The Effect of Subglottic Pressure on Fundamental Frequency of the Canine Larynx with Active Muscle Tensions

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Modulation of Fundamental Frequency by Laryngeal Muscles During Vibrato

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Summary: The variations in voice fundamental frequency (F_0) that occur during vibrato production may be produced, at least in part, by modulation of laryngeal muscle activity. We have quantified this relation by using a cross-correlation analysis of the changes in F_0 during vibrato and the changes either in motor unit firing rate or in gross electromyographic activity from the cricothyroid (CT) and the thyroarytenoid (TA) muscles. Two trained amateur tenors provided the data. Correlations were generally quite strong (mean r for the CT was 0.72 for singer 1 and 0.50 for singer 2; mean r for the TA was 0.31 for singer 2), thus providing support for previous evidence that fundamental frequency modulation in vibrato involves active modulation of the laryngeal motoneuron pool, especially by the CT muscle. In addition, phase delays between muscle modulation and changes in fundamental frequency were substantial (averaging ~130° for the CT and 140° for the TA). This finding may help provide insight regarding the mechanisms responsible for the production of vibrato. **Key Words:** Vibrato—Voice fundamental frequency—Electromyography—Single motor unit—Cricothyroid muscle—Thyroarytenoid muscle.

It is well known that the activity of various intrinsic laryngeal muscles affects voice fundamental frequency (F_0). The cricothyroid (CT) and thyroarytenoid (TA) muscles are key contributors to pitch control. Contraction of the CT muscle results in vocal fold lengthening and increased longitudinal tension of the vocal fold. TA muscle contraction increases the intrinsic tension in the body of the vocal fold. Quantitative descriptions of the covariations of length, CT activity, TA activity, and F_0 have been given previously (1–3).

The variations in F_0 that occur during the production of vibrato have been reported to be associated with modulation of laryngeal muscle activity. Specifically, examination of acoustic data and gross electromyographic (EMG) data has revealed EMG modulations during normal vibrato primarily for the CT muscle (4–7), but also for the TA muscle (5,6, 8,9), lateral cricoarytenoid muscle (5,8,9), and posterior cricoarytenoid muscle (6).

Shipp et al. (7) provided quantitative analyses of the relation between gross muscle activity of the CT and F_0 modulation during vibrato. Two key findings were that CT activity increased ~30% when switching from straight tone production to vibrato for low- and mid-range pitches and that the changes in F_0 followed the changes in CT activity by ~110° (this is termed the "phase delay").

The purpose of the present investigation was to quantify the relation between the modulation of the

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activity of single motor units from laryngeal muscles with changes in F_0 during the production of a natural vibrato. Compared to gross muscle activity, analysis of single motor units provides more detailed information about the neural control of the muscle, such as firing rates, recruitment and derecruitment thresholds, and burst duration. In this study, we concentrated on the interval between motor unit spikes for vibrato produced at various fundamental frequencies to examine if firing rate was modulated with the vibrato cycle. When single motor unit data were not adequate or available, modulations in the amplitude of gross muscle activity were examined in relation to F_0 changes. A cross-correlation analysis procedure was used to allow for quantitative evaluation of the correlation between the changes in muscle activity and F_0 and for the extent of the phase delay.

METHOD

Procedures

Two trained amateur singers, both tenors, produced vibrato while sustaining single pitches. Several pitches were sampled throughout their ranges. Bipolar hooked-wire stainless-steel electrodes were inserted percutaneously in the CT and TA muscles. Electrode placement was confirmed by the usual techniques developed previously by Hirano and Ohala (10). The voice was sensed by a microphone placed ~30 cm from the lips. (The delay of the acoustic signal from the vocal folds to the microphone was calculated to be ~1 ms and was considered to be inconsequential for this investigation.)

The EMG signal was recorded on an FM data tape recorder and the voice was recorded simultaneously on the tape. These two signals were converted to digital signals and recorded onto a personal computer using data acquisition software (DATAQ Codas) at a sampling rate of 25 kHz per channel. An example of these unprocessed data is provided in Fig. 1 (top panel: motor unit activity; bottom panel: voice, average F_0 = 285 Hz). Each record for analysis consisted of 2 s of data.

