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TEMPORAL CHARACTERISTICS OF THE JAW MOVEMENTS IN THE PRODUCTION OF CONNECTED VOWELS

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Introduction

There have been reported several phenomena in which the articulatory movements in opposite directions appear to exhibit different temporal characteristics.

For example, Kiritani et al. report that, in the production of /mami/ and /mima/ in Japanese, the timing of the /a/ to /i/ transition relative to the lip movement for the intervocalic /m/ appears to be earlier than that of the /i/ to /a/ transition.[1] It is also reported by Fujisaki et al. that, in the production of /ai/ and /ia/, the start of the formant transition is earlier for /ai/ than for /ia/, and the time constant of the formant transition is greater for /ai/ than for /ia/.[2] Sawashima et al. also found that the timing of the formant transition relative to the low-high or high-low pitch transition associated with word accent in Japanese is also earlier for /ai/ than for /ia/.[3]

In order to clarify the physiological basis of these phenomena, quantitative analysis of the dynamic characteristics of the articulatory movements involved is necessary.

Since several means are available for recording jaw movement, there have been several attempts at a quantitative analysis of the dynamic characteristics of jaw movement.[4] [5] However, in these studies, the number of subjects and/or speech samples was rather limited. For the present study, new, simple equipment for measuring jaw movement was developed to facilitate a large amount of data collection. Using this method, the movement of the jaw in the production of the vowel sequences in Japanese were observed, and the dynamic characteristics of the transitional movement from closed to open vowels and from open to closed vowels were compared.

Measuring Equipment

Fig. 1 shows a block diagram of the equipment for measuring the movement of the jaw.** A small magnet is attached to the lower frontal teeth and a small magneto sensing element is attached to the upper frontal teeth. The magneto sensing element measures the intensity of the magnetic field which varies according to the distance between the magnet and the sensing element and, thus, measures the distance between them.

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** The prototype of this equipment was devised by Mr. K. Hori of the Rion Co. Ltd. We wish to acknowledge our thanks to Mr. K. Hori for his valuable advice in the technical development of the present equipment.

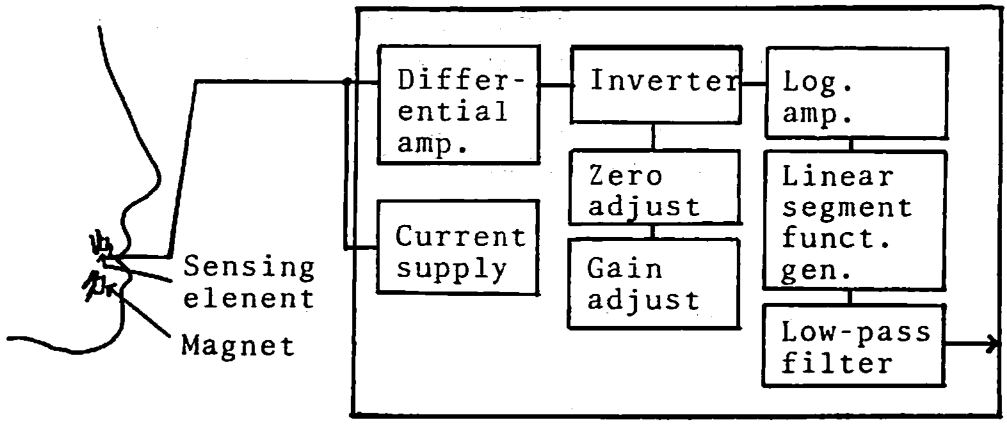

Fig. 1 *Block diagram of the jaw movement measuring equipment.*

The magnet used here was a small bar (2.4 x 3.8 x 7.0 mm, LM-22, Tohoku Metal Industries Ltd.), which was magnetized in the direction of its long axis. It was placed on the lower tooth with its long axis oriented horizontally. The sensing element was a magneto registor element (5 x 5 x 2 mm, DM202, Sony Corp.). The sensing element was attached to the upper teeth, its sensitive axis pararell with the long axis of the magnet.

