Title: Flow ball-assisted voice training: immediate effects on vocal fold contacting

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ABSTRACT

Objective: Effects of exercises using a tool that promotes a semi-occluded artificially elongated vocal tract with real-time visual feedback of airflow – the flow ball - were tested using voice maps of EGG time-domain metrics.

Methods: Ten classically trained singers (5 males and 5 females) were asked to sing *messa di voce* exercises on eight scale tones, performed in three consecutive conditions: baseline (‘before’), flow ball phonation (‘during’), and again without the flow ball (‘after’). These conditions were repeated eight times in a row: one scale tone at a time, on an ascending whole tone scale. Audio and electroglotographic signals were recorded using a Laryngograph microprocessor. Vocal fold contacting was assessed using three time-domain metrics of the EGG waveform using FonaDyn. The quotient of contact by integration, Q_{ci} , the normalized peak derivative, Q_{Δ} , and the index of contacting I_c , were quantified and compared between ‘before’ and ‘after’ conditions.

Results: Effects of flow ball exercises depended on singer’s habitual phonatory behaviours and on the position in the voice range. As computed over the entire range of the task, Q_{ci} was reduced by about 2% in five of ten singers. Q_{Δ} was 2-6% lower in six of the singers, and 3-4% higher only in the two bass-baritones. I_c decreased by almost 4% in all singers.

Conclusion: Overall, vocal adduction was reduced and a more gentler vocal fold collision was observed for the ‘after’ conditions.

Significance: Flow ball exercises may contribute to the modification of phonatory behaviours of vocal pressedness.

Keywords: Flow ball; Semi-occluded vocal tract; Vocal fold contacting; FonaDyn

1. INTRODUCTION

Exercises using a semi-occluded vocal tract (SOVTEs), i.e., with the vocal tract closed or constricted at one end (Titze, 2006), have been commonly used in voice pedagogy and rehabilitation (Berry, 1975; Linklater, 1976; Carroll & Sataloff, 1991; Habermann, 1980; Sovijàrvi, 1966; Aderhold, E., 1963; Coffin, 1987; Westerman, 1990, 1996; Verdolini et al., 1995, 1998; Nix, 1999; Laukkanen, 1992, Titze, 2002). Examples of this type of exercises can be found in the literature as early as 1927. Previous reports state that, for example, a narrowing of the mouth by the tongue tip and the alveolar ridge (Engle, 1927) or phonating while holding a hand over the lips (Aderhold, 1963), or while using a tight linguopalatal constriction narrowing the space between the upper and the lower teeth with a close front vowel (Lessac, 1967), result in a more resonant voice. Using ‘lip trills’, ‘tongue trills’, ‘raspberries’ and exercises with voiced bilabial fricatives have been reported to promote more efficient phonation (Nix, 1999; Laukkanen, 1992). In addition, artificially lengthening and constricting of the vocal tract have early been reported to have therapeutic effects on the voice (Spielβ, 1899). Phonating into tubes with the free end in water (Sovijärvi, 1964; Laukkanen et al., 1995) or into narrow tubes with the free end in air (Titze, 2006) increases the static back pressure (P_{back}) in the vocal tract to a point that it alters its acoustic impedance so that it matches the one in the glottis (Titze & Story, 1997). It has been claimed that this matching impedance feeds energy back to the glottis through the in-phase velocity created between supraglottal pressure and airflow (Laukkanen et al., 1996; Titze, 2006). A consequence would be a lowering of the first formant frequency (f_{R1}) with an increased input impedance in the range of the fundamental frequency (f_o) (Story et al., 2000). Such an effect accounts for a lowering of the phonation threshold pressure and average airflow, two key components when reducing vocal effort (Story et al., 2000) and producing vocal economy, i.e., the production of high sound level with low vocal loading (Titze et al., 1997). For example, Titze and associates (2002) found that the use of resistance straws when singing high pitches at high lung volumes would reduce the risk for trauma to the vocal folds. This effect could be because the aerodynamic effects of phonating into flow resistance tubes in decreasing the amplitude of vibration of the vocal folds (Titze et al., 2002). The result would then be a voice quality that is ideal from a physiological point of view, i.e., neither pressed nor breathy (Peterson et al., 1994; Verdolini et al., 1998).

A number of previous investigations have been concerned with impacts of different types of SOVTEs on voice production, as the physiology and implementation of these exercises can be quite distinct (i.e., frontal constriction, lengthening of the vocal tract, and creation of a second source of vibration) (Andrade et al., 2013). In fact, the degree of vocal tract occlusion seems to impact differently on airflow resistance: the higher the narrowing and lengthening of the vocal tract, the higher the resistance (Dargin & Searl, 2014). In addition, depending on whether or not there is a single source or a dual source of vibration into the vocal tract (i.e., the vocal folds alone or the vocal folds and the changes introduced into the intraoral pressure, respectively), SOVTEs can promote different effects on the acoustic properties of the vocal tract, measured as the difference between the first formant and the fundamental frequency (hence, f_{R1} - f_o difference). Exercises using hand-over-mouth, humming, and a flow resistance straw have been found to reduce f_{R1} - f_o difference, whereas those performed using tongue-trills, lip-trills, and LaxVox tubes were found to increase the difference f_{R1} - f_o . The first group of exercises were found to promote greater ease of phonation as compared to the second one (Andrade et al., 2013). More than tube length, different tube diameters and submerging depths of tubes in water result in different relationships between back pressure (P_{back}) and flow (U). For phonation in tubes submerged in water, the water depth determines an almost constant P_{back} as soon as U starts (when P_{back} overcomes the pressure corresponding to the water depth), whereas for narrow tubes in air, airflow changes produce relatively large changes in P_{back}. Such differences should be taken into consideration when implementing SOVTEs in voice pedagogy and therapy (Andrade et al., 2016).

