Journal of Speech and Hearing Research, Volume 37, 1020–1031, October 1994

Evaluation of a Reiterant Force-Impulse Task in the Tongue

Kate Bunton
Gary Weismer
Department of Communicative Disorders
University of Wisconsin-Madison

In the current study characteristics of a lingual force-impulse task were examined. In the task, neurologically normal adults were required to produce sequences of lingual force impulses that were modeled on sequences of syllables produced as reiterant speech. The goal of data analysis was to (a) compare the timing of the reiterant force sequences to the timing of reiterant speech sequences, (b) compare the force magnitudes to expected force variations associated with linguistic stress in the reiterant speech sequences, and (c) compare the reiterant force magnitudes to maximum lingual forces. Results indicated that reiterant force timing is typically slower than reiterant speech timing, that reiterant force magnitudes do not vary systematically as a function of stress variations in the reiterant speech utterances, and that reiterant force magnitudes are typically only a fraction of maximum lingual forces. Results are discussed in terms of the relationship between orofacial, nonspeech motor performance and speech production performance.

KEY WORDS: lingual force, oromotor integrity, dysarthria

A common strategy in the evaluation of persons with motor speech disorders includes testing of orofacial, nonverbal control using a battery of well-known tests. Whereas the majority of these tests are perceptual and nonstandardized (e.g., open and close the jaw rapidly, press with tongue against clinician-supplied resistance), they continue to be the dominant component of a motor speech evaluation (Gerratt, Till, Rosenbek, Wertz, & Boysen, 1991).

Throughout the last decade, a number of investigators have made an attempt to develop objective evaluations of orofacial nonverbal control. Barlow and his colleagues (Barlow & Abbs, 1983, 1986; Barlow & Netsell, 1986; Barlow & Rath, 1985; Barlow & Burton, 1990) have shown how force transducers for the lips, jaw, and tongue can be used to measure maximum and fine forces exerted by these structures. Initial attempts to relate fine force measures in orofacial structures to more traditional measures of speech deficit (i.e., speech intelligibility scores) have been reported by Barlow and Abbs (1986) and Barlow and Burton (1990) for adults with congenital spasticity and traumatic brain injury, respectively. Maximum force and/or pressure data, as well as estimates of fatigue during maximum effort, have also been reported for persons with amyotrophic lateral sclerosis (ALS) (Dworkin, Aronson, & Mulder, 1980; Dworkin & Aronson, 1986), as well as for adults and children with other neurological disorders (Robin, Somodi, & Luschei, 1991).

The studies cited above, in part or in whole, share certain features that may be regarded as assumptions. First, there is the assumption that *force* is an important measure in the evaluation of orofacial nonverbal performance. Force has been considered seriously as one of the likely variables controlled by the nervous system in producing motor behavior (Stein, 1982); indeed, one motivation for the measurement of force in orofacial structures was the strong relationship of force magnitudes and variabilities to the firing patterns of cortical motoneurones and the particular sensitivity of this relationship in the *submaximal* (fine) force range (see review of this

0022-4685/94/3705-1020

work in Barlow, 1984). The measurement of fine force control of orofacial structures was also appealing because theoretical analysis had suggested that the structures of the speech mechanism probably utilized no more than about 20% of their maximum force-generating capabilities for conversational speech production (Müller, Milenkovic, & MacLeod, 1984). There are, however, essentially no empirical data to support this latter estimate of force magnitudes during speech.

The second assumption, particularly relevant to studies of fine force control, is that a ramp-and-hold task is an appropriate model of force production during speech. All studies of orofacial fine force control (see also McNeil, Weismer, Adams, & Mulligan, 1990; Amerman, 1993), as well as studies of maximum force in orofacial structures (see also Wood, Hughes, Hayes, & Wolf, 1992), have used a task wherein the subject is given an explicit or implicit (i.e., maximum force) target and asked to match and hold that target from a zero force effort. No rationale has been developed in the literature for the choice of ramp-and-hold force tasks in the evaluation of orofacial control; moreover, models and empirically based theoretical perspectives from the general motor control literature suggest that *impulse*-type tasks are better analogs of actual movement control (Newell & Carlton, 1988; Corcos, Agarwal, Flaherty, & Gottlieb, 1990).

The third assumption, specific to studies of maximum force production, is that maximum effort tasks in orofacial structures may provide useful information about speech production in persons with motor speech disorders. The specific assumption seems to be that if weakness is detected in a maximum effort task, the structure will not be fully functional for speech (Darley, Aronson, & Brown, 1975). According to Luschei (1991), measures of maximum force production may provide insight into the ability to recruit motor units for rapid contractile efforts, such as those associated with speech production. There are apparently no data to support these views.

The fourth assumption, relevant to all studies cited here, is that the evaluation of orofacial *nonverbal* motor control is useful for understanding the nature of a speech production deficit in persons with motor speech disorders. This assumption is rarely treated explicitly in the literature, but has recently been examined in detail by Weismer and Forrest (1992), who argued that an analysis of approximately 20 relevant publications from 1964 to the present failed to support a compelling link between motor control for orofacial nonverbal and verbal movements. Moreover, Weismer and Forrest (1992) presented theoretical arguments against the use of orofacial, nonverbal tasks in the assessment of motor *speech* disorders (as opposed to their use for differential diagnosis of neurological disease, which is the primary responsibility of the neurologist; see Gerratt et al., 1991) and noted the absence in the literature of a well-developed, empirically driven rationale for the use of these tasks in understanding speech production deficits.

It is possible that convincing links between orofacial, nonverbal tasks and speech production behavior have not emerged in the literature because the most appropriate tasks and/or measurements have not been made. The generally negative profile in the literature does not necessarily imply an outright rejection of nonspeech tasks in the evaluation of motor speech disorders, but perhaps a rethinking of the rationale for, and design of, these tasks. One example of a different approach to evaluation of orofacial nonverbal control is found in McClean, Beukelman, and Yorkston (1987), who explored visuomotor orofacial force tracking of sinusoidally varying patterns in several dysarthric speakers. McClean et al. (1987) reasoned that continuously varying changes in muscle output may be more useful than step-like changes, as are required in ramp-and-hold tasks, for predicting movement performance during speech. McClean et al. obtained encouraging results, showing correlations between tracking success and speech intelligibility. The reasoning of McClean et al. (1987) that a dynamic task might be more sensitive than a static task as an indicator of orofacial control capabilities (see also Moon, Zebrowski, Robin, & Folkins, 1993) is broadly consistent with the theoretical position of Corcos et al. (1990), described above.

In the present experiment, we tried to incorporate the idea of dynamic force evaluation of orofacial, nonverbal control within a task that was modeled on speech-like sequences and required impulse-like force productions. We focused on *lingual* force production because of the importance of tongue dynamics in normal and disordered speech. Our initial evaluation of this task used healthy subjects with no known previous neurological problems and asked the following questions: (a) Is the temporal structure of sequences of force impulses and sequences of syllables similar or different when the syllable sequences serve as the model for the force impulse sequences? (b) Are stress variations inherent in the syllable sequences reflected in sequential variations in force-impulse magnitudes, under the assumption that stressed syllables are typically produced with greater muscle force than unstressed syllables (Lubker & Parris, 1970; Malecot, 1966, 1968)? and (c) Are the magnitudes of force impulses modeled on syllables relatively small compared to maximum lingual forces and, therefore, consistent with the suggestion by several authors (Barlow & Rath, 1986; Müller, Milenkovic, & MacCleod, 1984; McNeil, Weismer, Adams, & Mulligan, 1990) that articulatory forces are only a fraction of maximum orofacial force capabilities? Our general purpose in asking these questions was to assess the potential of a force-impulse task, modeled on syllable sequences, in serving as a useful evaluation of orofacial, nonspeech motor control. To the extent that the timing and force characteristics of the impulse-task resembled measured speech timing characteristics and inferred force variations associated with stress contrasts, the task might be useful to pursue among clinical populations.

