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LARYNGEAL GESTURES IN SPEECH PRODUCTION*

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This paper describes the physiological mechanisms of Laryngeal gestures for various phonetic distinctions in speech production. An orientation of the basic laryngeal gestures is presented in Part I, and detailed experimental data are discussed in Part II.

Part I. Basic Laryngeal Gestures

The framework of the larynx consists of four different cartilages: the epiglottis, thyroid, cricoid and arytenoid cartilages. The thyroid and cricoid cartilages are connected by the cricothyroid joint. The movements of this joint change the length of the vocal fold. Movements of the arytenoid cartilage on the surface of the cricoarytenoid joint contribute to the abduction/adduction of the vocal fold. Abduction of the vocal fold also results in an increase in the vocal fold length. Studies of the functional anatomy of the cricoarytenoid joint in human larynges (Sonesson, 1958; von Leden and Moore, 1961; Frable, 1961; Takase, 1964) have revealed that the main part of the joint movements is a rotating motion (abduction/adduction) of the arytenoid cartilage around the longitudinal axis of the joint. Other possible movements of the arytenoid are a small degree of the sliding motion along the longitudinal axis of the joint and a rocking motion with a fixed point at the attachment of the posterior cricoarytenoid ligament. In some classical textbooks a rotating motion of the arytenoid around its vertical axis has been described. However, this kind of joint movement is quite unlikely. The results of these studies have been summarized elsewhere (Sawashima, 1974).

Movements of the cricothyroid and cricoarytenoid joints are controlled by the intrinsic laryngeal muscles. Elongation of the vocal fold is achieved by contraction of the cricothyroid muscle. Movements of the arytenoid cartilage and the resultant abduction/adduction of the vocal fold are controlled by the abductor and adductor muscles. The posterior cricoarytenoid muscle is the only abductor muscle, while the other three – the interarytenoid, lateral cricoarytenoid and thyroarytenoid muscles – are the adductor muscles. Contraction of the cricothyroid muscle may also result in a small degree of glottal abduction. The vocalis muscle, which is the inner part of the thyroarytenoid muscle, contributes to the control of the effective mass and stiffeness of the vocal fold rather than to abduction/adduction movements.

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The layer structure of the vocal fold edge described by Hirano (1975) is shown in Fig. 1. As seen in the figure, the vocal fold consists of the mucosa epithelium, the lamina propria and the vocalis muscle. In the lamina propria, the superficial layer is the loose connective tissue, and the intermediate and the deep layers correspond to the vocal ligament. Based on this layer structure, Hirano proposed the structural model of the vocal fold. In his model, the vocal fold consists of three structures: cover, transition and body, each having different physical or mechanical properties. The cover includes the mucosa epithelium and the superficial layer of the lamina propria, the transition includes the intermediate and the deep layers, and the body includes the vocalis muscle. To simplify the model, we may consider the transition as a part of the body.

Hirano proposed this cover/body model in order to explain variations in the mode of vocal fold vibration with different laryngeal adjustments and also with various pathological conditions. Contraction of the cricothyroid muscle elongates the vocal fold, its effective mass being decreased. Because of the elongation of the vocal fold, the stiffness of both the cover and body increases. This is the situation of the vocal fold for phonation in the falsetto or the light register. Contraction of the vocalis muscle, in contrast, shortens the vocal fold, its effective mass being increased. Stiffness of the body increases while that of the cover decreases. Contraction of the vocalis muscle in combination with the cricothyroid usually takes place for phonation in the chest or the heavy register. Thus the difference in the mode of vocal fold vibration between the falsetto and the chest registers can be accounted for by the different conditions of the cover and the body.

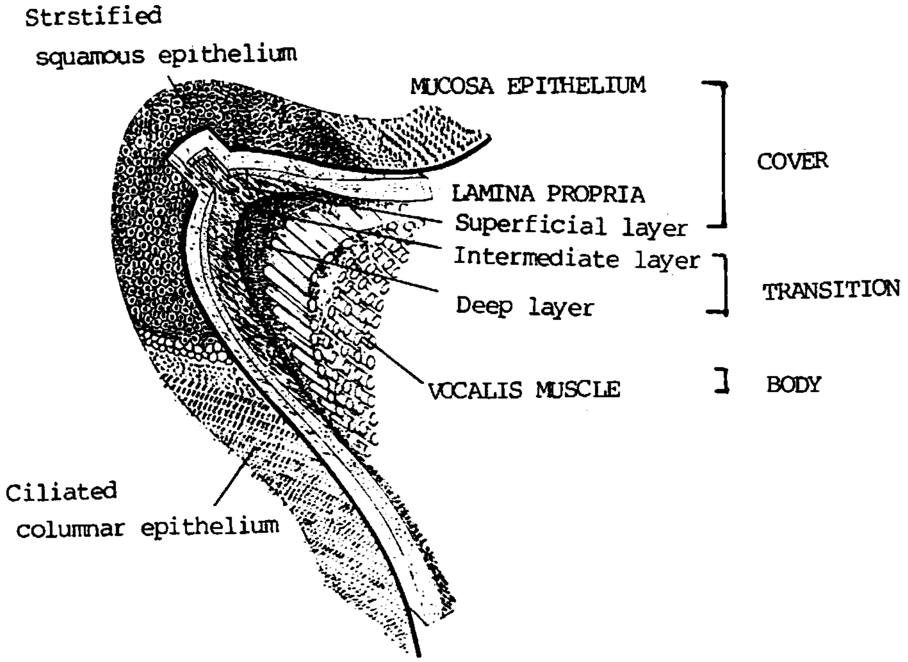


Fig. 1 Schematical presentation of the structure of the human vocal fold. (Hirano, 1975)

The entire larynx is supported by the extrinsic laryngeal muscles, of which the supra-hyoid and infra-hyoid muscles form the important members. These muscles contribute to the up and down movements of the larynx, as well as to articulatory adjustments such as jaw opening. Whether or not these muscles are the primary contributors to the control of phonation is still to be examined.

The basic features of the laryngeal adjustments may be summarized in the following four types:

1) abduction/adduction of the vocal folds
2) constriction of the false vocal folds and other supra-glottic laryngeal structures
3) changes in the length and thickness of the vocal fold
4) up and down movements of the larynx

Abduction/adduction of the glottis

This type of adjustment is used for the distinction of respiration vs. phonation, and also for the voiced vs. voiceless distinction during speech production. The vocal folds are fully abducted with an increase in the activity of the posterior cricoarytenoid muscle for deep inspiration. For quiet respiration, the extent of the glottal opening is approximately half that for the deep inspiration. This vocal fold position is known as the intermediate position. The activities of both the abductor and adductor muscles are minimal in the case of quiet respiration.

For normal phonation, the vocal folds are in the adducted position, and are set vibrating by transglottal air flow. In this position, a narrow spindle-shaped gap is usually seen in the membranous portion of the glottis before the vocal folds start to vibrate, as seen in Fig. 2. There is an increase in the activity of the adductor and vocalis muscles, coupled with a decrease in the activity of the posterior cricoarytenoid (abductor) muscles. The cricothyroid muscle is also activated for the phonation. The transglottal air flow may also generate the vocal fold vibration with the glottis open to a certain extent. The resultant voice is the breathy voice or murmur.

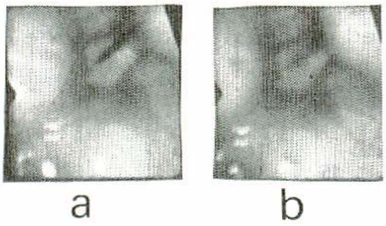


Fig. 2 Glottal views at the phonatry position immediately before (a) and after (b) the onset of vocal fold vibration.

The general picture of the glottal condition in the abduction/adduction dimension during speech is that the glottis is closed or nearly closed for voiced sounds while it is open for voiceless sounds, the extent of the glottal opening varying with different phonemes and phonological environments. An example of the glottal opening and closing movements for an utterance of a Japanese word [keikei] in a frame sentence is seen in Fig. 3 (Sawashima et al., 1976). It is seen that for the word-initial [k], there is a fairly large extent of glottal opening, although the glottal aperture is smaller than in the case of respiration. The distance between the tips of the arytenoid cartilages provides a good measure of the degree of glottal opening. For the word-medial [k], the glottal aperture is observed to be noticeably smaller than that for the word-initial [k].