Following the same line of thought, a study was carried out to investigate the P_{back} to U relationships of a new device applied to SOVTEs, the flow ball. Besides semi-occluding and artificially elongating the vocal tract, the lifting of the polystyrene ball that comes with this device provides real-time visual feedback of airflow during phonation. The P_{back} vs. U relationship resulting from this device was found to be similar to that of a straw of 3.7 mm diameter and 31 mm in length (Lã et al., 2017). Given this result, one may hypothesize that SOVTEs using a FB can promote effects similar to those of using straws.

Previous investigations have suggested a reduced vocal effort after SOVTEs with resistance straws. Given the positive association between the degree of vocal fold impact stress and contact quotient (CQ_{EGG}): the higher the CQ_{EGG}, the higher the impact stress (Verdolini et al., 1998), it seems appropriate to investigate the immediate effects of SOVTEs using the FB.

Few studies describe the effects of different SOVTEs on vocal folds' vibratory modes analysed by means of electroglottography (EGG) (Herbst, 2019); their results are not conclusive concerning the effects of SOVTEs on CQ_{EGG} . A single-subject evaluation of the effects of resonant tube phonation and straw phonation demonstrated a decrease in CQ_{EGG} after the exercise; and more so for the straw than for the tube (Guzman *et al.*, 2013). The difference between maximum and minimum CQ_{EGG} for the same token of sustained vowels, contact range (CQ_{r}), was compared between pre and post SOVTEs using narrow resistance straws. The CQ_{r} exhibited no statistical differences (Andrade et al., 2013). However, when using a dual source of vibration (e.g., lip-trills, tongue-trills, or water bubbling), a larger CQ_{r} was found in the post conditions. This result was attributed to a massage effect caused by changes in the intraoral pressure (Andrade et al., 2013). Later studies found effects of SOVTEs on CQ_{EGG} to be dependent on individuals, regardless of type of SOVTEs or device used to artificially elongate the vocal tract (Dargin & Searl, 2015). Another investigation comparing 8 SOVTEs for their effects on CQ_{EGG} in healthy and pathological voices, showed significant differences only when comparing the conditions 'before' to 'during', or 'during' to 'after' (Guzman et al., 2015). The straws used were 5 mm in diameter and 258 mm long, submerged 30 or 100 mm in water. No significant differences were found when comparing CQ_{EGG} 'before' and 'after' the SOVTEs. The differences found depended on the type of SOVTEs and on the presence of vocal pathology. For the healthy group of participants, CQ_{EGG} changed significantly between 'before', 'during' and 'after' for SOVTEs practiced with narrow straws in water and with hand-over-mouth technique. Exercises using resistant straws, lip trills, tongue trills and sustained consonant /m/ resulted in a lower CQ_{EGG} for the 'after' condition. The remaining SOVTEs demonstrated the opposite effect, i.e., an increase in CQ_{EGG} 'after'. For the group of pathological voices, CQ_{EGG} was higher after SOVTEs, for all types of exercises and tools used (Guzman et al., 2015).

The present study aims at further assessing the effects of SOVTEs on the vibratory patterns of the vocal folds, testing a new device that artificially elongates the vocal tract while providing real-time visual feedback of airflow during phonation: the flow ball. The assessment was done by creating and evaluating voice maps of EGG metrics, using a recent software tool, *FonaDyn* (Ternström et al., 2018a).

The rationale for using the flow ball (Figure 1) as a pedagogical tool is to help the student to develop a proprioceptive awareness of a high flow phonation. To achieve such goal, exercises are necessary with a flow that is more extreme than habitual. For example, phonating with a ball height of 10 cm will require flows of 0.4 L/s (Lã et al., 2017). The aim is not to teach singing with breathy phonation, but rather to increase the student's awareness of what glottal posturing is needed in order to achieve an optimal pressure to flow ratio with a complete vocal closure.

Figure 1. The flow-ball device used for the study (www.powerbreathe.com). A 140 mm long tube with a rectangular cross section of 7 by 10 mm. A basket with a narrow, upward facing opening of 3.9 mm diameter 12 mm is attached to the tube. The device was supplied with a polystyrene ball of Ø 29 mm.

2. METHODS

2.1. Participants and study design

Ten classically trained singers (5 males and 5 females, mean age 27.5 years, range 23 to 37), all post-graduate students at the University of Aveiro, Portugal, volunteered to participate (Table 1). All participants were students of the same teacher (author F.L.) at a university singing programme. They had all been practising singing exercises with phonating into straws and/or tubes of several diameters, submerged in water or not, as dictated by individual needs. However, they had not previously used the flow-ball device. The aim of the present study was to assess the immediate short-term effect of the device, before possibly embarking on a training programme. Such assessment would provide a first understanding of potential benefits of the tool. Prior to making the recording, participants signed a consent form, complying with each requirement of all applicable data protection and privacy laws. The participants were asked to sing *messa di voce* exercises, that is, sustaining a note from soft to loud and back to soft, on eight scale tones, with a total duration of about 15 seconds for each tone. The tones were chosen to match the voice category for both male and female participants.

Table 1. Scale tones sung as *messa di voce* by all participants.