Method

Subjects

Twenty young adults (10 females [22–27 years of age; $\bar{X}$ = 24.2 years]; 10 males [22–30 years of age; $\bar{X}$ = 25.6]) served as experimental subjects. No subject had a prior history of neurologic disease or speech, hearing, or language problems, and none were taking medications known to affect motor activity.

Reiterant Force Task: Theoretical Considerations

Data collection consisted of three phases. First, subjects were trained to produce the reiterant speech task. Next, recordings of the real speech utterances and reiterant versions were made. Finally, subjects were asked to produce reiterant force patterns that corresponded to the reiterant speech utterances.

The force impulse sequences investigated in this experiment were modeled on syllable patterns derived from real speech tasks. Liberman and Streeter (1978) suggested that reiterant speech tasks preserve patterns of duration in real speech within and across speakers. The expectation of force differences associated with stress differences is based on a limited amount of relevant data in the literature as well as inferences from articulatory kinematics. Lubker and Parris (1970) reported higher averaged labial pressures for /b/ and /p/ in prestressed, as compared to preunstressed, position but noted a large amount of intersubject variability for this effect.[1] Malecot's (1966, 1968) work in this area is consistent with the stress-related variations in force. In addition, the inference of force differences associated with stress differences can be made from articulatory kinematic data. Closing and opening movements for stop consonant articulation involve greater displacement and velocity for prestressed, as compared to preunstressed stops (Kelso, Vatikiotis-Bateson, Saltzman, & Kay, 1985; Ostry, Keller, & Parush, 1983). Because articulatory accelerations are likely to be highly correlated with velocities, the greater velocities in stressed environments should produce greater articulatory forces. Given these considerations, it was expected that a force sequence that successfully imitated a reiterant syllable sequence would reflect the varying forces and timing associated with stress and position variation.

Reiterant Force and Speech Tasks: Apparatus and Procedures

A lingual transducer designed to transduce force with roughly the same vectors as those utilized for the production of lingual-alveolar consonants was used. Speech utterances were selected to include lingual-alveolar consonants preceding stressed and unstressed syllables. Speech utterances were *daddy, daddy dear, daddy dear did, daddy dear did decadence,* and *daddy dear did decadence adore*. The systematic expansion of utterance length was included to evaluate possible length effects on force impulse sequence production (see below). Subjects were trained to produce reiterant versions of these sentences, using the syllable /dɑ/. The expected reiterant sequence for the seven-syllable utterance (*daddy dear did decadence*), for example, was [ˈdɑdədɑːdəˈdɑdədə]. There were two instances in the target utterances where a syllable was not initiated with a lingual-alveolar consonant (de*c*adence, *a*dore). In these cases subjects were instructed to produce a force as if it were initiated with a lingual-alveolar consonant. Ten repetitions of each of the selected utterances were randomized into a single task list (5 utterance × 10 repetitions = 50 utterances). To familiarize subjects with the target utterances, they were asked to read each utterance from the list aloud using a normal speaking rate. Subjects were then trained to produce the reiterant speech version of the utterances by substituting /dɑ/ (phonetically, [dɑ] or [də], depending on stress) for each syllable within the utterance. The actual data collection was begun when the experimenter was satisfied with a subject's performance on the reiterant speech task.

Productions of both the real sentences and reiterant speech task were recorded on magnetic tape with a 7-second pause between utterances. After all 50 utterance pairs were recorded, subjects were given a 5-minute rest period. The prerecorded utterances (real speech and reiterant speech) were then played back to the subject, and the subject was asked to tap the transducer for each syllable while attempting to preserve the articulatory effort and rhythm pattern of the reiterant speech utterance, which always followed its real-speech counterpart on the tape. Subjects were specifically instructed not to produce the successive force impulses with the tongue resting on the arm of the transducer, because pilot work had demonstrated that this resulted in variable background forces. Moreover, the tap strategy appeared to be more analogous to the force impulses produced by the transient tongue-tip contact with the alveolar ridge during a sequence of lingual-alveolar stops.

Maximum Force Tasks

For the maximum hold task, subjects were instructed to press their tongue as hard as possible against the apparatus and to sustain that effort for 3 seconds. A total of 4 trials were collected for each subject with a 1-minute rest between each trial. Subjects were also asked to tap the transducer with a maximum force. Maximum tap forces were collected as a potentially more appropriate reference for the submaximum force taps collected in the reiterant force task. A total of 4 maximum tap trials were collected.

Transducer and Processing of Signals

The lingual transducer was positioned between the incisors using citricon dental compound to increase the stability of the yoke. The contact arm extended into the oral cavity and was designed to translate the force generated by the tongue to an active arm located outside the oral cavity. The construction and performance of this kind of transducer has been described by Barlow and Abbs (1983). The transducer was calibrated using a series of gram weights.

The analog force signal was input to a bridge amplifier, low pass filtered (50 Hz) and digitized on-line at a sampling rate of 500 samples per second (data translation DT2821 A/D board, Cspeech software [Milenkovic, 1992]). Forces were monitored simultaneously on an oscilloscope connected in parallel with the data collection devices.

---

[1] Lubker and Parris (1970) used a miniature pressure transducer affixed to the lower lip to record pressures created by bilabial closure. Assuming that the area of labial contact was constant across stress conditions, labial force variations should follow directly the reported pressure variations.

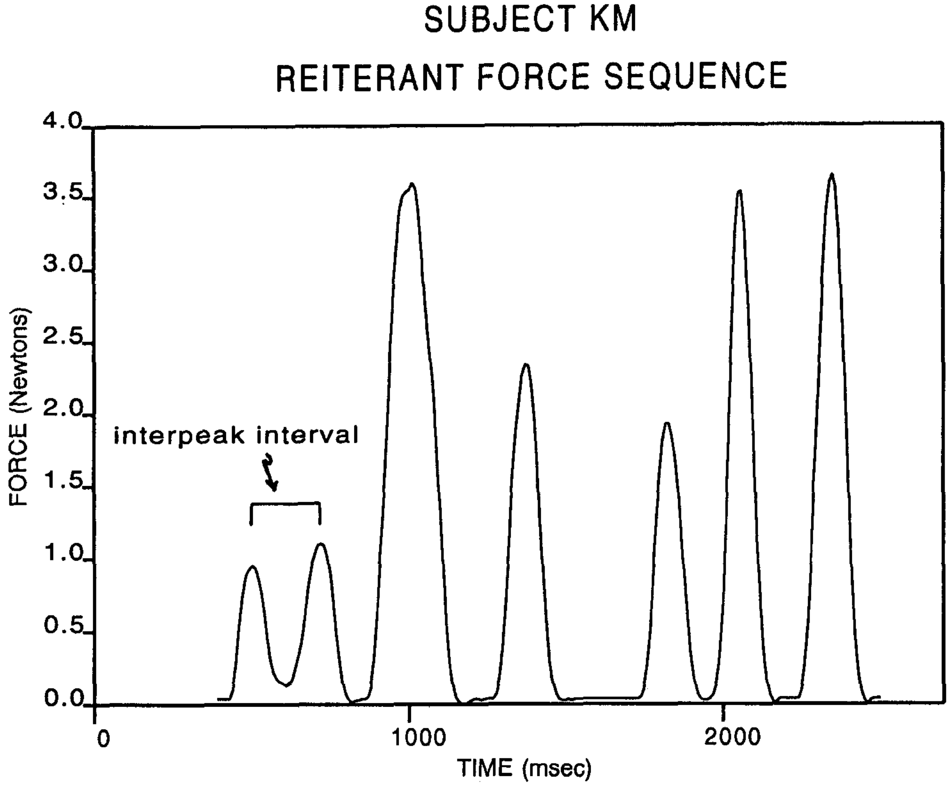

FIGURE 1. An example of a reiterant force sequence modeled on a seven-syllable reiterant speech utterance. The temporal interval between the first and second force impulses is indicated; this interval would correspond to the acoustic interval between the first and second bursts of the reiterant and real speech utterances. All other intervals would be measured using the same approach (see text).