Naturally, the relationship between the displacement and the output voltage of the magneto sensing element is nonlinear (Fig. 2 (b)), since the intensity of the magnetic field is, approximately, inversely proportional to the cube of the distance between the magnet and the sensing element. In order to obtain the linear relation-

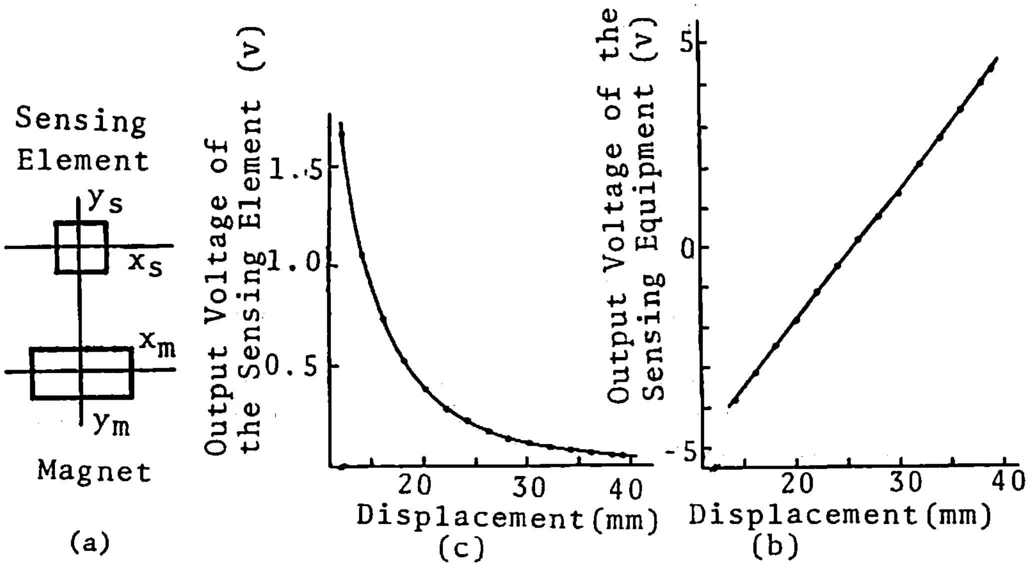

Fig. 2 (a) *Standard orientation of the magnet and the magneto sensing element.*
(b) *Displacement versus output voltage of the sensing element.*
(c) *Displacement versus output voltage of the measuring system.*

ship between the displacement and the output signal, the output signal from the sensing element was fed into a logarithmic amplifier. The output signal of the logarithmic amplifier was further fed into a linear segment function generator to correct the slight residual nonlinearity.

The relationship between the displacement and the final output voltage is shown in Fig. 2 (c). It can be seen that a satisfactory linearity was obtained.

The output characteristics shown in Fig. 2 (b) and (c) were measured for the standard (ideal) configuration of the magnet and the magneto sensing element, and is depicted in Fig. 2 (a). Namely, the magnet and the sensing element were located on the same plane, with the Xs-axis of the sensing element (field sensitive axis) being paralel with the Xm-axis of the magnet (magnetization axis). The Ym-axis of the magnet and the Ys-axis of the sensing element were alligned on a straight line and the displacement of the magnet was assumed to take place along this line.

In the experimental situations, deviations in the relative orientation of the magnet and the sensing element from the standard configuration were to some extent inevitable. In the following, the effect of possible deviation on measurement accuracy are examined.

Fig. 3 shows the output characteristics of the measuring system for several relative orientations of the magnet and the sensing element. In case (1), the magnet is displaced horizontally from its position in the standard configuration. In case (2), the magnet is rotated on the Xm-Ym plane. In case (3), the sensing element is rotated on the same plane. It can be seen in Fig. 3 (b) that these variations in the positioning of the magnet and the sensing element have little effect on the output characteristics of the measuring system. However, it can also be observed that when case (3) is combined with either case (1) or case (2), there is an appreciable change in the output characteristics. Case (4) shows the situation in which all three factors in case (1), (2) and (3) co-exist. In this case, the resulting measurement error is about 2 mm at most. However, even in this case, the linearity in the relationship between the displacement and the output voltage is little affected.