Participants	Voice category	Tones
S6-S10	Soprano	F4; G4; A4; B4; D#5; D#5; F5
S3-S5	Tenor	F3; G3; A3; B3; D#4; D#4; F4
S1, S2	Bass-Baritone	A2; B2; C#3; D#3; F3; G3; A3; B3; C#4; D#4

The task was performed in three consecutive conditions: baseline (‘before’), flow ball phonation (‘during’), and again without the flow ball (‘after’). This triplet was repeated eight times in direct succession, on one scale tone at a time, on an ascending whole tone scale. All exercises were performed standing. As an example, the resulting recording for one subject is illustrated in Figure 2. Note how the EGG waveshape in this example changes considerably from ‘before’ to ‘during’. This was typically the case, and it demonstrates that the use of the flow ball is affecting the vibratory behaviour of the vocal folds, whether directly through acoustic interaction, and/or indirectly through changes in laryngeal posturing. However, we avoid all quantitative assessment of the EGG waveshape in the ‘during’ condition, since (1) the SPL with the flow ball cannot be matched to the SPL without the flow ball, and (2) other methods such as MRI would be needed to track changes in laryngeal posturing.

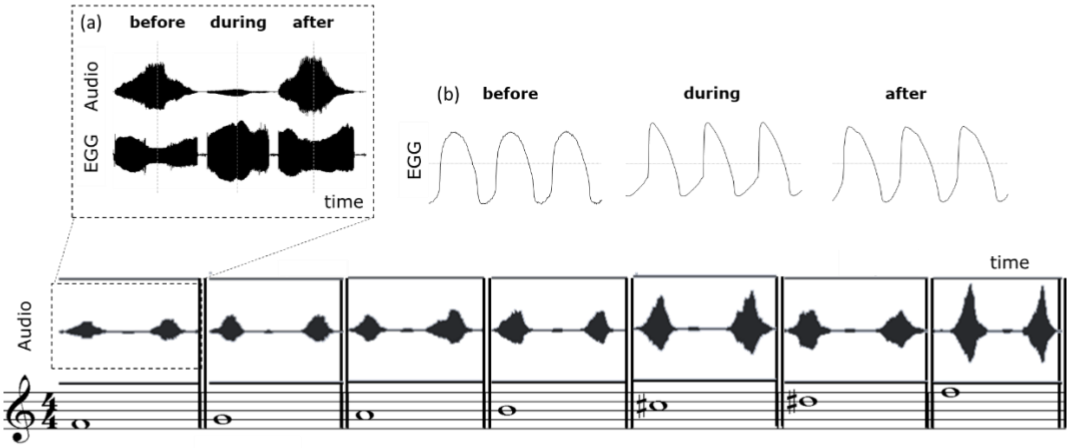

Figure 2. Example of the exercises sung in *messa di voce* for S02, a low voice male singer. The left magnified inset shows one instance of the ‘before’, ‘during’ and ‘after’ conditions. The right magnified inset shows examples of the corresponding EGG waveforms at maximum voice effort, in the three conditions.

For the exercise using the flow ball (‘during’ condition), the following instructions were given, based on SOVTE protocols from previous literature:

- keep your head straight, avoiding a forward head and neck position
- maintain a neutral tongue position with the tip touching the front lower teeth while performing the exercise
- avoid leakage at the lips while phonating into the device
- maintain the ball in the air (off the basket) and increase/ decrease its height following the sound intensity
- awareness should be on airflow rather than on sound quality

For the ‘after’ condition, participants were asked to try to retain the same kinaesthetic sensations of vocal tract shape and airflow as in the ‘during’ condition.

In Figure 2, we note in passing how the EGG amplitude happens to decrease with increasing voice intensity, *except* in the ‘during’ condition. Such a decrease could be due for instance to a change in the vertical position of the larynx, moving the vocal folds away from the EGG electrodes. Because such confounding variations due to a changing electrical path are well known to exist, the EGG metrics used here (Ternström, 2019) are designed to completely disregard the EGG amplitude. The EGG amplitude does not enter into the present analyses; it is only the *shape* of the normalized EGG pulse that is considered.

The two-channel voice and EGG signal files were edited manually using a signal editor (Soundswell Workstation, www.neovius.se/voicejournal) and then upsampled to 44.1 kHz per channel, using the ReSample tool in Soundswell. The upsampling was done for compatibility with FonaDyn. The signal bandwidth remains the same, 8 kHz, after upsampling, since no new information is added.

2.2. Recordings and procedures

All recordings were made in a sound treated room at the Department of Communication and Arts of Aveiro University, Portugal. A Laryngograph microprocessor (www.laryngograph.com) was used to record both audio and electrolaryngographic (ELG) signals. Although Adrian Fourcin, the founder of the Laryngograph company, argues in favour of the term ‘electrolaryngography’ (ELG) rather than ‘electroglottography’ (EGG), the term EGG will be used in this article. For recording the audio signal, a head-mounted omnidirectional electret condenser boom microphone (Knowles model EK3132) was used. The microphone-to-mouth distance was adjusted for each singer to avoid clipping, and then kept the same throughout the recording. The distance was noted for each singer and later used to correct the level calibration of the audio signal. For the recording of the EGG signal, two electrodes were placed on either side of the larynx and held in place by an elastic neckband. The audio and EGG signals were monitored visually in real time using the recording software SpeechStudio (www.laryngograph.com), thus ensuring correct electrode placement and audio acquisition. The sampling rate was 16 kHz per channel, giving a signal bandwidth of 8 kHz, and the sample resolution was 16 bits.