Data Analysis

Force. In the hold task, the average maximum tongue force was obtained by measuring the force trace displayed by Cspeech at 200-msec increments throughout the middle 1-sec interval of each of the 4 trials. The average maximum hold force was estimated by determining an average maximum force for a given trial (across the 4 measurement points), and then averaging these values across the 4 trials. The average maximum tongue tap force was calculated by measuring the peak of the four taps and computing the mean across the trials. Average maximum hold or tap forces were used to compute percent-of-maximum forces generated during the reiterant force task (see below).

In the reiterant force task, peak force values were measured at the release of each force impulse as illustrated in Figure 1. Measurements were made at the release of the tap so that the timing of the interpeak intervals would correspond to temporal landmarks in the acoustic signal, which consisted of stop bursts (see below). If the number of impulse peaks in the reiterant force pattern did not correspond to the number of syllables in the target utterance the trial was discarded.

Timing. For the reiterant force sequences, interpeak intervals were measured as shown in Figure 1 for a single interval from a seven-syllable trial. These intervals were considered to be analogous to interburst intervals measured for the real and reiterant speech utterances, using standard criteria, from combined waveform/spectrogram displays produced by Cspeech. For example, the interval between the first and second force peaks, as reflected in Figure 1, was taken to be analogous to the interval between the first and second stop bursts in the speech utterances. In the case of the real-speech utterances, the /k/ burst in *decadence* and the glottal-stop or first glottal pulse in a*dore* were taken as the boundaries for syllables. Although the primary comparisons of interval timing were between the reiterant force and speech sequences, the timing of the real speech utterances was measured to evaluate the correspondence between real and reiterant speech.

Results

The analysis of the entire data set showed no systematic effects due to utterance length; therefore, only data from the seven-syllable sequences (*daddy dear did decadence*) will be reported in detail here. Where appropriate, some reference to findings from other sequence lengths will be made. The full set of results can be found in Bunton (1993).

Reliability

Interjudge and intrajudge reliability was calculated for the peak force, interpeak timing, reiterant speech timing, and real speech timing measures. The examiner and a second examiner remeasured 60 randomly selected utterances (3 for each

TABLE 1. Interjudge and intrajudge reliability for the four measures in this investigation. Values are mean absolute measurement errors and standard deviations of those means (in parentheses). Correlation coefficients are reported for the original and reliability set of measures.

Measures	*M* (*SD*)	Correlation coefficient
Peak Force		
Interjudge	0.00235 N (0.00403)	1.00
Intrajudge	0.00682 N (0.04257)	0.998
Force Timing		
Interjudge	2.163 msec (2.898)	1.00
Intrajudge	5.310 msec (8.837)	1.00
Reiterant Speech		
Interjudge	0.4027 msec (1.1513)	1.00
Intrajudge	0.1174 msec (0.4453)	1.00
Real Speech		
Interjudge	1.256 msec (4.829)	1.00
Intrajudge	1.289 msec (1.945)	1.00

subject) to obtain estimates of reliability for the four measurements. Mean measurement errors and associated standard deviations, plus correlation coefficients, are listed in Table 1. Absolute mean errors for interjudge and intrajudge measurements were greater than 0 for all tasks; therefore, correlation coefficients could not actually equal 1.0, but were the result of computer rounding. The magnitudes of measurement errors were considered to be sufficiently small to eliminate the possibility that measurement error might account for some of the effects described below.

Maximum Forces

Mean forces and standard deviations for the maximum hold and maximum tap tasks are presented for each subject in Table 2. In the maximum hold task, maximum lingual forces across the female subjects ranged from 6.704 Newtons (N) to 28.822 N ($\bar{X}$ = 15.19 N) and across the male subjects from 8.303 N to 16.289 N ($\bar{X}$ = 11.72 N). Intrasubject standard deviations based on the 4 trials for individual subjects were typically small relative to the means. The variability in mean maximum performance across subjects is consistent with data reported by Barlow and Rath (1985) for maximum force produced by the upper and lower lips and for maximum tongue protrusion forces (anterior, left lateral, and right lateral) reported by Dworkin, Aronson, and Mulder (1980). The greater mean maximum hold force for females, as compared to males, is a reversal of the gender effect reported by Barlow and Rath (1985) for the lips but is consistent with lower lip data obtained by Amerman (1993).

TABLE 2. Mean maximum hold and maximum tap force productions and standard deviations (in parentheses). All values are reported in Newtons (N). Each mean and standard deviation is based on 4 trials.

Subject	Maximum hold (N)	Maximum tap (N)
Females		
DM	10.592 (0.672)	9.993 (0.609)
SB	6.704 (0.788)	6.191 (1.267)
KA	10.092 (0.170)	9.743 (0.717)
KE	20.618 (1.119)	20.263 (1.562)
MS	23.855 (0.649)	10.441 (0.668)
RS	16.947 (0.589)	11.400 (2.20)
DR	11.151 (1.166)	8.420 (2.48)
KM	13.105 (0.852)	10.430 (2.97)
HS	28.822 (1.649)	24.160 (2.26)
TH	10.072 (0.705)	10.270 (1.237)
Males		
JT	13.092 (0.277)	14.368 (1.705)
TK	12.289 (0.519)	6.987 (1.208)
TS	16.289 (0.112)	13.467 (1.604)
RT	10.026 (0.253)	10.138 (0.785)
JG	11.684 (0.284)	10.580 (0.785)
EW	15.217 (0.953)	18.283 (2.46)
MK	15.875 (0.857)	14.070 (3.40)
NA	11.151 (0.857)	9.849 (0.139)
BP	10.553 (0.979)	10.414 (0.641)
GW	8.303 (1.162)	8.395 (1.132)

All subjects appeared to have difficulty with the maximum tap task as evidenced by the shape of the force curves. Figure 2 illustrates this with a single maximum hold and maximum tap trace produced by subject EW. The maximum hold trace shows that the force was held for a period of time before release, consistent with the instructions to the subjects. In the maximum tap task, the force was expected to rise to a momentary peak and then decline, but the trace illustrates that the maximum force was held for approximately 300 msec before release. Maximum tap forces ranged from 6.191 N to 24.16 N ($\bar{X}$ = 12.13 N) for females and from 6.987 N to 18.283 N ($\bar{X}$ = 11.65 N) for males. The maximum tap forces were roughly comparable to the maximum hold forces.

Peak Force Measures: Reiterant Force Task

Mean peak forces and standard deviations in the reiterant force task were calculated for each impulse across repetitions of the seven-impulse sequence, corresponding to the seven-syllable utterance length. For 11 subjects at least one trial of the seven-syllable utterance had to be eliminated because the number of force impulse peaks did not correspond to the number of syllables produced during the reiterant speech task. Some subjects (KA, HS, JT) consistently had difficulty matching the number of impulses to the number of syllables. The number of measured trials, mean force values, and standard deviations for individual subjects are listed in Table 3.

