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Velocity curves of human arm and speech movements

D.J. Ostry[1], J.D. Cooke[2], and K.G. Munhall[3]

[1] Department of Psychology, McGill University, 1205 Dr. Penfield Avenue, Montreal, Canada H3A 1B1
[2] Department of Physiology, The University of Western Ontario, London, Ontario, Canada
[3] Haskins Laboratories, New Haven, Connecticut, USA

Summary. The velocity curves of human arm and speech movements were examined as a function of amplitude and rate in both continuous and discrete movement tasks. Evidence for invariance under scalar transformation was assessed and a quantitative measure of the form of the curve was used to provide information on the implicit cost function in the production of voluntary movement. Arm, tongue and jaw movements were studied separately. The velocity curves of tongue and jaw movement were found to differ in form as a function of movement duration but were similar for movements of different amplitude. In contrast, the velocity curves for elbow movements were similar in form over differences in both amplitude and duration. Thus, the curves of arm movement, but not those of tongue or jaw movement, were geometrically equivalent in form. Measurements of the ratio of maximum to average velocity in arm movement were compared with the theoretical values calculated for a number of criterion functions. For continuous movements, the data corresponded best to values computed for the minimum energy criterion; for discrete movement, values were in the range of those predicted for the minimum jerk and best stiffness criteria. The source of a rate dependent asymmetry in the form of the velocity curve of speech movements was assessed in a control study in which subjects produced simple raising and lowering movements of the jaw without talking. The velocity curves of the non-speech control gesture were similar in form to those of jaw movement in speech. These data, in combination with similar findings for human jaw movement in mastication, suggest that the asymmetry is not a direct consequence of the requirements of the task. The biomechanics and neural control of the orofacial system may be possible sources of this effect.

Offprint requests to: D.J. Ostry (address see above)

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Introduction

Several recent papers have dealt with the geometric form of the velocity curve of movements. Velocity curves have been described for a variety of cost functions (e.g. minimum jerk, minimum energy, optimum joint stiffness, harmonic oscillation; see Hasan 1986; Hogan 1984; Meyer et al. 1982; Nelson 1983) and there have been demonstrations that the form of the velocity curve is invariant under transformations of movement amplitude, path, rate, and inertial load (Atkeson and Hollerbach 1985; Evinger et al. 1981; Evinger et al. 1984; Hollerbach and Flash 1982; Munhall et al. 1985; Ostry and Munhall 1985; Ruitenbeek 1984; Soechting 1984).

The form of the velocity curve may thus provide two kinds of information about the control of voluntary movement. It may establish the existence of equivalence classes of movements characterized by a constant geometric form (e.g., Atkeson and Hollerbach 1985; Hollerbach and Flash 1982). It may also provide information on the implicit cost function in the production of movement (e.g., Hasan 1986; Hogan 1984; Nelson 1983).

Invariance of the form of the curve over transformations such as amplitude or duration is suggested by similarity of shape. Following Nelson (1983), a necessary quantitative condition for equivalence is the invariance of c in the relationship:

$$c = \frac{V_{max}}{V_{avg}} \qquad (1)$$

where V_{max} is the maximum instantaneous velocity, V_{avg} is average velocity, and c is a variable indicative of the form of the particular velocity curve.

If it can be shown that the value of c remains constant for movements of different amplitude, rate or load then the movements may share a common velocity curve. As an example, all hypothetical movements with constant acceleration and constant deceleration (a triangular velocity curve), have a value of c equal to 2; movements whose velocity curve is that of an undamped harmonic oscillator have $c = \pi/2$. If movements were made to minimize jerk, c would equal 1.56 for cyclical movements (Nelson 1983) and 1.88 for discrete movements (Hogan 1984). On the other hand, if the value of c is dependent on movement amplitude or duration, the geometric form of the curve varies with scale changes in the movement.

In this paper we have systematically studied the scaling that occurs in the form of the velocity curve as a result of changes in movement amplitude and duration. We have compared cyclical and discrete movements in three behaviors: flexion and extension of the elbow, movement of the tongue dorsum in the production of speech and movement of the jaw also in speech.

Method

The movements of the arm, tongue, and jaw were studied. The movements were of specified amplitude and were produced at two implicitly defined rates (fast, slow). Both discrete and continuous movements were assessed. Different subjects were tested for each articulator. Kinematic measures of movement amplitude, duration, and maximum instantaneous velocity were obtained.

Movement onset and termination were identified in both continuous and discrete conditions by points of zero-crossing on the velocity records. These points were selected in order to compare quantitative indicators of the form of velocity curves (see Eq. 1) with theoretical values reported in the literature (Hasan 1986; Hogan 1984; Nelson 1983).

