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JAW OPENING AND THE TIME CONSTANT OF JAW MOVEMENTS IN THE PRODUCTION OF SEQUENCES OF STATIONARY VOWELS AND VOWEL SEQUENCE WORDS

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1. Introduction

There have been some attempts to analyze the dynamic characteristics of the jaw movements in the production of vowel sequences [1),2)]. However, the influence of the adjacent vowels on the jaw opening for vowels in the production of vowel sequences have not been analyzed systematically.

In the present study, the movements of the jaw for vowel transitions were approximated by the response of a critically damped linear second order system to the input step function, which was considered to represent the target of the jaw opening for successive vowels. The degree of the jaw opening for each vowel and the time constant of the second order system for the vowel transition in the production of sequences of stationary vowels were analized. The jaw movements for three-mora words consisting of vowel sequences were also analized and the jaw opening for each vowel in the words was compared with that in sequences of stationary vowels.

2. Measurement of the jaw opening and estimation of the time constant in the production of sequences of stationary vowels

2-1. Speech samples

The movements of the jaw were recorded using a PSD (optical spot position sensitive detector). The details of the method are described elsewhere [3),4)].

Table 1 gives the speech samples. The samples were connected vowels in the form of /V_1 V_2 V_3 V_4 V_5 V_1/; 5 vowel sequences followed by a repeat of the first vowel of the sequence. Each vowel was uttered so as to have a stationary part. Four utterances for each speech sample were stored in the computer. Subjects were two male adults. In this preliminary study, a set of 8 vowel transitions, indicated in Table 1 by underlinings, were analyzed. In this set of transitions, the transitions from close to open vowels and from open to close vowels were included, where /a/ and /e/ were assumed to be open

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Table 1 List of speech samples
(sequences of stationary vowels)

a i u e o a

o e u i a o

i e a u o i

o u a e i o

—— : transitions analyzed in the present study.

Table 2 List of test words
(three-mora words consisting of vowels)

