

Mechanisms of speaker adaptation to semi-occluded vocal tract exercises: Insights from computational phonation modeling

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ABSTRACT:

Semi-occluded vocal tract exercises (SOVTE) are vocal exercises involving partial occlusion in the front part of the vocal tract, often through phonation into a narrow tube. Although SOVTE are widely used in voice therapy and pedagogy, the physiological mechanisms underlying their therapeutic benefits remain unclear. In this computational study, voice production at different vocal fold configurations with and without semi-occlusion was investigated in a three-dimensional model. Semi-occlusion significantly increased phonation threshold pressure under conditions of weak vocal fold adduction. Under conditions of strong vocal fold adduction, semi-occlusion reduced mean glottal area and increased the duration of glottal closure. These findings suggest two possible adaptation mechanisms through which SOVTE may guide speakers toward an efficient phonatory configuration. For speakers with hypofunctional voice, increased respiratory effort associated with elevated phonation threshold pressure may encourage increased vocal fold adduction. For speakers with habitually tight vocal fold adduction, increased duration of vocal fold contact may alter mechanosensory feedback and promote compensatory reductions in vocal fold adduction. Together, these adaptations may facilitate adoption of an intermediate vocal fold adduction configuration, which is associated with high vocal efficiency and reduced risk of vocal fold injury. Such adaptation effects may persist briefly after SOVTE but gradually diminish over time.

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I. INTRODUCTION

Semi-occluded vocal tract exercises (SOVTE) are vocal exercises involving partial occlusion of the vocal tract, often in the front part of the oral cavity or at the lips. These include vocal exercises with bilabial fricatives, phonation while covering the mouth, or phonation into a small-diameter straw or a relatively large-diameter tube submerged in water. Semi-occlusion in the form of nasals is often an important component in other vocal exercises or voice therapy approaches (e.g., resonant voice therapy; Verdolini Abbott, 2008). SOVTE were initially used in voice training by singers and voice professionals (Laukkanen *et al.*, 1996; Bele, 2005), but have increasingly been used in voice therapy, with the goal of improving vocal efficiency and reducing risk of vocal fold injury (Titze, 2006; Simberg and Laine, 2007; Gaskill and Quinney, 2012; Guzman *et al.*, 2017; Patel *et al.*, 2019; Pozzali *et al.*, 2024). Clinical findings showed that SOVTE provide immediate improvement in vocal fatigue and voice quality (e.g., Sampaio *et al.*, 2008; Savareh *et al.*, 2023; Ford *et al.*, 2024; Apfelbach and Guzman, 2024), although the long-term effects are not significantly superior compared to other treatments (e.g., Pozzali *et al.*, 2024).

Several scientific rationales have been proposed to explain the therapeutic benefits of SOVTE in improving voice production and voice quality. It is generally assumed that semi-occlusion at the lips increases the input inertance of the vocal tract, which has been shown to enhance source-filter interaction, lower the phonation threshold pressure, and improve vocal efficiency (Titze and Story, 1997; Story *et al.*, 2000; Titze, 2006). Semi-occlusion, particularly with small-diameter straws, increases the back pressure immediately above the vocal folds, which has been hypothesized to help push apart the top edges of the vocal folds and reduce vocal fold collision (Titze, 2006), thus reducing risk of vocal fold injury. Semi-occlusion at the lips also increases the sound pressure inside the oral cavity and oral vibratory sensation, which may help familiarize patients with the feeling of resonant voice, providing them with a goal to aim for in natural speech with a more open vocal tract (Titze, 2006).

These proposed rationales focus largely on the direct mechanical effect of SOVTE (i.e., the immediate modification of the glottal fluid-structure interaction involved in voice production) rather than on the adaptation effect, in which speakers adjust their laryngeal and vocal tract configurations in response to the presence of semi-occlusion at the lips. The direct mechanical effect of SOVTE on voice production, regardless of its magnitude, likely disappears immediately once the semi-occlusion is removed. Thus, any

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post-SOVTE effects on voice production, whether immediate or long-term, must arise from the adaptation effect, that is, from adjustments in laryngeal and vocal tract configurations made by speakers during SOVTE that persist after the semi-occlusion is removed. Understanding these laryngeal and vocal tract adjustments made in response to SOVTE is essential for explaining and predicting both the immediate and long-term effects of SOVTE.

