Electromyography of the Intrinsic Laryngeal Muscles During Phonation

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Electromyographic studies of the laryngeal muscles during phonation have been widely reported in the literature, with the classic experiments of Paaborg-Andersen (1957, 1965), in particular, providing a basis for describing the laryngeal control of phonation. Nonetheless, a number of questions about the control of fundamental frequency and intensity within and across vocal registers and the reliability of EMG measures, in general, have remained unanswered. This was due, largely, to the technical problems inherent in using concentric needle electrodes and the difficulty in extracting subtle changes in muscle activity patterns from raw EMG data. However, recent advances in both EMG recording and processing techniques have provided the necessary capability for answering these questions. On the one hand, hooked-wire electrode insertion techniques (Hirano and Ohala, 1969) have made possible the simultaneous recording of the intrinsic laryngeal musculature with a minimum of equipment interference and subject discomfort. On the other hand, the use of a digital computer to average the integrated curves of a number of tokens of a given vocal maneuver (Cooper, 1965; Gay and Harris, in press) has provided a convenient and accurate means of displaying the average strength of contraction of a given muscle or muscle group.

The primary purpose of this experiment was to describe, in detail, the actions of the intrinsic laryngeal muscles during various vocal frequency- and intensity-changing maneuvers. In addition, the conditions of the experiment were designed to simulate those of an earlier study (Sawashima et al., 1969) in order to obtain data on the reliability of repeated EMG measurements.

PROCEDURES

Subjects were five adults, four male and one female, all native speakers of American English. The female subject was a trained singer.

For each subject, an attempt was made to record from the five intrinsic muscles simultaneously. However, this goal was reached only for two of the five subjects. Unsatisfactory recordings were obtained for the vocalis.

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1 By reason of both past experience and the verification techniques employed, we are confident that we isolated the vocalis muscle. However, since the insertion was not viewed directly, we cannot be virtually certain that the electrode field did not include any potentials from the "external" thyroarytenoid.
muscle of one subject, for the interarytenoid muscle of another, and for the posterior cricoarytenoid and cricothyroid muscles of the third.

The EMG data were collected by following our usual procedures of hooked-wire electrodes, after the type described by Basmajian and Stecko (1962), and computer processing (Hirose, 1971; Port, 1971).

The acoustic measurements of fundamental frequency and relative intensity were made from oscillographic records obtained from a Honeywell Visicorder optical oscillograph.

Electromyographic data were collected for three different conditions of phonation:

1) **Frequency Control: Chest Register** - a stepwise change in fundamental frequency (as an arpeggio, "do-mi-sol-do-sol-mi-do") for phonation of a sustained /a/ at both moderate and loud intensity levels.

2) **Frequency Control: Falsetto** - sustained phonation of /a/ at high pitch-chest register, low pitch-falsetto, high pitch-falsetto.

3) **Intensity Control** - sustained phonations of /a/ for combinations of three pitch conditions (low pitch-chest, high pitch-chest, falsetto) and three intensity conditions (low, moderate, high).

4) **Vocal Attack** - sustained phonation of /a/ with three different attacks: breathy, simultaneous, glottal. (Data not presented here.)

All utterances were repeated successively between ten and twenty times. For each trial of frequency control, subjects were instructed to keep constant intensity regardless of the change in frequency of voice. The subjects were allowed ample practice and, in addition, were able to monitor intensity levels by means of a db meter. In the intensity control experiment, the subjects were asked to phonate at three different intensity levels for each fundamental frequency level, maintaining a constant fundamental frequency for each intensity level. Where necessary, the subjects used earphones to match their fundamental frequencies to the output of a sine wave oscillator.

**RESULTS AND DISCUSSION**

**Frequency Control: Chest Register**

In general, the data of this series show that increases in fundamental frequency are accompanied by progressive increases in the activity of the tensor muscles of the larynx. This is clearly illustrated in Figure 1, which summarizes the low-intensity arpeggio data for a single male subject. Since the averaged EMG curves remained at a relatively steady level throughout the duration of each arpeggio step (except for some overshoot at the onset of phonation), each step is shown by a single data point, which represents the graphic average (straight line fit) of the curve between 300 and 500 msec after the onset of phonation. Although an increase in fundamental frequency produces an increase in the activity of all intrinsic muscles, the greatest increase is for the cricothyroid and vocalis muscles. Note also the activity of the posterior cricoarytenoid, which increases markedly at the highest pitch level. Apparently, the posterior cricoarytenoid, as an antagonist to the cricothyroid, can also act as a tensor of the vocal folds. Figure 2 shows the same data for the high-intensity arpeggio. Here, the same activity pattern is evident but
Low-Intensity Arpeggios

![Graph showing EMG activity in μV versus fundamental frequency in Hz for different vocal structures.]

