MANDIBULAR CONTRIBUTIONS TO SPEECH PRODUCTION

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ABSTRACT

In this paper we examine jaw opening and closing action during the production of a variety of vowels and consonants. Of interest was the identification of potential neural control strategies and biomechanical contributions underlying speech production by evaluating, separately and in combination, kinematic and electromyographic (EMG) activity of the jaw at normal and fast speaking rates. We found that EMG and movement characteristics for jaw opening were systematically related and varied according to vowel identity. However, at a fast speaking rate, jaw motion differences were reduced or eliminated for the different vowels, and EMG and movement characteristics for jaw closing were less consistently related and showed fewer consonant-related variations. Inspection of jaw opening and closing movement relations for the different CVCs revealed strong covariation across the movement cycle. In contrast, EMG relations were less related suggesting a substantial biomechanical contribution to jaw closing movement characteristics. Jaw actions were found to be organized around a movement cycle (syllabic unit) suggesting a codependent programming across movement phases (opening/closing). One of the consequences of increased speaking rate was the use of an overall lower than normal peak jaw position for the vowels and consonants and an apparent compensation of the reduced jaw motion by the tongue. Together these results suggests that speech motor control is organized according to vocal tract level goals that span opening and closing actions rather than targets associated with individual articulators.

1. INTRODUCTION

Vocal tract actions for speech reflect an interaction of linguistic influences and motor control principles filtered through the peripheral biomechanical properties of the respective articulators. One important articulatory component of many vocal tract actions is the mandible. The mandible in conjunction with the tongue is involved in the production of most vowel sounds, and it assists many other articulators, such as the lips and tongue, in the production of many consonant sounds. As such, the mandible is a multidimensional articulator engaged in a wide range of speech behaviors and an ideal articulator in which to evaluate underlying neuromotor organization. As a prerequisite to detailed hypotheses regarding the role of the mandible in the speech motor control process, the present experiment was designed to examine jaw muscle activity and associated movement changes

The focus of the present investigation was twofold. First, to describe some of the jaw movement characteristics associated with the production of vowels and consonants separately and in combination. As such, the spatial position of the jaw and the associated displacement, velocity and duration of jaw opening and closing motion will be examined to determine the role of the mandible in these basic speech motor actions. While the jaw is actively involved in the production of vowels and consonant, the degree to which it is related to either is of some theoretical significance. Second, previous speech perturbation investigations (mechanical perturbation or bite block studies) suggest that speech movements are not organized according to individual articulators but are organized at some higher level [1,2,3,4,5]. In order to determine the role of the jaw in the neuromotor organization for speech, changes in spatial movement characteristics accompanying rapid speech were examined

2. METHOD

2.1 Subjects

Two normal adult American English speakers (one female and one male) served as subjects for this investigation. For this report only the most robust data, from the female subject, will be presented. When significantly different, the data from the second subject will be described.

2.2 EMG and jaw motion recording

Hooked-wire electrodes were placed in four mandibular muscles; two associated with jaw opening (anterior belly of the digastric [ABD] and mylohyoid [MH]) and two associated with jaw closing (medial pterygoid [MPT] and masseter [MAS]). Electrodes were constructed from 50μm diameter platinum wire and inserted into the respective muscles. Bipolar EMG recordings from jaw opening muscles were obtained from separate insertions placed approximately 7 mm apart. For the jaw closing muscles, recordings were obtained from twisted bipolar wires with approximately 2 mm interelectrode distance. The electrode placements and verification techniques were modified from those described by Hirose[6].

Two dimensional jaw movement was transduced optoelectronically from custom-fitted jaw splints designed to minimize interference with the subjects' articulation. For the female subject, the head was restricted from moving in the anterior-posterior direction. Inferior-superior head motion was simultaneously obtained and used to correct jaw motion for head movement artifact. Muscle activity and movement signals were digitized off-line with 12 bit resolution. Movement signals were digitized at 500 Hz and software smoothed using a 42 msec triangular window Jaw movements were numerically differentiated using a central difference algorithm and filtered again with a 42 msec time constant. EMG signals were hardware filtered at 500 Hz, digitized at 1000 Hz, and subsequently low pass filtered at 20 Hz. Acoustic recordings were obtained simultaneously; they were hardware filtered at 4.8 kHz and sampled at 10 kHz.

