13. Beyron H: Occlusal relations and mastication in Australian Aborigines. Acta Odontol Scand 22:597, 1964.
14. Koivumma KK: Cinefluorographic analysis of the masticatory movements of the mandible. Suom Hammaslaak Toim 57:306, 1961.
15. Gibbs CH, Merrerman T, Reswick JB, Derda HJ: Functional movements of the mandible. J PROSTHET DENT 26:604, 1971.
16. Alexander TA, Gibbs CH, Thompson WJ: Investigation of chewing patterns in deep bite malocclusion before and after orthodontic treatment. Am J Orthod 85:21, 1984.
17. Neill DJ: Masticatory function. J Dent Assoc S Afr 37:631, 1982.
18. Jemt T, Karlsson S, Hedegard B: Mandibular movement of young adults recorded by intraorally placed light emitting diodes. J PROSTHET DENT 42:669, 1979.
19. Ahlgren J, Owall B: Muscular activity and chewing force: A polygraphic study of human mandibular movements. Arch Oral Biol 15:271, 1970.

Reprint requests to:
DR. D. J. NEILL
GUY'S HOSPITAL
MEDICAL AND DENTAL SCHOOLS
GUY'S TOWER
LONDON SE1 9RT
ENGLAND

Computer-based assessment of habitual mastication

F. Mongini, M.D., D.D.S., Ph.D.,* G. Tempia-Valenta, D.D.S., and G. Benvegnu, D.D.S.****
Turin University, School of Dentistry, Torino, Italy

Mandibular movements during chewing have been examined by several authors.[1-12] The various means used included cineradiography,[3,4] photoelectric devices or light-emitting diodes,[6,10] record of variations induced in a magnetic field,[7-9] implanted radionucleotides,[11] and others. Other authors have analyzed electromyographic (EMG) activity of the masticatory muscles during chewing and in conjunction with the recording of mandibular movements.[13-18]

Examination of a chewing sequence should include the study of single cycles in space, versus time, and of mean masticatory movement; to assess the mean can be difficult because of the variability of the chewing cycles. Numerical analysis should provide data on displacement and EMG values at a sufficient number of levels of jaw separation both for opening and for closing movements. Furthermore, if several chewing cycles are computed to assess a mean chewing movement, cycles toward opposite sides tend to abate reciprocally. Therefore statistical studies usually have been performed on unilateral voluntary masticatory movements and in other studies single cycles of habitual mastication were described with little or no attempt to draw statistical data.

For these reasons we developed and tested a system for the analysis of mandibular movements and EMG activity during habitual mastication.[19] We applied this system to a group of normal individuals for the study of masticatory function in a condition of health.

MATERIAL AND METHODS

Six men and six women 14 to 44 years of age were selected. They had complete Class I dental arches, no malocclusion, no history of dysfunction, and no objective signs at inspection, palpation, and auscultation of the temporomandibular joint (TMJ). After a brief explanation of the purposes of the study they were asked to sit in a wooden chair as comfortably as possible with the head leaning against a support in an upright position. After insertion of the electrodes and movement recording system they were given a predetermined amount of crisp bread (30 mm long and 12 mm wide sticks) and were asked to place it on the tongue and bring the teeth into the maximum intercuspation position (ICP). At a given signal from the computer the subject started to chew normally. Data were recorded for 15 seconds (i.e., almost the duration of one masticatory sequence). Three tests were performed for each individual.

Electromyography

Bipolar surface electromyography was performed with Ag/AgCl disk electrodes applied bilaterally on the masseter and anterior parts of the temporal muscles. They were placed 15 mm apart along the direction of the muscles fibers by using anatomic landmarks. The ground electrodes were placed on the ears. Skin impedance was reduced by alcohol scrub and the electrodes were secured with adhesive strips and filled with paste

Supported by grants of C.N.R. (Italian Research National Council) and of the Department of Education.

*Director, Center for Gnathology and Pathophysiology of the Masticatory Function.
**Resident, Center for Gnathology and Pathophysiology of the Masticatory Function.

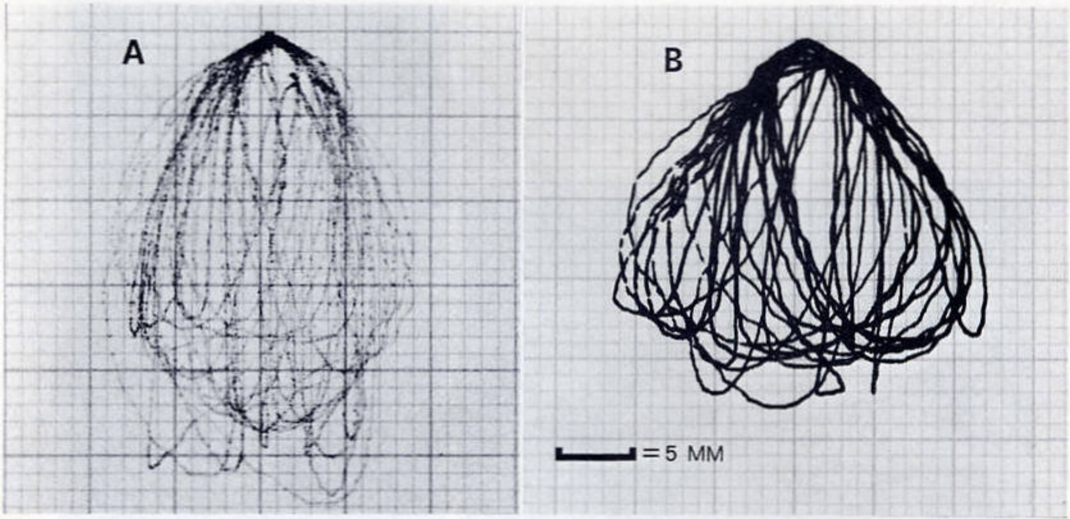


Fig. 1. A, Subject 2 and **B,** five sequences recorded on frontal plane with XY chart recorder. Note that despite variability of movements their distribution is rather balanced and symmetrical.