aua	aue	eua	eue
aia	aie	eia	eie
ueu	uei	ieu	iei
uau	uai	iau	iai

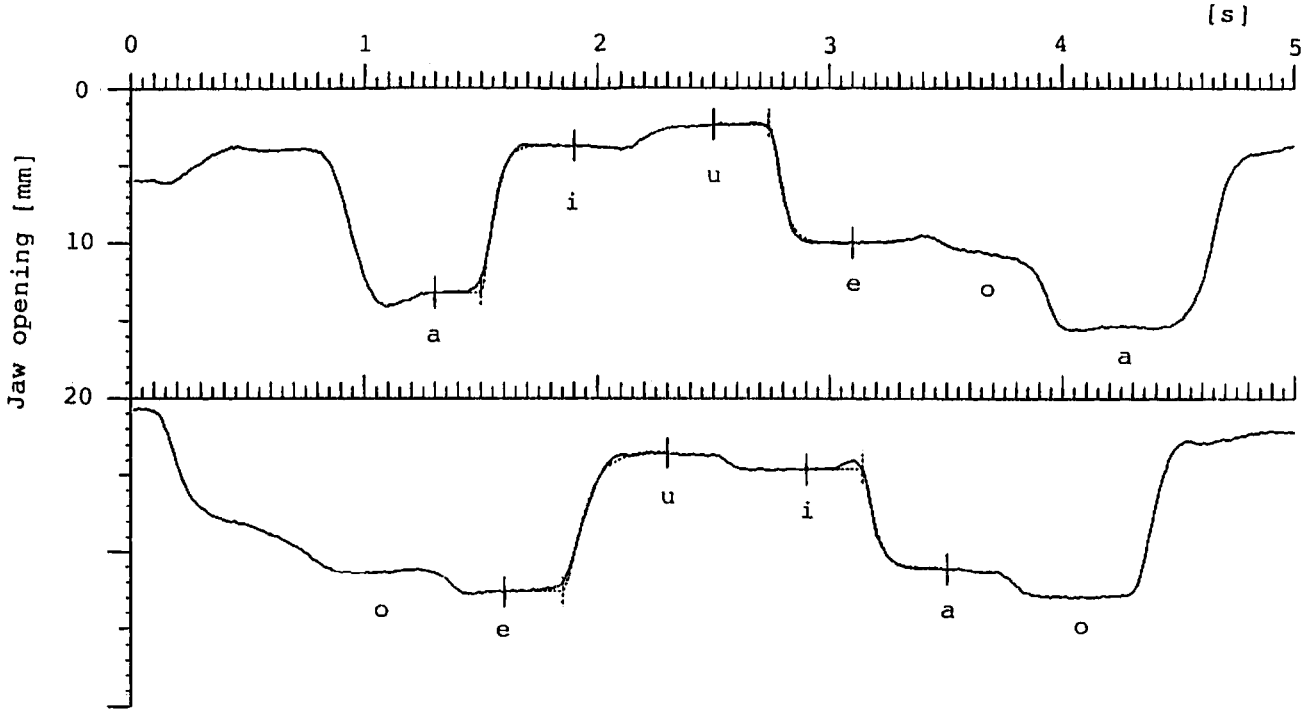


Fig.1 Examples of observed jaw movements (solid curves) and approximated jaw movements (broken curves) for sequences of stationary vowels. (Subj.1)

| : Moment at which the jaw opening for the stationary vowel was measured.

¦ : Starting moment of the transition.

vowels and /i/ and /u/ were assumed to be close vowels. (The Japanese vowel /o/ was omitted because of the occasional interference of the solid wire bearing the LEDs with the lip protrusion [4].)

2-2. Method of analysis

The jaw opening during the production of stationary vowels keeps an almost stationary level. The averaged jaw opening over 50 ms at the middle of the period in which the jaw opening keeps the stationary level for each stationary vowel was evaluated.

The jaw movement in the transition from a stationary vowel to a following vowel was approximated by the response function of a critically damped linear second order system to the input step function, whose target level was given by the jaw opening for the following vowel. The time constant and the starting moment of the transition which gave the best approximation were estimated.

Fig.1 shows examples of the observed jaw movements (solid curves) and the approximated jaw movements (broken curves). The vertical solid line indicates the moment at which the jaw opening for the stationary vowels was measured, and the vertical dashed line indicates the estimated starting moment of the transition.

2-3. Results

Fig.2 shows the measured jaw opening for the stationary vowels. The open circle and the vertical line connected to the open circle indicate the average and the standard deviation of the jaw opening over four repetitions for each vowel in each context, respectively. The horizontal broken line indicates the average of the jaw opening for each vowel.

For both subjects, the averaged jaw opening for the stationary vowels was greatest for /a/, followed by /e/, /i/ and /u/ in order [5]. In the speech samples analyzed in the present study, there are two types of contexts for open vowels /a/ and /e/. One is the open vowel preceded by an open vowel and followed by a close vowel, such as /eau/ and /oeu/, and the other is preceded by a close vowel and followed by an open vowel, such as /iao/ and /ueo/. For both subjects, the jaw opening for /a/ was greater in the former case than in the latter case. Similarly, for subject 1, the jaw opening for /e/ was greater in the former case than in the latter case. These results suggest that the difference in the jaw opening occured because of two factors: a following vowel and a preceding vowel. However, since the speech sample did not contain every possible context, it is impossible to conclude which factor influenced more on the difference in the jaw opening. The variation of jaw openings for close vowels due to different adjacent vowels was smaller than for open vowels.