Arm movements

Subjects produced horizontal movements about the right elbow in response to step changes in a visual target (see Thomas et al. 1976 for a description of the system). The subjects held a vertical rod attached to a manipulandum handle. The arm was supported just distal to the elbow and moved freely about a pivot point in a horizontal plane at the level of the shoulder. A narrow vertical bar, displayed on a video monitor, served as a target. The angular position of the arm that was being moved was displayed as a vertical cursor. Both position and velocity were sampled at a 200 Hz rate. The position signal was obtained from a position potentiometer; the velocity signal came directly from a tachometer. The data were then low-pass digitally filtered using a zero phase-lag fourth-order Butterworth filter with a cut-off frequency of 10 Hz.

In the discrete condition, the subjects made a series of step tracking movements that involved alternate flexion and extension about the right elbow. The target changed position once every three seconds. The subject's task was to realign the cursor and the target. The movement amplitudes used were 20°, 40°, and 60°. The elbow movements were centered about a sagittal plane to the body. Subjects produced 20 flexion and 20 extension movements in each of three amplitude by two movement duration combinations.

In the continuous movement condition, subjects made a continuous series of alternating flexion and extension movements. Narrow vertical bars which were displayed continuously on a video monitor indicated the movement start and end positions. Twenty flexion and extension movements were again collected in each of the three amplitude by two movement duration conditions.

Explicitly defined movement amplitudes and implicitly defined durations were used in this study in order to provide subjects with comparable tasks for limb and speech movement. Although there are no explicitly defined articulatory target positions in speech, relatively small differences in position can have substantial acoustic consequences. For example, the difference in elevation of the tongue which results in the production of the vowel *a* as opposed to the *o* is approximately 0.5 cm. Thus, in the absence of extensive subject training, explicit visual targets for arm movements best parallel the articulator positioning in speech.

As a control for differences in performance between explicit and implicitly defined target positions, we repeated for all three subjects the entire limb movement manipulation using three implicitly defined spatial targets (small, medium and large amplitude movement). We found the performance of the subjects to be more variable when the target positions were implicitly defined. However, none of major findings reported below differed as a consequence of whether the targets were experimenter-defined or subject-defined.

Tongue dorsum movements

Tongue dorsum movements were recorded during the production of the consonant-vowel sequences *ka* (large amplitude movement) and *ko* (small amplitude movement). The data were collected by using a computerized pulsed-ultrasound system (Keller and Ostry 1983). A single element ultrasound transducer (Picker 3.5 MHz; 7.5 cm focus) was positioned externally, below the chin along the mid-line of the mandible, just anterior to the hyoid bone. The transducer was placed in an orientation that was perpendicular to the Frankfort horizontal (see Keller and Ostry 1983 for details related to transducer placement). The transducer was secured during recording by using a modified hockey helmet. The principal movement component in the production of these consonant-vowel sequences is parallel to the ultrasound beam.

In order to produce these sequences the tongue moves from a position at the palate for the release of the consonant to an open or lowered position for the production of the vowel. Only the data from the lowering gesture are reported here. For the kinematic patterns of both raising and lowering movements of the tongue dorsum see Ostry et al. (1983).

Subjects produced 30 movements in each of the two amplitude by two movement duration combinations. In the discrete condition subjects were instructed to maintain final articulator position by sustaining the acoustical production of the vowel for approximately one second. In the continuous condition, utterances were recorded in trials that were four seconds in duration.

The tongue movements were sampled at a 1 kHz rate. The data were then analyzed by dividing the duration of the trial into 45 ms intervals and fitting natural cubic spline functions to the set of knots formed by the interval averages at their midpoints. The spline-fit data had a bandwidth of approximately 20 Hz; the average absolute difference between the spline and the raw data was about 0.025 cm/measurement (Keller and Ostry 1983). Velocities were obtained from the spline-fitting program. No additional filtering was done to the data.

Jaw movements

Jaw lowering movements were recorded during the production of the consonant-vowel sequences *ta* (large amplitude) and *te* (small amplitude). Jaw movements were monitored by using a linear voltage displacement transducer (LVDT, Trans-Tek 0243). The LVDT consists of a light-weight circular transformer with a metallic core which generates an output voltage that is linear with the position of the core. The LVDT was held in a fixed orientation during recording by means of a modified hockey helmet. One end of the core of the LVDT was inserted into the transformer and the other was attached to the midline of the jaw just posterior to the mental notch. As the metallic core changes position within the transformer during speech, a voltage is produced which varies linearly with the elevation of the jaw.

In order to produce these consonant-vowel sequences the jaw moves from an elevated position for the release of the alveolar consonant to an open or lowered position for the production of the vowel. As in the case of the tongue movements, only the lowering movements of the jaw were scored. Subjects produced 30 movements for each of the two amplitude by two movement duration combinations.

The jaw position signal was low-pass filtered with a cut-off frequency of 30 Hz, then digitally sampled at a 1 kHz rate. The data were then fit with natural cubic spline functions with the knots spaced at 16 ms intervals. Velocities were obtained from the spline-fitting program. As in tongue movements, no other filtering was carried out.