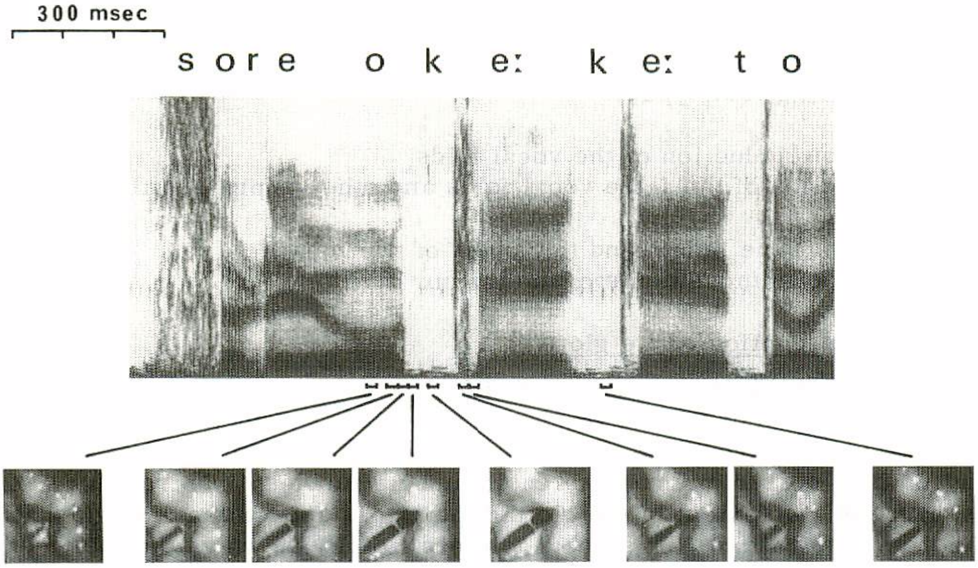


Fig. 3 Selected frames of a laryngeal film and a sound spectrogram of the utterance [keikei] in a frame sentence. (Sawashima et al., 1976)

Some languages such as Korean, Chinese and Hindi show a phonemic distinction between aspirated and unaspirated voiceless stops. Time curves of the glottal width for aspirated and unaspirated voiceless stops in Fukienese are shown in Fig. 4 (Iwata et al., 1979). In the figure, the abscissa indicates the time axis and the ordinate the glottal width. The vertical line near the middle of the time axis is the time point of the oral release. In the aspirated stops there is a great degree of glottal opening, and the peak glottal width is reached near the time point of the oral release. For the unaspirated stops, the glottis is also open but the size of the glottal aperture is far smaller. Furthermore, the glottis is closed or nearly closed at the oral release.

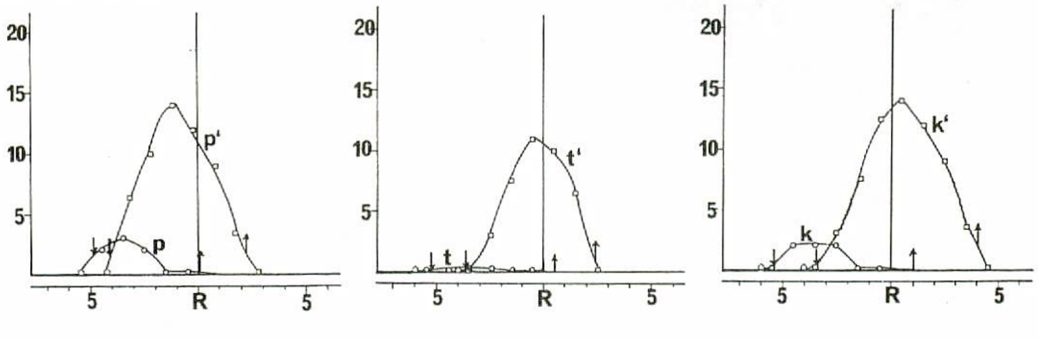


Fig. 4 Time curves of the glottal width for aspirated and unaspirated stops in Fukienese. (Iwata et al., 1979).

The abduction/adduction of the glottis is mainly controlled by the posterior cricoarytenoid (abductor) and the interarytenoid (adductor) muscles (Hirose and Gay, 1972; Hirose and Ushijima, 1978; Hirose et al., 1978). Time curves of the glottal width and integrated EMG curves of the two muscles for the [s] of the Japanese word [iseH] in a frame sentence uttered by two subjects are shown in Fig. 5a. Figure 5b shows the same display for the voiceless sound sequence [si̥ss] in /siQseH/ where the vowel /i/ between the word-initial [s] and the medial [ss] is unvoiced. There is a clear reciprocal pattern in the activity of the two muscles – suppression of the interarytenoid (INT) muscle and activation of the posterior cricoarytenoid (PCA) muscle – for glottal opening corresponding to the voiceless sounds. Contrary to the voiceless sounds, there is an exactly reverse pattern – activation of INT and suppression of PCA – for the voiced segments where the glottis is closed. For both subjects, it is seen that the extent as well as the time course of the glottal width is well represented by the activity patterns of the two muscles, although there seems to be some subject-to-subject variation in the relative extent of the contribution of these muscles.

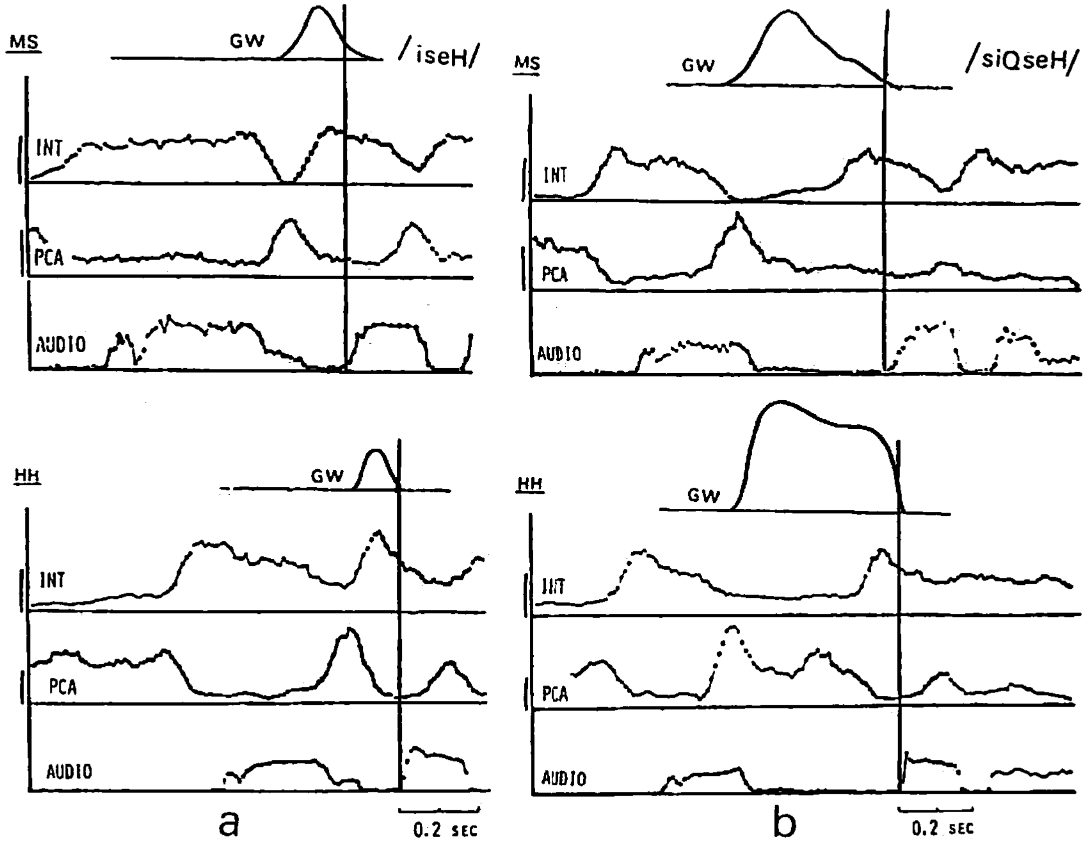


Fig. 5 Time curves of the glottal width and EMG patterns of INT and PCA for the [s] of /iseH/ (a) and the [siss] of /siQseH/ (b). (Sawashima et al., 1978)

Voiced/voiceless distinction is achieved by control of the glottal conditions in combination with the aerodynamic conditions at the glottis. Figure 6 shows transillumination traces for the syllables containing voiced and voiceless sounds in Japanese in a frame sentence. Abduction/adduction of the vocal folds as well as the presence or absence of the vocal fold vibration can be observed in each trace. It is noted that the intervocalic /h/ is voiced in spite of a considerable degree of glottal opening. In the /h/ here, there is no constriction in the vocal tract, and the resulting fast air flow through the glottis enables the vocal fold to maintain vibration. For the medial [t] of/te˥te/, in contrast, the vocal fold vibration ceases immediately after the oral closure in spite of a very small glottal opening. The oral closure prevents the air from passing through the glottis. Thus the extent of the glottal opening itself is not necessarily a crucial condition for the cessation of the vocal fold vibration. A gradual cessation of the vocal fold vibration in [s] may also reflect the aerodynamic condition at the glottis caused by the oral constriction. The aerodynamic effect on the vocal fold vibration with the closed glottis is also observable in voiced consonants. For [d], there is a decrease in both the amplitude and frequency because of the oral closure. For [n], however, no such change is observable because the nasal passage is open for the air flow.

