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Similarities in the Control of the Speech Articulators and the Limbs: Kinematics of Tongue Dorsum Movement in Speech

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The kinematics of tongue dorsum movements in speech were studied with pulsed ultrasound to assess similarities in the voluntary control of the speech articulators and the limbs. The stimuli were consonant–vowel syllables in which speech rate and stress were varied. The kinematic patterns for tongue dorsum movements were comparable to those observed in the rapid movement of the arms and hands. The maximum velocity of tongue dorsum raising and lowering was correlated with the extent of the gesture. The slope of the relationship differed for stressed and unstressed vowels but was unaffected by differences in speech rate. At each stress level the correlation between displacement and peak velocity was accompanied by a relatively constant interval from the initiation of the movement to the point of maximum velocity. The data are discussed with reference to systems that can be described with second-order differential equations. The increase in the slope of the displacement/peak-velocity relationship for unstressed versus stressed vowels is suggestive of a tonic increase in articulator stiffness. Variations in displacement are attributed to the level of phasic activity in the muscles producing the gesture.

A basic question in movement control is whether similar principles can account for both the action of muscles about a single joint and the more complex movements of speech. Similar patterns have been found to characterize the timing of cyclical movements of limb and facial muscles in locomotion and mastication (see Grillner, 1981, and Luschei & Goldberg, 1981, for reviews), and some parallels between cyclical movements and speech have been described (Folkins, 1982; Fowler, 1977; Kelso, Tuller, & Harris, 1981; Tuller, Kelso, & Harris, 1982). A further set of parallels can also be identified between the kinematic patterns of speech and limb movements. In this article we present some similarities and differences between single joint movements and the movements of the speech articulators in terms of the kinematics of tongue dorsum movements during the production of sequences that vary in speech rate and stress.

In voluntary anisometric contractions of the muscles of the hands and arms in humans, movements of greater amplitude have been found to have greater peak velocities (Cooke, 1980; Freund & Büdingen, 1978; Hallett & Marsden, 1979). In addition, in rapid elbow and finger flexions the interval from movement initiation to the point of maximum velocity appears to be independent of differences in movement extent. Freund and Büdingen (1978), Ghez and Vicario (1978a), and Ghez (1979) reported relatively constant intervals from movement onset to the point of peak velocity for maximally rapid movements of differing extent, though Lestienne (1979) observed that peak velocity occurs earlier in time for high-speed movements when distance is held constant.

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A correlation between the velocity and extent of the movement has also been reported for a variety of consonant–vowel (CV) and vowel–consonant (VC) gestures in speech involving displacements of the tongue dorsum, tongue tip, lips, and jaw (Abbs, 1973; Kent & Moll, 1972a, 1972b; Kent & Netsell, 1971; Kozhevnikov & Chistovich, 1965; Kuehn & Moll, 1976; Perkell, 1969; Stone, 1981; Sussman, MacNeilage, & Hanson, 1973). There may also be a constant interval from movement onset to the point of peak velocity. Lofqvist and Yoshioka (1981) reported that the interval from vowel offset to peak velocity of glottal abduction is essentially constant for a variety of VC transitions involving voiceless stops and fricatives in Japanese and Swedish; in Icelandic, peak abduction velocity has been found to occur later for stops than for fricatives.

Parallels in the control of the speech articulators and the limbs should be reflected in the similarity of their kinematic patterns. A single articulator should show a correlation between displacement and peak velocity, and as in limb movements, the time from movement onset to peak velocity should be independent of differences in movement extent. Although kinematic parallels in themselves are not likely to resolve the issue of similarities in the control of speech and limb movements, the particular kinematic patterns that are observed may aid in the identification of common principles of control. Our present approach has been to interpret kinematic data obtained from both speech and limb movements relative to models of the biomechanics of the limb (cf. Cooke, 1980; Feldman, 1980a, 1980b). Parameters of the biomechanical model (e.g., viscosity, stiffness, zero-length) and physiological counterparts (e.g., the tonic recruitment threshold of motor units, their gradient of recruitment, and firing frequencies) might thus provide a basis for kinematic similarity in speech and limb behavior.

The identification of variables, which are controlled in either speech or limb movements, can be aided by examining factors that affect the relationship between displacement and maximum velocity. Cooke (1980), for example, has shown that the slope of the relationship between displacement and maximum velocity changes with the speed of the movement. The variation is consistent with the view that increases in movement speed are produced by increases in the overall stiffness of the limb musculature. Feldman (1980a, 1980b) has suggested that such changes in stiffness are brought about by changes in zero-lengths, that is, by controlling the joint angle or muscle length at which the tonic recruitment of motor units in agonist and antagonist muscles begins.

The commonality between speech and limb movements should extend to variables that are unique to the different motor tasks. In speech movements, relationships between displacement and peak velocity should be preserved in the manipulation of variables such as rate and stress. These variables provide a particularly appropriate test of the similarity between speech and limb control as there have been several reports that rate and stress affect articulator displacements and velocities in different ways. With increases in stress, subjects consistently increase both displacement and peak velocity of jaw opening (Tuller, Harris, & Kelso, Note 1). Peak amplitude and duration of vowel-related electromyographic (EMG) activity have also been shown to increase with stress (Tuller, Harris, & Kelso, 1982). With rate changes, on the other hand, displacements and velocities are not necessarily linked, as speakers appear to change rate in different ways (Kuehn & Moll, 1976; Tuller et al., Note 1). With increases in speaking rate, there have been reported reductions in articulator displacement with velocity unchanged (Kent & Moll, 1972a) or increased (Gay, 1981), increases in peak velocity with displacement unchanged (Abbs, 1973), and reductions in both displacement and velocity (Kent & Moll, 1972a).

In the present study, pulsed ultrasound is used to monitor tongue dorsum movements during the production of sequences in which speech rate and stress are varied orthogonally (see Keller & Ostry, 1983, for a discussion of the use of pulsed ultrasound for the study of tongue movements in speech). Relationships between articulator displacement, maximum velocity, and the time from movement initiation to maximum velocity are examined in terms of patterns in the raw data. Trial-to-trial variation among movements was ex-

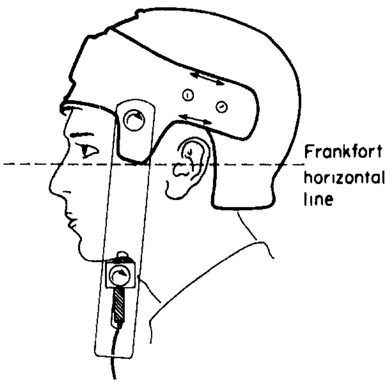

Figure 1. Placement of the ultrasound transducer for the measurement of vertical movements of the tongue dorsum in the back cavity. (The harness, a modified athletic helmet, maintains the transducer at a constant distance from the cranium. The transducer is held in position by a horizontal Plexiglas bar attached to two vertical Plexiglas beams. The orientation of the transducer in the median plane is determined by rotation to a position appropriate to the measurement of posterior linguo-palatal constrictions [see text].)

amined rather than differences between conditions to enable direct comparisons to similarly treated limb movement data. This also reflected the view that an adequate model of speech control has to account for kinematic relationships on a within-condition basis.

