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THE EFFECTS OF FOOD CONSISTENCY ON JAW MOVEMENT AND POSTERIOR TEMPORALIS AND INFERIOR ORBICULARIS ORIS MUSCLE ACTIVITIES DURING CHEWING IN CHILDREN

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Summary—The possible effects of food consistency on the number of chews and the lapse of time in a chewing sequence, the jaw-movement pattern and velocity, and jaw and lip muscle activity during chewing were investigated. Fifteen healthy children with good occlusion were selected. First, each subject freely chewed hard (HJ) and soft (SJ) types of jelly without specifying the chewing side. The number of chews and elapsed time in a masticatory sequence (from the start of chewing to the completion of the final swallow) were measured. Second, the subjects performed right- and left-sided chewing of the same food. The electromyograms (EMG) of posterior temporalis (PT) and inferior orbicularis oris (OI) muscles on the right and left sides and associated jaw movement records were sampled. The HJ was chewed more times and with a longer time until finally swallowed ($p \leqslant 0.0007$) than the SJ. The HJ chewing also showed broader masticatory loops ($p \leqslant 0.0199$) in the frontal view and higher peak activities ($p \leqslant 0.0007$) for the PT muscle. The closing phase was longer when chewing the HJ than SJ, but the opening and intercuspal phases remained stable. More lateral excursion of the jaw was seen when chewing the HJ, but the jaw-movement trajectories in the sagittal and vertical directions were not affected by the change in consistency of the food. The jaw-closing velocities for the HJ chews were significantly slower ($p \leqslant 0.0351$) than those for the SJ chews in three directions. The HJ chews also revealed a longer duration between the onset of EMG burst for the PT muscle and the beginning of the centric occlusion ($p \leqslant 0.0146$). The OI muscle showed increased activity in accord with jaw opening, and consistent reciprocal cyclic activity with the PT muscle in terms of temporal associations ($r \geqslant 0.5250$; $p \leqslant 0.0495$). The OI muscle started to burst at a later part of the intercuspal phase, and frequently showed secondary activity in the jaw-closing and intercuspal phases. The peak activity for the ipsilateral OI muscle was significantly higher ($p \leqslant 0.0106$) than that for the contralateral OI muscle for both the HJ and SJ. The OI muscle activity, however, did not differ between the hard and soft jellies. Thus the number of chews and the time elapsed from the start of chewing until the completion of the final swallowing of food in a chewing sequence increased when chewing a harder food. Also, the PT and OI muscle activity and associated jaw-movement patterns appear to be centrally regulated but peripheral information on food consistency might also modify the motor output to the PT muscle. The consistency of food, however, might not be influential in modulating the basic form of perioral motility during chewing.

Key words: chewing, electromyography, food consistency, human, inferior orbicularis oris muscle, jaw movement, posterior temporalis muscle.

INTRODUCTION

Although rhythmic masticatory movement is centrally regulated (Dellow and Lund, 1971; Nakamura *et al.*, 1979; Nozaki, Iriki and Nakamura, 1986; Lund and Enomoto, 1988), the central pattern generator is also sensitive to and dependent on oral sensory feedback for the genesis and continual modification of intricate chewing performance (Lund and Dellow, 1971; Luschei and Goodwin, 1974; Thexton, 1974; Sessle, 1976). Recent studies have strongly suggested that periodontal pressoreceptors provide positive feedback to the jaw-closing muscles during mastication (Lavigne *et al.*, 1987; Morimoto *et al.*, 1989; Ottenhoff *et al.*, 1992). Increasing the hardness and toughness of food increases the jaw-closing muscle activity (Gorniak and Gans, 1980; Oron and Crompton, 1985), which is mainly due to an excitation of periodontal pressoreceptors. Previous studies (Ahlgren, 1966; Steiner, Michmann and Litman, 1974; Plesh, Bishop and McCall, 1986; Proschel and Hofmann, 1988) have documented the dependency of the rate and duration of chewing on the consistency of food in humans. Food hardness also influences masticatory jaw-movement patterns in monkeys (Luschei and Goodwin, 1974), man (Ahlgren, 1976; Gibbs and Lundeen, 1982), and rabbits (Morimoto *et al.*, 1985). Increasing the hardness of the food alters the balance of muscular forces that govern lateral

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Abbreviation: EMG, electromyogram (-graphy).

movements of the jaw, and results in exaggeration of the medially directed grinding stroke during the later phase of jaw closure, thus generating an increase in shearing forces in the rabbit (Lavigne *et al.*, 1987; Inoue *et al.*, 1989; Morimoto *et al.*, 1989). An enhancement of lateral jaw excursion has also been observed in adult humans (Gibbs and Lundeen, 1982; Proschel and Hofmann, 1988). This signifies a contribution of the posterior temporalis muscle to the change in jaw-movement pattern during chewing in response to the change in occlusal load, as the human posterior temporalis muscle ipsilateral to the chewing side moves the mandible laterodorsally in the earlier part of the jaw-closing phase, while the contralateral muscle accomplishes the final lateromedial slide in the same phase (Moller, 1974). Although previous reports (Plesh *et al.*, 1986; Horio and Kawamura, 1989) have documented the activity of the masseter muscle, which is known as the major forcible muscle, during the chewing of foods with different toughnesses, information on the activity of the human posterior temporalis muscle, i.e. the displacement muscle, and its association with the food consistency has been limited, despite the kinesiological significance of this muscle.

In cats, increasing the hardness and toughness of the food increases the swallowing threshold, i.e. the number of chews that are necessary to process the food for swallowing (Thexton, Hiiemae and Crompton, 1980; Gorniak and Gans, 1980). A similar finding has been reported in man (Horio and Kawamura, 1989), but, in the same report, there was also a group of subjects who did not show a significant increase in the swallowing threshold even when chewing hard food. This variable is also known to be influenced by the occlusal state (Kawamura and Nobuhara, 1957). The reported variation in responses might therefore be due to the use of natural foods whose properties are hard to control and of subjects with unspecified occlusal states. Clinically, it is commonly recognized that the presence of malocclusions can lead to a reduction in chewing efficiency. Based on the aforementioned neurophysiological findings, the validity of this statement can be tested using the possible influence of spatial location/latitude of the teeth on the motor output to the masticatory muscles, if the food properties are kept constant. To date, however, the use of artificial food whose chemical and physical properties are well controlled has been limited in investigating the characteristics of masticatory performance in awake humans with different types of occlusions.

The lip muscle also plays an important part during chewing, including the maintenance of the anterior oral seal. The function of the lips is related to the presence of specific types of malocclusions, e.g. the retroclined upper incisors and constricted maxilla associated with cleft lip and palate, the anterior open bite, or the proclined upper incisors associated with deep overbite (Proffit, 1986). The resting activity of the inferior orbicularis oris muscle might determine the incisor position (Lowe and Takada, 1984). For these reasons, lip function has received considerable attention by clinicians and neurophysiologists alike. However, little information is available on changes in lip motility and its association with jaw movement during chewing in response to changes in food hardness, especially in growing children.