Table I. Mean displacement values on frontal plane for all subjects

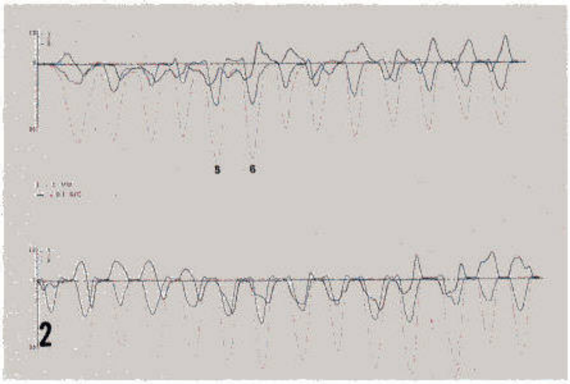
	Clockwise					Counterclockwise				
	Opening movements		Closing movements			Opening movements		Closing movements		
Level	N	M	N	M	*p*	N	M	N	M	*P*
0	182	−0.13 ± 0.69	195	0.03 ± 0.70	*	175	−0.20 ± 0.63	189	−0.31 ± 0.70	—
1	232	−0.07 ± 1.08	245	0.79 ± 0.85	***	248	−0.09 ± 1.07	249	−0.79 ± 1.07	***
2	268	−0.07 ± 1.69	272	1.39 ± 1.20	***	296	−0.14 ± 1.62	298	−1.34 ± 1.51	***
3	272	−0.18 ± 2.11	274	1.95 ± 1.51	***	303	−0.21 ± 2.00	303	−2.04 ± 1.78	***
4	274	−0.16 ± 2.38	274	2.49 ± 1.65	***	305	−0.22 ± 2.26	305	−2.51 ± 1.94	***
5	274	−0.12 ± 2.56	274	3.04 ± 1.86	***	306	−0.25 ± 2.43	306	−2.94 ± 2.14	***
6	274	−0.06 ± 2.73	275	3.48 ± 2.08	***	306	−0.28 ± 2.59	306	−3.29 ± 2.35	***
7	274	0.03 ± 2.85	275	3.99 ± 2.29	***	306	−0.32 ± 2.66	306	−3.73 ± 2.49	***
8	274	0.10 ± 2.96	274	4.38 ± 2.46	***	306	−0.33 ± 2.77	306	−4.06 ± 2.62	***
9	273	0.34 ± 3.14	273	4.91 ± 2.57	***	306	−0.35 ± 2.89	306	−4.43 ± 2.83	***
10	272	0.37 ± 3.13	272	5.13 ± 2.66	***	306	−0.38 ± 2.95	306	−4.70 ± 2.94	***
11	273	0.58 ± 3.22	272	5.29 ± 2.77	***	305	−0.41 ± 3.04	306	−4.83 ± 3.12	***
12	271	0.69 ± 3.23	271	5.39 ± 2.83	***	304	−0.42 ± 3.06	304	−4.93 ± 3.21	***
13	269	0.96 ± 3.27	271	5.43 ± 2.92	***	303	−0.50 ± 3.15	303	−4.96 ± 3.30	***
14	259	1.00 ± 3.38	261	5.51 ± 2.92	***	301	−0.52 ± 3.20	301	−4.84 ± 3.39	***
15	256	1.33 ± 3.52	258	5.32 ± 3.00	***	290	−0.62 ± 3.31	295	−4.67 ± 3.49	***
16	240	1.37 ± 3.43	243	5.03 ± 2.97	***	275	−0.50 ± 3.23	279	−4.40 ± 3.57	***
17	225	1.44 ± 3.35	224	4.61 ± 2.94	***	250	−0.32 ± 3.09	256	−4.05 ± 3.61	***
18	190	1.60 ± 3.25	190	4.30 ± 2.80	***	217	−0.32 ± 3.30	220	−3.69 ± 3.75	***
19	133	1.35 ± 3.23	139	4.06 ± 2.85	***	171	−0.50 ± 3.37	174	−3.42 ± 3.60	***
20	83	1.63 ± 3.08	77	3.72 ± 2.99	***	120	−0.39 ± 3.25	107	−2.91 ± 3.43	***
A					***	A				***

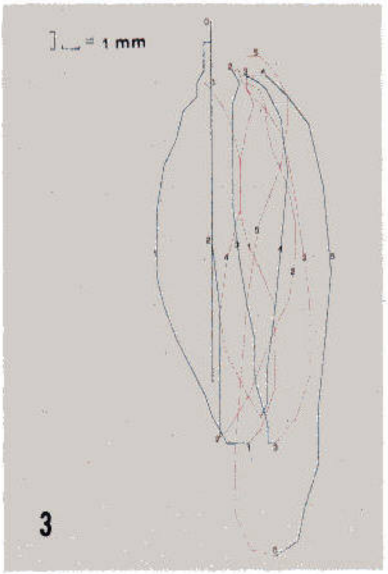
Level = level of jaw separation in mm; N = number of times displacement occurred; M = mean displacement in mm ± SD (positive values = right; negative values = left); A = statistical analysis of mean difference between displacement values at any given level and next of opening movements compared to that of closing movement; * = $p < .05$; *** = $p < .001$.

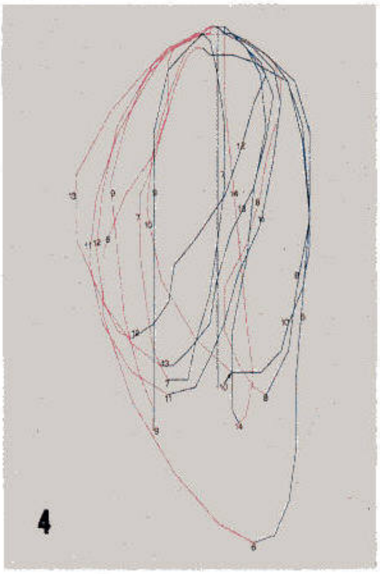
(Redux paste, Hewlett-Packard, Waltham, Mass.). The signals were bandwidth-limited (−3 dB down at 100 and 1000 Hz) and amplified with an EMG amplifier having an input impedance greater than 1000 MOhms.

Jaw movement

Chewing movements were recorded with a Sirognatograph (Siemens Inc., Erlangen, Germany), which records variations of a magnetic field induced by a magnet cemented at the lower central incisors. Details of







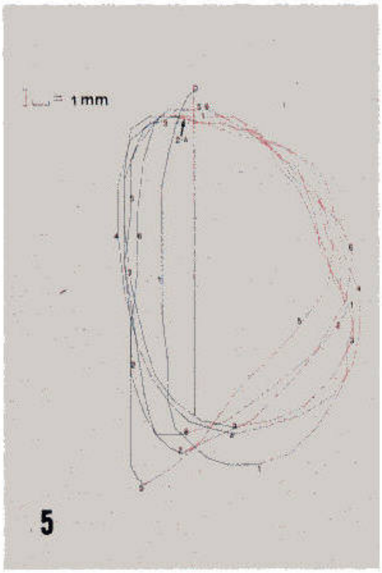


Fig. 2. Subject 2. Chewing movements versus time during a masticatory sequence. X (blue) = sagittal displacement; Y (green) = frontal displacement; Z (red) = vertical displacement. Note that in first four closing strokes, points of stoppage on vertical axis are approximately at same level. Zero line is reached after two more vertically extended cycles (5 and 6). Other more extended cycles occur with a certain rhythmicity.

Fig. 3. Subject 2. First five cycles of masticatory sequence recorded with plotter on frontal plane. Blue lines = opening; red lines = closing. Cycles 1 to 4 stop at almost same level vertically but at different locations of frontal plane. These cycles are all counterclockwise. Cycle 5 is more extended and shows a reverse pattern; it precedes a change of mastication side (Fig. 4).