Two general observations concerning these data can be made. First, the variability for a given tap within a subject was sometimes quite large, as evidenced by the large within-tap, across-trial standard deviations. For example, it was not unusual to obtain standard deviations approaching 50% or more of the mean force impulse (see female subjects DM, SB, DR, KM, and TH; and male subjects JT, TK, RT, JG, EW, and GW). An example of this variability is shown for the first six trials of subject KM's reiterant force trials (Figure 3). Note the differences in peak force magnitude across trials and the number of peaks produced for each trial. The second observation is that the magnitude of peak force taps within one utterance length did not always predict the magnitude for another utterance length, even for the same subject. Subject DM, for example, produced mean forces for tap 1 in the four- and seven-syllable utterances of 1.676 N and 0.583N, re-

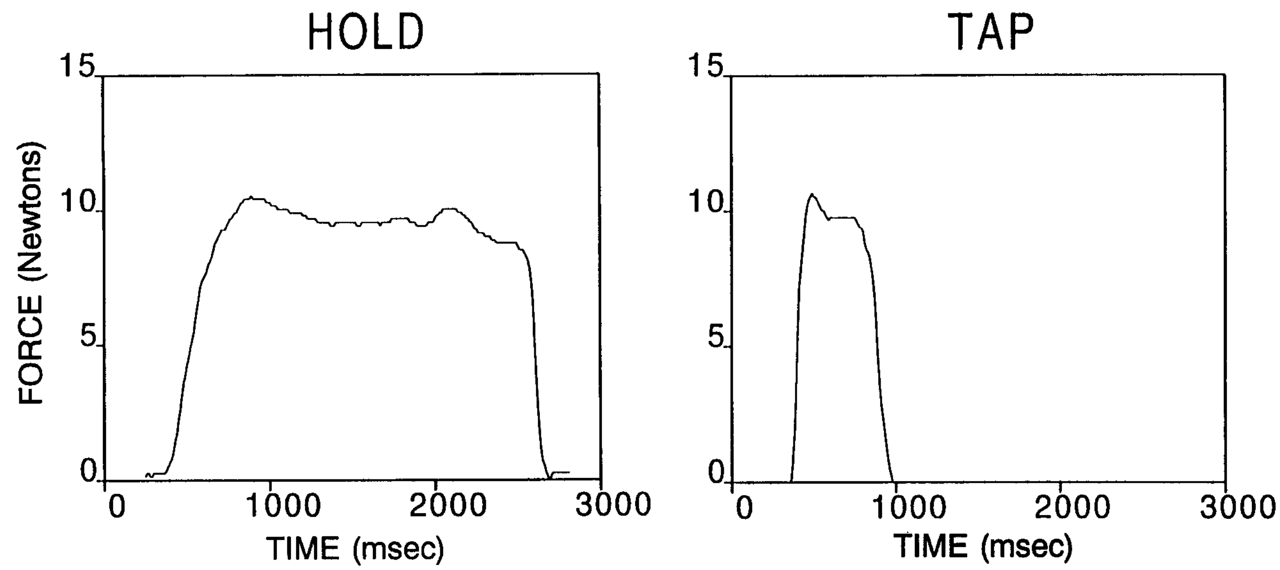

FIGURE 2. An example of a maximum force trace from the hold (left) and tap (right) conditions.

spectively (Bunton, 1993). Both of these observations tend to suggest that the performance on this task was not particularly stable, at least in terms of peak force magnitude.

With respect to force tap magnitudes reflecting stress contrasts in the speech utterances, greater force was expected on the stressed, as compared to unstressed, syllables. Comparisons between the first and second force taps (corresponding to the stress difference in /ˈdædi/, with greater stress on the first syllable) and the fourth and fifth force taps (corresponding to /dɪd ˈdɛ/, with greater stress on the second syllable) were undertaken to evaluate this hypothesis. Analysis of these force differences showed that no subject produced statistically significant ($p \leq 0.05$) force variations for these contrasts.

Percent Maximum Force Produced During Reiterant Force Tasks

The magnitudes of impulse force used during the reiterant force task were expressed as percentages of maximum force, using both the maximum hold and maximum tap forces as references. Results suggested that the percentages did not differ, depending on which maximum force was used to normalize the data. Thus, the percentage-of-maximum force data reported here are based only on the maximum hold-forces; these data are reported in Table 4. For females, reiterant force impulse peaks ranged from 3.0% to 25.4% of maximum, whereas for males, the corresponding range was 0.7–55.6%. Müller, Milenkovic, and MacLeod (1984) esti-

TABLE 3. Mean peak force values and standard deviations (in parentheses) for individual subjects. All values are reported in Newtons (N).

Subject	*n*	tap 1	tap 2	tap 3	tap 4	tap 5	tap 6	tap 7
Females								
DM	10	0.583 (0.222)	0.358 (0.268)	0.539 (0.108)	0.522 (0.311)	0.556 (0.346)	0.309 (0.122)	0.462 (0.374)
SB	10	1.282 (0.556)	1.364 (0.674)	1.788 (1.068)	1.723 (1.054)	1.499 (0.617)	1.151 (0.442)	2.122 (1.419)
KA	4	0.386 (0.112)	0.976 (0.873)	1.095 (0.211)	1.191 (0.108)	1.003 (0.228)	1.108 (0.247)	0.947 (0.213)
KE	10	4.351 (0.556)	4.767 (0.764)	4.621 (1.021)	4.527 (0.654)	3.856 (1.363)	3.725 (0.691)	4.700 (0.553)
MS	10	0.903 (0.508)	0.819 (0.309)	1.134 (0.393)	1.326 (0.475)	0.748 (0.379)	0.671 (0.295)	1.016 (0.216)
RS	9	0.606 (0.209)	0.723 (0.246)	0.735 (0.251)	0.804 (0.295)	0.706 (0.295)	0.699 (0.297)	0.892 (0.343)
DR	10	0.929 (0.806)	0.792 (0.548)	1.167 (0.985)	0.951 (0.502)	0.414 (0.428)	0.316 (0.355)	1.028 (0.953)
KM	9	1.612 (0.916)	1.451 (1.064)	2.716 (1.044)	2.006 (0.648)	1.982 (1.061)	1.599 (1.495)	2.211 (1.711)
HS	3	4.074 (1.476)	4.390 (1.011)	4.913 (1.506)	6.230 (2.370)	3.324 (1.149)	4.211 (1.500)	6.280 (1.740)
TH	10	1.116 (0.705)	0.704 (0.239)	0.992 (0.379)	1.225 (0.679)	0.801 (0.527)	0.447 (0.231)	1.301 (1.151)
Males								
JT	3	0.364 (0.044)	0.373 (0.298)	0.454 (0.381)	0.792 (0.604)	0.267 (0.019)	0.741 (0.691)	0.646 (0.609)
TK	8	0.186 (0.123)	0.241 (0.099)	0.225 (0.052)	0.258 (0.269)	0.207 (0.136)	0.245 (0.081)	0.250 (0.212)
TS	9	8.477 (2.072)	6.023 (2.696)	7.350 (2.511)	7.026 (2.671)	8.421 (2.177)	6.572 (2.932)	6.864 (1.650)
RT	10	0.384 (0.233)	0.694 (0.342)	0.706 (0.305)	0.600 (0.361)	0.267 (0.183)	0.444 (0.794)	0.452 (0.354)
JG	10	0.454 (0.325)	0.268 (0.241)	0.551 (0.475)	0.569 (0.532)	0.417 (0.390)	0.252 (0.317)	0.497 (0.584)
EW	7	2.472 (1.539)	3.892 (2.530)	3.012 (2.339)	1.941 (1.007)	1.582 (1.487)	1.411 (0.824)	2.330 (1.231)
MK	9	2.599 (1.163)	4.146 (1.444)	3.415 (1.612)	3.568 (1.598)	3.637 (1.507)	3.839 (1.729)	3.601 (1.290)
NA	10	4.041 (1.247)	4.335 (0.965)	4.626 (1.372)	4.606 (1.619)	4.505 (0.956)	3.860 (1.297)	4.777 (1.607)
BP	9	2.042 (0.529)	1.448 (0.442)	2.359 (0.898)	2.202 (1.028)	2.147 (0.855)	1.995 (1.229)	2.282 (0.793)
GW	9	1.358 (0.624)	2.222 (1.253)	2.208 (0.941)	2.202 (0.924)	1.818 (0.855)	1.942 (0.873)	2.443 (1.312)