Our purpose now was to examine whether, in human preadolescents with good occlusion, there are any influences from food hardness on the number of chews and the lapse of time in a masticatory sequence, jaw-movement pattern and velocity, and jaw and lip muscle activities during chewing. For this purpose, specially made soft and hard types of gummy jelly, which share common physical and chemical properties except hardness, were used. The resulting information forms a normative database for comparison with other groups of individuals who have various types of malocclusions.

MATERIALS AND METHODS

Subjects

Fifteen healthy children (2 boys and 13 girls, mean age 11 years, SD, 11 months) with good occlusion, intact mixed dentitions and no clinical signs of jaw dysfunction were selected. Informed consent was obtained from all the subjects. The subjects and their parents had given their consent to participation after receiving a full explanation of the aims and design of the study.

Test foodstuffs

Hard and soft types of gummy jelly (Ezaki Glico, Osaka, Japan) were specially prepared for the study. The composition of the test food is given in Table 1. Both types were almost equal in size (square, 20 × 20 mm; average thickness, 8 mm), weight (about 5 g), colour (yellow), taste (orange) and sugar content. The hardness of the two types were 633 and 103 g, respectively, in terms of Bloom strength (Jackson, 1990). The hard jelly was almost as hard as boneless ham and the soft jelly as pancake. The Bloom strength expresses the gel strength of the finished product, i.e. the force needed to produce a fixed deformation, commonly used by confectionery manufacturers. The test food forms a coherent bolus during chewing.

Data recording and analyses

Each subject was seated in an upright but relaxed position with the head unsupported and naturally oriented. Beckman-type, paired, silver, surface electrodes (8 mm dia, NT-213U, Nihon-Kohden, Tokyo,

Table 1. Summary of ingredients of the hard and soft jellies

	Weight %	
Ingredients	Hard jelly	Soft jelly
Corn syrup (moisture content 25%)	25.09	20.79
Granulated sugar	25.09	20.79
Sorbitol (70% w/w)	5.38	4.45
Maltose	25.09	20.79
Gelatine solution (350 Bloom gelatine, 45.3% w/w)	11.31	26.51
Concentrated orange juice	5.97	4.95
Citric acid solution	1.88	1.56
Colouring agent (β-carotene)	0.02	0.02
Flavouring agent	0.17	0.14

Japan) with an interelectrode distance of 1 cm were fixed in place in the direction of muscle fibres to record the EMG activity from the posterior parts of the temporalis and the inferior orbicularis oris (Moller, 1966) on the right- and left-hand sides. Hair was removed with a miniature electric razor (ES156, Panasonic, Tokyo, Japan) to ensure satisfactory electrode placement for the posterior temporalis. The skin was cleaned with alcohol swabs and lightly abraded by rubbing with a skin-preparation gel (skin-Pure, Nihon Kohden) to reduce the electrode-to-skin impedance. A ground electrode (NM-511S, Nihon-Kohden) was secured to the right wrist. The electrodes were filled with a saline contact paste (Elefix, Nihon Kohden) to increase the conductivity and reduce electrode-to-skin resistance. The EMG equipment consisted of buffer amplifiers (JB101J, Nihon Kohden) and input amplifiers (AB-651J, Nihon Kohden). The input stages provided an input-resistance differential of 180 MΩ and a common resistance of 1000 MΩ. Each amplifier had a 3 dB-point frequency of 0.08 Hz and 10 kHz. The common-mode rejection under the operating conditions was better than 80 dB at 60 Hz. Artefacts were filtered at frequencies of 15 Hz and 3 kHz. The output noise was less than ± 5 mV peak-to-peak, equal to an input signal of $\pm 5\ \mu V$ at 10 kHz. The input amplifiers were electromagnetically shielded so that the overall noise level would be less than ± 1.0 mV, corresponding to an input noise of $\pm 1.0\ \mu V$. Movement of a lower incisor point in space was also recorded simultaneously by means of a non-invasive transducer (Kinesiograph Model K-5, Myotronics Inc., Seattle, U.S.A.). In brief, the position of a small magnetic transducer attached to the labial surfaces of lower central incisors at the habitual maximum intercuspal position (CO position) was zeroed to the origin. The magnetometers were carried on a light frame and aligned with a facebow so that the midsagittal plane, the horizontal plane paralleled to the Frankfort horizontal and at a right angle to the midsagittal and the frontal planes, and the frontal plane were arranged in space to meet with the origin (Hannam, Scott and DeCou, 1977).

Two experiments were made as follows.

Experiment 1. The subjects freely chewed a piece of jelly. Chewing side was not specified. The number of chews and the time elapsed in a masticatory sequence (from the start of chewing until the food was finally swallowed) were measured by the kinesiograph. This task was performed each of three times for the hard and soft jellies, and a mean of three trials was used as a representative value for each subject. Measurement was made by monitoring jaw-movement trajectories on the kinesiograph. The subjects raised a hand as a sign of completing the final swallow.

Experiment 2. Each subject performed deliberate unilateral chewings on the posterior teeth for both types of jelly at a frequency which he/she felt natural and comfortable. A computer (PC-386GS, Epson, Tokyo, Japan) started sampling the biosignals from the sixth chewing stroke for seven data channels (four EMG and three jaw displacements) automatically at 2 kHz by counting pulses derived by the vertical jaw-displacement signal of the kinesiograph. The slice level was determined as the vertical jaw displacement of 2 mm below the habitual intercuspal (CO) position, i.e. the origin. Because output signals from the kinesiograph show non-linear distortion, they were corrected to a mean estimation error of 0.16 mm by means of a non-linear interpolation method (Nagata, Takada and Sakuda, 1991). Data recording was continued until the computer had counted 15 chewing strokes. The digitized EMG signals were absolute valued for full-wave rectification, averaged with a moving interval of 1 ms and a window time of 5 ms, and transferred, together with the kinesiographic signal, to a biosignal database (Nagata and Takada, 1991) in a hypertext machine (Quadra 800, Apple, U.S.A.) for subsequent analyses. A detailed description of the recording system has been published previously (Takada, Nagata and Sakuda, 1988; Takada, 1992).

The chewing data were visually checked on the computer monitor so as to reject the deviant strokes that were often caused by swallowing saliva or bolus relocation. The COout and COin were defined as the time points when the transducer attached to the lower incisors crossed the aforementioned slice level on jaw opening and closing. Chewing strokes were categorized into medial- and lateral-out types according to the pattern of jaw-movement trajectories on the frontal plane. When the lateral jaw positions at the time point of COout was equal or medial to those at the time point of the COin, the stroke was termed as the medial-out type. The reverse was defined as the lateral-out type. The incidences of the medial-out type were determined for the right- and left-sided chews for each of the hard and soft jellies.

Each masticatory cycle was divided into open, close, and intercuspal phases. The slice level to determine the beginnings of the open and intercuspal phases was defined as the vertical jaw position of 2 mm below the habitual intercuspal position. The beginning of the jaw-closing phase was defined as the time of the maximum jaw-opened position. For jaw-movement variables, durations of the opening, closing, and intercuspal phases and a chewing cycle were computed. Positions and velocities of the lower incisor point at the jaw positions of 2 and 5 mm inferior to the habitual intercuspal position and the lower incisor position at the maximum opening were also calculated for each masticatory cycle. In addition, the following EMG variables were defined and measured:

Peak amplitude (μV). Maximum amplitude during a masticatory cycle.

