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Journal of Phonetics (1981) 9, 175–188

Electromyographic study of the jaw muscles during speech

Betty Tuller
Cornell University Medical College, New York, NY, U.S.A.
and Haskins Laboratories, New Haven, CO 06510, *U.S.A.*

Katherine S. Harris
The Graduate School, The City University of New York, NY, U.S.A.;
and Haskins Laboratories, New Haven, CO 06510, *U.S.A.*

and

Bob Gross
Louisiana State University, The Medical Center, New Orleans, LO 70112, *U.S.A.*

Received 16*th August* 1979

Abstract: An investigation of the role of the mandibular muscles during the production of speech is reported here. Electromyographic (EMG) recordings from superficial and deep masseter, anterior and posterior temporalis, medial pterygoid, superior and inferior lateral pterygoid, and the anterior belly of the digastric muscles were obtained for four speakers of American English. For one of the speakers, mandibular movement was monitored simultaneously with the EMG recordings using a modified thyroumbrometer (Ewan & Krones, 1974). The subjects read lists of nonsense words containing the vowels /a/, /i/ and /u/ in VCV combination with the consonants /p/, /t/, /k/ and /f/. The results indicate that the traditional classification of masseter, temporalis and medial pterygoid as jaw elevators, and lateral pterygoid and anterior belly of digastric as jaw depressors is not adequate for describing control of the jaw in speech.

Introduction

One focus of current speech research has been the spatial and temporal coordination among articulators, particularly compensation to perturbed (Folkins & Abbs, 1975) or restricted movement of a given articulator (Lindblom, Lubker & Gay, 1979; Gay & Turvey, 1979) or to a change in the shape of an articulator (Hamlet & Stone, 1976, 1978). The jaw lends itself to studies of this kind in that it is intimately involved with other articulators, particularly the lips and tongue, yet is accessible to experimental manipulation.

In the study of interarticulator coordination, analysis of simultaneous movement and electromyographic information should result in a more complete understanding of articulatory control than that allowed by either source alone. However, attempts to execute such experiments are hampered by the ambiguity of existing evidence as to the muscles responsible for movement of the mandible during speech. The assumption that muscles that effect mandibular movement during chewing have similar speech functions may be incorrect.

0095–4470/81/020175 + 14 $02.00/0

The chewing cycle must minimally be viewed as consisting of lowering, raising, and occlusal phases. The jaw muscles undergo isotonic contraction during lowering and raising of the mandible, but during the final part of the raising phase, muscular contraction gradually changes from isotonic to isometric (Dubner, Sessle & Storey, 1978). Isometric contraction during occlusion allows for the development of tension necessary to crush and grind food. In contrast, during speech gestures, the jaw muscles rarely, if ever, undergo isometric contraction with the concomitant development of tension. Moreover, there is evidence that the lowering and raising phases of the masticatory cycle have a different mandibular trajectory from jaw lowering and raising during speech (Gibbs & Messerman, 1972). For example, the lateral excursions evident in chewing are largely absent from speech movements, and the vertical lowering of the jaw in chewing is typically two to four times greater than the vertical lowering of the jaw in speech.

The latter difference between speech and chewing gestures is particularly intriguing in light of the complex nature of the temporomandibular joint (Sarnat, 1964; Sicher & DuBrul, 1970). The temporomandibular joint has two compartments, an upper one in which the condyles undergo translation, and a lower one in which the condyles rotate on a hinge axis so that lowering and raising the mandible is not effected by a simple hinge movement of the mandibular condyles. Lowering the mandible combines initial forward translation of the condyles with subsequent rotation. In other words, in lowering the jaw the mandibular condyles move forward and rotate downward. Raising the jaw is a reversal of the lowering gesture such that the condyles rotate upward, then translate backward. Insofar as both the magnitude of jaw lowering and the degree of condylar rotation are smaller for speaking than chewing, the two events imply different relationships between the muscular determinants of condylar translation and rotation. Muscles active during mandibular gestures that are not normal components of speech (e.g. clenches, extreme retrusions and hinge openings) cannot be assumed to function during speech.

Speech and non-speech may also differ with respect to the average speed of jaw movement; jaw movements that are speech gestures are typically faster than non-speech jaw movements. The speed of movement required for an articulator is functionally related to the contraction time of the motor units within the relevant muscles. Contraction time (the time from initiation of the twitch to peak tension) has been measured in at least three jaw-raising muscles – medial pterygoid (MacNeilage, Sussman, Westbury & Powers, 1979), masseter and temporalis (Yemm, 1977). Mean contraction time of medial pterygoid is approximately one-half the mean contraction time of masseter and temporalis. If the different contraction times reflect different speeds of movement required of the muscles, then speech and non-speech gestures may be effected by different sets of muscles. Specifically, the longer contraction times of masseter and temporalis would be suited to non-speech movements, whereas the shorter contraction time of medial pterygoid would be more suited to speech gestures.

