MEASUREMENT OF MANDIBULAR CONTROL IN VOWELS AND ITS RELEVANCE TO THE ARTICULATORY DESCRIPTION OF THE VOWEL SYSTEMS OF KOREAN AND JAPANESE*

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Abstract

The acoustic and phonetic characteristics of vowels are determined primarily by the vocal tract area function, specified by the configuration of the lips and the tongue, the latter being controlled by two articulatory factors: jaw opening and tongue retraction. A method of direct observation of jaw opening during vowel articulation was developed using a pair of artificial gums with needles to be fitted on both gums of a speaker. Measurement of jaw opening for the isolated vowels of Korean and Japanese revealed the ternary character of jaw control in both languages, leading to discrete articulatory descriptions for the structures of the respective vowel systems. Results of measurement on connected vowels indicated some hysteresis characteristics of jaw opening, which cause considerable coarticulatory interference between successive vowels. The articulatory description of Korean vowels was utilized for the analysis of vowel harmony in disyllabic words of Korean, and revealed some inter-syllabic constraints between articulatory features of vowels.

1. Introduction

According to traditional articulatory phonetics, vowel articulation is specified by three factors: tongue elevation (high-low), tongue retraction (front-back) and lip rounding (rounded-unrounded). [1] Although the validity of these factors has not been fully proved by physical or physiological measurements, it seems to be reasonable to express the degree of tongue retraction in terms of the position of center of gravity of the mobile part of the tongue body along the longitudinal axis of the vocal tract, and the degree of lip rounding in terms of the resultant decrease in the mouth area with other articulatory conditions being kept equal, and to adopt these two as basic parameters for describing vowel articulation.

It is, however, doubtful that the conventional measure for tongue elevation, expressed in terms of the vertical position of the highest point on the mid-sagittal contour of the tongue surface, may serve as the basic parameter, since the position of the point is not the direct object of control by the articulatory musculature, but is the result of combined control of jaw opening and tongue retraction. Furthermore, no tactile feedback is available for the precise control of this point's position in vowels, and its position is subject to considerable variations because of the small curvature of the tongue contour. [2] On the other hand, the opening angle of the

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mandible has been proved to be essential for determining the global configuration of the vocal tract, [3, 4] and thus is believed to be one of the primary articulatory factors which are under direct control by motor commands for speech production.

Previous efforts to measure jaw opening, [5-8] however, seem to have failed to reveal the quantal nature of jaw control because of coarticulatory interference and combined effects of other articulatory controls. In this paper we describe a new method for the measurement of jaw opening during production of both isolated and connected vowels, and apply the results to articulatory descriptions of the vowel systems of Korean and Japanese.

2. Measurement of jaw opening in isolated Korean and Japanese vowels [9]

The measurement of the degree of jaw opening was accomplished by a simple photographic method with the implement of special angle indicators. Since the position of the mandible cannot be externally observed, photographic measurements without the aid of special instruments are hardly satisfactory for the accurate observation of degree of jaw opening. To cope with this situation, a pair of artificial gums were constructed to fit each individual subject, and a needle which projected from the mouth was attached to each of them. These artificial gums with needles allow complete closure of the jaw and cause little interference with normal arti ulation of vowels. The needles serve as the direct indicators of mandibular opening and eliminate the need of any device for fixing the subject's head. A piece of paper of known size is attached to the upper needle for the normalization of picture size. The aperture of the jaw during articulation of an isolated and sustained vowel is measured from a lateral view photograph of the subject's head, and can be expressed in terms of the opening angle, since mandibular displacement is comparatively small in this case and thus may be considered as rotation around a fixed axis. The position of the axis can be determined from three photographs taken with different degrees of jaw opening. An example of a tracing of such a photograph is shown in Fig. 1.

The subjects were a native speaker of standard Korean (BK, a male adult), and a native speaker of standard Japanese (KM, a female adult). They were shown a randomized list of vowel letters from their respective native languages, and were asked to sustain each vowel for an interval of about three seconds and then pause about two seconds, restoring the neutral position of the jaw after each utterance to eliminate coarticulation. One picture was taken for each utterance at the instant when the articulation was observed to be most stationary. Shutter clicks of the camera were recorded along with speech signals for comparison of acoustic and articulatory measurements.