Maximum opening to peak time (ms). Duration between periods of the maximum open position and the peak amplitude.

Onset to peak time (ms). Duration between the periods of onset and peak of EMG burst. The onset time was defined as the period of the first raw digitized data point that revealed muscle activity greater than baseline plus 3 SD maintained for at least 50 ms. The mean baseline muscle level and its SD were calculated from the first 20 out of 73 data points, in ascending order of amplitude, that constitute a complete course of a single masticatory cycle.

Onset to CO time (ms). Duration between onset of EMG burst and the beginning of the habitual intercuspal position (CO time). The CO time was defined as the period of the first data point at which the

Table 2. The number of chews and the lapse of time in a masticatory sequence during natural chewing, and the incidence of the medial-out strokes during unilateral deliberate chewing determined for 15 subjects for the hard and soft jelly chews

Variable	Hard jelly median (minimum–maximum)	Soft jelly median (minimum–maximum)	Probability*
Number of chews (times)	59.7 (25.0–165.3)	32.7 (10.3–102.3)	0.0007
Lapse of time (s)	56.0 (19.3–115.0)	25.7 (6.0–71.0)	0.0007
Incidence of medial-out type stroke (%)	100.0 (83.1–100)	95.8 (73.0–100)	0.0199

*Wilcoxon test for paired observations.

vertical jaw-displacement signal of the kinesiograph took the voltage correspondent to less than 0.2 mm below the habitual intercuspal position.

Peak to end time (ms). Duration between the periods of peak amplitude and cessation of EMG burst. The end time was defined as the period of the first data point that revealed muscle activity of less than the baseline plus 3 SD maintained for at least 20 ms.

Onset to end time (ms). Duration between the onset and end of EMG discharge.

Finally, the onset and end of EMG burst and the time of maximal opening with respect to the COout were determined.

Values for these variables were computed for each masticatory cycle and a mean of 15 complete cycles was calculated for each subject. Also, jaw-displacement records were further processed to determine mean trajectories in three dimensions in each subject for each of the hard and soft chews. In addition, to understand the overall temporal changes in jaw-movement patterns and EMG in a masticatory cycle, each of the aforementioned three phases was divided into 25 equally spaced time points, and mean jaw displacements and EMG voltages at corresponding phase points were calculated for each subject.

Statistical analyses

Initially, a null hypothesis that each variable has a normal distribution was tested by a χ^2 test (Shibata, 1981). We then adopted a paired t-test for comparison of data between the right- and left-hand sides, between the two types of jelly, and between the ipsilateral and contralateral sides if the null hypothesis was accepted. If the assumption of normality was not justified, the Wilcoxon test for paired observations was used. Accordingly, the Pearson correlation coefficient or Spearman rank-correlation coefficient was calculated for the onset and end time of EMG burst between the posterior temporalis and the inferior orbicularis oris muscles and between the muscle and jaw-movement variables for the hard and soft chews, respectively, depending on whether the distribution showed normality. The level of $p \geq 0.05$ was assumed as not significant. These tests were done by means of a statistical analysis software (StatView II, Abacus Concepts, Inc., CA, U.S.A.).

RESULTS

Experiment 1

Medians, minima and maxima for the number and lapse of time of chews until the food was finally swallowed are provided in Table 2. When compared with the soft jelly, the hard jellies were chewed more times and showed a longer lapse of time until finally swallowed.

Experiment 2

Incidences of medial-out strokes for the right- and left-sided chews did not differ significantly in chewing hard or soft jelly. Hence, the mean of both sides was employed as a representative value. Medians, minima and maxima for the incidences of medial-out strokes during unilateral chewing for both types of jelly are given in Table 2. The great majority of the chewing patterns entailed the medial-out strokes for both the hard and soft chews, but the incidence for the hard chews was significantly higher than for the soft chews.

Because most records revealed medial-out chewing strokes, only the results of analyses for the data that showed this type are provided. Comparison between the right- and left-sided chews was made for all the jaw movement and EMG variables in each of the hard and soft jelly records, with the chewing side assigned as a negative direction for the lateral jaw displacement. Significant differences were not determined between the right- and left-hand sides for any variables. Accordingly, the data for both sides were pooled for subsequent analyses. The pooled EMG data were rearranged so that they could be expressed as records ipsilateral and contralateral to the chewing side.

Figure 1 provides mean movement trajectories of a lower incisor point determined for the hard and soft chews. Comparisons of the durations of each phase and a chewing cycle and jaw positions between the hard and soft chews are given in Table 3. Significant differences were not found between the hard and soft jellies for the durations of the jaw-opening and intercuspal phases. However, the durations of closing phase and a chewing cycle for the hard jelly chews were significantly longer than those for the soft. Prolongation of the chewing cycle was caused by a lengthening of the jaw-closing phase.

Lateral jaw displacements for the hard jelly chews at 2 and 5 mm below the habitual intercuspal position were significantly larger than those for the soft-jelly chews in the opening phase and smaller in the closing phase. Hence, the masticatory loop for the hard chews was broader than for the soft. In contrast to the lateral directions, there were no significant differences for the anteroposterior and vertical distances between the hard and soft jelly cycles.

Jaw-movement velocities in space determined at specific jaw positions during chewing of the hard and soft jellies are provided in Table 4. Velocities on jaw opening and closing for the hard jelly chews in all three directions at 2 and 5 mm below the habitual intercuspal position were significantly slower than those for the soft jelly. The differences between the velocities of the hard and soft jelly chews at the vertical jaw position of 2 mm below the habitual intercuspal position in the closing phase were about 2 to 2.5 times as large as those at the same vertical positions in the opening phase.

Table 5 provides a statistical summary of the EMG variables determined for the hard and soft chews, and the probabilities of significance of difference between the two types of jelly. We could not justify the assumption of normality for the EMG variables, excluding the peak amplitude. Both the ipsilateral and contralateral posterior temporalis showed larger peak amplitudes when chewing the hard jelly. This means that the harder the food, the stronger contraction shown by the posterior temporalis in the intercuspal phase. Regarding the temporal aspect of muscle responses, the maximal opening to peak time, the onset to peak time, the onset to CO time and the onset to end time for the hard jelly showed significantly larger values than those for the soft jelly both for the ipsilateral and contralateral posterior temporalis. The peak to end time for both types of jelly did not differ significantly. As for the inferior orbicularis oris, significant differences were not found for any EMG variables between the hard and soft chews for either the ipsilateral or contralateral side. Figure 2 presents data from one subject for single, hard and soft jelly chewing strokes.