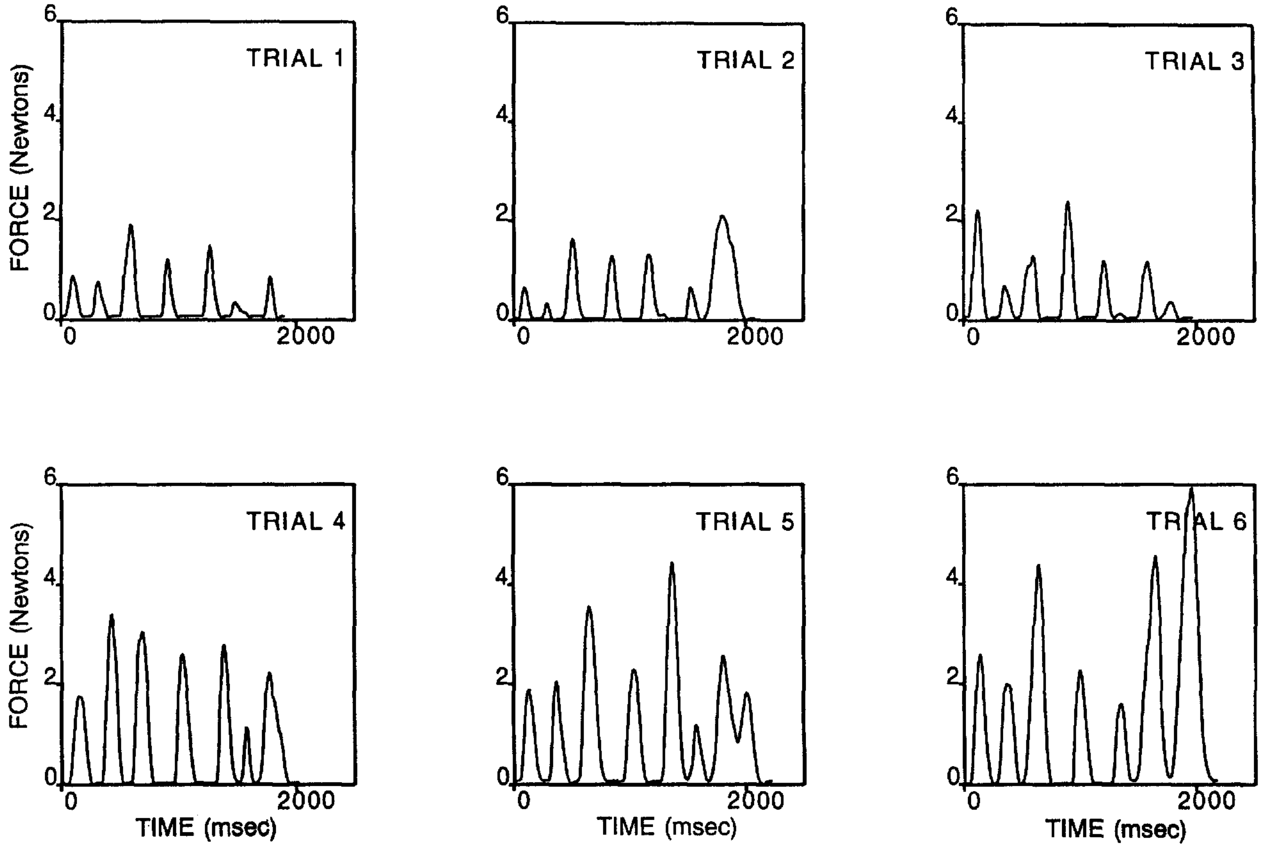

FIGURE 3. Reiterant force traces from the first 6 trials of subject KM's 10 trials.

mated that subjects use approximately 5–20% of maximum force during speech production, a range that captures approximately 67% of the female percentages and 33% of the male percentages reported in Table 4. For a given subject, percentage of maximum force was not consistent across utterance lengths (Bunton, 1993), but within an utterance, percentages did not appear to vary much.

TABLE 4. Percentage of maximum force used during the seven syllable reiterant force task based on maximal hold force values.

Subject	tap 1	tap 2	tap 3	tap 4	tap 5	tap 6	tap 7
Females							
DM	5.5	5.8	3.3	13.9	20.7	26.0	15.3
SB	19.1	20.7	20.3	18.1	17.0	20.3	21.6
KA	9.7	10.1	9.6	6.8	9.8	9.6	12.1
KE	21.1	21.4	23.1	5.1	5.4	4.9	5.2
MS	3.7	8.6	3.4	26.6	28.8	25.7	27.8
RS	3.5	5.3	4.2	10.8	11.2	11.8	12.2
DR	8.3	11.0	7.1	22.4	22.8	21.9	22.3
KM	12.3	15.4	7.8	4.7	10.8	5.5	12.6
HS	14.1	16.8	6.3	4.3	6.4	4.7	7.0
TH	11.5	11.3	9.4	10.4	13.8	8.5	11.2
Males							
JT	2.7	2.5	2.8	2.6	3.5	3.1	6.1
TK	1.5	2.6	1.9	3.5	1.8	3.2	2.1
TS	52.0	62.9	36.9	44.7	45.1	54.5	26.5
RT	3.4	3.4	6.9	6.8	7.1	6.9	5.5
JG	3.8	4.2	2.29	2.5	4.7	5.2	3.7
EW	16.2	13.5	25.6	21.2	19.7	16.4	52.1
MK	16.3	18.4	26.1	29.4	21.5	24.2	5.9
NA	36.2	41.0	39.0	44.2	41.4	46.9	5.3
BP	19.3	19.6	13.7	13.9	22.3	22.6	10.6
GW	16.3	16.1	26.7	26.4	26.5	26.3	25.3

Timing Measurements: Reiterant Force and Speech Tasks

Group means and standard deviations for measurements of interpeak timing in the reiterant force task and interburst intervals in the real speech and reiterant speech tasks are reported in Table 5. These group data suggest that intervals in the reiterant force tasks were, with a single exception (interval 3-4, male group), always of greater duration than the corresponding intervals in the reiterant speech and real speech tasks. In the male group, mean interval durations for the reiterant speech tasks were always greater than the corresponding intervals in the real speech task; data for the female group were split exactly in half for the comparison of reiterant and real speech intervals. The relatively large standard deviations present for all intervals and both subject groups is consistent with other observations of large variation in speaking rate across individuals (Miller, Grosjean, & Lomato, 1984).

Another way to examine the timing differences between the reiterant force and speech tasks is to plot cumulative timing functions across the six measured intervals. When such plots were prepared for individual subjects two trends emerged. Seventeen subjects demonstrated a divergence of the curves as the utterance unfolded. This is illustrated in the

TABLE 5. Group means (in msecs) and standard deviations (in parentheses) of interpeak (reiterant force task) and interburst (reiterant and real speech tasks) durations for the seven syllable utterance. All intervals referred to as "syllables."

	n	syllable 1–2	syllable 2–3	syllable 3–4	syllable 4–5	syllable 5–6	syllable 6–7	TUD
Females								
Real speech	75	197.51 (22.13)	184.43 (29.56)	351.97 (42.53)	284.59 (49.19)	175.72 (11.89)	97.62 (21.14)	1291.8 (117.2)
Reiterant speech	85	174.85 (21.6)	183.2 (33.24)	383.0 (81.36)	393.6 (193.8)	164.3 (24.1)	159.27 (43.73)	1458.2 (277.2)
Force timing	85	252.88 (50.76)	282.96 (67.59)	430.8 (98.4)	425.8 (136.7)	259.19 (80.75)	301.9 (107.7)	1953.5 (343.5)
Males								
Real speech	84	170.66 (21.42)	215.77 (91.26)	357.90 (141.9)	277.14 (80.18)	161.87 (43.53)	85.15 (20.59)	1268.5 (297.2)
Reiterant speech	84	176.79 (71.24)	335.0 (160.6)	457.5 (292.4)	488.8 (156.4)	180.29 (86.66)	185.4 (89.4)	1823.7 (545.1)
Force timing	84	250.8 (87.20)	395.2 (170.0)	439.8 (148.3)	517.9 (253.8)	291.2 (105.1)	294.5 (128.5)	2189.5 (608.7)

top panel of Figure 4, where cumulative duration is plotted as a function of syllable interval number for reiterant force (boxes) and speech (circles) tasks, respectively. The remaining three subjects maintained similar timing intervals for both tasks. An example is provided in the bottom panel of Figure 4.