Method

Subjects

Three native speakers of Canadian English participated in the experiment. One of the subjects, R. F., was also a fluent second-language speaker of Quebec French.

Apparatus and Data Acquisition

Tongue dorsum movements and the acoustic speech signal were recorded simultaneously by using a computerized pulsed-ultrasound system (for a full description, see Keller & Ostry, 1983).

The tongue dorsum position was monitored at a 1-kHz rate with a Picker model 104 A-scan Ultrasonoscope and a single 3.5-MHz pulsed-echo ultrasound transducer. The ultrasound signals passed from the transducer placed beneath the chin through the skin and muscular tissue of the tongue body and were reflected in proportion to changes in acoustic impedance, with the amplitude of the reflection corresponding to differences in tissue density along the signal path (see McDicken, 1981, for a review of ultrasound technology).

A timing circuit measured the interval between the emission of the ultrasound burst and the reception of the large amplitude echo corresponding to the boundary between the muscular tissue of the tongue and the air in the oral cavity. The position of the tongue dorsum was estimated by assuming an average speed of ultrasound in human skeletal muscle of 1,540 m/sec (Goss, Johnston, & Dunn, 1978). The resolution of the system was assessed by taking repeated ultrasound measurements of a 6-cm block of Plexiglas. The standard deviation, of 10 samples of 3,455 observations each, averaged .58 mm. Samples that are recorded for analysis purposes, based on about 35 observations each, thus include a standard error due to system resolution of approximately .10 mm.

The measured distance of the tongue dorsum from the transducer crystal and a concurrent speech sample, obtained through a 12-bit analog-to-digital converter, were stored by a Cromemco CS-2 microcomputer. Individual trials lasted 3.455 sec each.

Transducer Placement

The pulsed-ultrasound transducer was placed externally along the inferior midline of the mandible just anterior to the hyoid bone. The position and orientation of the transducer were maintained during testing by means of an adjustable head harness, which held the transducer at a constant distance from the cranium (see Figure 1). Once the transducer was secured for recording, its anterior–posterior movement was negligible. The apparatus has no significant effect on the extent of vertical jaw movements (Keller & Ostry, 1983).

According to a standard placement procedure, the orientation of the transducer in the median plane was determined by rotating the probe to a position that both maximized the measured displacement of the tongue dorsum from the position for /k/ to the position for /a/ and maintained the traditional order of back vowel heights, /u, o, a/, in the tongue dorsum measurement. The transducer was aligned laterally with the axis connecting the nasion to the gnathion.

These placement criteria could usually be satisfied by orienting the transducer at about 90° to the Frankfort horizontal line, a maxillary reference line connecting the lowest point of the inferior margin of the orbit to the upper margin of the external auditory meatus (Zemlin, 1981, p. 388). The Frankfort horizontal is approximately parallel to the line formed by joining the anterior and posterior nasal spines.

In contrast to X-ray measurements, the estimates of tongue dorsum position that are obtained with this procedure correspond to distances along the axis of the ultrasound beam rather than to spatial coordinates of tissue points in the oral cavity. Accordingly, the terms *displacement* and *velocity* are used here to refer to positions and rates of change along the measurement axis, not to individual tissue points. It is nevertheless possible to interpret tongue dorsum displacements in a maxillary reference frame if the stimuli are restricted to consonants and vowels that are articulated primarily in the posterior oral cavity (Keller & Ostry, 1983).

Data Analysis

The analysis of the ultrasound data involved a pooling of measurements of tongue dorsum position and the application of natural cubic spline functions to the averaged values (de Boor, 1978). This was accomplished by dividing the duration of a trial into 45-msec intervals and averaging the measurements in each interval to provide knots for a spline-fitting program. Keller and Ostry (1983) reported that with interval midpoints, or knots, separated by 45 msec or less, the average absolute difference between the cubic spline and the raw data was about .03 cm/measurement. Tongue dorsum velocities were calculated by differentiating the functions that were fit to the original position or displacement data. Numerical values for points in the displacement, velocity, and acoustic records were obtained by using a computer-assisted measuring program in which the user positioned a cursor at a desired location on a record presented simultaneously on the computer screen and in a numerical readout.

Stimuli

The stimuli were CV pairs, involving velar stop-consonants /k/ and /g/ combined with back vowels /a/ and /o/. The sequences were produced at fast and slow speech rates, either with alternate vowels stressed or with all vowels equally stressed. Speech rate, stress, vowel, and consonant were combined orthogonally. Back vowels and consonants were selected for the study because of the ease of ultrasound recording in this region of the oral cavity.

It should be noted that articulatory movements for these stimuli are not restricted to tongue dorsum movement even though all segments are articulated in the back cavity. For example, in the /ka/ articulatory movement, /a/ entails pharyngeal constriction that is accomplished partially by jaw lowering and partially by moving the tongue backwards and down from the velum.

Procedure

The experiment was divided into blocks of 16 trials with each of the 16 stimulus combinations (2 [consonants] × 2 [vowels] × 2 [speech rates] × 2 [stress patterns]) recorded once in each block. Each trial consisted of the repeated production of a single CV pair at one of the two speech rates in either the equal-stress or the alternate-stress condition. The subject was able to produce about three to five repetitions of a stimulus on each trial. The order of trials in each block was balanced according to a Williams square to eliminate first-order carry-over effects (Cochran & Cox, 1957). The transducer was positioned at the beginning of each block, and the placement was verified according to the criteria previously described. The transducer was not subsequently moved during a block of trials.

A total of 12 blocks of trials (with about 3 to 5 observations per trial) was recorded for each subject over a 3 day period. In the scoring of the data, recorded tokens were excluded from analysis if (a) either voicing or oral release was not clearly distinguishable in the acoustical record or if (b) multiple peaks in the displacement record made it difficult to identify the points of initiation or termination of a gesture. Although a detailed record of the incidence of rejections was not kept, the overall rate was low and relatively uniformly distributed across conditions. The results reported below are based on about 35 CV tokens from each subject for each of the 16 different stimulus sequences.