Constriction of the false vocal folds and other supraglottic laryngeal structures

A typical example of supraglottic laryngeal constriction with the glottis open is observed in whispered phonation, as seen in Fig. 7 (Weitzman et al., 1976). Here, an adduction of the false vocal folds takes place with a decrease in the size of anterior-posterior dimension of the larynx cavity. This type of laryngeal constriction becomes more exaggerated for the strong, so-called "stage" whispering. This particular gesture for whispering is considered to contribute to the prevention of the vocal fold vibration by the transglottal airflow, and also to facilitate the generation of turbulent noise in the farynx cavity.

The physiological mechanism behind supraglottic laryngeal constriction is not clear. There seems to be no systematic study on this type of laryngeal adjustment. Our experiences with laryngeal EMG indicate that in whispering there is a greater activity of the lateral cricoarytenoid muscle as compared with normal phonation. This might be related to supraglottic laryngeal constriction. An increase in the activity of PCA to a certain extent combined with a decrease in INT activity also appears to characterize the whispered phonation. This should account for the glottal abduction in whispering. The activity of the cricothyroid (CT) muscle is observed to be suppressed for whispering.

The supraglottic laryngeal constriction with the closed glottis is typically observed for the glottal stop as seen in Fig. 8. The figure shows the laryngeal view for the glottal stop as the syllable-final applosive sound in Fukienese (Iwata et al., 1979). This type of gesture is also observable for the syllable-final stops in English (Fujimura and Sawashima, 1971). The gesture prevents the air from the lung from passing through the glottis. The lateral cricoarytenoid muscle appears to show a high degree of activity also for this particular gesture.

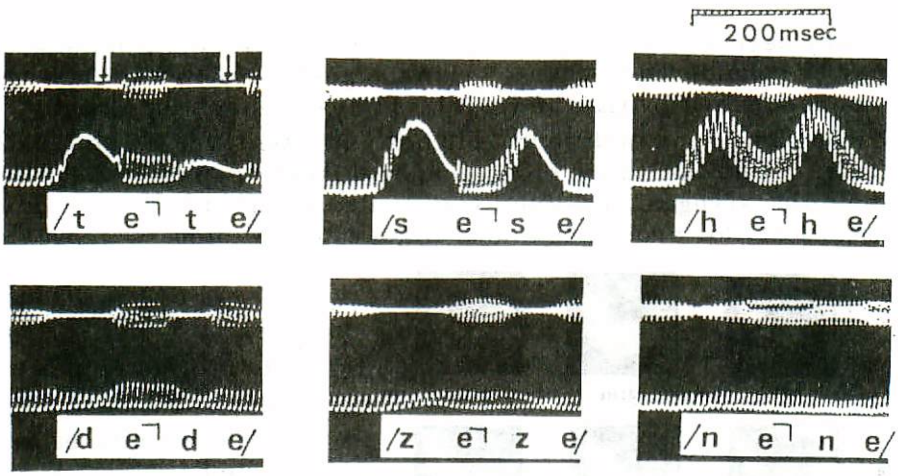
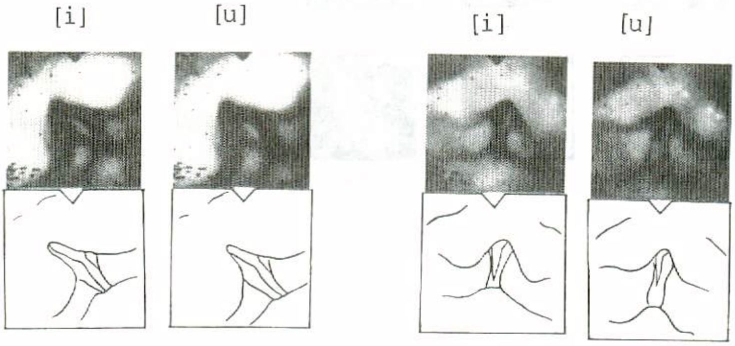


Fig. 6 Photoelectric glottograms for Japanese consonants.



Subj. S.

Subj. H.

Fig. 7 Laryngeal pictures for whispered vowels.

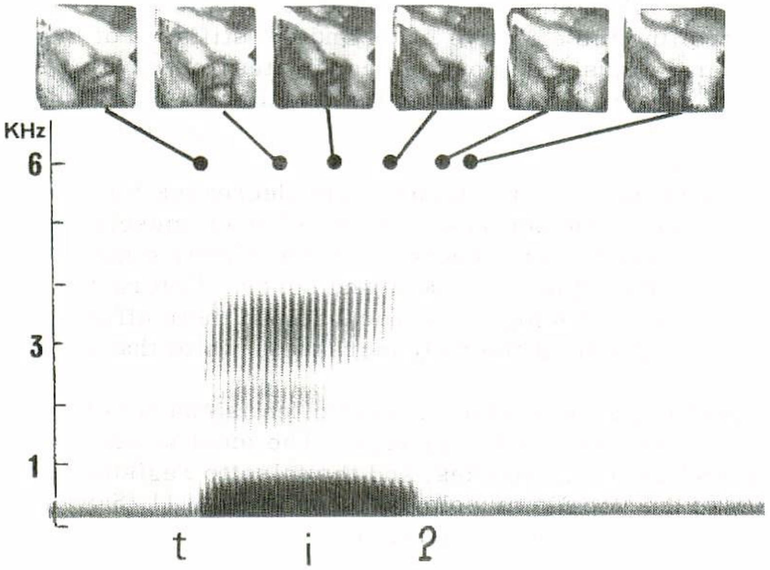


Fig. 8 Selected frames of a laryngeal film and a sound spectrogram for the utterance [tiʔ] in Fukienese.

A lesser degree of supraglottic laryngeal constriction with the glottis closed may be considered to characterize the gesture known as "laryngealization", as pointed out by Gauffin (1977). Figure 9 shows laryngeal pictures for sustained phonations in different pitches and intensities. The pictures suggest that, in addition to the elongation or thickening of the vocal folds, the supraglottic laryngeal constriction may also contribute to vocal pitch control especially for producing a loud voice with low pitch.

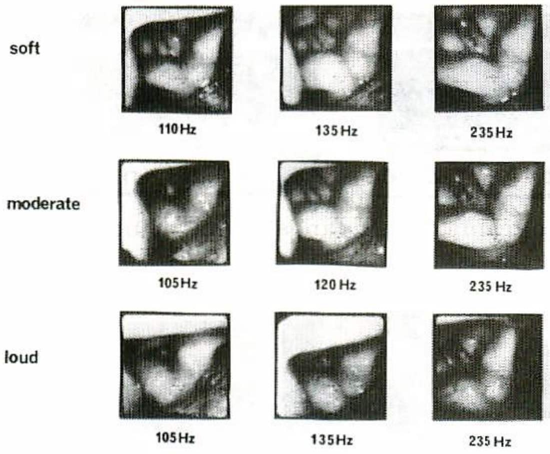


Fig. 9 Laryngeal pictures for sustained phonations in different pitches and intensities.

Changes in the length and thickness of the vocal folds

A good example for this type of adjustment is the control of vocal pitch, Fo during voicing. Fo control at the larynx is considered to be achieved mainly by controlling the effective mass and the stiffness of the vocal folds. Among the intrinsic muscles, possible candidates contributing to these controls are the cricothyroid and the vocalis muscles. Figure 10 shows the EMG curves of these two muscles for stepwise Fo changes during sustained phonation in the chest register (Sawashima et al., 1969). The activity of both muscles increases for raising pitch and decreases for lowering pitch. As mentioned above, contraction of the cricothyroid muscle elongates the vocal folds. The results are a decrease in the effective mass and an increase in the stiffness of both the body and cover. Contraction of the vocalis muscle results in a thickening of the vocal folds, their effective mass being increased. The stiffness of the body increases, while that of the cover decreases.