Intrasubject Variability

Intrasubject timing variability for the real speech, reiterant speech, and reiterant force timing intervals was calculated to determine the across-trial stability of the tasks. Average intrasubject variability was calculated by taking the mean of the individual subject standard deviations for a given syllable, within gender. As shown in Figure 5, results suggest that averaged intrasubject variability tended to be greatest in the reiterant force task (triangles), followed by the reiterant speech task (boxes) and real speech task (circles). This

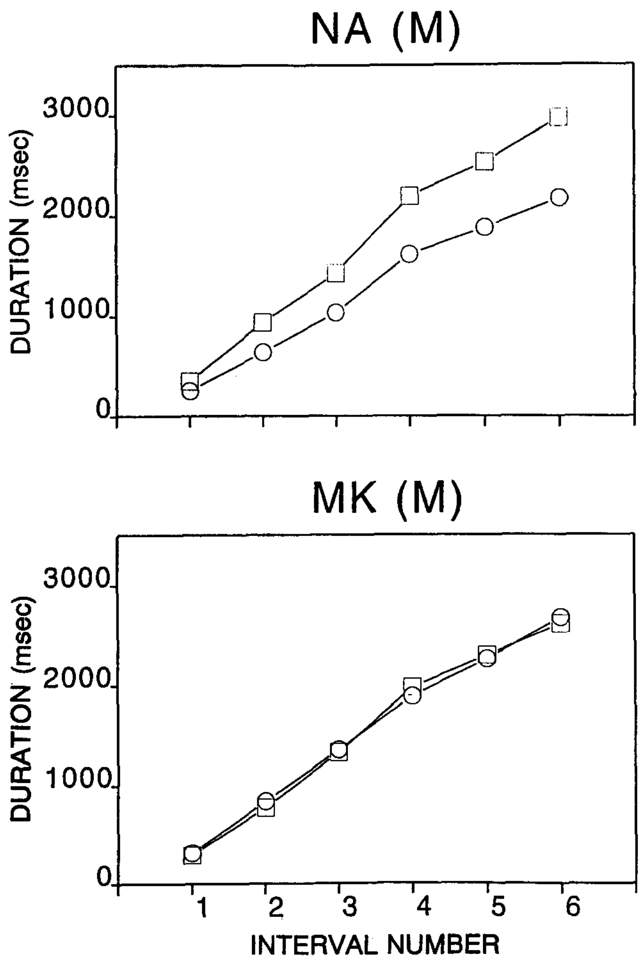

FIGURE 4. Examples of cumulative timing patterns, across measurement intervals, for subjects showing divergence (top) and similarity (bottom) of reiterant force (boxes) and speech (circles) timing.

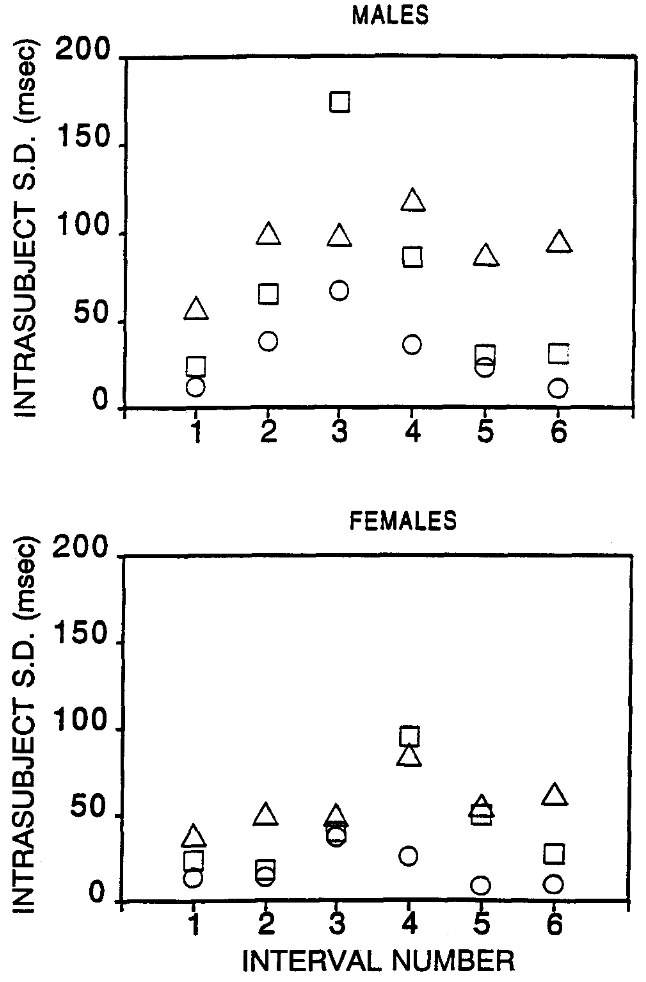

FIGURE 5. Intrasubject timing variability in reiterant force (triangles), reiterant speech (boxes), and real speech (circles) tasks, plotted across measurement intervals (see Figure 1) for males (top) and females (bottom). All plotted points are the means of the individual subject standard deviations computed for the total trials per task.

pattern was consistent across utterance lengths (Bunton, 1993). Intrasubject variability in the real speech task was consistent with data presented by Allen (1973), who estimated that the standard deviation of speech segment durations is typically 5–10% of the mean duration.

Discussion

Peak Force as a Function of Underlying Stress Contrast

Peak force measurements were completed to determine if normal subjects' performance in the reiterant force task mimicked stress patterns produced during speech. Comparisons of peak forces that corresponded to stressed-unstressed contrasts in the reiterant speech tasks demonstrated that no statistically significant force contrasts were produced by subjects. Subjects' peak force standard deviations across the 10 repetitions of an utterance length were also very large. This high variability for reiterant taps suggests that subjects were not able to produce peak forces consistently. One possible conclusion, then, is that subjects were unable to maintain adequate control during the reiterant force task to reproduce the force differences associated with stress contrasts.

There are other explanations, however, for the failure to obtain peak force differences corresponding to stress contrasts. First, several subjects complained that the placement of the lingual transducer did not allow them to tap the transducer with the tip of their tongue as expected for a lingual-alveolar consonant. Instead they used the body of their tongue to hit the transducer. Thus, placement of the transducer may have limited subjects' ability to produce forces that were representative of contrasts produced during speech. Second, other measures of force, such as the rate of impulse growth or area under the impulse, may have reflected the stress contrasts even in the absence of peak force differences. Because rate of force impulse growth is typically correlated with peak force magnitude (Newell & Carlton, 1988), this explanation for the lack of force contrasts does not seem particularly likely. A third possibility is that the lack of force contrasts related to stress contrasts in the reiterant speech utterances reflects the lack of specificity of force in speech. Although previous data and considerations from the literature suggest that force differences should be associated with stress contrasts (see above), there is one view of speech production that is based on the idea that because many articulatory gestures are "stopped" by fixed vocal tract structures, the underlying gesture does not require precise specification of forces (Perkell & Nelson, 1982; Fujimura & Kakita, 1979). In this view, after force reaches some threshold it can vary over a wide range, or saturate, without having much effect on articulatory placement or precision. In the current study, many subjects (DM, KA, MS, RS, TH, JT, TK, RT, and JG) consistently produced peak forces in the reiterant force task that were less than 10% of their maximum force. If subjects were using a saturation-based strategy of articulation, higher peak forces would be expected. Thus, the saturation explanation does not seem likely for the lack of consistent force differences associated with stress contrasts. Lastly, it is possible that articulatory force differences are not reliably associated with stress contrasts. If this is the case, the absence of stress-conditioned force differences in the current study would be consistent with force control in speech production. Studies that measure forces or articulatory pressures during stop consonant production are needed to resolve these issues.

