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THE POSTERIOR CRICOARYTENOID AS A SPEECH MUSCLE

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The posterior cricoarytenoid muscle (PCA) is a very unique muscle among those of the intrinsic laryngeal muscle group. First, PCA is the only abductor muscle of the vocal fold, though it is innervated by the recurrent laryngeal nerve, which also innervates all the adductor muscles of the larynx. Secondly, as originally stated by Semon (1881), PCA has been believed to have relatively higher vulnerability when compared with the adductors. Thirdly, recent histological and histochemical studies suggest that PCA has peculiar characteristics in its structural as well as chemical properties, among the intrincic laryngeal muscles.

The larynx is often referred to as the organ of phonation. However, phylogenetic studies indicate that the most primitive function of the larynx is its protective mechanism for the airway (Negus, 1962). In this sense, the most primitive larynx is to be found in the family of the lung fish. In Lepidosiren (Amazon Mud Fish), for example, the glottis is seen to be a longitudinal slit in the floor of the pharynx, with muscle fibers capable of closing it only in a sphincteric manner. In other words, there are no "opening" or dilator fibers in this particular species. The dilator fibers appear as an indication of the next stage in the evolution of the larynx. In Protopterus (African Mud Fish), the margins of the glottis are pulled apart by long, circular fibers arising from the connective tissues near the base of the scull and terminating near the margin of the glottis. Air can be readily taken into the lung when the glottis is open. The dilator fibers in this species are usually considered to be a primitive form of PCA. It should be noted that there is no cartilagenous framework for attachment of the muscles of the primitive larynx at this stage of evolution. The laryngeal cartilages develop at a later stage and, accordingly, the laryngeal muscles, including PCA, develop a new function of mobilizing the cartilages, with superadded arytenoid cartilages hinged on the cricoid. Paired dilator muscles arise from the cricoid to be inserted into the arytenoid cartilages with the function of pulling them apart. A sphincteric girdle surrounds the larynx, except its anterior portion, as the adductor group, which is divided up into segments.

During the course of evolution described above, the larynx has developed several significant functions other than the primitive protective mechanism. One of the most important functions of the larynx is no doubt the mechanism of sound production. In man, in particular, a sound production mechanism at the level of the larynx is essential for human communication by speech.

There has been a general tendency for the description of laryngeal physiology for voice production to be confined mainly to the adduction function of the vocal folds. This is in a sense natural, since glottal closure is necessary for voicing, a basic prerequisite for speech production. Mainly for this reason, the role of PCA in speech has not been systematically investigated, although its function as a respiratory muscle has been well documented in the literature (Suzuki and Kirchner, 1969).

As for the function of PCA in phonation. Faaborg-Andersen (1957) first reported on EMG activity of PCA in phonation and stated that it decreased during sustained phonation but started to increase a few milliseconds prior to the end of audible voice. Kotby and Haugen (1970), on the other hand, observed increasing activity in the PCA during phonation and postulated that the PCA is not simply an abductor of the vocal fold. Dedo (1970) also reported increasing activity in the PCA during phonation in some of his clinical cases. These authors, however, reported exclusively on sustained phonation and the fundamental frequency was not specified.

As for PCA activity for consonant production, Hiroto et al. (1967) examined laryngeal muscle activity for some Japanese words containing an intervocalic /s/ and stated that there was a temporary change in the EMG activity of PCA corresponding to voiceless consonant production. In their experiments, they observed that there was an apparent increase in PCA activity for the production of /s/ accompanied by a decrease in the activity of the adductors. Hirano and Ohala (1969) showed one example of a raw EMG trace of the PCA, demonstrating increasing activity for release of glottal stops with reciprocally decreasing activity in the interarytenoid.

In 1972, the present author reported on the results of a systematic study of the activity pattern of the intrinsic layyngeal muscles in speech with special reference to the voicing distinction in American English (Hirose and Gay, 1972). In this report, the positive contribution of PCA in the production of voiceless sounds was emphasized. Since that time, physiological data have been accumulated by the same author to further clarify the role of PCA in speech for different kinds of languages.

The aim of the present paper is to describe the function of the PCA comprehensively with special reference to its role in speech articulation. The descriptions are based on the analyses of laryngeal EMG data and fiberoptic observations of the glottis. In the present series of experiments native speakers of American English, Japanese and Danish served as the subjects for their own languages except for one particular series, in which one of the American English speakers, a phonetician, produced labial stops of five different phonetic types.

Experimental Method

All of the EMG data were obtained by means of the hooked-wire electrode technique, a detailed description of which has been given elsewhere (Hirose et al. 1971). Briefly, PCA is reached perorally under indirect laryngoscopy with topical anesthesia. A specially designed probe is used for this purpose and the tip of the electrodes is directed to the point of insertion as illustrated in Fig. 1. The EMG data are recorded on a multichannel data recorder together with the acoustic signals. The signals are then reproduced for visual inspection of raw traces or for further processing by means of a digital computer system to obtain a convenient quantitative record of muscle activity in the form of a display of averaged EMG amplitude versus time (Kewley-Port, 1973; Hirose, 1971).

For the assessment of fiberoptic data, a fiberoptic movie of the glottis is taken either separately from the EMG experiment or, in a limited number of cases, simultaneously with the EMG experiment, in order to compare the pattern of glottal gestures with that of muscle activity. In

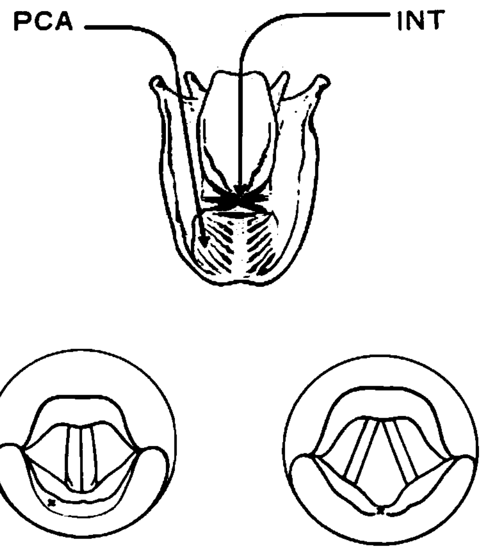


Fig. 1: Schematic drawings illustrating the direction and the point of insertion of hooked-wire electrodes into PCA (left) and INT (right). A cross mark in the lower figures indicates the point of insertion from an indirect laryngoscopic view.

most cases, movies are taken at a film rate of 50 - 60 frames per sec and frame-by-frame analysis is made to estimate the glottal width by measuring the distance between the vocal processes.