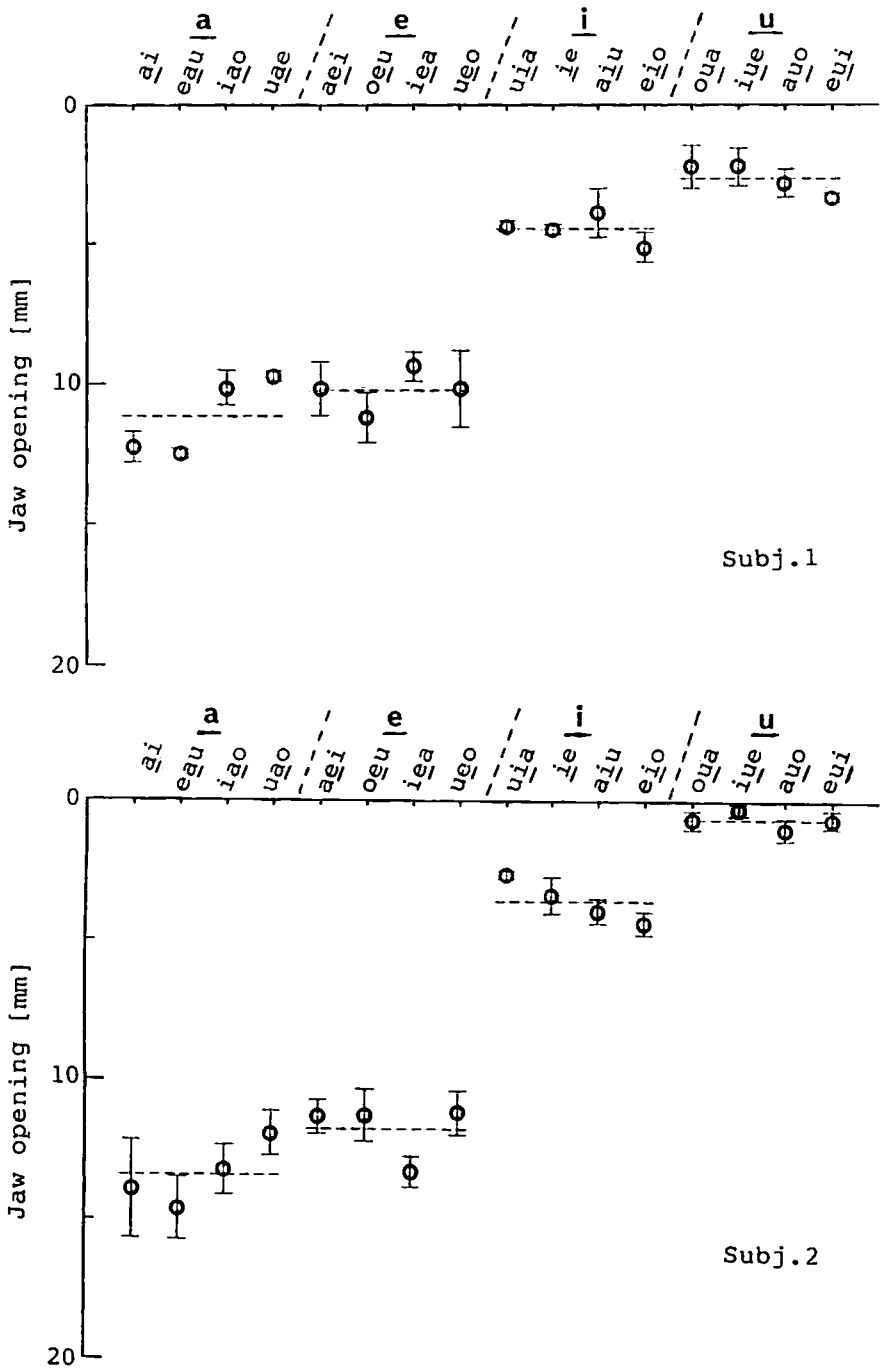


Fig.2 Measured jaw opening for stationary vowels.

Φ : Average and standard deviation over four repetitions.

-------- : Average for each vowel.

Fig.3 shows the estimated time constants for the vowel transitions. The open circle and the vertical line connected to the open circle indicate the average and the standard deviation of the time constant over four repetitions for each vowel transition, respectively. The horizontal broken line indicates the average for the close to open vowel transitions or for the open to close vowel transitions.

For subject 1, the time constants for the open to close vowel transitions were greater than for the close to open vowel transitions. For subject 2, however, there was no significant difference in the value of the time constant between the open to close vowel transitions and the close to open vowel transitions [5].