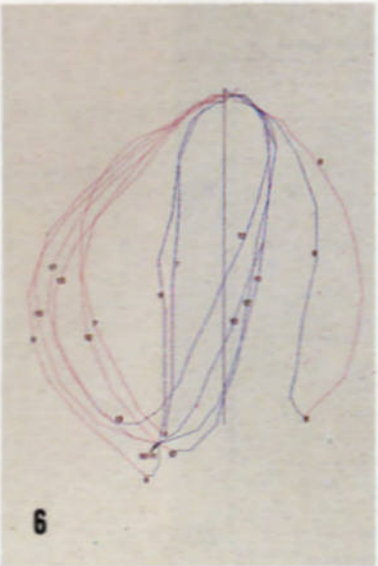
Fig. 4. Subject 2. Cycles 6 to 14. Most cycles are now clockwise and end in or close to ICP. Cycle 6 is well extended vertically.

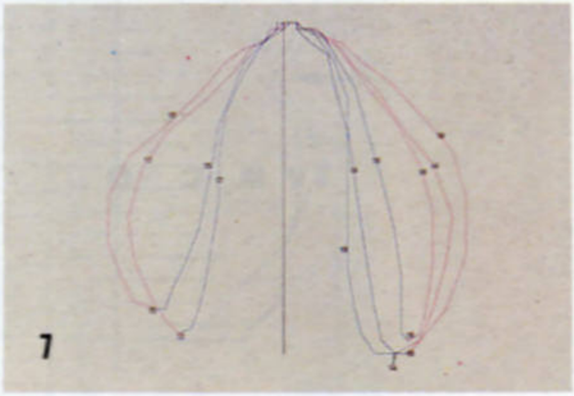
Fig. 5. Subject 5. Cycles 1 to 6 show a repetitive pattern with opening mostly parallel and close to midsagittal plane and closing concave and on opposite side. Movements are counterclockwise and stop at levels within 1 mm of each other on vertical axis.

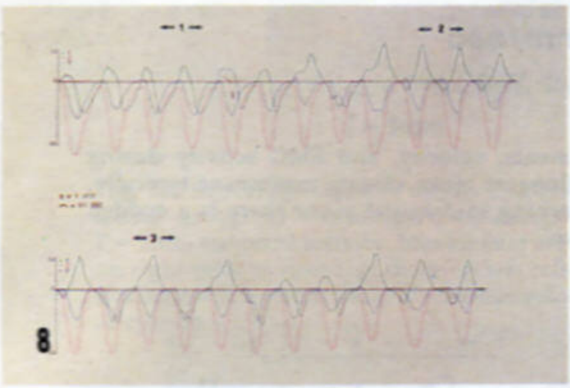
the recording system have been described in previous works.[19,20] The sensor carrying the headframe was centered according to the magnet and oriented to the Frankfort horizontal plane.

Data processing

Jaw movements were graphically recorded on the frontal and sagittal planes with an XY chart recorder (Easterline Angus, Indianapolis, Ind.). Signals from the







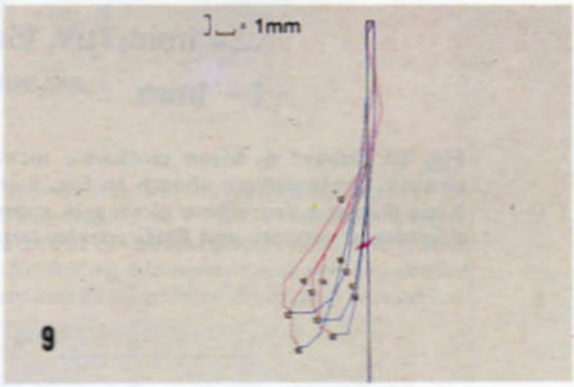


Fig. 6. Subject 5. Cycles 7 to 13 are clockwise (except for cycle 8) and stop close to ICP.

Fig. 7. Subject 5. Cycles 14 to 18 are alternating between left and right masticatory sides. Opening and closing of same cycle are on same masticatory side.

Fig. 8. Subject 5. Chewing movements versus time. Distribution of different envelopes of motion along masticatory sequence in this subject lead to a typical rhythm, characterized by three main patterns. Note also that at beginning of mastication, velocity is higher during opening than during closing.

Fig. 9. Subject 6. In middle of chewing sequence a group of droplike cycles alternate between left and right. Here cycles located on right masticatory side converge toward midsagittal plane in first half of movement and then run mainly vertical.

Sirognathograph recorder were sampled by the software every 20 msec at a rate of 50 Hz and EMG signals were sampled every 0.625 msec at a rate of 1.6 KHz.

Software provided the following data at 21 different degrees of jaw opening and closing from 0 to 20 mm: (1) number of times the movement occurred, (2) mean displacement on the frontal and sagittal planes, (3) velocity on the XYZ axis and actual velocity, and (4) mean EMG activity from the masseter and anterior temporal muscles. The mean values for each parameter were computed from values contained in each 1 mm area of vertical displacement. Additional information included (1) mean point of maximal opening and mean point of closing, (2) mean duration of opening, closing, and of the occlusal phase, and (3) the number of times the 0 level was reached. All data were computed separately for clockwise and counterclockwise chewing cycles with the selection made according to the direction of the closing movement. Numeric data were obtained through the printer while plotter tracings of mean movement, EMG activity, and velocity in space (frontal and sagittal planes) were also made. Mean EMG activity values versus time were also obtained. Finally, the mandibular displacement during single cycles in the last masticatory test could be graphically reproduced in space and versus time (displacement along the XYZ axis). The first two cycles of each chewing sequence were not included in the computation of mean data.

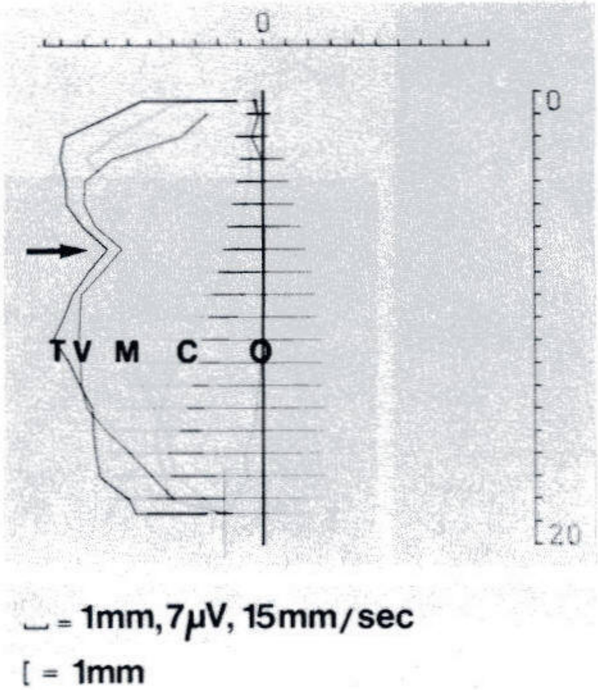


Fig. 10. Subject 6. Mean clockwise movements, velocity, and EMG activity during closing. Cycle pattern shown in Fig. 9 influences mean closing movement typically. Note that at point where closing is approaching midsagittal plane there is a sudden decrease of velocity and EMG activity *(arrow).*

