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ELECTROMYOGRAPHY OF THE INTRINSIC LARYNGEAL MUSCLES DURING PHONATION

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Electromyographic (EMG) studies of the laryngeal muscles during phonation have been widely reported in the literature, with the classic experiments of Faaborg-Andersen[1,2] in particular, providing a basis for describing the laryngeal control of phonation. Nonetheless, a number of questions regarding 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 extrapolating 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[3] have enabled the simultaneous recording of the intrinsic laryngeal musculature with a minimum of equipment interference and subject discomfort. Also, the use of a digital computer to average the integrated EMG curves of a number of tokens of a given vocal maneuver[4,5] 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,[6] in order to obtain data on the reliability of repeated EMG measurements.

METHOD

Subjects. 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 for only two of the five. Unsatisfactory recordings were obtained for the vocalis muscle* of one subject, interarytenoid muscle of another, and posterior cricoarytenoid and cricothyroid muscles of the third.

Electrode Insertion Techniques. Hooked wire electrodes, of the type described by Basmajian and Stecko,[7] were used for all insertions. Briefly, this procedure consisted of threading a pair of thin wires through the cannula of a hypodermic needle and bending

* 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.

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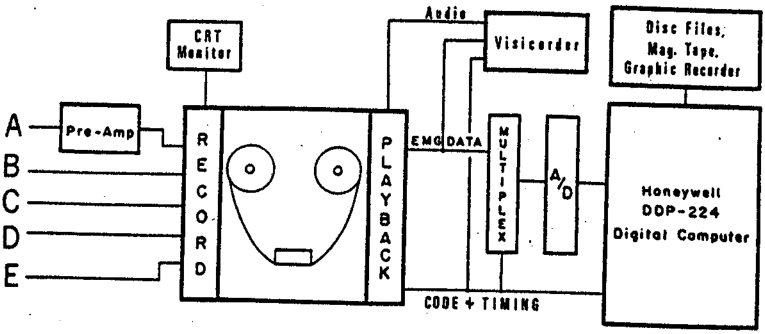

Fig. 1. Block diagram of EMG recording and processing system. A: EMG (8 channels); B: air pressure (2); C: voice; D: banter; E: digital code and timing.

the exposed ends of the wires back over the needle to form hooks. The entire assembly was inserted into the muscle after which the needle was withdrawn. This left only the hooked ends of the wires anchored into the muscle. Removal of the wires required only a slight tug. In this experiment, a platinum-iridium alloy (90%-10%) wire (.002 inch diameter and polyester enamel coated) was used in conjunction with either a No. 26 or 27 gauge needle.

The interarytenoid and posterior cricoarytenoid muscles were reached perorally while the vocalis, lateral cricoarytenoid and cricothyroid muscles were reached percutaneously, after the procedure described by Hirano and Ohala.[8] Premedication consisted of the administration of 5 to 10 mgs Valium® and 7 to 10 drops of tincture of belladonna. Subjects were seated in an examining chair throughout the experiment.

For the peroral insertions, an anesthesia procedure utilizing Cetacaine® spray and a gargle of 2 ml of 2% Xylocaine® was sufficient to desensitize the pharyngeal and laryngeal areas to a point where indirect laryngoscopy could be easily tolerated. A Xylocaine-soaked cotton swab was then applied to the specific areas selected for implantation. The interarytenoid and posterior cricoarytenoid muscles were reached by using an L-shaped rod with the carrier needle epoxy-bonded to the shorter arm, extending approximately one inch beyond the end of the shaft. The needle was threaded in the conventional manner. The entire assembly was directed to the point of insertion by indirect laryngoscopy.[8]

The percutaneous insertions were preceded by topical administration of 2% Xylocaine through a Pan Jet 70 air jet, at the site of the needle insertions. The vocalis was reached by insertion through the cricothyroid space at the midline, with the needle directed upwards and laterally into the inferior surface of the muscle. Insertion for the lateral cricoarytenoid was also through the cricothyroid space with the needle directed posteriorly, slightly laterally and upwards into the muscle along its longitudinal axis. The cricothyroid was reached by insertion below the lower edge of the thyroid cartilage, lateral to the midline, with the needle directed posterolaterally and upwards.