2.3. EGG analysis

In order to assess whether the amount and character of vocal fold contacting is influenced by SOVTEs using a flow ball, an EGG method was employed. The amount of vocal fold contacting was assessed using three time-domain metrics of the EGG waveform that were recently proposed by Ternström (2019): (1) the quotient of contact by integration, Q_{ci}, (2) the normalized peak derivative, Q_{Δ}, and (3) a combination of these two, the index of contacting, I_c . The advantages of these metrics over the conventional CQ_{EGG} and the peak dEGG are that their definitions do not rely on identifying any thresholds or events in the

EGG signal. The new metrics all assume EGG pulses that are normalized to the interval [0…1] in both amplitude and duration. For a detailed specification of how these metrics are defined and computed, the reader is referred to that article, published with Open Access.

In brief, Q_{ci} is the *area* under the normalized EGG pulse. It increases with the relative duration of contacting, regardless of the shape of the EGG pulse, and without regard for the events of vocal fold collision or decontacting. Hence neither this nor any other EGG-based *contact* quotient is identical to the *closed* quotient for glottal airflow (Lã & Sundberg, 2015).

Q_{Δ} is the amplitude of the peak derivative over the normalized pulse. It is conceptually similar to the inverse of the normalized amplitude quotient (NAQ) introduced by Alku (2002) for glottal airflow, but scaled such that a sinusoidal pulse (no contacting) receives a minimum Q_{Δ} value of +1. If the medial faces on contact are flat and parallel, then the peak derivative of the contact area will be very high (even if the collision speed is low!). In principle, it can go to infinity. In practice, it is limited by the bandwidth of the EGG signal, which in the present study was limited to 8 kHz by the 16 kHz sample rate.

The I_c is defined as $Q_{ci} \times {}^{10}\log(Q_{\Delta})$, which usefully produces a value near zero for no contacting, and a value of around +1 for very firm and rapid contacting. This permits some interpretation also of the very low-amplitude EGG signals that occur when the vocal folds are vibrating but not colliding, when the contact quotient essentially loses its meaning (Herbst & Ternström, 2006).

The EGG waveform changes considerably across the voice range (Ternström et al., 2018b), so it is important to compare waveforms, pre and post SOVTEs with the flow ball always at the same f_o and sound level. The FonaDyn tool facilitates such a comparison by creating voice maps (Pabon, 2018), that is, color-coded surface plots of each metric, with f_o on the horizontal axis and SPL on the vertical axis. The plane of $f_o \times$ SPL will be referred to as the *voice field*. FonaDyn automatically segments the EGG cycles, computes all metrics of interest for each cycle, and averages the metric values into 2D histograms, with a bin size of one semitone and one decibel. The average in each bin is then taken as the value of the metric at any given f_o and SPL (both of which are computed from the *audio* signal). A periodicity, or 'clarity' threshold is applied that inhibits the detection of EGG cycles when phonation is not sufficiently periodic (McLeod & Wyvill, 2005). For this study, that threshold was set to 0.96. Also, a cycle-count threshold was applied, at a minimum of five EGG cycles per bin.

For convenience of analysis, all 'before' productions of each subject were concatenated consecutively into one file, and all 'after' productions into another. Voice maps were then made of the aggregated 'before' and 'after' productions respectively, even though these were not produced contiguously in time. It was not meaningful to create voice maps of the 'during' productions, since the audio SPL is completely different when using the flow ball.

2.4. Mapping of EGG metrics

Each cell in a given voice map, at a given position of f_o and SPL, holds a cycle average of the metric of interest; here: Q_{ci}, Q_{Δ}, or I_c . Each map is made up of some hundreds of non-empty cells. Figure 3 shows an example of voice maps of the three metrics, for the 'before' productions of singer S01.

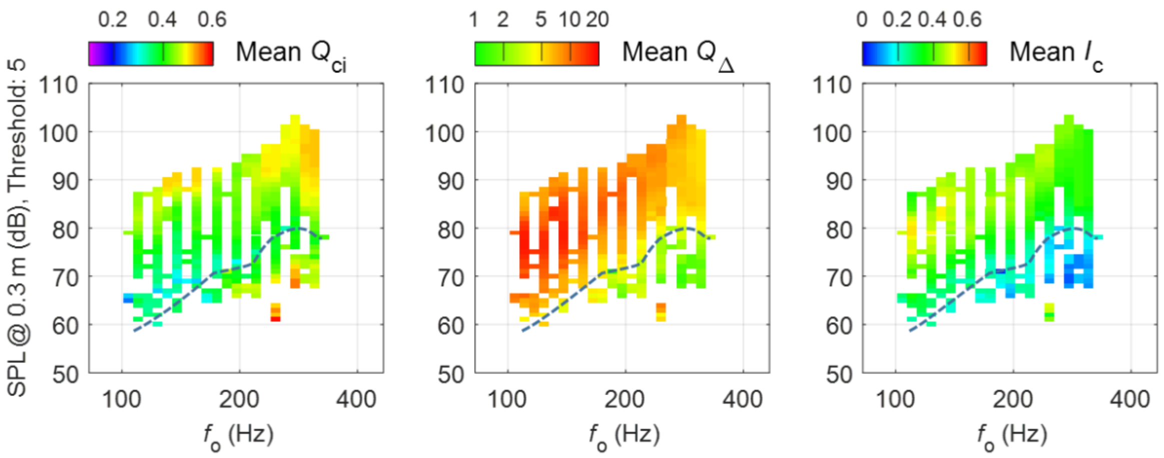

Figure 3. Example of voice maps of the three metrics Q_{ci}, Q_{Δ}, and I_c (left to right), for the 'before' productions of singer S01. The dashed line indicates approximately the onset of full VF contacting, based on Q_{Δ}, and copied to Q_{ci} and I_c.