Results

Form of the velocity curve

Figures 1–3 show ensemble-averaged velocity curves for jaw lowering, tongue dorsum lowering, and elbow extension normalized on both the horizontal and vertical axes. Normalization was carried out on individual velocity curves before averaging. Continuous and discrete movements are shown separately.

The normalized velocity curves for jaw lowering movements are shown in order of increasing relative acceleration duration (Fig. 1). As can be seen, the curves for continuous movement differ in form as a function of movement duration. Acceleration duration is less than deceleration duration for slow movements, whereas, for fast movements, acceleration and deceleration durations are similar. In discrete movements, the form of the velocity curve varies in a non-systematic manner.

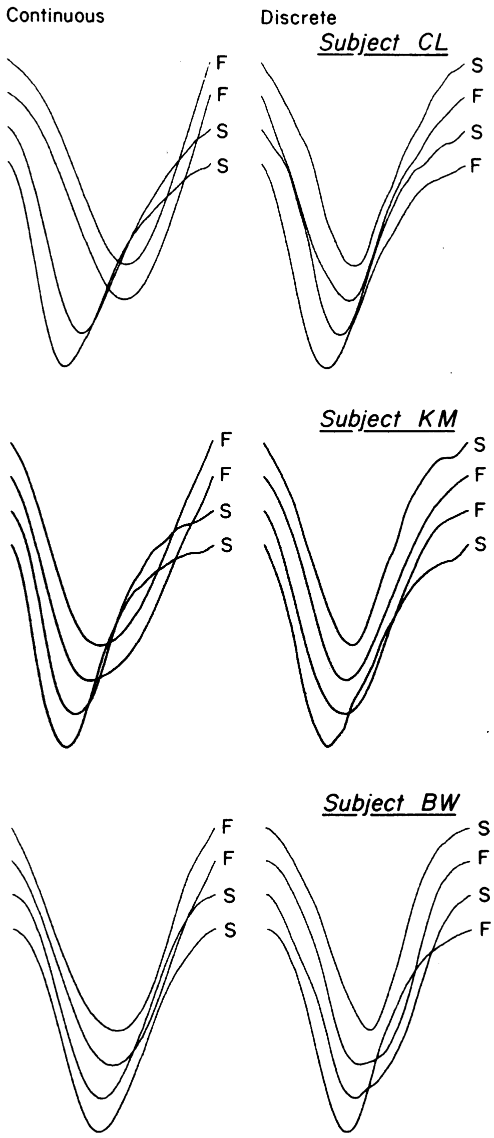

Fig. 1. Ensemble averaged velocity curves for jaw lowering movements in speech, normalized on both horizontal and vertical axes. Curves are shown for both continuous and discrete movements at fast (F) and slow (S) rates. Two curves are shown at each speech rate, one for the vowel *a* (large amplitude movement), the other for the vowel *e* (small amplitude movement). The curves are presented in order of scaled acceleration duration. For continuous movement, the curves can be seen to differ in shape as a function of movement rate but not movement amplitude. For discrete movement, the form of the curve varies in a non-systematic manner over differences in movement amplitude and rate

Figure 2 shows the averaged tracings of the tongue dorsum lowering movement. The normalized curves are again shown in order of increasing relative acceleration duration. As observed in jaw movement, the velocity curves of the tongue differ in form as a function of rate. For subjects CL and SP, the curves for continuous movement are similar to those for continuous movement of the jaw. Specifically, the shape of the curve varies as a function of movement