Maximal Force Production

The range of maximal hold and maximal tap force values across both the female and male subject groups was large; however, the range of maximal forces produced was similar for the two subject groups and is very much like across-subject variability reported for maximum forces generated by the lips (Barlow & Rath, 1985; Amerman, 1993) and tongue (Dworkin, Aronson, & Mulder, 1980). Reasons for high intrasubject and intersubject variability on maximal performance tasks in general have been addressed by Kent, Kent, and Rosenbek (1987). It seems reasonable to conclude that the vary large range of "normal" maximal forces exerted by orofacial structures limits the diagnostic utility of these measures in clinic settings.

There were no differences in maximal force values between maximal hold and tap tasks. Force traces for both tasks showed that the maximal force was held for a period of time before release, even though the maximal tap was held for a much shorter time. This suggests that subjects failed to produce true maximal taps, that is, impulse forces as in the reiterant force task, but instead produced abbreviated maximal holds.

Percent of Maximum Force

Percentage of maximum force used during the 50 reiterant force trials was not consistent for individual subjects. Subjects were able to use a relatively consistent percentage of maximum within a given trial of a specific utterance length, but standard deviations across the 10 trials of an utterance length were high. This provides additional evidence that subjects were not able to control the magnitude of the reiterant forces. Lack of familiarity, transducer orientation, or a saturation-based articulatory strategy, may have been responsible for these variable percentages, as discussed above.

Müller, Milenkovic, and MacLeod's (1984) estimate that articulatory forces for speech production are typically 5–20% of maximum force has become somewhat of a benchmark in the literature (see review in Barlow, 1991), but supporting data are not available. The range proposed by Müller, Milenkovic, and MacLeod (1984) captures 67% and 33% of forces produced in the reiterant force task by females and males, respectively. If the range is extended to include forces below 5% (i.e., a range of 0–20% of maximum), 75% of the forces produced by females and 61% by males would be included. Thus, the reiterant force tasks did seem to elicit the kinds of submaximal forces assumed to be used in speech production. Although this is an encouraging finding for further development of the task, the apparent instability of the submaximal force peaks is still troubling. It is possible that a less intrusive transducer would permit the production of less variable force taps; clearly, additional work on articulatory force production is needed to clarify this aspect of the task.

Timing

One way to judge the representativeness of the reiterant force task is to compare the timing of its intervals to the timing of corresponding intervals in the reiterant speech task. The present data suggest that reiterant force sequences are typically slower and more variable than reiterant speech sequences. In the current study, however, there was also a tendency for reiterant speech intervals to be longer and more variable than their corresponding real speech intervals. The tendency for different timing in the reiterant and real speech tasks is not consistent with data presented by Lieberman and Streeter (1978). They reported that duration patterns from reiterant speech were very stable across repetitions. One explanation for the difference between the current results and those from Lieberman and Streeter is that subjects in the latter study were allowed to practice the reiterant speech task until they felt comfortable with it, before the recording of the experimental utterances. In the present study practice was limited, suggesting that the novelty of the speech task may have contributed to inflated variability.

Does the fact that performance in the reiterant speech task was not an entirely faithful reflection of real speech timing complicate the interpretation of differences between reiterant force and speech timing? This question should be considered carefully because a primary purpose of the present study was to evaluate a nonspeech task of orofacial control that was modeled as closely as possible on speech. Perhaps the timing characteristics of the reiterant force task are due more to the timing of the reiterant speech utterances—the model for the force sequences—than to something inherent to the force task itself. Several considerations lead us to the conclusion, however, that the reiterant force timing *was* qualitatively different from timing in either of the speech tasks. First, for most of the subjects the difference between the timing of reiterant force intervals and reiterant speech intervals was substantially greater than the difference between reiterant and real speech intervals. Examination of individual subject data (Bunton, 1993) showed that the mean difference (computed across intervals) between the reiterant force and speech intervals was typically around 100 msec, whereas the corresponding mean difference between reiterant and real speech intervals was around 20 msec. Second, the evaluation of intrasubject, interval timing variability (Figure 5) suggested several cases in the reiterant force task for which the large averaged standard deviations instances could not be attributed solely to the larger mean interval value.[2] This suggests that the timing of the reiterant force sequences was relatively unstable compared to the timing of the reiterant speech and real speech sequences. Based on these considerations, the timing characteristics of the reiterant force sequences do not seem largely attributable to the characteristics of the reiterant speech models. Rather, the force sequences often seem to be uniquely slower and more variable than the speech sequences.

Task Considerations

It is certainly possible that the slow and variable timing characteristics of the reiterant force sequences could have been modified with practice in the direction of *speech* timing characteristics. Practice may also have reduced the variability of reiterant force peak magnitudes and led to force differences corresponding to stress differences in the reiterant speech utterances. The novelty of the reiterant force task, compared to the highly practiced nature of articulatory tasks, almost guarantees a difference in performance speed and variability between force and speech intervals. To our knowledge, none of the nonspeech, orofacial control tasks studied in the literature has involved a *substantial* practice component. To the extent that many of these tasks are investigated for their potential as diagnostic tools, the requirement of extensive practice for meaningful data (i.e., data that bear on the speech production capabilities of a patient) is obviously undesirable. The realities of clinical application, however, should not eliminate the need to study practice effects on performance in any nonspeech, orofacial motor control task. If McClean et al. (1987) are correct in characterizing different orofacial tasks used to evaluate speech motor capabilities as lying on a continuum whose endpoint is real speech production, it may be possible to move the present task even closer to speech production through extensive practice of force sequencing. In addition, the task could be made more speechlike by using a transducer that would allow force taps with nearly the same lingual dynamics as those occurring in speech production. A thin force transducer affixed to the alveolar ridge could accomplish this goal. Similarly, the reiterant force task could include phonation, which would establish aeromechanical conditions in the vocal tract similar to those in speech by guaranteeing an egressive airflow during the force taps. Such studies may, in fact, help answer the question of whether these kinds of nonspeech tasks are different from speech production performance by degree or kind. Of course, the continued addition of speechlike conditions would eventually yield a speech task, which may not be desirable if the assessment of orofacial, nonverbal control is judged to be a useful endeavor.

Conclusions

This experiment was designed to test the feasibility of using a dynamic nonspeech task as an analog of articulatory sequences. This task incorporated the idea of sequences of

---

[2] As discussed by Crystal and House (1988) and Weismer (1991), timing interval standard deviations tend to grow monotonically with the magnitude of the timing interval, so that longer intervals will have greater variabilities. A global rule of thumb is that the magnitude of the standard deviation will be approximately 5–10% of the mean magnitude for segment and syllable-sized intervals.

force impulses, much like the assumed requirement of force control during speech production. Results suggest that subjects did not consistently mark stress contrasts with variations in peak force and that peak force production was highly variable in all situations. However, the peak forces produced in the reiterant force task did tend to fall in the submaximal range previously hypothesized for speech production. Measurements of timing in the force and speech tasks indicated clearly that force timing was slower than speech timing. Overall, the results seem to suggest that the reiterant force and speech tasks were characterized by different control characteristics, but whether these differences are qualitative or quantitative cannot be answered here. Additional study of articulatory force or pressure production during speech is needed to clarify some of the issues raised in this study.

Acknowledgments

This investigation was supported in part by NIDCD R01 DC00319; we are grateful for that support. We would like to thank Kris Tjaden and Julie Liss for helpful comments on an earlier version of the manuscript. We dedicate this paper to the memory of Dr. Eric Müller, scientist, colleague, and friend extraordinaire.

