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Objective Assessment of the Effects of Semi-Occluded Vocal-Tract Techniques on Vocal Performance

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ABSTRACT

Semi-Occluded Vocal Tract Exercises (SOVTE), which are based on the increase of the vocal tract impedance through the semi-occlusion of the mouth, are mainly used by speakers and singers, but their use is increasing also in voice therapy. The device VocalFeel®, which is made up of a facemask, a humidifier-filter with a unidirectional valve and a bubble equipment, combines the benefits of SOVTE with the surface hydration of the vocal folds. In this paper, preliminary results are provided that refer to tests performed by 13 Italian singers, which were equipped with a contact microphone and a microphone in air. A first objective assessment of the effects of SOVTE on the vocal performance has been made through the estimation of acoustic parameters extracted from the recorded vocal signals and the comparison of these parameters before and after the SOVTE. The main outcomes are an increase of the energy in the medium frequency-range (from 1 kHz to 4 kHz), the Singing Power Ratio and the Cepstral Peak Prominence Smoothed. Furthermore, an increase in the voice-production efficiency has been estimated by comparing the intensities of the signal in air to the signal at the output of the contact microphone.

Keywords: Voice analysis, Semi-Occluded Vocal Tract Exercises, Singing Power Ratio

1. INTRODUCTION

Semi occluded vocal tract exercises (SOVTE) are widely used in the fields of voice therapy and didactics, aiming at improving vocal economy and efficiency. The rationale and theoretical underpinnings for SOVTE have been described by Titze (1). SOVTE promote an increase in vocal tract impedance, resulting in changes in the inertive reactance (2-6), with favorable effects on voice production due to a reduction of phonation threshold pressure (5, 7) and an increase of skewing of the glottal flow waveform (faster cessation of the glottal flow) (4,5). The increasing vocal tract impedance can affect the glottal function through acoustic-aerodynamic interactions and mechanic-acoustic interactions (2, 8, 9).

Many different SOVTE exist and have been described so far. The common feature of these exercises is the reduction of the cross-sectional area of the vocal tract at or near the lips. Some of the most known SOVTE are represented by lip and tongue trills (10), humming (11), hand-over-mouth (12), resonance tubes (13), flow resistant straws (14) and LaxVox (15).

Andrade et al. (16) have recently studied various types of SOVTE by acoustic and

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electroglottographic (EGG) analysis. According to their results, SOVTE could be classified into two groups basing on their physiology: steady exercises (hand-over-mouth, humming and straw) and fluctuating exercises (tongue-trill, lip-trill and Lax Vox). Steady exercises, which show steady EGG contact quotient (CQ) and fundamental frequency (F0), seem to promote an easier phonation. Fluctuating exercises, which instead show fluctuating CQ and F0, make use of a secondary vibrating source, thus obtaining a "massage effect" on the vocal tract and a proprioceptive feedback. In addition to this classification, the cited study shows the benefits of mixing steady and fluctuating SOVTE, obtaining a massage effect as well as an easier phonation.

Various techniques have been used to investigate the effects of these vocal exercises, such as acoustic analysis (17-22) and EGG (23-28). Other studies have been carried out performing aerodynamic, electromyographic, radiological or endoscopic analysis (29-36).

The use of ventilation masks for SOVTE has been first proposed by Borragan A.T. (Centro de Foniatria y Logopedia, Santander) in order to perform both steady exercises and combined steady-fluctuating exercises. Preliminary studies aimed at investigating the effects of SOVTE performed with a ventilation mask have shown positive effects in terms of self-assessment, acoustic and perceptual voice quality, both in healthy singers and dysphonic subjects (37, 38).

This paper deals with the effects of SOVTE performed with a new device (VocalFeel®), which combines the benefits of SOVTE with the vocal fold hydration. An experimental campaign has started to objectively assess the immediate effects of such an equipment on the vocal performance of singers. The objective assessment is based on the estimation of acoustic parameters of the recorded vocal signal of singers, which are equipped with a contact microphone and a microphone in air. The former allows the signal related to the vocal-folds vibration to be sensed, while the latter is used to acquire the signal at the output of the mouth.

In the following sections, method and material for data collection are described and the estimated acoustic parameters are defined. Then, the preliminary results that refer to a set of 13 singers are reported and, eventually, the final comments are provided.