In all cases, correct electrode placement was confirmed by monitoring an oscilloscope during various functional maneuvers. At the same time, the muscle signals were amplified and fed to a loudspeaker for auditory monitoring.[8]

Data Recording and Processing. In order to obtain a convenient quantitative record of muscle activity, the raw EMG signal can be easily transformed into a display of amplitude versus time by the processes of full-wave rectification and RC smoothing (integration). Generally speaking, the envelope of the integrated curve is an indication of the strength of the muscle contraction. This is only an approximation, however, as the amplitude of the recorded signal varies with the distance between the electrodes and the active motor units of the muscle. Further, since productions of identical utterances vary from one token to the next, a number of these curves must be averaged before a reasonably accurate picture of muscle activity at a given electrode position can be obtained.

The basic data processing procedure followed in this experiment was to collect myographic data for a number of tokens for each of several phonatory conditions and, using a digital computer, average the integrated EMG signals at each electrode position.

A block diagram of the EMG recording and processing system used in this experiment is shown in Figure 1.* The system contains 14 data channels of which eight are for the recording of myographic signals. The other inputs are for the acoustic signal,[4] air pressure data, a banter channel for the operator's comments, and two channels for a clock track and digital code pulse. In addition, a calibration signal alternates with the EMG signals intermittently throughout the run. This signal is used by the computer to calculate the EMG levels in actual microvolts.

The purpose of the digital code pulse (octal format) is to identify each utterance for the computer. This pulse code is laid down on the tape, automatically, at one second intervals. Before actual processing, the computer receives instructions on how any number of tokens of a given utterance are to be superimposed or lined up with each other. This is done by marking the time interval between the nearest code pulse and any preselected line-up point, which in this experiment is the onset of phonation. During the data processing run, all calculating and tabulating operations are done automatically. The averaged output curve is plotted on a strip chart recorder.

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

Experimental Conditions. Electromyographic data were collected for four 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 vowel /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. (The trained singer was able to sing an arpeggio completely in falsetto.)

3. Intensity control: Sustained phonations of /a/ for combinations of three pitch (low pitch-chest, high pitch-chest, falsetto) and three intensity (low, moderate, high) conditions.

4. Vocal attack: Sustained phonation of /a/ with three different attacks: breathy, simultaneous, glottal.

All utterances were repeated successively in isolation between 10 and 20 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 cricothyroid and the vocalis muscles. This is clearly illustrated in Figure 2, 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 over-shoot 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 to 500 msec after the onset of phonation at each frequency level.

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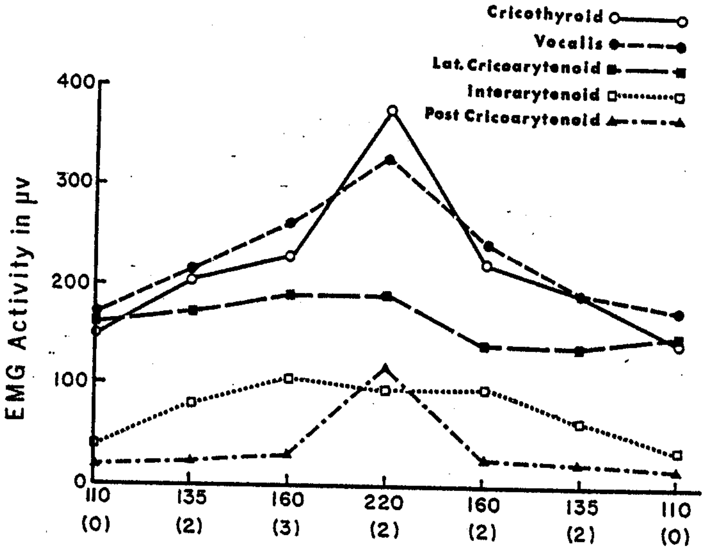
* The installation shown is in operation at Haskins Laboratories, Inc., New Haven, Connecticut.