A curve was created from the voice signal that reflected the changes in F_0 with vibrato production. The fundamental period of the voice was marked using the peak detection algorithm of the DATAQ data analysis program for the computer; accurate marking of each cycle was confirmed visually by one of the investigators. With use of the computer software, a constant voltage signal was then created, integrated, reset with each peak of the voice F_0 cycle, and held until the next peak. This resulted in a record consisting of short horizontal line segments whose voltage reflected the interval between each vibratory cycle of the vocal folds. The reciprocal of this signal was calculated and plotted, creating a record of variations in F_0 across time with increasing frequency represented by an upward deflection. Because of the reset-and-hold procedure, the curve was offset in time by one cycle period. To correct this, the value of an average F_0 cycle period, considered to be the best estimate of the offset, was subtracted from the time base. The frequency curve for the voice data illustrated in Fig. 1 is shown in the bottom half of Fig. 2 (average vibrato rate = 4.7 Hz). [This vibrato rate is relatively low, but falls within the range of rates often reported (11,12). Our frequency analysis technique was extremely precise, thus resulting in accurate values. It is possible, however, that the singer produced slower vibrato than usual because of the laboratory environment and experimental procedures (12).] The small, high-frequency variations in the frequency curve reflect vocal jitter. The larger, slower fluctuations reflect the vibrato.

Analysis of records with single motor unit activity was similar to the procedure used for the vibrato curve. Motor unit spikes were marked using the computer software's peak detection algorithm and validated by visual inspection. These marks were used to create a record of unit firing rate, exactly as

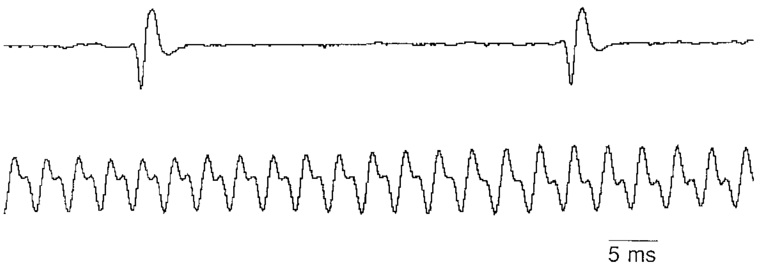

FIG. 1. Single motor unit from the cricothyroid muscle (top) and voice waveform (bottom) of singer 1.

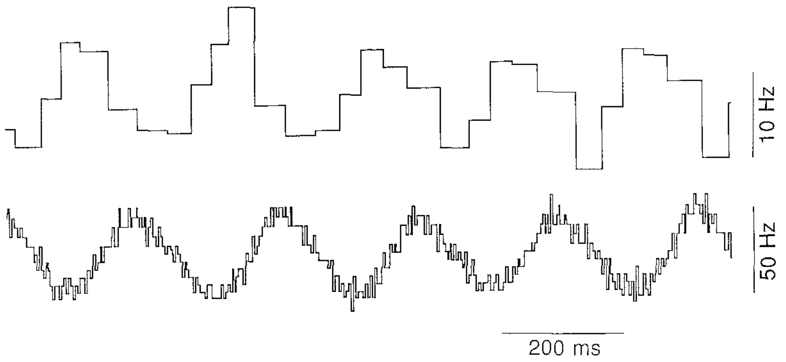

FIG. 2. Curves representing the motor unit firing rate (top) and the voice F_0 (bottom) derived from the same data sample used in Fig. 1. Mean motor unit firing rate = 25.3 Hz; mean voice F_0 = 285 Hz.

described previously for the creation of the voice F_0 record. The curve representing motor unit firing rate was corrected by subtracting the value of the average motor unit firing period from the time base. The frequency (firing rate) curve for the motor unit illustrated in Fig. 1 is shown in the top half of Fig. 2 (average firing rate = 25.3 Hz). The horizontal line segments are longer than those in the voice F_0 curve because the intervals between motor unit spikes were, of course, longer than those between F_0 cycles.

Gross EMG data records were rectified and smoothed with the computer software's moving average algorithm. This created a curve that reflected changes in the amplitude of the EMG over time.

The two frequency curves, for voice and motor unit activity, or the frequency curve for voice and the amplitude curve for gross EMG, were cross-correlated. The results of this procedure on the curves illustrated in Fig. 2 are given in Fig. 3. The peak of the curve corresponds to a correlation coefficient of 0.86. The phase delay at this peak value is 72 ms, which, based on the frequency of the vibrato cycle (4.7 Hz), corresponds to a phase delay of 122°.