A variety of speech tasks were recorded including steady state vowel productions, repetitions of C1VC2 monosyllables, where C1 was /p, t, k, s, l/, V was /æ, ɛ, ɔ, aɪ, ɑ, eɪ, i/ and C2 was /p, t, k, b, d, f, s, l/, at comfortable and fast rates, repetition of sentence length material with varying emphatic stress, and oral reading paragraph length material. The present report will focus on CVC production at a normal speaking rate and a subject-determined fast rate. Figure 1 displays a representative sample of the signals used for the present analysis scheme. Shown are the acoustic signal, jaw displacement in the y dimension, the derived jaw velocity, and associated EMG activity from one jaw opening muscle (ABD) and one jaw closing muscle (MPT).

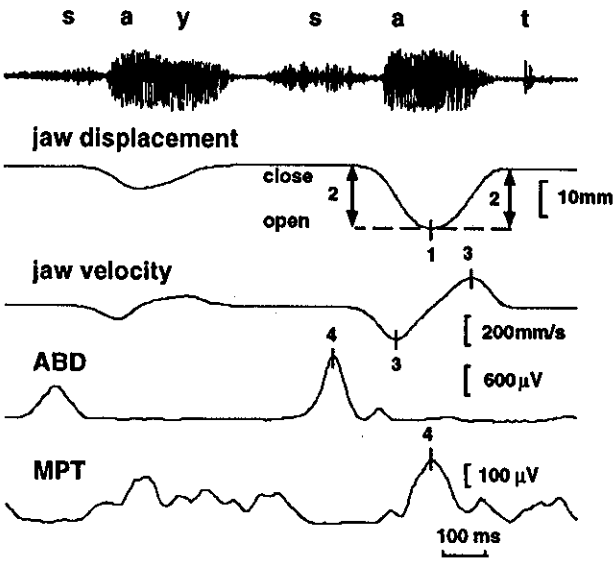

Fig. 1. Illustration of the variables measured in the present study; peak jaw opening position for the vowel (1), jaw opening/closing displacement (2), peak jaw opening/closing velocity (3), and peak EMG amplitude (4). Movement duration is defined as the interval between the onset and offset of respective peak displacements (1 - 2).

3. RESULTS

Initial analysis focused on the degree to which the inferior-superior and anterior-posterior jaw motions were independent.

Presented in Figure 2 are scatter plots of the measured jaw displacements and jaw velocities in the inferior-superior (Y) and anterior-posterior (X) directions for the opening movements associated with vowel production.

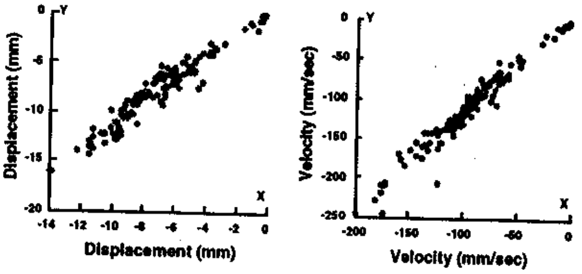

Fig. 2. Relationship of jaw motion (displacement, left panel; velocity, right panel) in the horizontal (X) and vertical (Y) planes with respect to gravity.

As can be seen, jaw motion in the two directions are highly correlated with product-moment coefficients at r = .97 (displacement) and r = .98 (velocity). Similar results were obtained for the jaw closing action for the second consonant with correlations at r = .97 (displacement) and r = .94 (velocity). For the second subject, the correlations between the inferior-superior and anterior-posterior directions were reduced. Because of the highly correlated nature of the two dimensional jaw motion, the results will focus on the inferior-superior motion of the jaw for the opening and closing actions.