In case (5), the magnet is rotated around the Xm-axis. However, the output characteristics remain essentially the same as those for the standard configuration, indicating that the magnet used here can be regarded as a rod within the measurement range considered here. Consequently, in case (6), in which the magnet and the sensing element are first positioned as in the case (4) and then rotated around the Xm- and Xs-axis respectively, the output characteristics are nearly the same as in case (4).

Throughout all the cases examined above, it was confirmed that the change in the proportional constant between the displacement and the output voltage was less than 4%.

Two other factors are considered in case (7) and (8). The effects of these factors can be estimated by simple geometrical calculations. In case (7), the magnet and the sensing element are not located on the same plane. This results in a 3.5% change in the proportional constant. Case (8) shows the situation in which the sensing element is rotated around the Xs-axis. It is estimated that, for a rotation of 10 degrees, the change in the intensity of the measured magnetic field is about 2%. Thus, it appears that the effect of this rotation in practical situations is relatively small.

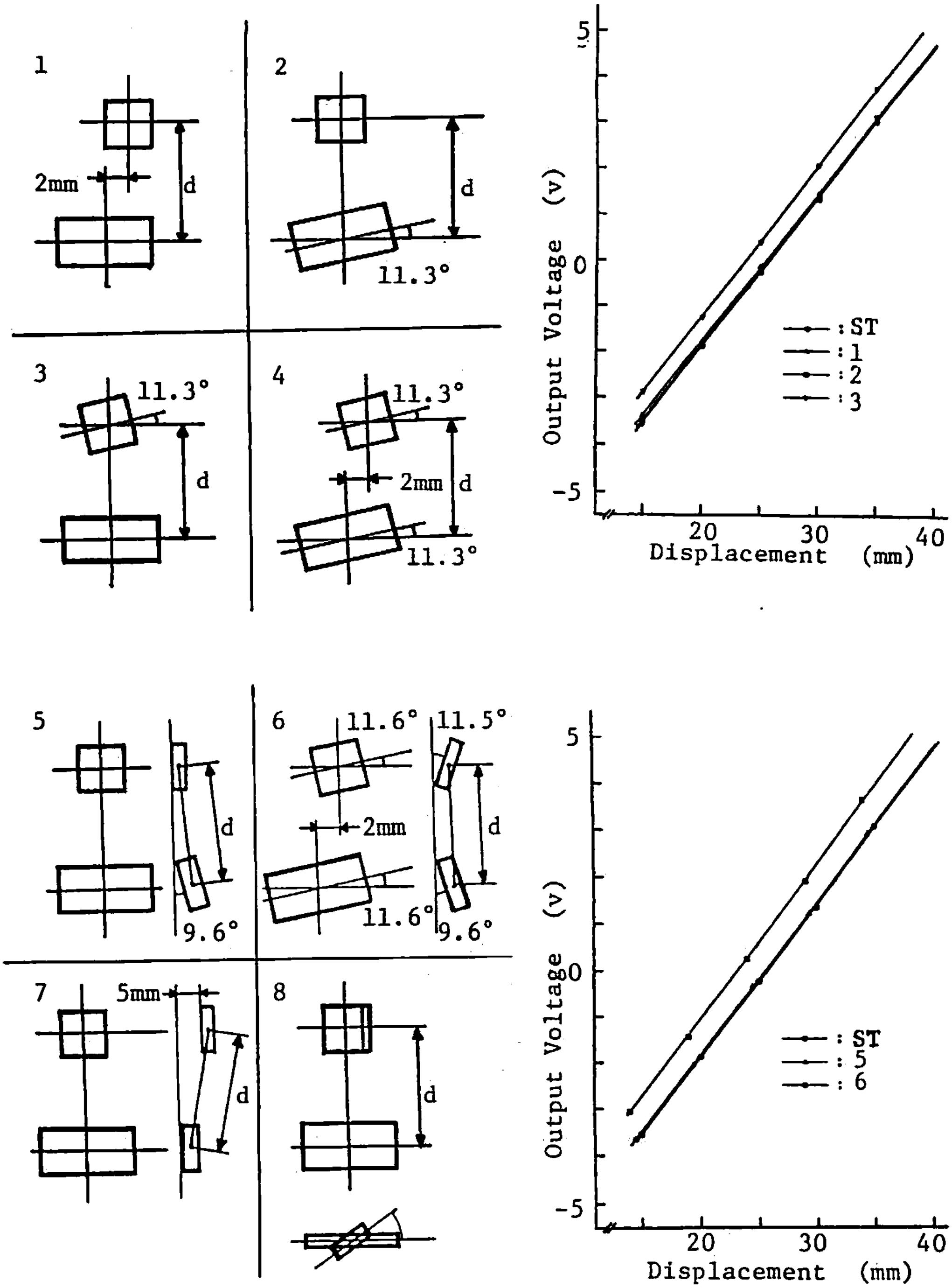

Fig. 3 *Relationship between the displacement and the output voltage under various conditions of the relative orientation of the magnet and the sensing element.*

In summary, it may be concluded that in practical situations, variations in the proportional constant between the displacement and the output voltage will be less than 10%. In all of the cases examined above, sufficient linearity between the displacement and the output voltage is maintained.

The output voltage of the sensing element is naturally influenced by the terrestrial magnetic field. This effect is considerably large and can not be ignored if the orientation of the subject's head (hence, the orientation of the sensing element) can vary freely. However, it was observed that, for a 30-degree rotation of the Xs-axis in the horizontal plane or, for a 10-degree rotation in the vertical plane, the change in the output voltage was 30 μV, which corresponds to a measurement error of 0.5 mm when the magnet-sensing element distance is 35 mm. Thus, it was considered unnecessary to fix the subject's head to avoid measurement error due to the terrestrial magnetic field. A mirror was placed in front of the subject and the subject was instructed to simply try to keep a constant head position.