2. METHOD AND MATERIAL

2.1 Equipment

The subjects that have been involved in this study have used a device named VocalFeel®, which combines the benefits of SOVTE with the vocal fold hydration. It is made up of a facemask, a humidifier-filter with a unidirectional valve and a bubble equipment and allows the execution of both steady and fluctuating impedance techniques. The results reported in this paper only refer to the immediate effects of SOVTE that are based on static impedance.

The vocal signals of the subjects that have participated to the experiment have been simultaneously recorder with a contact microphone and a microphone in air. The latter is maintained to a fixed distance (about 1 m) from the mouth of the involved subjects.

The contact microphone is a piezoelectric sensitive element that is embedded in a flexible necklace and is connected to the device Vocal Holter® Med. This device records and pre-processes the signal at the output of the contact microphone, which is mainly sensitive to the vocal-folds vibration and is not affected by the pressure in air. The signal is acquired using a sample rate of 22050 Sa/s and converted into digital samples with 16 bit of resolution.

The microphone in air, which allows the vocal signal at 1 m from the subject mouth to be sensed, is the model M2211 from NTi AUDIO. The microphone is connected to the input of an audio board (MOTU model Audio Express), which is configured with a sample rate of 44100 Sa/s and 16 bit of resolution.

All the experiments were performed in the anechoic chamber of the Department of Energy at Politecnico di Torino. The chamber has a volume of about 45 m^3 and its noise floor is of 25 dBA.

The Figure 1 shows one of the singer that participated to the experiment while performing the SOVTE inside the anechoic chamber. In the same figure, the contact microphone and the microphone in air are visible and a detail of the used facemask is shown in the right-side of the picture.

Figure 1 – One of the singer inside the anechoic chamber: the picture refers to the exercises performed with VocalFeel® (a detail of the facemask is shown in the right-side of the picture).

2.2 Subjects

In the first part of the experimental campaign, 13 trained Italian contemporary commercial singers (8 males and 5 females, average age 29 years, standard deviation 11 years) with no voice complaints have participated to this study. After a preliminary warm-up, each subject has performed the following protocol inside the anechoic chamber, while wearing the necklace that embeds the piezoelectric contact microphone (see Figure 1):

1) singing twice a part of a song at comfortable intensity and tonality for a time interval of about 30 s remaining in front of the microphone in air at a distance of about 1m;
2) performing the SOVTE using the facemask in static-impedance condition (see Figure 1); each subject has been asked to sustain as long as possible the five vowels /a/, /e/, /i/, /o/, /u/; then he/she had to perform a glissando from the lowest to the highest frequency for each of the five vowels; eventually, each subject has been asked to sing the same song of the step 1) while wearing the facemask;
3) repetition of the step 1) in the same nominal conditions.

The whole procedure required a time interval of about 20 min for each subject.

2.3 Acoustic parameters

The vocal tracks acquired during the steps 1) and 3) described in the previous section have been processed in order to estimate the parameters of interest. Apart from a down-sampling to 22050 Sa/s of the signal at the output of the microphone in air, the same processing algorithms have been used for the signals at the output of both microphones.

Initially, the available samples have been grouped in 1024-point frames (about 46 ms frame-length) for the estimation of cepstral parameters, and in 4096-point frames (about 186 ms frame-length) for the other parameters. The root mean square value (RMS_{frame}), the harmonic-to-noise ratio (HNR_{frame}) and the fundamental frequency ($F0_{\text{frame}}$) of each frame have been estimated and a classification in valid or non-valid frames have been performed according to the following rule:

$$\begin{aligned}&\textbf{IF}\left[\left(RMS_{\text{frame}} > \frac{RMS_{\text{aver}}}{2}\right)\text{AND}\left(HNR_{\text{frame}} > 0\text{ dB}\right)\text{AND}\left(\frac{\left|F0_{\text{frame}} - F0_{\text{frame-1}}\right|}{F0_{\text{frame-1}}} < 0.5\right)\right] \Rightarrow \text{valid frame}\\ &\textbf{ELSE}\text{ non - valid frame}\end{aligned} \tag{1}$$

where RMS_{aver} is the mean value of the parameter RMS_{frame} along the whole recording.