3. Approximation of the jaw movement for sequences of stationary vowels based on the averaged jaw opening and the averaged time constant

3-1. Method of approximation

The jaw movements for sequences of stationary vowels were approximated based on the jaw opening and the time constant which were averaged under several conditions. The mean square errors between the approximated jaw movements and the observed jaw movements were evaluated. Two conditions of the jaw opening for stationary vowels and three conditions of the time constant were prepared. The conditions of the jaw opening were as follows:

- J_1 : The average of the jaw opening over four repetitions for each vowel in each context. (The value is indicated by the open circle in Fig.2)
- J_2 : The average of the jaw opening for each vowel without taking account of the context. (The value is indicated by broken line in Fig.2)

The conditions of the time constant for the vowel transitions were as follows:

- T_1 : The average of the time constant over four repetitions for each vowel transition. (The value is indicated by the open circle in Fig.3)
- T_2 : The average of the time constant for the open to close vowel transition or for close to open vowel transition. (The value is indicated by the broken line in Fig.3)
- T_3 : The average of the time constant over all transitions.

The starting moment of the transition which gave the best approximation was also estimated.

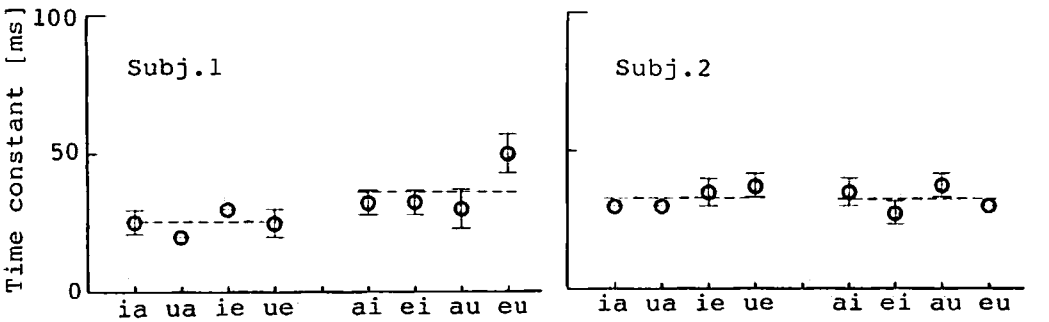


Fig.3 Estimated time constant for vowel transitions.

$\overline{\Phi}$: Average and standard deviation over four repetitions.

---------: Average for close to open vowel transitions or for open to close vowel transitions.

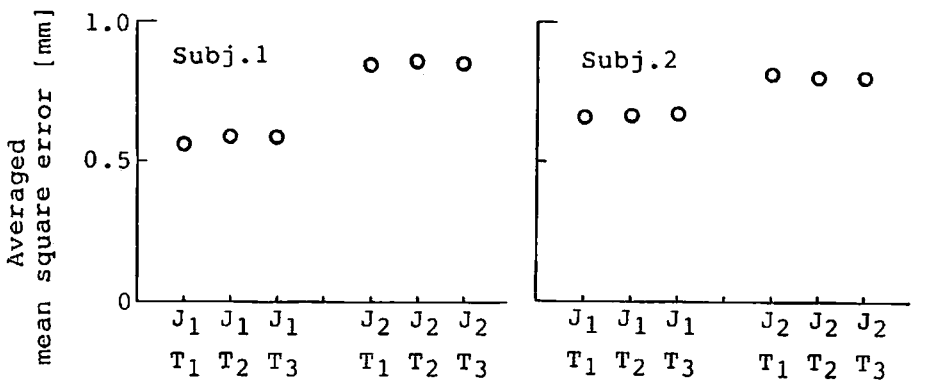


Fig.4 Averaged mean square error between the approximated jaw movement and the observed jaw movement under several conditions.

Conditions of the jaw opening.

J_1 : The average of the jaw opening over four repetitions for each vowel in each context.

J_2 : The average of the jaw opening for each vowel without taking account of the context.

Conditions of the time constant.

T_1 : The average of the time constant over four repetitions for each vowel transition.

T_2 : The average of the time constant for the open to close vowel transitions or for the close to open vowel transitions.

T_3 : The average of the time constant over all transitions.