Figure 2 summarizes the results of measurement of jaw opening for (a) isolated Korean vowels and (b) Japanese vowels. An empty circle represents the average jaw opening angle as defined above for five utterances of each vowel, and the solid line segment indicates the range between the maximum and the minimum for each vowel. These results suggest that both Korean and Japanese vowels can be categorized into three groups from

the point of view of the degree of jaw opening. Namely, in the case of the eight Korean vowels, [i], [ɯ] and [u] can be considered as one group with smaller jaw openings, [e], [ɔ] and [o] as another group with medium jaw openings, [æ] and [a] as the third group with larger jaw openings. The categorization is seen to be valid also for the five vowels of Japanese, which lacks [u], [ɔ] and [æ] as compared to Korean.

These findings were confirmed by the analysis of variance which indicated that the differences in jaw opening among the three vowel groups were always highly significant, while most of the differences between vowels within each group failed to reach significance at the 5% level. These results allow us to infer that the control of jaw opening for isolated vowels of both Korean and Japanese languages is basically discrete and can assume only three values, while some intra-group differences may be the secondary effects of other articulatory controls. For instance, the differences between jaw openings for [i] and [ɯ] as well as for [e] and [o], though only significant at the 5% level, may be the results of differences in tongue retraction and/or lip rounding.

In addition to the control of jaw opening, controls of tongue retraction and lip rounding can determine distinctions among vowels in a group with the same degree of jaw opening. Namely, in the case of Korean vowels with smaller jaw openings, tongue retraction (front-back) determines a binary distinction between [i] versus [ɯ] and [u], while lip rounding (rounded-unrounded) determine a binary distinction between [u] versus [i] and [ɯ]. Similar distinctions are made among Korean vowels with medium and larger jaw openings. In the case of the five vowels of Japanese, only tongue retraction plays the distinctive role for vowel groups with smaller and medium jaw openings, while differences in the degree of lip rounding are not distinctive even though they are present.

On the basis of this evidence, a system for the specification of vowel articulation can be proposed in terms of three parameters: Jaw opening, tongue retraction, and lip rounding. In the case of Korean vowels, the control for jaw opening is ternary, while the control for tongue retraction is binary, and the control for lip rounding is binary for retracted tongue position and irrelevant otherwise. Thus the articulation of the Korean vowels can be represented by a prism-shaped structure as shown in Fig. 3(a). In the case of Japanese vowels, the control for jaw opening is also ternary, and the articulatory diagram can be represented by the structure shown in Fig. 3(b). In comparison with the vowel prism of Korean, the Japanese vowel system is characterized by the degeneracy of the rounded-unrounded dimension in back vowels and the degeneracy of the front-back dimension in the most open vowels, resulting in a five vowel system, with no distinction between [ɯ]/[u], [ɔ]/[o], and [æ]/[a], as is made in Korean.

The acoustic consequence of these articulatory controls are illustrated by Fig. 4, which shows the first and the second formant frequencies of the eight vowels of the Korean speaker in an F_1-F_2 diagram. The formant frequencies were extracted by the method of 'Analysis-by-Synthesis' in the frequency domain, [10] and were determined with an accuracy of ± 5 Hz. Comparison with the articulatory description in Fig. 3(a) indicates that the primary effect of opening the jaw is an increase in the first formant frequency (F_1), while that of retracting the tongue is a decrease in the second

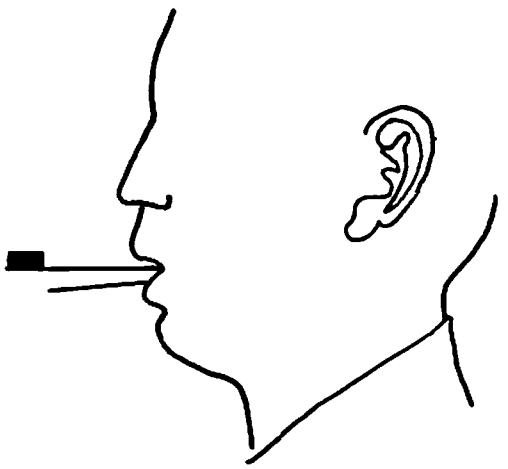

Fig. 1. An example of a tracing of a photograph in the utterance of the Korean vowel [e].