Experimental Results

Fig. 2 illustrates an example of raw EMG traces of PCA and the interarytenoid (INT) for the pair /əpʌp/ , /əbʌp/ produced by a native American English speaker. In this figure a comparison is made for the /p/ vs. /b/ contrast in word-medial prestress position.

For the test word containing /b/, PCA activity begins to be suppressed before the onset of the utterance and it stays suppressed throughout the entire utterance. For /əpʌp/, on the other hand, PCA shows increasing activity for production of /p/ after apparent suppression for the preceding vowel and the activity becomes suppressed again for the stressed vowel following /p/. In both cases, there is a sharp increase in PCA activity at the end of the utterance, most likely for glottal opening for word final /p/ and for the following inspiration. In this figure it is also indicated that INT always shows a pattern of activity reciprocal to that of PCA.

The pattern of PCA activity for consonant articulation is more clearly seen in the examples of an averaged EMG curve shown in Fig. 3. In this figure, an averaged pattern of PCA activity is compared in the same subjects as in Fig. 2 for the pairs /p/ vs. /b/ and /s/ vs. /z/, both in prestress and poststress medial positions, respectively. The zero on the

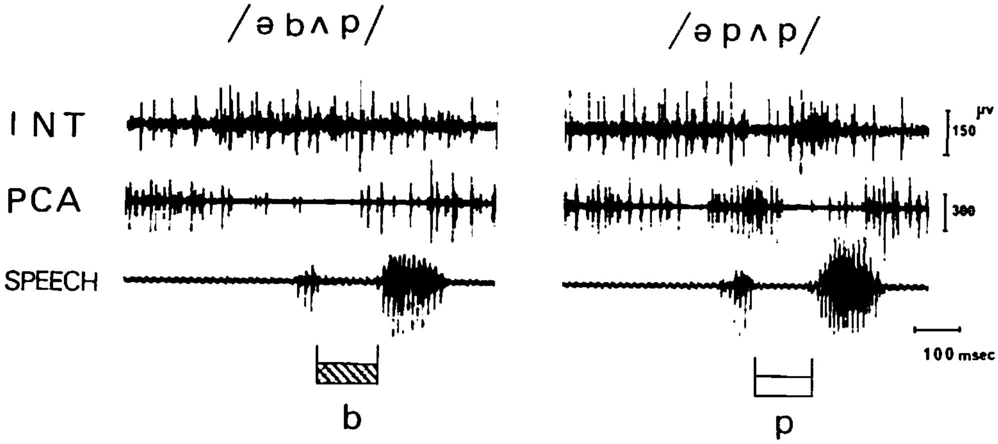


Fig. 2: Raw EMG traces of PCA and INT for utterances /əbʌp/ and /əpʌp/ produced by a native American English speaker. The segmentation below the speech signals indicates the intervocalic consonantal portion of the test utterances.

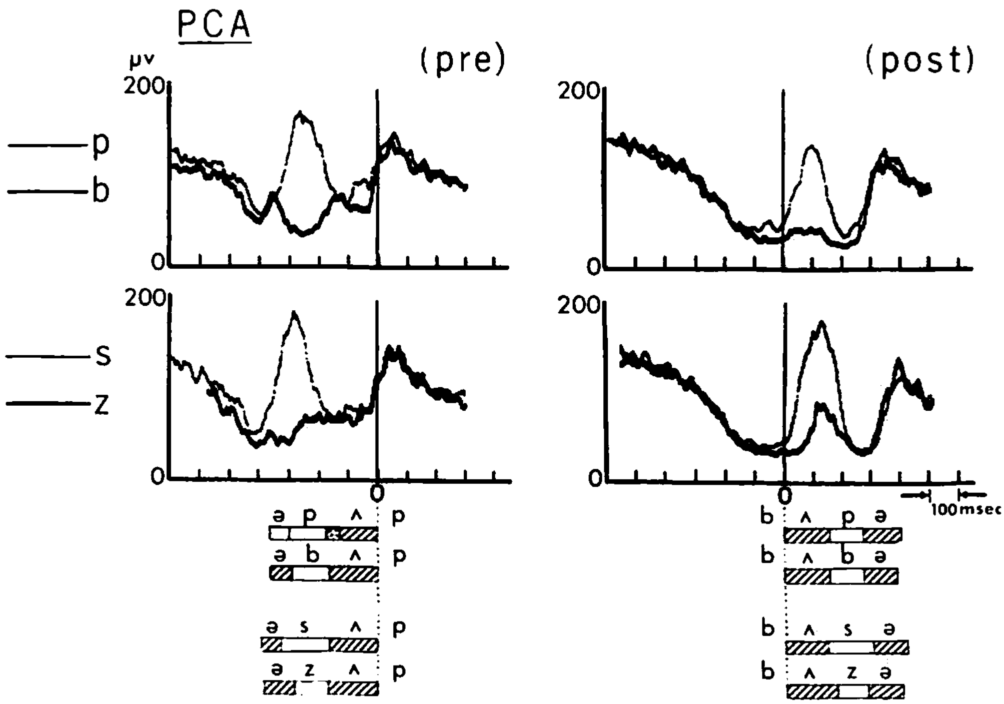


Fig. 3: Averaged EMG curves of PCA for the comparison between /p/ and /b/ (upper) and /s/ and /z/ (lower), embedded in prestress medial position (left) or in poststress medial position (right) of test utterances produced by a native American English speaker.

time axis indicates the line-up point for averaging, which marks the implosion of word final /p/ in the left half of the figure (voiced-voiceless comparison in prestress position) and the vowel onset of the first syllable in the right half (comparison in poststress position). A marked elevation of PCA activity is always noted for the production of voiceless consonants. For voiced consonant production, on the other hand, PCA activity is generally suppressed. However, close observation of the curves reveals that the PCA shows relatively higher activity for the segment /z/, particularly in poststress position, when compared to the neighboring vowel segments. It is also noted that the peak of PCA activity is somewhat lower for the segment of the poststress voiceless stop than for that of the prestress one.

Fig. 4: Peak values of averaged PCA activity for stops and fricatives embedded in the same utterance types as in Fig. 2 with two stress conditions. The results obtained from two native American English speakers are pooled. In subject LJR all possible voiced-voiceless groups are illustrated. In subject LL, only /p/ vs. /b/ and /s/ vs. /z/ pairs are examined.

