Control of Fundamental Frequency, Intensity, and Register of Phonation*

Thomas Baer, †Thomas Gay, †and Seiji Niimi++

ABSTRACT

Electromyographic activity of several intrinsic and extrinsic laryngeal muscles was recorded as untrained singers produced systematic changes in fundamental frequency (F₀), intensity, and register of phonation. For one subject, subglottal pressure was recorded simultaneously. Cricothyroid muscle activity varied most consistently with F₀ over most of the range of F₀, although the activity of several other muscles was also related to F₀. Vocalis muscle activity varied most consistently with the shift between chest and falsetto registers. Subglottal pressure varied consistently with changes in vocal intensity. Activity of the extrinsic muscles was correlated with F₀ at both the high and low extremes of the chest voice range. For at least one subject, the extrinsic muscles seemed to be solely responsible for varying F₀ at its low extreme. The activity of muscles not directly associated with the larynx also changed systematically with F₀ at the high extreme.

Recent electromyographic (EMG) studies of the control of fundamental frequency, intensity, and register of phonation have dealt with the intrinsic laryngeal muscles (e.g., Hirano, Ohala, and Vennard, 1969; Hirano, Vennard, and Ohala, 1970; Gay, Hirose, Strome, and Sawashima, 1972) or with the extrinsic muscles and subglottal pressure (Shipp and McClone, 1971). Simultaneous recording of intrinsic and extrinsic laryngeal muscles and subglottal pressure has been reported for speech intonation (e.g., Collier, 1975) but not for singing. Thus, the purpose of this study is to reexamine the nature of the control of phonation by the intrinsic and extrinsic muscles of the larynx and by subglottal pressure.

For this study, four untrained singers produced systematic changes in fundamental frequency (F₀), intensity, and register of phonation while EMG activity was recorded using hooked-wire electrodes (Basmajian and Stecko, 1962; Hirose, 1971). For subject TB, subglottal pressure was also measured, using a cannula

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†Also University of Connecticut Health Center, Farmington.

++On leave from the University of Tokyo, Japan.

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inserted through the cricothyroid space. Each note was produced on the syllable /bi/. Each vocal maneuver was repeated 10 to 15 times, and average results were calculated using the Haskins Laboratories EMG data processing system (Kewley-Port, 1973). This system computes average activity from several repetitions of an utterance as a function of time offset from a predetermined lineup point associated with each token.

Figure 1 shows a typical result. The subject produced one-octave arpeggios starting from a fundamental frequency in the middle of his chest-voice range. The arpeggios were performed at three different intensity levels. Average activity was calculated for each of these conditions using for lineup point the onset of voicing for the first (lowest) note (shown on the left-hand side of the figure) and also using the onset of voicing for the fourth (highest) note (shown on the right-hand side of the figure).

Average activity of the cricothyroid (CT) and vocalis (VOC) muscles was found to vary systematically with fundamental frequency, but not with intensity. (Activity of the VOC muscle was sometimes more closely correlated with \( F_0 \) than is shown in Figure 1). Subglottal pressure varied systematically with intensity (or vocal effort), but its variation with frequency was smaller and less systematic. This close correlation between subglottal pressure and intensity is qualitatively in agreement with the results of other investigators (e.g., Isshiki, 1964). We plan to investigate the relationship between subglottal pressure and fundamental frequency in more detail in the future.

Figure 2 shows similar results from subject KK—a female. Two lineup points have been used, and the results have been superimposed in their overlap region. Cricothyroid and VOC activity vary systematically with fundamental frequency but not with intensity. Activity of two extrinsic muscles, the thyrohyoid (TH) and the sternohyoid (SH), is shown. The pulsatile structure of the TH plots shows that its activity is related to the segmental gestures for producing the syllables. However, the symmetric envelope of activity centered about the second lineup point shows that its level of activity is also related to \( F_0 \). The plots of SH activity show tendencies similar to those of the TH, though they appear less dramatic in this run. The TH activity shows some differences in activity for the highest intensity condition.

In several runs, EMG activity was recorded from the inferior constrictor muscle. The electrodes were directed toward the cricopharyngeal part of the muscle, and these placements were verified using activity during swallowing. The results were inconsistent across subjects. In Figure 3, the upper plots show the inferior constrictor data corresponding to the data in Figure 2. The only increases in activity are associated with the first note and the last note. This activity appears to be related to the production of the lowest frequencies, although it could also be related to maneuvers associated with the beginning and end of the phrase. These two interpretations could be differentiated by performing descending-ascending rather than ascending-descending arpeggios in the same range, but such maneuvers were not performed. The lower plots in Figure 3 show the inferior constrictor activity corresponding to the plots in Figure 1. Here, inferior constrictor activity increases with both \( F_0 \) and intensity except for the high intensity condition, for which there is an increase of activity associated with the first and last notes. For the other two conditions, there is a decrease of activity immediately before the onset of the first note, and a small increase of activity at the end of the phrase. The meaning of these results
Figure 1: EMG activity and subglottal pressure during arpeggios at three intensity levels. Subject TB.
RUN: 1KK
TWO-SECOND ARPEGGIOS: 220-440Hz

Figure 2: EMG activity of intrinsic and extrinsic muscles during arpeggios at three intensity levels. Subject KK. (Same legend as Figure 1.)
ACTIVITY OF THE INFERIOR CONSTRICTOR MUSCLE DURING ARPEGGIOS

Figure 3: EMG activity of the inferior constrictor muscle during arpeggios at three intensity levels. Subjects KK and TB. (Same legend as Figure 1.)
is unclear, and must be further investigated with repeated insertions on the same (and other) subjects and with other vocal maneuvers.