This study aims to provide alternative, adaptation-based mechanisms for the therapeutic benefits of SOVTE. Previous studies (Zhang, 2020, 2021b) have shown that maximum vocal efficiency and minimum risk of injury are achieved with an intermediate vocal fold adduction configuration that balances the initial glottal gap and vocal fold vertical thickness (i.e., thin vocal folds tightly approximated or thick vocal folds loosely approximated). Such intermediate configurations are also advantageous because they are associated with relatively low phonation threshold pressures (Zhang, 2021a). However, the mechanisms through which speakers may adapt their laryngeal configuration toward these optimal states during SOVTE remain unclear. The goal of this study is therefore to identify potential adaptation mechanisms through which SOVTE may promote the adoption of such intermediate vocal fold adduction configurations, as inferred from computational simulations. The computational approach is essential because it provides insights into changes in vocal fold vibration and the voice source induced by SOVTE that are difficult to measure directly in human subjects or *ex vivo* laryngeal models.

In general, semi-occlusion at the lips increases supraglottal pressure (P_{sup}) and decreases transglottal pressure, thereby increasing the minimum lung pressure required to initiate and sustain phonation. Thus, one possible adaptation mechanism is *effort-driven* adaptation: by increasing phonation threshold lung pressure, SOVTE may encourage speakers to adopt an intermediate vocal fold adduction configuration that is associated with low phonation threshold pressure, particularly when they are instructed to avoid excessive respiratory effort. It will be shown below that this mechanism is expected to be especially relevant under conditions of weak vocal fold adduction, where semi-occlusion substantially increased phonation threshold pressure. For conditions of strong vocal fold adduction, the effect of semi-occlusion on the phonation threshold pressure was smaller. However, in these conditions, semi-occlusion brought the vocal folds together closer during vibration and produced a higher closed quotient (CQ) compared with phonation without vocal tract semi-occlusion. Thus, a second possible adaptation mechanism is *mechanosensory-driven* adaptation. The resulting increase in vocal fold contact duration may provide a sensory feedback cue for speakers to reduce adductory laryngeal muscle activity. Together with instructions to avoid excessive vocal effort, these adaptation mechanisms may facilitate the adoption of an intermediate vocal fold adduction configuration that improves vocal efficiency and reduces the risk of vocal fold injury.

II. METHOD

A. Computational model and simulation conditions

The same three-dimensional body-cover vocal fold model as in a previous study (Zhang, 2022) was used in this study. In that study, voice production was investigated with different vocal tract shapes, including a /u/ vocal tract extended by an 8 cm long tube with an inner diameter of 5 mm. In the present study, additional voice simulations were performed with the /u/ vocal tract extended by an 8 cm long tube with a smaller inner diameter of 2.5 mm, similar to the coffee stirring straw often used in SOVTE. Voice production was then compared across three vocal tract configurations: the /u/ vocal tract, /u/ vocal tract extended by a 5 mm-inner diameter tube, and /u/ vocal tract extended by a 2.5 mm-inner diameter tube. The /u/ vocal tract configuration was considered because a /u/-like configuration is more realistic for phonation through a narrow tube at the lips, whereas other vowel configurations may be difficult or nearly impossible to phonate through the narrow tube.

The details of the body-cover computational model have been described in our previous studies (Zhang, 2017, 2019, 2020). Briefly, each vocal fold layer is modeled as a transversely isotropic, nearly incompressible, linear material with a plane of isotropy perpendicular to the anterior–posterior (AP) direction. The glottal flow is modeled as a one-dimensional quasi-steady glottal flow model taking into consideration viscous loss, as described in detail in Zhang (2017). Vocal fold contact occurs when portions of the vocal fold cross the glottal midline, in which case a penalty pressure perpendicular into the vocal fold is applied to the contact surface of the vocal fold (Zhang, 2019). The parameters of the penalty pressure model are selected to ensure small penetration depth of the vocal folds crossing the glottal midline so that the corresponding penalty pressure would approximate the true contact pressure (Zhang, 2019). The vocal tract is modeled as a one-dimensional waveguide coupled with a yielding vocal tract wall (Story, 1995). This voice production model has been shown to qualitatively and quantitatively reproduce experimental observations (Zhang and Luu, 2012; Farahani and Zhang, 2016; Yoshinaga and Zhang, 2025).