The temperature change in the output voltage of the sensing element during the experiment was about 120 μV/10 degree. Consequently, when the magnet is attached to the teeth, it was necessary to wait till the temperature drift of the sensing element ceases. Then, in order to compensate for the effect of the temperature change, the level of the input signal to the logarithmic amplifier was adjusted to a specified value by a zero level adjustor in the measuring system. After this adjustment, the magnet was attached to the teeth.

Data Recording and Analysis

The speech samples used were as follows. 1) Continuous sequences of two stationary vowels: $V_1 V_2$ (V_1, V_2 = i, e, a, o, u). The duration of each vowel was about 0.5 second. 2) Meaningless words of the type $V_1 V_2 V_1$ (V_1, V_2 = i, e, a, o, u). The test words were uttered in the carrier phrase /____ desu/ at a relatively fast speaking rate. The duration of each utterance was about 0.6 second.

For each test word, six tokens of the utterance were recorded. The subjects were four male adults. The output signal of the measuring system was fed into a computer together with the amplitude envelope signal of the speech wave. The sampling rate was 100 Hz.

Fig. 4 shows examples of the time functions of the jaw movement for the $V_1 V_2$ and $V_1 V_2 V_1$ utterances. For the $V_1 V_2$ utterance, 1) the jaw position for the stationary state of the vowel; and 2) the displacement and peak velocity during the transition from the first to the second vowel were measured. It often happens that, even during the apparent steady state phonation of the vowel, there is a slight gradual change in jaw position. In the present study, the time interval during which the jaw movement could be regarded as approximately linear with regards to time was selected, and the mean jaw position over this time interval was measured for each vowel. The time of the start and end of this interval was determined by visual inspection of the computer display of the time function of the jaw movement.

For the $V_1 V_2 V_1$ utterances, the displacement and the peak velocity during the transition from the word initial to the word medial vowel were measured.

