Acoustic correlates of laryngeal-muscle fatigue: Findings for a *phonometric* prevention of acquired voice pathologies

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Abstract

This presentation focuses on the problem of defining valid acoustic correlates of vocal fatigue seen as a physiological condition that can lead to voice pathologies. Several findings are reported based on a corpus of recordings involving electromyography (EMG) of laryngeal muscles and voice acoustics. The recordings were obtained in sessions of vocal effort extending across 12-14 hours. A known technique for estimating muscle fatigue is applied involving "spectral compression" of EMG potentials. The results show critical changes at given times of day. In examining the effects of these changes on voice acoustics, there is no linear correlation with respect to conventional acoustic parameters, but peaks in voice tremor occur at points of critical change in muscle fatigue. Further results are presented showing the need to take into account compensatory muscle actions in defining phonometric signs of vocal fatigue.

Index Terms: voice, muscle fatigue, EMG, acoustics, vocal fatigue, vocal pathology, prevention

1. Introduction

In numerous countries, work-related injuries to the hearing system are prevented by applying measurable *audiometric* standards and enforcing the use of protective gear. The situation is quite different when it comes to work-related injuries to the voice system, which occur at alarming rates in certain professions. For instance, one survey using endoscopic examinations of 1,046 teachers revealed vocal-fold pathologies in about one out of five individuals [1]. Despite decades of research, however, no measurable *phonometric* standard has emerged that could support a prevention of work-related voice disorders.

One central reason for this failure is the problem of defining a condition of voice use that can represent a risk. Such a condition is "voice fatigue". Most investigations have attempted to identify acoustic signs of voice fatigue by reference to vocal loading tasks and self-reports of felt fatigue. However, tasks used to induce vocal fatigue vary substantially across studies, and results have been inconsistent and often conflicting [2]. In this context, a number of authors have attempted to quantify the effects of vocal loading by comparing acoustic or aerodynamic measures and reports of felt fatigue, with varying success. [2] The main drawback is that *fatigue* relating to voice production is not an acoustic or aerodynamic condition but a physiological condition that bears on laryngeal muscles. Without a physiological measure, one cannot estimate the effects of vocal loading on laryngeal structures, nor how reports of felt fatigue reflect the state of the vocal system. Continued vocal effort in a state where there is laryngeal "muscle fatigue" can lead to tissue fatigue, lesions, and the growth of scaring masses constituting a voice pathology.[3] However, in the absence of a physiological measure of muscle fatigue, there can be little progress in isolating valid phonometric correlates of vocal fatigue as potential warning signs.

This issue guided a series of studies where the aim was to define physiological aspects of fatigue in laryngeal muscles so as to isolate critical acoustic signs. By reference to this approach, the following presents a synthesis of findings in three parts. The first part summarizes the results of a study [4] that used EMG to define measurable aspects of fatigue in muscles of the larynx during sustained vocal effort. Based on these findings, the second part summarizes the results of analysis where 19 acoustic parameters were correlated with estimates of muscle fatigue. The third part deals with the interpretation of the isolated acoustic signs. On this point, EMG data is presented to show that one has to take into account compensatory effects in laryngeal muscles in explaining the behavior of signs of vocal fatigue.

2. Physiological estimates of voice fatigue

A well known technique used to estimate muscle fatigue consists in applying a Fourier analysis to contraction potentials collected by means of EMG. When muscles contract in performing a task requiring effort, frequency components shift toward lower values as fatigue sets in. This spectral shift can be measured in terms of "mean percentile frequency" (i.e. the mean frequency of spectral components between the 5^{th} to 95^{th} percentile range). [5] The shift occurs from the fact that pools of motoneurons fire at given intervals during contractions and, in conditions of prolonged muscle contraction, the intervals become longer. When such spectral compression occurs, more and more motoneurons, sometimes extending to neighboring muscles, are recruited to maintain a force output. [6] This can create a stiffening of contractile tissues such that continued vocal effort in these conditions may create a potential for epidermal lesions leading to edema, nodules, or polyps [3].

Using the above EMG technique, measures of spectral shifts were applied to the contraction potentials of the lateral cricoarytenoid muscles (LCA) of seven subjects while they performed tasks of vocal effort during a waking day (12 to 14 hours). The LCA muscles are glottal adductors and compressors, and are particularly involved in vocal effort (for a demonstration, and the protocol used to localize LCA muscles, see [4]). In the task, the subjects produced loud speech (peaks of 74 dBA at one meter) for five minutes every fifteen minutes. Between each of the 50 loud vocalizations, EMG was recorded while the subjects produced a moderately high [ɑ:] at a given level of a VU meter. Analyses of EMG showed spectral shifts displayed in Fig. 1, where each value represents a running average over seven measures.