The vocal fold geometry is parameterized by various geometric parameters including AP length, vertical thickness, medial–lateral depth, and initial glottal angle (Fig. 1, left panel). In this study, the vocal fold length was set to 17 mm. Two important geometric variables, the initial glottal angle α and the medial surface vertical thickness T , were systematically varied to produce different conditions of vocal fold adduction. Specifically, the initial glottal angle α was varied from -1.6° , 0° , 1.6° , 4° , to 8° . This range corresponds to an inter-vocal process distance between -0.5 and 2.4 mm, which is similar to that investigated in previous experimental studies (Gauffin and Sundberg, 1989; Jiang and Titze, 1994; Isshiki, 1998; Berry *et al.*, 2001). The negative initial glottal angle corresponds to a pressed vocal fold configuration, whereas the 0 – 1.6° and 4 – 8° initial glottal

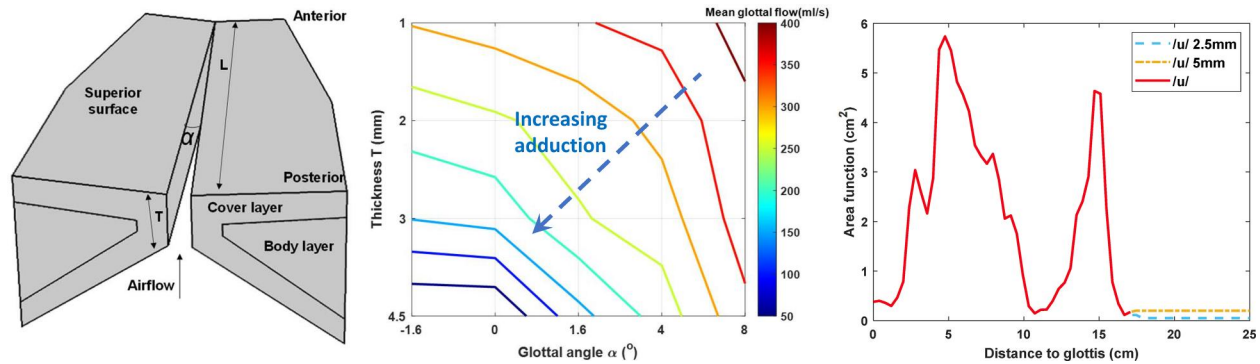


FIG. 1. The three-dimensional vocal fold model (left) and the vocal tract area functions (right). The middle panel shows the contours of mean glottal flow for a subglottal pressure of 2.2 kPa and the /u/ vocal tract for different combinations of initial glottal angle α and the medial surface vertical thickness T , which produce varying degrees of vocal fold adduction.

angles roughly correspond to a barely abducted and breathy vocal fold configuration, respectively. The medial surface vertical thickness was varied from 1, 2, 3, to 4.5 mm, which covers the ranges reported in previous experimental studies (Hollien, 1960; Hollien and Curtis, 1960; Wu and Zhang, 2016; Traser *et al.*, 2026; Zhang *et al.*, 2026) and investigated in previous numerical studies (Titze and Talkin, 1979; Zhang, 2016, 2017). These two geometric controls specify the degree of vocal fold adduction in the horizontal and vertical plane, and have been shown in our previous studies to have a large effect on voice production (Zhang, 2016, 2021a). Figure 1 (middle panel) shows the contour plot of the mean glottal flow for a constant subglottal pressure for different combinations of thickness and initial glottal angle. Thin vocal folds coupled with large initial glottal angles produce a weak adductory configuration, whereas thick folds coupled with negative/small initial glottal angles produce a strong and tight adductory configuration. In contrast to previous studies that define vocal fold adduction solely based on the initial glottal gap in the horizontal plane (Verdolini *et al.*, 1998; Berry *et al.*, 2001), Fig. 1 shows that a continuum of intermediate adductory configurations can be achieved with a balance between the initial glottal angle and thickness: from thin folds coupled with a negative/small initial glottal angle to thick folds coupled with a large initial glottal angle.