Analysis of the transitional movements was performed only for those utterances

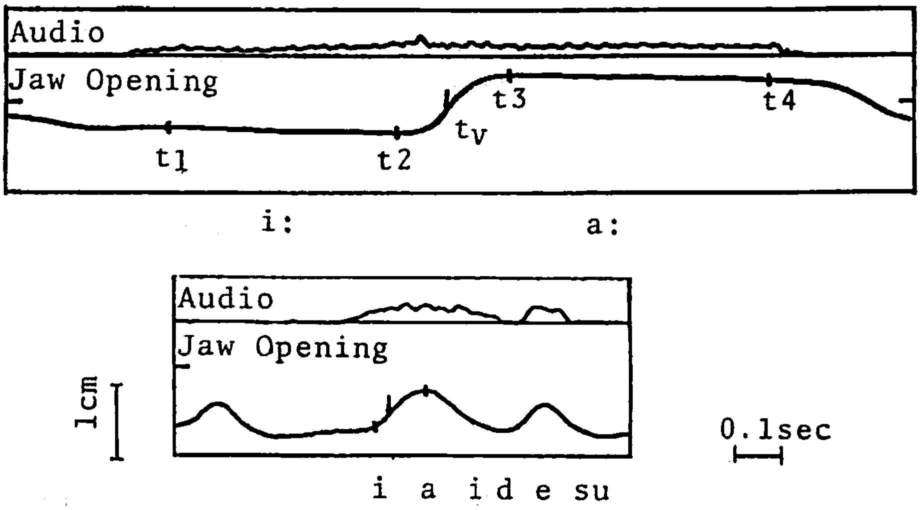

Fig. 4 *Examples of the time functions of the jaw opening and the speech envelope for the $V_1 V_2$ and $V_1 V_2 V_1$ utterances.*

which contained a pair of open and closed vowels (e.g. /ai/ and /aia/ etc.). Here, the vowels /i/ and /u/ are classified as closed vowels and the vowels /a/, /o/ and /e/ are classified as open vowels.

Results

Fig. 5 shows the means and the standard deviations of the jaw opening for the five vowels in word initial position (V_1) in the $V_1 V_2$ utterances. For each vowel, the jaw openings for the four different second vowels are given separately. The value of the jaw opening is given as the magnitude of the displacement relative to the position of the jaw when the teeth were clenched.

It can be seen in Fig. 5 that the relative magnitudes of the jaw opening for the five vowels showed considerable variation from subject to subject. In the case of subject 1, the jaw opening was smallest for /u/ and became greater in the order of /i/, /o/, /e/ and /a/. The difference in the jaw opening among the five vowels were rather discrete. For subject 2, the jaw opening for /i/ and /u/ was nearly the same and the jaw opening for /o/, /e/ and /a/ was also nearly the same. In this case, it appears that the five vowels were divided into two groups with regards to jaw opening. For the remaining two subjects, the vowels /o/ and /e/ had nearly the same degree of jaw opening, and the vowel /a/ had a greater jaw opening than /o/ and /e/. The jaw opening for the vowels /i/ and /u/ was clearly different, and /i/ had a larger jaw opening than /u/.

The general tendency in the relative magnitude of the jaw opening for the five vowels may be summarized as /u/≤/i/</o/≤/e/</a/. However, the difference in the jaw opening between consecutive vowels in the above formula show considerable inter subject variations