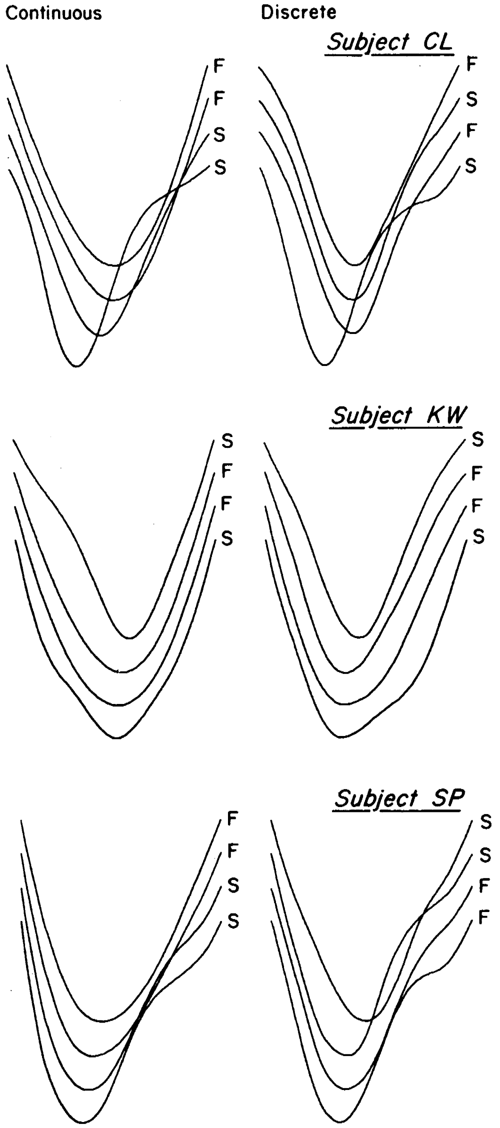

Fig. 2. Normalized velocity curves for tongue dorsum lowering movements in speech. As in jaw movements, two curves, one for *a* and the other for *o*, are shown for each speech rate. Curves are shown in order of scaled acceleration duration. The patterns for continuous and discrete movement are similar to those observed for the jaw

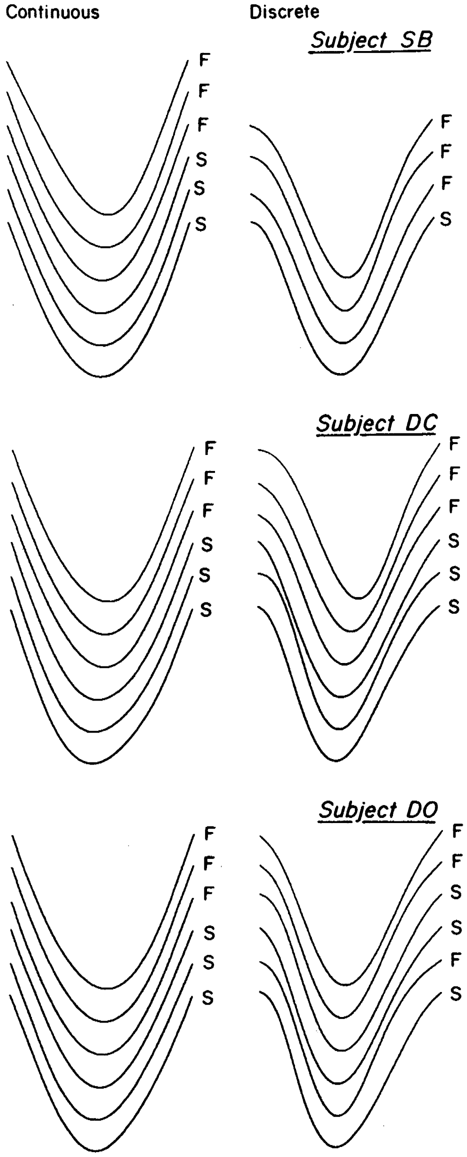

Fig. 3. Normalized velocity curves for elbow extension movement. Three curves, one for each movement amplitude, are shown at each rate. The curves are shown in order of scaled acceleration duration. In both continuous and discrete conditions, relative acceleration durations are less for slow movements. The pattern for elbow flexions was similar but is not shown

duration; relative acceleration duration is less for slow movements than for fast movements. This pattern is not observed for subject KW. As is the case in discrete jaw movements, the curves for tongue movement in the discrete condition cannot be classified on the basis of the movement amplitude (*o* versus *a*) or duration.

Figure 3 shows the averaged tracings for elbow extensions. The patterns for elbow flexion were similar but are not shown in the figure. Unlike tongue and jaw movements in speech, the velocity curves appear similar in form. However, small but consistent changes in the relative duration of the acceleration phase of the movement were observed for all subjects. The curves for continuous and discrete movements differ in form. This results from differences in task requirements; discrete movements begin and end at rest and consequently require greater changes in acceleration near movement endpoints than continuous movements.

To summarize, the velocity curves for continuous speech movements of the tongue and jaw differed in form as a function of movement duration but were similar for movements of different amplitude. The velocity curves for continuous elbow movements were similar in form over differences in both amplitude and duration. However, there was a slight tendency for these curves as well to differ in form as a function of movement duration. In discrete movement, there was no systematic pattern to the shapes of the velocity curves of the tongue and jaw. The velocity curves for discrete elbow movement appeared similar to one another in form. However, as in continuous movement, the relative acceleration durations were less in the slow condition.

Changes in form with movement duration

The form of the velocity curve of movements was examined quantitatively by evaluating the ratio of maximum to average velocity as a function of movement duration. If the form of the velocity curve is invariant, the ratio of maximum to average velocity is necessarily constant over differences in duration. The average value of the ratio in each of the experimental conditions is given in Table 1.

For both tongue and jaw lowering movements in speech, the ratio of maximum to average velocity was greater for discrete than for continuous movement ($p < 0.001$, in all cases). The ratio was also greater for slow than for fast movement in both discrete and continuous conditions ($p < 0.001$). Two exceptions were the jaw lowering movement for subject BW and the tongue lowering movement for KW where no difference in the ratio was observed as a function of duration.