A dashed line, derived by experience from the Q_{Δ} map, has been added to indicate the approximate onset of full contacting of the vocal folds. When the vocal folds are not colliding, the EGG signal is of small amplitude, nearly sinusoidal and somewhat noisy. Note how Q_{ci} therefore is higher and somewhat speckled at the lowest levels. However, such soft phonation is not commonly used by classically trained singers. Note also how Q_{Δ} (and therefore also I_c) tends to decrease with increasing f_o. This is mostly an effect of the number of in-band harmonics (here, < 8 kHz) decreasing as f_o increases. To eliminate this dependency, it is possible to constrain the EGG signal to, say, ten harmonics, and then compute the EGG metrics from the constrained signal (Ternström et al., 2018a). However, this dependency will not matter for the purposes of the present study, since the metrics will always be compared at the same f_o in the 'before' and 'after' conditions.

One may now plot a *delta map* that visualizes the change from 'before' to 'after'. Figure 4 shows an example of voice maps of the 'before' and 'after' conditions, and the corresponding delta map. In each cell or given location (f_o , SPL), the comparison is expressed as the ratio between the two values of a given metric ‘after’ and ‘before’. The use of ratios rather than differences is convenient for visualization, because relative changes are independent of the magnitude of the metric under observation. The magnitudes of Q_{ci} and I_c are in the range [0…1], while Q_{Δ} is always ≥ 1. Ratios > 1 indicate an increase from ‘before’ to ‘after’ and are mapped to shades of green. Ratios < 1 indicate a decrease from ‘before’ to ‘after’ and are mapped to shades of red. No difference (ratio = 1) is rendered as light gray. It can be seen that there are often connected regions of green and red shades in the delta maps, which means that there are systematic differences between ‘after’ and ‘before’. It is also clear that, for a given metric, the effect can be an increase or a decrease, depending on the location in the voice field. Maps of all individuals are provided in Appendix A. Given that these local effects are notoriously individual, as was found also in a previous study of EGG and lung volumes (Ternström et al., 2018b), we decided to test whether even the very coarse method of simply taking the ratio of change, averaged over *all cells* (=bins) in the entire delta map, would still demonstrate an effect.

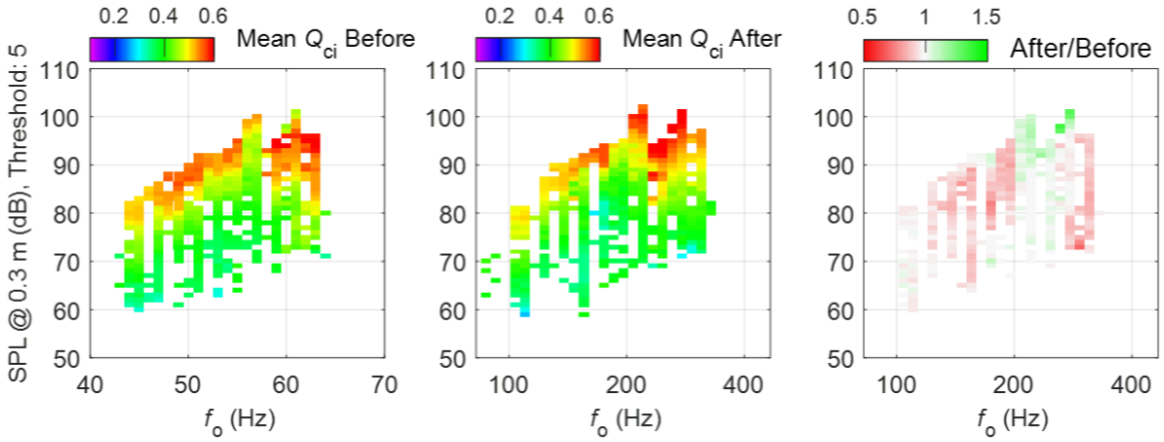

Figure 4. Example of a voice map comparison. Left: the voice map of Q_{ci} of subject S02 ‘before’; centre: ditto, ‘after’; right: the delta map showing the cell-by-cell pairwise ratios, on a red-gray-green scale for the interval [0.5, …, 1.5] where light gray

represents a ratio of 1.0 (no change). Here, the geometric mean of all ratios was 0.95 (< 1, red, reduction in ‘after’) which was significant (*p* < 0.001, see also Table 2).

2.5. Statistical Analysis

For testing the statistical significance of the comparisons of ‘after’ to ‘before’, the paired cell-by-cell differences, rather than the ratios, were computed, for all positions in a delta map that were non-empty both ‘before’ and ‘after’. In most cases, the distribution of these differences was not normal. Therefore, the statistical significance of these differences was computed with the non-parametric Wilcoxon signed-rank test, at a significance level of $p < 0.05$. Also, a one-sample t-test was carried out to assess the significance of the overall percentages of change for each metric; these were normally distributed as determined by a Kolmogorov-Smirnov test.

2.6. Comparison of Q_{ci} to Q_x and CQ_{HYBRID}

Herbst & Ternström (2006) and Herbst (2019) discuss and evaluate in some depth the several definitions of CQ_{EGG} that can be found in the literature, concluding that a definitive definition has yet to be decided upon. Most CQ_{EGG} metrics are based on thresholds and do not account for the pulse shape, only the pulse width. For instance, they can be ambiguous if in the EGG pulse shape there are multiple peaks that cross the threshold. Ternström (2019) proposed Q_{ci} for having the advantages that it is free from thresholds, and gives transient-free results even for EGG pulses with sporadic local maxima during the opening phase. Since Q_{ci} is defined as the area under the normalized pulse, it does not suffer from threshold ambiguities; nor is it influenced by local extrema in the EGG derivative. Still, Q_{ci} is highly correlated and similar, though not identical, to other widely used metrics of the EGG contact quotient. This is demonstrated by the following two examples.