3-2. Results

Fig.4 shows the mean square errors between the approximated jaw movements and the observed jaw movements. Errors are averages over 8 transitions which are indicated in Table 1 by underlining. The mean square erorrs were greater for the condition J_2 than for J_1, while the mean square errors were almost the same for the conditions T_1,T_2 and T_3. One of the possible reasons for these results is that the influence of the difference in the jaw opening for stationary vowels caused by the different adjacent vowels is greater than the influence of the variation in the time constant for the transition caused by the difference in the direction of the jaw movement on the accuracy of the approximation of the jaw movements.

4. Approximation of the jaw movements for three-mora, vowel-sequence words based on the measured jaw opening and the estimated time constant in sequences of stationary vowels

4-1. Test words

The jaw movements for the words consisting of vowels were approximated based on the jaw opening for the vowels and the time constant for the vowel transition which were obtained for the sequences of stationary vowels. The words for which the jaw movements were approximated were three-mora words in the form of /V_1 V_2 V_3/ ($V_1 \neq V_2$ and $V_2 \neq V_3$, V=a,e,i and u). In this study, the jaw movements for 16 words in which open vowels and close vowels alternated with each other, as shown in Table 2, were used. The words were uttered within the carrier sentence /_desu/. The jaw movements for each test word in three utterances were stored in the computer [3].

4-2. Method of approximation

The standardized jaw movement for each word over three repetitions was obtained as follows. At first, the duration from the beginning of the utterance to the moment of the implosion for /d/ was averaged over 16 words. Each time function of the jaw movement was expanded or contracted linearly to adjust the duration to the average. Then, the time functions of the jaw movements were averaged over three repetitions for each word.

In this preliminary study, the target of the jaw openings for each vowel were assumed to be the averaged jaw opening for each vowel without taking account of the context in the sequences of stationary vowels. The time constant of the second order system for the transition was assumed to be the averaged time constant over all transitions in the sequences of stationary vowels. The starting moment of the step for the first vowel and the changing moment of the step function for successive vowels were estimated so as to obtain the best approximation. The jaw

movement was approximated from the starting moment for the first vowel to a moment prior to the implosion of /d/ by 40 ms. Since the jaw opening at the peak for /d/ in the time function of the jaw movement for the vowel-sequence words was less than that for /u/ and since the jaw opening for /u/ was almost the same as the closed position of the jaw, the target of the jaw opening for /d/ was assumed to be at the same level as in the case where the jaw is closed. The time constant for the transition from V_3 to /d/ was assumed to be the same value as the averaged time constant over all transitions in the sequences of stationary vowels for each subject. The initial jaw opening and the initial velocity of the jaw opening at the starting moment of the jaw movement for the first vowel were obtained from the time function of the observed jaw movement.