We reconfirmed the well-known fact that extrinsic muscle activity contributes to the control of $F_0$ at both extremes of a subject's chest-voice range (e.g., Sonninen, 1956). Results from the low extreme are shown in Figure 4. The subject produced an ascending scale at the rate of one note per second starting at about his lowest note. Average activity of each of four laryngeal muscles and of subglottal pressure was measured for each note and plotted as a function of the fundamental frequency of the note in the figure. As the figure shows, there was no significant change in CT or VOC activity for the lowest notes, and subglottal pressure was held fairly constant throughout. However, there were clearly changes in activity of the two strap muscles—the sternothyroid (ST) and thyrohyoid (TH)—for the lowest notes. Although we had no reliable insertions into muscles other than the ones shown in Figure 4, it seems reasonable to conclude that the ST and TH, and possibly other extrinsic muscles, were responsible for producing the lowest fundamental frequencies. This result is of interest for both singing and speech, since the low extreme of the $F_0$ range for singing overlies the range of $F_0$ commonly used for speech.

At the high extreme, we examined the control of register for subject TB, who could reliably produce the same note in either chest-voice or falsetto. The results of shifting from falsetto to chest-voice on three different notes are shown in Figure 5. The subject sang the syllable /bi/, first in falsetto and then in chest-voice. The lineup point for averaging was the onset of the chest-voice note. The plots on the left-hand side of the figure show the activity of the CT and VOC muscles and of subglottal pressure. The plots on the right-hand side of the figure show activity of the inferior constrictor (IC) muscle and one strap muscle, the TH. In all cases, the activity of the VOC muscle was greater in chest-voice than in falsetto. The level of CT activity increased at the shift from falsetto to chest-voice for the 220- and 330-Hz notes, but there was only a very small increase for the 440-Hz note. The TH shows no change of activity for the lower two notes, but an increase of activity for the shift into chest-voice in the highest note. These results are consistent with the notion that the VOC muscle is most closely associated with the control of register, while the CT and strap muscles produce compensatory activity to regulate fundamental frequency. Both subglottal pressure and IC activity consistently increased during the shift from falsetto to chest-voice. The significance of this increase is difficult to assess, especially since intensity was not controlled in these maneuvers. Although the results are not shown here, equivalent results showing a general decrease of activity were obtained when the shift was made from chest-voice to falsetto.

Figure 6 shows a plot of intrinsic muscle activity at the high extreme of the chest-voice range for subject SN. The subject produced ascending scales at the rate of one note per second, and average activity for each note was plotted as a function of the $F_0$ of the note, as in Figure 4. In addition to the increase of CT and VOC activity with fundamental frequency, both the lateral cricoarytenoid (LCA) and posterior cricoarytenoid (PCA) muscles showed some increase of activity with fundamental frequency. Although we were not fortunate in achieving good PCA insertions, this figure shows at least one example in which there was a small but systematic increase in PCA activity at the high $F_0$ extreme. Such a result was reported by Gay et al. (1972), but was not evident in the data of Shipp and McGlone (1971).
Figure 4: EMG activity and subglottal pressure versus fundamental frequency in low chest-voice. Subject TB.
Figure 5: EMG activity and subglottal pressure during register shifts on three different notes. Subject TB. The numbers in parentheses represent the full-scale values in hundreds of microvolts (EMG) or centimeters of water (subglottal pressure).
Figure 6: EMG activity of the intrinsic muscles versus fundamental frequency in high chest-voice. Subject SN.
Figure 7: EMG activity of several muscles during arpeggios in high chest-voice. Subject M.
A final point is made in Figure 7. In an otherwise unrelated experiment in which insertions were made into several muscles of the tongue and pharynx as well as the LCA, subject TB produced some systematic fundamental frequency changes. This figure shows the EMG activity of several muscles—the lateral cricoarytenoid (LCA), levator palatini (LEV), styloglossus (SG), inferior longitudinal of the tongue (IL), mylohyoid (MH), inferior constrictor of the pharynx (IC), superior constrictor (SC), and genioglossus (GG)—during arpeggios in the high extreme of the subject's range. The lineup point is the onset of phonation of the highest note. Although the activity of several muscles is correlated with fundamental frequency, at least some of these (such as the LEV and the intrinsic tongue muscles) are sufficiently unrelated to the larynx that they are unlikely to directly affect F₀. Rather, they seem to reflect a general increase in muscle activity in the head and neck when "reaching" for the highest notes. Although this is an extreme example, it might serve to warn that caution must be observed in the interpretation of EMG results, especially when trying to impute cause-and-effect between the action of a specific muscle and a specific acoustic result.

REFERENCES