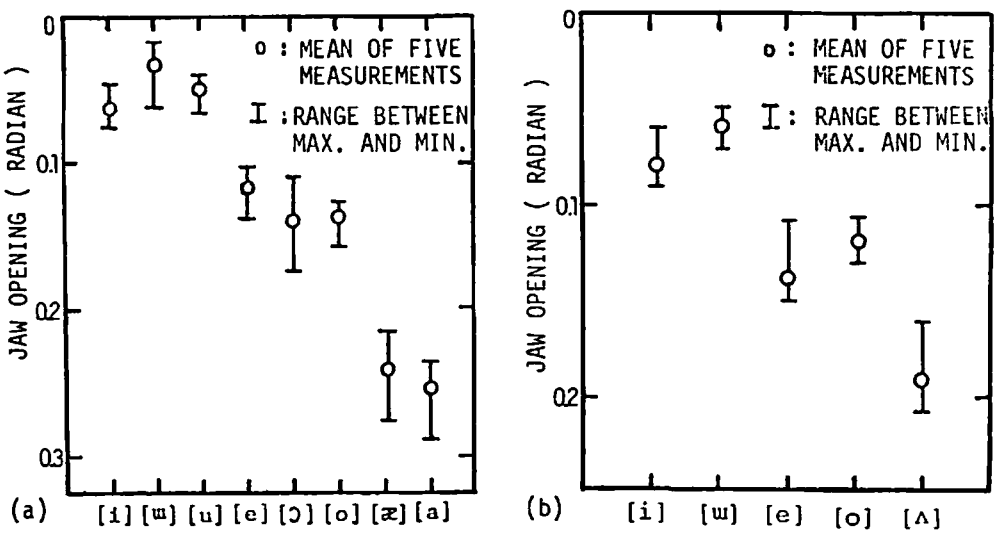

Fig. 2. Jaw opening angles of the eight Korean vowels (a) and the five Japanese vowels (b).

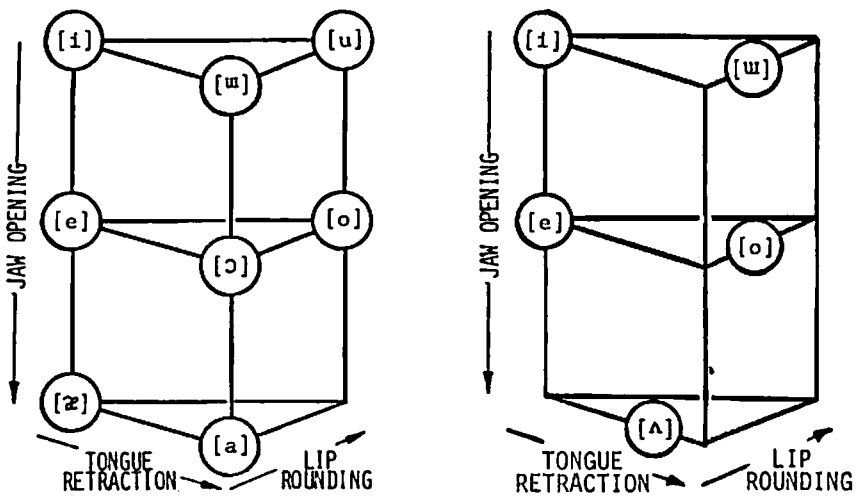

Fig. 3. Articulatory representation of the Korean vowel system (a) and the Japanese vowel system (b).

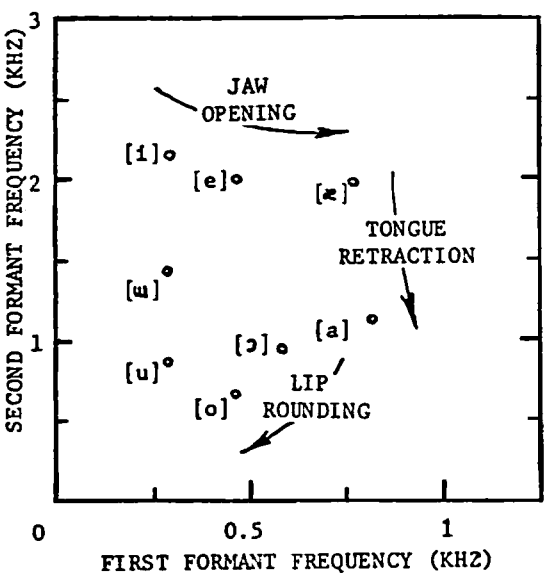

Fig. 4. F_1 - F_2 diagram of Korean vowels uttered by BK.

formant frequency (F_2). On the other hand, rounding the lips decreases both F_1 and F_2 in vowels with medium jaw openings, but is seen to affect mostly F_2 in vowels with smaller jaw openings. The effects of these articulatory controls can best be explained in terms of coefficients of the cosine series expansion of the vocal tract area function. [11]

3. Measurement of Jaw Opening in Connected Vowels of Korean and Japanese [12]

As a preliminary step in the investigation of jaw control in connected speech, measurements were made of jaw openings for two vowels uttered in succession. The total number of such vowel pairs in Korean and Japanese is 56 and 20, respectively. Randomized lists of these vowel pairs were pronounced by the same speakers as in the experiments with isolated vowels, and the photographs were taken at instants where the articulation of each vowel was observed to be most stationary. Figure 5 shows a plot of averaged jaw opening of each vowel at the initial position ($\bar{\theta}_1$) or at the final position ($\bar{\theta}_2$) against its value when the same vowel is uttered in isolation ($\bar{\theta}$). The results show that jaw openings for vowel pairs are generally exaggerated as compared to isolated vowels, which may be caused by the necessity of realizing the respective target configurations within a comparatively short time.