RESULTS

For singer 1, one particular motor unit from the CT was observable for pitches D3 (147 Hz), D4 (294 Hz), and G4 (392 Hz). Twenty-eight data records were made and analyzed for this single motor unit. The average vibrato rate plotted against the average F_0 for each of the 28 records is plotted in Fig. 4. Note that vibrato was faster at the highest of the three pitches sung by this subject ($\bar{x}$ = 4.65, 4.64, and 4.97 Hz at the low, middle, and high pitches, respectively), a phenomenon reported previously by Horii (13) but not observed by Shipp et al. (12). In Fig. 5, the average firing rate of the motor unit is

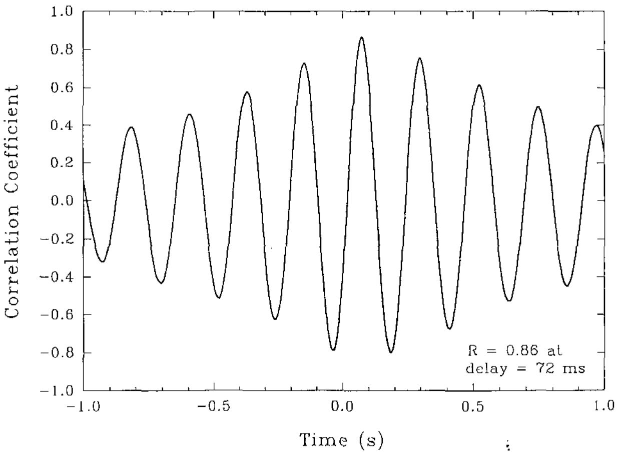

FIG. 3. Results of a cross-correlation analysis of the frequency curves illustrated in Fig. 2.

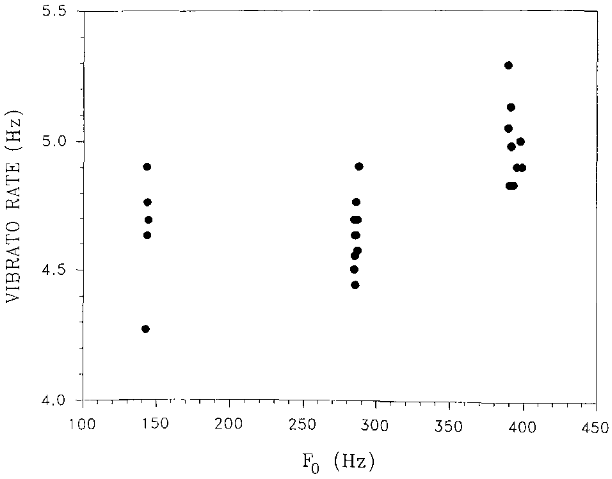

FIG. 4. The rate of the F_0 modulations during vibrato (vibrato rate) plotted according to average F_0 for the 28 data samples from singer 1.

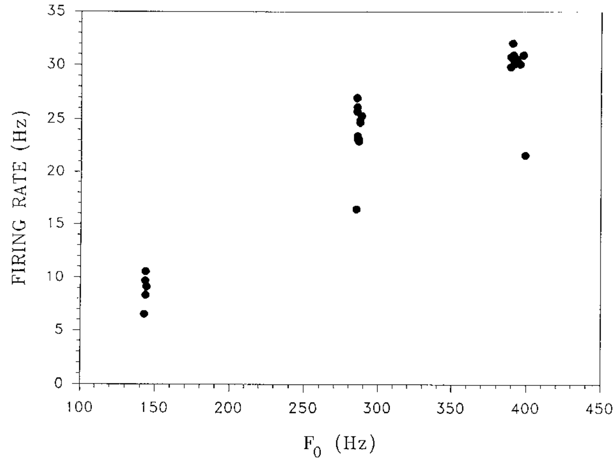

FIG. 5. Motor unit firing rate from the cricothyroid muscle of singer 1 plotted against the average F_0 for the 28 data samples.

plotted against the average F_0 for each record. The motor unit had a slower firing rate at the low pitch than at the higher pitches ($\bar{x}$ = 8.87, 23.8, and 29.8 Hz at the low, middle, and high pitches, respectively).