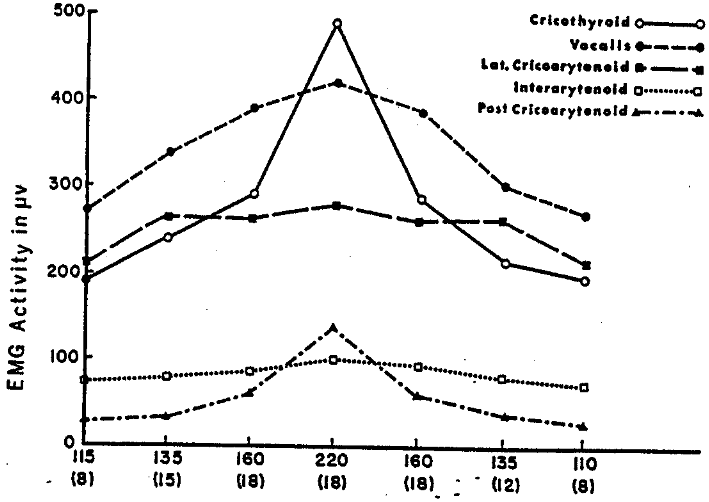


Fig. 2. Average EMG levels for low intensity arpeggios produced by subject LJR. Points along the curves represent averages of EMG data for the fundamental frequencies noted along the abscissa. Intensity levels (in dB) relative to the first arpeggio step (=0) are shown beneath the frequency values.

Fig. 3. Average EMG levels for high intensity arpeggios produced by subject LJR. Points along the curves represent averages of EMG data for the fundamental frequencies noted along the abscissa. Intensity levels (in dB) relative to the first arpeggio step of the low intensity arpeggio are shown beneath the frequency values.

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 at the highest pitch level. Apparently the posterior cricoarytenoid can also act as a tensor of the vocal folds. Figure 3 shows the same data for the high intensity arpeggio. Here the same activity pattern is evident but with higher levels for both the tensor muscles and the interary-

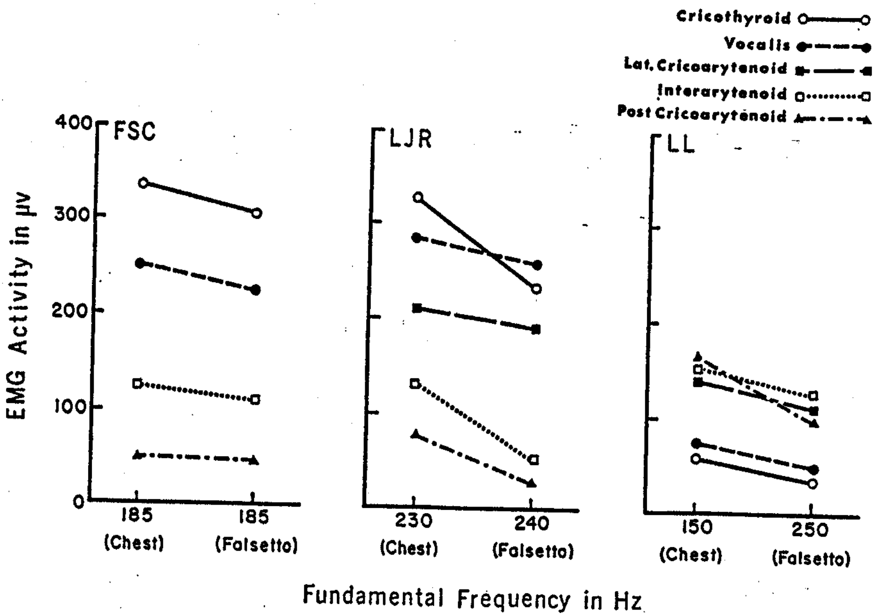


Fig. 4. Average EMG levels for sustained phonations in high chest register and low falsetto register for three subjects.

tenoid muscle. Posterior cricoarytenoid activity is also apparent, again 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 accompanying stepwise increases in fundamental frequency and a general heightening of overall muscle activity for the higher intensity series. However, some individual 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, however, 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, however, the higher frequency steps were characterized by only slight increases in adductor activity.