A well-established tool for analysing EGG signals is the Speech Studio system developed by Fourcin and associates (www.laryngograph.co.uk). According to its manual, this software measures a contact quotient Q_x as that fraction of a cycle that is spent above a threshold at 30% of the peak-to-peak amplitude of the EGG pulse. The results can be exported to a text file that includes the Q_x of every pulse. For a comparison with Q_{ci} , four 'before' productions were chosen from the present material. The choice was based on auditory and visual identification of widely differing phonation types, i.e., breathy and pressed, from a female and a male subject. The recordings were run through Speech Studio to obtain Q_x values for every cycle, and also through FonaDyn 2.0 to obtain the matched Q_{ci} values of the same cycles. Figure 5 shows that, for these samples, the relationship between Q_x and Q_{ci} is practically linear, $Q_{ci} \approx 0.725 \cdot Q_x + 0.0845$, with a high correlation coefficient, $r > 0.99$. When $Q_x = 0.3$, Q_{ci} is also close to 0.3.

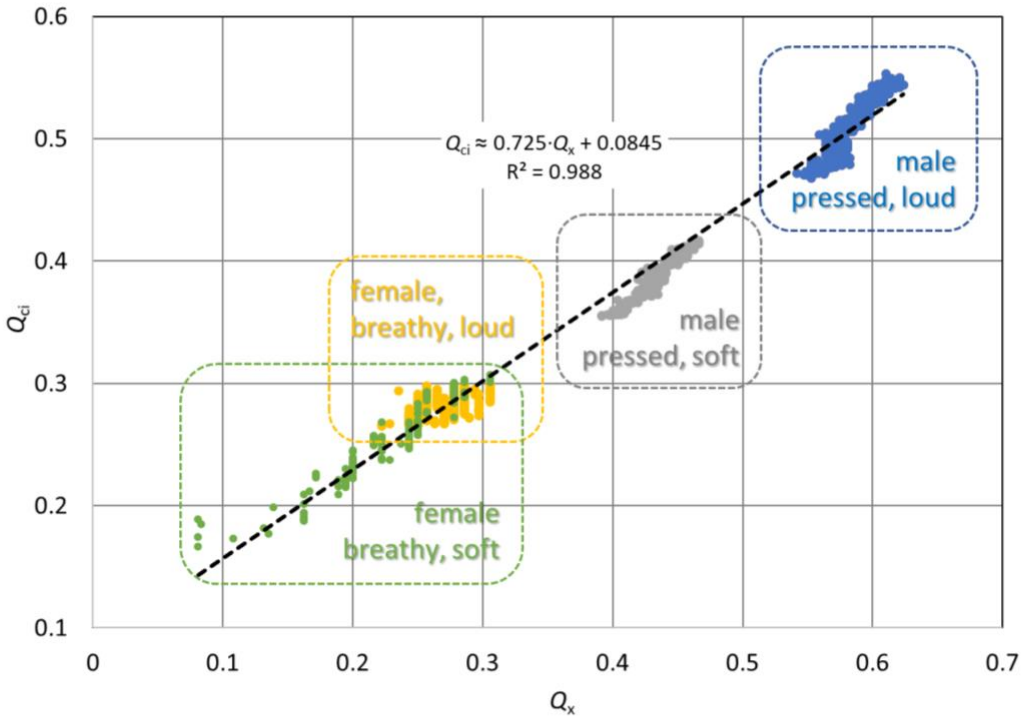

Figure 5: Comparison of the quotient of contact by integration Q_{ci} (vertical) to the threshold-based measure Q_x (horizontal) of the Speech Studio system, for four different types of phonation in singing. Each point represents one EGG cycle.

Another well-known definition of the EGG contact quotient is the dEGG-hybrid *CQ* (Howard, 1995). It is defined as the fraction of the cycle from the dEGG peak to the first point below 3/7 of the EGG maximum amplitude. We compared Q_{ci} also to this *CQ*, using the entire voice map data of the present material, and also those of another study (Patel and Ternström, 2019) of 26 male and female untrained speakers exercising their full voice range. A useful rule of thumb was found that, for both studies, $Q_{ci} \approx 0.75 \cdot CQ + 0.1$, with a correlation coefficient r on the order of 0.9. This relationship of Q_{ci} to *CQ* is very similar to that of Q_{ci} to Q_x, as found above. The correlation of Q_{ci} to *CQ* was typically > 0.9 for "normal" EGG pulse shapes and < 0.9 for more unusual ones. This is as expected and intended, since the pulse area and the time above threshold are two different things.

3. RESULTS

In Appendix A, we present the individual voice maps of all subjects and metrics: 'before', 'after', and the delta maps of the ratios 'after'/'before'. The subjects S01-S05 are male, and S06-S10 are female. The need for making such maps becomes evident when observing the large individual differences in how the chosen metrics vary over f_o and SPL. Note also how each singer is quite consistent when repeating the task 'before' and 'after'.

Table 2 summarizes the data in the delta maps, for each metric 'after' and 'before', by the arithmetic mean difference, the statistical significance of that difference, and the geometric mean ratio. Also, the overall means and standard deviations across all singers are given. The ratios expressed as percentage changes are also illustrated in Figure 6.

Table 2. Means of cell-by-cell comparisons of 'after' to 'before', taken over the entire delta map, per metric and per subject, and overall means and standard deviations (SD) across all singers. Significance level: * $p < 0.05$. Q_{ci} = quotient of contact by integration; Q_{Δ} = normalized peak derivative; I_c = index of contacting.