The muscles believed to effect non-masticatory mandibular movements (other than speech) are as follows.

Muscle descriptions

Masseter is a thick, powerful muscle that runs from the zygomatic bone to the mandible. It has a superficial portion in which the fibers run down and back to the angle of the mandible, and a deep portion in which the fibers are more nearly vertical. It is generally accepted that masseter elevates and clenches the jaw (Ahlgren, 1966; Møller, 1966, 1974; Woelfel, Hickey, Stacy & Rinear, 1960). Superficial masseter also acts to protrude the jaw whereas deep masseter acts to retrude the jaw.

Temporalis is a large, fan-shaped muscle that runs from the lateral surface of the cranium to the coronoid process and ramus of the mandible. The fibers of the anterior portion run almost vertically; hence, their line of pull acts to elevate the mandible. The posterior portion of temporalis runs horizontally forward to the anterior edge of the root of the zygoma. The fibers then bend downward and attach to the mandibular notch. Posterior temporalis elevates and retrudes the jaw and moves it laterally.

Medial (internal) pterygoid runs parallel to the masseter but is deep to the mandible. Together, masseter (particularly the superficial portion) and medial pterygoid form a sling around the angle of the mandible, pulling upward and forward, providing a mechanism for powerful elevation and clenching of the jaw.

Lateral (external) pterygoid is composed of two partially discrete portions, both of which run from the outer surface of the lateral pterygoid plate to the neck of the mandible. The fibers of the superior portion run horizontally, whereas the fibers of the inferior portion run in a forward and upward direction. Lateral pterygoid appears to act during mandibular protrusion. Electromyographic activity has also been recorded in this muscle during both depression and elevation of the mandible. Hickey, Stacy and Rinear (1957), Møller (1966) and Woelfel *et al.* (1960) found lateral pterygoid to be active during jaw lowering, whereas Carlsöo (1956), Hickey *et al.* (1957), Møller (1966) and Griffin & Munro (1969) recorded lateral pterygoid activity during jaw elevation. Recent evidence has suggested that the inferior and superior heads of lateral pterygoid function independently (Grant, 1973; McNamara, 1973); activity was evident in the superior head during jaw raising but not lowering or protrusion, whereas the inferior head was active during jaw lowering and protrusion but not raising.

The anterior belly of digastric (ABD) runs from the deep surface of the body of the mandible to the hyoid bone. It is generally referred to as a depressor of the mandible, although it may also function to stabilize the hyoid bone. It is maximally active when lowering the jaw against resistance (Griffin & Malor, 1974).

Mandibular muscles shown to be involved in chewing and large temporomandibular movements have been, in the past, studied in experiments involving speech gestures. For example, Sussman, MacNeilage & Hanson (1973) used electromyography (EMG) to study labial-mandibular control and coordination in speech. They recorded EMG activity from masseter, medial pterygoid, and anterior belly of digastric muscles but found only the digastric to be active for speech gestures. Neither masseter nor medial pterygoid could be consistently related to jaw movement. Folkins & Abbs (1975) also monitored EMG activity in masseter and medial pterygoid, as well as in anterior temporalis. In contrast with Sussman *et al.* (1973), Folkins and Abbs found that medial pterygoid was indeed consistently related to jaw movement in speech, although masseter and anterior temporalis were not. More recently, Folkins, Zimmerman & Cooper (1978) did find low levels of speech-related activity in masseter and temporalis. Medial and lateral pterygoid were active at higher levels although lateral pterygoid activity was not related to jaw movement in a consistent fashion.

Without more precise information as to which muscles function to control the mandible during normal speech gestures, it is impossible to obtain an accurate account of the coordination of the jaw with other articulators, or articulatory compensation to restricted or perturbed movement. Accordingly, the experiment reported here examined the functional role of certain mandibular muscles during the production of a small inventory of speech gestures. As an example of how these data may be used, we also examined the effect of different phonetic environments on muscle activity for a given speech gesture; these data will be reported separately.

Method

EMG recordings were collected using bipolar hooked-wire electrodes of the type described by Hirose (1971). During insertion of the electrodes the subject was in a slightly reclined position and breathed nitrous oxide to reduce discomfort. Detailed descriptions of electrode placement and insertion techniques may be found in Ahlgren (1966) and Gross & Lipke (1979). Verification of electrode placement used those non-speech maneuvers for which each muscles role is well established (Ahlgren, 1966; Carlsöo, 1952, 1956; Møller, 1966, 1974; Moyers, 1950).