Results

The kinematics of tongue dorsum movement were assessed with respect to differences in speech rate, stress, voicing, and vowel height. Correlational analyses were used to study relationships between the kinematic variables. All tests were conducted on a within-subjects basis.

Some general features of tongue dorsum movement in speech are shown in Figure 2, which is an ultrasound record of the position and velocity of the tongue dorsum and the acoustic speech signal during the repeated production of /kaká/ at a moderate speech rate with alternate vowels stressed. The upper peaks of the displacement tracing correspond to the position of the tongue dorsum during oral closure. The points at the bottom of the tracing give the position of the tongue dorsum for the back vowel /a/. The numerical values for tongue dorsum position correspond to the distance in centimeters from the crystal of the ultrasound transducer to the dorsum of the tongue. Values for velocity are given in cm/sec.

It can be seen that pulsed ultrasound estimates of tongue dorsum displacement and peak velocity are consistent with values obtained with X-ray techniques (cf. Kent & Moll, 1969, 1972a; Kuehn & Moll, 1976; Perkell, 1969). Several prominent kinematic features can also be identified. The stressed vowels involve greater displacements and have greater peak velocities than the unstressed vowels. Thus, as reported previously, when speech gestures differ in extent, the displacement observed for both raising and lowering movements is correlated with its peak velocity (Abbs, 1973; Kent & Moll, 1972a, 1972b; Kent & Netsell, 1971; Kozhevnikov & Chistovich, 1965; Kuehn & Moll, 1976; Perkell, 1969; Sussman et al., 1973).

A second feature is the close temporal correspondence between the maximum tongue-dorsum-lowering velocity and the onset of voicing in English. For unstressed vowels, peak-lowering velocity coincides approximately with oral release, as measured acoustically, whereas for stressed vowels, peak-low-

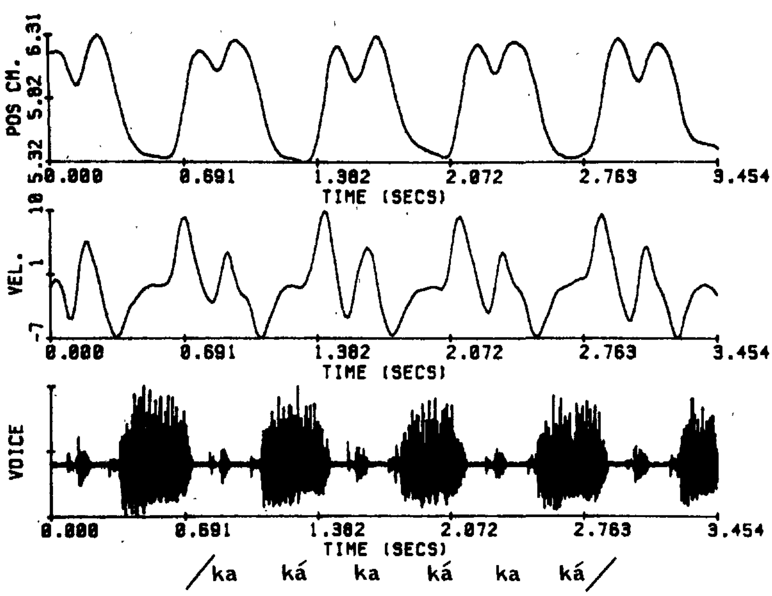

Figure 2. Top: Ultrasound record of displacement of tongue dorsum during repetitions of /kaká/, shown at a bandwidth of 11.5 Hz. (The upper peaks correspond to the position of the tongue dorsum for linguopalatal closure; points at the bottom of the tracing give the position of the tongue dorsum for the back vowel /a/. Values on the ordinate correspond to the distance in centimeters from the crystal of the ultrasound transducer to the dorsum of the tongue.) Middle: Velocity (Vel.) record showing the rate of tongue dorsum raising (positive values) and lowering (negative values). Bottom: Corresponding acoustic record. (Unstressed vowels are shown as the smaller of the two types of signal.) Subject: Male native speaker of English.

ering velocity occurs somewhat later, at about the time of voice onset. Abbs (1973) reported a similar correspondence between voicing and peak velocity, noting that peak-jaw-lowering velocity was synchronized with the onset of voicing, and peak-raising velocity with its termination.

The inequalities that are observed in the peaks of the position trace are presumably due to trial-to-trial differences in the trajectory of the tongue dorsum combined with measurement variation due to the compression of lingual tissue against the palate. Transmission of ultrasound into the palatal tissue is not likely to contribute to the inequalities, as the saliva on the tongue produces a readily detectable change in acoustic impedance. Because differences in the peaks of the position trace are not systematically related to differences between conditions, variation attributable to them can be viewed as measurement error.

Tongue Dorsum Kinematics

The phenomena described here were studied in detail by measuring individual tokens in the manner shown in Figure 3. Each lowering and raising gesture was measured for total displacement, duration, and peak velocity. There were also several measures that divided the gesture into components preceding and following peak velocity. Voice-onset time was likewise divided with respect to peak velocity, with an initial component specifying the time from oral release to maximum tongue-lowering velocity (shown as A in Figure 3), and a final part, the time from maximum tongue-lowering velocity to voice onset (B in Figure 3). Displacement and duration estimates were calculated by assuming that points of zero velocity marked the initiation and termination of the gesture.

The effects of speech rate, stress, vowel, and consonant on the duration, extent, and maximum velocity of tongue dorsum gestures were assessed by analysis of variance. The vowel was found to affect both tongue dorsum displacement and peak velocity, with all subjects having greater average displacements for /a/ than for /o/. The observed displacement for /a/ (averaged over subjects, speech rate, and stress) was .71 cm; the displacement for /o/ was .61 cm (maxillary reference). Average peak velocity for /a/ was 7.52 cm/sec and for /o/, 6.87 cm/sec. Differences in both displacement and peak velocity were reliable: for displacement (subjects D.O., K.M., and R.F.), $F(1, 1486) = 139.09$, $p < .01$, $F(1, 1620) = 722.61$, $p < .01$, and $F(1, 1294) = 110.01$, $p < .01$, respectively; for peak velocity (subjects D.O., K.M., and R.F.), $F(1, 1486) = 223.0$, $p < .01$, $F(1, 1620) = 548.47$, $p < .01$, and $F(1, 1294) = 28.79$, $p < .01$, respectively. (Degrees of freedom for the error term are based on within-cell variation.) In contrast, movement duration was not dependent on vowel height. The average duration of both /a/ and /o/ was 180 msec (Fs < 1, for all subjects). The similarity of movement durations for different vowel heights is consistent with previous reports (Kent & Moll, 1969; Kuehn & Moll, 1976).