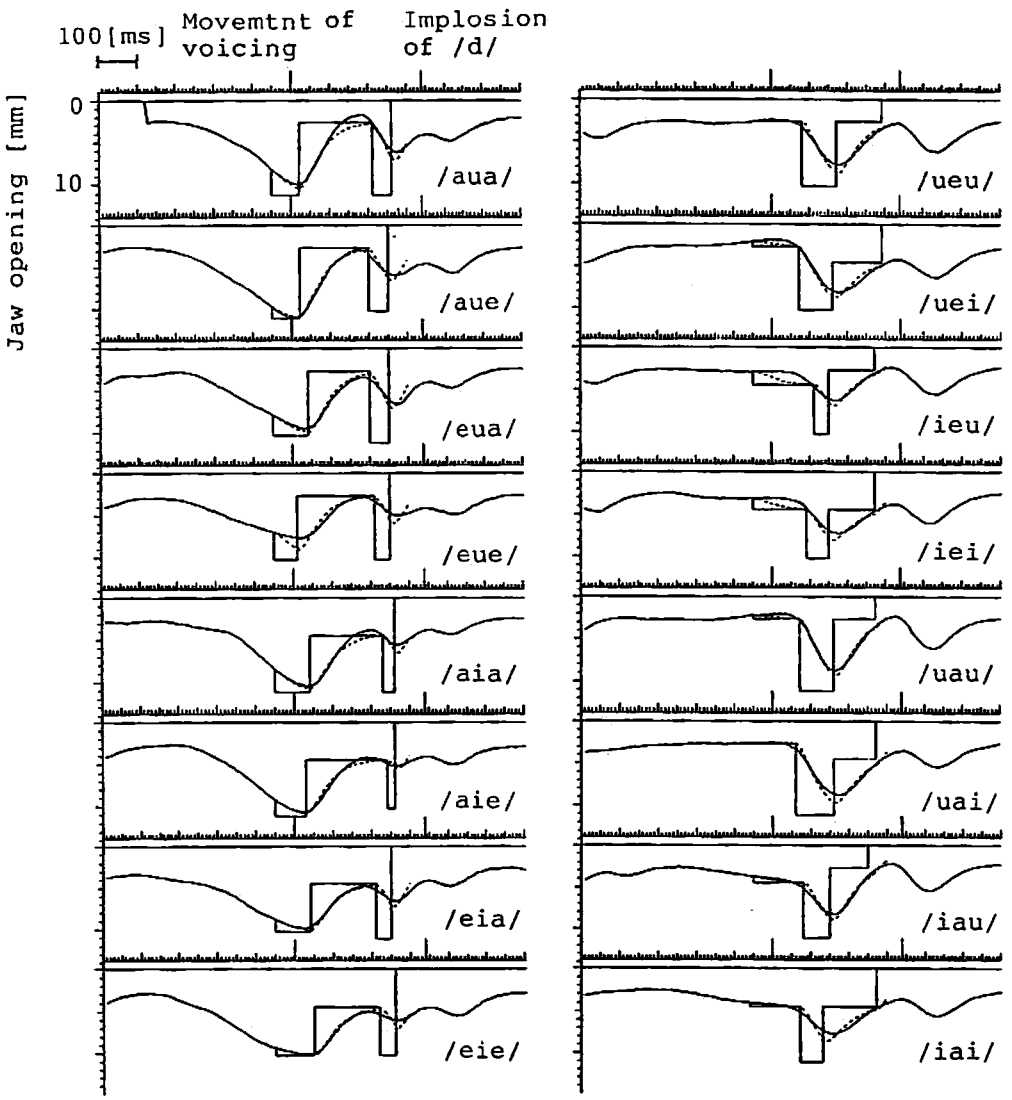
4-3. Results

Fig.5 shows the observed jaw movements (solid curves), the approximated jaw movements (broken curves) and the estimated input step functions (solid rectangular lines). The approximated jaw movement showed a greater jaw opening than the observed jaw movement at the changing moment of the step function from the opening movement to the closing movement. For the words whose second vowel was a close vowel, such as /aua/ and /aia/, whenever an error between the approximated jaw movement and the observed jaw movement occured, the level of the step as the input for the critically damped second order system was greater than the peak for the close vowel, and, as a result, the approximated jaw movement showed a greater jaw opening than the observed jaw movement at the peak for the close vowel.

These results suggest that the target of the jaw opening for each vowel in the production of the vowel-sequence words was less than in the production of the sequences of stationary vowels.