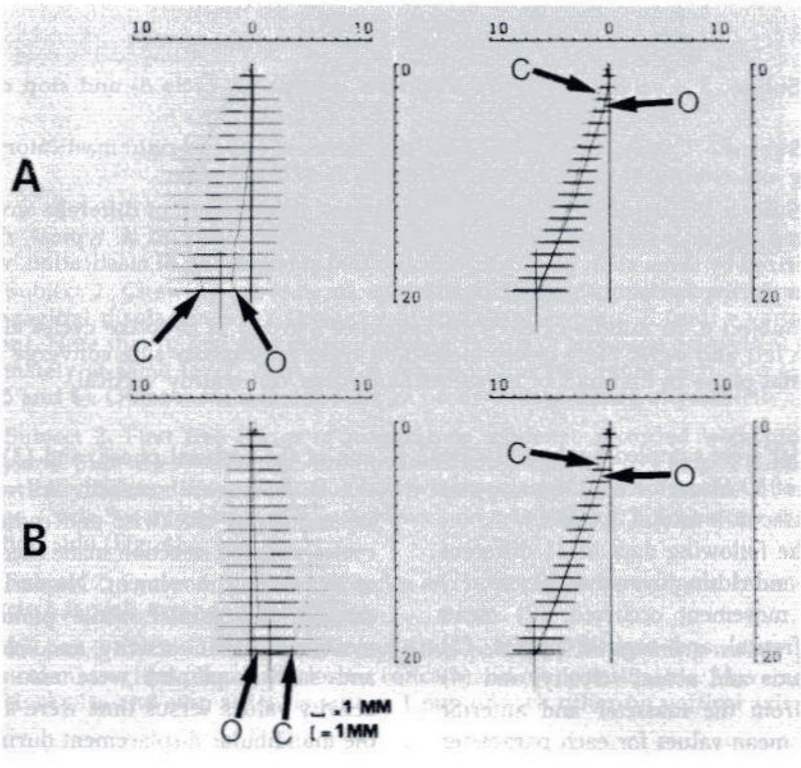


Fig. 11. Mean opening (O) and closing (C) for whole group on frontal (left) and sagittal (right) planes. *A* = clockwise cycles; *B* = counter-clockwise cycles; horizontal lines = SD. On frontal plane different pattern between opening and closing is evident. On sagittal plane mean opening is slightly ahead of mean closing.

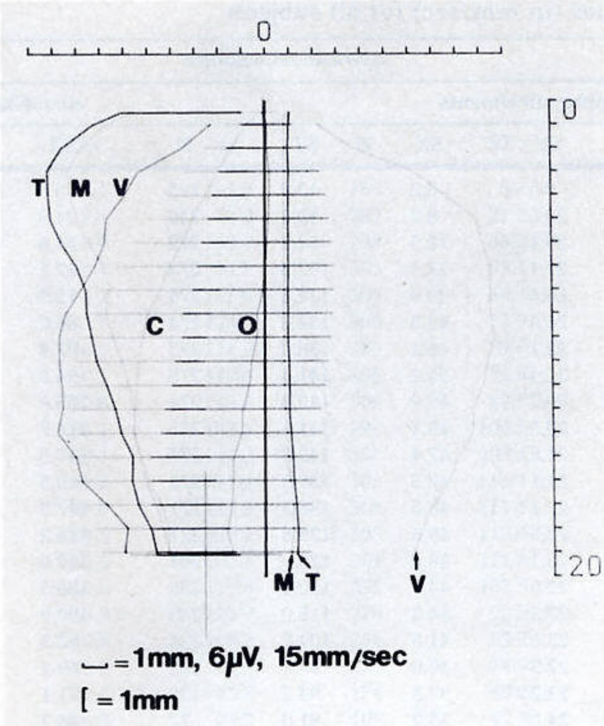


Fig. 12. Superimposition of mean clockwise movements, velocity, and EMG activity for whole group. *O* = opening; *C* = closing; *V* = velocity; *M* = EMG masseter activity; *T* = EMG temporal activity. Movements are recorded on frontal plane. V, M, and T lines on right refer to opening; those on left refer to closing. Movement and velocity during closing are somewhat parallel whereas velocity and EMG activity diverge in second half of closing.

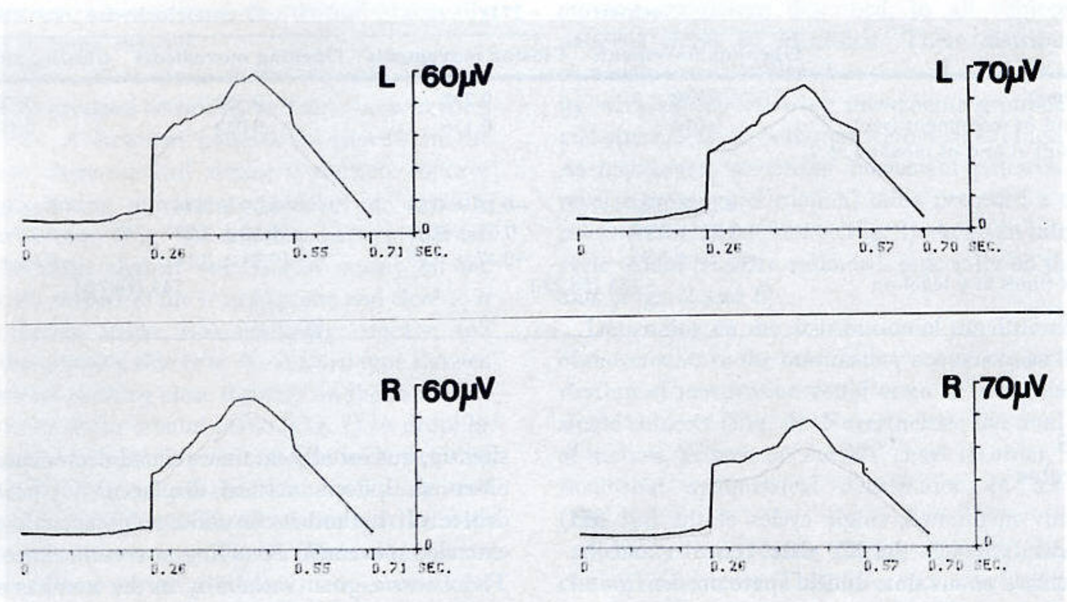


Fig. 13. EMG activity versus time for whole group. Black line = temporal muscle; grey line = masseter muscle. Mean duration of opening, opening plus closing, and full cycle is also given. *A* = clockwise cycles; *B* = counterclockwise cycles; *L* = left muscles; *R* = right muscles.