Masseter. Activity from the superficial and deep portions was recorded separately. Placement of the electrodes in the superficial portion was verified by its activity during protrusion of the mandible and clenching. Placement in the deep portion was verified by its activity during clenching of the mandible.

Temporalis. EMG activity was recorded separately from anterior and posterior temporalis. Electrode placement in the anterior portion was verified by activity in the muscle during elevation, but not retrusion, of the mandible. Electrode placement in the posterior position was verified by its activity during retrusion of the mandible.

Medial (internal) pterygoid. Placement was verified by activity during elevation and clenching of the mandible.

Lateral (external) pterygoid. Activity from the two heads was recorded separately. Electrode placement in the superior head was verified by its strong activity during clenching but not protrusion of the mandible. Placement of the electrode in the inferior head was verified by its activity during protrusion of the mandible.

The anterior belly of the digastric (ABD). Verification of electrode placement was achieved by its activity during large-excursion jaw lowering, particularly against resistance.

The EMG potentials were recorded onto magnetic tape, rectified, subsequently soft-ware integrated with a time constant of 35 ms, and averaged using the Haskins Laboratories EMG system described by Kewley-Port (1973, 1974).

The subjects were three adult females and one adult male. Three of the four subjects were naive as to the purpose of the experiment. Subjects BE and CC have Class I occlusions, following Angle's classification of the forms of occlusion (Kerr, Ash & Millard, 1978), showing a normal relationship between maxillary and mandibular dentition. Subject BT has a Class II occlusion with the mandible in a posterior relationship to the maxilla. Subject VR has a Class III occlusion, in which the mandible is protruded relative to its normal relationship with the maxilla.

Jaw displacement in the vertical and horizontal dimensions was measured for subject CC, simultaneously with the recording of EMG potentials using a modified version of the thryoumbrometer (Ewan & Krones, 1974). This device consists of an array of photocells and a PDP 11/34 computer. An inflexible pointer that had been custom-made for the subject was extended from her lower teeth. A d.c. light source cast the shadow of the pointer onto the photocells of the thyroumbrometer. The vertical and horizontal position of the jaw was computed from the photocell voltages. The computer output voltage was a staircase function, each step change indicating a 0.5 mm change in vertical jaw position; horizontal jaw position could not be measured to the same degree of accuracy. The jaw displacement signal and the EMG potentials were recorded simultaneously onto separate channels of an FM data recorder.

The speech utterances were four-syllable nonsense words of the form /əkV$_1$CV$_2$pə/. In all cases, either V$_1$ or V$_2$ was /a/ whereas the other vowel varied among the set /a, i, u/. The consonant (C) was either /p/, /t/, /k/ or /f/. The 20 utterance types were randomly ordered and repeated six times at a comfortable speaking rate. Subjects were instructed to produce the second and third syllables of the utterance with equal stress, with the first and last syllables unstressed. The end of periodicity in the acoustic signal of the first vowel (V$_1$) was the point chosen for aligning tokens for averaging, and is represented by the zero point on the abscissa in the figures.

One year and ten months after the original EMG recording session, subject VR repeated the experiment with electrode insertions into the anterior belly of the digastric, medial pterygoid and both heads of lateral pterygoid. The original 20 utterance types were randomly ordered and repeated 12 times at a comfortable speaking rate. All other instructions were identical to the first recording session and EMG data from both sessions were processed in identical fashion.

Results

The patterns of EMG activity will be presented separately for non-speech maneuvers, speech gestures specific to phonetic segments, and coarticulation. Within these divisions, the pattern of activity of each muscle will be discussed. The magnitude of the speech-related activity was assessed as a per cent value of the maximum level of activity achieved during non-speech gestures.

Non-speech maneuvers

Deep and superficial masseter functioned independently for all subjects. Deep masseter was always active during retrusion and clenching of the mandible. Subject CC used deep masseter to elevate the jaw from extremely low positions. In contrast, superficial masseter was active during protrusion and clenching of the mandible for all subjects, and during elevation of the mandible for three subjects (BT, CC, VR).

Anterior temporalis was active for all subjects during mandibular elevation and clenching. Posterior temporalis was active for all subjects during mandibular retrusion and clenching.

Medial pterygoid was consistently active for clenching, elevation and protrusion of the mandible. For two subjects (BE, CC) medial pterygoid also functioned during retrusion of the jaw.

Superior head of lateral pterygoid was active during jaw elevation and clenches for three (BE, BT, VR).

Inferior head or lateral pterygoid was active during mandibular protrusion and depression for all subjects. For two subjects (BE, VR) this muscle showed low levels of activity during mandibular retrusion.

Anterior belly of the digastric acted during large-excursion lowering and retrusion of the jaw for all subjects, and during protrusion of the jaw for subjects BE, CC, and VR.