A different pattern was observed for elbow movement. As in speech, the ratio was greater in the discrete than in the continuous condition ($p < 0.001$). However, the ratio did not vary systematically as a function of duration. The mean value of V_{max}/V_{avg} can be seen to decrease with increases in duration; this difference was not found to be reliable by post-hoc statistical tests ($p > 0.05$).

In order to ensure that the scoring convention used here for the movement start and end points did not bias the estimates of the ratio, median values of *c* were computed as well. Medians are less influenced than means by outlying data points. The pattern for medians was very similar to that observed for means: the difference between means and medians never exceeded 0.12 and averaged 0.05, 0.03, and 0.02 for tongue, jaw and arm movements, respectively.

Table 1. Mean values of ratio of maximum to average velocity for movements of the tongue, jaw and elbow. Standard errors are given in parentheses

	Continuous		Discrete	
	Fast	Slow	Fast	Slow
Tongue lowering movement				
Subject CL				
V_{max}/V_{avg}	1.65 (0.01)	2.37 (0.06)	2.11 (0.05)	2.40 (0.07)
Subject KW				
V_{max}/V_{avg}	1.54 (0.01)	1.94 (0.05)	2.00 (0.08)	1.90 (0.07)
Subject SP				
V_{max}/V_{avg}	1.69 (0.02)	2.00 (0.03)	2.15 (0.07)	2.23 (0.07)
Jaw lowering movement				
Subject CL				
V_{max}/V_{avg}	1.89 (0.02)	2.35 (0.03)	2.51 (0.07)	2.84 (0.09)
Subject KM				
V_{max}/V_{avg}	1.76 (0.02)	2.15 (0.03)	2.35 (0.06)	2.81 (0.11)
Subject BW				
V_{max}/V_{avg}	1.80 (0.01)	2.06 (0.03)	2.97 (0.11)	2.81 (0.07)

	Continuous		Discrete	
	Fast	Slow	Fast	Slow
Elbow flexion				
Subject SB				
V_{max}/V_{avg}	1.46 (0.01)	1.43 (0.01)	1.85 (0.01)	[a]
Subject DC				
V_{max}/V_{avg}	1.48 (0.01)	1.40 (0.01)	1.94 (0.04)	1.87 (0.02)
Subject DO				
V_{max}/V_{avg}	1.45 (0.01)	1.50 (0.01)	2.12 (0.04)	2.02 (0.02)
Elbow extension				
Subject SB				
V_{max}/V_{avg}	1.53 (0.01)	1.54 (0.01)	1.92 (0.01)	[a]
Subject DC				
V_{max}/V_{avg}	1.49 (0.01)	1.56 (0.01)	1.87 (0.01)	1.84 (0.03)
Subject DO				
V_{max}/V_{avg}	1.55 (0.01)	1.58 (0.01)	1.94 (0.04)	1.85 (0.02)

[a] Due to a recording error, subject SB had few observations in the slow discrete condition. This condition was not assessed quantitatively

In summary, for tongue and jaw movement, the ratio of maximum to average velocity increased significantly with increases in movement duration. The ratio was also greater for discrete than for continuous movements. In elbow movement, the ratio did not vary systematically as a function of rate but as in speech movement was consistently greater in the discrete than in the continuous condition.

Table 2. Movement durations of the tongue, jaw and elbow in ms. Standard errors in ms are given in parentheses. The significance of the difference between the acceleration and deceleration durations is indicated