In the chest register, a rise in vocal pitch is characteristically achieved by contractions of both muscles. The most noticeable difference in muscle control between the chest and the falsetto registers is observed in the activity of the vocalis muscle, as seen in Fig. 11 (Sawashima et al., 1969). In the falsetto, as compared to the chest voice, there is a marked decrease in the EMG level in VOC, accompanied with a slight decrease in CT activity. The difference in the muscle control between the two registers

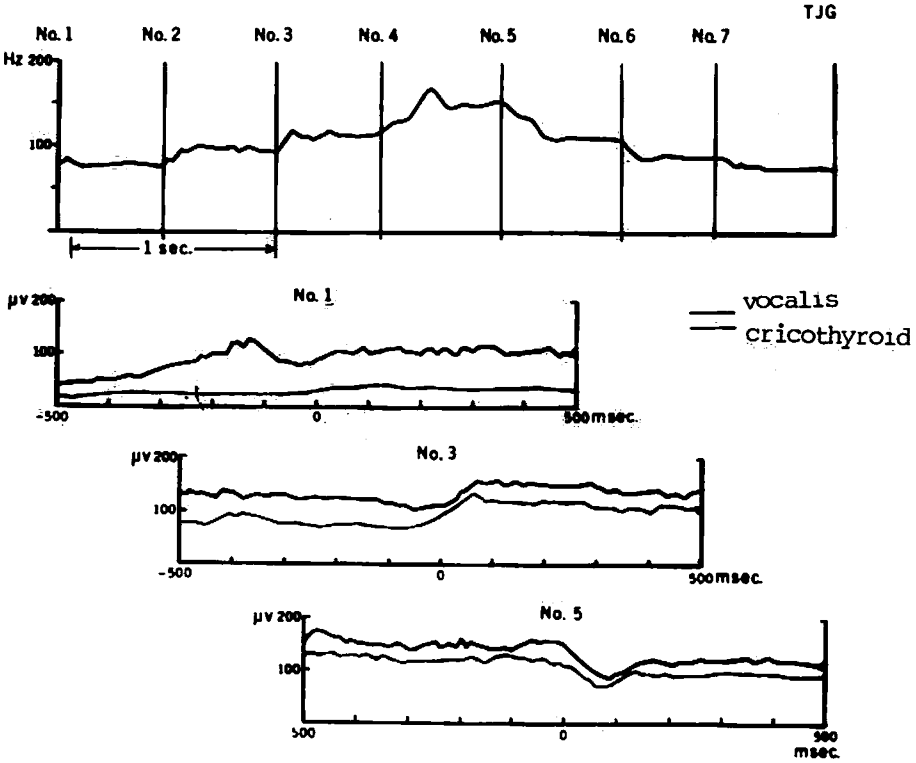


Fig. 10 EMG patterns of CT and VOC for sustained phonation in stepwise changes in F_0.

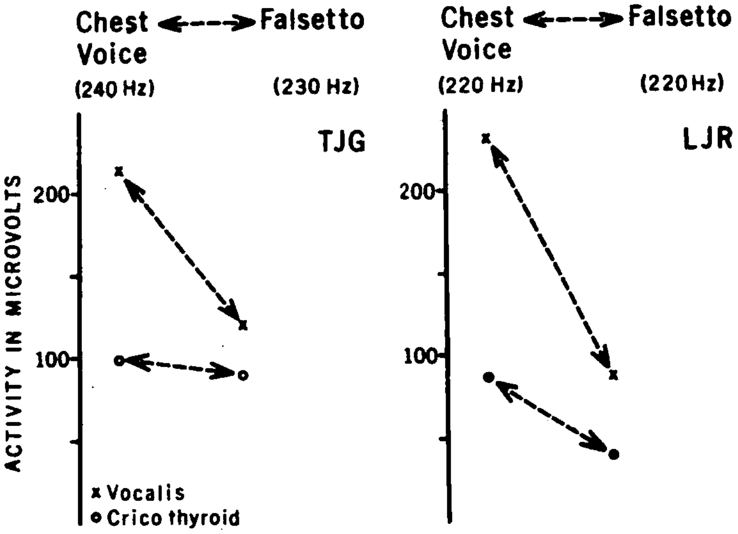


Fig. 11 EMG levels of CT and VOC for phonations in chest and falsetto registers.

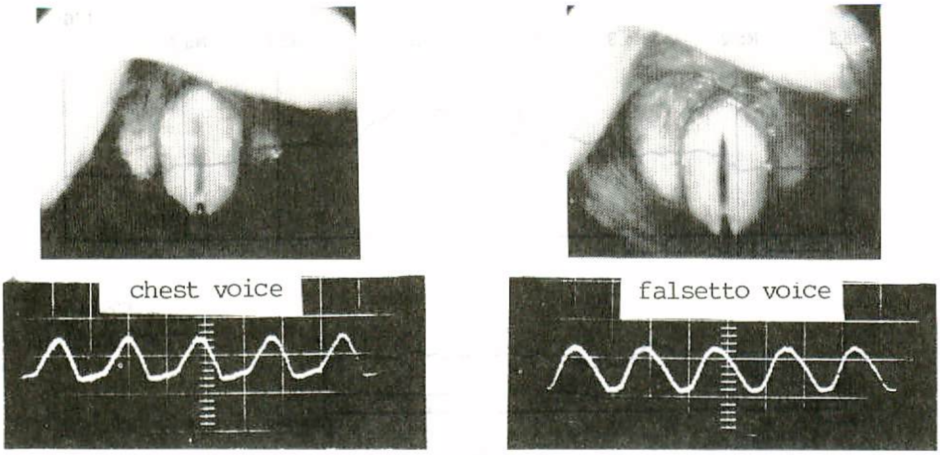


Fig. 12 Laryngeal views and photoelectric glottograms for chest and falsetto voices.

results in the difference in the physical conditions of the cover and body of the vocal folds, which are reflected in the mode of vocal fold vibration. The laryngeal views and the transillumination traces of the glottal vibrations for the two registers are contrasted in Fig. 12.

In speech, CT is the only muscle which is uniquely related to Fo changes, as shown in Fig. 13. At the bottom of the figure, two different Fo contours for the sentences /i⌝ zininaru/ and /izi⌝ ninaru/ are illustrated. In the upper part of the figure are shown the EMG patterns of the cricothyroid (CT), the sternohyoid (SH) and the sternothyroid (Sth) muscles for the two sentences. The activity of the sternothyroid also appears to be correlated to Fo lowering in this particular case. The problem concerning the participation of the extrinsic laryngeal muscles, especially for the pitch lowering, is discussed below in Part II.

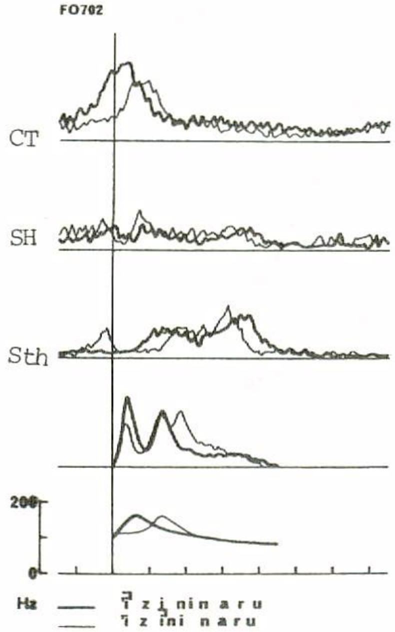


Fig. 13 Laryngeal EMG patterns and F_0 contours for utterances of /i⌝ zininaru/ and /izi⌝ninaru/. (Simada and Hirose, 1971).

Stiffening/slackening of the vocal fold for voicing distinction has been proposed by Halle and Stevens (1971). According to their proposal, stiffening of the vocal folds takes place for voiceless consonants, and slackening for voiced consonants. In this problem also, the activity levels of CT and VOC may provide good physiological correlates of stiffening/slackening controls. Experimental data so far obtained indicate that this problem still needs to be examined, as discussed in Part II.

Up and down movements of the larynx

This type of adjustment is typically seen in the action of swallowing, and also very often during speech with vocal pitch control and voiced voiceless distinction. But the contribution of these movements to the phonetic distinctions still needs to be examined, except for specific adjustments such as the elevation of the larynx for the ejective sound and the lowering of the larynx for generating or maintaining the vocal fold vibration with the vocal tract closed.

Part II. Laryngeal Articulatory Adjustments

The basic laryngeal mechanisms are considered to consist of three different postures of the larynx, i. e., those for breathing, phonation and airway protection. These postures are also widely used in the production of different languages as glottal adduction-abduction gestures or glottal stop gesture. The principal mechanism underlying adduction-abduction is reciprocal activation of the adductor and abductor groups of the larynx.