The correlation coefficients from the cross-correlation procedure for each of the records are plotted in Fig. 6. The best correlations were found for the middle of the three pitches ($\bar{x}$ = 0.85, SD = 0.08) and were generally good for most of the samples at the higher ($\bar{x}$ = 0.68, SD = 0.14) and lower ($\bar{x}$ = 0.50, SD = 0.23) pitches. The one low-pitched sample with a poor correlation coefficient (r = 0.11) involved activity of the motor unit that was well coordinated with the vibrato cycle, but was inconsistent in the number of times it fired per cycle. A portion of this record is provided in Fig. 7. Note that the motor unit fired twice per vibrato cycle initially, then switched to a single spike per cycle and then reversed back to double spikes. The cross-correlation procedure does not handle this situation well.

According to the phase delays calculated for the 28 data records for singer 1, changes in F_0 followed changes in CT motor unit firing rate by an average of 127.4° (SD = 10.7°). In Fig. 8, the phase delays are plotted against the vibrato rate. It appears that there may be a weak relationship such that the phase delays tend to be greater at the faster vibrato rates (r = 0.395).

For singer 2, a few single motor units could be detected from the CT data, but only at the low-frequency end of his range [G2 (98 Hz) and C3 (131 Hz)]. At these low frequencies, the CT motor unit discharge was inconsistent, probably because the motoneurons were close to their recruitment threshold. In addition, the singer's vibrato was somewhat inconsistent and uneven at these low pitches. We measured 16 2-s records of single motor unit activity from the CT for singer 2, but only 1 yielded adequate results—the cross-correlation coefficient was 0.64, and the phase delay was 97.3°. Gross EMG data were obtained from both the CT and the TA for singer 2. Of the 14 data records for the CT, including productions at three pitches (D4, G4, A4), the correlations between gross CT activity and changes in F_0 during vibrato were modest (mean r = 0.5, SD = 0.13). The average phase delay was 131.8° (SD = 14.1°). The activity of singer 2's TA was not well correlated with the F_0 (12 records, mean r = 0.31, SD = 0.13). The average phase delay for the TA was 140.3° (SD = 15.9°).

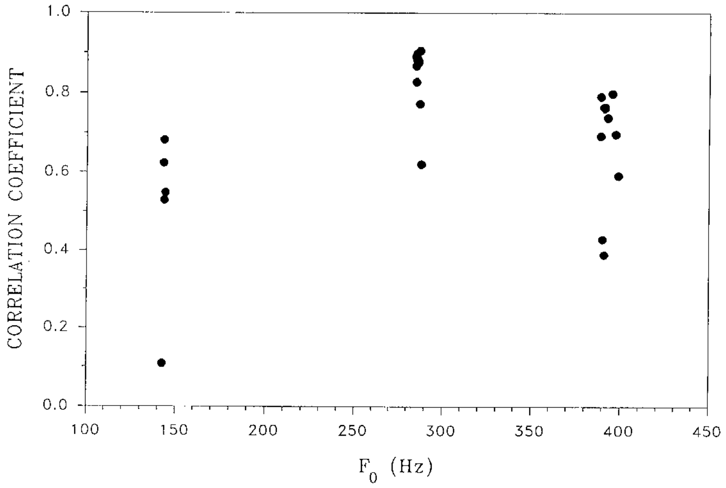

FIG. 6. Correlation coefficients from the cross-correlation analysis of the two frequency curves (modulations in motor unit firing rate and voice F_0) plotted against average F_0 for the 28 data samples from the cricothyroid muscle of singer 1.

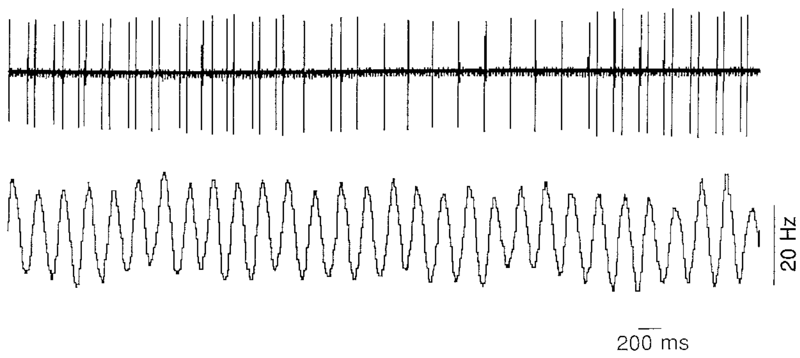

FIG. 7. The data sample from the cricothyroid muscle of singer 1 that yielded a correlation coefficient of 0.11. Note the change in the pattern of motor unit activity (top) with the F_0 modulations associated with vibrato (bottom) over time. Mean motor unit firing rate = 6.6 Hz; mean voice F_0 = 143 Hz.