		Q_{ci}			Q_{Δ}			I_c		
	Singers	mean diff	sign. level	percent change	mean diff	sign. level	percent change	mean diff	sign. level	percent change
Males	S01	-0.001	NS	-0.04%	0.293	*	**4.11%**	0.007	*	**3.18%**
	S02	-0.017	*	**-3.91%**	0.192	NS	2.96%	-0.010	*	**-2.27%**
	S03	0.000	NS	-0.30%	-0.330	*	**-5.84%**	-0.010	*	**-4.58%**
	S04	0.004	NS	1.16%	-0.272	*	**-4.31%**	-0.006	*	**-1.55%**
	S05	-0.008	*	**-2.03%**	-0.078	*	**-1.89%**	-0.010	*	**-3.57%**
Females	S06	0.003	NS	1.12%	-0.108	*	**-3.39%**	-0.005	*	**-2.61%**
	S07	0.009	*	**2.56%**	-0.123	*	**-3.34%**	0.002	NS	1.15%
	S08	-0.001	*	**-0.30%**	-0.187	*	**-5.70%**	-0.011	*	**-5.84%**
	S09	0.001	NS	0.38%	-0.081	NS	-1.76%	-0.005	*	**-3.33%**
	S10	-0.007	*	**-1.58%**	-0.019	NS	-0.74%	-0.005	*	**-2.52%**
Overall	Mean	-0.002		-0.29%	-0.071		-1.99%	-0.017		-0.81%
	SD	0.007		1.84%	0.191		3.35%	0.0064		0.38%

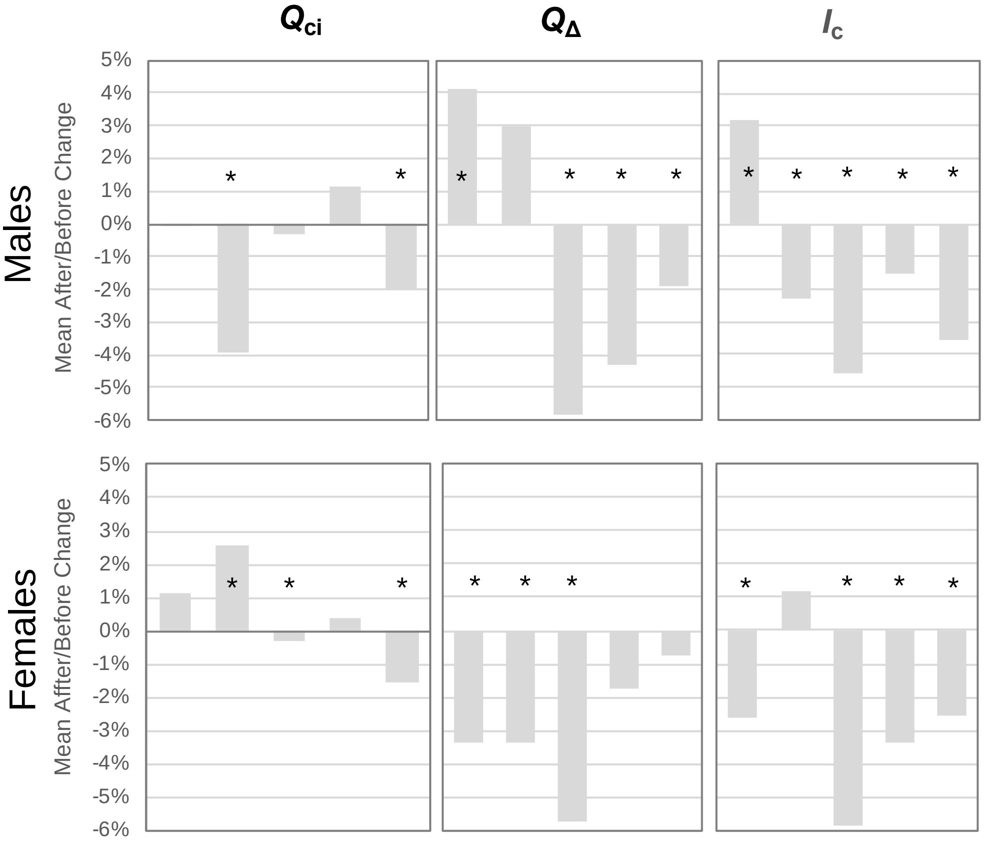

Figure 6. Bar graphs of the relative changes in the three metrics, as geometric means over the difference map, per subject. Top row: male singers S01-S05, bottom row: female singers S06-S10. Asterisks denote statistically significant changes. Q_{ci} = quotient of contact by integration; Q_{Δ} = normalized peak derivative; I_c = index of contacting.

4. DISCUSSION

It is conceivable that the effect of using a SOVTE using the flow ball would be quite different in different parts of the voice range; and different also depending on the singer's habitual phonatory behaviours. Indeed, this is what emerges from the voice maps presented here, substantiating the need for a shift from isolated scalar metrics at a few selected pitches or levels, to mapping *distributions* of scalar metrics across the voice field (Ternström &

Pabon, 2019). However, the challenge then arises to quantify such results in a meaningful way.

Here, voice maps of EGG time-domain metrics were used to explore and quantify the effects of performing a SOVTE using the flow ball device. The task was to perform, on each of eight scale tones, a *messa di voce* three times: without the flow ball device ('before'), with it ('during') and again without using the flow ball device ('after'). The results therefore indicate whether or not using the flow ball had an *immediate*, short-term effect on the subject's phonation for each *messa di voce* exercise. Although there were often considerable individual differences within each participant's *tessitura*, our primary research question was to test the overall effect of the flow ball exercise. Therefore, the effect size is reported only as the gross average over each entire delta map.