The 4096-point valid frames have been processed according to a FFT algorithm using a Hamming weighting window in order to minimize the effects of non-coherent sampling. Then, the following parameters have been estimated from the amplitude of each obtained spectrum in order to describe the energy spectral distribution:

- ✓ $E_{\text{B2-1}} = |E_2 - E_1|$ (dB): absolute value of the difference between the energy E_2 in the band B_2 (from 1 kHz to 4 kHz) and the energy E_1 in the band B_1 (from 10 Hz to 1 kHz);

- $E_{B3\text{-}1} = |E_3 - E_1|$ (dB): absolute value of the difference between the energy E_3 in the band B_3 (from 4 kHz to 9 kHz) and the energy E_1 in the band B_1 (from 10 Hz to 1 kHz);
- Singing Power Ratio (*SPR*, dB): absolute value of the difference between the peak value in the band from 2 kHz to 4 kHz and the peak value in the band from 10 Hz to 2 kHz.

For each recording, the mean values of the three parameters have been obtained and the experimental standard deviations of the mean values have been estimated as a measure of the intra-subject reproducibility:

$$\overline{E_{\mathrm{B2,1}}} = \frac{1}{N}\sum_{i=1}^{N} E_{\mathrm{B2,1i}};\ \overline{E_{\mathrm{B3,1}}} = \frac{1}{N}\sum_{i=1}^{N} E_{\mathrm{B3,1i}};\ \overline{SPR} = \frac{1}{N}\sum_{i=1}^{N} SPR_{\mathrm{i}};\ s\left(\overline{E_{\mathrm{B2,1}}}\right) = \frac{\sigma\left(E_{\mathrm{B2,1i}}\right)}{\sqrt{N}};\ s\left(\overline{E_{\mathrm{B3,1}}}\right) = \frac{\sigma\left(E_{\mathrm{B3,1i}}\right)}{\sqrt{N}};\ s\left(\overline{SPR}\right) = \frac{\sigma\left(SPR_{\mathrm{i}}\right)}{\sqrt{N}} \qquad (2)$$

where N is the number of valid frames for each available track.

An example of spectrum amplitude for a male singer is shown in Figure 2, where the subdivision in the bands B_1, B_2 and B_3 is highlighted and the energy values in the three bands are reported. Figure 3 shows instead another spectrum amplitude and highlights the definition of the parameter *SPR*.

The Sound Pressure Level (SPL_{air}, dB) at 1 m from the subject has been estimated by the signal at the output of the measuring chain based on the microphone in air. Such a measuring chain has been previously calibrated using a reference tone at 1 kHz with an *SPL* value of 94 dB in order to obtain traceable measurements. The intensity has been also estimated for the signal at the output of the contact microphone (SPL_{con}), even though it is expressed in an arbitrary measuring unit, hereafter referred as $\mathrm{dB_{arb}}$, since the calibration of this measuring chain is not performed. However, each subject maintained the contact microphone in the same position during the whole experiment and the measuring chain did not suffer from important drift in the time-interval required to complete the described protocol, thus making meaningful the comparison between the intensity estimated before and after the exercises performed with the facemask. Also for these parameters, the mean values and the experimental standard deviation of the mean values are estimated for each of the available track.

The valid frames are also processed in order to estimate the parameter Cepstral Peak Prominence Smoothed (*CPPS*) according to the following procedure (39,40):

- for each 1024-point (46 ms) frame, the Fast Fourier Transform algorithm is implemented twice to obtain the cepstrum;
- a two-step smoothing procedure is performed: a time smoothing cepstra is obtained along a time-window of 14 ms (seven shifts of 2 ms), then the smoothing of the cepstra magnitude is performed in the cepstral domain across quefrency using a seven-bin window;
- a regression line is estimated on the smoothed cepstrum in the quefrency versus cepstral magnitude domain excluding the first millisecond;
- the parameter *CPPS* is obtained as the difference (dB) between the peak in the cepstrum and the value of the regression line at the peak quefrency.

This processing algorithm has been implemented for each available recording, thus obtaining a *CPPS* histogram, which is represented by means of nine descriptive statistics: mean ($CPPS_{\mathrm{mean}}$), median ($CPPS_{\mathrm{median}}$), mode ($CPPS_{\mathrm{mode}}$), fifth percentile ($CPPS_{\mathrm{5prc}}$), and 95th percentile ($CPPS_{\mathrm{95prc}}$), standard deviation ($CPPS_{\mathrm{std}}$), interval between the maximum and the minimum value ($CPPS_{\mathrm{range}}$), kurtosis ($CPPS_{\mathrm{kurt}}$) and skewness ($CPPS_{\mathrm{skew}}$).