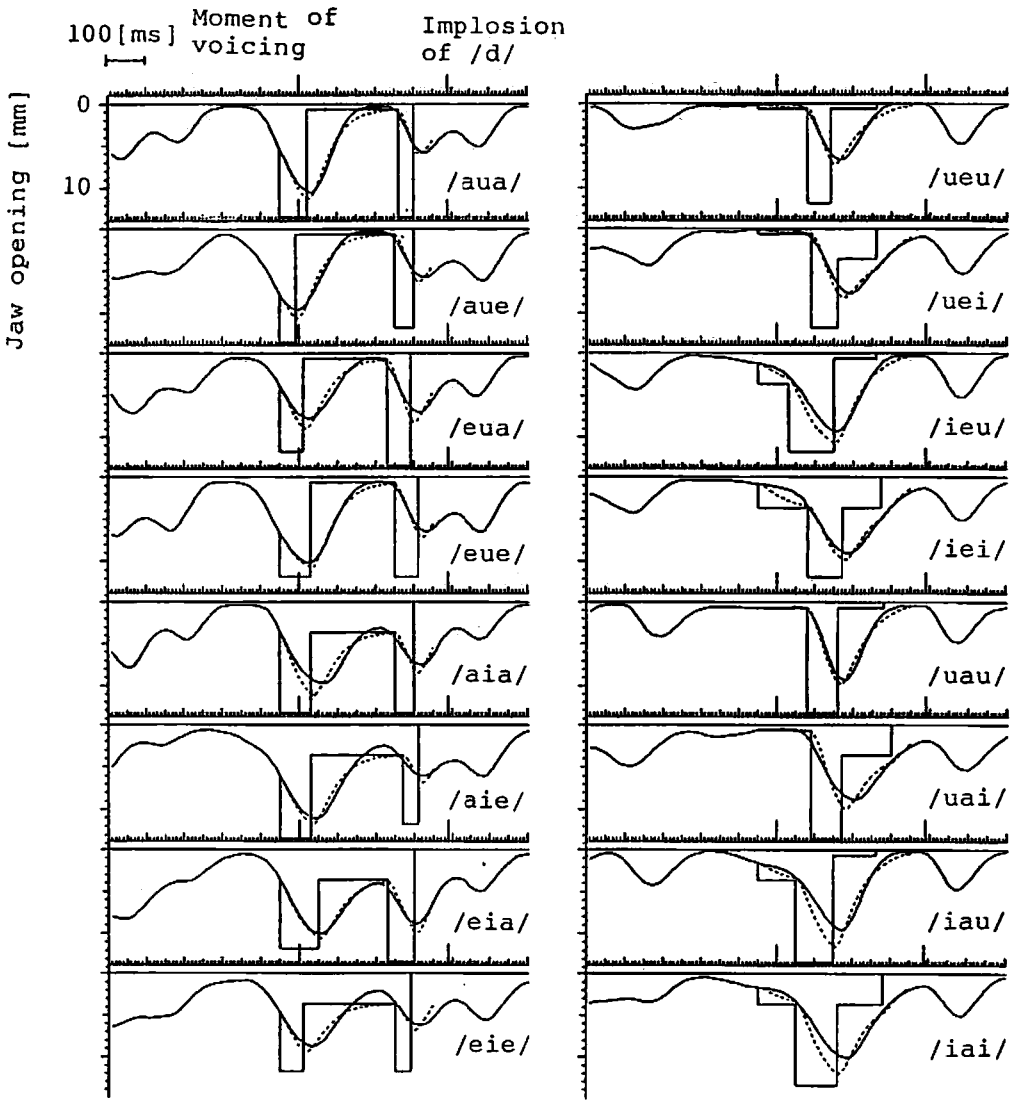
5. Comments

The jaw opening for each vowel and the time constant for the transitions in the vowel sequences were obtained by the time function of the jaw movement in sequences of stationary vowels. Although the set of speech samples which were used to obtain the jaw opening and the time constant did not contain every possible combination of vowel sequences, differences in the jaw opening due to different adjacent vowels were observed for /a/ in both subjects and for /e/ in subject 1. Further investigation is needed using a complete set of speech samples which contains every combination of vowel sequences. For the time constant, a difference due to the difference in the direction of the movement of the jaw was observed for subject 1, while a difference in the time constant was not observed for subject 2.



(a) Subject 1

Fig.5 Observed jaw movements (solid curves), approximated jaw movements (broken curves) and step functions (solid rectangular lines) for three-mora words.



(b) Subject 2

Fig.5 Observed jaw movements (solid curve), approximated jaw movements (broken curves) and step functions (solid rectangular lines) for three-mora words(continued).

The influence of the difference in the jaw opening caused by the adjacent vowel on the accuracy of the approximation of the jaw movement is greater than the influence of the difference in the time constant caused by differences in the direction of the jaw movement.

Analisis of the jaw movements for the three-mora words showed that the target of the jaw opening for each vowel in the production of the vowel-sequence words was less than in the production of the sequences of stationary vowels. The rules for changing the target of the jaw opening for each vowel in words should be examined to get a better approximation of the jaw movements in the production of words consisting of vowels.

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