Fig 1 shows that, despite large fluctuations, critical changes in the spectra of contraction potentials may be inferred at given times. Specifically, between 3:30 and 6:30 p.m., spectral estimates definitely shift downwards and do not regain the levels obtained at the start of the test (horizontal line). One should note that this shift occurred across subjects with widely differing attributes and lifestyles.[4] Moreover, rises and falls in values suggested that changes in the spectra of potentials were not linked to bleeding or edema, and there was no drift in recorded signals indicating a deterioration of EMG with time. In Fig 1, the inferred critical shifts are indicated with an arrowhead on the time axis and these points were of central importance in subsequent acoustic analyses.

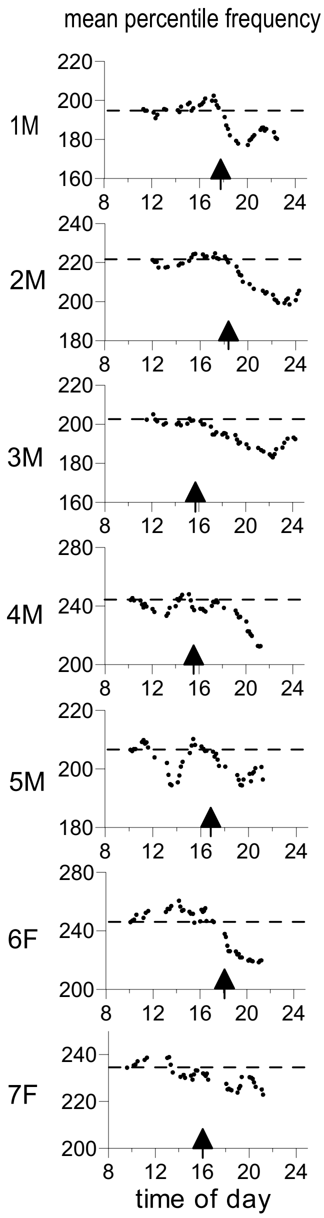

Figure 1: *Running average frequency of EMG spectra (5th-95th percentile) across time of day. M=male; F=female. The arrowheads indicate the time at which spectral estimates definitely shift downwards and remain below starting values. These points are taken to indicate "critical change" in muscle fatigue.[4]*

3. Acoustic signs of laryngeal-muscle fatigue

The subjects of Fig. 1 also produced vocalizations at regular intervals during the test. These voice samples provided a means of exploring possible acoustic correlates of fatigue in laryngeal muscles.

3.1. Procedure and recording conditions

Subjects were instructed to produce normal-pitch [ɑ:] according to a point on a VU display. This visual feedback provided a means of controlling voice intensity. The vocalizations were recorded at 44.1 kHz on a *Tascam* DAT-recorder (model DA-P1, TEAC) using a phantom-powered microphone (AT831b, Audio-Technica) placed at 10-13 cm and 45 degrees from the speakers lips.

3.2. Analysis

The analysis of these recordings focused on 19 parameters as calculated by a widely used software package, *MDVP-Advanced* (version 2.7.0, Kay Elecmetrics). The parameters are listed in Table 1 and represent five categories of measures (for technical definitions, see [7]).

Table 1. Parameters analyzed using *MDVP* (Kay Elem.).

1. Fundamental frequency:		
F0	(Hz)	"Average Fundamental Frequency"
2. Frequency perturbation:		
vF0	(%)	F0 variation
Jita	(s)	Absolute jitter
Jitt	(%)	Jitter percent
RAP	(%)	Relative average perturbation
PPQ	(%)	Pitch perturbation quotient
sPPQ	(%)	Smoothed pitch perturb. quotient
3. Amplitude perturbation:		
vAM	(%)	Amplitude variation
ShdB	(dB)	Shimmer dB
Shim	(%)	Shimmer percent
APQ	(%)	Amplitude perturbation quotient
sAPQ	(%)	Smoothed amplitude perturb. quotient
4. Tremor:		
Fftr	(Hz)	F0 tremor frequency
Fatr	(Hz)	Amplitude tremor frequency
FTRI	(%)	F0 tremor intensity index
ATRI	(%)	Amplitude tremor intensity index
5. Noise:		
NHR	(n)	Noise-to-harmonic ratio
VTI	(n)	Voice turbulence index
SPI	(n)	Soft phonation index

It is important to note that systems such as *MDVP* can present fluctuating results with changes in sample lengths and settings. To reduce these fluctuations, the following settings and procedures were applied throughout the analysis.

1. A constant sample length of 3000 ms was used starting with steady portions of voice waveforms just after the onset burst.
2. For the tremor parameters, the range was set from 1 Hz to 12 Hz; and intensity threshold for tremor was set to 0.
3. For the perturbation parameters, the smoothing factor was set to 50.