Figure 3 summarizes the mean temporal changes in EMG and jaw-movement patterns in a masticatory cycle during chewing of the hard and soft jellies. There were temporal coordinations between EMGs of the ipsilateral and contralateral sides and between

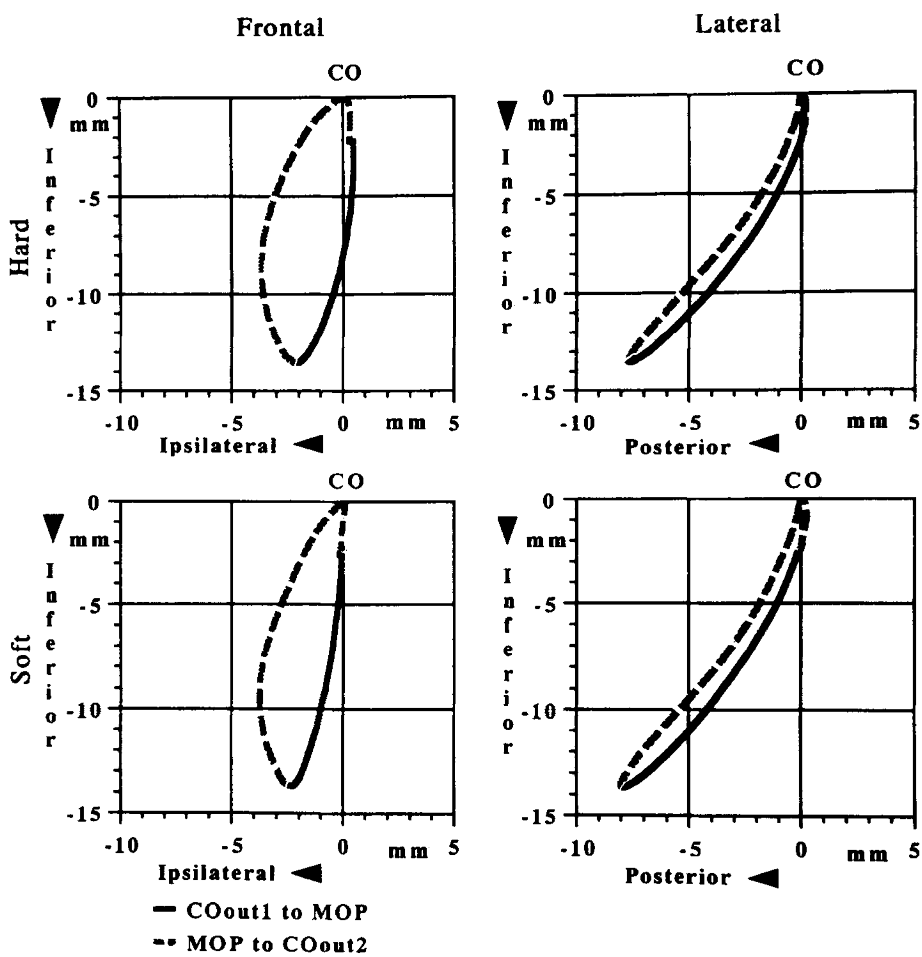

Fig. 1. Mean movement trajectories of a lower incisor point. Top, mean of the hard jelly (HJ) chews (number of subjects, 15); Bottom, mean of the soft jelly (SJ) chews (number of subjects, 15); Left, frontal view; Right, lateral view. Black line, opening phase; dashed line, closing and intercuspal phases. CO represents the centric occlusion position. The slice level was adjusted to 2 mm inferior to the CO position. Unit, mm. MOP, time of maximal opening. For details, see the text.

Table 3. Means and SDs for the durations of respective chewing phases and a chewing cycle and jaw position variables determined for 15 subjects for the hard and soft jelly chews and probabilities of significance of mean difference between the hard and soft jelly chews

Jaw displacement variable	Hard jelly Mean	Hard jelly SD	Soft jelly Mean	Soft jelly SD	Probability
Duration (ms)					
Opening phase	176	32	169	26	0.2910
Closing phase	201	38	176	29	0.0012
Power phase	288	48	282	51	0.4852
Chewing cycle	665	70	627	73	0.0043
*Position (mm)**					
Lateral					
COout 2 mm	0.4	0.7	−0.1	0.7	0.0092
COout 5 mm	0.3	1.0	−0.3	0.9	0.0046
MOP	−2.1	0.8	−2.3	1.0	0.2786
COin 5 mm	−3.0	0.7	−2.8	0.8	0.0077
COin 2 mm	−2.0	0.6	−1.8	0.6	0.0005
Anteroposterior					
COout 2 mm	0.4	1.1	0.5	1.2	0.4632
COout 5 mm	−0.8	2.2	−0.8	2.1	0.7943
MOP	−7.2	3.7	−7.3	4.0	0.8242
COin 5 mm	−1.6	2.6	−1.7	2.6	0.4567
COin 2 mm	−0.1	1.4	−0.1	1.4	0.8687
Vertical					
MOP	−13.3	3.2	−13.1	3.2	0.5605

*COout 2 mm and COout 5 mm denote vertical jaw positions of 2 and 5 mm inferior to the habitual intercuspal position on jaw opening. COin 2 mm and COin 5 mm represent the identical positions on jaw closing. MOP, maximal opening time.

the posterior temporalis and inferior orbicularis oris. These were common to both types of jelly. The ipsilateral posterior temporalis started to discharge from around the time of maximal opening, showed a gradual increase in activity with its peak coincident with the intercuspation of teeth, and ceased its activity slightly after the midpoint of the intercuspal phase. Table 6 shows the probabilities of significance of difference between muscle responses ipsilateral and contralateral to the chewing side. Table 7 shows Spearman rank-correlation coefficients for paired-muscle variables. There was a consistent delay in onset of burst of the contralateral posterior temporalis when compared with the ipsilateral posterior temporalis. The onset to end time for the ipsilateral posterior temporalis was significantly longer when compared with the non-working side of the hard jelly chews. Both the ipsilateral and contralateral posterior temporalis ceased their activity almost at the same time for the hard and soft chews. Despite these similarities, the time of peak activity for the ipsilateral posterior temporalis in the hard jelly chews preceded significantly that for the contralateral posterior temporalis. The onset time for the ipsilateral posterior temporalis activity was highly correlated with the time of the maximum jaw opening. The end time of the ipsilateral posterior temporalis burst was significantly correlated with the end time of a chewing cycle, which was equal to the beginning of the subsequent chewing cycle. The contralateral posterior temporalis showed significant correlations between the time of onset of burst and the time of the maximum gape for the hard jelly chews, and between the end of burst and the beginning of a subsequent chewing cycle, although the onset and the time of maximum gape for the same muscle during the soft jelly chews did not correlate.

The peak activity of the ipsilateral inferior orbicularis oris was significantly higher than that of the contralateral muscle in chewing the hard and soft jellies. For both types of jelly, the inferior orbicularis oris revealed a weak but consistent level of activity during the jaw-closing and intercuspal phases. This is explained by a relatively large variation in the inferior orbicularis oris activity during the aforementioned phases. There were significant correlations between the onset of burst and the beginning of the subsequent chewing cycle, both for the ipsilateral and the contralateral inferior orbicularis oris. In contrast, distinct associations were not found between the end of burst and the time of maximum jaw opening for the ipsilateral and the contralateral inferior orbicularis oris.