These results are in general agreement with the investigations of activity in mandibular muscles during chewing and large temporomandibular movements (cf. Gross & Lipke, 1979), and imply that electrode placements did not change significantly between the time of verification and actual experimental maneuvers. In a later section, the levels of activity recorded during the non-speech gestures will be compared with the levels of activity recorded during speech.

Speech gestures

Jaw displacement. Measurements of mandibular displacement during speech were obtained for subject CC; no non-speech maneuvers were performed. As noted above, the accuracy of the system for monitoring jaw movement in the horizontal plane is significantly less than the accuracy of monitoring vertical movement. Consequently, the measurements were sufficient to detect systematic movement patterns in the vertical, but not horizontal, dimension.

In vowel production, vertical mandibular positions were lowest for /a/ and highest for /u/. During the onset of consonant constriction the mandible was highest for /t/ and /f/, slightly lower for /p/ and lowest for /k/. Electromyographic differences were examined to determine whether they reflect the differences in vertical jaw displacement. For this subject, the level of activity in the most consistently active jaw depressor (inferior head of lateral pterygoid) was directly related to the amount of mandibular lowering required for production of the vowel (Fig. 1). Activity in the jaw elevator (medial pterygoid) did not change systematically as a function of mandibular height required for a given consonant. Activity was greatest when moving from the lowest jaw position, that is from the vowel /a/, to the following consonant, regardless of the identity of the consonant. EMG recordings from all subjects were examined to determine which muscles were responsible for the jaw movements during speech.

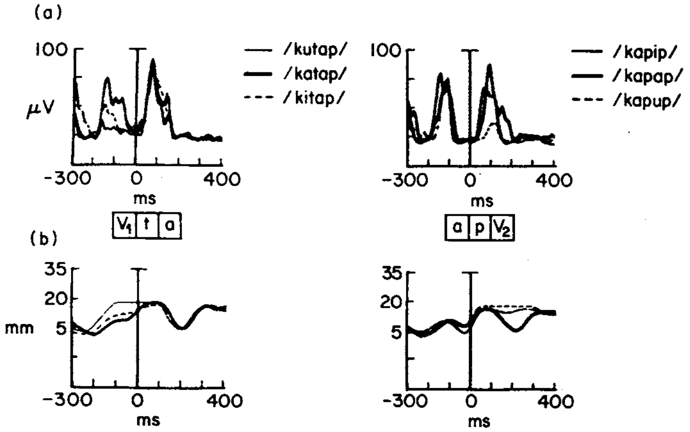

Figure 1 **(a) Averaged EMG activity of the inferior head of the lateral pterygoid muscle. (b) Vertical mandibular movement for subject CC.**

EMG results. The EMG patterns during speech gestures are distinct from the patterns associated with non-speech maneuvers. Deep and superficial masseter, and anterior and posterior temporalis were never active in a manner consistently related to jaw movement during speech, even when non-speech activity in these muscles was substantial. The four remaining muscles generally showed consistent activity during speech gestures, medial pterygoid and superior lateral pterygoid associated with raising the jaw, inferior lateral pterygoid and anterior belly of digastric lowering the jaw.

Table I presents muscle activity for speech gestures expressed as a percentage of the same muscle's non-speech maximum. It should be noted that the individual differences are very large. To assess whether these individual differences are a function of varying electrode

Table I **Muscle activity for speech gestures as a percentage of each muscle's non-speech maximum**

		Muscle			
Subject	Vowel	Medial pterygoid	Lateral pterygoid (superior)	Lateral pterygoid (inferior)	ABD
BE	/a/	–	178	26	53
	/i/	–	154	15	30
	/u/	–	130	15	30
BT	/a/	40	35	100	–
	/i/	21	10	100	–
	/u/	17	9	41	–
CC	/a/	21	*	89	36
	/i/	21	*	79	37
	/u/	17	*	72	9
VR (1)	/a/	130	61	0	184
	/i/	84	54	69	141
	/u/	78	56	102	126
VR (2)	/a/	45	69	31	63
	/i/	41	61	22	34
	/u/	37	58	21	32

For the jaw-raising muscles, values represent activity recorded when the jaw moved from the vowel indicated to the following consonant. For the jaw-lowering muscles, values represent activity recorded when moving from the consonant constriction to the following vowel. –, activity not specific to the gesture; *, bad electrode insertion.

placements, we repeated the experiment with subject VR. From Table I, it is apparent that the ratio of muscle activity for speech and non-speech gestures differed from those observed during the first experimental session. However, the pattern of activity among speech gestures was basically consistent from session to session. The pattern of activity across sessions changed only for the inferior head of lateral pterygoid. In the first recording session, activity in this muscle was distributed among the vowel articulations in a pattern different from that occurring for all other subjects. In the second session, the pattern of activity in the inferior head of lateral pterygoid was similar to the pattern for all other subjects. Thus, in the data analyses presented below, the absolute values of muscle activity are not crucial and are likely to change across recording sessions. What appears to be consistent is the pattern of muscle activity distributed among speech gestures.