4. To ensure a degree of reliability, running averages across seven data points were used in correlation analyses..

3.3. Results

The analyses based on running averages showed that, across subjects, none of the parameters listed in Table 1 presented consistent correlations with the observed spectral estimates of laryngeal-muscle fatigue. However, closer inspection of the tremor parameters (Fatr, Fftr, FTRI, and ATRI) indicated the presence of negative correlations across six of the seven subjects on at least one tremor variable. More importantly, plots of the changes in tremor revealed systematic rises at certain times of the day, which sometimes accompanied changes in F0. Fig. 2 shows the patterns in question with respect to the Fatr parameter, which presented the clearest peaks.

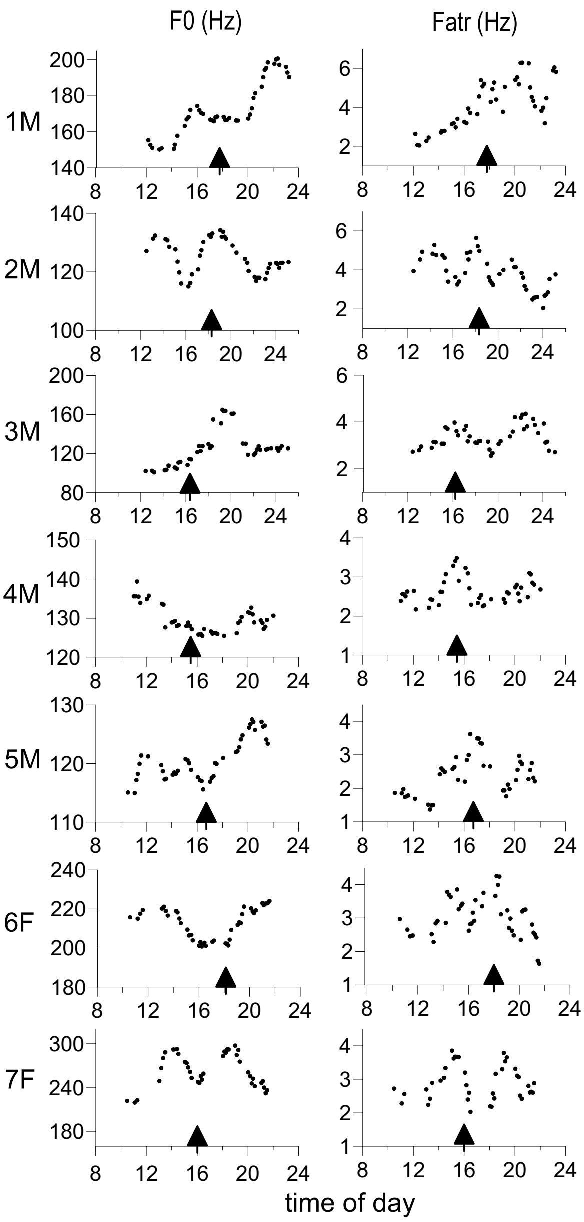

Figure 2: *F0 and Fatr across time of day (running averages). Note that momentary rises in Fatr occur near the points of critical change in muscle fatigue (indicated by the arrowheads on the time axis).*

What is central in Fig. 2 is that, across subjects, peaks in Fatr correspond, within a narrow time frame, to the points of critical change in muscle fatigue (indicated by the arrowheads by reference to Fig. 1). As it appears, changes in muscle fatigue may lead to slight increases tremor at given times of day. However, such rises did not persist and the voices of number of subjects appear to stabilize or return to lower-frequency tremor.

One possible explanation of this stabilization can bear on rising F0 at some point after the tremor peaks, which is particularly evident for some subjects (e.g., 5M and 6F in Fig. 2). This suggests that other muscles such as the cricothyroid muscle (CT) may be used to create added tension by "pulling" on the folds so as to stabilize vocal-fold vibrations. This latter hypothesis was investigated by examining contractions of the LCA and CT muscles in one subject.

4. Compensatory effects

One of the subjects (M1 in Fig. 1) was initially implanted with two sets of electrodes to record potentials of the CT and LCA muscles. This allowed the observation of possible compensatory effects where the CT muscles could serve to stabilize the voice in conditions of induced fatigue. In this case, varying activity of muscles was evaluated by reference to the root-mean-square (RMS) values of recorded potentials.

4.1. EMG recording and subject's task

A monopolar technique was used and the implantation, including the localization of muscles followed the protocol of Hillel.[8] EMG potentials were recorded approximately every 15 minutes over a period of nearly 13 hours during the subject's productions of [ɑː] at a slightly higher than normal pitch (a total of 50 samples was used). As noted above, these vocalizations were semi-controlled for intensity by reference to VU displays. The EMG signals were pre-amplified and band-pass filtered from 3 Hz to 1 kHz using *Grass* P511 amplifiers, and output from the amplifiers was digitized at 5 kHz per channel using a 12-bit acquisition card (model ATMIO16E-10, National Instr.). In the analysis stage, software routines (*Labview 6.01*, National Inst.) were applied to band-pass filter the signals between 5 and 500 Hz (using a 4th order Butterworth function). Software was also used to calculate RMS along with running averages over seven data points.

