding value during ipsilateral bolus placement. Sub refers to subject's identification number.

the LM. In all subjects, this difference was more pronounced with the masseter than anterior temporal muscles.

Habitual mastication

Figure 5 summarizes the findings about the selection of a preferred chewing side, based upon analysis of all chewing cycles in the three sequences recorded from each subject. Of the 12 subjects, three were predominantly left chewers and seven predominantly right chewers. Two subjects did not clearly favour one side more than the other.

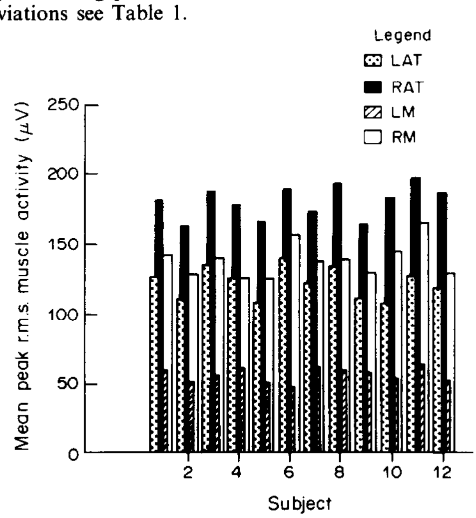
Different working sides were called up with distinct regularity in six subjects. An example of this timed side-switching is illustrated in Fig. 6, a polygraphic display of jaw movement versus time. Subsequences within the complete sequence differed because the final angulation of the frontal-plane projection of the movement, during the approach to maximum intercuspation, was either related to the left or right cuspal working side inclines.

In 27 of 48 muscles, mean peak r.m.s. activities exceeded the mean activity level of the particular muscle during deliberate function with ipsilateral bolus placement. Individual findings are summarized in Table 4 with subjects ordered according to the

Table 2. Mean peak r.m.s. muscle activity during deliberate, right-sided bolus placement

Subject	RWP* (mean)	LAT† (μV)	RAT† (μV)	LM† (μV)	RM† (μV)
1	1.00	126 ± 47	182 ± 45	58 ± 36	141 ± 56
2	1.00	110 ± 26	163 ± 39	50 ± 21	128 ± 34
3	1.00	134 ± 46	188 ± 48	54 ± 36	139 ± 53
4	0.96	125 ± 52	178 ± 48	60 ± 39	126 ± 61
5	1.00	108 ± 28	167 ± 37	50 ± 24	125 ± 30
6	1.00	140 ± 34	190 ± 45	46 ± 26	157 ± 36
7	1.00	122 ± 39	174 ± 44	61 ± 33	138 ± 39
8	1.00	134 ± 47	194 ± 53	58 ± 36	138 ± 48
9	1.00	112 ± 44	165 ± 40	57 ± 29	130 ± 47
10	1.00	108 ± 36	184 ± 28	53 ± 18	145 ± 39
11	0.98	128 ± 51	198 ± 61	63 ± 30	166 ± 51
12	1.00	119 ± 40	187 ± 56	52 ± 28	138 ± 38

*RWP = right working preference, see Materials and Methods.
†For abbreviations see Table 1.



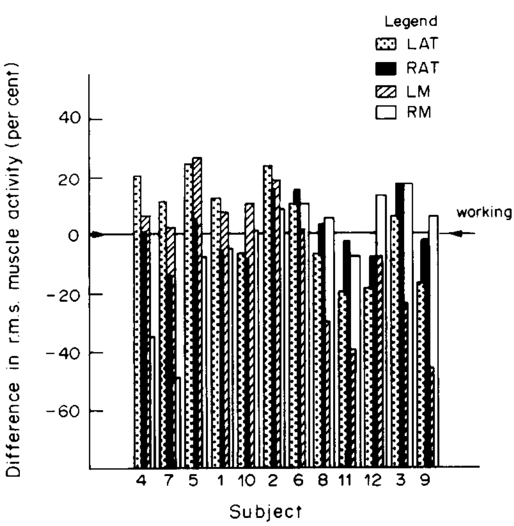


Fig. 5. Comparison of within subject and muscle mean peak r.m.s. muscle activity between deliberate ipsilateral and habitual bolus placement. Mean peak responses observed for habitual chewing were referenced (in per cent) to the corresponding value recorded for deliberate chewing with ipsilateral bolus placement. Note in 27 of 48 muscles that the mean peak response for habitual chewing exceeded the value established for that muscle during ipsilateral bolus placement. Sub refers to subjects identification number. Subjects are ordered according to the criteria of increasingly right bolus placement during preferred chewing.

probability of right bolus placement during habitual mastication.