3. RESULTS

The immediate effects of SOVTE have been estimated comparing the parameters extracted from the available recordings before and after the exercises performed using the device VocalFeel®. The effects on the quality of the singer's voice have been investigated through the parameters that are related to the energy spectral distribution, i.e. $E_{\mathrm{B2,1}}$, $E_{\mathrm{B3,1}}$ and *SPR*, and through the parameter *CPPS*. The effect in terms of "efficiency" in the voice production has been instead investigated using parameters related to the signal intensity, i.e. SPL_{air} and SPL_{con}.

3.1 Voice quality

The immediate effects on the voice quality have been estimated in the same way for the microphone in air and for the contact microphone through the difference of the parameters $\overline{E_{B2,1}}$, $\overline{E_{B3,1}}$ and $\overline{SPR}$:

$$\Delta E_{\mathrm{B2,1}} = \overline{E_{\mathrm{B2,1\_A}}} - \overline{E_{\mathrm{B2,1\_B}}};\quad \Delta E_{\mathrm{B3,1}} = \overline{E_{\mathrm{B3,1\_A}}} - \overline{E_{\mathrm{B3,1\_B}}};\quad \Delta SPR = \overline{SPR_{\mathrm{A}}} - \overline{SPR_{\mathrm{B}}} \qquad (3)$$

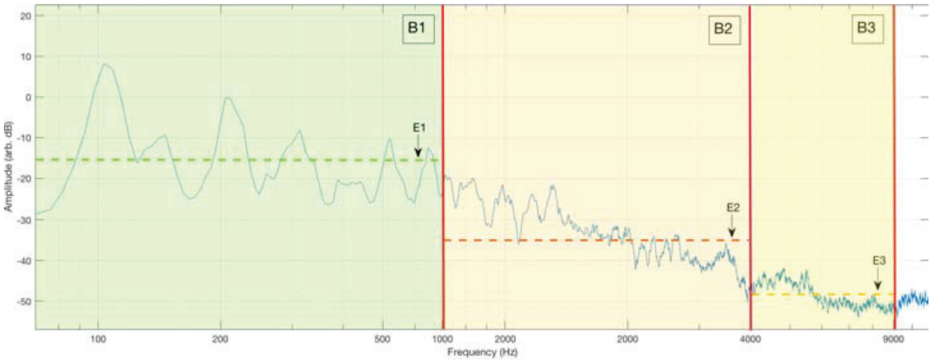

Figure 2 – Spectrum amplitude and indication of the energy values in the bands B_1, B_2 and B_3.

where the suffix A and B identify the values after and before the SOVTE, respectively.

According to the given definitions, a negative value of the parameters of expressions (3) highlights an increase of the energy in the medium-high part of the spectrum, which in the singing voice is interpreted as an improvement of the resonance quality. As an example of results, the Figure 4 shows the parameters $\Delta E_{\mathrm{B2,1}}$ and ΔSPR that have been obtained processing the signal at the output of the microphone in air. The bars of each subject, which represent the experimental standard deviations, highlight a good intra-subject reproducibility. For 8 out of 13 subjects, an increase in the parameter $\Delta E_{\mathrm{B2,1}}$ has been observed, while the parameter ΔSPR shows an increase for 10 out of 13 subjects.

A summary of the results obtained for the group of the involved subjects is reported in the Table 1 for the microphone in air and for the contact microphone. For each parameter, the mean value of the group and the experimental standard deviation of the mean are reported. For the microphone in air, the most significant improvement has been obtained for the parameters ΔSPR (mean value of – 1.5 dB and standard deviation of 0.6 dB) and $\Delta E_{\mathrm{B2,1}}$ (mean value of – 0.8 dB and standard deviation of 0.4 dB), while the parameter $\Delta E_{\mathrm{B3,1}}$ does not show significant changes. The same outcomes have been obtained for the contact microphone, with the parameters ΔSPR and $\Delta E_{\mathrm{B2,1}}$ that are equal to -4.0 dB and –1.8 dB, respectively, and standard deviations of 1.3 dB and 0.7 dB, respectively.