Reliable interactions were observed between the vowel and stress level. The difference between /a/ and /o/, in both displacement and peak velocity, was greater when /a/ and /o/ were stressed rather than unstressed. Average displacements for /a/ and /o/ as unstressed vowels were .26 and .30 cm, and as stressed vowels, .95 and .79 cm, respectively. The tendency to neutralize unstressed vowels in English has been reported elsewhere (Lindblom, 1963).

Consonantal voicing was found to affect both displacement and peak velocity. For both raising and lowering gestures of tongue dorsum, displacements and maximum velocities were less for /k/ than for /g/. Average displacements (over differences in direction, rate, and stress) for /k/ and /g/ were .64 and .68 cm; averaged peak velocities for /k/ and /g/ were 6.97 and 7.52 cm/sec, respectively. Two of the three subjects (D.O., K.M.) showed reliable displacement differences for voicing, $F(1, 1486) = 368.43$, $p < .01$, and $F(1, 1620) = 29.98$, $p < .01$, respectively. The third subject (R.F.) showed no reliable displacement difference, $F(1, 1294) = 3.59$, $p > .05$. All subjects showed reliably greater peak

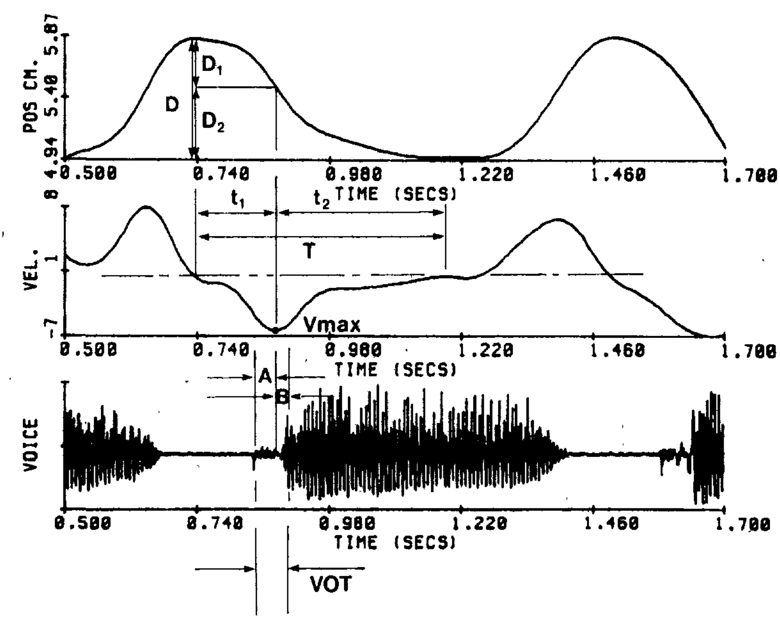

Figure 3. Ultrasound record of displacement and velocity (Vel.) of tongue dorsum and corresponding acoustic signal during the production of /ka/ at a normal speech rate with all vowels equally stressed. (As in Figure 2, the upper peaks correspond to the position of the tongue dorsum during oral closure. The numerical values for tongue dorsum position indicate the distance in centimeters between the ultrasound transducer and the dorsum of the tongue. Duration [T], displacement [D], and voice-onset time [VOT] are all partitioned with respect to the point of maximum tongue-lowering velocity. Durations labeled A indicate the time from oral release to maximum velocity; durations labeled B indicate the time from maximum velocity to voicing.)

velocities for the voiced stop-consonant, $F(1, 1486) = 102.00, p < .01$; $F(1, 1620) = 91.17, p < .01$; $F(1, 1294) = 8.27, p < .01$, respectively. The result is consistent with reports that tongue dorsum displacements and velocities are greater for voiced than for voiceless stops (Kent & Moll, 1969; Parush, Ostry, & Munhall, in press; but cf. Kozhevnikov & Chistovich, 1965, for evidence of greater raising velocities to voiceless stop closures). The greater displacements associated with the voiced stop-consonant may be attributed to a lower hyoid bone and hence a lower tongue position in that context (Kent & Moll, 1969).

As reported elsewhere, changes in speech rate were produced differently by the different subjects (Kuehn & Moll, 1976; Tuller, Harris, & Kelso, Note 1). All subjects reduced articulator displacement in the fast-speech condition: for D.O., K.M., and R.F., $F(1, 1486) = 105.67, p < .01$; $F(1, 1620) = 195.46, p < .01$; $F(1, 1294) = 422.09, p < .01$, respectively, with an average difference in tongue dorsum displacement of .07 cm between fast and slow speech rates. However, the reduction in displacement was accompanied by an increase in maximum velocity (8.02 cm/sec at the fast rate vs. 7.13 cm/sec at the slow rate) for subject D.O., $F(1, 1486) = 156.37, p < .01$; no change in maximum velocity (8.06 cm/sec vs. 8.09 cm/sec) for subject K.M., $F(1, 1620) < 1$; and a reduction in maximum velocity (5.99 cm/sec at the fast rate vs. 6.13 cm/sec at the slow rate) for subject R.F., $F(1, 1294) = 8.63, p < .01$.

Stress differences, on the other hand, resulted in similar kinematic patterns, with all subjects increasing the duration, displacement, and maximum velocity of the tongue dorsum gesture for stressed vowels. The average duration of the tongue-dorsum-lowering gesture was 230 msec for the stressed vowel and 96 msec for the unstressed vowel. The difference in duration was reliable ($ps < .01$) for all subjects. The average displacement for stressed vowels was .87 cm and for unstressed vowels .28 cm, with average peak velocities for stressed and unstressed vowels of 8.58 cm/sec and 4.84 cm/sec, respectively. The differences were again reliable ($ps < .01$) for all subjects.

Correlational Analyses

Relationships between kinematic variables were assessed with correlational analyses. These were conducted for each subject separately, on a within-condition basis. A separate analysis was carried out for each of the 48 conditions that resulted by combining the 2 (vowels) × 2 (consonants) × 2 (speech rates) × 3 (stress levels) × 2 (gesture directions [raising and lowering]). The three stress levels were the unstressed vowels in the alternate-stress condition and stressed vowels in both the alternate- and equal-stress condition. Each analysis involved a calculation of correlations on all possible pairs of measurement variables (see Figure 3), using as data the approximately 35 observations collected for each condition. The aim of this approach was to identify relationships be-

Table 1
Proportions of Reliable Positive (+) and Negative (−) Correlations Showing All Combinations of Measurement Variables

Measurement variable	T1 +	T1 −	T2 +	T2 −	T +	T −	D1 +	D1 −	D2 +	D2 −	D +	D −	V max +	V max −
T1	—	—	.00	.11	.56	.00	.38	.00	.00	.23	.05	.00	.00	.03
T2			—	—	.54	.00	.00	.13	.44	.00	.02	.01	.01	.02
T					—	—	.08	.00	.10	.00	.08	.00	.02	.06
D1							—	—	.18	.09	.71	.00	.44	.00
D2									—	—	.78	.00	.51	.00
D											—	—	.74	.00

Note. T = duration; D = displacement; and V max = maximum velocity (see Figure 3).

tween kinematic variables that were preserved across differences consonant, vowel, rate, and stress.