DISCUSSION

We studied modulations in the firing rate of a single motor unit from the CT muscle over a wide range of voice F_0 and found that these correlated well with variations of fundamental frequency during vibrato production by a trained tenor. This finding supports previous literature (4–7). On average, the change in fundamental frequency followed the change in modulations of muscle activity during vibrato by 127°. Shipp et al. (7) also found substantial phase delays between changes in the amplitude of gross EMG in the CT and frequency changes with vibrato.

The fact that this motor unit could be studied over a relatively large range of vocal pitches (one octave and a fourth) was quite remarkable. The CT is thought to be inactive at low pitches and so active at high pitches that recruitment of additional motor units would obscure the view of the motor unit being studied. This may have been a unique opportunity, although we hope that this research can be replicated in the future. Nonetheless, the present findings are consistent with previous literature that involved measures of gross EMG.

Gross EMG data from the CT and TA muscles for singer 2 correlated with F_0 variations in vibrato, but the correlations were not as strong as those obtained for singer 1. This may be due to the nature of singer 2's vibrato—its frequency excursions (typically 12 Hz or 0.5 st) were not as extensive as singer 1's (typically 30 Hz or 2.0 st). It also may be related to the difference in the analyses between the subjects in that the activity of a single motor unit may follow the frequency changes in vibrato more closely than would the amplitude of gross EMG activity. The phase delay results were quite similar. Single motor unit analyses from this subject's data were problematic, as described previously.

The substantial phase delays found for all data records may contribute to the understanding of some of the basic mechanisms that produce vibrato. Studies of muscle physiology provide insight regarding the dynamic characteristics of muscle contraction based on phase information. Mannard and Stein (14) frequency-modulated electrical stimuli to

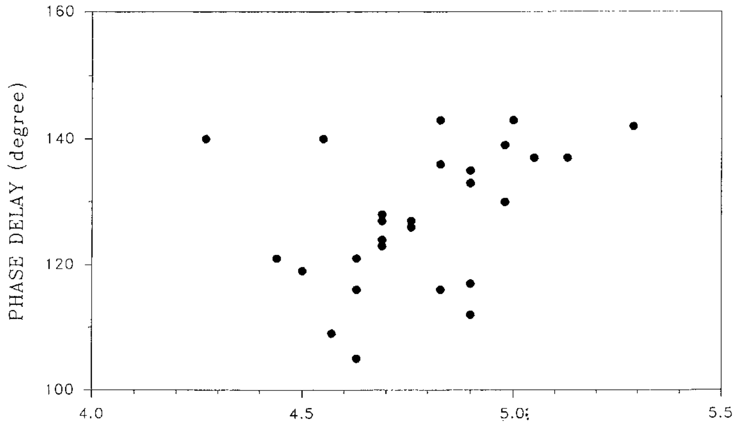

FIG. 8. The phase delays between the modulation in motor unit firing rate and F_0 modulations during vibrato plotted against vibrato rate for the 28 data samples from the cricothyroid muscle of singer 1. The correlation coefficient for these two variables is 0.395.

the nerve of the soleus muscle of anesthetized cats. They found that the isometric force response curves for gain and phase were fit well by a critically damped second-order low-pass filter function. This same result was reported recently when the nerve to the soleus was electrically stimulated using amplitude, frequency, or a combination of amplitude and frequency modulation (15). Thus, the low-pass model of isometric muscle contraction dynamics appears to be robust.

In the low-pass model of cat soleus described by Baratta et al. (15), modulation at ~2 Hz was associated with a phase lag of 90°. A similar corner, or "cutoff," frequency was obtained for the human soleus muscle (16). If this line of analysis is used in the case of the present study, the 5-Hz variations in motor unit firing rate or EMG modulation can be considered an input modulation to the CT muscle and the changes in F_0 can be considered the output of the muscle. The fact that the phase delays were an average of 122° implies the corner frequency of CT is somewhat less than 5 Hz, perhaps closer to 4 Hz.