References

Allen, G. D. (1973). Segmental timing control in speech production. *Journal of Phonetics, 1,* 219–237.

Amerman, J. D. (1993). A maximum-force-dependent protocol for assessing labial force control. *Journal of Speech and Hearing Research, 36,* 460–465.

Barlow, S. M. (1984). Fine force and position control of select limb and orofacial structures in the upper motor neuron syndrome. (Doctoral dissertation, University of Wisconsin). *Dissertation Abstracts International 45,* SEC B, P0474 (University Microfilms No. 84-05411)

Barlow, S. M. (1991). Recent advances in clinical speech physiology. *NIDCD Monograph, 1,* 183–195.

Barlow, S. M., & Burton, M. K. (1990). Ramp-and-hold force control in the upper and lower lips: Developing new neuromotor assessment applications in traumatically brain injured adults. *Journal of Speech and Hearing Research, 33,* 660–675.

Barlow, S. M., & Abbs, J. H. (1983). Force transducers for the evaluation of labial, lingual, and mandibular motor impairments. *Journal of Speech and Hearing Research, 26,* 616–621.

Barlow, S. M., & Abbs, J. H. (1986). Fine force and position control of selected orofacial structures in the upper motor neuron syndrome. *Experimental Neurology, 94,* 699–713.

Barlow, S. M., & Netsell, R. (1986). Differential fine force control of the upper and lower lips. *Journal of Speech and Hearing Research, 29,* 163–169.

Barlow, S. M., & Rath, E. (1985). Maximum voluntary closing forces in the upper and lower lips of humans. *Journal of Speech and Hearing Research, 28,* 373–376.

Bunton, K. (1993). *Evaluation of repeated force impulse tasks in the tongue.* Unpublished master's thesis, University of Wisconsin-Madison.

Corcos, D. M., Agarwal, G. C., Flaherty, B. P., & Gottlieb, G. L. (1990). Organizing principles for single-joint movements IV. Implications for isometric contractions. *Journal of Neurophysiology, 64,* 1033–1042.

Crystal, T. H., & House, A. S. (1988). A note on the variability of timing control. *Journal of Speech and Hearing Research, 31,* 497–502.

Darley, F. L., Aronson, A. E., & Brown, J. R. (1975). *Motor speech disorders.* Philadelphia: W. B. Saunders Co.

Dworkin, J. P., & Aronson, A. E. (1986). Tongue strength and alternate motion rates in normal and dysarthric patients. *Journal of Communication Disorders, 19,* 115–132.

Dworkin, J. P., Aronson, A. E., & Mulder, D. W. (1980). Tongue force in normal and in dysarthric patients with amyotrophic lateral sclerosis. *Journal of Speech and Hearing Research, 23,* 828–837.

Fujimura, O., & Kakita, Y. (1979). Remarks on quantitative description of the lingual articulation. In B. Lindblom & S. Ohman (Eds.), *Frontiers of speech communication research* (pp. 17–24). London: Academic Press.

Gerratt, B. R., Till, J. A., Rosenbek, J. C., Wertz, R. T., & Boysen, A. E. (1991). Use and perceived value of perceptual and instrumental measures in dysarthria management. In C. A. Moore, K. M. Yorkston, & D. R. Buekelman (Eds.), *Dysarthria and apraxia of speech: Perspectives on management* (pp. 173–184). Baltimore: Paul H. Brookes Publishing Co.

Kelso, J. A. S., Vatikiotis-Bateson, E., Saltzman, E. L., & Kay, B. (1985). A qualitative dynamic analysis of reiterant speech production: Phase portraits, kinematics, and dynamic modeling. *Journal of the Acoustical Society of America, 77,* 266–280.

Kent, R. D., Kent, J. F., & Rosenbek, J. C. (1987). Maximum performance tests of speech production. *Journal of Speech and Hearing Disorders, 52,* 367–387.

Liberman, M. Y., & Streeter, L. A. (1978). Use of nonsense-syllable mimicry in the study of prosodic phenomena. *Journal of the Acoustical Society of America, 63,* 231–233.

Lubker, J. F., & Parris, P. J. (1970). Simultaneous measurements of intraoral pressure, force of labial contact, and labial electromyographic activity during production of the stop consonant cognates /p/ and /b/. *Journal of the Acoustical Society of America, 47,* 625–633.

Luschei, E. S. (1991). Development of objective standards of nonspeech oral strength and performance. In C. A. Moore, K. M. Yorkston, & D. R. Buekelman (Eds.), *Dysarthria and apraxia of speech: Perspectives on management* (pp. 3–14). Baltimore: Paul H. Brookes Publishing Co.

Malecot, A. (1966). Mechanical pressure as an index of "force of articulation." *Phonetica, 14,* 169–180.

Malecot, A. (1968). The force of articulation of American stops and fricatives as a function of position. *Phonetica, 18,* 95–102.

McClean, M., Beukelman, D., & Yorkston, K. (1987). Speech muscle visuomotor tracking in dysarthric and nonimpaired speakers. *Journal of Speech and Hearing Research, 36,* 276–282.

McNeil, M. R., Weismer, G., Adams, S., & Mulligan, M. (1990). Oral structure nonspeech motor control in normal, dysarthric, aphasic and apraxic speakers: Isometric force and static position control. *Journal of Speech and Hearing Research, 33,* 255–268.

Milenkovic, P. (1992). *Cspeech* [Computer program]. University of Wisconsin-Madison.

Miller, J., Grosjean, F., & Lomato, C. (1984). Articulation rate and its variability in spontaneous speech: A reanalysis and some implications. *Phonetica, 41,* 215–225.

Moon, J. B., Zebrowski, P., Robin, D. A., & Folkins, J. W. (1993). Visuomotor tracking ability of young adult speakers. *Journal of Speech and Hearing Research, 36,* 672–682.

Müller, E., Milenkovic, P., & MacLeod, G. (1984). Perioral tissue mechanics during speech production. In J. Eisenfeld & C. DeLisi (Eds.), *Mathematics and computers in biomedical applications* (pp. 363–371). North Holland: Elsevier Science Publishers B.V.

Newell, K. M., & Carlton, L. G. (1988). Force variability in isometric responses. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 37–44.

Ostry, D. J., Keller, E., & Parush, A. (1983). Similarities in the control of the speech articulators and the limbs: Kinematics of tongue dorsum movements in speech. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 622–636.

Perkell, J., & Nelson, L. (1982). Articulatory targets and speech motor control: A study of vowel production. In S. Grillner, B. Lindblom, J. Lubker, & A. Persson (Eds.), *Speech motor control* (pp. 187–206). Oxford: Pergamon.

Robin, D. A., Somodi, L. B., & Luschei, E. S. (1991). Measurement of tongue strength and endurance in normal and articulation disordered subjects. In C. A. Moore, K. M. Yorkston, & D. R. Buekelman (Eds.), *Dysarthria and apraxia of speech: Perspectives on management* (pp. 173–184). Baltimore: Paul H. Brookes Publishing Co.

Stein, R. B. (1982). What muscle variables does the central nervous system control? *Behavioral and Brain Sciences, 4,* 535–578.

Weismer, G. (1991). Assessment of articulatory timing. *NIDCD Monograph, 1,* 84–95.

Weismer, G., & Forrest, K. (1992). *Issues in motor speech disorders: A position paper.* Paper presented at the Conference on Motor Speech, Boulder, CO.

Wood, L. M., Hughes, J., Hayes, K. C., & Wolfe, D. L. (1992). Reliability of labial closure force measurements in normal subjects and patients with CNS disorders. *Journal of Speech and Hearing Research, 35,* 252–258.

Received September 15, 1993
Accepted April 13, 1994

Contact author: Gary Weismer, PhD, Department of Communicative Disorders, 1975 Willow Drive, University of Wisconsin-Madison, Madison, WI 53706.