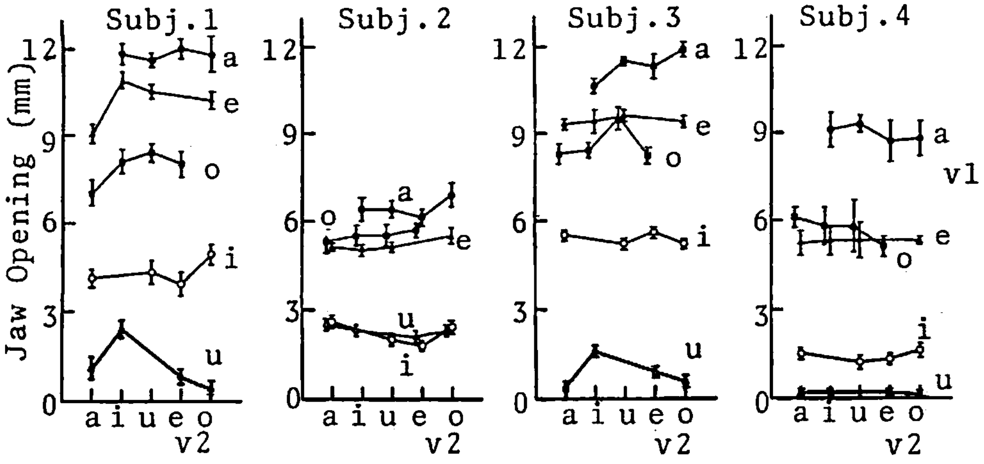

Fig. 5 *Mean and standard deviation of the jaw opening for V_1 in $V_1 V_2$ utterances. The jaw openings of each vowel paired with different second vowels are measured separately.*

Fig. 6 shows the peak velocity during the transitional movement in the $V_1 V_2$ utterances. The abscissa is the magnitude of the displacement during the transition and the ordinate is the peak velocity.

It can be observed that, in all four subjects, the peak velocity has a strong positive correlation with the magnitude of the displacement. Namely, the peak velocity is, on the average, proportional to the distance between the initial and the final state of the transition. This result agrees with the results of previous studies.[6] [7] In these figures, the data points for the closed vowel to open vowel transition are represented by open marks and the open vowel to the closed vowel transition by the filled marks. It can be seen that subjects 1 and 2 show little difference between the two types of transition. Among the four subjects, only subject 4 shows a clear difference between the two types of transition. Namely, for this subject the peak velocity for the close to open vowel transition is greater than that for the open to closed vowel transition when the peak velocities for the same magnitude of displacement are compared. In subject 3, the peak velocities for /eu/ and /ou/ are apparently smaller than that for /ue/ and /uo/. For the other test words, a difference between the two types of transition was not observed.

The peak velocity in the transitional movement in the $V_1 V_2 V_1$ utterances is shown in Fig. 7. In this case, all four subjects show the clear tendency for the peak velocity in the closed to open transition to be greater than that in the open to closed vowel transition. In the case of the $V_1 V_2$ utterances, subjects 1 and 2 show little difference between the two types of transition. However, for the $V_1 V_2 V_1$ utterances, the difference can be clearly observed. For subjects 3 and 4, the difference is greater for the $V_1 V_2 V_1$ utterances than for the $V_1 V_2$ utterances.

