

Laryngeal muscles and articulatory control

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The present study continues earlier work on laryngeal control in speech with particular reference to adjustments in Swedish voiceless consonants and consonant clusters. Electromyographic recordings were obtained from four intrinsic laryngeal muscles together with simultaneous transillumination and acoustic signals. Results indicate that the vocalis and lateral cricoarytenoid muscles participate in the control of both articulation and phonation (F_0). The interarytenoid muscle appeared to be involved only in articulatory adjustments. Activity in the cricothyroid was mostly related to F_0 change; however, this muscle also showed an increase in activity for voiceless sounds. In addition, the vocalis muscle appeared to participate in glottal adduction without complete closure in voiceless clusters with the lateral cricoarytenoid and the interarytenoid playing no particular roles. The results suggest the need of studying laryngeal behavior in speech within a general systems framework for movement control.

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INTRODUCTION

Voiceless consonants are normally produced with glottal abduction and adduction in the form of a continuous opening and closing gesture (Löfqvist, 1980). In single voiceless consonants, the control of the gesture involves at least the posterior cricoarytenoid (abduction) and the interarytenoid (adduction) muscles which show a reciprocal relationship (Hirose, 1976; Hirose *et al.*, 1978; Hirose and Ushijima, 1978; Hirose and Sawashima, 1981; Sawashima and Hirose, 1983).

In clusters of voiceless consonants, one or more articulatory gestures occur depending on the nature of the segments in the cluster. Thus sounds requiring a high rate of air flow, such as fricatives and aspirated stops, tend to be produced with a separate opening gesture. This has been a consistent finding in several studies of laryngeal articulation in different languages (Löfqvist and Yoshioka, 1980, 1981; Yoshioka *et al.*, 1981; Yoshioka *et al.*, 1982). In such clusters, variations in glottal opening do occur even though the glottis stays open during the whole cluster. Electromyographic recordings from intrinsic laryngeal muscles during voiceless cluster production have revealed a pattern of muscular activity suggesting that a strict reciprocity between the posterior cricoarytenoid and the interarytenoid muscles may not always hold true. In particular, variations in posterior cricoarytenoid activity, highly correlated with changes in glottal opening, have consistently been observed, with an increase in activity for glottal abduction and a decrease in activity for

glottal adduction. However, the interarytenoid may be suppressed during the whole cluster or show only slight changes in activity related to the glottal movements (Löfqvist and Yoshioka, 1980).

Our earlier work on laryngeal motor control in voiceless consonant clusters sampled only the activity of the posterior cricoarytenoid and the interarytenoid muscles. The contribution of other laryngeal muscles to laryngeal articulation thus remained unclear in this set of experiments. It would therefore be of interest to supplement those studies with recordings from additional laryngeal muscles in order to obtain a more complete picture of laryngeal articulatory control. The present experiment was thus designed to make simultaneous recordings of laryngeal electromyographic activity and articulatory movements using the same subject and similar linguistic material as in the study of Löfqvist and Yoshioka (1980).

I. METHOD

Electromyographic recordings were obtained from the interarytenoid (INT), lateral cricoarytenoid (LCA), vocalis (VOC), and cricothyroid (CT) muscles. Bipolar, hooked wire electrodes were used. Verifications of electrode position were made using selected speech and nonspeech maneuvers. The EMG signals were recorded on FM tape for subsequent computer processing. For processing, the signals were rectified and integrated over a 5-ms window and sampled at 200 Hz. For averaging, the signals were aligned with reference to a predetermined, acoustically defined lineup point, such as

stop release burst or vowel onset, and integrated over 35 ms.