There was a marked separation of activity between the posterior temporalis and inferior orbicularis oris muscles (Table 7). Almost synchronous with the cessation of the posterior temporalis activity, the inferior orbicularis oris started to show burst activity in the intercuspal phase. They showed a gradual

Table 4. Means and SDs for jaw-movement velocities (mm/s) in space determined at specific jaw positions during chewing of the hard and soft jellies and probabilities of significance of mean difference between the hard and soft jelly chews

Jaw position and direction	Jaw movement velocity (mm/s) Hard jelly Mean	Hard jelly SD	Soft jelly Mean	Soft jelly SD	Probability
COout 2 mm*					
Lat	−0.3	8.1	−4.6	7.4	0.0191
A/P	−11.8	12.7	−17.9	17.7	0.0051
Ver	−44.7	10.2	−57.0	14.0	0.0012
Total	48.6	9.4	63.2	11.8	0.0001
COout 5 mm					
Lat	−6.1	10.2	−11.9	8.9	0.0252
A/P	−43.1	29.7	−51.5	26.6	0.0053
Ver	−96.6	24.8	−106.9	31.6	0.0060
Total	110.4	23.9	123.2	28.5	0.0038
COin 5 mm					
Lat	24.4	14.3	31.4	15.6	0.0034
A/P	34.6	19.8	41.2	25.5	0.0351
Ver	66.3	23.6	80.1	25.6	0.0001
Total	82.9	20.5	100.7	22.1	0.0001
COin 2 mm					
Lat	31.2	12.5	41.6	21.2	0.0126
A/P	23.0	26.7	35.2	35.3	0.0047
Ver	66.9	34.6	96.2	45.8	0.0001
Total	82.5	34.4	117.9	44.8	0.0001

*COout 2 mm and COout 5 mm denote vertical jaw positions of 2 and 5 mm inferior to the habitual intercuspal position on jaw opening. COin 2 mm and COin 5 mm represent the identical positions on jaw closing. Data from 15 subjects were processed for statistical analysis. Lat, lateral jaw displacement; A/P, anteroposterior jaw displacement; Ver, vertical jaw displacement.

Table 5. Means and SDs for the peak-amplitude variables and medians, minima and maxima for the remaining muscle variables determined for the posterior temporalis (PT) and inferior orbicularis oris (OI) muscles during chewing of the hard and soft jellies for 15 subjects and probabilities of significance of difference between the two types of jelly

Muscle variable	Hard jelly Mean		SD	Soft jelly Mean		SD	p*
Peak amplitude (μV)							
IpsiPT	185		44	170		45	0.0007
ContraPT	180		61	160		63	0.0001
IpsiOI	169		42	173		39	0.5577
ContraOI	150		42	153		39	0.6500
EMG time variables	Median	Min.	Max.	Median	Min.	Max.	p**
MOP to peak time (ms)							
IpsiPT	225	150	317	204	120	334	0.0231
ContraPT	233	150	375	211	143	368	0.0026
IpsiOI	−87	−158	−6	−76	−146	−28	0.5321
ContraOI	−86	−163	−37	−89	−193	−28	0.7333
Onset to peak time (ms)							
IpsiPT	204	137	301	178	107	292	0.0007
ContraPT	194	129	259	143	104	318	0.0125
IpsiOI	119	49	248	135	65	274	0.2330
ContraOI	146	75	182	166	16	223	0.2805
Onset to CO time (ms)							
IpsiPT	280	184	348	215	161	257	0.0008
ContraPT	229	174	296	177	139	347	0.0146
IpsiOI	179	94	292	153	56	287	0.1728
ContraOI	163	80	265	138	51	318	0.1252
Peak to end time (ms)							
IpsiPT	149	85	227	149	86	210	0.2219
ContraPT	152	82	213	149	87	205	0.4955
IpsiOI	24	5	174	50	5	163	0.4955
ContraOI	40	3	135	68	7	129	0.8203
Onset to end time (ms)							
IpsiPT	379	265	470	320	209	465	0.0007
ContraPT	340	286	420	309	212	406	0.0106
IpsiOI	144	59	327	184	73	379	0.1118
ContraOI	184	89	304	195	120	306	0.1914

*Paired t-test for paired observations; **Wilcoxon test for paired observations.

increase in activity during the jaw-opening phase with peak time at somewhere between the midpoint and the last one-third of the opening phase. As for the association between the posterior temporalis and inferior orbicularis oris, the onset time of burst for the ipsilateral posterior temporalis correlated with the end time of burst for the ipsilateral inferior orbicularis oris. The end time of burst for the ipsilateral posterior temporalis also had significant correlations with the onset time of burst for the ipsilateral inferior orbicularis oris. Regarding the contralateral side, significant correlations were found between the onset time of the posterior temporalis burst and the end time of the inferior orbicularis oris burst and between the end time of burst for the posterior temporalis and the onset time of burst for the inferior orbicularis oris.

DISCUSSION

In mammals, the act of swallowing is dependent on the consistency of the food bolus (Doty, 1968). Solid food is chewed to a particular consistency and size suitable for swallowing. Besides the exposure of food to saliva, the kinematic process of chewing can be described, in its peripheral sense, mainly by the frequency of chewing, the magnitude and duration of masticatory muscle activity, and the direction and speed of jaw movement. Hardness of food is known to influence temperature rises in the facial skin surface overlying the masticatory muscles during chewing (Morimoto *et al.*, 1991). Changes in the aforementioned variables in response to changes in controlled oral load in relation to an understanding the role of sensory feedback in the control of the motor output from the central pattern generator can only be evaluated quantitatively by using proper foods that have similar physical and chemical properties except for toughness. We therefore developed and used special gummy jellies as test food, as gelatin-based foods can provide similar taste, shape, size, flavour and homogeneity with different texture or consistency (Arai, Yamada and Nishisaka, 1992). There is a possibility that the corn syrup might react with the salivary amylase, which might eventually soften the consistency of the hard jelly. However, we consider that the time for chewing the jelly in the current experiment is too short for the hard jelly to become as soft as the soft jelly.

The masticatory sequence can be divided into three series, the preparatory, the reduction and the preswallowing series in that order (Schwarz *et al.*, 1989). Our main purpose was to investigate the effects of food consistency on masticatory movement with particular focus on lateral jaw movements and related posterior temporalis activity. Because the wide lateral jaw excursion during closure and the remarkable burst of activity in jaw-closing muscles are characteristic of masticatory cycles during the reduction series in both man and rabbit, we examined the 15 cycles after the sixth cycle from the start of chewing. We had confirmed that these cycles constitute the reduction series when chewing the current test foods. Also, in most cases, the first five cycles formed the preparatory series.

Jaw-movement patterns in the frontal view during chewing have been classified into many categories (Ahlgren, 1966; Proschel, 1987). We divided the chewing patterns simply into the medial- and lateral-out strokes. These types generally correspond to the normal and inverted chewing patterns as described by Proschel (1987). The direction of jaw movement at the slice level of 2 mm below the habitual intercuspal position was chosen as a criterion to divide the chewing patterns into the two major categories, as the lateral jaw displacement at the aforementioned level revealed the smallest variation among those at the levels ranging between 2 and 8 mm inferior to the