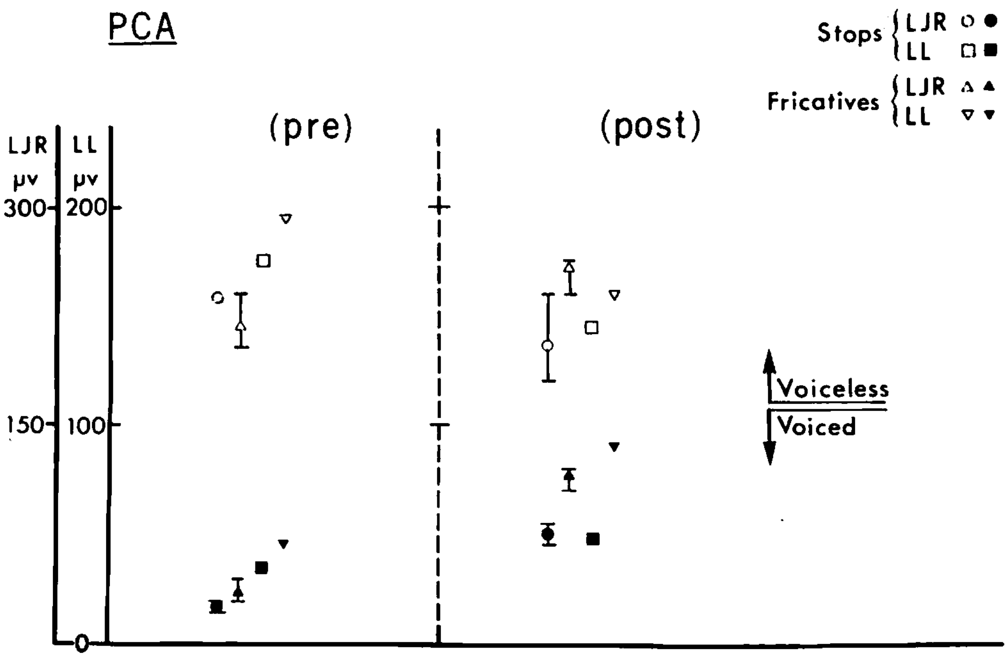
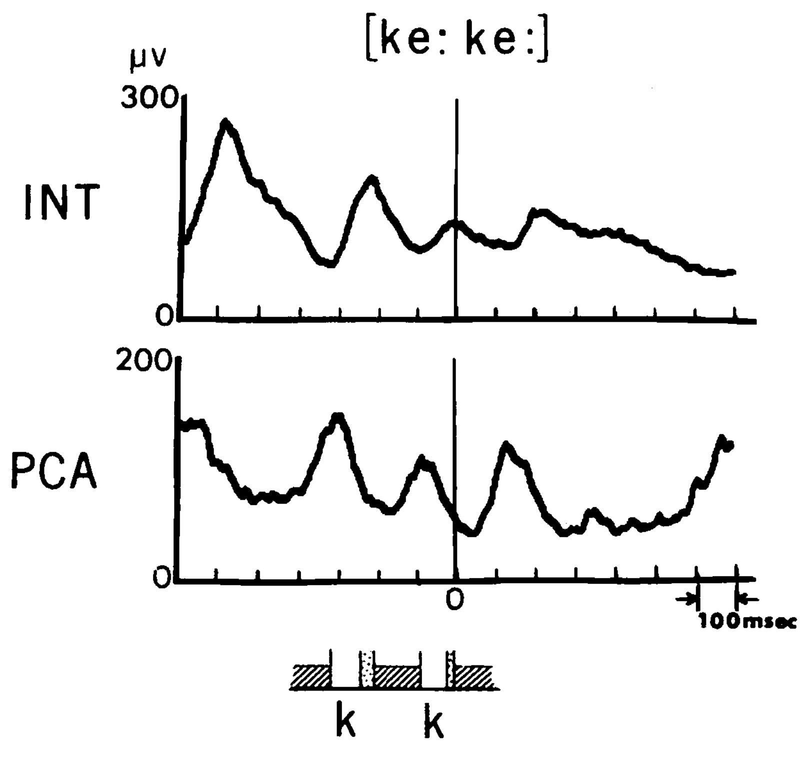


Fig. 4 compares peak values of PCA activity for the consonant segments in the same kind of stimuli as in Fig. 3, determined for two American English speakers. The figure indicates that PCA activity is definitely higher in the production of the voiceless consonants than for the voiced, regardless of the difference in manner of articulation as well as in stress status. However, the figure also indicates that the difference in peak values between voiced and voiceless pairs is less dominant in poststress position. Fig. 4 further shows that there is relatively higher PCA activity for voiced fricatives in poststress position as compared either with voiced stops in the same phonetic environment or with the same consonantal type in prestress position. Partial activation of PCA for voiced fricatives would indicate a less tightclosure of the glottis, which seems compatible with the evidence of a partially open glottis observed in transillumination study (Lisker et al. 1969).

The influence of phonetic environments on peak PCA activity is more clearly observed in the case of Japanese subjects. Fig. 5 illustrates the averaged EMG curves of PCA and INT in a Japanese subject for the test utterance "soreo keekee to yuu", where a four-mora meaninful word with initial and medial voiceless stops is embedded in a frame sentence. The PCA shows increasing activity for /k/'s in the test utterance but the peak value is clearly higher for word-initial /k/ than for word-medial /k/. In

Fig. 5: Averaged EMG curves of INT and PCA for the test utterance "soreo keekee to yuu" produced by a native Japanese subject. "0" on the abscissa marks the line-up point for averaging which was taken at the onset of the vowel after word-medial /k/.



order to examine the relationship between PCA activity and glottal dynamics, high speed motion pictures were taken of the glottis of the same subject used in the EMG experiment during the production of the same types of utterances. For the voiceless portion of the test utterances, separation of the arytenoids and widening of the glottis were always observed. Fig. 6 shows a comparison between the averaged time course of PCA activity (upper curve) and glottal width (lower curve) for the test word [ke:ke:]. It appeared that the temporal course of glottal width is comparable to that of PCA activity — with some delay. This holds true for all the utterance types examined (Hirose and Ushijima, 1974).