4.2. Results

In Fig 3, running averages of RMS amplitudes are presented in terms of the gains in activity for CT and LCA muscles relative to the mean value of the first seven RMS values. One can see that, as activity levels tend to decrease in the LCA muscles, those of the CT muscles increase (note also that the vertical line marks the time at which activity in CT leads to a rising F0, as seen in M1 of Fig. 2).

In sum, these observations accord with the principle that, as muscle fatigue sets in, recruitment of additional fibers extending to different muscles is needed to maintain a force output [6]. In the present case, additional tension on the folds exerted by the pulling action of the CT muscles may be used by some subjects to reduce instability or tremor in vocal-fold vibrations, but this would also entail, at some point, rises in F0. Such effects likely explain the results of several reports of rising F0 in conditions of induced vocal fatigue.[9]. However, F0, as seen in Fig. 2, may not as such capture changes in fatigue across subjects. It will also be recalled that, by the aforementioned principle, fatigue in extrinsic muscles, including strap muscles, might only arise in conditions where fatigue is already manifest in intrinsic muscles.

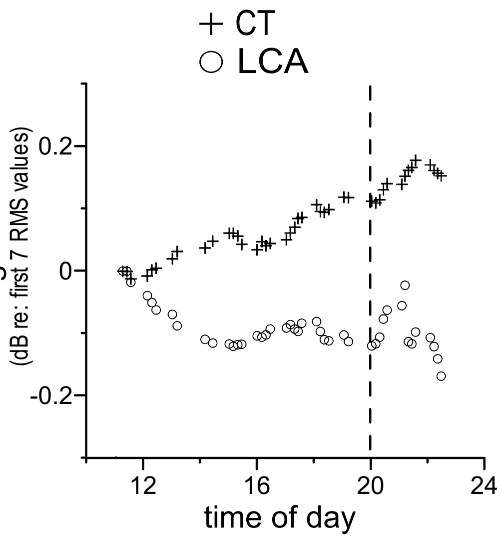

Figure 3: *Gain of CT and LCA m. for M1 across time of day. The vertical slashed line indicates the onset of tendency to raise F0, as seen in M1 of Fig. 2.*

5. Discussion and conclusion

The above results, though preliminary in several respects, offer a perspective on how one might go about defining valid phonometric signs of vocal fatigue and why there has been little progress in this area. Perhaps most important is the fact that fatigue is a physiological condition and progress has been hampered by the lack of a physiological definition of fatigue bearing on the structures of the voicing system [2]. Without this, it is difficult to evaluate the effects of different tasks of vocal effort used to induce fatigue (and which can vary from from 20 minutes [10] to several days [11]) or how subjects' reports of felt fatigue reflect the state of their voice system. Considering this central problem, the present report made use of a measurable sign of fatigue in laryngeal muscles to isolate related changes in voice acoustics. The obtained results illustrate a second basic problem bearing on the failure to consider compensatory effects.

In particular, the above results show that none of 19 conventional acoustic parameters present consistent linear correlations with fatigue in muscles involved in voicing. Instead, non-linear relations appear: critical shifts in muscle fatigue as estimated by the spectral compression of LCA potentials corresponded to a brief rise in voice-tremor parameters. Though the rises did not persist, they were surprisingly consistent given the above test where subjects had widely differing attributes (some were habitual smokers, one was a professional athlete, all had different professions, ages varied from 20 to 50 years), and were not restricted in their usual behaviors (participants drank, ate, and smoked at will during the test). In considering that voice tremor did not necessarily persist, we examined the possible effects of CT muscles in stabilizing the voice as suggested by reports of rising F0 for some individuals in tasks of vocal effort (see [9] among others). The results showed that, as activity levels in LCA muscles tended to decrease, activity in CT muscles increased and, at one point, this increase led to a rise in F0 for the subject. This agrees with frequent suggestions that F0 rises (or the actions of muscles contributing to F0) can serve to stabilize the voice, which can explain the non-persistent aspect of voice tremor. Such compensatory behavior implies that seeking an acoustic sign that could evaluate voice fatigue non-invasively might not proceed by simple comparisons of parameter values and normative scales. Currently, a number of voice-analysis systems adopt such an approach (e.g. *MDVP*). However, the above data of Fig. 2 show that voices bear an inherent tremor and that only a relative rise may correspond to critical changes in fatigue of laryngeal structures. Furthermore, repeated observations of individual rises in F0 in fatigue-inducing conditions make it clear that speakers may use different structures to stabilize voice tremor. Current systems are simply not adapted to capturing such compensatory changes that relate to fatigue.

6. References

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