Table II. Mean velocity values (in mm/sec) for all subjects

	Clockwise									
	Opening movements					Closing movements				
LEV	N	SZ	SY	SX	ST	N	SZ	SY	SX	ST
0	182	7.1	9.5	5.2	13.0	195	5.8	9.4	3.9	11.7
1	232	24.2	20.6	8.7	33.0	245	24.9	20.8	10.9	34.3
2	268	44.7	29.1	13.3	54.9	272	41.6	27.1	17.3	52.6
3	272	84.3	29.1	24.5	92.5	274	67.2	35.0	26.2	80.2
4	274	103.8	26.6	33.9	112.4	274	75.9	39.4	24.8	89.0
5	274	122.9	24.0	43.0	132.4	274	86.0	44.0	26.1	100.0
6	274	125.9	22.1	46.4	136.0	275	87.9	43.2	25.7	101.3
7	274	130.4	21.4	50.2	141.4	275	94.5	41.8	28.4	107.2
8	274	130.0	20.7	49.9	140.8	274	103.6	41.7	31.6	116.1
9	273	131.4	20.5	48.4	141.5	273	114.7	35.1	36.9	125.5
10	272	133.9	21.8	47.4	143.7	272	119.5	33.1	39.2	130.0
11	273	129.1	21.1	47.5	139.3	272	119.5	29.5	41.5	129.9
12	271	125.4	22.1	48.5	136.3	271	117.5	29.7	42.2	128.4
13	269	117.9	22.8	48.6	129.5	271	116.2	30.2	41.9	127.2
14	259	118.3	23.1	48.4	129.9	261	119.0	32.5	42.5	130.5
15	256	109.1	22.9	44.9	120.2	258	106.5	37.3	39.3	119.5
16	240	103.5	23.3	44.2	115.0	243	100.9	39.9	39.4	115.4
17	225	93.1	23.6	41.6	104.7	224	82.3	44.0	35.3	99.7
18	190	86.2	22.3	40.0	97.6	190	69.4	41.1	31.2	86.5
19	133	82.2	23.2	37.3	93.2	139	71.1	43.3	29.3	88.3
20	83	68.9	24.0	35.2	81.0	77	46.2	41.1	27.2	67.5

SZ, SY, SX = velocity along th[illegible] coordinates; ST = actual velocity; other symbols as in Table I.

Table III. Mean dura[illegible] of opening and closi[illegible] nean pause, mean displacement along three coordinates at end of [illegible] ning and closing, an[illegible] nber of times 0 level on Z (vertical) axis was reached

	Clockwis[illegible] = 274)		Counterclockwise (N = 306)	
	Opening movements	Closing movements	Opening movements	Closing movements
Duration (sec)	0.250	0.292	0.251	0.310
Pause at end of movement (sec)	0.013	0.156	0.012	0.131
Displacement at end of movement (mm)				
X	−6.13 ± 2.67	−0.15 ± 0.55	−6.39 ± 2.44	−0.16 ± 0.57
Y	2.52 ± 3.19	0.06 ± 0.68	−1.60 ± 3.17	−0.37 ± 0.75
Z	−19.09 ± 3.53	−0.47 ± 0.65	−19.33 ± 3.14	−0.63 ± 0.85
Number of times at 0 level on vertical axis	154 (56.2%)		143 (46.7%)	

Values for all subjects.

RESULTS

Single cycles

As already mentioned, single cycles of the last test were examined through the XY chart recorder and the plotter tracings, versus time and in space on the frontal and sagittal planes (Figs. 1 to 9).

Despite the individual and interindividual cycle differences some similar characteristics were observed. Cycles at the beginning of mastication were, in most subjects, well extended on the vertical plane (>20 mm). In the subsequent cycles, vertical displacement decreased slightly, but usually no time-related decrement could be observed. Indeed, vertical displacement showed some degree of rhythmicity in most subjects with one more extended movement occurring at certain times (Fig. 2). There was a great variability in the number of strokes needed to reach ICP, with a minimum of two and a maximum of 13 (mean 7.75 ± 2.94 SD). Again, no gradual, time-related approach to ICP was evident. Instead, most subjects at the beginning of the chewing sequence stopped during several closing strokes at points that were close to each other on the Z axis (at 2 to 4 mm

Counterclockwise									
Opening movements					Closing movements				
N	SZ	SY	SX	ST	N	SZ	SY	SX	ST
175	7.6	9.8	5.5	13.5	189	5.7	9.0	4.7	11.6
248	24.4	20.6	8.1	32.9	249	21.2	19.8	9.0	30.3
296	42.7	28.0	13.9	53.0	298	36.2	24.0	15.1	46.0
303	85.9	28.3	28.1	94.7	303	55.1	26.3	19.8	64.2
305	102.9	26.4	34.2	111.6	305	64.3	29.5	22.6	74.3
306	118.8	22.8	42.7	128.3	306	73.9	34.0	25.5	85.2
306	127.1	21.2	46.6	137.0	306	79.8	36.0	25.0	91.0
306	132.2	20.6	50.1	142.8	306	85.5	36.8	26.3	96.7
306	130.6	20.0	50.8	141.6	306	89.9	34.4	27.8	100.2
306	131.2	19.8	51.1	142.1	306	103.5	31.9	30.9	112.6
306	133.9	18.6	50.1	144.2	306	109.4	29.8	33.6	118.3
305	131.3	18.7	48.8	141.4	306	111.4	28.0	37.5	120.8
304	125.4	18.0	49.0	135.9	304	111.1	29.1	38.9	121.2
303	119.1	17.7	48.1	129.7	303	112.6	30.1	40.8	123.5
301	115.1	17.9	45.5	125.1	301	111.8	32.1	41.7	123.6
290	109.5	17.6	44.8	119.6	295	102.5	34.7	41.6	115.9
275	101.7	17.4	43.3	111.9	279	98.5	39.6	41.1	113.8
250	95.4	18.0	40.5	105.2	256	83.2	44.7	37.7	101.7
217	85.5	19.6	38.8	95.9	220	74.9	45.8	34.7	94.4
171	75.5	22.4	32.6	85.3	174	65.2	48.5	29.9	86.6
120	68.7	26.7	29.0	79.2	107	42.3	49.4	27.6	70.7

from ICP), but could be variably located on the X and Y axes (Figs. 2 to 6).

The pause between one closing and opening increased gradually and was maximum when ICP was reached (Figs. 2 and 8). The pause between opening and closing within the same cycle was much shorter and practically nonexistant in some subjects.