The overall pattern of correlations is presented in Table 1, which shows, for each combination of measurement variables, the proportion of tests that were reliable at the .001 level. The proportion shown in each cell is based on 144 separate analyses involving 2 (vowels) × 2 (consonants) × 2 (speech rates) × 3 (stress levels) × 2 (directions) × 3 (subjects). The main features of the table are consistent relationships between displacement and maximum velocity, indicating a linkage between these variables in the individual gesture, and the absence of a relationship between movement extent and the time from the initiation of the gesture to the point of maximum velocity. In addition, the total duration and extent of the movement are not correlated. These observations are considered in the next section.

Relationship between articulator displacement and peak velocity. All subjects showed reliable correlations between the displacement of the tongue dorsum and its peak velocity; 30 of 48 tests of this relationship were reliable ($p < .01$) for D.O., 47 for K.M., and 42 for R.F. The proportion of variance accounted for in the correlation between displacement and peak velocity for D.O., K.M., and R.F. averaged .41, .66, and .51, respectively. Significant relationships occurred more often for the unstressed vowel in the alternate-stress condition than for the stressed vowel in either the equal- or alternate-stress conditions; the proportion of variance accounted for averaged .75 for conditions involving the unstressed vowel as compared to .44 and .40 for the stressed vowel in the equal- and alternate-stress conditions, respectively. Reliable correlations occurred equally often for fast and slow speech rates, with the proportion of variance accounted for averaging .54 in fast conditions and .52 in slow conditions. Lowering gestures of tongue dorsum produced a slightly larger number of reliable displacement/peak-velocity correlations; the proportion of variance accounted for in lowering gestures averaged .56 as compared to .48 for raising gestures.

An example of the relationship between displacement and peak velocity is presented

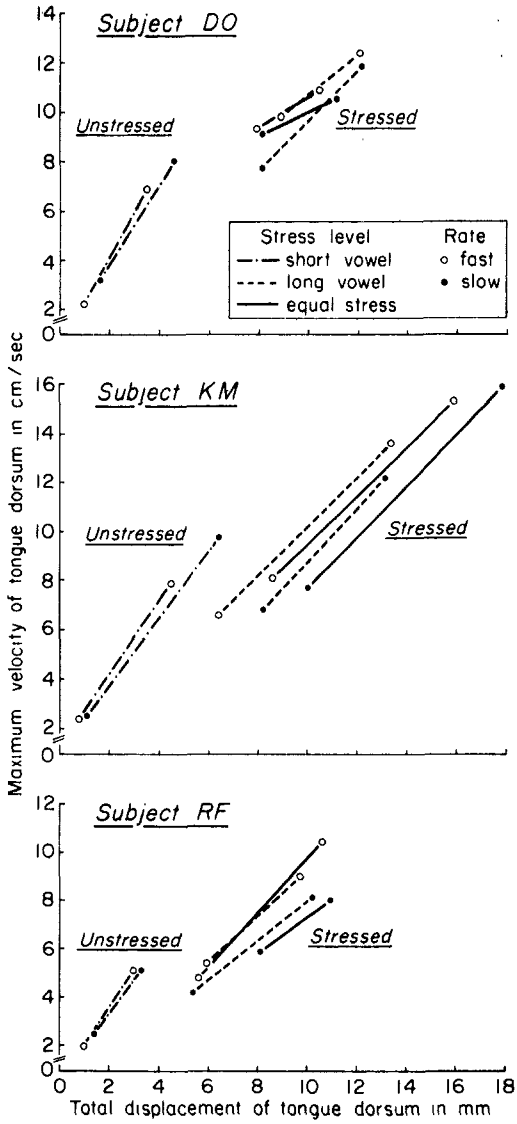

Figure 4. Relationship between tongue dorsum displacement and peak velocity for repetitions of a particular consonant–vowel sequence, /kaká/, at both fast and slow speech rates with alternate vowels stressed. (The range of displacements observed in each condition is indicated by the extent of the regression lines. The figure shows the relationship for the lowering gesture only.)

in Figure 4. The plot shows the linear relationships between displacement and peak velocity for repetitions of /kaká/, with alternate vowels stressed. Both fast and slow speech rates are shown. The range of displacements in this condition is indicated by the extent of the regression line. The figure suggests that the slope of the displacement/peak-velocity relationship changes with stress but is not affected by differences in speech rate.

The effects of speech rate and stress on the relationship between displacement and peak velocity were studied systematically by conducting regression analyses for all combinations of rate and stress without regard to differences in vowel or consonant. The resulting

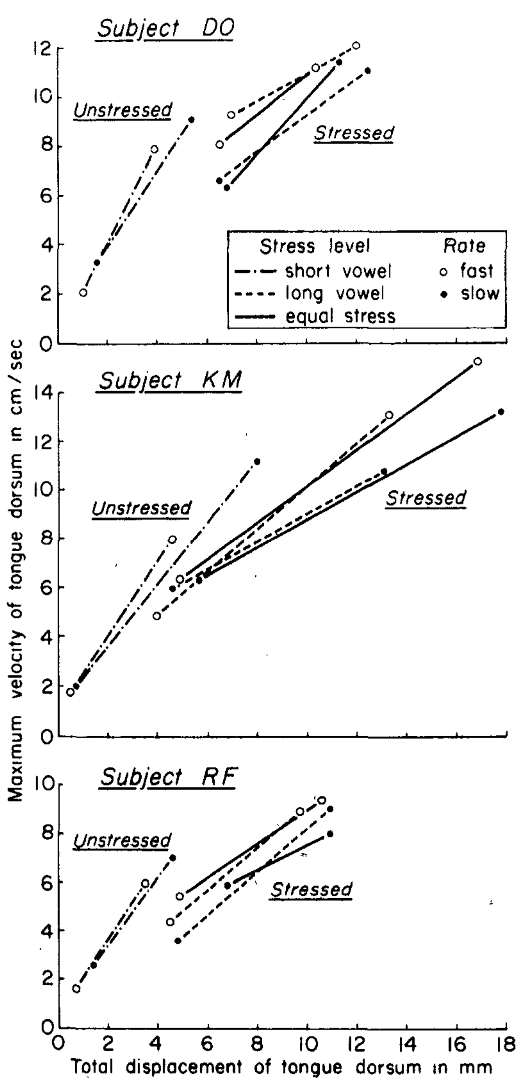

Figure 5. Relationship between tongue dorsum displacement and peak velocity shown without regard to differences in vowel or consonant at both fast and slow speech rates with alternate vowels stressed. (As in Figure 4, the regression lines extend over the range of values obtained in each condition. Likewise, the relationship is shown for the lowering gestures only.)