The level of muscle activity for speech gestures was generally highest either when raising the jaw from the open vowel /a/ to the following consonant constriction or when lowering the jaw from the consonant constriction to the open position for /a/. In order to clarify presentation of the results, the levels of activity reported below represent these maximal movements. For levels of activity corresponding to jaw movements to and from /i/ and /u/ refer to Table I.

Medial pterygoid activity associated with speech gestures was observed for three speakers. Data for one of these three speakers are presented in Fig. 2. Medial pterygoid activity associated with elevating the jaw from its position for /a/ reached 21% (subject CC) and 40% (subject BT) of the maximum activity for non-speech elevation of the jaw and clenching the teeth. In contrast, for subject VR peak medial pterygoid activity associated with moving from /a/ to the following consonant constriction reached 130%

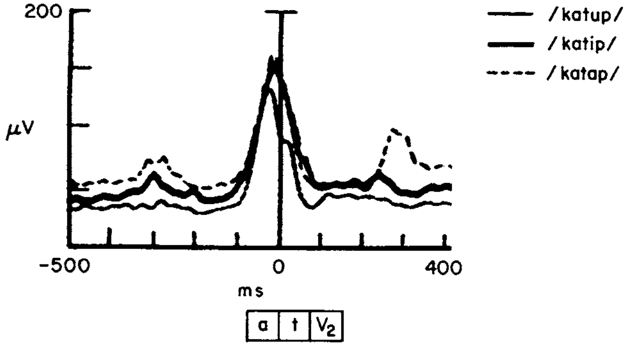

Figure 2 Averaged EMG activity of the medial pterygoid muscle for subject BT.

of its non-speech maximum activity. Thus, there was no consistent relationship between the maximum activity for speech and non-speech gestures.

The superior head of lateral pterygoid was active during elevation of the mandible for three speakers. Figure 3 presents these data for one subject, in μV. When viewed in relation to maximum activity in the superior head of lateral pterygoid during the non-speech gestures of elevating and clenching the mandible, peak activity for moving from /a/ to the following consonant constriction reached 178%, 35%, and 61% for speakers BE, BT, and VR, respectively. The relationship between activity in superior lateral pterygoid during speech and non-speech shows no consistent pattern across speakers.

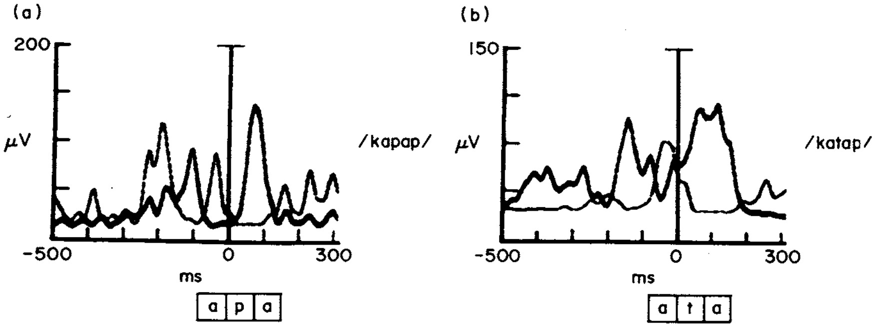

Figure 3 Averaged EMG activity of the superior and inferior heads of the lateral pterygoid muscle for (a) subject BE and (b) subject BT. ——, superior head; ——, inferior head.

The inferior head of lateral pterygoid was active for the production of the vowels, presumably to lower the mandible (Fig. 3). This activity was also examined in relation to the maximum activity achieved during non-speech gestures. For subject BE, peak activity in the inferior head of lateral pterygoid when lowering the jaw to /a/ was only 26% of the non-speech maximum level. For subject BT, peak inferior lateral pterygoid activity associated with speech and non-speech gestures were identical: peak activity for /a/ was 100% of the maximum achieved for mandibular protrusion. For subject CC, peak activity in the inferior head of lateral pterygoid reached 89% of the non-speech maximum level. Again, the relationship of muscle activity in speech and non-speech gestures is inconsistent across speakers.

The pattern of activity in inferior lateral pterygoid is distributed differently among the vowel articulations of subject VR in that the level of activity is near base line for production of /a/ but high for production of /i/ and /u/. The only case in which the inferior head of lateral pterygoid was active for production of a consonant was for the production of /f/ by subject VR, possibly reflecting a protrusive component of the elevating gesture.