It is generally well 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[6] that the functions of these two muscles differ in regulating fundamental frequency in that the activity for the cricothyroid muscle varies more linearly with changes in frequency. In a strict sense, however, neither seem to bear what might be called 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,[1] 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 et al.[9] 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; but its actions, when evident, seem less consistent and proportional than those of the tensors. The interarytenoid reveals the same variability, depending on the particular subject.

Briefly summarizing, 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 at especially the higher frequency levels. Adductor muscle action probably plays a secondary role with specific contributions varying with the individual.

Frequency Control: Falsetto. Previous experiments [1,2,6,9] 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 4 confirm this, and indicate that a shift from high chest voice to low falsetto is reflected by a generalized relaxation of all the laryngeal muscles. However, increased pitch within falsetto was 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 subglottal air pressure (expiratory muscle forces) with or without adjustments in glottal resistance. As with previous EMG studies of intensity control, the data of this study provide direct information on only the laryngeal tension aspect; inferences to subglottal pressure contributions are *a priori* and, thus, somewhat speculative.

The results of earlier EMG studies of the larynx have been contradictory regarding the mechanism of intensity control. Both Faaborg-Andersen[1] and Sawashima et al.[10] report no significant change in the activity of the vocalis or cricothyroid muscles with changes in intensity, while Hirano et al.[9] suggest active participation of the vocalis and lateral cricoarytenoid in regulating intensity in chest register, with a reduction in 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 5 summarizes the data for three subjects. Again, each data point represents the averaged muscle activity levels between 300 and 500 msec after the onset of phonation.

The top row of Figure 5 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 such changes in activity could be responsible for the rather larger increases in intensity levels produced, especially in light of the high physical effort required to produce such

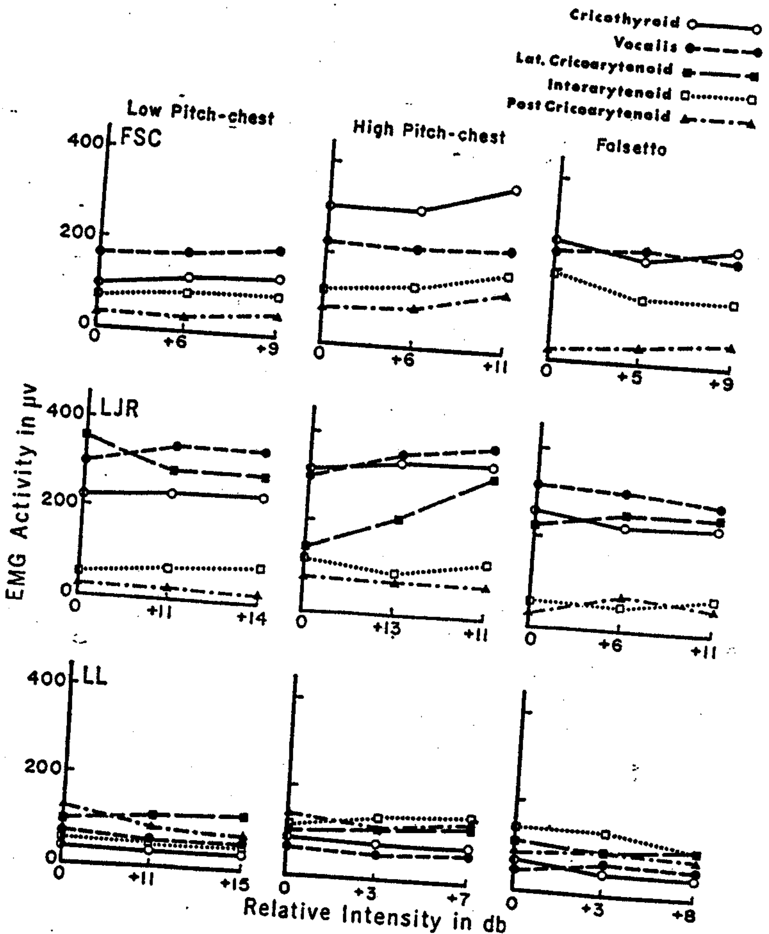


Fig. 5. Average EMG levels for three frequency and three intensity conditions, for three subjects. Fundamental frequency levels for low pitch-chest, high pitch-chest, and falsetto are as follows: FSC:105, 190, 200 Hz; LJR:130, 180, 320 Hz; LL:95, 190, 290 Hz. Intensity levels are relative to the lowest intensity condition (=0) of each set.