**Note:** Points along the curves represent averages of EMG data for the fundamental frequencies noted along the abscissa for Subject LJR. Intensity levels (in db) relative to the first arpeggio step (=0) are shown beneath the frequency values.
High-Intensity Arpeggios

![Graph showing EMG activity in μV across different fundamental frequencies in Hz (Relative Intensity in db)]

**Note:** Points along the curves represent averages of EMG data for the fundamental frequencies noted along the abscissa for Subject LJR. Intensity levels (in db) relative to the first arpeggio step (=0) are shown beneath the frequency values.
with higher levels for both the tensor muscles and the interarytenoid muscle. Posterior cricoarytenoid activity is also apparent, following the curve of the cricothyroid.

With respect to the cricothyroid, vocalis, and posterior cricoarytenoid muscles, the data obtained from the other subjects showed quite similar activity patterns, with progressive increases of activity accompanying stepwise increases in fundamental frequency and a general heightening of overall tensor activity for the higher intensity series. However, some variability was found for the adductor muscles. The increase in activity for the interarytenoid muscle at high intensity was peculiar to this subject. Other subjects also showed individual patterns of adductor muscle activity. One subject, for example, showed a marked increase in lateral cricoarytenoid activity at only the highest arpeggio step for both intensity conditions. Generally though, the higher frequency steps were characterized by only slight increases in adductor activity.

It is generally agreed that the cricothyroid and vocalis muscles are primarily responsible for the control of fundamental frequency. The data of this experiment show, further, that the actions of the two muscles vary systematically with both upward and downward changes in fundamental frequency. It has also been suggested (Sawashima et al., 1969) that the functions of these two muscles in regulating fundamental frequency differ in that the activity for the cricothyroid muscle varies more linearly with changes in frequency. The data obtained here show, rather, similar changes in activity patterns for both muscles. In a strict sense though, neither seems to bear a linear relationship to fundamental frequency.

The posterior cricoarytenoid finding is an interesting one and one which is in disagreement with the data of Faaborg-Andersen (1957), which showed relaxation of the posterior cricoarytenoid with increases in fundamental frequency. The contribution of the adductor muscles to changes in fundamental frequency is also less than straightforward. Hirano, Ohala, and Vennard (1969) suggest that the lateral cricoarytenoid participates in the regulation of fundamental frequency. The data of this experiment show that, indeed, the lateral cricoarytenoid sometimes does show increased activity with increases in pitch, but its actions, when evident, seem less consistent than those of the tensors. The interarytenoid reveals the same variability, depending on the particular subject.

Briefly summarizing then, the dominant muscle forces in regulating fundamental frequency in chest register are those of the cricothyroid and vocalis, with some antagonistic action of the posterior cricoarytenoid, especially at the higher frequency levels. Adductor muscle action probably plays a secondary role with specific contributions varying with the individual.

**Frequency Control: Falsetto**

Previous experiments (Faaborg-Andersen, 1957, 1965; Hirano et al., 1969; Sawashima et al., 1969) have shown that vocalis muscle activity (and often cricothyroid muscle activity) decreases with a shift in register from chest voice to falsetto. The data shown in Figure 3 confirm this and indicate, moreover, that a shift from high chest voice to low falsetto is reflected by a generalized relaxation of all the laryngeal muscles. However, increases in pitch
Sustained Phonation - Different Registers

**Fig. 3**

<table>
<thead>
<tr>
<th></th>
<th>FSC</th>
<th>LJ R</th>
<th>LL</th>
</tr>
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<tbody>
<tr>
<td>185</td>
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<td>185</td>
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<td>150</td>
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<td>250</td>
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**Fundamental Frequency in Hz**

**Note:** Points represent averages of EMG data for fundamental frequencies in the registers noted and shown along the abscissa, for three subjects.
within falsetto were accompanied by greater overall muscle activity. In the case of the trained singer, the muscle activity pattern for an arpeggio sung entirely in falsetto mirrored the pattern for chest voice, but with a lower corresponding level of muscle activity, i.e., the average EMG level for the first step in falsetto (260 Hz) was lower than that for the highest step (also 260 Hz) in the chest voice arpeggio.

Intensity Control

Generally speaking, the regulation of vocal intensity can be accounted for by changes in glottal resistance (laryngeal tension), by subglottal air pressure, or by both. As with previous EMG studies of intensity control, the data of this study provide direct information on only the laryngeal tension aspect; subglottal pressure contribution can be made only by inference.

The results of earlier EMG studies of the larynx are somewhat contradictory regarding the mechanism of intensity control. Both Faaborg-Andersen (1957) and Sawashima et al. (1958) report no significant change in the activity of the vocalis or cricothyroid muscles with changes in intensity, while Hirano et al. (1969) suggest active participation of the vocalis and lateral cricoarytenoid in regulating intensity in chest register, with a reduction of activity in falsetto.