relationships for lowering gestures are shown in Figure 5. The range of displacements is again indicated by the extent of the regression lines. For D.O., K.M., and R.F., the proportion of variance accounted for averaged .51, .72, and .55, respectively. Overall, there is a marked similarity between the patterns observed in individual conditions (e.g., Figure 4) and those observed over differences in vowel and consonant. In both cases, the slope of the displacement/peak-velocity relationship appears to be indifferent to speech rate, whereas it varies with stress.

Tests were conducted for differences in slope as a function of speech rate at each stress level separately and for differences between stress levels, regardless of rate. Raising and lowering gestures were tested separately. Overall, relatively few reliable differences occurred in the slope of the displacement/peak-velocity relationship with changes in speech rate. Subject K.M. showed slope changes in the unstressed vowel as a function of speech rate on both raising and lowering gestures of tongue dorsum, $t(278) = 6.23$, $p < .001$, and $t(278) = 3.58$, $p < .001$, respectively; D.O. showed a slope difference for the unstressed vowel but for lowering movements only, $t(276) = 5.30$, $p < .001$. K.M. also showed a difference in slope with changes in speech rate for the stressed vowel in the alternate-stress condition, $t(278) = 4.78$, $p < .001$. In contrast, all subjects showed reliable differences in the slope of the displacement/peak-velocity relationship as a function of stress. For lowering movements, the slope for the unstressed vowel was greater than the slope for the stressed vowel in both the equal-stress and the alternate-stress condition ($p < .001$, for all subjects). As might be expected, stress effects on raising gestures were less consistent, with only D.O. and R.F. showing reliable changes in the slope of the displacement/peak-velocity relationship with differences in stress.

Time from movement initiation to maximum velocity. The time from movement initiation to the point of maximum velocity was relatively uninfluenced by variations in the extent of the gesture. It did, however, differ for stressed and unstressed vowels. Out of a total of 48 tests per subject of the relationship between displacement and the time to peak velocity (2 [vowels] × 2 [consonants] × 2 [rates] × 3 [stress levels] × 2 [directions]), there were only six reliable correlations ($p < .01$) for subject D.O., seven for subject K.M., and zero for subject R.F. There was thus little evidence that the slope differed from zero. For those correlations that were reliable, the median increases in the time to peak velocity with increases in displacement for subjects D.O. and K.M. were 8.7 and 4.8 msec/mm, respectively.

Factors influencing the time from movement onset to maximum velocity were studied further by conducting regression analyses on all combinations of rate and stress, without regard to the consonant or vowel. The resulting patterns for tongue-dorsum-lowering movements are shown in Figure 6 for the three subjects separately. The range of displacements is again indicated by the extent of the regression lines. For D.O. and R.F. in this analysis, the interval from movement onset to peak velocity at each stress level was relatively constant over differences in displacement. Of the six regression lines shown in Figure 6 and the six others computed for raising movements, D.O. had only one slope that was reliably different than zero, and R.F. had two slopes different than zero. In contrast, in 7 of 12 tests for K.M., the time to peak velocity increased reliably with displacement.

Relationship between lingual velocity and voice-onset time. An examination of Figure 2 indicates a correspondence between the timing of voice onset and the peak-lowering velocity of the tongue dorsum. Abbs (1973) reported similar correspondence between jaw movement and voicing. The present relationship between voicing and velocity was examined in detail by partitioning the voice-onset time into two intervals, one from oral release, as measured acoustically, to the point of maximum tongue-dorsum-lowering velocity, the other from the point of maximum lowering velocity to the onset of voicing.

A main finding can be seen by examining ultrasound records for repetitions of /ka/ and /ga/ with alternate vowels stressed (see Figure 7). The figure shows that for English speakers, times from oral release to the point of maximum lowering velocity (durations A and B) differ for stressed and unstressed vowels but are approximately equal for voiced and voiceless consonants. In the stressed condition, the maximum lowering velocity for /ka/ is reached prior to the onset of voicing, whereas for /ga/, voicing precedes the point of maximum velocity.

Overall, the interval from oral release to the point of maximum tongue-dorsum-lowering velocity was relatively constant across differences in speech rate, voicing, and vowel height, although values differed for stressed

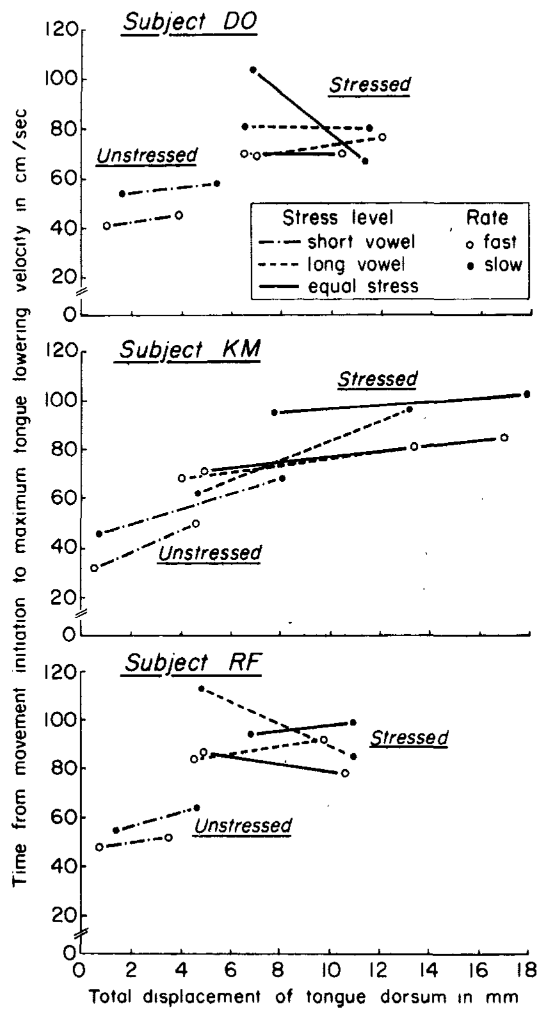

Figure 6. Relationship between tongue dorsum displacement and the time from movement onset to peak-lowering velocity. (The relationship is shown without regard to differences in vowel or consonant at both fast and slow rates with alternate vowels stressed. The range of displacements is indicated by the extent of the regression lines.)