	Continuous		Discrete	
	Fast	Slow	Fast	Slow
Duration of tongue lowering movement				
Subject CL				
Acceleration	65 (1.2)**	82 (2.7)*	80 (4.0)*	97 (6.0)*
Deceleration	60 (1.3)	153 (7.9)	106 (4.3)	173 (8.9)
Subject KW				
Acceleration	57 (1.0)*	103 (5.7)	82 (4.4)*	104 (7.7)**
Deceleration	48 (0.8)	105 (3.8)	108 (8.7)	143 (9.5)
Subject SP				
Acceleration	52 (1.0)*	74 (2.2)*	93 (4.4)*	106 (7.6)*
Deceleration	78 (1.8)	156 (3.9)	168 (9.3)	162 (10.2)
Duration of jaw lowering movement				
Subject CL				
Acceleration	56 (0.8)*	102 (3.5)*	145 (9.2)*	193 (11.0)*
Deceleration	59 (0.8)	115 (2.3)	204 (13.9)	222 (18.2)
Subject KM				
Acceleration	53 (0.8)*	79 (2.5)*	72 (3.5)*	115 (8.5)*
Deceleration	73 (1.2)	142 (4.3)	112 (5.1)	203 (15.4)
Subject BW				
Acceleration	44 (0.8)***	79 (3.8)**	84 (6.4)*	158 (9.9)*
Deceleration	34 (0.7)	144 (3.5)	159 (8.3)	236 (11.4)
Duration of elbow flexion movement				
Subject SB				
Acceleration	123 (2.3)**	280 (3.8)*	121 (2.2)***	336 (14.8)
Deceleration	133 (3.5)	313 (6.1)	115 (1.5)	321 (5.3)
Subject DC				
Acceleration	93 (1.2)*	284 (3.4)*	125 (2.0)**	289 (5.2)*
Deceleration	87 (1.1)	268 (4.2)	116 (4.9)	358 (6.2)
Subject DO				
Acceleration	120 (3.0)	358 (7.6)*	113 (1.3)*	300 (3.5)*
Deceleration	123 (3.2)	404 (10.9)	169 (7.0)	366 (8.0)
Duration of elbow extension movement				
Subject SB				
Acceleration	140 (3.4)*	303 (4.2)	126 (2.4)*	318 (3.7)*
Deceleration	113 (2.1)	295 (5.1)	117 (2.7)	341 (8.9)
Subject DC				
Acceleration	93 (1.8)*	257 (2.3)*	122 (2.0)*	283 (5.1)*
Deceleration	85 (1.2)	307 (4.6)	110 (2.3)	342 (6.2)
Subject DO				
Acceleration	139 (4.3)***	380 (7.9)***	120 (1.8)*	280 (5.6)*
Deceleration	123 (3.4)	403 (10.5)	141 (5.2)	357 (8.5)

* $p < 0.001$
** $p < 0.01$
*** $p < 0.05$

Velocity curve asymmetry

The velocity curves were asymmetrical to varying degrees. The asymmetry was evaluated by measuring the curves to obtain acceleration and deceleration durations. Acceleration duration was defined as the time from the initiation of the movement at zero velocity to the point of maximum velocity. Deceleration duration was the time from the point of maximum velocity to the endpoint of the movement at zero velocity. Average acceleration and deceleration durations (and their standard errors) are shown for all articulators in Table 2.

The general features of this table are as follows: with the exception of fast continuous movements, deceleration durations of both the tongue and jaw are longer than the acceleration durations in all but one case. In fast continuous movement there is no systematic pattern to the magnitudes of acceleration and deceleration duration. In contrast, deceleration durations in elbow movements consistently exceed acceleration durations only in the case of slow discrete movements. The statistical significance of the differences between acceleration and deceleration duration is shown in the table.

Differences between arm and speech movements

The form of the velocity curve might depend on specific task requirements as well as the biomechanics and neural control of the articulator. It was not possible to directly assess the relative magnitude of these influences across the various kinds of movements in the present study. However, we have obtained some evidence on the role of task requirements in producing the asymmetry observed in the velocity curves of the orofacial movements. This evidence comes from a control study in which subjects produced simple raising and lowering movements of the jaw without talking. The movements were made in both discrete and continuous conditions at fast and slow rates.

We assumed that if the asymmetry was not dependent on the characteristics of the speech task, it should also be present in the control task in spite of the freedom from the requirements for articulator coordination in speech. On the other hand, if differences in the shape of velocity curves were task related, then a task involving simply raising and lowering of the jaw, without the accompanying

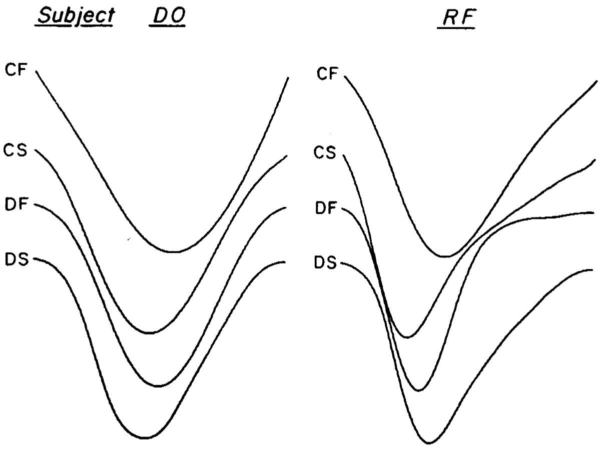

Fig. 4. Normalized velocity curves for non-speech lowering movements of the jaw. Averaged tracings for both continuous (C) and discrete movements (D) are shown at fast (F) and slow (S) rates. As in continuous speech movements, relative acceleration durations are less for slow movements than for fast movements

coordinative requirements of speech, might have velocity curves whose form reflected the differences between these tasks. For example, the form of the curves in the non-speech control condition might, like those of the elbow, be unaltered by differences in rate.

Two subjects were tested using the experimental set-up described previously. Twenty repetitions of jaw raising and lowering were recorded both at a fast and a slow rate. The normalized ensemble averaged velocity curves for the jaw lowering movements are shown in Fig. 4.