Activity in the anterior belly of the digastric (ABD) was seen during speech in only three of the four speakers. One speaker's data are presented in Fig. 4. The maximum level of activity in ABD was associated with jaw lowering for production of the open vowel /a/. The magnitude of the muscle activity was assessed as a per cent of the maximum activity recorded in ABD during non-speech gestures, in this case large-excursion lowering of the mandible. For subject BE, peak ABD activity achieved for production of /a/ reached 53% of the maximum activity of ABD for non-speech jaw lowering. For subject CC, maximum ABD activity during speech was 36% of the maximum activity during non-speech gestures. In contrast, for subject VR peak ABD activity associated with the production of /a/ was 184% of the maximum activity in ABD during non-speech lowering of the jaw.

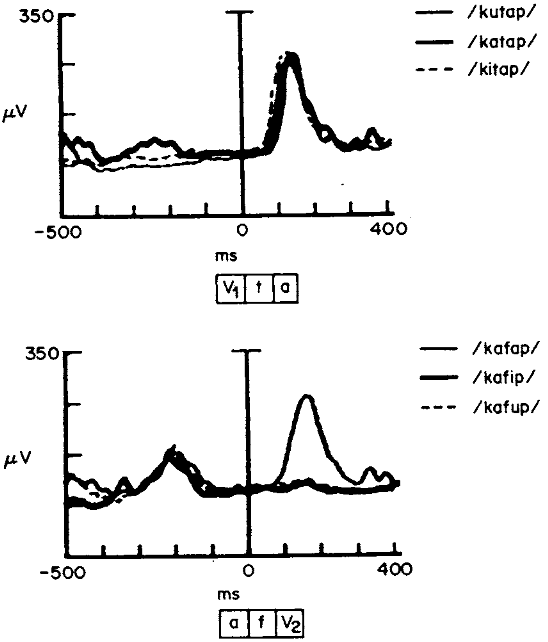

Figure 4 Averaged EMG activity for the anterior belly of the digastric muscle for subject VR.

The basic pattern that emerges is that medial pterygoid and superior lateral pterygoid act in relation to raising the jaw, whereas inferior lateral pterygoid and anterior belly of the digastric function to lower the jaw. Note that for each subject the two heads of lateral pterygoid functioned as two separate muscles: the inferior head was active during jaw lowering, the superior head during jaw elevation. The superior head of lateral pterygoid has been thought to stabilize the mandibular condyles, particularly when the upper and lower teeth are in contact. When speakers produce the speech sample used in this study it is likely that the teeth are rarely, if ever, in contact. However, consistent superior lateral pterygoid activity occurred in relation to the gesture of jaw elevation. Thus, superior lateral pterygoid has an elevating function during speech rather than the stabilizing function normally ascribed to it. The activity patterns of the inferior and superior heads were basically reciprocal and within each subject were patterned differently for each vowel gesture.

Coarticulation – results and discussion

The data reported here may also be used to examine coarticulatory effects on mandibular displacement and its underlying muscle activity. Mandibular displacement for the consonant was examined in relation to both the preceding and following vowels (Figs 5 and 6). Production of /f/ and /t/ was insensitive to changes in V_1 or V_2. The position of the mandible for /p/ showed no anticipation of V_2 but varied with changes in V_1. Mandibular displacement for /k/ showed both carryover and anticipatory effects of the preceding ($t = 3.81, P < 0.05$) and following ($t = 7.70, P < 0.01$) vowels.