The reciprocal activity pattern between the two groups of the laryngeal muscles has been revealed by recent electromyographic studies combined with fiberoptic observation. In particular, the posterior cricoarytenoid (PCA) is found to be important for the active vocal fold abduction for those speech sounds produced with an open glottis (Hirose, 1976). The reciprocity between the PCA and the adductors has been observed for different languages including American English, Japanese, Danish and French.

Figure 14 shows an example of averaged EMG curves of the inter-

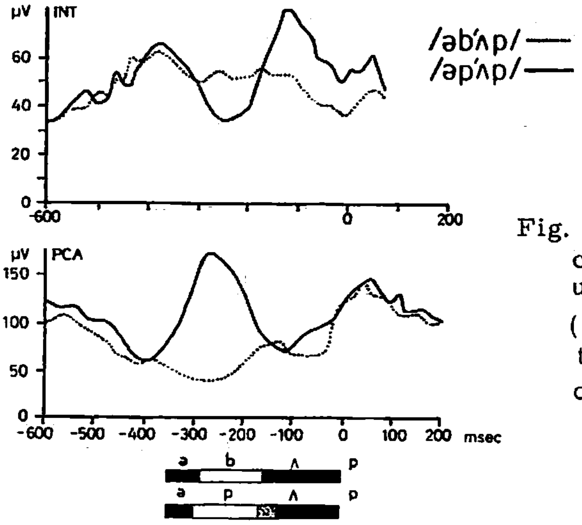


Fig. 14 Superimposed averaged EMG curves of INT and PCA for the utterances / / (–) and / / (. . .). The line-up point (zero on the abscissa) indicates voice offset of the stressed vowel.

arytenoid (INT), the adductor and PCA for a pair of test words /əpʌp/ and /əbʌp/ produced by an American English speaker (Hirose and Gay, 1972). It can be seen that PCA activity is suppressed for the voiced portion of the test words, while it increases for the production of the intervocalic voiceless stop /p/ as well as for the word final /p/. On the other hand, the INT shows a reciprocal pattern when compared with that of the PCA in that its activity increases for the voiced portion and decreases for the voiceless portion of the test words.

The glottal opening gesture and its timing were further observed in more complicated phonetic conditions in American English. For example, a recent study on American English clusters like /sk/ sequences revealed interesting findings (Yoshioka, Löfqvist and Hirose, 1979). Figure 15 compares /sk/ sequences in different phonetic conditions represented by three utterance types: "I may scale," "my ace caves" and "I mask aid." Note that there are two distinct peaks in the PCA activity curve for the /sk/ sequence when a word boundary intervenes, where the glottal width curve also shows two separate peaks.

This type of reciprocal control of the laryngeal muscles associated with glottal adduction-abduction gestures has been found not only in the typical voiced-voiceless contrast but also in more complex phonetic conditions. As an extreme example, one of our previously reported data on laryngeal adjustment for five-way distinction in labial stops produced by an American phonetician is shown in Figure 16, in which the activities of PCA and INT are compared among five phonetic types: voiced inaspirates, implosive voiced inaspirates, voiced aspirates, voiceless aspirates and voiceless inaspirates (Hirose, Lisker and Abramson, 1972). Each stop type was

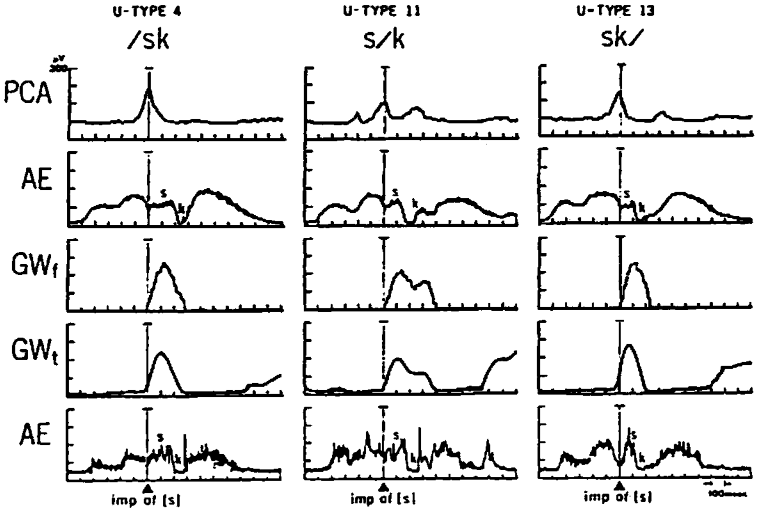


Fig. 15 Averaged EMG of PCA, averaged audio envelopes, representative plots of glottal width using fiberoptics, corresponding glottograms and audio envelopes for three utterance types: "I may scale" (type 4), "my ace caves" (type 11) and "I mask aid" (type 13). (From Yoshioka et al., 1979).

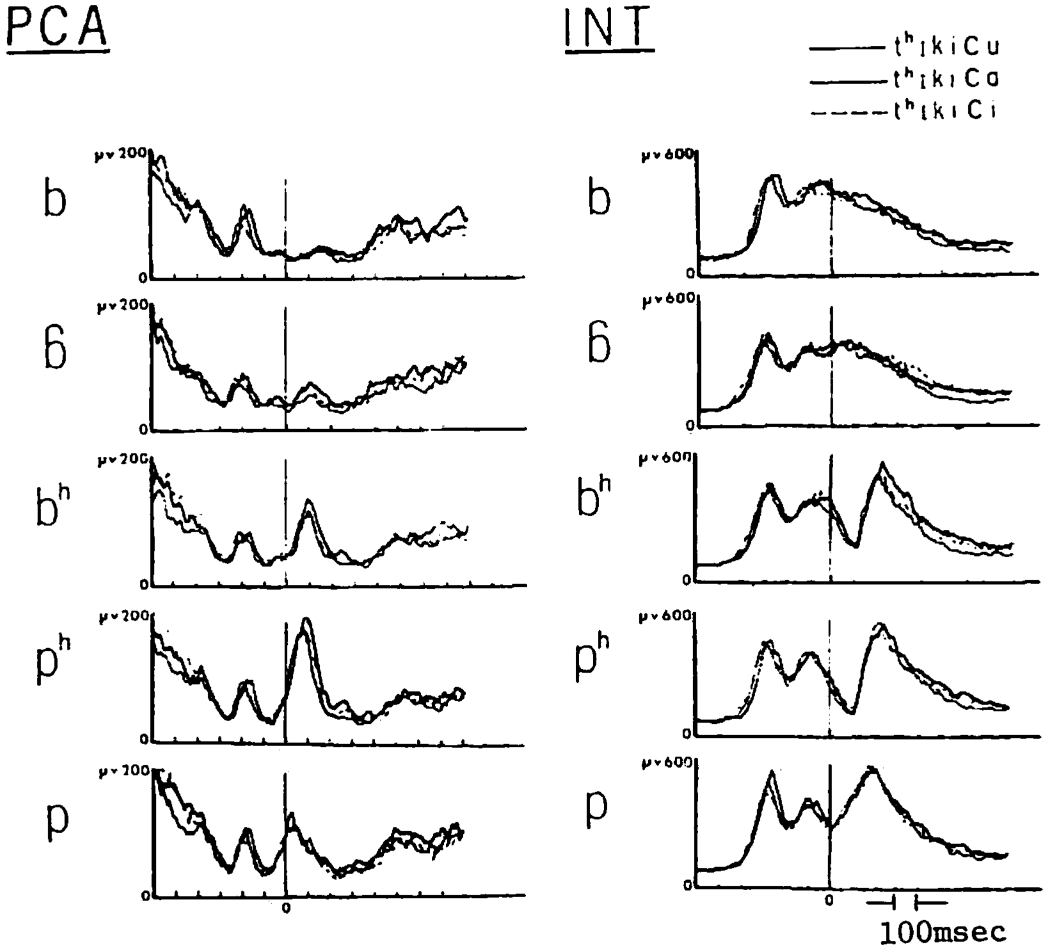


Fig. 16 Averaged EMG curves of PCA and INT for test utterances containing five phonetically different labial stops embedded word-medially. For each type, three curves are superimposed, each of which represents a different vowel carrier following the stop consonant.

embedded in a nonsense trisyllabic word "t^{h}ikiCV," where C stands for each type of stop and V for /i/, /a/ and /u/. The zero on the time axis marks the line-up point for averaging which was taken at the implosion of each stop closure. For each type, three curves are super-imposed, each of which represents three different vowels in the word-final position. It can be seen here that, regardless of the difference in the final vowels, the three curves for each stop show similar contours. Further, it must be noted here that, except for the variation relevent to the phonetic difference among the labial stops, the contours of the five different types are quite similar. This would indicate that the pattern of activity of each of the two muscles for the carrier portion of the test utterance is constant, irrespective of the difference in the embedded labial stops.