Mechanically, each vocal fold layer is characterized by its transverse Young's modulus E_t , the AP Young's modulus E_{ap} , the AP shear modulus G_{ap} , and density. The effect of these mechanical properties on voice production has been investigated in detail in our previous studies (Zhang, 2017, 2020, 2021a). To reduce the number of conditions to be simulated, in this study the body and cover layers were set to have identical mechanical properties, with E_t , G_{ap} , and E_{ap} set to 2, 10, and 40 kPa, respectively. Simulations with systematic variations in vocal fold stiffness, particularly the transverse stiffness in the coronal plane, will be performed in future studies to investigate potential effects of stiffness on SOVTE.

As mentioned earlier, three vocal tract conditions were considered in this study (Fig. 1; right panel). The first vocal tract shape corresponded to the close vowel /u/ produced by

a male subject. The second and third vocal tract configurations were included to investigate the effect of semi-occlusion at the lips, by extending the /u/ vocal tract with an 8 cm long tube with an inner diameter of 5 and 2.5 mm, respectively, simulating a straw as often used in straw phonation. The effective mass, stiffness, and damping per unit area of the vocal tract wall were set to 16.3 kg/m², 2187.0 kN/m³, and 13980 N.s/m³, respectively (Milenkovic and Mo, 1988).

B. Simulations and data analysis

For each vocal fold and vocal tract condition, a half-second of voice production was simulated for a constant subglottal pressure ranging from 100 Pa to 2.4 kPa, similar to Zhang (2022). For each condition, the phonation threshold pressure was determined as the minimal subglottal pressure where self-sustained vocal fold vibration was observed. Additional data analysis was performed on the last half of each simulation where vocal fold vibration either reached or approached a steady state. The mean supraglottal pressure (P_{sup}) immediately above the vocal folds at the glottal exit was extracted. The mean glottal area (A_{g0}) and peak-to-peak amplitude (A_{gamp}) were calculated from the glottal area waveform. The closed quotient (CQ) was calculated as the fraction of the cycle in which the glottal flow waveform falls within the lower 10% between the minimum and maximum glottal flow rate. The peak vocal fold contact pressure was calculated as the maximum vocal fold contact pressure across the medial surface over time.

III. RESULTS

A. Phonation threshold pressure

Figure 2 shows the phonation threshold pressure as a function of the initial glottal angle and vocal fold thickness for the three vocal tract configurations. For the /u/ vocal tract, in general, the phonation threshold pressure is the lowest at conditions with an initial glottal angle of 0° and 1.6°, particularly for thick vocal folds (thickness $T=3$ and 4.5 mm). This is consistent with the observation in Zhang (2017).

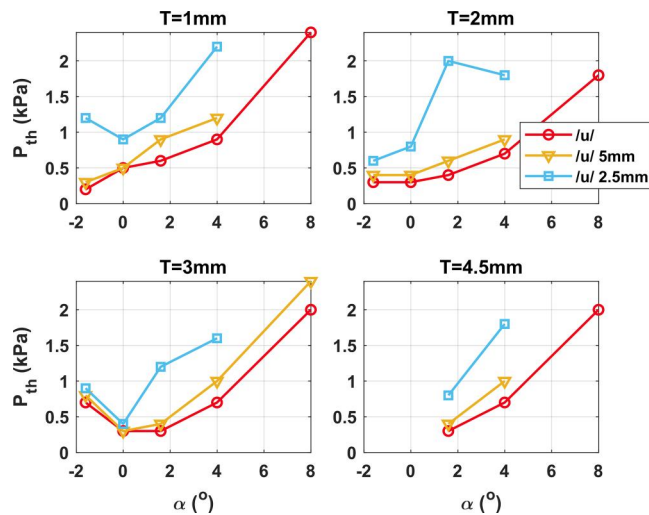


FIG. 2. Phonation threshold pressure P_{th} as a function of the initial glottal angle α and vertical thickness T for three vocal tract shapes: /u/, /u/ extended with a 5 mm diameter tube, and /u/ extended with a 2.5 mm diameter tube.