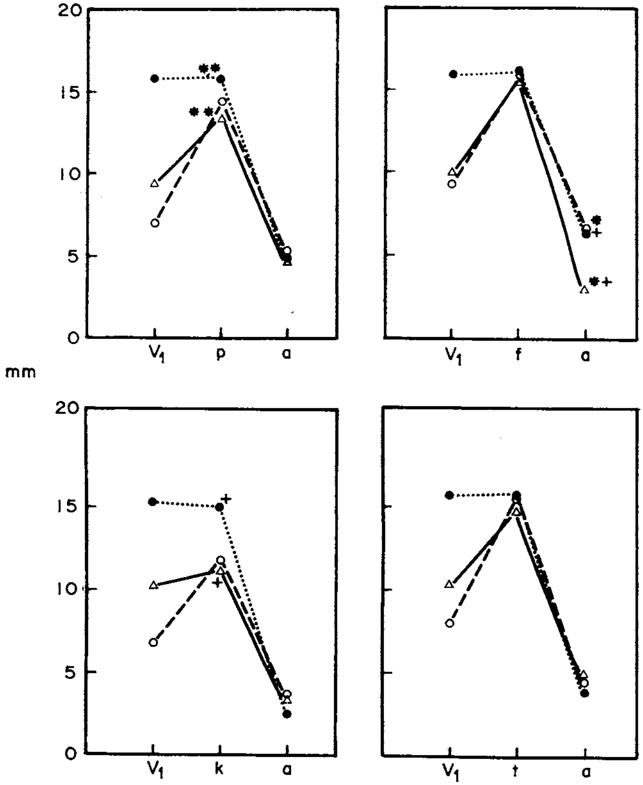

Figure 5 Vertical movement of the mandible is represented (in mm) for subject CC. Movement curves were averaged over V_1, holding C and V_2 constant. /a/, ○ – – – ○; /i/, △ —— △; /u/, ● · · · · ●. **, $P < 0.001$; *, $P < 0.01$; †, $P < 0.05$.

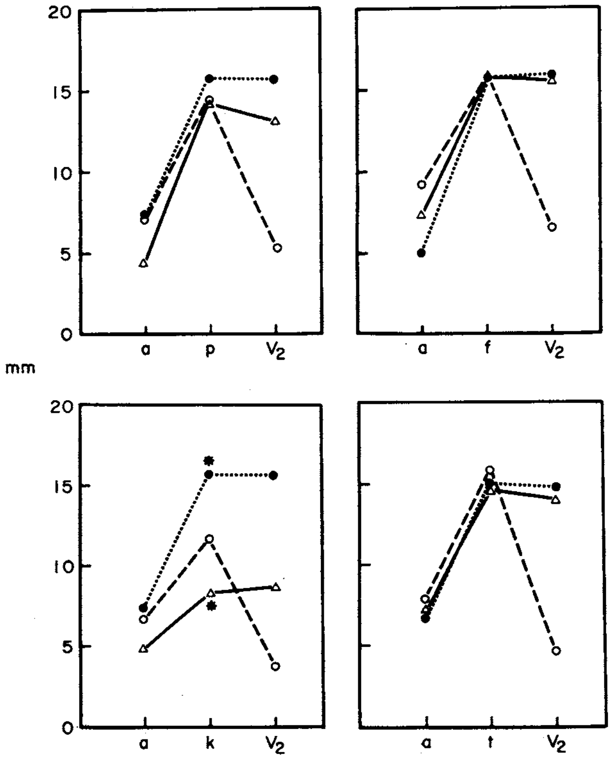

Figure 6 Vertical movement of the mandible for subject CC. Curves represent averages pooled over V_2, holding C and V_1 constant. /a/, ○ – – – ○; /i/, △ —— △; /u/, ● · · · · ●; *, $P < 0.01$.

Variations in mandibular height during vowel production were examined as a function of the intervocalic consonant. In no case was mandibular position for V_1 effected by changes in the following consonant; that is, there was no evidence of anticipatory changes in mandibular height (Fig. 7). Jaw position for V_2 was examined as a function of the preceding consonant. In symmetrical utterances /aCa/ jaw position for V_2 was significantly affected by the consonant ($t = 5.64, P < 0.01$), resulting in mandibular height for the vowel of the order /ka/, /ta/, /pa/, /fa/ (lowest to highest; Fig. 7). These carryover effects of the consonant on V_2 were also evident in mandibular displacement for /aCi/ (/ki/ > /pi/ > /ti/ > /fi/, $t = 10.14, P < 0.001$), and /uCa/ (/ka/ > /pa/ > /ta/ > /fa/, $t = 4.86, P < 0.01$; Fig. 7). Utterances of the form /aCu/ and /iCa/ showed no carryover effect of C on V_2. Again, in no case were anticipatory effects evident.

Jaw position during vowel production was examined as to whether it was effected by the other vowel in the sequence (Figs 5 and 6). In all cases, jaw position for V_1 never anticipated V_2. Jaw position for V_2 showed carryover effects of V_1 only when the intervocalic consonant was /f/. However, the changes in jaw position were complex and, unlike the results reported by Gay (1974), do not simply reflect or invert jaw height for V_1. For all other intervocalic consonants, jaw position for V_2 was insensitive to jaw position for V_1.