In order to investigate the coarticulatory effects between vowels uttered in succession, jaw openings were measured for a sequence of sustained vowels uttered continuously. Figure 6(a) indicates jaw openings for the back vowels of Korean uttered first in the increasing order and then in the decreasing order of jaw opening ([ɯ] → [ɔ] → [a] → [ɔ] → [ɯ]), but sustaining each vowel for a period of about two seconds. The result appears to indicate hysteresis characteristics of jaw control and suggests that the coarticulatory effect of a preceding vowel may remain even after the articulation of the next vowel attains its steady state. The corresponding formant frequencies (F_1 and F_2) are shown in Fig. 6(b), which indicates a similar hysteresis loop in the first formant frequency, and shows that the coarticulatory effect in jaw opening is not compensated for by other articulatory factors.

4. Articulatory Interpretation of Vowel Harmony in Korean [13]

The phenomenon of vowel harmony is a consequence of statistical or deterministic constraints on vowels that can occur within a word or form a diphthong. Although in the case of the Korean language these constraints are traditionally stated in phonetic terms, it is suspected that they may be of articulatory origin and may more properly be stated in articulatory terms. The articulatory description of the structure of the Korean vowel system proposed in section 2 provides a basis for the analysis and interpretation of these constraints.

A total of 814 disyllabic words of Korean origin were selected from a dictionary of contemporary Korean [14] on the basis of common usage, and the correlation between articulatory features of the first and the second vowel (V_1 and V_2) within a word was analyzed statistically. Table 1 shows classification of articulatory differences between V_1 and V_2, and indicates

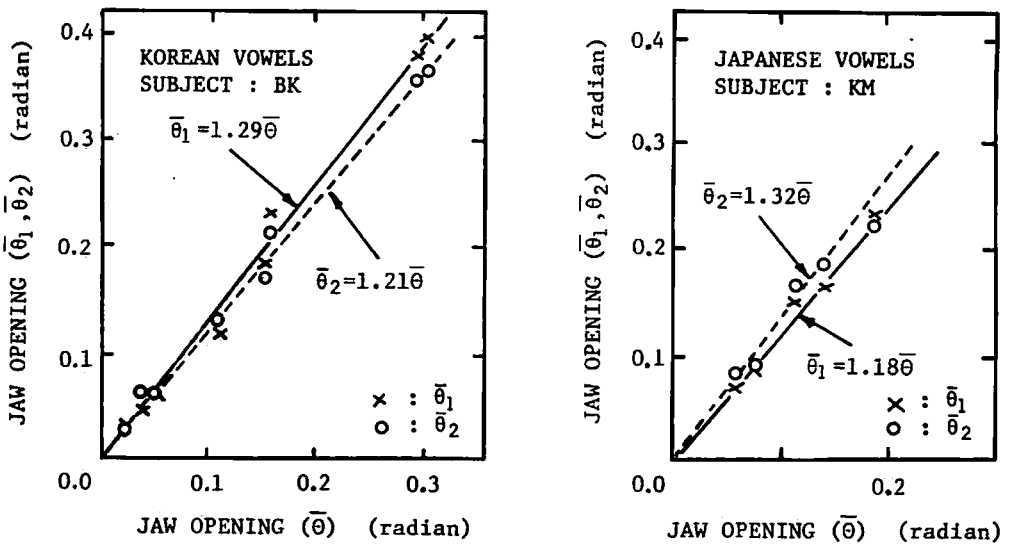

Fig. 5. Averaged jaw opening of a vowel at the initial position ($\bar{\Theta}_1$) and at the final position ($\bar{\Theta}_2$) versus its value when uttered in isolation ($\bar{\Theta}$).