In the case of continuous movement, the velocity curves in the non-speech control study were similar in form to those observed for jaw movement in speech. In both, the relative duration of the acceleration phase was less for slow movement than for fast. This is consistent with the idea that the asymmetry observed in continuous jaw movement is not a consequence of the requirements of the task per se. (see discussion for further details).

In the discrete condition, subject DO shows a pattern similar to that observed in continuous movement. However, subject RF shows the opposite pattern. It is noteworthy that, in this demonstration and in the discrete speech movements of the tongue and jaw, the form of the velocity curve varies in a non-systematic manner. We studied this further by examining a number of discrete movement tokens. We often found that speech movements did not start and stop at rest. That is, these movements were not, in fact, discrete. Figure 5 gives examples of "discrete" jaw lowering gestures in both the speech and the non-speech control condition. As is evident from the records, subjects tend to initiate discrete jaw lowering movements in speech from a position in which the mandible is lowered relative to oral closure. Then in order to produce a speech sound, the mandible, tongue and lips are elevated to occlude the oral cavity at which point the "discrete" lowering gesture begins. Similar behavior has also been observed for the laryngeal movements in speech (Hirose et al. 1980).

The variability of the kinematic form of discrete speech movement is presumably a consequence of the fact that discrete movements of the tongue and jaw are uncommon in naturally occurring activities. They are not present to any substantial degree in speech, mastication or suckling movements. However, neither the variability of the curve nor the apparent inability to produce discrete speech move-

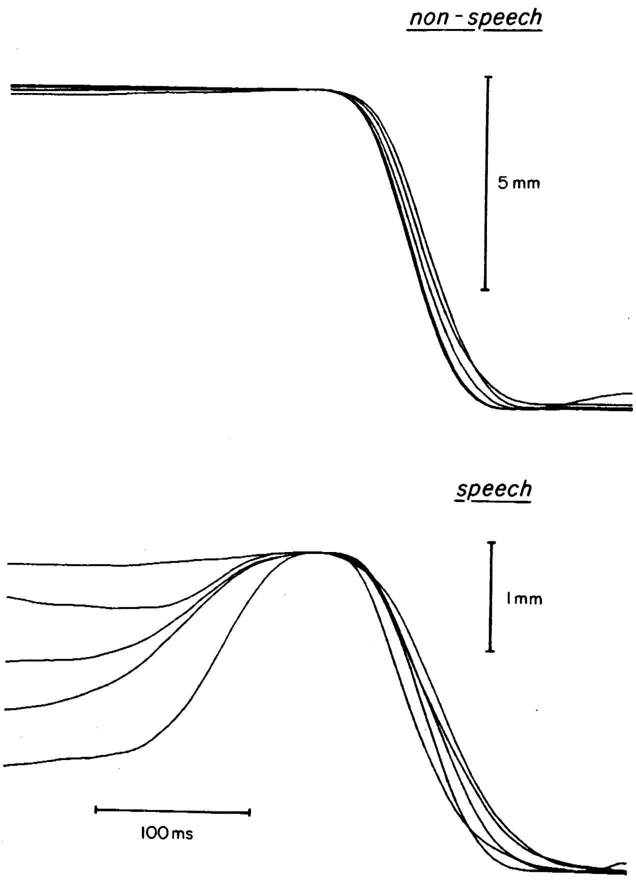

Fig. 5. The upper panel gives position records for a single subject, showing the first five trials recorded for discrete non-speech jaw lowering movement. The lower panel gives position records for a different subject again showing the first five trials for discrete jaw lowering movement in the production of the utterance *ta*. Similar patterns were observed for the other subjects

ments seem to be related to the biomechanics of the temporomandibular joint: the control study of jaw movement showed that there is no biomechanical reason that would preclude discrete movement (see Fig. 5, upper panel).

Before turning to the discussion, a number of points should be made regarding the comparability of the data obtained from different subjects and the potential problems associated with the use of one-dimensional measurement techniques in the study of speech. Since different subjects participated in the three studies, some of the kinematic differences observed will be the result of individual variation in performance of the tasks. However, the patterns observed for each articulator were generally consistent across subjects. This suggests that the findings obtained here would be similar to those which would result from a strictly within subjects design.

The data for both tongue and jaw movement were obtained with transducers that are restricted to unidimensional measurement. Although it would have been desirable to monitor the movements in three dimensional space, the facilities were not available to do so. We minimized the likelihood of artifact in these studies by using utterances whose principal direction of motion coincides with that of the measurement axis of the transducer. In addition, we obtained evidence for the main finding, a rate dependent asymmetry in the velocity of orofacial movement, under a variety of conditions: the asymmetry was obtained with ultrasound and LVDT measurements of tongue and jaw movements, respectively, and was also observed for a variety of different jaw movement tasks each involving different subjects.