Semi-occlusion at the lips in general increased the phonation threshold pressure. This was particularly the case for semi-occlusion with the narrower 2.5 mm tube, where the phonation threshold pressure was significantly higher than the other two vocal tract conditions (/u/ without semi-occlusion and /u/ extended by the 5 mm tube). The magnitude

of this increase in phonation threshold pressure appears to depend on the initial glottal angle, with the increase in phonation threshold pressure much larger in conditions of large glottal angles ($\alpha = 4^\circ$ and 8°). For conditions with $\alpha = 8^\circ$, no phonation was observed in the subglottal pressure range investigated (up to 2.4 kPa) when the vocal tract was semi-occluded with the 2.5 mm tube. Phonation under this condition would thus require a substantially higher subglottal pressure and higher respiratory effort than those without semi-occlusion.

The differential effects of semi-occlusion on phonation threshold pressure at different initial glottal angles may be related to the increased vocal tract resistance and inertance due to semi-occlusion, which appear to have opposite effects. An increased vocal tract resistance increases the supraglottal pressure (P_{sup}) (see below), particularly at large initial glottal angles, and thus increases phonation threshold pressure. In contrast, an increased inertance is known to lower the phonation threshold pressure (Titze and Story, 1997).

B. Effects on voice production

Figure 3 shows the effects of semi-occlusion on selected measures of voice production for a subglottal pressure of 2.2 kPa. Note that measures are shown only for conditions where phonation was observed. Increasing degree of semi-occlusion increased the mean supraglottal pressure