The envelopes of motions shown by the different cycles could be grouped according to their characteristics (Figs. 4 to 9). A frequent pattern, as viewed on the frontal plane, demonstrated almost symmetric concave opening and closing movements running on opposite sides to each other (Fig. 4). Another pattern had an opening movement slightly curved and mostly on the same side with respect to the frontal plane and close to it while the closing stroke was markedly concave and located on the opposite side (Fig. 5). A third type showed both movements running close together on the same side or in the middle of the frontal plane (Fig. 7). A droplike pattern was also present in some subjects with a closing movement converging toward the midsagittal plane well before the point of stoppage. The latter was reached with an almost vertical movement (Fig. 9). The conversion of the movement (from curved to vertical) was concomitant with a decrease of velocity (Fig. 10). Finally, some cycles had a partially or totally reverse movement on one side with respect to midsagittal plane (with opening external to closing) that sometimes preceded a change in side of mastication (Fig. 3).

On the sagittal plane, cycles were more repetitive and mostly downward and backward. Closing strokes could be partly or totally located ahead of opening movements but, as mastication proceeded, they were tendentially located more posteriorly.

Although not every individual showed all of the movement patterns described, in all subjects several patterns could be identified. Their distribution was obviously not at random but showed a certain rhythmicity with similar chewing movements grouped together and alternating on both masticatory sides (Figs. 2 and 8). As mentioned, particular movement patterns (such as reverse envelope of motion) often preceded a change of sides within the sequence (Fig. 3). At given intervals one cycle would be more extended, especially on the vertical axis (Figs. 2 and 8).

Depending on the distribution of the different groups of movements in the masticatory sequence, an individual rhythm of mastication could often be recognized in the single subjects (Fig. 8). Nevertheless, the total envelope of motion, as seen on the XY chart recorder, showed a somewhat symmetrical distribution in all subjects (Fig. 1).

Velocity was higher during opening than during closing movements. This difference was well marked at the beginning of the chewing sequence and tended to decrease gradually and disappear as mastication proceeded (Figs. 2 and 8). During closure, a decrease in velocity was related to the contact with the bolus and the crushing activity at the beginning of the sequence. In other movements, a decrease in velocity was due to other

Table IV. Mean EMG activity (in μV) for all subjects

	Clockwise									
	Opening movements					Closing movements				
Level	N	LM	RM	LT	RT	N	LM	RM	LT	RT
0	182	5.4	5.9	6.2	6.4	195	27.2	28.0	33.7	30.1
1	232	4.6	4.7	5.2	5.9	245	39.0	40.2	46.2	43.6
2	268	5.0	4.9	5.0	5.7	272	45.9	46.6	54.5	51.6
3	272	4.9	5.0	5.2	5.9	274	48.6	50.1	59.0	55.2
4	274	4.8	4.9	5.1	5.8	274	49.4	49.2	56.6	55.0
5	274	4.6	4.8	5.0	5.8	274	47.6	47.6	56.1	54.4
6	274	4.6	4.8	5.1	5.7	275	45.8	44.5	52.2	51.6
7	274	4.9	5.0	5.3	5.8	275	41.7	40.8	47.9	47.8
8	274	4.9	4.9	5.3	5.7	274	39.6	39.2	47.2	45.4
9	273	4.7	4.7	5.2	5.8	273	39.5	40.2	46.5	45.1
10	272	4.7	4.7	5.2	5.7	272	38.9	38.4	45.9	43.8
11	273	4.9	4.9	5.6	6.1	272	37.7	36.2	44.6	42.6
12	271	4.8	5.0	5.9	6.2	271	37.3	34.5	43.6	40.0
13	269	5.1	5.3	6.2	6.1	271	36.2	32.9	42.5	37.9
14	259	5.2	5.7	7.3	6.6	261	36.9	33.2	42.8	36.3
15	256	5.2	6.0	8.2	7.1	258	35.7	31.2	40.4	33.4
16	240	5.6	6.3	7.9	7.3	243	35.7	29.4	41.0	33.7
17	225	6.1	7.2	8.8	7.9	224	33.5	26.3	38.7	32.1
18	190	6.4	7.0	9.3	8.3	190	29.5	24.4	35.3	28.9
19	133	7.2	6.5	8.9	7.9	139	30.0	24.3	35.5	27.6
20	83	9.2	7.6	9.7	8.5	77	28.5	21.1	32.3	26.0

LM = left masseter muscle; RM = right masseter muscle; LT = left temporal muscle; RT = right temporal muscle. Other symbols as in Table I.

factors such as a change in direction during the movement (Figs. 9 and 10).

A preferred side of mastication (i.e., with cycles on one side at least 30% more frequent than cycles on the other side) was found in five subjects. However, in only two of them were cycles on one side 40% more frequent than on the other side and none of them showed unilateral mastication.

There was a great intersubject variability in the amount of times level 0 was reached during the masticatory sequence. In the entire group, values were 154/274 (56%) for the clockwise cycles and 143/306 (47%) for the counterclockwise cycles.

Mean chewing movements

Statistically significant differences could be assessed between mean opening and closing movements both individually and in the whole group (Table I and Fig. 11). Mean openings ran prevalently close and parallel to the midsagittal plane and could be located on the same side as the closing stroke or partly on the opposite side. The closing stroke was curved with maximum displacement in the middle third of the movement. Here the movement was markedly variable (high SD values) whereas it became more repetitive when it approached ICP. On the sagittal plane, movements were more repetitive and posterior displacement increased gradually as the degree of jaw opening increased. Mean opening was usually slightly ahead of closing movement and an anterior component (i.e., more anterior than ICP) was rarely present and was limited to the initial phase of opening. In individuals with a preferred side of mastication the patterns described were more evident on that side. Individual characteristics of mean movements were often an obvious consequence of the distribution of the different patterns previously described for the single cycles within the masticatory sequence. Despite interindividual variations, data for the whole group confirmed the presence of some patterns that characterize normal mastication in man, as already observed in previous work (Fig. 11).[20]

Mean velocity values showed a typical distribution (Table II and Fig. 12). During opening a marked acceleration was present at the beginning whereas maximum values were reached in the middle third of the movement and were followed by gradual deceleration. During closing, maximum values were rapidly reached in the first half of the movement and a gradual decrease was present in the second half. The distribution of different cycle patterns in the whole masticatory sequence could influence the mean data characteristically (Figs. 9 and 10).

Velocity variations affected especially the vertical component of the movement. Velocity data on the Z axis showed a pattern that was almost superimposable on those of total velocity whereas data of velocity on the X and Y axis were distributed more linearly (Table II). Duration of mean opening was significantly shorter than of mean closing (Table III). Other parameters concerning the mean movement are reported in Table III.