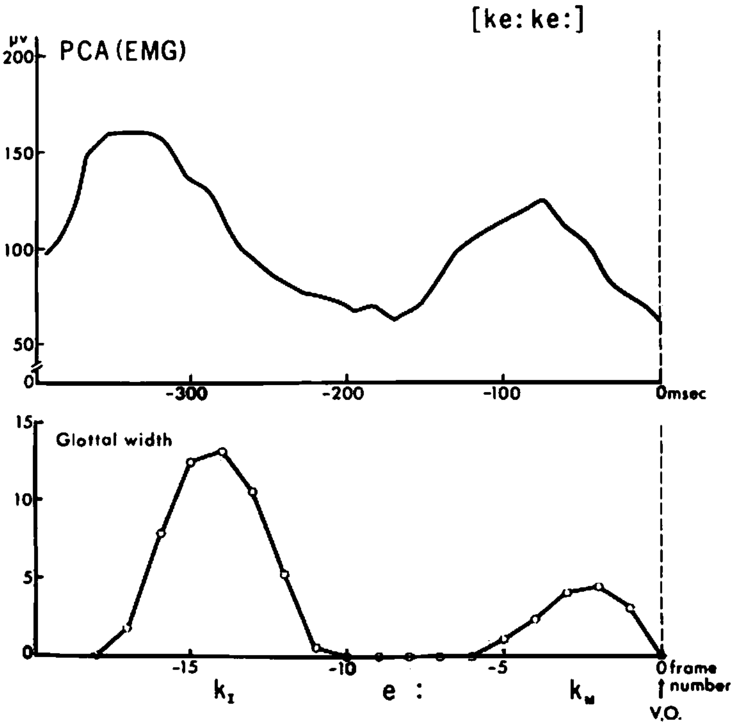


Fig. 6: Comparison of the time course of PCA activity and glottal width for the test word [ke:ke:] in the same subject as presented in Fig. 5.

Figure 7 shows the relationship between the peak values of averaged PCA activity and maximum glottal width for all types of voiceless segments used in the experiment. They include geminates and devoiced vowel segments in word-medial position. The letters "I" or "M" attached indicate whether the consonant is placed in word-initial position or word-medial. It is shown that PCA activity for voiceless stops in initial position is consistently higher than that in medial position, while there is no appreciable difference in PCA activity for voiceless fricative /s/ with regard to the difference in phonetic environment. More important is the finding that the maximum glottal width is generally larger when the peak PCA activity is higher. A statistical test shows that there is a significant positive correlation between these two parameters at the 0. 01 level of confidence (r=0.86).

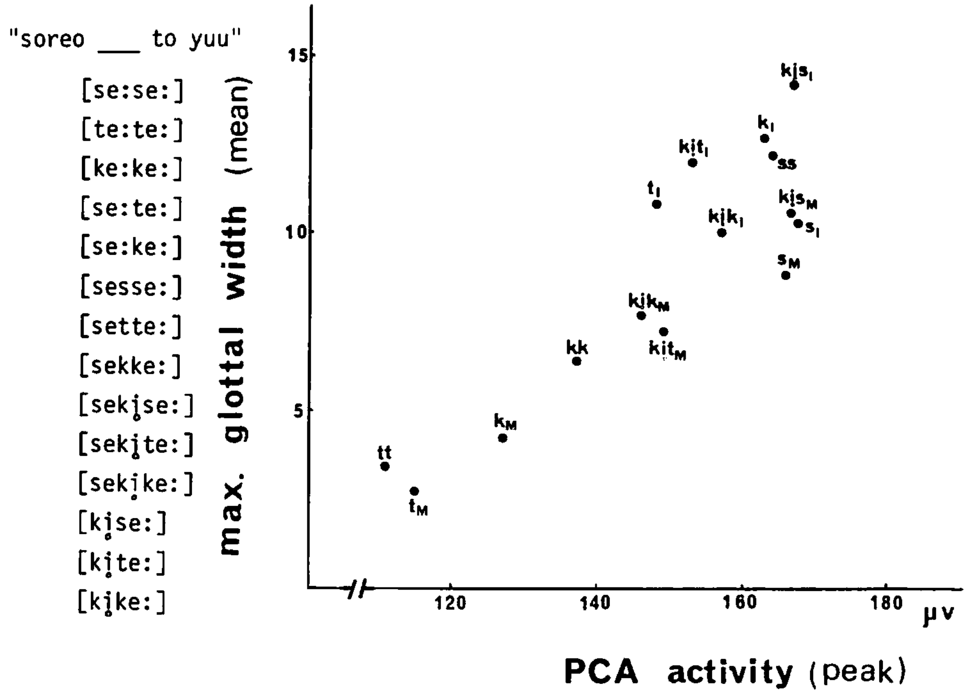


Fig. 7: Relationship between the maximum glottal width (ordinate - arbitrary scale) and peak value of averaged PCA activity (abscissa) for the voiceless segments in some selected test utterances of Japanese.

In Danish, stop consonants ptk and bdg are phonologically distinct only in syllable-initial position. Both categories are voiceless and the main difference between the two categories is that of aspiration. It has been revealed photoglottographically (Frøkjaer-Jensen et al., 1971) or by fiberoptic observation (Rischel, personal communication) that there is a wide-open glottis for Danish ptk, whereas bdg have a smaller aperture. It was argued by Frøkjaer-Jensen et al. that the open glottis for bdg might be due to aerodynamic forces and not to neural command to the abductor. A preliminary EMG study on a native Danish speaker revelaed, however, that there is evidence for an active muscle control for glottal opening not only for ptk but also for bdg. Fig. 8 illustrates an example of averaged EMG patterns of INT and PCA for a native Danish speaker comparing /p/ vs. /b/, contrasting in word-initial position (Fischer-Jørgensen and Hirose, 1974). In this example it is shown that PCA shows a small peak about 50 msec after the line-up point (implosion of the stop consonants in question) for /p/, but a slightly smaller peak at the line-up for /b/. This is another piece of evidence that PCA is actively involved in fine glottal adjustment for consonant production.