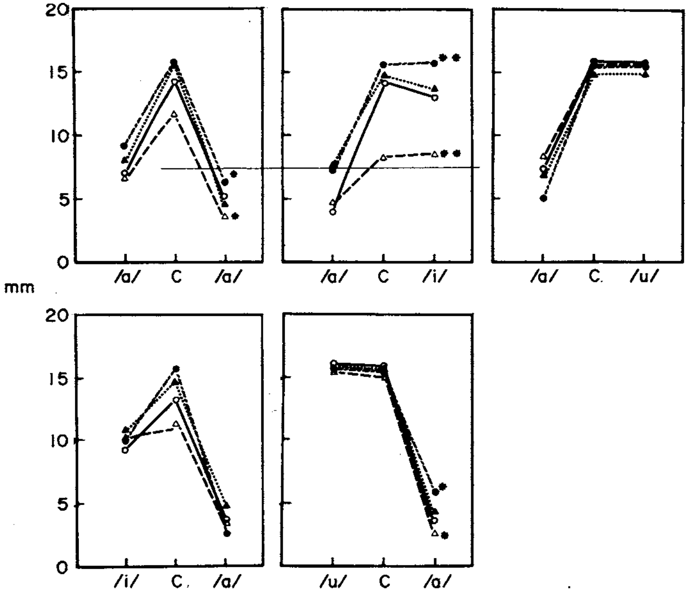

Figure 7 Movement of the mandible in the vertical dimension for subject CC. Curves are pooled over consonants, holding V_1 and V_2 constant. p, ○ —— ○; f, ● – – – ●; k, △ – – – △; t, △ · · · · △. **, $P < 0.001$, *, $P < 0.01$.

The EMG activity was examined for vowel-to-vowel coarticulatory effects. For those muscles which showed consistent EMG activity in speech there was no carryover effect of V_1 on V_2 or anticipatory effect of V_2 on V_1 (see Figs 1, 2 and 4).

In sum, although the trajectory of the mandible during the speech utterances used in this study are in basic agreement with those noted by Perkell (1969) and Gay (1974), less coarticulatory influence was evident than found by Gay (1974). We extended Öhman's (1966) hypothesis of vowel-to-vowel coarticulation by suggesting that EMG activity and the resulting jaw displacement for any given vowel might be dependent on the other vowel in a VCV sequence. However, neither EMG activity related to jaw lowering for V_1 nor jaw position achieved for V_1 was observed to anticipate V_2. EMG activity related to V_2 was not affected by V_1: actual jaw position for V_2 was sensitive to V_1 only when the intervocalic consonant was /f/.

General discussion

The data reported here support the traditional classification of masseter, temporalis and medial pterygoid as jaw elevators, and the anterior belly of digastric and inferior lateral pterygoid as jaw depressors, for the performance of non-speech maneuvers. However, this classification does not apply when the activity concerned is speech. No consistent relationship was found between mandibular movement for the speech sounds used in this study and activity of anterior or posterior temporalis, or superficial or deep masseter. However, superficial masseter may be associated with production of phonetic segments for which the jaw is assumed to be in a more protruded position than those examined here (e.g. s, sh). (Ewan, pers. comm.; Sussman *et al.*, 1973; Tuller, Harris & Gross, unpublished data).

For the limited inventory of speech gestures reported here, medial pterygoid and superior lateral pterygoid are active during jaw elevation while inferior lateral pterygoid and anterior belly of the digastric act during jaw depression. The functional differentiation of inferior and superior lateral pterygoid for both speech and non-speech gestures agrees well with the data obtained by Grant (1973) and McNamara (1973). The inferior lateral pterygoid functions during lowering of the jaw whereas the superior lateral pterygoid functions during raising of the jaw.

Notable, however, are the many individual differences among speakers, differences not consistent across speech and non-speech gestures. Although this variability may reflect structural differences among speakers, Angle's method of classifying mandibular occlusion does not allow one to predict the pattern of EMG activity in the jaw muscles. Differences in the structure of the temporomandibular joint and/or the angle and placement of muscle attachments may also increase the variability in muscle activity across speakers. Given the complex nature of the temporomandibular joint, the "jaw lowering gesture" in different speakers may consist of different relative amounts of condylar translation and rotation, resulting in different EMG patterns across speakers. Moreover, the relationship between speech and non-speech is not fixed; in these data the vertical displacement for a maximally lowered jaw did not bear a fixed relation to the lowest mandibular position that occurred when the person was speaking.

In conclusion, investigators have recognized the need for simultaneous recording of different types of information when studying labial-mandibular or lingual-mandibular coordination, during normal or disrupted speech. One source of information is the muscle activity underlying mandibular movement. This study suggests that when studying muscle activity related to jaw raising during speech, the investigator should monitor medial pterygoid and superior lateral pterygoid. The study of electromyographic activity during jaw lowering in speech gestures should include inferior lateral pterygoid and anterior belly of the digastric. The pattern of muscle activity during speech may illuminate the nature of speech motor control, but only if the monitored muscles are indeed those directly relevant to the movement.

This work was supported by NINCDS grants NS-13617, NS-13870 and BRS grant RR-05596 to the Haskins Laboratories. We wish to thank T. Baer, T. Gay, W. Ewan, K. Kirchmeier and S. Josell for making equipment and facilities available to us and ensuring that all ran smoothly, and F. Bell-Berti for comments on an earlier version of this paper.

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