and unstressed vowels (see Figure 8). For stressed vowels, the duration of the interval from oral release to maximum lowering velocity for D.O., K.M., and R.F. averaged 34, 46, and 34 msec, respectively, whereas for unstressed vowels the average values were 5,

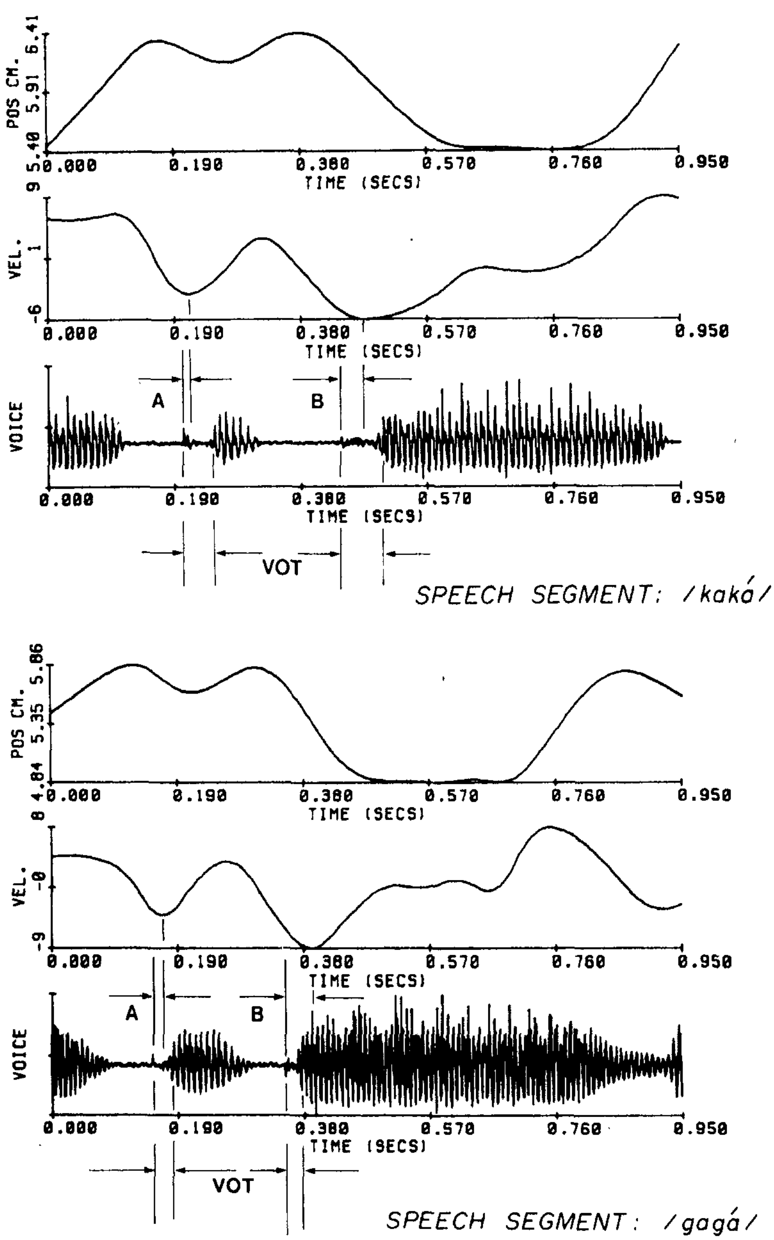

Figure 7. Ultrasound records of displacement and velocity (Vel.) of tongue dorsum and corresponding acoustic signal for repetitions of /kaká/ and /gagá/ with alternate vowels stressed. (Unstressed vowels are the smaller of the two acoustic signals. Oral closure for the stop-consonant corresponds to maximum displacement values; the position for the vowel /a/ corresponds to minimum displacement values. Durations labeled A indicate the time from oral release to maximum tongue-lowering velocity for unstressed vowels; durations labeled B indicate time from oral release to maximum velocity for stressed vowels. VOT = voice-onset time.)

19, and 6 msec, respectively. The differences between stressed and unstressed vowels were reliable for all subjects (D.O., K.M., and R.F.): $F(2, 637) = 735.66$, $p < .01$, $F(2, 727) = 396.20$, $p < .01$, and $F(2, 609) = 242.44$, $p < .01$, respectively. Subjects D.O. and K.M. also showed an interaction between vowel height and stress, such that the interval from oral release to maximum velocity was longer for /a/ than for /o/ in the case of the stressed vowel only, $F(2, 637) = 13.01$, $p < .01$, and $F(2, 727) = 15.37$, $p < .01$, respectively. For two of the subjects, D.O. and R.F., the time from oral release to maximum velocity was unaffected by speech rate (Fs < 1), whereas K.M., on the other hand, showed a longer interval at the slower speech rate, $F(1, 727) = 25.78$, $p < .01$. K.M., but not D.O. or R.F., also showed a longer interval from oral release to maximum velocity for the voiceless stop-consonant, $F(1, 727) = 24.47$, $p < .01$.

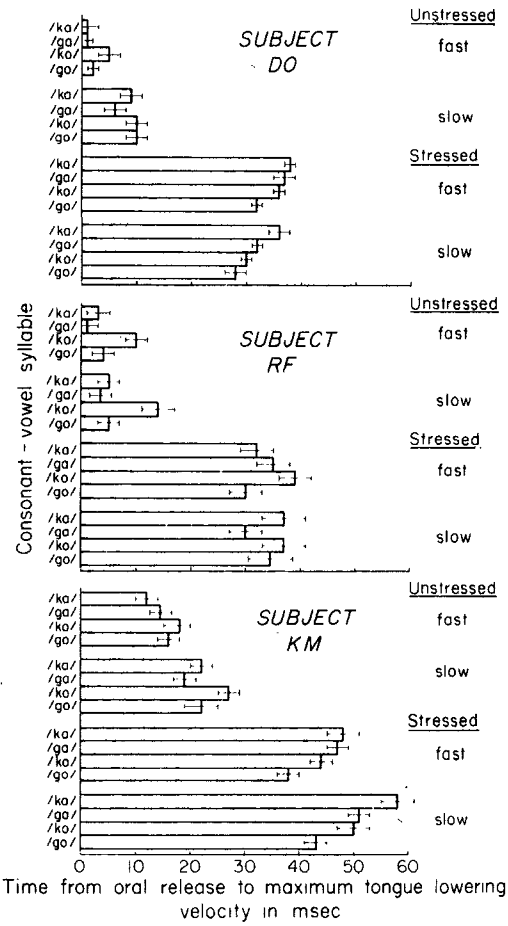

Figure 8. Time from oral release to maximum tongue-dorsum-lowering velocity for three subjects producing consonant–vowel pairs at fast and slow rates in stressed and unstressed conditions.