Counterclockwise									
Opening movements					Closing movements				
N	LM	RM	LT	RT	N	LM	RM	LT	RT
175	5.4	4.1	6.0	6.3	189	25.0	19.9	26.7	25.0
248	4.5	4.2	5.0	5.2	249	36.7	28.9	42.1	35.4
296	4.2	3.7	4.3	5.0	298	42.4	34.7	47.4	40.3
303	4.4	3.6	4.5	4.9	303	49.8	40.2	58.3	49.9
305	4.3	3.6	4.7	5.0	305	52.5	41.5	62.2	54.2
306	4.1	3.6	4.6	4.9	306	51.9	41.7	60.2	52.2
306	4.2	3.5	4.6	5.1	306	49.3	39.7	59.1	51.0
306	4.2	3.7	4.7	5.1	306	46.7	37.4	55.8	47.5
306	4.2	3.7	4.7	5.0	306	45.2	33.6	51.8	43.1
306	4.3	3.5	4.8	5.0	306	43.8	33.2	50.1	42.0
306	4.3	3.6	5.2	5.1	306	41.9	32.3	48.8	41.4
305	4.3	3.7	5.3	5.1	306	39.9	30.6	44.9	40.2
304	4.5	3.9	5.6	5.4	304	39.3	29.8	44.6	39.9
303	4.7	4.0	5.9	5.7	303	37.9	29.2	42.5	38.5
301	4.9	4.2	6.4	5.8	301	36.7	28.7	40.6	37.0
290	5.0	4.6	6.9	6.1	295	34.8	28.3	39.0	36.1
275	5.2	4.9	7.1	6.4	279	34.2	28.2	38.0	36.7
250	5.8	5.1	7.8	7.1	256	33.9	28.4	37.4	36.7
217	6.2	5.2	7.9	7.2	220	34.0	27.8	35.2	36.2
171	7.5	6.2	9.6	8.9	174	33.2	27.1	33.4	35.1
120	7.8	5.3	9.2	8.1	107	31.7	22.9	29.2	27.7

During closing, data concerning velocity and mandibular movements were distributed similarly (Fig. 12).

Electromyography

During opening, the masseter and the temporal muscles obviously showed a low mean EMG activity. A slight increment could be observed for both in the final stage of opening (Table IV and Figs. 12 and 13). At closing, a spurt was often observed at the first level in which the data were computed (20 mm). This was partly an artifact because this level was a mean in which higher levels of jaw opening were also computed. As the closing movement proceeded, EMG masseter and temporal muscle values increased gradually to a peak of 3 to 4 mm from ICP. After that they gradually decreased; some consistent EMG activity was still present at the beginning of the pause between closing and the next opening and decreased to minimum values at the end of it (Table IV and Figs. 12 and 13). Individual differences involved the steepness and regularity of the incremental phase and the characteristics of the phase of decrement. The decremental phase showed a typical pattern in several subjects. After a sudden drop, the EMG value decreased more slowly or even increased again to a second peak that was followed by final decrement in both muscles (Fig. 14).

Examination of the plotter tracings of single cycles made clear that the point of sudden drop of mean EMG activity between the two peaks corresponded to the points of stoppages close to each other along the Z axis respectively reached by several subjects at the beginning of the chewing sequence (Figs. 2 and 3). The decrease of EMG activity to minimal values at these points accounted for the drop that was observed in the mean values for all cycles. This pattern might be observed in only one mean chewing movement (clockwise or counterclockwise) or in both, depending on the side of mastication of the cycles involved. Subjects reaching ICP at the beginning of the sequence did not show this pattern. Data distribution for masseter and temporal muscles was quite similar; although some subjects showed higher peak values on the side of mastication this did not significantly influence the data for the whole group. However, the increment of EMG activity during closure was steeper on the masticatory side in most subjects. (Fig. 13).

Comparison of EMG activity with velocity during closing showed a different pattern in the first half of the movement as opposed to the second half. In the first phase the two factors ran grossly parallel. In the second phase, however, they showed a typical dichotomy with velocity decreasing gradually well before the peak EMG activity was reached. At this point velocity values were already relatively low (40% less than maximum velocity in the whole group) (Fig. 12 and Tables II and V).

DISCUSSION

Mastication is considered a rhythmic event with timing that is generated in the reticular substance of the brain stem and can be modified by inputs from the central and peripheral nervous system.[21-23] In the study of oral motor behavior and its influencing mechanisms,

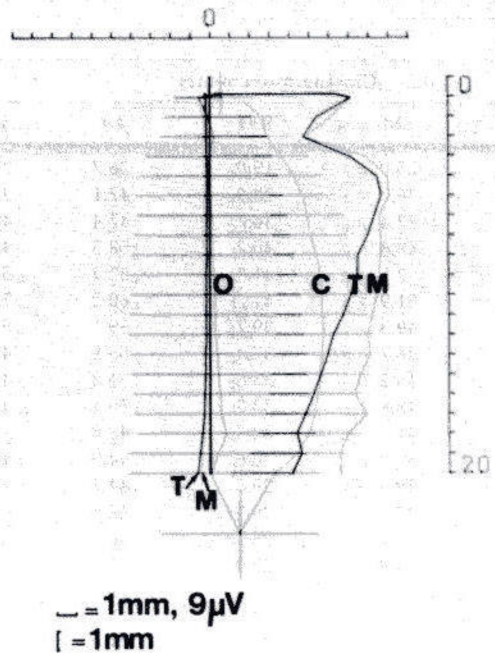


Fig. 14. Subject 2. Superimposition of mean counterclockwise movements and EMG activity. Note sudden decrease of mean EMG activity during closure at 3 mm from ICP resulting from initial pattern of chewing sequence (Figs. 2 and 3).

the assessment of habitual mastication is important because unilateral mastication involves a cortical input that might modify some of the parameters examined. For similar reasons we chose a common type of bolus that had to be swallowed after the chewing sequence was completed.

The data obtained in this study confirm the rhythmicity of mastication and the importance of peripheral input. As mentioned, most subjects exhibited points of stoppage close in the first chewing cycles to each other on the Z axis. This finding is not only the result of sheer mechanical factors (bolus resistance) because otherwise the points of stoppage would gradually approximate ICP at any given chewing cycle. This pattern is observed, for instance, when a subject chews a hard gum unilaterally.[24]

Stoppage occurred repetitively on the Z axis so that the consequent decrement of EMG activity at that level characteristically influenced the mean EMG pattern of the whole sequence at the same level. This factor might be viewed as a means of collecting sensory information for the CNS by testing the characteristics of the bolus at a given vertical level, but at different locations of the frontal and sagittal planes and according to different directions of approach. Similarly, the periodic occurrence of more extended or reverse chewing cycles might be involved with the reinforcement of sensory input or the change of the masticatory side. The mechanical factor seems to be of secondary importance in the variability of single cycles. Indeed, similar envelopes of motion could be observed at different stages of the chewing sequence.