Transillumination (Sonesson, 1960) was used to record laryngeal articulatory movements. Comparisons between transillumination and fiberoptic films (Löfqvist and Yoshioka, 1980) and also between transillumination and high-speed films (Baer *et al.*, 1983) have shown good agreement. A fiberscope provided illumination of the glottis, and the light passing through the glottis was sensed by a phototransistor placed on the surface of the neck just below the cricoid cartilage. The signal from the transistor was recorded on another channel of the FM recorder. For averaging, the transillumination signal was aligned with the EMG signals and integrated over 5 ms. In order to obtain an estimate of the speed of glottal movements, the derivative of the averaged transillumination signal was calculated. Before differentiation, the averaged signal was smoothed with a 15-ms window.

Conventional acoustic recordings were obtained simultaneously and recorded in direct mode. Measures of fundamental frequency and voice onset time were made. The rectified and integrated audio signal was combined with the electrical and biomechanical signals.

The linguistic material consisted of voiced and voiceless consonants and voiceless consonant clusters that occurred in Swedish words. A native male speaker, one of the authors, read the linguistic material 15 times from randomized lists. The material was similar to that used by Löfqvist and Yoshioka (1980) and consisted of the three Swedish proper names "Li," "Lis," and "Kvists" combined with the six Swedish verbs "bilar," "pilar," "filar," "vilar," "helar," and "ilar."

Due to technical problems in recording several channels of bioelectrical and biomechanical information, the present material was recorded during two separate experimental sessions. In the results presented in Sec. II, the recordings of LCA, VOC, and CT were all obtained in the same session, while INT was recorded in a separate session. We should emphasize, however, that transillumination signals and EMG records of VOC and CT were obtained in both runs. These data were qualitatively identical across sessions and thus allow comparisons between recordings obtained on different occasions. Also, the averaged records of movement, VOC, and CT represent tokens recorded on a single occasion.

II. RESULTS

Figure 1(a) presents averaged EMG and movement records for utterances containing single voiceless and voiced stops. In these utterances, the main stress of the utterance occurs on the first syllable of the second word (i.e., on the /i/ in "pilar" and "bilar"). This syllable has the fundamental frequency peak of the utterance as shown by the F_0 curves.

From Fig. 1(a) it is evident that the voiceless stop is produced with an opening gesture of the glottis but that no such gesture occurs for the voiced stop. The LCA, VOC, and INT show suppression of activity during the glottal opening gesture for the voiceless stop. The stop is aspirated with a mean VOT of 60 ms (s.d. 9.6).

For the voiced stop, there is no suppression of LCA, VOC, and INT during the closure period. The INT maintains a steady level of activation for both the stop and the following vowel; in fact, the activity of INT remains almost identical throughout the utterance.

Figure 1(b) presents results for clusters of voiceless consonants. Again, the main stress of the utterance falls on the first vowel of "pilar." To the left is shown a sequence of voiceless fricative and voiceless stop separated by a word boundary: "Lis pilar." In this case, the word initial voiceless stop in "pilar" is aspirated (mean VOT 57 ms, (s.d. 8.3)). A longer cluster is shown to the right in Fig. 1(b) containing a word final sequence of fricative-stop-fricative followed by a word boundary and a voiceless aspirated stop: "Kvists pilar." Mean VOT for the word initial labial stop is 51 ms (s.d. 8.2).

In the movement records (GA and VEL) of Fig. 1(b), we see that glottal opening is constantly changing in these voiceless clusters. A separate opening gesture is found for the fricatives and for the aspirated stops; between these maxima of glottal opening the vocal folds are adducted without complete closure.

Inspection of the EMG records in Fig. 1(b) reveals that the activity of LCA and the INT is generally suppressed during the clusters. Some variations in activity can be found for these two muscles during the clusters, but they are very small and do not appear to be directly related to glottal movements. The VOC shows a strikingly different pattern of activity. For this muscle, variations in activity occur in synchrony with the glottal movements—an increase in activity associated with glottal adduction and a decrease in activity associated with glottal abduction.