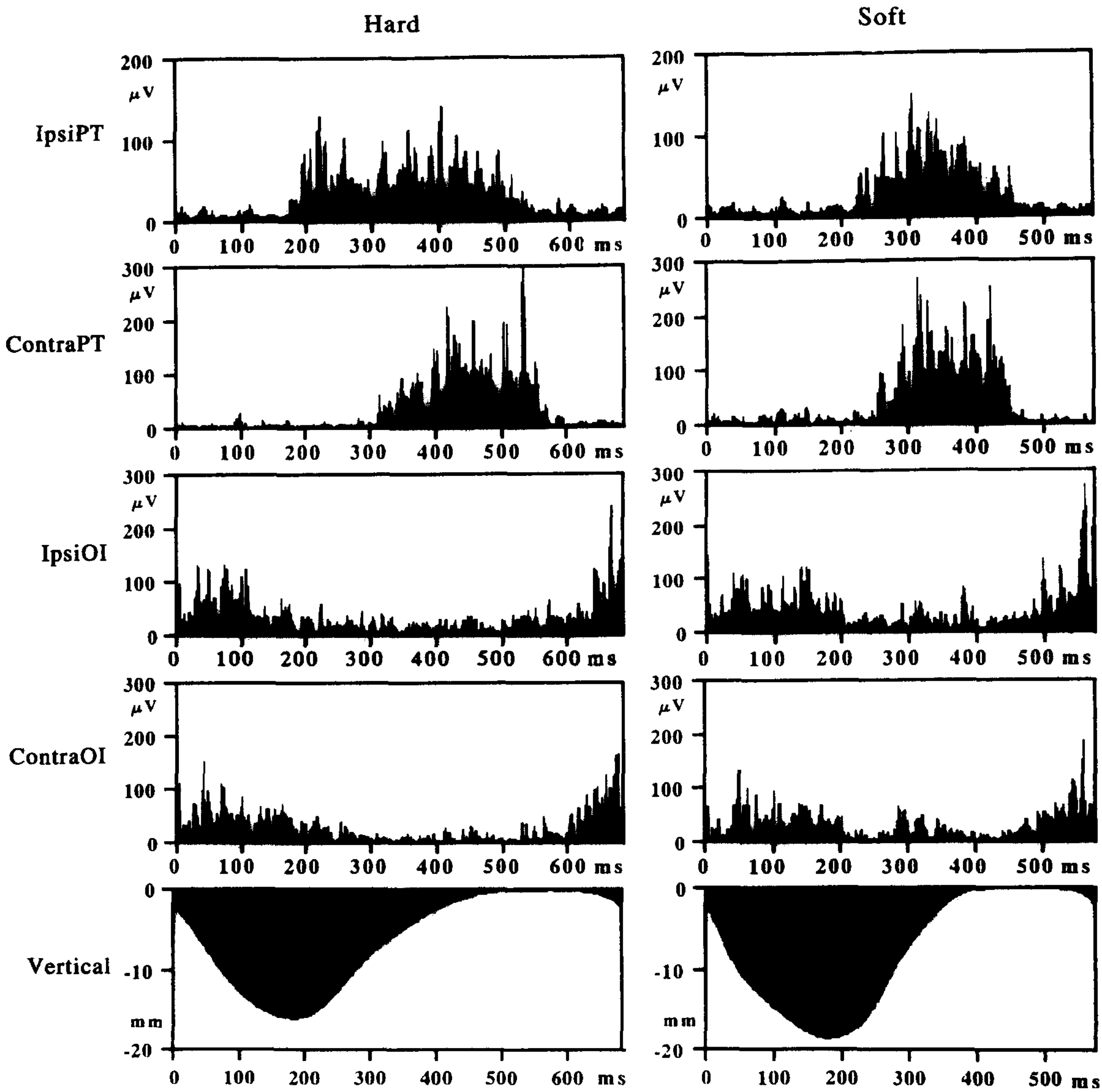

Fig. 2. Rectified, digitized muscle responses during single hard- and soft-jelly chewing cycles by one subject. Left, hard jelly (HJ) chew; Right, soft jelly (SJ) chew; IpsiPT, ipsilateral posterior temporalis muscle; ContraPT, contralateral posterior temporalis muscle; IpsiOI, ipsilateral inferior orbicularis oris muscle; ContraOI, contralateral inferior orbicularis oris muscle; Vertical, vertical jaw displacement; Unit, μV for EMG, mm for jaw movement and ms for time. Vertical jaw displacement, measured at the incisor point, is shown in the bottom traces, with opening indicated by the downward deflection. Time zero corresponds to beginning of jaw opening defined at the slice level of 2 mm below the centric occlusion (CO) position.

habitual intercuspal position (see Fig. 1). The incidences of medial-out strokes for the soft and hard foods were slightly higher than those reported for the pooled samples of adults who exhibited good occlusion and Angle Class II, Division 2 malocclusion (Proschel and Hofmann, 1988). This may be due to