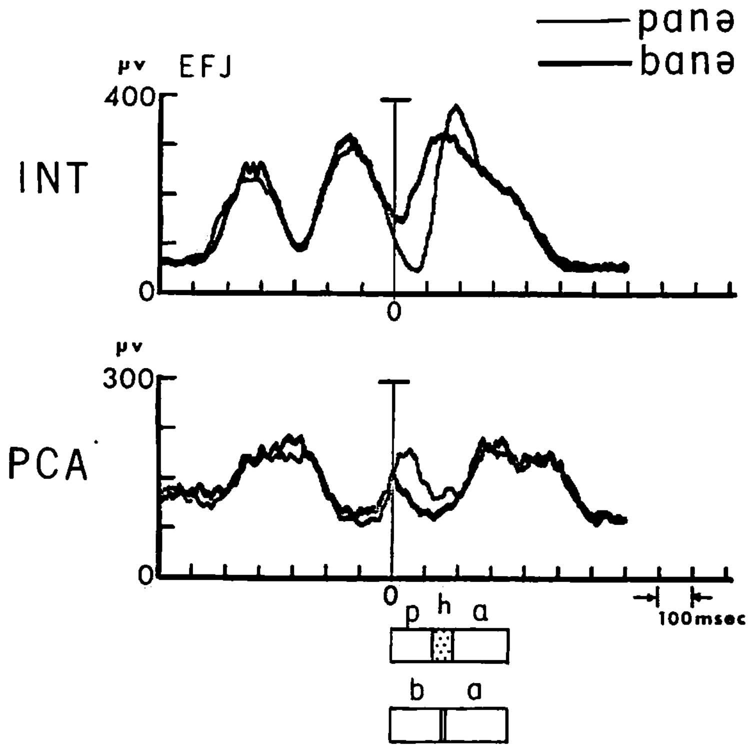


Fig. 8: Averaged EMG curves of INT and PCA for the Danish test utterances comparing the word-initial /p/ vs. /b/ contrast in meaningful words, which are preceded by a carrier "han sagde" [han sa:]. The line-up for averaging ("0" on the abscissa) is taken at the implosion of the stop consonant in question.

In addition to the above experiments dealing with a two-way distinction between consonants, laryngeal adjustment for a five-way distinction in the same manner of articulation was examined with an American English speaker, a phonetician, who produced labial stops of five phonetic types, i. e., voiced inaspirates[b], implosive voiced inaspirates [ɓ], voiced aspirates [b^h], voiceless aspirates [p^h] and voiceless inaspirates [p]. Each stop type was embedded in a nonsense trisyllabic word "t^hɪkV_1CV_2", where C stands for each type of stop, V_1 for /i/ or /u/ and V_2 for /i/, /a/ or /u/. Fig. 9 illustrates the pattern of PCA activity for the five different types. The "0" on the time axis marks the line-up point for averaging which was set at the implosion of each stop closure. For each type, three curves are superimposed, each of which represents three different vowels in the word-final position. It can be seen that regardless of the difference in the final vowel, the three curves for each stop show similar contours. Further, it should be noted that, except for the differences relevant to the phonetic differences among the labial stops, the contours of the five different types are quite similar. This indicates that the pattern of PCA activity for the carrier portion of the test utterance is constant, irrespective of the difference

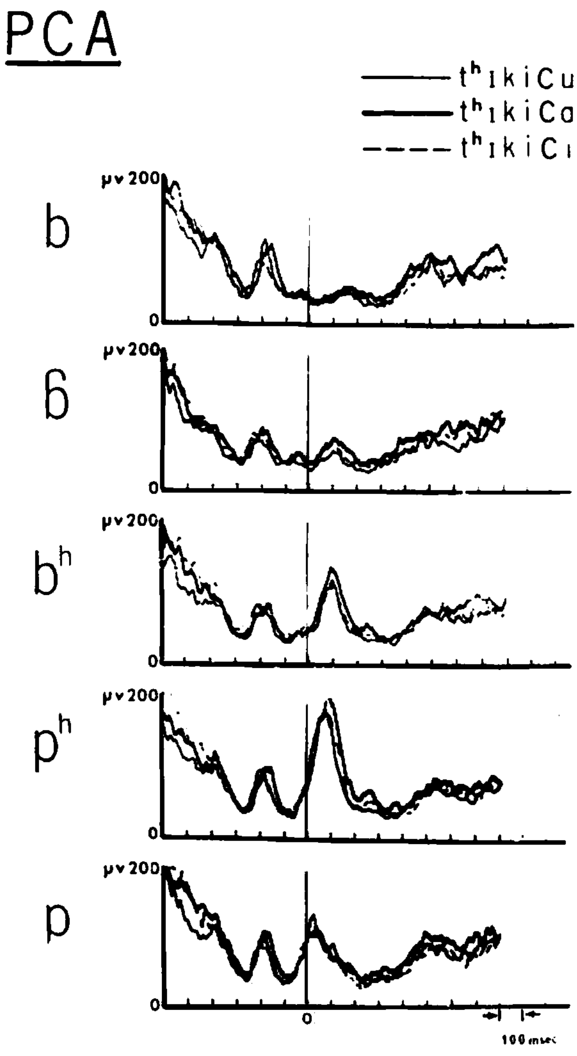


Fig. 9: Averaged EMG curves of PCA for test utterances containing five phonetically different types of labial stops embedded word-medially. For each type, three curves are superimposed, each of which represents a different vowel carrier following the stop consonant.