3.1 Jaw Opening-vowels

In the present investigation, jaw position was periodically sampled with the teeth in contact to allow evaluation of jaw position for the different vowels and consonants. Presented in Figure 3 is a summary of the results for jaw opening position, displacement, velocity, and movement duration for the vowels used in the present study at both speaking rates.

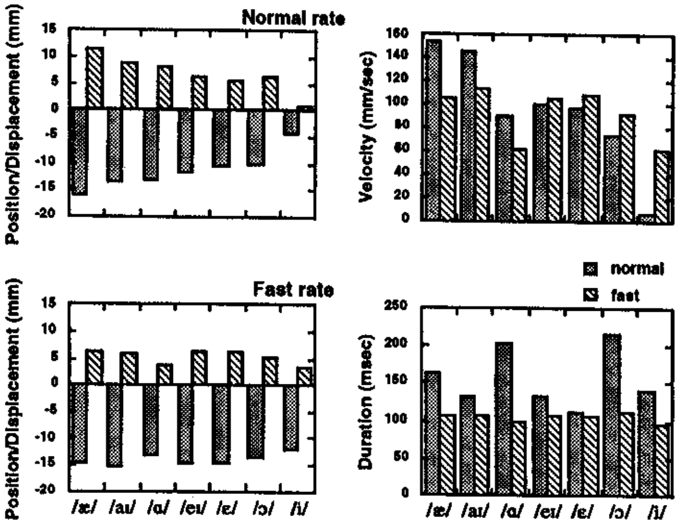

Fig. 3. The left panels (top and bottom) present the maximum jaw opening position (negative bars) and peak jaw opening displacement (positive bars) for the different vowels at the two different speaking rates (Normal and Fast). The right panels present the peak jaw opening velocity (top) and jaw opening movement duration (bottom) for the different vowels at the two speaking rates.

A number of interesting results can be seen. First, jaw opening position and opening displacement vary as a function of the vowel identity with /æ/ the most open and /i/ the most closed. Second, jaw opening velocity generally scales according to displacement with the two variables highly correlated (r = .9) as was shown in former papers [7]. Third, jaw opening duration varies considerably for the seven vowels ranging from approximately 110 msec to 220 msec. At the fast speaking rate, the systematic relation between vowel identity and jaw position/displacement disappears. It appears that at the fast rate, the jaw's contribution to the different vowels becomes less differentiated with the jaw generally maintaining a lower spatial position with reduced opening displacement. Jaw opening velocity is decreased for some vowels and is increased for others while jaw opening movement durations become more similar due to the increase in speaking rate.

Muscle activity from the two jaw opening muscles was also related to the identity of the specific vowel and as such varied as a function the respective jaw opening displacement. Because the peak EMG amplitude for ABD and MH were highly correlated (r = .9) only results for ABD will be presented. Figure 4 shows the relationship between peak EMG amplitude and the jaw opening displacement for the normal and fast speaking rates. At the fast rate, EMG burst duration was reduced as was EMG rise time (time from EMG onset to peak amplitude); peak amplitude was unchanged at the fast speaking rate.

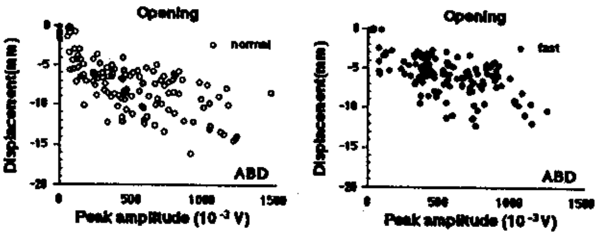

Fig. 4. Relationship of the peak EMG amplitude (ABD) to the peak jaw opening displacement at the normal (left) and fast (right) speaking rates for all CVC contexts.