The call for different working sides during preferred performance required a data format different from the averaging techniques usually applied for deliberate unilateral chewing. Averaging the electromyographic response of a number of chewing cycles may create an unrepresentative pattern. The format shown in Fig. 7, based upon a grid matrix of the numerical r.m.s. values in time, avoided the averaging of data derived from different conditions. In addition, plotting the r.m.s. muscle activity traces of each chewing cycle from a given muscle confirmed the expected, large variation both in time and amplitude of the electromyographic pattern of a jaw elevator during natural sequences.

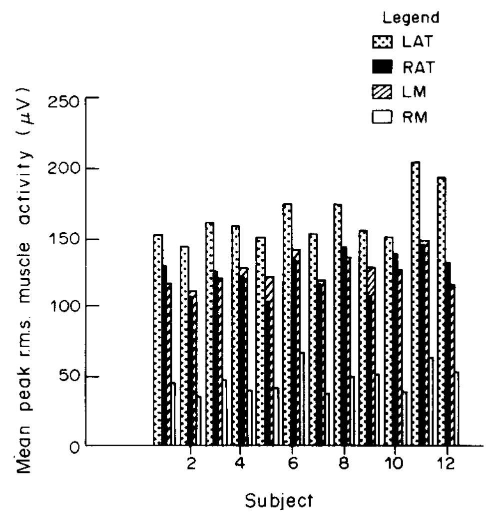
DISCUSSION

It is reasonable to conclude that the mandible approaches maximum intercuspation from a lateral position during the closing path of chewing in man. Contacts on the cuspal inclines of the working side are usually established (for review see Bates, Stafford and Harrison, 1975; Gibbs *et al.*, 1981). The gliding across the teeth into maximum intercuspation, or another form of occlusal stoppage when food is between the teeth, is referred to as the buccal phase of the chewing cycle (Mills, 1978); this kind of

Table 3. Mean peak r.m.s. muscle activity during deliberate, left-sided bolus placement

Subject	RWP* (mean)	LAT† (μV)	RAT† (μV)	LM† (μV)	RM† (μV)
1	0.00	152 ± 40	129 ± 45	116 ± 36	45 ± 28
2	0.00	143 ± 28	107 ± 34	110 ± 31	35 ± 19
3	0.00	161 ± 60	125 ± 54	126 ± 46	47 ± 30
4	0.00	158 ± 52	121 ± 35	128 ± 39	40 ± 25
5	0.00	150 ± 42	103 ± 28	121 ± 44	41 ± 31
6	0.04	174 ± 58	133 ± 38	141 ± 47	66 ± 32
7	0.00	153 ± 32	115 ± 44	118 ± 26	38 ± 20
8	0.00	174 ± 41	143 ± 36	135 ± 26	50 ± 28
9	0.08	155 ± 53	108 ± 61	129 ± 55	52 ± 36
10	0.00	151 ± 38	139 ± 46	127 ± 30	39 ± 22
11	0.05	205 ± 47	146 ± 45	148 ± 56	64 ± 37
12	0.00	194 ± 56	132 ± 47	117 ± 42	54 ± 39

*RWP = right working preference, see Materials and Methods.
†For abbreviations see Table 1.