It can also be seen that PCA activity increases for the following three

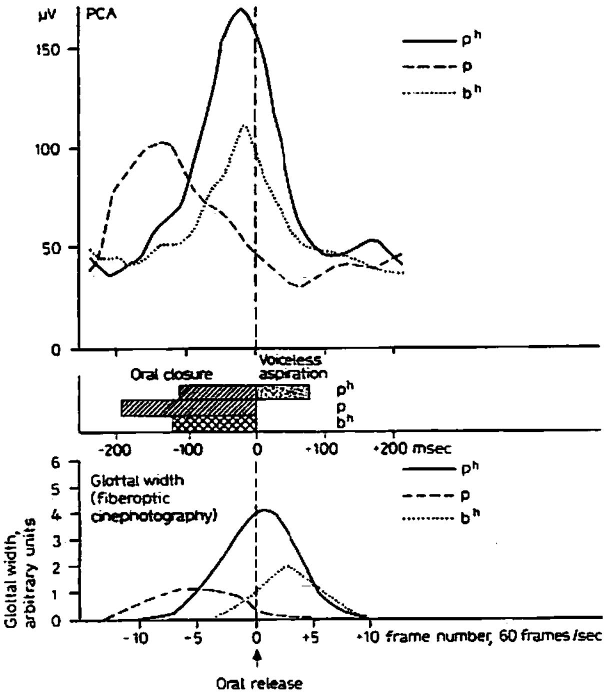


Fig. 17 Comparison of the time courses between averaged PCA activity and glottal opening gesture. All curves are lined up at the oral release.

labial stop types: voiced aspirates, voiceless aspirates and voiceless inaspirates, while corresponding INT suppression can also be seen for these three types. Further, for the three types, analysis of a fiberoptic movie taken separately in the same subject reveals separation of the arytenoids corresponding to stop production.

Thus, the degree of glottal abduction appears to be controlled by activation of PCA associated with INT and other adductor suppression. For glottal adduction, the lateral cricoarytenoid (LCA) in this subject appeared to provide supplementary adduction control. Similar findings were also obtained in other experimental conditions. As Dixit (1975) claimed and other anatomical studies have suggested, the action of INT alone does not seem to fully adduct the vocal fold. Rather, it may be plausible to consider that INT provides the finer adjustments of the glottal aperture for various speech sounds possibly with supportive action of LCA, once the larynx has been geared to "speech mode" by the activation of all the adductors and the suppression of PCA.

Figure 17 shows the relationship between the pattern of PCA activity and the time course of the glottal width measured at the vocal processes for the three stop types showing arytenoid separation (Hirose, 1977b). The curves are lined up at the articulatory release taken as time zero on the abscissa, and durations of oral closure and aspiration are also illustrated. It is shown in this figure that there is a good agreement not only in degree but also in timing between PCA activity and opening gesture of the glottis.

Thus, we must fully realize that, in addition to the control of the degree of glottal adduction-abduction dimension, the control of laryngeal timing is also quite essential in phonetic realization of different types of consonants. As explicitly discussed by Abramson (1977), various languages of the world make extensive use of the timing of the vulvular action of the larynx relative to supraglottal articulation in order to distinguish classes of consonants, although certain non-laryngeal features such as pharyngeal expansion may also be linked with laryngeal timing.

One may argue that these results were not obtained from a native speaker of the specific language. However, our subsequent analysis of the laryngeal behavior in the speaker of a comparable language such as Hindi, has generally confirmed the above findings. Recent fiberoptic studies by Benguerel and Bhatia have also confirmed that the timing of glottal gestures relative to the oral release clearly distinguishes among the three stop types of Hindi discussed above.

The contribution to voicing distinction of each intrinsic laryngeal muscle other than PCA and INT is not completely understood as yet. Figure 18 shows an example of averaged EMG curves of the thyroarytenoid

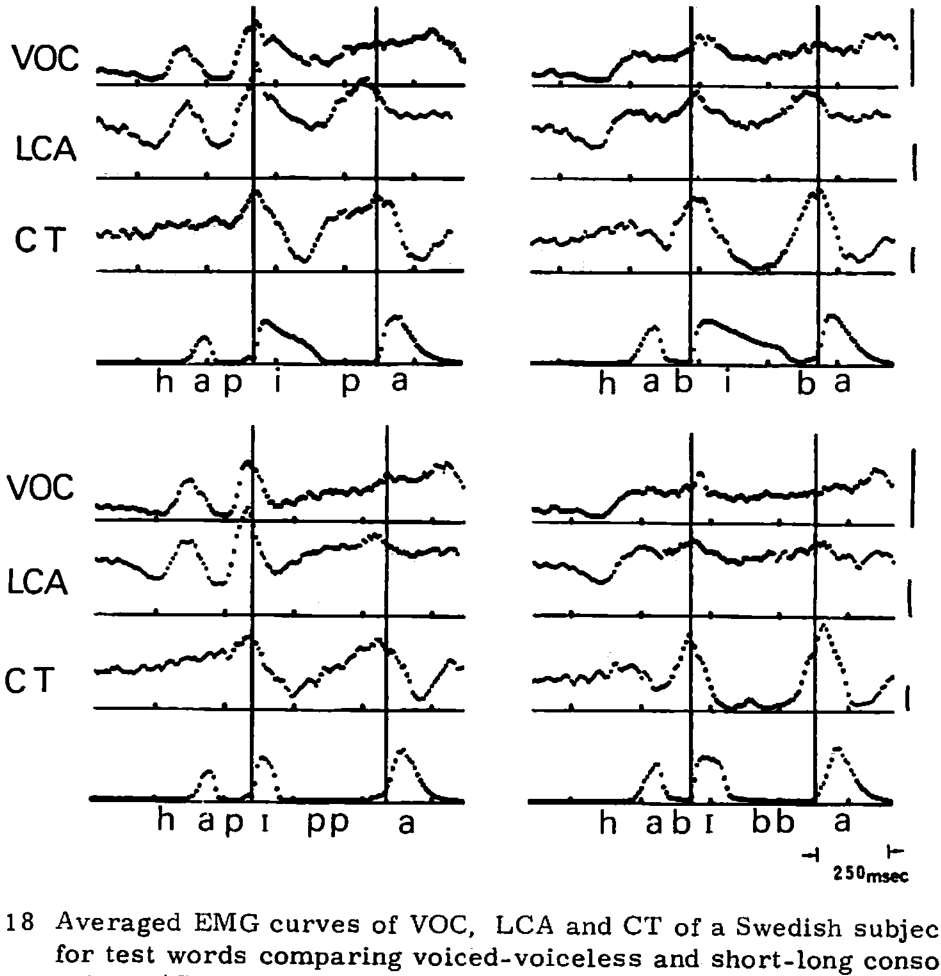


Fig. 18 Averaged EMG curves of VOC, LCA and CT of a Swedish subject for test words comparing voiced-voiceless and short-long consonant pairs. (Cal. 100 V)

(VOC) LCA and CT for the production of a Swedish labial stop pair /p/ vs. /b/ in different phonetic environments, where we can compare voiced-voiceless as well as long vs. short contrasts (Hirose, 1977a). As can be seen, both VOC and LCA are more clearly suppressed for short and long voiceless consonants given in the left half of the figure, when compared to their voiced counterparts. This would indicate that, at least in this case, these adductors are involved in voicing distinction. It can also be seen that CT suppression is less marked for voiceless consonants than for voiced.