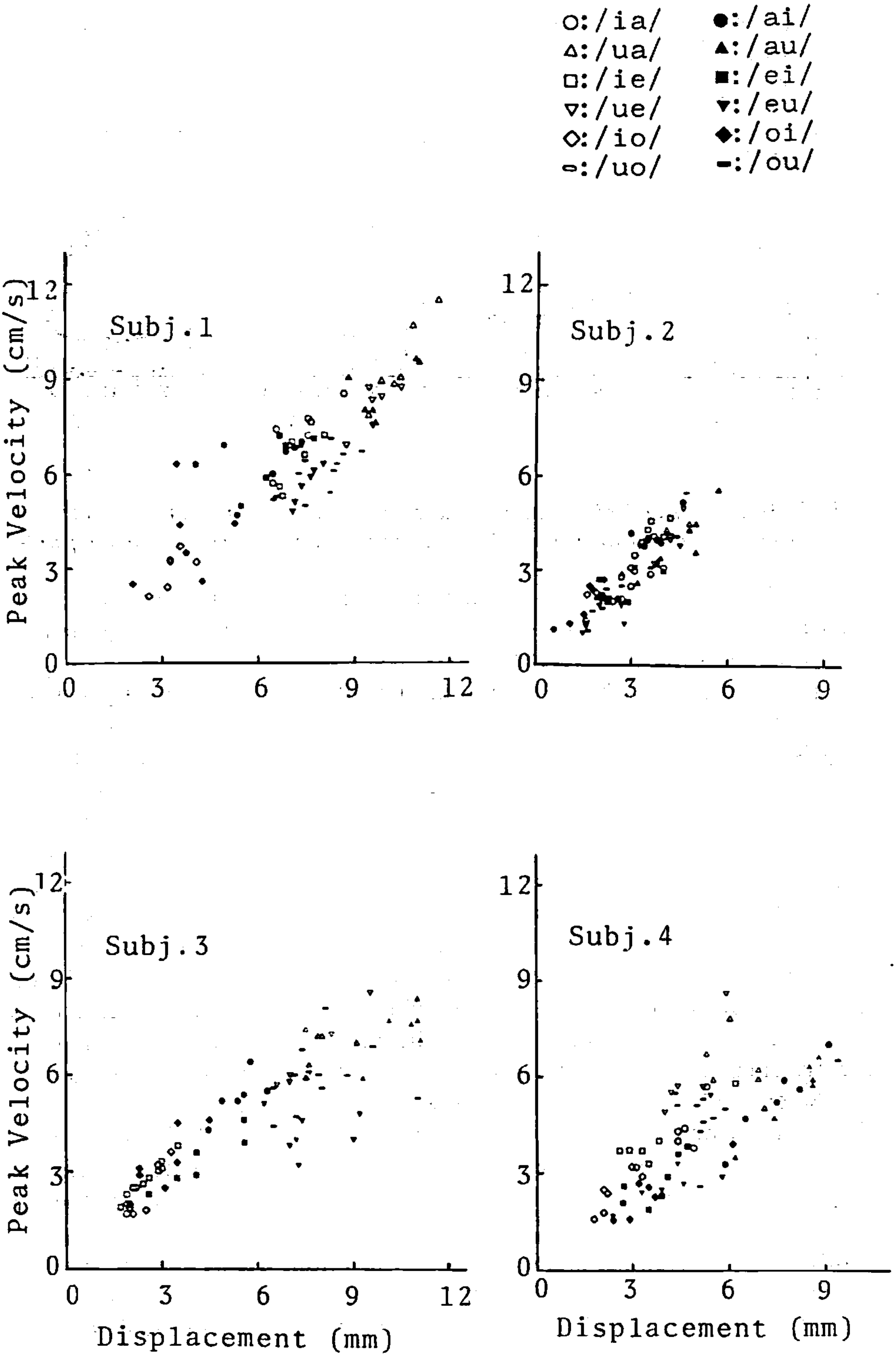

Fig. 6 *Displacement versus peak velocity for the $V_1 V_2$ transition in the $V_1 V_2$ utterances.*