The results show that, for the contact quotient Q_{ci} , five of ten singers exhibited significant but small effects. Four of them reduced Q_{ci} by about 2% (Figure 6). Although this may seem like a small change when compared to findings in previous studies (e.g., Guzman et al, 2015), it is the *average* change across the whole voice map, i.e., over the ensemble of trials. Typically, larger effects were seen locally, e.g., in soft voice, or at high pitch (see the delta maps of the individual singers).

The individual variation is in line with previous findings on the effects of SOVTEs on the CQ_{EGG} (Dargin & Searl, 2015). The Q_{ci} metric is a metric primarily related to vocal fold adduction (provided that phonation is above the threshold of vocal fold collision). A greater adductive force will prolong the portion of the phonatory cycle for which the vocal folds are in contact. In this sense, the flow ball promoted a less adductive behaviour in four of the five singers in whom a significant change in Q_{ci} was observed.

The reduced adduction can be seen also in the Q_{Δ} metric, when comparing 'after' to 'before'. It was 2-6% lower in six of the singers, and 3-4% higher only in the two bass-baritones, S1 and S2 (Figure 6). From purely geometric considerations, it can be inferred that the Q_Δ metric depends both on the speed with which the vocal folds approach each other, and on the shape and posturing of the medial faces of the vocal folds, in terms of their flatness and contacting angle. A lowered transglottal pressure, as invoked by semi-occluding the vocal tract with the flow ball (the 'during' condition), will reduce the vibration amplitude and hence the transversal velocity of the vocal folds, assuming that f_o remains the same, which was the case for all the comparisons made here. Here, the decrease in Q_Δ presented 'after' by six of the singers could imply either that the transglottal pressure remains somewhat lowered, or that the vocal folds posturing has changed toward more gradual contacting, conceivably reducing the impact stress on the medial faces. In the two bass-baritones, the observed increase in Q_Δ happens mostly in soft phonation, as can be seen in the delta maps (subjects S01 and S02 in Appendix A). This indicates that in the 'after' condition, the low male voices achieved a more abrupt vocal folds closure in soft phonation. This could mean that in the 'after' condition, they were able to maintain vocal fold contacting down to a lower SPL than in the 'before' condition.

The purpose of the I_c metric is twofold: (1) it combines information related both to deceleration at vocal fold collision (Q_Δ) and the proportion of cycle time spent in contact; and (2) it overrides the large Q_{ci} values observed in very soft phonation, by reporting near-zero values when there is no vocal fold contact. In six singers, I_c decreased by almost 4%, on average, in the 'after' condition, reflecting generally an overall promotion of gentler vocal fold collision. Singer S1 exhibited an increase of 3%, which again happened in the softest part of his *messa di voce,* as shown by inspection of his delta map of I_c . When pooling the results across all singers, the I_c metric was the only one exhibiting a significant relative change, a reduction of -0.81% in the 'after' condition.

The comparisons here were always made at paired f_o and SPL locations, so they test for an immediate effect *within* each scale tone trial. There may be a carry-over or training effect of using the flow ball that would affect subsequent repetitions on ascending scale tones. The order of the scale tones was not randomized, but always ascending by whole tone steps. Hence, if there was a training effect over trials, or an effect of increasing f_o, these effects did not completely obscure the immediate effect observed.

It may well be that using a flow-ball will modify the singer's breath management during expiration; for instance, controlling the flow will involve a conscious counteraction of the elastic recoil of filled lungs and thus perhaps affect phonation indirectly by way of tracheal pull (Ternström & al, 2018b). However, since in the present study we did not monitor the breathing, such effects cannot be discriminated.

Here Q_{ci}, Q_{Δ} and I_c were computed directly from the EGG waveform, preconditioned with high-pass and low-pass filters. In other recent studies by author S.T. (Ternström et al., 2018b; Patel & Ternström, 2019), these parameters have been computed from a processed version of the EGG waveform that has been spectrally constrained to the first ten Fourier components, or harmonics. For Q_{ci} this makes a negligible difference. However, that method limits the maximum Q_{Δ} that can be obtained, and so the Q_{Δ} and I_c values reported here cannot be directly compared to those in the other studies. However, it does not affect the conclusions drawn here, since all 'before'-'after' comparisons are made pairwise at the same values of f_o and SPL.

5. CONCLUSIONS

Overall, the use of a FB device in performing a *messa di voce* exercise has short-term effects on vocal fold contacting similar to those of using other SOVT tools. From the EGG results, it can be inferred that, on the whole, using the FB induces less adductive phonation and gentler vocal fold collision in immediately repeated trials. Only the I_c metric showed a significant reduction across *all* singers. Further study will be needed to relate this metric to the underlying physiological events. The individual differences that were seen in the voice maps and in the relative changes point to the need for further developing measurements that can be mapped over the voice range and hopefully related to the perceived aspects of voice function. Voice maps seem to be a promising method of following the effects of SOVTEs from voice training and clinical points of view. The individual differences seen here point to the need for tailoring the exercise to the singer, and not the other way around.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge all participants who kindly volunteered to participate in this study. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. However, the authors would like to thank also the Swedish Research Council for the projects that allowed the development of the software used in this project’s data analysis (2010-4565 and 2013-0642) and KTH and the Program for Research Talent Attraction of the Comunidad de Madrid, Spain (Atracción de Talento Investigador C. de Madrid / Proyecto 2018-T1/HUM-12172) for the authors’ faculty time spent in this investigation.

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