3.2 Jaw Closing-consonants

Presented in Figure 5 is a summary of the results for jaw closing position, displacement, velocity, and movement duration for the consonants used in the present study at both speaking rates. The position results reflect the peak position of the jaw associated with the production of the second consonant in the different CVCs. In contrast to the jaw opening results, the jaw position and displacement appears unrelated to consonant identity. Similar to the opening results, jaw closing peak displacement and peak velocity were highly correlated (r = .9). At the fast rate, the jaw maintains a lower position and the closing displacement is reduced from the normal rate. It can also be seen that the closing movement duration doesn't reflect the same range observed for the opening movements at the normal speaking rate.

For the closing movements, EMG activity was moderately related to the closing displacement of the jaw. Presented in Figure 6 is the relationship between the peak EMG amplitude from a jaw closing muscle (MPT) and the associated jaw closing displacement. Similar to the results for the opening action, peak amplitude was unchanged while burst duration and rise time decreased at the fast rate.

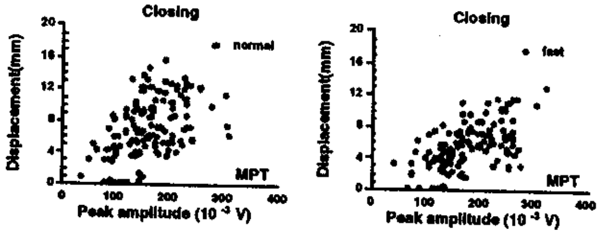

Fig. 6. Relationship of the peak EMG amplitude (MPT) to the peak jaw closing displacement at the normal (left) and fast (right) speaking rates for all CVC contexts.

3.3 Opening/Closing relations

In contrast to the jaw opening results, it appears that jaw closing actions are less related to phonetic context. It is possible that since the jaw is only secondarily involved in consonant production, jaw closing actions may be more related to the preceding oral opening actions than to consonant identity. The final analysis focused on the degree to which variations in closing movements can be explained by variations in jaw opening actions for vowel production. Since EMG amplitude for the opening and closing muscles were shown to be related to jaw opening and closing displacements respectively, the EMG and movement characteristics were examined.

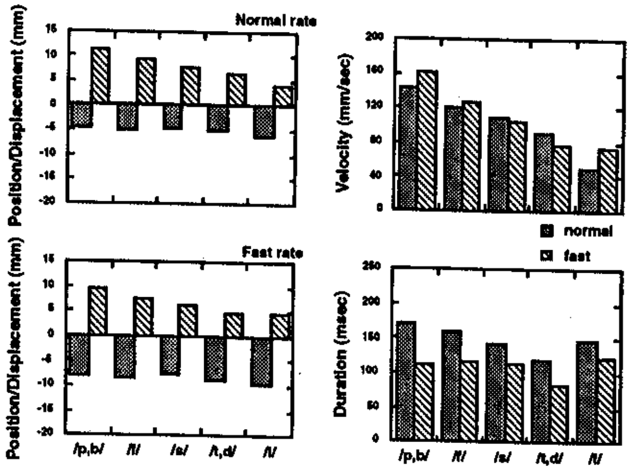

Fig. 5. Similar to Figure 3, the left panels (top and bottom) present the maximum jaw closing position (negative bars) and peak jaw closing displacement (positive bars) for the different consonants at the two different speaking rates (Normal and Fast). The right panels present the peak jaw closing velocity (top) and jaw closing movement duration (bottom) for the different consonants at the two speaking rates.

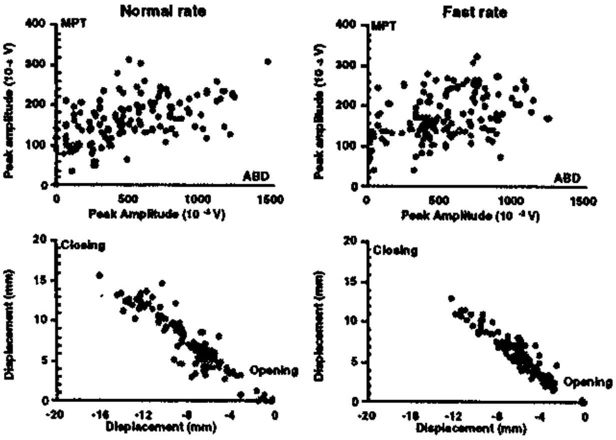

Fig. 7. Comparison of the variation in the jaw opening (ABD) and closing (MPT) muscle activity (top) and resulting opening and closing displacement for all CVC contexts at the two speaking rates.