changes. It would seem more likely that the increases in relative intensity were controlled more by expiratory muscle forces.

For each subject, under similar conditions of fundamental frequency and vocal intensity, average muscle activity levels for the cricothyroid and vocalis muscles were greater for stepwise singing (experimental condition 1) than phonating (condition 3). The differences were on the order of 10% to 20% depending on the particular subject. Also, whereas the cricothyroid and vocalis muscles showed relatively small increases across intensity changes in this part of the experiment, the average activity levels for both muscles were as much as 50% greater for the high intensity arpeggio, as opposed to the low intensity arpeggio at each corresponding frequency level. These findings raise the question of whether different mechanisms regulate vocal intensity, and perhaps fundamental frequency, for stepwise singing and phonating; that is, whether there is a trading relationship between laryngeal and subglottal forces

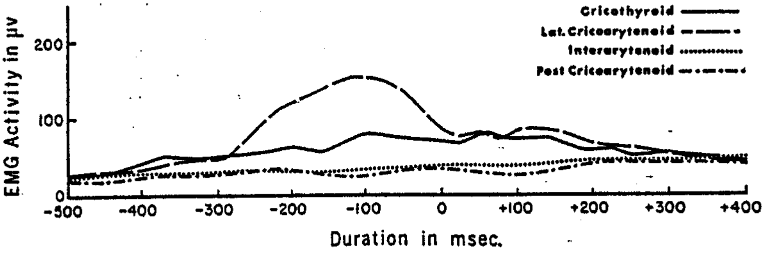


Fig. 6. Averaged EMG curves for glottal attack produced by subject AP. 0 = onset of phonation.

depending on whether a specific frequency level is aimed for or not.

It might be suggested further that such differences could be responsible for some of the opposing viewpoints found in the literature. For example, in a previous study, Hirano et al.[9] found that cricothyroid activity decreased as intensity increased. They suggested that this is a compensatory mechanism for regulating fundamental frequency under the condition where other factors which increase the intensity can also raise the pitch. 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 et al'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.

Vocal Attack. Averaged EMG data were obtained for three different types of vocal attack: breathy, simultaneous and glottal.

The primary differences in the muscle activity between a breathy and simultaneous attack are in the relative time course of the averaged EMG curves of both abductor and adductor muscles. For a breathy attack, the posterior cricoarytenoid shows continuous activity until immediately before the voice onset, while its activity steeply decreases well before the voice onset for a simultaneous attack. The adductors usually show more gradual increase in activity for a simultaneous attack than for a breathy attack. More interesting, perhaps, is the mechanism for glottal attack. For each of the subjects, a marked increase in activity of the lateral cricoarytenoid, with or without concurrent vocalis activity (depending on the subject), preceded a glottal attack. This is illustrated in Figure 6. It would seem then that the glottal resistance necessary for producing a glottal attack is accomplished primarily by greater medial compression rather than by simply the increased tension of the folds themselves.

Reliability of Repeated Measurements. As we mentioned earlier, the conditions of this experiment were designed to simulate those of an earlier one on the tensors of the larynx by Sawashima et al.[6] Two subjects in that experiment served as 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 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 vs hooked wire), different experimenters did the insertions, and the second experiment followed the first after over a one year interval. The basic question, therefore, seems to be answered – EMG measurements are repeatable. It is at least a possibility that some of the contradictory results found by different investigators can be attributed to intersubject variability and not necessarily to only variations in data recording techniques.

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