Figure 19 compares the patterns of EMG suppression of INT, VOC, LCA and CT for the consonantal segments of Japanese test words in which voiced and voiceless stops and fricatives placed in both word-initial and word-medial positions were considered for paired comparison (Hirose and Ushijima, 1978). For each muscle, the leftmost point indicates the value of the averaged EMG peak for the vowel segment preceding the consonant, which is unanimously taken as 100%. The EMG value for the consonantal segment is plotted toward the right side of each figure, again taking the peak value for the preceding vowel to be 100%. The figure shows that INT suppression is consistently more marked for voiceless than for voiced cognates if the comparison is made in the same phonetic environment. On the other hand, the degree of suppression of LCA and VOC appears to be different depending primarily on the phonetic environment, and not on voicing dis-

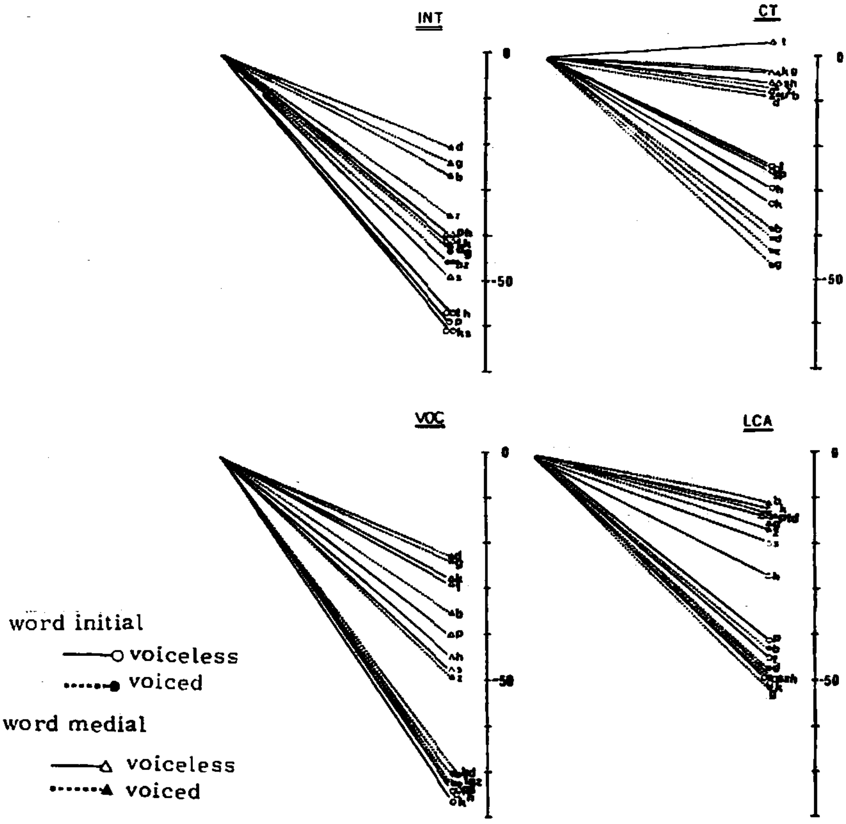


Fig. 19 The degree of suppression of averaged EMG activity of four different muscles around the obstruents in the test utterances.

tinction. In the same environment, suppression appears to be more marked in VOC than in LCA. Suppression of CT is not remarkable in the word-medial position, whereas in the word-initial position, it is generally more marked for the voiced cognates (Hirose and Ushijima, 1978).

As suggested by Dixit (1975), CT can contribute to the increase in tension of the vocal fold, which might eventually be relevant for eliminating voicing. In this sense, it might be plausible to consider the relatively high CT activity in the production of a voiceless consonant in certain cases as one possible factor in enhancing voicelessness. However, this is not always the case. Our studies on American English, French and Hindi did not confirm CT contribution to voicelessness and, in the case of Danish, a relatively high activity of CT was seen for voiced /h/, which was produced with an open glottis. Thus, the interpretation of the apparent high CT activity in certain consonantal segments is still unresolved and further investigation is warranted.

It has been pointed out that another dimension independent of glottal adduction-abduction must be taken into consideration in the case of laryngeal control relating to specific phonetic phenomena (Hirose, 1977b). An example is the Korean forced stop which has been known to be accompanied by distinct, sharp activation of VOC, as shown in Figure 20 (Hirose, Lee and Ushijima, 1974). Represented here are the averaged EMG curves of VOC and CT for the production of Korean nonsense words CV1 preceded by a carrier sentence /ikəsi/, where C stands for three types of stops and V for

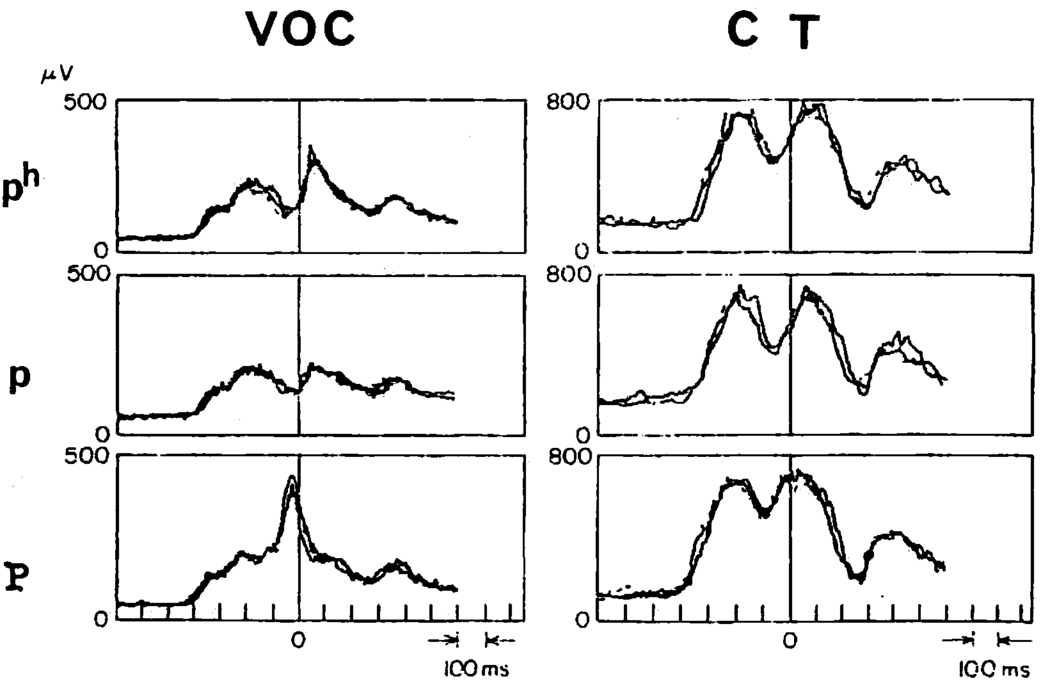


Fig. 20 Averaged EMG curves of VOC and CT for the three bilabial stops of Korean in word-medial position. In each type, three curves are superimposed for the postconsonantal vowels /i/, /a/ and /u/. The zero on the abscissa marks the line-up for averaging, which corresponds to the stop release.

/i/, /a/ and /u/. Here again, difference in the post-consonantal vowel does not yield any discernible variation in EMG patterns for each consonant type.

Recently, we had an opportunity to perform an additional EMG study on a native Korean phonetician asked to produce three types of Korean stops. It was confirmed in this case too that VOC showed higher activity immediately before the articulatory release of forced type stops when compared to the other types of stops, although the activation of VOC in this case is not so sharp as illustrated in the figure. A similar type of VOC activity is also found in the case of the Danish stød. Whether this mode of contraction is necessary for a relatively fast-response voice trigger mechanism is still open to discussion, but the dimension of tension control of the vocal fold seems to be another important correlate of laryngeal adjustment.

Our recent fiberoptic studies on applosives in the word-final position in Fukienese, a dialect of southern China, revealed interesting findings on laryngeal adjustment (Iwata, Sawashima, Hirose and Niimi, 1979). In the production of isolated applosives, there was observed a closed glottis without glottal vibration accompanied by the glottalization gesture, which was represented by a rapid adduction of the false vocal folds immediately after the oral closure.

Selected frames of the laryngeal views for a typical sample of the isolated form are shown in Figure 21, where closed glottis without vibration is observed for the syllable final /t/ produced by a native speaker of Fukienese. Immediately after implosion, a rapid adduction of the false vocal fold can be seen. The lower curve in the figure indicates the distance between the two false vocal folds; this distance reaches a minimum point at about 100 to 120 msec after the implosion. It is assumed that the syllabic ending may be signified by the glottalization in the syllable ending as a demarcating signal. This demarcating signal, however, is often less marked in sentences or phrases, under the influence of phonetic conditions like speech tempo or following segments, and final applosives may be assimilated to the following segments, although a considerable individual difference does exist on this point.

The principal mechanism for pitch change is to increase or decrease the longitudinal tension of the vocal fold, and the function of CT is certainly related to this mechanism. In particular, the increase in longitudinal tension and stretch of the vocal fold is obtained by CT activation. However, the mechanism of pitch lowering is not so straight-forward as compared to the case of pitch elevation. As for the contribution of the strap muscles to pitch lowering, their activities often appear to be a response to a change in conditions rather than the cause, lacking the lead in time in relation to physical effects of pitch change.