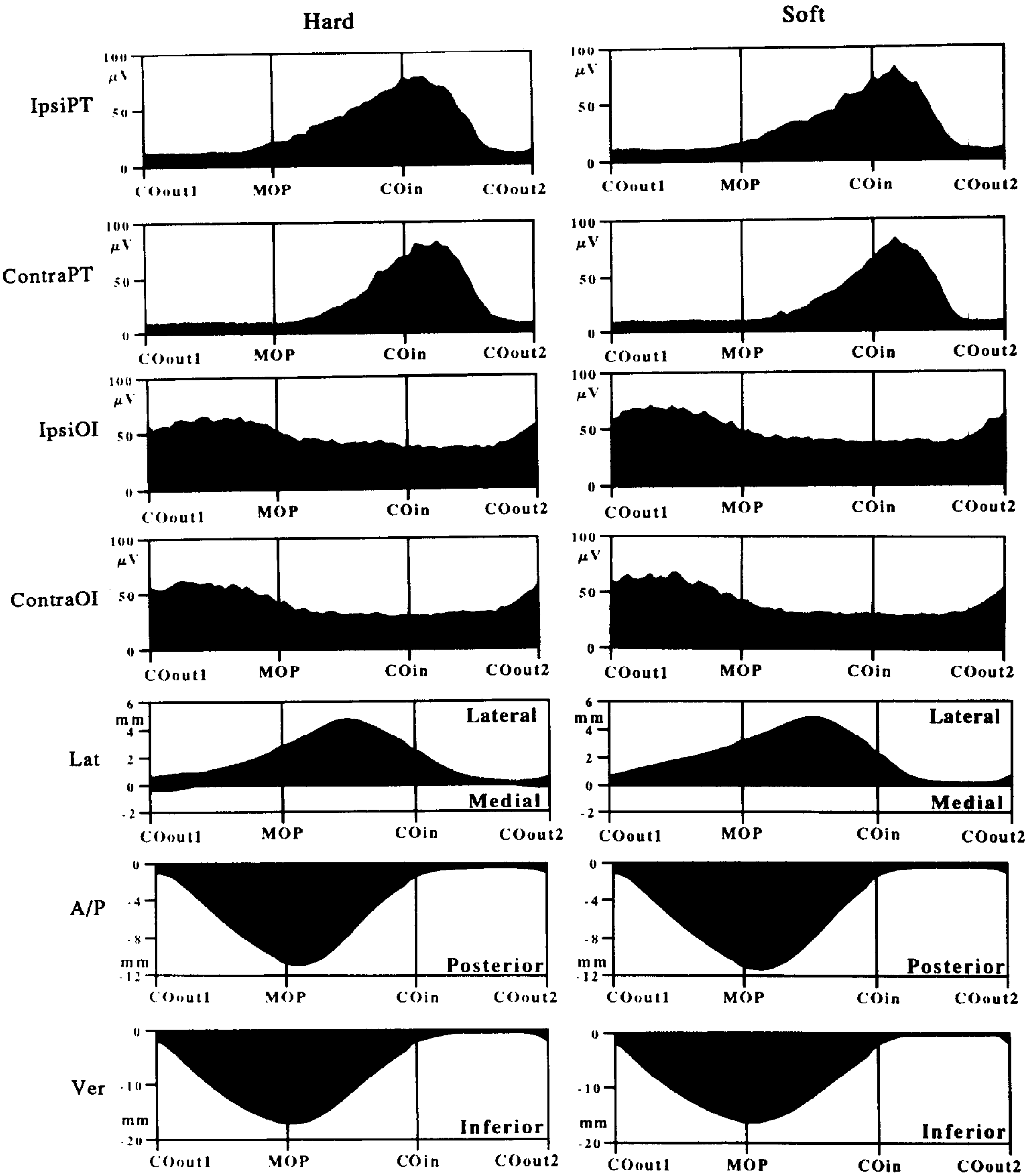

Fig. 3. Mean responses of the ipsilateral posterior temporalis muscle (IpsiPT), the contralateral posterior temporalis muscle (ContraPT), the ipsilateral inferior orbicularis oris muslce (IpsiOI) and the contralateral inferior orbicularis oris muscle (ContraOI) and jaw-movement trajectories during unilateral chewing of hard and soft jellies. Lat, lateral jaw displacement; A/P, änteroposterior jaw displacement; Ver, vertical jaw displacement. Left, hard jelly (HJ) chews; Right, soft jelly (SJ) chews; Mean phase-point values for each subject were averaged for all subjects ($n = 15$) and joined and enclosed the heavy dark areas. The SDs at each point are joined and enclosed by the light-stippled areas. In each data-set, the vertical lines indicate divisions of the averaged chewing cycle from left to right, into its opening, closing and intercuspal phases. COout, beginning of jaw-opening phase; MOP, time of maximum jaw-opening; COin, end of jaw closing phase. Unit μV for EMG and mm for jaw displacement.

Table 6. Probabilities of significance of difference between ipsilateral and contralateral EMG variables for the hard and soft jelly chews

Paired observations	Probability for significance of difference*	
	Hard jelly	Soft jelly
Peak amplitude (μV)		
IpsiPT vs ContraPT	0.4479	0.1822
IpsiOI vs ContraOI	0.0086	0.0014
MOP to peak time (ms)		
IpsiPT vs ContraPT	0.0064	0.1118
IpsiOI vs ContraOI	0.5701	0.6002
Onset to peak time (ms)		
IpsiPT vs ContraPT	0.0995	0.1118
IpsiOI vs ContraOI	0.2560	0.7299
Onset to CO time (ms)		
IpsiPT vs ContraPT	0.0031	0.0409
IpsiOI vs ContraOI	0.0995	0.5337
Peak to end time (ms)		
IpsiPT vs ContraPT	0.7764	0.7764
IpsiOI vs ContraOI	0.1252	0.1556
Onset to end time (ms)		
IpsiPT vs ContraPT	0.0468	0.2115
IsiOI vs ContraOI	0.1914	0.4603

*Paired t-test for the peak amplitude and Wilcoxon test for the time variables.

the differences in occlusal types or age distribution of the subjects selected, or in types of food used. The high incidence of medial-out strokes in the current study is not consistent with the findings of Wickwire *et al.* (1981), who documented wide lateral excursions in opening movements as typical in the mixed dentition. This is probably due to the difference in age distribution of the subjects. We used children in the late mixed dentition, while they used those in the deciduous to early mixed dentition stages.

In agreement with previous reports (Thexton *et al.*, 1980; Morimoto *et al.*, 1985; Horio and Kawamura, 1989), we found a prolongation of the time from the beginning of chewing until the final swallowing when chewing hard food. We also found more frequent chews and a prolongation of each masticatory cycle in chewing harder food. These are consistent with the findings of Ahlgren (1976). There has been a divergence in opinion as to the effect of toughness of food on phase durations of a masticatory cycle. Thexton *et al.* (1980) found that prolongation of the opening phase was associated with softer foods while an increase in the closing phase was associated with harder foods in cats. Prolongation of both the opening and power phases was reported in rabbits (Morimoto *et al.*, 1985). In man, prolongation may be found in the opening and intercuspal phases (Plesh *et al.*, 1986) or the opening and closing phases (Proschel and Hofmann, 1988). Such discordance may be ascribed to the differences in species, the properties of test food used for comparison and/or the measuring methods employed, including measurement accuracy. In the present study, the closing phase was longer when chewing hard than soft food, while the opening and intercuspal phases remained stable. The increased duration of the closing phase is accounted for by elongation of the distance of the jaw-closing trajectory, which is expressed as the widening of the masticatory loop together with a slowing down of the jaw-closing velocity, as will be discussed below.

Although a previous report (Wickwire *et al.*, 1981) has described a child, aged 12 years, who had no difference in jaw-movement patterns on chewing hard and soft food, the jaw-movement pattern of the hard jelly chews in our study revealed grinding strokes when compared with the slim forms that were characteristic of the soft jelly chews. Our results agree with those of Proschel and Hoffmann (1988). Animal experiments (Lund, McLachlan and Dellow, 1971; Lund and Dellow, 1971) have shown that lateral jaw movement is under reflex control and can modify the rhythmic chewing cycle. This is supported by observations on human mastication (Schaerer, Stallard and Zander, 1967; Hannam *et al.*, 1981; Takada, 1992) which suggested that lateral jaw movement is reflexly modulated by sensory feedback from receptors in or around teeth. Lateral jaw excursion is enhanced when chewing hard objects (Drechsler *et al.*, 1973; Gibbs and Lundeen, 1982; Morimoto *et al.*, 1985; Lavigne *et al.*, 1987; Proschel and Hofmann, 1988; Inoue *et al.*, 1989). The occlusal force vector is more likely to have a non-axial component when chewing hard and elastic food than

Table 7. Spearman rank-correlation coefficients between temporal EMG and jaw-movement variables and their probabilities of significance

Paired variables			Hard jelly		Soft jelly	
			r_s	Probability	r_s	Probability
IpsiPT onset time	vs	IpsiOI end time	0.5857	0.0284	0.5250	0.0495
IpsiPT end time	vs	IpsiOI onset time	0.5429	0.0422	0.5679	0.0336
ContraPT onset time	vs	ContraOI end time	0.5594	0.0363	0.7143	0.0075
ContraPT end time	vs	ContraOI onset time	0.7607	0.0044	0.6036	0.0239
IpsiPT onset time	vs	Duration of open phase	0.8351	0.0018	0.8536	0.0014
IpsiPT end time	vs	Chewing cycle	0.8150	0.0023	0.9321	0.0005
ContraPT onset time	vs	Duration of open phase	0.6165	0.0211	0.4321	0.1059
ContraPT end time	vs	Chewing cycle	0.8954	0.0008	0.8964	0.0008
IpsiOI onset time	vs	Chewing cycle	0.6434	0.0161	0.6286	0.0187
IpsiOI end time	vs	Duration of open phase	0.4409	0.0990	0.4750	0.0755
ContraOI onset time	vs	Chewing cycle	0.8007	0.0027	0.7786	0.0036
ContraOI end time	vs	Duration of open phase	0.2924	0.2740	0.3250	0.2240

r_s, Spearman rank correlation coefficients.