Presented in the top portion of Figure 7 is the relationship between the opening and closing EMG peak amplitude for both speaking rates. Correlation coefficients were modest ranging from $r = .5$ for the normal rate to $r = .39$ for the fast rate. In contrast, the opening/closing displacements were highly correlated with coefficients of $r = .94$ (normal) and $r = .95$ (fast). The correlation of opening and closing actions indicates that these movements are dependent and that jaw closing is more likely related to the extent of oral opening than to consonant identity. The disparity in the correlation of opening and closing muscle activity with the movement displacement suggests that mechanical properties of the jaw are contributing to the opening/closing relations.

4. DISCUSSION

The present investigation is a preliminary report of jaw muscle and associated movement characteristics for a variety of vowel and consonant sounds. Previous investigation of jaw muscle activity during speech and chewing have suggested that the neuromotor organization for speech and nonspeech may be fundamentally different [8; however see 9]. The present results suggest that within a task (speech) the neuromotor organization appears to be quite similar. For example, jaw muscle activity was found to be systematically related to the extent of jaw motion and velocity and displacement were found to scale linearly across phonetic contexts. Jaw opening associated with vowel production was found to vary primarily in the spatial domain reflecting changes in overall jaw height. Secondary variations were noted according to opening movement duration. It is suggested that these two movement characteristics are necessary and sufficient to categorize vowels of the language.

Jaw closing actions while assisting in consonant production, were found to be primarily influenced by the preceding vowel. That is, in the present context, the extent and speed of jaw closing is heavily influenced by the oral opening action regardless of the consonant identity. While there were some consistent consonant-related effects, such as those accompanying unvoiced sounds compared to voiced cognates, these appear restricted to relative timing or phasing of the opening/closing actions rather than to spatial characteristics of jaw motion.

Two points can be from the movement changes associated with changes in speaking rate. First, the movement changes in both the opening and the closing actions suggest the possibility of an overall reorganization of the underlying motor control system. However, it should be noted that the most significant neuromotor change observed was a reduction in the EMG burst duration; peak EMG amplitude was unchanged and EMG rise time was changed minimally. Changes in speaking rate can be viewed as a change in an underlying oscillatory or rhythmic mechanism with a concomitant reduction in overall movement duration. Movement displacement and velocity changes may be direct consequences of the change in the frequency of the underlying rhythmic mechanism. For jaw opening, the faster speaking rate resulted in smaller displacements and lower peak velocities, a finding consistent with this interpretation. For jaw closing, however, there was a trend for the velocities to be somewhat higher at the fast speaking rate. However, since jaw closing EMG changes did not mirror the jaw closing velocity changes, the higher jaw closing velocities may have resulted from passive biomechanical considerations such as the change in the opening/closing phasing [10] and/or the finding that the jaw was operating in a different part of its' operating space (see Figures 3 and 5). It is plausible that a change in a single dimension, such as movement frequency, may result in a variety of kinematic changes with no fundamental change in the underlying motor control system

Second, it is obvious from the movement characteristics associated with speaking rate changes that the neuromotor organization for vowels does not include a spatially-defined jaw target. Rather, increases in speaking rate resulted in a compression of the degree of jaw movement variation associated with the different vowels apparently requiring greater contribution/ compensation from the tongue. It appears that speech motor actions are organized according to overall vocal tract actions rather than according to the actions of individual articulators. As such, the fundamental units of speech motor control are on the order of vocal tract configurations and consistent with the construct of a phonetic gesture.

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