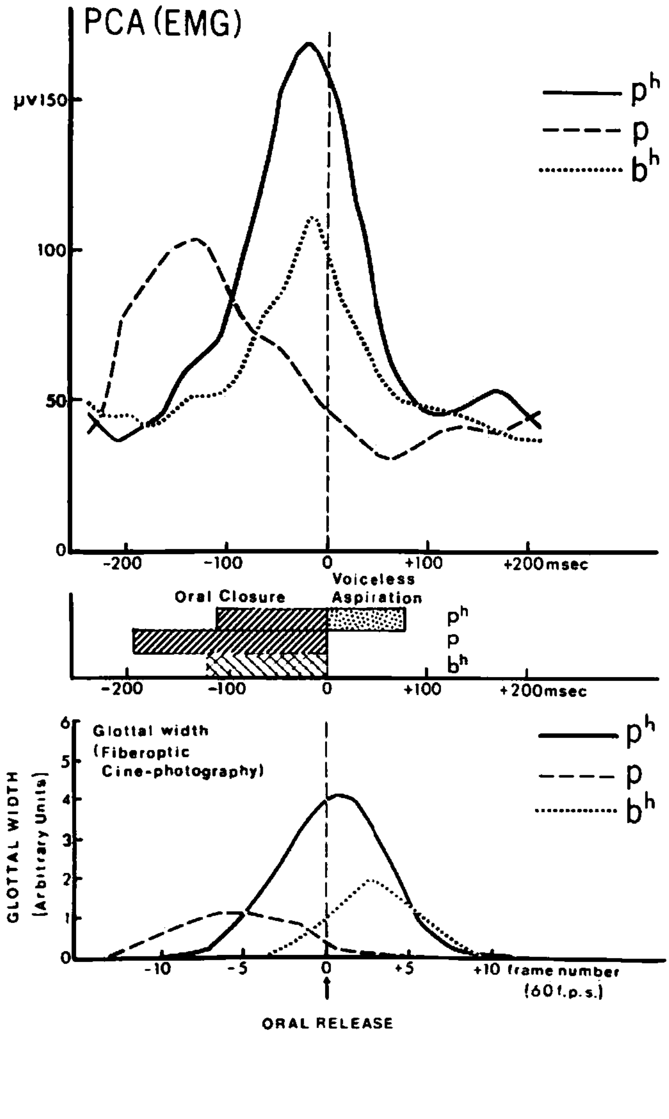


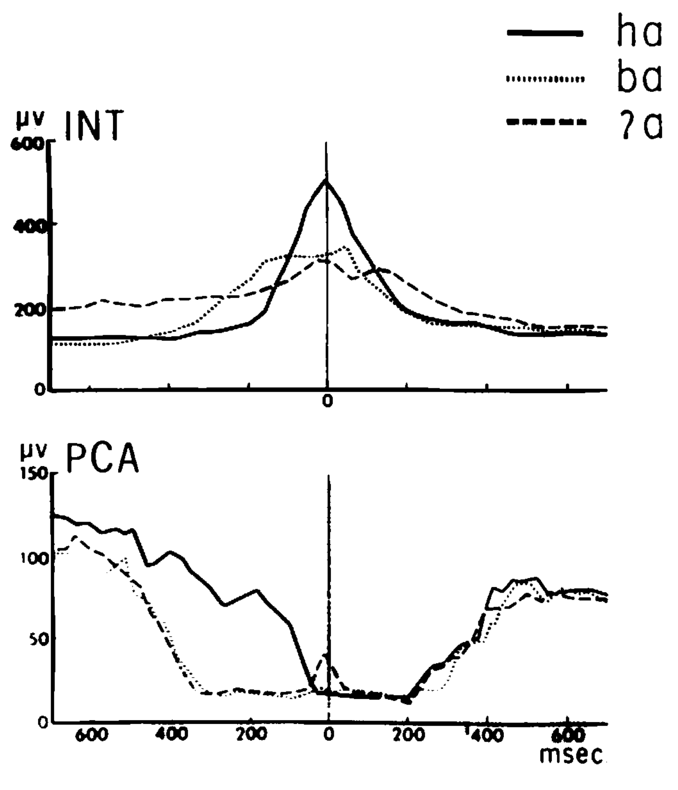
Fig. 10: Comparison of the time courses between averaged PCA activity and glottal width for three stop types produced with glottal opening gesture. All the curves are lined up at the oral release.

in the embedded labial stops. In this figure, PCA activity increases for labial stop types of the "bottom" three: voiced aspirates, voiceless aspirates and voiceless inaspirates. For these three types, analysis of a fiberoptic movie taken separately in the same subject revealed separation of the arytenoid corresponding to stop production. Fig. 10 shows the relation between the patterns of PCA activity and the time course of the glottal width measured at the vocal processes for the three types. In this figure, the curves are lined up at the articulatory release (time "0" on the abscissa) and durations of oral closure and aspiration are also illustrated. It is shown in this figure that there is good agreement in both timing and degree between PCA activity and the opening gesture of the glottis, both factors being considered as physiological determinants of different phonetic types of a more than binary distinction.

In a separate series of experiments, the patterns of PCA activity for the glottal adjustment for absolute initial voiced-voiceless contrast and for different types of vocal attack, were investigated (Hirose and Gay, 1973).

It is found in breathy attack that the glottal adjustment is characterized by continuous PCA activity during the prephonatory period, where PCA stays active until immediately before the onset of voicing (Fig. 11). The

Fig. 11: Averaged EMG curves of INT and PCA for different types of vocal attack. The line-up point for averaging is taken at the onset of voicing. In this experiment isolated monosyllabic words [ha], [ba] and [ʔa] are used to represent breathy, soft and hard attack.



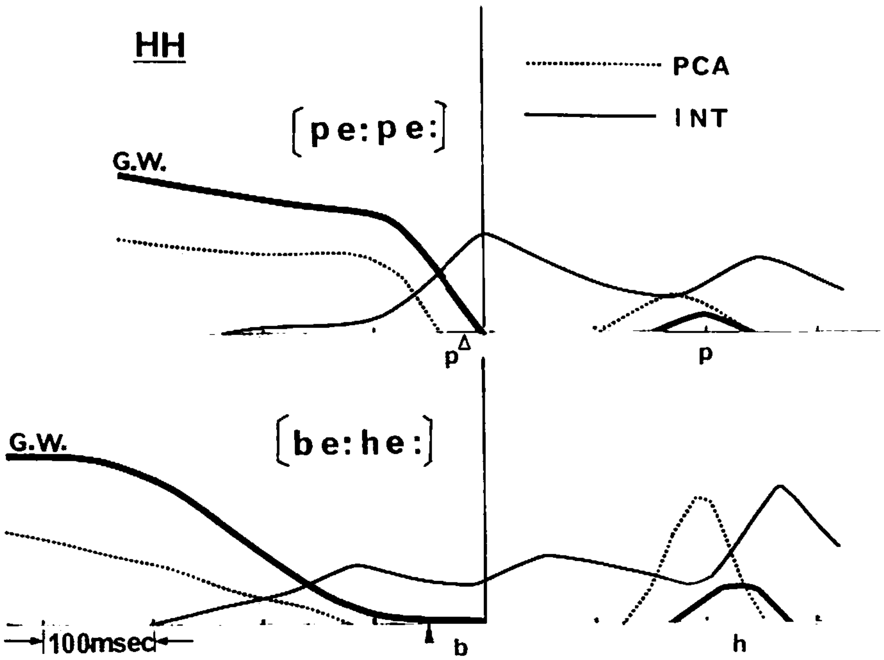


Fig. 12: Comparison between the time courses of the glottal width (G. W.) and the averaged EMG curves of INT and PCA for the test utterances "peepee to yuu" (upper) and "beehee to yuu" (lower) produced by subject HH. An open triangle indicates the release of the voiceless stop and a solid triangle indicates the onset of voicing of [b]. The line-up for averaging is taken at the onset of the vowel in the first syllable.