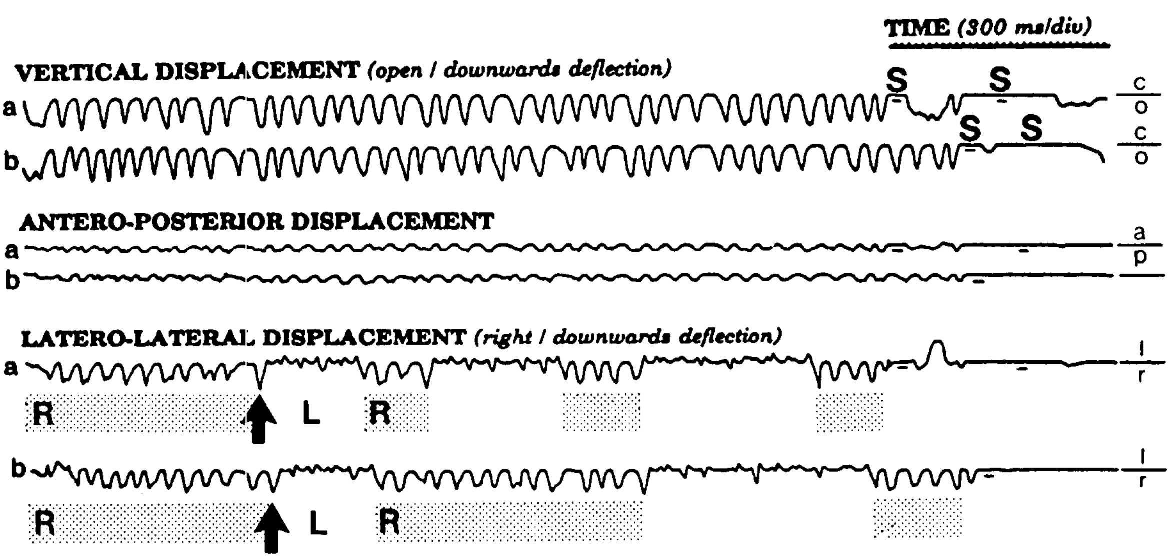


Fig. 6. Polygraphic display of jaw movement versus time during habitual mastication. Abbreviations a,b denote two different masticatory sequences of the same subject, S refers to the swallowing cycles. Note in the polygraphic display of the laterolateral movement the arrow pointing to the timed switching of chewing sides. Abbreviations such as R refer to right-sided and L left-sided chewing; c/o closed/open; a/p anterior/posterior; l/r left/right displacement. Time between tick marks represents 300 ms.

Table 4. Probability of right bolus placement during preferred performance

Subject	RWP* (mean)	RWP* (SD)
1	0.57	0.10
2	0.70	0.08
3	0.96	0.03
4	0.03	0.05
5	0.31	0.13
6	0.75	0.10
7	0.11	0.08
8	0.85	0.04
9	0.96	0.02
10	0.59	0.05
11	0.89	0.07
12	0.89	0.01

*RWP (right working preference) refers to the quotient of the number of chewing cycles with right working side divided by the total number of chewing cycles in the masticatory sequence. Mean and standard deviation (mean ± SD) are based upon analysis of three masticatory sequences of habitual chewing for each subject.

movement was found in my investigation. The beef used in my experiments provided a coherent bolus, so that the mandible consistently approached the occlusal phase with a lateral swing and therefore a well-defined working side. Jaws opening started from maximum intercuspation (or some other form of occlusal stoppage with food between antagonistic teeth) with little or no gliding contact to the other side (Fig. 1).

My work confirms earlier reports (Hedegard *et al.*, 1967; Sheppard *et al.*, 1968; Wictorin *et al.*, 1968, 1971) that habitual chewing in man is bilateral and rarely just unilateral. There is, however, a general preference for right-sided chewing (Hildebrand, 1931; Yurkstas, 1965), often expressed in the first chewing cycle (Delport *et al.*, 1983), which my observations confirm. Hand, foot, eye and ear preference are not distinctly correlated with the preferred side for mastication (Hoogmartens *et al.*, 1980; Delport *et al.*, 1983), and the preference cannot be explained.

The regular call to different working sides within masticatory sequences by 6 of the 12 subjects is of interest (Fig. 6). No neurophysiological explanation for this timed side-switching of working sides can be offered, but as it occurred in half of the subjects, it is unlikely to be an accidental finding. Because of this switching, small parts of complete masticatory se-