when chewing soft food, and teeth are known to be more sensitive to non-axial forces than those directed along the long axis of the teeth (Hannam, 1982). We therefore speculate that information on food consistency, i.e. hardness and elasticity, is transmitted to the central nervous system so that it can serve to modify the basic pattern of jaw movement by producing a horizontal excursion of the jaw in the final aspect of the closing phase and the initial part of the intercuspal phase which facilitates the generation of stronger shearing force between functional cusps of molar teeth and the food bolus. The higher incidence of medial-out strokes for the hard jelly chews may also be explained in a similar context. Both the ipsilateral and contralateral posterior temporalis showed a longer time from the onset of the burst until the habitual intercuspal position and a longer duration of activity in chewing hard than soft food. Because the posterior temporalis acts not only to close the jaw but also to rotate and/or stabilize it in a horizontal plane, the results indicate that the hardness of food is sensed so that the motor output to the posterior temporalis from the central pattern generator is modified to alter the jaw-movement trajectories in the lateral direction. A recent study (Liu *et al.*, 1993) has suggested that such regulation of jaw movement and associated EMG activity dependent on food consistency is done automatically. In contrast to the lateral displacement, the jaw-movement trajectories in the sagittal and vertical directions were not affected by the change in food hardness. Therefore, it appears that the influence of the food consistency on the central pattern generator in regulation of the masticatory jaw-movement pattern has directional sensitivity. As for the initial part of the jaw-opening phase when chewing hard food, the contralaterally directed trajectories found here might indicate an earlier participation of the contralateral inferior lateral pterygoid, as this is the first muscle to commence its burst in human masticatory movement (Wood, Takada and Hannam, 1986). In summary, it appears that the jaw-movement orbit is altered by altering the motor output to specific muscles selectively, where periodontal and neighbouring sensory afferents may have considerable influence. It can be speculated that a feedback controller or the central pattern generator, which manipulates or takes part in modification of motor output, has a sensitivity unique to the direction of jaw displacement and the spatial position of the jaw in the production of jaw-movement trajectories during chewing.

We found increased posterior temporalis activity during the hard jelly chews. This is explained by positive feedback from periodontal pressoreceptors (Lavigne *et al.*, 1987; Morimoto *et al.*, 1989), which facilitates efficient comminution of the food by grinding. A similar increase in the peak EMG activity during the chewing of hard food was found in the human masseter (Horio and Kawamura, 1989).

Jaw-closing velocities for the hard jelly chews were significantly slower than those for the soft jelly. In contrast to the jaw-movement trajectories, this slowing down occurred uniformly in three directions. A possible explanation might be an influence from muscle-spindle afferents but the spindles from jaw-closing muscles are known to be silent during the fastest movements of jaw closure (Goodwin and Luschei, 1975). In a companion study, Goodwin and Luschei (1974) reported no discernible change in the jaw-movement pattern or rate of chewing or EMG pattern of jaw muscles during chewing in monkeys whose trigeminal mesencephalic nucleus had been destroyed. They suggested that muscle-spindle afferents may make little contribution to modifying the motor output to the jaw-closing muscles during chewing. Although we cannot rule out the possibility that the jaw-closing movement has interfered mechanically with the physical property of the hard jelly itself, there were some clues that strongly suggest the contribution of central regulation in explaining the slowing down of jaw movement in chewing the hard jelly. First, the speed slowed down not only in the jaw-closing phase but also in the jaw-opening. Jaw-closing velocities near the habitual intercuspal position were between about 50 and 100 mm/s, so we suggest that an optimal speed of jaw movement is generated or chosen in response to the sensory feedback that detects the consistency of food from the peripherals in an initial few strokes, as noted by Boyd and Sherman (1975), and is automatically controlled centrally by a feed-forward control thereafter. Otherwise, teleologically, the velocities in this zone appear to be too fast to sense the obstacles and alter the jaw-movement orbit for their avoidance.

An effect of temporal summation of sensory input over multiple chewing cycles upon the general trend of subsequent cycle characteristics has also been postulated (Thexton *et al.*, 1980). Secondly, the jaw-opening velocities in three directions near the habitual intercuspal position were slower when chewing harder food, but the durations of the opening phase did not differ between the hard and soft chews. As the jaw-opening speed for the hard jelly at the maximum gape was faster than for the soft jelly, it appears that there is an acceleration or catching up of jaw-opening speed midway in the jaw-opening phase when chewing hard food to compensate for the delay.

Very little information is available on the spatio-temporal relations between the jaw and lip muscle activities and jaw-movement patterns during chewing in young human adolescents. We recorded EMG activity from the lower lip, because EMGs from the inferior orbicularis oris were more suitable for uniform quantitative evaluation than those from the superior orbicularis oris (Moller, 1966).

In agreement with previous studies (Moller, 1966; Schieppati, Di-Francesco and Nardone, 1989), the inferior orbicularis oris showed an increase in activity in accord with jaw opening. We found strong correlations between the start of the burst of inferior orbicularis oris activity and the end of burst of posterior temporalis activity for the hard and soft chews. Conversely, the timing of the cessation of the inferior orbicularis oris burst correlated with that of the onset of the posterior temporalis activity. In other words, the inferior orbicularis oris and the posterior temporalis showed reciprocal cyclic activity. It should also be noted that, at the current spontaneous pitch of chewing, the inferior orbicularis oris started to show bursts not in the jaw-opening phase but at the later part of the intercuspal phase. Schieppati *et al.* (1989) have, however, documented the commencement of the EMG burst of this muscle as in the opening phase for the low frequency (about 1 Hz) of chewing. The EMG signals in Figs 1, 2, 3 and 8 in their report, however, show an earlier onset of bursts for the inferior orbicularis oris in the later part of the occlusal phase, irrespective of frequency of chewing. Our results, taken together, indicate a possible central regulation of the basic form of facial motility during chewing of food.

In contrast to the minimum jaw-closing muscle activity in the jaw-opening phase, the inferior orbicularis oris was not always inactive in the jaw-closing and intercuspal phases. This is consistent with the findings of Moller (1966), which documented a secondary activity during jaw closure. We also found a large variation in inferior orbicularis oris activity during these phases. The peak activity for the ipsilateral muscle was significantly higher than that for the contralateral inferior orbicularis oris, irrespective of the food consistency. Because the peak activity was seen in the jaw-opening phase, the observed difference may indicate more contraction of the inferior orbicularis oris on the ipsilateral side or a contribution from the ipsilateral buccinator (Blanton, Biggs and Perkins, 1970; Moller, 1974) in accomplishing a tight oral seal to keep the food bolus and saliva in the mouth. The inferior orbicularis oris activity did not differ between the hard and soft foods. Accordingly, the overall findings suggest that the motor output to the inferior orbicularis oris is modulated by a sensory feedback from the mouth even when the chewing is mainly on the posterior teeth (Bratzlavsky, 1972; Fanardjian, Kasabyan and Manvelyan, 1983). It appears that timing of the burst and magnitude of activity for the inferior orbicularis oris are possibly influenced by the position and size but, to a lesser extent, the consistency of the food bolus in the mouth.

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