The fact that most singers have vibrato that is modulated at ~5 Hz may result, at least in part, from the basic physiology of the laryngeal muscles. If the input to these muscles were modulated at the same amplitude but at frequencies significantly higher than 5 Hz, the response of the muscles would be too low to produce much F_0 variation. To produce such a rapid vibrato, modulation rates would have to be extreme (i.e., the muscles would turn on and off at high rates), and the nervous system may be incapable of this. Titze et al. (17) have suggested that the production of vibrato involves a peripheral oscillator that shows resonant properties, because of either physical characteristics or feedback control. Perhaps the phase lag associated with 5-Hz modulation is critical to oscillation in this system, whereas the larger lags that would occur with higher vibrato rates would be incompatible with oscillation.

In summary, this investigation examined and quantified the relation between the modulation of laryngeal muscle activity and changes in F_0 during vibrato produced by two trained singers. The change in firing rates of single motor units and amplitude modulations of gross muscle activity were cross-correlated with changes in F_0. In general, the modulations of muscle activity and F_0 were well correlated, especially when the firing rate of a single motor unit from the CT muscle was analyzed. In addition, substantial phase delays between the modulated signals suggest that the frequency at which laryngeal muscles can oscillate, and thus the vibrato rate, may be limited by the physiological responses of the muscles.

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REFERENCES

1. Fujimura O. Body-cover theory of the vocal fold and its phonetic implications. In: Stevens K, Hirano M, eds. *Vocal fold physiology*. Tokyo: University of Tokyo Press, 1981: 271–88.
2. Titze I, Jiang J, Druker D. Preliminaries to the body-cover theory of pitch control. *J Voice* 1988;1:314–9.
3. Titze IR, Luschei ES, Hirano M. The role of the thyroarytenoid muscle in regulation of fundamental frequency. *J Voice* 1989;3:213–24.
4. Mason RM, Zemlin WR. The phenomenon of vocal vibrato. *NATS Bull* 1966;22:12–7.
5. Hirano M, Vennard W, Ohala J. Regulation of register, pitch and intensity of voice. An electromyographic investigation of intrinsic laryngeal muscles. *Folia Phoniatr* 1970;22:1–20.
6. Martin F, Thumfart WF, Jolk A, Klingholz F. The electromyographic activity of the posterior cricoarytenoid muscle during singing. *J Voice* 1990;4:25–9.
7. Shipp T, Doherty ET, Haglund S. Physiologic factors in vocal vibrato production. *J Voice* 1990;4:300–4.
8. Niimi S, Horiguchi S, Kobayashi N. The physiological role of the sternothyroid muscle in phonation. An electromyographic observation. *Ann Bull RILP* 1988;22:163–70.
9. Niimi S, Horiguchi S, Kobayashi N, Yamada M. Electromyographic study of vibrato and tremelo in singing. In: Fujimura O, ed. *Vocal physiology: voice production, mechanisms, and functions*. New York: Raven Press, 1988;403–14.
10. Hirano M, Ohala J. Use of hooked-wire electrodes for electromyography of the intrinsic laryngeal muscles. *J Speech Hear Res* 1969;12:362–73.
11. Hakes J, Shipp T, Doherty ET. Acoustic characteristics of vocal oscillations: vibrato, exaggerated vibrato, trill, and trillo. *J Voice* 1988;1:326–31.
12. Shipp T, Leanderson R, Sundberg J. Some acoustic characteristics of vocal vibrato. *J Res Sing* 1980;4:18–25.
13. Horii Y. Frequency modulation characteristics of sustained /a/ sung in vocal vibrato. *J Speech Hear Res* 1989;32:829–36.
14. Mannard A, Stein RB. Determination of the frequency response of isometric soleus muscle in the cat using random nerve stimulation. *J Physiol* 1973;229:275–96.
15. Baratta R, Zhou B-H, Solomonow M. Frequency response model of skeletal muscle: effect of perturbation level and control strategy. *Med Biol Eng Comput* 1989;27:337–45.
16. Bawa P, Stein RB. Frequency response of human soleus muscle. *J Neurophysiol* 1976;39:788–93.
17. Titze IR, Solomon NP, Luschei ES, Hirano M. Interference between normal vibrato and artificial stimulation of laryngeal muscles at near-vibrato rates. *J Voice* 1994;8:215–23.