Discussion

The maximum velocity of tongue dorsum raising and lowering was shown to be correlated with the extent of the gesture. The slope of the relationship differed for stressed and unstressed vowels but was unaffected by differences in speech rate. At each stress level the correlation between displacement and peak velocity was accompanied by a relatively constant interval from the initiation of the movement to the point of maximum velocity. These kinematic relationships are similar to those observed in nonrepetitive speech movements (Parush et al., in press) and in the voluntary movement of the hands and arms.

The kinematic linkage of displacement and peak velocity is characteristic of systems that can be described with second-order differential equations (Cooke, 1980). The second-order relationship is indicative of the viscoelastic inertial nature of the orofacial structures. In the context of second-order systems, the kinematic patterns associated with differences in speech rate and stress can be interpreted in terms of changes in biomechanical variables (e.g., zero-length, stiffness) and corresponding physiological changes in the tonic and phasic activity in the muscles producing the gesture. Specifically, differences in stress can be attributed to tonic changes in the stiffness of the tongue, while differences in the extent of the movement at a particular stress level can be related to differences in the level of the phasic EMG activity.

The suggestion that stress differences reflect changes in the tonic control of articulator stiffness derives from the work of Cooke (1980), who showed that changes in the slope of the displacement/peak-velocity relationship could be predicted on the basis of static muscle stiffness, the coefficient of the zero-order term in a second-order system. Increases in the slope correspond to increases in muscle stiffness. The increase in the slope of the displacement/peak-velocity relationship observed here for unstressed versus stressed vowels may thus result from an increase in the stiffness of the tongue for these vowels. This could be accomplished for both raising and lowering movements of the tongue dorsum by increasing the slope of the static length–tension relationship in the agonist muscles (Cooke, 1980) or, alternatively, by altering the muscle lengths at which tonic recruitment of motor units in both agonists and antagonists begins (Feldman, 1980a, 1980b; Feldman & Latash, 1982). Feldman has shown that the control of recruitment thresholds could result in changes in the stiffness of the limb as a whole without the direct regulation of the stiffnesses of individual muscles.

In contrast to stress changes that appear to depend on differences in articulator stiffness, differences in displacement at a given stress level may be determined by the extent of phasic activity, with articulator stiffness constant. The suggestion that stiffness is constant over movements of differing extent is supported by recent evidence of constant angular stiffness during rapid elbow movements in humans (Cooke, 1982).

In limb movements, differences in movement extent appear to vary systematically with the amplitude of the impulse applied to agonist and antagonist muscles. In rapid movement about the elbow, the duration of the first agonist burst is essentially constant. The amplitude and peak velocity of the movement vary systematically with the amplitude of the EMG activity (Hallett & Marsden, 1979; Lestienne, 1979; Marsden, Obeso, & Rothwell, 1981). A related pattern is observed in voluntary isometric contractions of hand muscles in humans (Freund & Büdingen, 1978) and extensions of the forearm in cats (Ghez & Vicario, 1978b). In rapid isometric contraction, the peak tension or force in the muscle is correlated with the peak rate of tension change; the time from the initiation of the contraction to the peak rate of tension change is essentially constant. As in the anisometric case, the peak force varies with the amplitude of the EMG activity.

In speech movements, the relationship between articulator displacement and EMG activity may be somewhat more complex. For example, although differences in articulator displacement appear to vary with the amplitude of EMG activity (e.g., Gay & Ushijima, 1975; Gay, Ushijima, Hirose, & Cooper, 1974; Harris, 1971, 1973; Sussman & MacNeilage, 1978; Sussman et al., 1973; Tuller, Harris, & Kelso, 1982), articulator displacement also appears to be related to EMG duration. As in limb movements, EMG activity in speech is distributed across the muscles involved in a gesture. However, the fixed ratios of activity observed in limb movements (Bouisset, Lestienne, & Maton, 1977) do not appear to be preserved, at least in jaw-closing muscles in speech (Folkins, 1982). Another possibility to describe the distribution of EMG activity in speech is that the action of synergistic muscles is complementary, as is suggested, for example, in the trade-off of activity levels of the lip elevators orbicularis oris inferior and mentalis (Abbs, 1979). An orderly relation may thus emerge between the combined activity of agonistic muscles and the resulting extent of the movement of the speech articulator.

Speech rate differences could be produced by differences in phasic activity without changes in articulator stiffness. This follows from the insensitivity of the slope of the displacement/peak-velocity relationship to changes in speech rate. However, this suggestion on the control of speech rate should be viewed as tentative, as average values for displacement and peak velocity at different speech rates can vary in what appears to be a nonlinked fashion. Such an effect could be produced by subtle differences in articulator stiffness (as indicated by changes in the slope of the relationship between displacement and peak velocity) combined with appropriate changes in phasic EMG activity. It should be noted, however, that even in cases where the slope of the relationship clearly changes, for example, with rate changes in rapid elbow flexions in humans (Cooke, 1980), the basic linkage of displacement and maximum velocity is preserved.

In summary, we would like to suggest that the control of the tongue dorsum in speech is achieved by both a tonic regulation of articulator stiffness, which produces differences associated with stress (this might be achieved by the control of recruitment thresholds of agonist and antagonist motor units), and a modulation of phasic activity, which results in differences in the extent and perhaps the rate of the gesture at a given stress level. Related accounts of the control of second-order systems are presented by Feldman (1980a, 1980b) and Meyer, Smith, and Wright (1982) for voluntary limb movements in humans and by Ghez (1979) for rapid forearm movements in cats.

The data from this study relate to the question of whether speech rate and stress are controlled by the nervous system in similar ways (cf. Tuller, Harris, & Kelso, 1982). The subjects showed consistent relationships between displacement and peak velocity within all combinations of speech rate and stress. However, the idea that stress and speech rate were differently regulated was supported both by the evidence that the slope of the displacement/peak-velocity relationship was indifferent to changes in speech rate but varied with stress, and by the additional evidence of differences with stress, but insensitivity to speech rate in the interval from oral release to peak-lowering velocity. A possibility yet to be tested is that the differences due to speech rate and stress can both be accounted for in terms of changes in biomechanical variables (such as stiffness) that accompany differences in the duration of the gesture (Ostry & Munhall, Note 2).

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