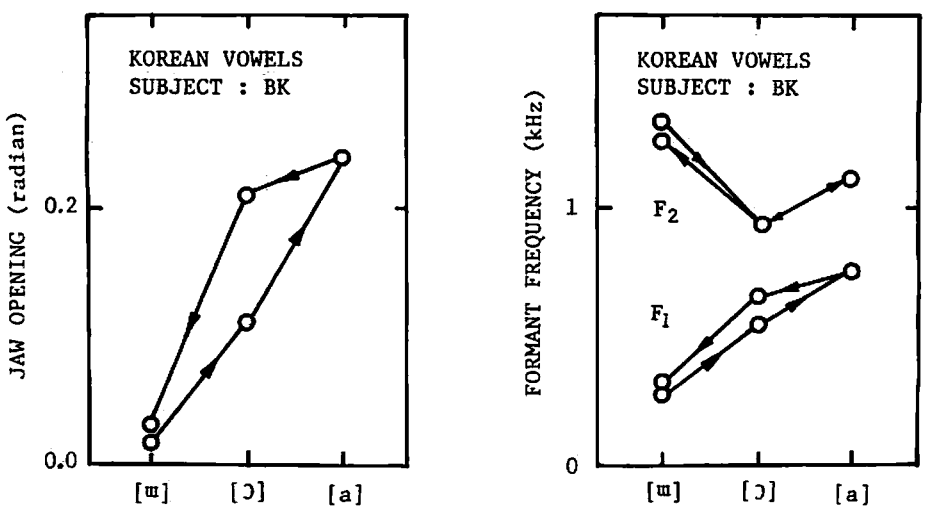

Fig. 6 Examples of asymmetry of jaw control (left) and the corresponding format frequencies (right) in transitions between certain vowel combinations in Korean.

Table 1. Classification and rate of occurrence (%) of articulatory differences between V_1 and V_2 in 814 disyllabic words of Korean.

participating articulators			rate of occurrence	total
jaw	tongue	lips		
			21.4	21.4
x			14.3	25.2
	x		9.1	
		x	1.8	
x		x	21.7	41.0
x	x		15.1	
	x	x	4.2	
x	x	x	12.4	12.4

total for
jaw: 63.5, tongue: 40.8, lips: 40.1.

Table 2. Analysis of directions of simultaneous changes in two or more articulatory features in transitions from V_1 to V_2 .

lips \ jaw	+	-	total
+	1.1	43.0	44.1
-	46.3	9.6	55.9
total	47.4	52.6	100.0

tongue \ jaw	+	-	total
+	7.1	10.6	17.7
-	4.9	67.4	72.3
total	12.0	78.0	100.0

lips \ tongue	+	-	total
+	35.3		35.3
-		64.7	64.7
total	35.3	64.7	100.0

tongue & lips \ jaw	+	-	total
+	5.0	36.6	41.6
-	19.8	38.6	58.4
total	24.8	75.2	100.0

jaw { + opening, - closing ; tongue { + retracting, - protruding ; lips { + rounding, - unrounding

that, among the three articulators, the jaw is most frequently involved in V_1-V_2 transitions and is often accompanied by change(s) in other articulator(s). Analysis of direction of changes in the individual articulatory features indicates closing the jaw and protruding the tongue as well as releasing the rounded lips occur much more frequently than changes in the opposite direction.

Further analysis of correlation between simultaneous changes in two or more articulatory features, as shown in Table 2, indicates that a high negative correlation exists between jaw opening and lip rounding (with a correlation coefficient $r = -0.79$), while a fairly high positive correlation exists between jaw opening and tongue retraction ($r = +0.59$). It also follows from the Korean vowel system that, when both the lips and the tongue are involved in V_1-V_2 transitions, the direction of change in one feature is completely predictable from that of the other. Furthermore, when all three articulators are involved, the correlation between the jaw and the tongue/lips is found to be rather low ($r = -0.13$).

5. Conclusions

For the purpose of obtaining articulatory descriptions of the Korean and Japanese vowels, a new system has been proposed which adopts tongue retraction and lip rounding but substitutes jaw opening for conventional tongue elevation. A method for direct observation of the degree of jaw opening has been developed, and the results of measurement have revealed that the control of jaw opening is ternary, as opposed to the binary controls of tongue retraction and lip rounding, leading to a prism-shaped articulatory diagram for the Korean and Japanese vowel systems. The relationship between the vowel systems of Korean and Japanese has been discussed, indicating systematic tendencies of vowel degeneration in the latter. Jaw openings of individual vowels in pairs or longer sequences have been measured by the same method, and the results have indicated some evidences of overshoot as well as hysteresis in jaw control, which are not compensated for by other articulatory factors. Finally the phenomenon of vowel harmony in Korean has been analyzed and interpreted in terms of articulatory constraints.

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