The cricothyroid correlates closely with the overall F_0 pattern. Furthermore, a slight decrease in activity can be seen during the voiceless clusters in Fig. 1(b). For the obstruents in Fig. 1, there is a small increase in activity at the onset of the voiceless segments in "Li pilar," "Lis pilar," and "Kvists pilar"; such an increase is not found for the voiced stop in "Li bilar."

III. DISCUSSION

While only a single subject was used in this study, the kinematic data are in agreement with previous studies of laryngeal behavior in voiceless consonant and consonant cluster production (cf. references given above). Furthermore, the EMG records of INT also replicate Löfqvist and Yoshioka (1980), perhaps not surprisingly since the same subject was recorded.

These data bear on several issues concerning laryngeal control in speech. There is some controversy and uncertainty about the function of laryngeal muscles in the control of voicing and articulation, in particular concerning the role of the LCA. For example, this muscle has been shown to be suppressed for both voiced and voiceless obstruents in Japanese (Hirose and Ushijima, 1978). On the other hand, Collier *et al.* (1979) noted that this muscle did not correlate with the voicing distinction in Dutch but rather with manner of production (i.e., stop versus fricative). We should add that stud-

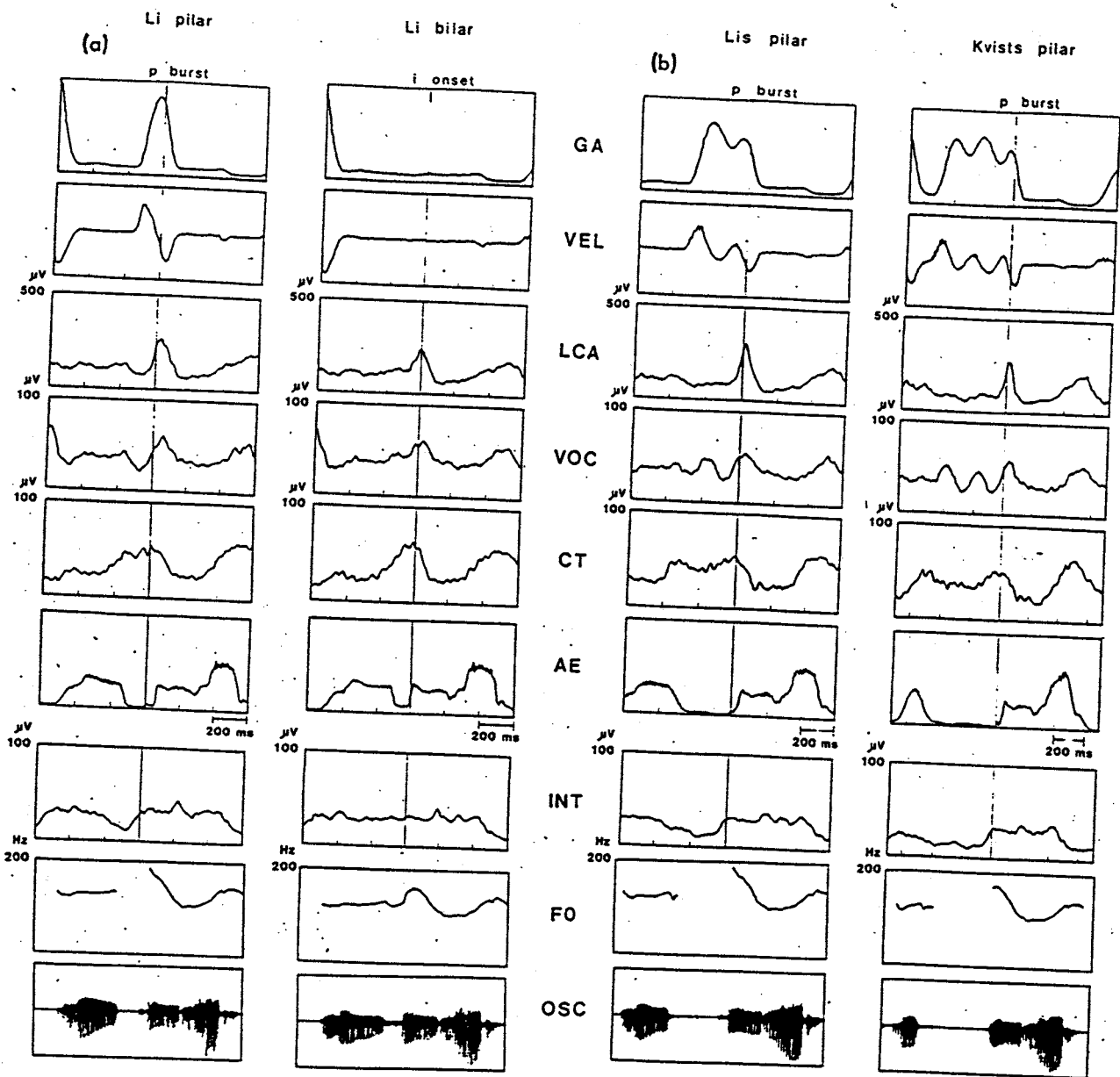


FIG. 1. (a) (Left) Records of the utterances "Li pilar" and "Li bilar." The curves represent from top to bottom, glottal area (GA) with increasing area displayed upwards, velocity of glottal movements (VEL), averaged EMG activity of lateral cricoarytenoid muscle (LCA), vocalis muscle (VOC), cricothyroid muscle (CT), averaged, rectified, and integrated audio signal (AE), averaged EMG activity of the interarytenoid muscle (INT), fundamental frequency curve of a single utterance (F0), and the acoustic waveform of a single utterance (OSC). (b) (Right) Records of the utterances "Lis pilar" and "Kvists pilar." Curves as in (a).

ies of Dutch voiceless consonants have showed them to be produced with a glottal opening gesture and activation of the posterior cricoarytenoid muscle (Slis and Damsté, 1967; Yoshioka *et al.*, 1982).