For the descriptive statistics of the *CPPS* distribution, the differences between the values obtained after and before the SOVTE have been also estimated and the obtained results, which only refer to the microphone in air, are summarized in the Table 2. One should note that a moderate increase of the parameters that measure the location of the distribution (mean, median, 5th and 95th percentiles) can be considered significant, while the parameters related to the dispersion and to the distribution shape have not shown significant changes. The increase of the $CPPS_{\mathrm{mean}}$ (mean value of the group equals to + 0.4 dB and standard deviation of 0.2 dB) represents a markers of improvement of the voice quality, since high values of *CPPS* corresponds to vocal signals characterized by a good regularity of the harmonic components and a high energy of these components with respect to the non-harmonic components.

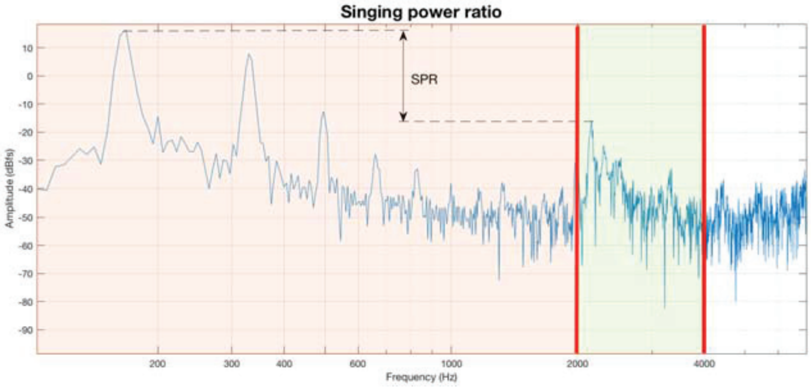

Figure 3 – Another example of spectrum amplitude with the definition of the parameter *SPR*.

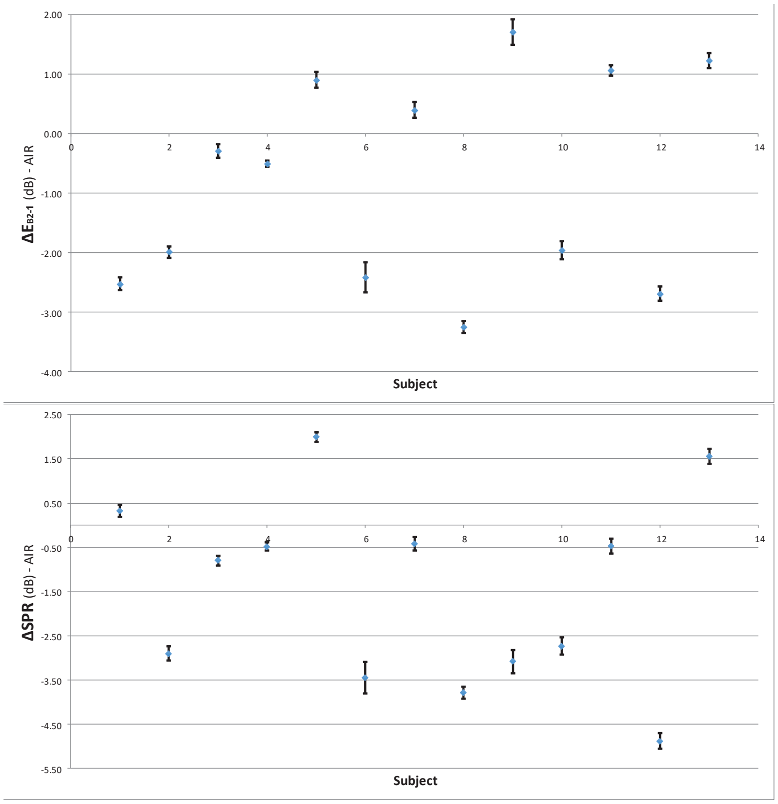

Figure 4 – The parameters $\Delta E_{\mathrm{B2,1}}$ and ΔSPR of the 13 involved subjects estimated from the microphone in air.

Table 1 – Mean value and experimental standard deviation of the mean of the parameters $\Delta E_{\mathrm{B2,1}}$, $\Delta E_{\mathrm{B3,1}}$ and ΔSPR for the group of 13 Italian singers involved in the experiment.