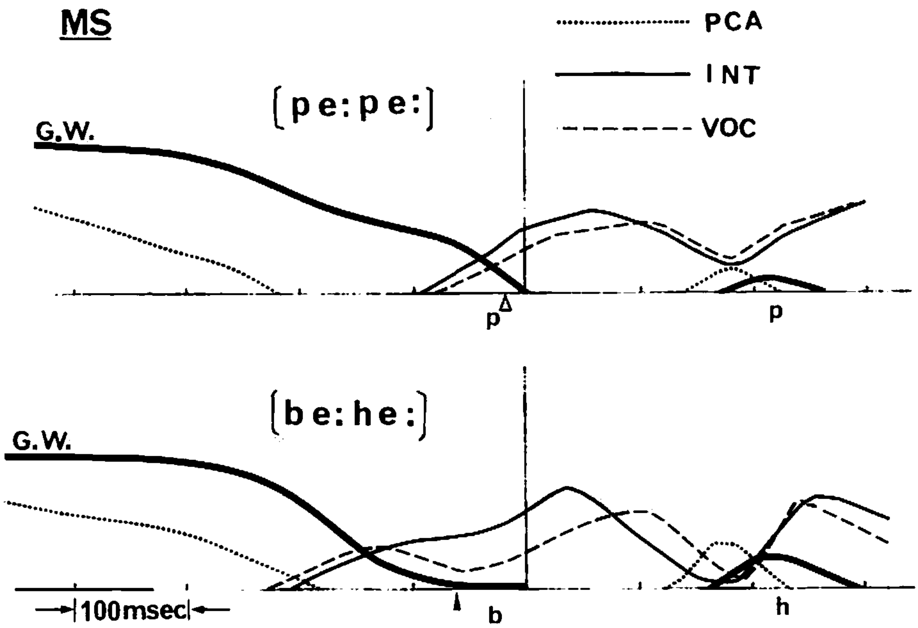


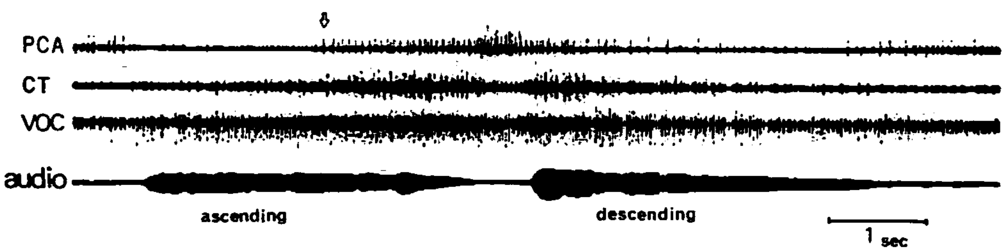
Fig. 13: Comparison between the time courses of the glottal width and the averaged EMG curves of INT, PCA and vocalis (VOC) for the same pairs as in Fig. 14, produced by subject MS.

relatively high prephonatory PCA activity in conjunction with suppressed adductor activity seem to be physiological correlates of the open glottis for initial [h] production, which has been observed fiberscopically or in a high speed movie.

In the experiments comparing the voiced-voiceless contrast in absolute initial position in meaningful Japanese words, simultaneous EMG-fiberoptic recordings revealed that there are apparently two different strategies for keeping the glottis open until immediately before the onset of the first vowel preceded by word-initial voiceless consonants. In one subject, the glottis remains open by continuous PCA activity and delayed onset of activation of the adductors (subject HH in Fig. 12). In the other subject, however, the glottis remains open or does not close because both abductor and adductors are inactive for a short period immediately before voice onset (subject MS in Fig. 13). It should be noted, however, that even the second subject shows consistent PCA activity for the opening gesture of the glottis in the production of voiceless consonants in word-medial position. In other words, the apparent individual difference is observed only for the laryngeal adjustment for voicelessness in absolute initial position. These findings suggest that the adjustment for open glottis is accomplished by a positive contribution of PCA particularly when the laryngeal control is in the so-called speech mode, but in absolute initial position, the adjustment for open (or non-closed) glottis can also be made passively by transient suppression of both abductor and adductor groups of the vocal fold (Sawashima et al. 1975).

As described above, the main function of PCA in speech is primarily related to the opening gesture of the glottis during articulatory adjustments. It has been argued, however, that a backward counterpull of PCA should be

Fig. 14: Raw EMG traces of PCA, cricothyroid (CT) and VOC recorded when an untrained subject sang the ascending and descending scales successively. Note that PCA activity appears in the range of high chest register, as indicated by an arrow.



necessary for preventing a tendency toward displacing the arytenoid cartilage anteriorly during phonation, since the adductors pull essentially from an anterior direction. Even though the argument seems plausible, there have been very scarce substantiative data available in the literature. Fig. 14 illustrates increased PCA activity in the range of high chest register which was observed when an untrained subject sang ascending and descending scales successively. The finding is in agreement with our previous report on the laryngeal muscle activity during phonation (Gay et al. 1972). In any case, apparent increase in PCA activity is only observable in the range of high chest register which is certainly higher than normal speech range. Thus, the apparent PCA activity may serve for bracing the arytenoid, but does not seem to be primarily important for speech articulation.

Comments

The data presented in this report further confirm our belief that PCA plays an important role in speech articulation. The most characteristic pattern is that PCA shows increasing activity for those articulatory adjustments which are associated with the gesture of glottal opening. More accurately speaking, it is shown electromyographically that the opening gesture of the glottis during speech articulation is accomplished by active participation of PCA with reciprocal suppression of the adductors of the larynx.

As shown in our systematic analysis of EMG and fiberoptic data on Japanese voiceless sounds, the degree and timing of PCA activity are directly responsible for determining the size and temporal course of the glottal opening for voiceless segments, although the suppression of the adductors should also be taken into consideration for a complete description of voiceless sound production. It should be reemphasized that PCA activity is primarily related to the abduction gesture and not necessarily to voicelessness. It is known that vocal fold vibration can occur with open glottis in different kinds of languages. In Japanese, for example, intervocalic /h/ often becomes voiced. The glottal width for intervocalic /h/ is, however, usually as wide as for intervocalic /s/. Fig. 15 shows PCA activity patterns for intervocalic /h/ and /s/ in a Japanese subject producing meaningful Japanese sentences. It is clear in this figure that the degree and timing of averaged PCA activity is almost the same for /s/ and /h/, even though the latter is found to be voiced in acoustic analysis. Fiberoptic analysis in the same subject revealed that the maximum glottal widths for intervocalic /s/ and /h/ are quite comparable though vocal fold vibration is consistently observed for /h/. Thus, as stated by Sawashima (1973), the difference in voicing between /s/ and /h/ is likely due to the difference in airflow through the glottis depending on the degree of supraglottal constriction. Table I shows intraoral pressure and oral airflow measured in the Japanese subject whose EMG data are presented in Fig. 15, for the same types of test utterances. It is obvious that the intraoral pressure is much lower and the airflow is much larger for /h/ when compared with /s/. The comparison between /h/ and /s/ provides one example of PCA participation in the opening gesture of the glottis regardless of voicing distinction.