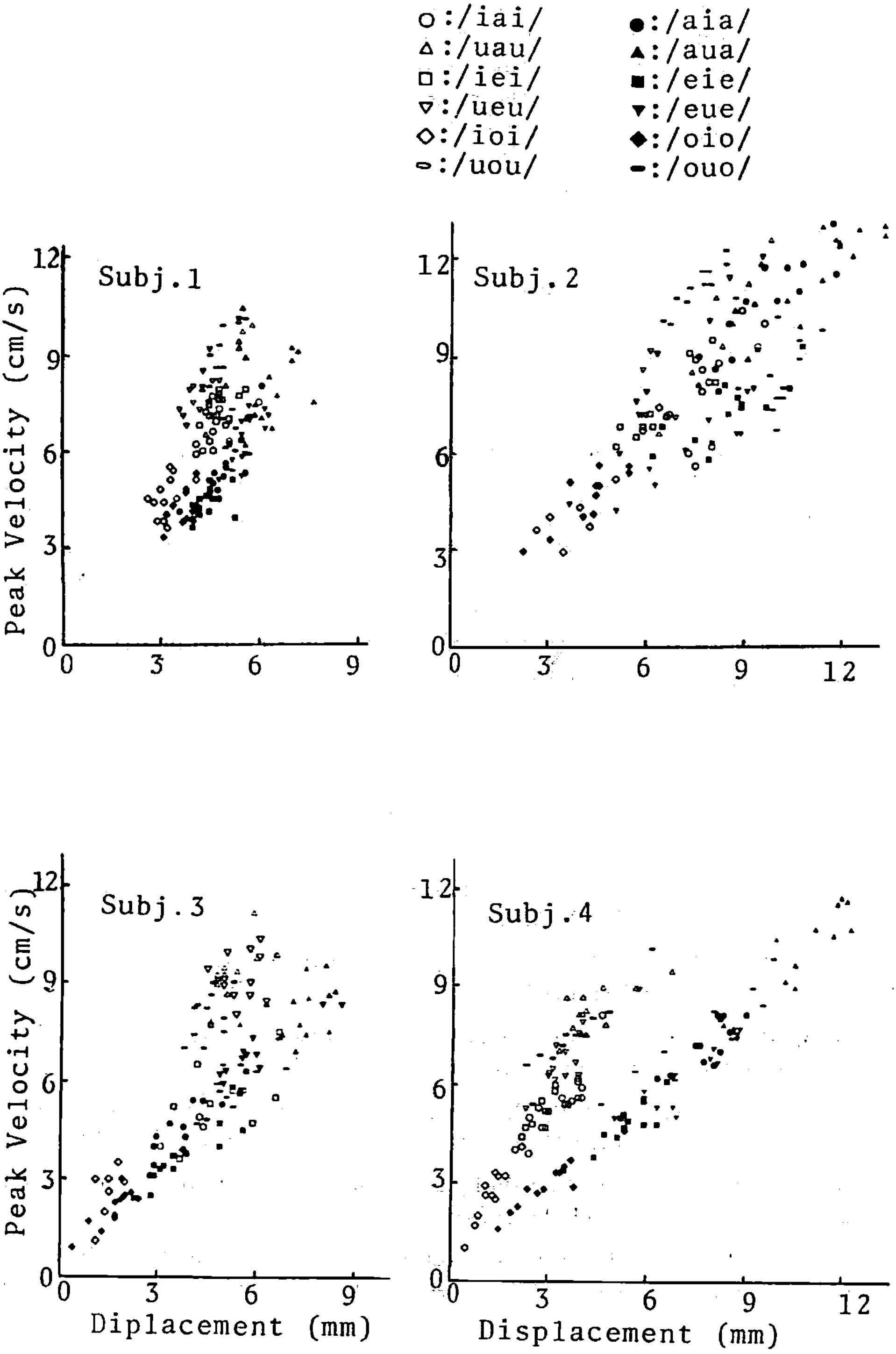

Fig. 7 *Displacement versus peak velocity for the $V_1 V_2$ transition in the $V_1 V_2 V_1$ utterances.*

Comment

In the present paper, a new method for measuring the movement of the jaw was described. In this method, only a small magnet and a small magneto sensing element are attached to the lower and upper teeth, respectively, of the subject. At the same time, the intensity of the measured magnetic field is relatively strong because of the small distance between the magnet and the sensing element, and small variation in the orientation of the head (and, hence, the sensing element) relative to the terrestrial magnetic field does not cause measurement error. Consequently, it is not necessary to fix the subject's head during the recording session. Thus, the present method causes little discomfort for the subject, facilitating longer and more stable data recording sessions and a larger amount of data collection.

In the present study, it was observed that for the $V_1 V_2 V_1$ utterances with a relatively fast speaking rate there was a clear difference in the peak velocity between the open to closed vowel transition and the closed to open vowel transition. However, for the transition from one steady state vowel to another in the 'slow' $V_1 V_2$ utterances, the difference was smaller or not present. Thus, it appears that the difference in the peak velocity between the opening and the closing movement of the jaw is not a direct reflection of simple mechanical factors. It may be concluded that a difference in the mode of the control of the jaw movement between the 'slow' $V_1 V_2$ utterances and the 'fast' $V_1 V_2 V_1$ utterances contributes to the observed difference between the opening and the closing movements.

The influences of the various utterance modes on the asymmetry in opening and closing movements should be explored further.

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