Both LCA and VOC participate in aspects of phonation and laryngeal articulation. The former is illustrated by changes in muscle activity accompanying the F0 pattern of the utterance. Similar patterns of LCA and VOC activity have been obtained for stress contrasts in English words such as /p̥ermit/ and /p̄ermit/ (Sawashima and Hirose, 1983). With respect to laryngeal articulation, activity of LCA and VOC is suppressed during voiceless consonants. The peak of LCA and VOC activity at the vowel carrying the sentence stress in Fig. 1(a) is also higher when the vowel is

preceded by a voiceless obstruent. This difference most likely reflects the extra activity required of the two muscles in contributing to glottal adduction and onset of phonation. Unlike the LCA and VOC, the INT does not show any activity related to F0 change. However, it participates in control of laryngeal articulation for voiceless consonants.

The CT participates in F0 control. However, its contribution to laryngeal articulation has been debated, and the experimental evidence is equivocal on this point. In the present study, a small increase in CT activity was observed at the onset of voiceless segments. In this case, the CT might cooperate in glottal abduction. Such an increase in CT activity could possibly be related to the well-known higher F0 of a vowel following a voiceless obstruent as compared to a vowel

following a voiced obstruent (Hombert *et al.*, 1979). This question remains to be further investigated in a wider variety of phonetic contexts.

Our data suggest caution in assigning a particular role to a given muscle in movement control. For example, the present results suggest that activation of VOC when the glottis is open in a voiceless cluster contributed to glottal adduction. However, when the glottis is closed, activation of the VOC affected F_0 control, most likely by tensing and stiffening the vocal fold. In speech as in other coordinated movements, muscles seem to work in synergistic units. In current studies of upper articulators in speech production a more general systems approach has provided insights into the organization and control of coordinated movements (Hughes and Abbs, 1976; Abbs, 1979; Kelso, 1981; Tuller *et al.*, 1982). Future studies of laryngeal behavior in speech might profit from the same approach.

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