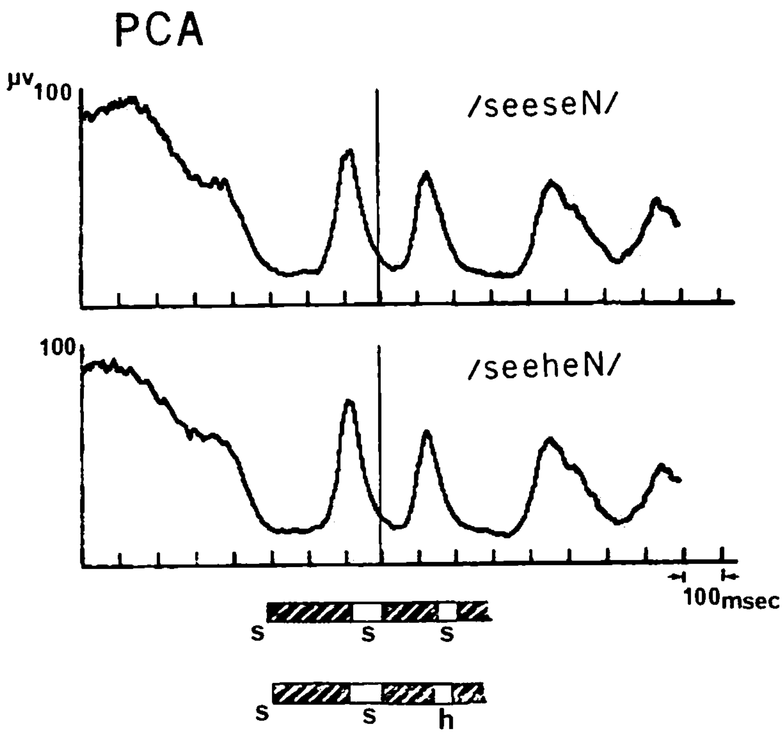


Fig. 15: Averaged PCA curves for the utterances "sorewa seesen desu" (upper) and "sorewa seehen desu" (lower) produced by a Japanese subject, comparing intervocalic /s/ and /h/. The line-up is taken at the onset of the vowel after word-initial /s/.

	P_o (mmH_2O)		U (ml/sec)	
	mean	(SD)	mean	(SD)
/s/	63.8	(4.97)	500	(38.7)
/h/	23.6	(3.96)	817	(41.3)

Table I: Comparison of intraoral pressure (P_o) and oral airflow (U) measured in the same subject as in Fig. 15. P_o was measured by means of a S & W oscillator type transducer (Nr. 13211) and U by an electro-aerometer (Type 508/4). All the data were obtained at the Institute for Phonetics, University of Copenhagen.

It has often been claimed that PCA is relatively more vulnerable to injuries or disease than the other intrinsic laryngeal muscles. Early in 1881, Semon noted that the PCA has higher proclivity and is more susceptible than the adductors, according to his clinical experiences. Negus (1931) stated that the evidence of comparative anatomy is strongly in favor of the truth of "Semon's law". He believed that the sphincteric activity serves a vital function and is more ancient in origin than its antagonist, the abductor, so that the phylogenetically younger abductor is more vulnerable and loses its vitality earlier than the adductors. In the field of clinical otolaryngology, as a matter of fact, it has been observed that the abductor function seems less resistive than the adductors. For example, when there is a progressive degenerative process in the brainstem level or expansive lesions along the peripheral course of the recurrent laryngeal nerve that causes progressive compression paralysis of the nerve, it is not rare to observe the dysfunction of the abductor as the first sign of the disease before the complete paralysis takes place. Although the real nature of the apparent vulnerability of the abductor seems still open to question, more substantial explanation than the simple phylogenetic assumption as given by Negus has been postulated from various viewpoints.

In recent years, biological and histochemical studies have revealed new aspects of basic features of the laryngeal muscles. In general, the results indicate that the intrinsic laryngeal muscles should be classified as relatively "tonic" muscles which carry an aerobic metabolism suitable for sustained contraction. In particular, PCA has been regarded as the highest for aerobic metabolism. For example, Matzelt and Vosteen (1963) investigated the pattern of enzyme activities in human laryngeal muscles and reported that aerobic metabolism was highest in PCA, while lowest in the vocalis (VOC); and INT was ranked between the two. Similar results were obtained by Hefter (1967) and by Ganz (1971).

Studies on muscle microstructure have revealed that the mitochondria is relevant to cell metabolism. By means of electronmicroscopy, Matzelt and Vosteen (1963) observed a dense population of the mitochondria in PCA but fewer mitochondria in the other laryngeal muscles. They interpreted their results as another indication of specialization of PCA as a "tonic" muscle.

Ganz (1971) made a histological study dealing with the measurements of the mean capillary length for estimating the degree of blood supply in the human laryngeal muscles. He found that capillary development was more dominant in the intrinsic laryngeal muscles than in the thyrohyoid. Among the intrinsic muscles, the best developed capillary blood supply was found in PCA, suggesting more efficient oxygen supply to this particular muscle.

If these observations are correct, it can be inferred that the apparent vulnerability of PCA may well be due to its easy susceptibility to oxygen deficiency.

However, these results of histological and/or histochemical studies are not always in unanimous agreement with those of other investigators. Tomita et al., (1967) for example, found that the population of the mitochondria is similar among different intrinsic laryngeal muscles. They further observed no significant difference in phosphorilase activity between the adductor and abductor groups of the larynx, although the laryngeal muscles per se were generally found to be more "tonic" than the femoral muscle. Kawano (1968) measured oxygen consumption in the intrinsic laryngeal muscles and reported that oxygen consumption was highest in INT, followed by VOC and PCA in that order. He also found in his electron-microscopic study that population of the mitochondria was larger in INT than in PCA.

The diversity of the opinions on the characteristics of PCA suggests that further basic research is mandatory for deeper understanding of the nature of this particular muscle. It should also be noted at this point that direct inference from microstructural or metabolic properties of a given muscle to its functional characteristics might sometimes be risky.

It seems reasonable to consider that the laryngeal function for speech first developed at the evolutional stage of humans. Lieberman et al. (1972) postulated that the anatomical condition of primates is so significantly different from that of humans that they are unable to produce speech sounds including vowels for mutual communication. As he pointed out, human linguistic ability must be viewed as the result of a long evolutionary process that involved changes in anatomical structure and functional differentiation. The explicit laryngeal adjustments during speech production certainly reflect highly developed mechanisms for human communication. In this sense, one should not overlook the important role of PCA, often regarded simply as a respiratory muscle, in the production of complicated human speech signals.

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