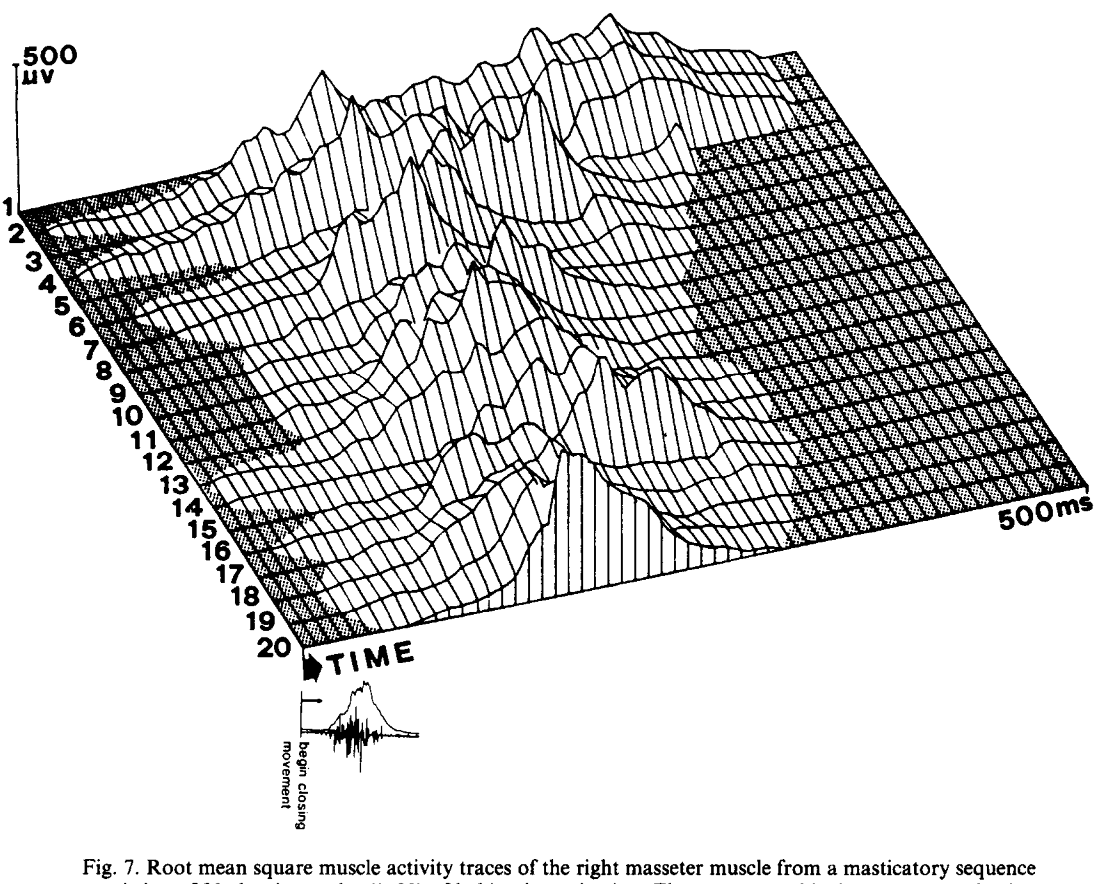


Fig. 7. Root mean square muscle activity traces of the right masseter muscle from a masticatory sequence consisting of 20 chewing cycles (1–20) of habitual mastication. Electromyographic data were sorted using onset of jaw closing in each chewing cycle as common point of reference and a grid, representing the numerical r.m.s. activity in time was computed. The grid was drawn with each grid node offset vertically the amount proportionally to the r.m.s. value at each grid location.

quences during habitual chewing should not generally be selected for analysis.

With deliberate, unilateral chewing, mean peak r.m.s. muscle activities during contralateral bolus placement were consistently smaller than during ipsilateral bolus placement. This agrees with earlier reports which indicate that integrated muscle activity (Møller, 1966) or occlusal forces, when measured by means of a piezo-electric force transducer incorporated into a three-unit bridge (Graf, 1975), are lower on the balancing than the working side. A neural substrate, similar to that proposed for locomotion, which takes the form of an interlimb co-ordination circuit between a pattern generator and the motoneurone pool (Halbertsma, Miller and van der Meché, 1976) may account for differences in the excitation level between the working and balancing side. Such differences may at least in part account for differences in the reflex excitability of jaw muscles: for example, the jaw-jerk reflex is markedly enhanced in the masseter contralateral to the biting side (Goldberg, 1972). Also the higher frequencies of silent periods from interference contacts on the balancing side rather than from working-side contacts (Schaerer, Stallard and Zander, 1967) point to a difference in excitability between the two sides. A possible explanation for this difference is that the directional sensitivity of the periodontal mechano-sensitive apparatus is more likely to be exposed to non-axial forces on the balancing than the working side (Dubner, Sessle and Storey, 1978). It is relevant that despite such differences in excitation sudden changes in load during chewing are associated with inhibition in both the working and non-working side, jaw-closing musculature (Stohler and Ash, 1984).

If habitual mastication was strictly unilateral, the same mean peak r.m.s. voltages as during deliberate chewing on the same side should be expected. Because none of the subjects had a strictly unilateral preference for a working side during habitual mastication, mean peak r.m.s. voltages were expected to be smaller on the predominant chewing side when compared to values from deliberate function on the same side. This would be due to the significantly lower activity levels found in contralateral bolus placement and to the fact that during habitual mastication a given muscle is not only involved in working—but in balancing—side function as well. However, the mean peak activity was not always smaller; in more than half of the muscles, greater mean peak r.m.s. activities were found during habitual mastication than during deliberate unilateral function of that muscle with ipsilateral bolus placement. This may be because of more vigorous chewing with habitual performance.

Great variability in the peak electromyographic response of jaw elevators in small numbers of chewing cycles of preferred mastication has been reported (Møller, 1966). Peak response per cycle can be averaged for both deliberate unilateral as well as habitual mastication no matter when it occurs, because it is independent of time. However, for time and sequential values, conventional time-averaging techniques, which are commonly used to describe deliberate, unilateral chewing cannot be applied to habitual mastication. Time-amplitude averaging does not make allowance for intrinsic changes in working side or for the changing nature of the bolus within a complete masticatory sequence. My computation of a matrix representing the numerical values of the electromyogram in time provides an alternative data format.

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