Discussion

The velocity curves of human tongue and jaw movement were found to differ from the curves for movement about the elbow. In the continuous condition, the velocity curves of elbow movement were similar in shape in spite of differences in both movement amplitude and duration. In contrast, the velocity curves of tongue and jaw movement differed in shape as a function of duration but were similar for movements of different amplitude. Thus, the curves for elbow movement, but not for tongue or jaw movement, appear to be geometrically equivalent in form.

In the discrete condition, there were no systematic patterns to the velocity curves of the tongue or jaw. The assumption of scalar equivalence of the form of velocity curves was clearly untenable. The velocity curves for discrete elbow movement were more similar to one another. However, there were small but systematic changes in the symmetry of these curves as a function of duration. Thus, here as well, the curves were, strictly speaking, not members of a single scalar family.

Invariance in the form of velocity curves was assessed quantitatively by examining changes in the ratio of maximum to average velocity as a function of movement duration. A necessary condition for invariance is that the ratio remain constant over scale changes in the movement. In the present study, the ratio of maximum to average velocity increased systematically as a function of duration for movements of the tongue and jaw. In elbow movements, variations in the ratio were not systematically related to duration. Thus, by this test, the assumption of scalar equivalence of velocity curves was tenable only in the case of elbow movement.

The velocity curves of arm and orofacial movements tended to be asymmetrical such that deceleration took more time than acceleration. Exceptions were fast continuous speech movements and rapid elbow movements in both discrete and continuous conditions. Changes in the symmetry of the velocity curves as a function of movement duration is further evidence that the shape of these curves is not strictly invariant with scale changes in the movement.

Although the velocity curves of arm movement have been found to differ in shape as a function of duration, they are much less affected than the velocity curves of speech. Consequently, it is reasonable to compare quantitative measures of the form of the velocity curve of arm movement to theoretical values reported in the literature. This comparison bears on the problem of identifying the implicit cost function in the production of voluntary movement.

Theoretical values of the ratio of maximum to average velocity have been reported for a number of criterion functions. This includes values for the minimization of energy and jerk (Hogan 1984; Nelson 1983) and the optimization of joint stiffness (Hasan 1986). The calculation for minimum energy and jerk were based on polynomial approximations to the kinematic form of the movement. The value for stiffness comes from a model of limb dynamics in which the stiffness and the equilibrium position of the joint are controlled. The findings for arm movement in this study correspond best to the theoretical values for the minimum energy criterion ($c = 1.50$) in continuous movement (Nelson 1983) and the minimum jerk criterion ($c = 1.88$) in discrete movement (Hogan 1984). The value for the best stiffness solution is also within the range of the data in the discrete condition ($c = 1.97$; Hasan 1986).

Differences between arm and speech movements

The main difference between arm and speech movements was a rate dependent asymmetry which was observed in the velocity curves of orofacial movements but not in the curves of arm movements. Some possible sources of this difference are the characteristics of speech versus limb movement tasks, differences in neural control, biomechanical differences and loading due to gravity. The patterns of inter-articulator compensation may also differ (see Gracco and Abbs 1986; however, these were not assessed in the present study.

The possibility that the physical influence of gravitational loading accounts for the difference between the velocity curves of arm and speech movement is addressed by findings on the kinematic pattern of laryngeal adduction gestures in speech (Munhall et al. 1985; also see Atkeson and Hollerbach 1985). Laryngeal adductions, like the elbow movements of this study, are primarily in the horizontal plane and hence not subject to the influence of gravity. Nevertheless, they display the same rate dependent asymmetry as jaw movements which are influenced by gravity.

The form of the velocity curve may be influenced by the various anatomical, histochemical, and physiological differences between the orofacial articulators and the limbs. These differences include muscle architecture, muscle histochemical profiles, motor unit properties, reflex organization, and central function generation (English 1985; Luschei and Goldberg 1981; Grillner 1982). To date, no studies have been reported on the influence of these factors on the velocity curve. An important first step in evaluating their role would be a systematic comparison of the electromyographic patterns of jaw and arm movement under conditions of rate and amplitude manipulation.

The role of task requirements in producing the asymmetry observed in tongue and jaw movements was assessed by comparing jaw movement in speech with the curves from a non-speech control study. The jaw movement manipulations presumably had in common the biomechanical properties of movement about the temporomandibular joint and the mechanisms of neural control. They differed in terms of the requirements of the task. The speech task involved relatively precise coordination among the muscles of the vocal tract; the non-speech control gesture required a different and presumably less extensive form of inter-articulator cooperation with fewer constraints on timing.

The data showed that in continuous movement, the velocity curves for the non-speech control gesture were similar in form to the curves for jaw lowering in speech. The velocity curves for jaw movement in mastication are likewise similar in form (Ostry 1986). Thus, the kinematic form of human jaw movement does not appear to be differentially determined by particular task requirements. The most promising alternatives to account for the asymmetry of form seem to be articulator biomechanics and/or neural control.

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