It seems reasonable to assume that any given cycle accomplishes various tasks, such as positioning of the bolus, collection and reinforcement of sensory information, crushing the bolus, and change of the masticatory side. However, depending on the envelope of motion, different cycles might be more specifically oriented toward the performance of one or a few of these tasks. Thus, ample and repetitive movements with prevalently curved closing strokes are probably most effective in crushing the bolus and are present in groups, alternating with other envelopes of motions. Globally seen, the distribution of movements is rather symmetrical and well balanced in the whole region of function (Fig. 1).

The comparison of velocity data with those from mandibular displacement and EMG activity during closing of the jaw allows some further considerations. As mentioned, there seems to be a direct correlation between velocity and movement pattern. Maximum velocity corresponds or is close to the point of maximum lateral displacement, after which values decrease gradually as the mandible approaches the midsagittal plane. During the latter phase, EMG values increase bilaterally. The peak value corresponds to lower velocity values and to a mean mandibular position of approximately 3 to 4 mm from ICP on the vertical axis and close to the midsagittal plane (2 mm mean lateral displacement in the whole group) (Fig. 12). This seems to indicate the tendency to change gradually from a prevalently isotonic to a prevalently isometric type of muscle contraction, in correlation with the forces applied to crush the bolus and with the necessity of performing more refined movements in a position close to intercuspation. Indeed, here single movements were more repetitive (i.e., they had lower standard deviation values) (Table I).

SUMMARY AND CONCLUSIONS

A computer-based system to assess mandibular movements and EMG masseter and temporal muscle activity during habitual mastication was applied to 12 healthy subjects and the chewing performance was tested with a standardized bolus of crisp bread. A Siemens Sirognatograph instrument was used to record mandibular movements while EMG signals were recorded with surface silver-silver electrodes. Software provided data of single chewing cycles in space and versus time, of mean mandibular displacement during opening and closing, mean velocity, and EMG activity. Clockwise and counterclockwise cycles were computed separately. The data obtained allow the following conclusions:

1. Habitual mastication is a rhythmic event with

different envelopes of motion that alternate characteristically in each subject.

2. Each chewing cycle accomplishes several tasks but, depending on its envelope, is probably more oriented to a specific performance.

3. A mean chewing cycle can be constructed for each individual. Its pattern depends on the distribution of different envelopes of motion that alternate during the masticatory sequence.

4. During closure, a prevalently isotonic and a prevalently isometric phase of muscle contraction can be distinguished.

5. Mean movement and EMG data for the whole group are not distributed at random, but according to a typical pattern.

6. The system seems to be finalized to a well-balanced function and distribution of loads.

REFERENCES

1. Hickey JC, Allison ML, Woelfel JB, Boucher CO, Stacy RW: Mandibular movements in three dimensions. J PROSTHET DENT 13:72, 1963.
2. Ahlgren J: Mechanism of mastication. Acta Odontol Scand 24:(Suppl): 1966.
3. Modica R, Juliani G, Ragni G: Analisi roentgencinematografica dei movimenti masticatori nella normoocclusione ed in alcune disgnazie. Mondo Odontostomat 10:213, 1968.
4. Hedegard B, Lundberg M, Wictorin L: Masticatory function—A cineradiographic study. IV: Duration of the masticatory cycle. Acta Odontol Scand 28:859, 1970.
5. Gibbs CH, Messerman T, Reswick JB, Derda HJ: Functional movements of the mandible. J PROSTHET DENT 26:604, 1971.
6. Gillings BRD, Graham CH, Duckmanton NA: Jaw movements in young adult men during chewing. J PROSTHET DENT 29:616, 1973.
7. Jankelson B, Swain CW, Crane PP, Radke JC: Kinesiometric instrumentation: A new technology. J Am Dent Assoc 90:834, 1975.
8. Lemmer J, Lewin A, van Rensburg LB: The measurement of jaw movement. I. J PROSTHET DENT 36:211, 1976.
9. Lewin A, Lemmer J, van Rensburg LB: The measurement of jaw movement. II. J PROSTHET DENT 36:312, 1976.
10. Waysenson B, Salomon J: Three-dimensional recordings of envelopes of motion related to mandibular movements. J PROSTHET DENT 38:52, 1977.
11. Salomon JA, Waysenson BD: Computed-monitored radionuclide tracking of three-dimensional mandibular movements. J PROSTHET DENT 41:340, 1979.
12. Gibbs CH, Lundeen H: Jaw movements and forces during chewing and swallowing and their clinical significance. *In* Gibbs CH, Lundeen H, eds: Advances in Occlusion. Littleton, Mass., 1982 John Wright · PSC, 1982, p 2.
13. Møller E: The chewing apparatus. An electromyographic study of the action of the muscles of mastication and its correlation to facial morphology. Acta Physiol Scand 69(Suppl):280, 1966.
14. Møller E: Computer analysis of electromyographic data in clinical studies of oral function. Scand J Res 78:411, 1970.
15. Hannam AG, De Cou RE, Scott JD, Wood WW: The relationship between dental occlusion, muscle activity and associated jaw movement in man. Arch Oral Biol 22:25, 1977.
16. Hannam AG, Scott JD, De Cou RE: A computer-based system for the simultaneous measurement of muscles activity and jaw movement during mastication in man. Arch Oral Biol 22:17, 1977.
17. Hannam AG, Inster WC, De Cou RE, Scott JD: Speed of jaw movement during mastication and clenching tasks in man. J Dent Res 56:442, 1977.
18. Stohler GS, Ash MM: Demonstration of chewing motor disorder by recording peripheral correlate of mastication. J Oral Rehabil 12:49, 1985.
19. Mongini F, Fabris E, Tempia-Valenta G: A computerized system to study masticatory function. J Craniomandib Pract 2:225, 1984.
20. Mongini F, Tempia-Valenta G: A graphic and statistical analysis of the chewing movements in function and dysfunction. J Craniomandib Pract 2:125, 1984.
21. Kawamura Y: Neurogenesis of mastication. *In* Kawamura Y, ed: Physiology of Mastication. Basel, Karger, 1974, p 77.
22. Hannam AG: Mastication in man. *In* Bryant P, Gale E, Ruth J, eds: Oral Motor Behaviour. NIH Publication No. 79:1745, 1979, p 87.
23. Sessle BJ: Mastication in man: Comments and critique. *In* Bryant P, Gale E, Ruth J, eds: Oral Motor Behaviour. NIH Publication No. 79:1745, 1979, p 128.
24. Lewin A: Electrognathographics. Chicago, 1985, Quintessence, p 47.

Reprint request to:
DR. FRANCO MONGINI
CLINICA ODONTOSTOMATOLOGICA DELL'UNIVERSITÀ
CORSO POLONIA 14–10126
TORINO, ITALY