In this series, EMG data were obtained for combinations of three pitch conditions (low-chest, high-chest, falsetto) and three intensity conditions (low, moderate, high). Figure 4 summarizes the data for three subjects. Again, each data point represents the averaged muscle activity between 300 and 500 msec after the onset of phonation.

The top row of Figure 4 summarizes the intensity data for Subject FSC. At low pitch-chest, there are only very slight increases in muscle activity across changes in intensity. At high pitch-chest, activity increases are sharper for the cricothyroid, lateral cricoarytenoid, and posterior cricoarytenoid, but vocalis activity levels off. There is a general leveling off or reduction for all muscles in falsetto. The curves for LJR show less general increase, except for vocalis and interarytenoid activity in high pitch-chest. The curves for LL, on the other hand, are relatively flat for all sets, with even some reduction of activity at high-intensity falsetto.

Except in three instances, muscle activity levels remained relatively steady or increased only slightly across changes in vocal intensity. Levels for falsetto were especially steady. Larger increases are more evident among sets, that is, as a function of fundamental frequency change. Also, given even the slight increases related to intensity, it would seem unlikely that the small changes in activity observed could be responsible for the large increases in intensity levels produced.

Another finding is worth mentioning. In a previous study, Hirano et al. (1969) found that cricothyroid activity decreased as vocal intensity increased. They suggested that this is a compensatory mechanism for regulating fundamental frequency under conditions of increased laryngeal tension (high intensity). This pattern of muscle activity was not evident for any of the present subjects. Generally, cricothyroid activity either leveled off or increased slightly across increases in intensity. However, since Hirano, Ohala, and
Intensity Control - Sustained Phonation

Low Pitch-chest  
High Pitch-chest  
Falsetto

FSC

Low Pitch-chest  
High Pitch-chest  
Falsetto

LJR

Low Pitch-chest  
High Pitch-chest  
Falsetto

LL

Note: Points in each graph represent averages of EMG data for three intensity levels. Data are shown for three pitch levels (chest register-low pitch; chest register-high pitch; falsetto) for each of three subjects. Intensity levels (in db) are relative to the lowest intensity level produced for each frequency (=0) and are shown along the abscissa. Fundamental frequencies are:

<table>
<thead>
<tr>
<th>Subject</th>
<th>Chest-Low</th>
<th>Chest-High</th>
<th>Falsetto</th>
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<tbody>
<tr>
<td>FSC</td>
<td>105 Hz</td>
<td>190 Hz</td>
<td>200 Hz</td>
</tr>
<tr>
<td>LJVR</td>
<td>130 Hz</td>
<td>180 Hz</td>
<td>320 Hz</td>
</tr>
<tr>
<td>LL</td>
<td>95 Hz</td>
<td>190 Hz</td>
<td>290 Hz</td>
</tr>
</tbody>
</table>

Fig. 4
Vennard's subjects produced swelltones while the present subjects phonated steady-state vowels, both results are probably equally tenable, if the contextual differences are taken into account.

Reliability of Repeated Measurements

As was mentioned at the onset, the conditions of this experiment were designed to simulate those of an earlier one on the tensors of the larynx by Sawashima et al. (1969). Two subjects in that experiment were also subjects in the present one.

The arpeggio data for both subjects were quite consistent across the two experiments. Although actual levels differed, activity changes were always systematic. This was further confirmed when a second opportunity arose during the course of this experiment to obtain another set of arpeggio data for one of the subjects (LJR). Again, analysis showed systematic changes in tensor muscle activity for stepwise changes in fundamental frequency along with increased activity of the posterior cricoarytenoid at the highest pitch levels.

Tensor muscle relaxation accompanying a shift to falsetto was also consistent for the two studies. Unfortunately, since much of the intensity and voice onset data were fragmentary, other meaningful comparisons could not be made. One final comparison, though, was possible. In the present experiment, Subject TG was one of two who showed a large peak in vocalis activity for glottal attack. This was the same pattern evident in the first experiment.

These similarities are interesting, especially in light of the fact that different electrodes were used for the first experiment (concentric needle as opposed to hooked wire), that different surgeons did the insertions, and that the second experiment was separated from the first by over a year. The basic question then seems to be answered: EMG measurements are repeatable. It is at least a possibility, then, that some of the contradictory results found by different investigators can be attributed to intersubject variability and not necessarily to variations in data recording techniques.

REFERENCES


Hirose, H. (1971) Electromyography of the articular muscles: Current instrumentation and technique. (See this Status Report.)
Port, D. (1971) The EMG data system. (See this Status Report.)