Microphone in air					
$\overline{\Delta E_{B2,1}}$	$s\left(\overline{\Delta E_{B2,1}}\right)$	$\overline{\Delta E_{B3,1}}$	$s\left(\overline{\Delta E_{B3,1}}\right)$	$\overline{\Delta SPR}$	$s\left(\overline{\Delta SPR}\right)$
-0.8 dB	0.4 dB	-0.4 dB	0.4 dB	-1.5 dB	0.6 dB

Contact microphone					
$\overline{\Delta E_{B2,1}}$	$s\left(\overline{\Delta E_{B2,1}}\right)$	$\overline{\Delta E_{B3,1}}$	$s\left(\overline{\Delta E_{B3,1}}\right)$	$\overline{\Delta SPR}$	$s\left(\overline{\Delta SPR}\right)$
-1.8 dB	0.7 dB	-0.3 dB	0.6 dB	-4.0 dB	1.3 dB

Table 2 – Mean value and experimental standard deviation of the mean of the descriptive statistics of the *CPPS* distribution for the group of 13 Italian singers involved in the experiment.

Microphone in air								
Parameter	$\Delta CPPS_{\mathrm{mean}}$	$\Delta CPPS_{\mathrm{median}}$	$\Delta CPPS_{\mathrm{std}}$	$\Delta CPPS_{\mathrm{range}}$	$\Delta CPPS_{\mathrm{5prc}}$	$\Delta CPPS_{\mathrm{95prc}}$	$\Delta CPPS_{\mathrm{skew}}$	$\Delta CPPS_{\mathrm{kurt}}$
mean value	0.4 dB	0.4 dB	-0.02 dB	0.1 dB	0.4 dB	0.3 dB	-0.02 dB	0.1 dB
exp. std. dev.	0.2 dB	0.3 dB	0.05 dB	0.3 dB	0.3 dB	0.2 dB	0.07 dB	0.1 dB

3.2 Voice efficiency

A first estimation of the efficiency increase in the voice production has been obtained comparing the mean value of the parameters SPL_{air} and SPL_{con} before and after the execution of the SOVTE. One should note that the mere differences between these parameters could be considered questionable, since they could be related to the subject's willingness to increase the intensity of his/her voice. In order to obtain an evaluation of the vocal production efficiency that is free from the will of the subjects, the parameter $\Delta SPL_{\mathrm{rel}}$ is defined:

$$\Delta SPL_{\mathrm{rel}} = \Delta SPL_{\mathrm{air}} - \Delta SPL_{\mathrm{con}}; \quad \Delta SPL_{\mathrm{air}} = \overline{SPL_{\mathrm{air,A}}} - \overline{SPL_{\mathrm{air,B}}}; \quad \Delta SPL_{\mathrm{con}} = \overline{SPL_{\mathrm{con,A}}} - \overline{SPL_{\mathrm{con,B}}}; \tag{4}$$

that compares the increase of the voice intensity in air after the SOVTE to the same increase obtained from the contact microphone. The estimated value of the parameter $\Delta SPL_{\mathrm{rel}}$ is +0.6 dB (mean value of the group of 13 subjects; standard deviation 0.4 dB), thus showing a significant increase in the voice-production efficiency after the use of the facemask. This outcome highlights that higher values of SPL_{air} are obtained for lower values of SPL_{con}, that means that higher voice intensity are obtained with lower or same vocal effort.

4. CONCLUSIONS

An experimental campaign has been started in order to objectively assess the effects of Semi-Occluded Vocal Tract Exercises performed by means of a new device, which combines the benefits of SOVTE with the vocal folds surface hydration. The vocal signal before and after the execution of the SOVTE has been simultaneously acquired with a microphone in air and a contact microphone and the parameters of interest have been estimated for both microphones. Preliminary results, which have been provided for a set of 13 trained Italian contemporary commercial singers, highlight that the parameters related to the energy spectral distribution are good markers of the voice-quality improvement, as well as the parameter *CPPS*, which shows a moderate improvement. In addition, an increase of the efficiency in the voice production has been found by comparing the intensity of the vocal signal in air to the intensity of the signal at the output of the contact microphone, thus indicating that higher voice intensity can be obtained with a lower vocal effort thanks to the SOVTE. With the aim of validating these preliminary results, which only refer to the immediate effects of static-impedance based exercises, the authors are recruiting other singers in order to enlarge the data set. Furthermore, the effects of fluctuating exercises and medium-term effects will be investigated through experiments that will involve other subjects.

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