Figure 22 shows examples of EMG curves of LCA, CT and SH for single tokens of isolated two-mora words in Japanese, in four different accent types found in the Kinki dialect (Sugito and Hirose, 1978). It is obvious that CT activation is related to pitch rise with some lead in time. As for pitch drop, the decrease in CT activity and increase in SH appear to correlate with the F_0 contour, particularly in types A and B. However, in type A there is an obvious time lag between the onset of decline in CT activity and the start of an increase in SH activity. Thus, SH seems to play a role in assisting or enhancing a sharp pitch descent as seen in these cases, but it is not likely that SH acts as the primary pitch lowerer. A similar claim was made by

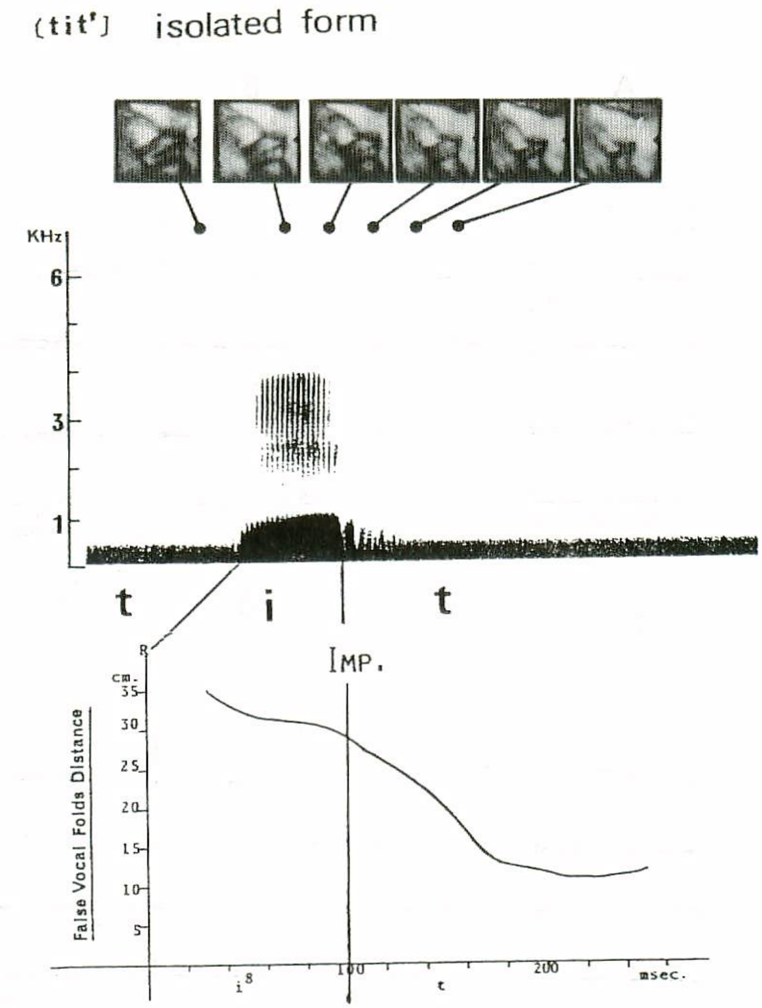


Fig. 21 Selected frames of the glottal view for [tit] in the isolated form with the wideband spectrogram, and the pitch contour.

Collier (1975) on Dutch intonation control with respect to laryngeal adjustments.

It is also interesting to note that there is SH activation before the voice onset only for the so-called low-start types: types B and C. This increase in SH activity has also been found in other cases, by Atkinson (1978) for example, and taken as an indication of SH's role in preparing the larynx for the speech mode in certain specific cases. This topic seems to need further investigation.

The physiological correlates of stress seem very complex in nature. As the so-called "extra energy" theory suggests, extra energy can be applied to the stressed vowel. Also, as many acoustical and perceptual studies have revealed, a rise in pitch appears to be one of the most important correlates of stress.

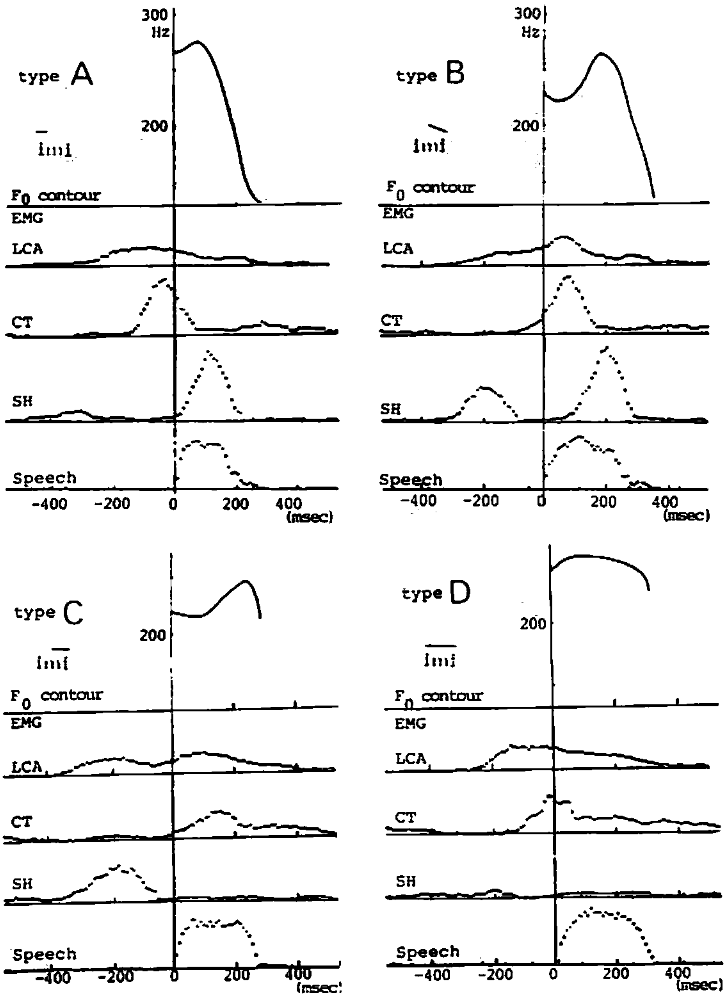


Fig. 22 Integrated and smoothed EMG curves of LCA, CT and SH, and F_0 contours for single tokens of two-mora words in Japanese, in four different accent patterns found in the Kinki dialect. A vertical bar indicates the onset of voicing.

Figure 23 compares averaged EMG curves of CT, INT and LCA together with F_0 contours for the words "pérmit" and "permít" produced by a native speaker of American English. It is obvious that the CT activity pattern closely relates to pitch contour in this case also. In addition, it can be seen that the other two muscles also appear to be activated for the production of stress. Of course, other physiological factors must be taken into consideration when we interpret the results shown in this figure. For example, INT shows increasing activity for the initiation of utterance, and LCA activation can be related partly to the tendency toward glottal stop gesture for the final /t/. In any case, however, it is not easy to conclude whether the general tendency toward the increase in activity of these muscles

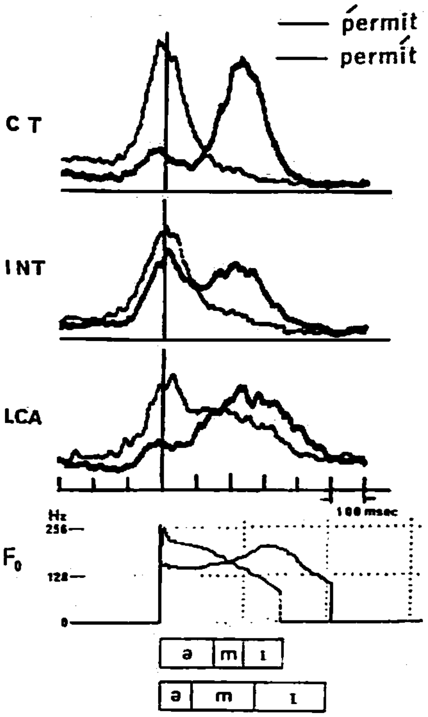


Fig. 23 Averaged EMG curves of CT, INT and LCA, and pitch contours for the pair "pérmit" and "permít" produced by an American English speaker.

related simply to the rise in pitch, or whether it is to be regarded as an evidence of extra effort.

In the foregoing, we have presented several topics related to laryngeal control in speech. We believe that the human larynx is not simply an organ of phonation, but serves as an important organ for speech articulation. It is expected that future research will further unravel the role of the human larynx in both phonation and articulation.

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