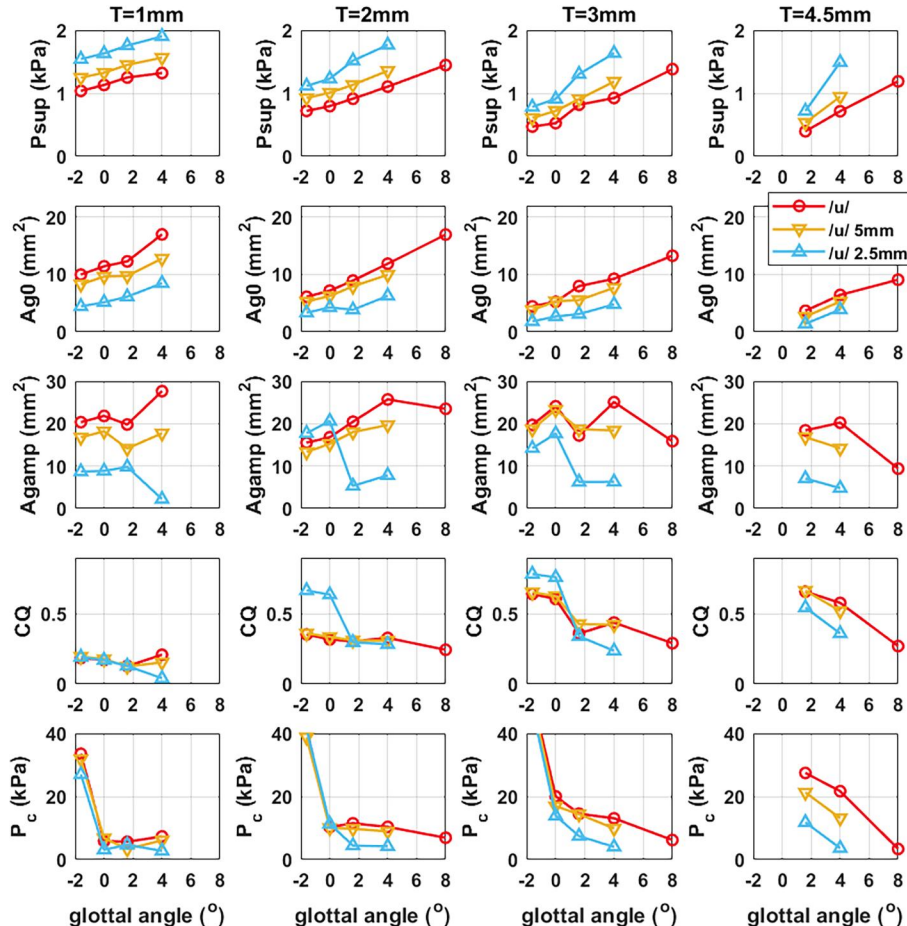


FIG. 3. Effects of semi-occlusion on selected measures of voice production, including the mean supraglottal pressure (P_{sup}), mean glottal area Ag_0 during phonation, Ag_{amp} of the glottal area waveform, CQ, and peak vocal fold contact pressure P_c , as a function of the initial glottal angle and medial surface vertical thickness T . The mean subglottal pressure was 2.2 kPa.

(Psup) immediately above the vocal folds (i.e., the back pressure). This increase in the Psup was larger for conditions of weak vocal fold adduction, i.e., conditions with large glottal angles or small thicknesses, which have a lower laryngeal resistance to airflow. Note that there was significant Psup buildup even for the /u/ vocal tract without semi-occlusion. This high Psup was not surprising considering the narrow airway in the epilarynx region (minimum area of 29 mm²) and the oral cavity (minimum area of 11 mm²; Fig. 1) of the /u/ vocal tract. Considering that a narrow epilarynx is present in almost all vowels, this suggests that natural semi-occlusion and considerable back pressure buildup already exist in most vowels even without tube extension. The mean pressure within the vocal tract decreased toward the lips. Although not shown in Fig. 3, the mean oral pressure behind the lips was significantly lower than the Psup, and the lower range of the oral pressure was consistent with those reported in the literature (e.g., Guzman *et al.*, 2013a; Maxfield *et al.*, 2015).

The increase in the supraglottal pressure (Psup) reduced the mean glottal area Ag0 (second row in Fig. 3) for all vocal fold and vocal tract conditions, which is consistent with the observation in Titze (2006). Although the subglottal pressure pushes the vocal folds upward and laterally and thus opens the glottis, the supraglottal pressure (Psup) tends to resist this glottis-opening effect of the subglottal pressure by pushing the vocal folds downward and closing the glottis. As a result, vocal tract semi-occlusion, especially the one with the 2.5 mm tube, produced a tighter effective vocal fold adduction than phonation without semi-occlusion.

For a given subglottal pressure, increasing supraglottal pressure (Psup) also decreased the transglottal pressure, thus reducing the vibration amplitude, as observed in the decreased glottal area amplitude Agamp in most conditions (third row, Fig. 3). However, for conditions with small/negative glottal angles, the reduction in the glottal area amplitude was much smaller, and was even reversed for conditions with $T = 2$ mm and $\alpha \leq 0^\circ$, where the glottal area

amplitude actually increased when semi-occluded with the 2.5 mm tube.

This smaller reduction/ increase in glottal area amplitude, together with the reduced mean glottal area, produced in these conditions a vibratory pattern where the vocal folds remained closed for an increased duration, with the CQ (fourth row, Fig. 3) much higher than that without the semi-occlusion. In contrast, for other conditions with a significantly reduced vibration amplitude, the CQ either decreased slightly or remained the same.

Figure 4 shows the CQ as a function of the subglottal pressure for different combinations of thickness and initial glottal angle. The increase in CQ with semi-occlusion was noticeable for conditions of strong vocal fold adduction (i.e., thick folds with negative/small initial glottal angles; lower left corner of Fig. 4). In contrast, for conditions with large initial glottal angles or small thicknesses ($T = 1$ mm), the CQ either stayed the same or decreased.

The peak vocal fold contact pressure (bottom row, Fig. 3) decreased with semi-occlusion in most conditions, particularly for conditions of weak vocal fold adduction. The amount of reduction in the peak contact pressure followed a similar trend in the reduction in the glottal area amplitude, indicating that the reduction in the peak contact pressure was likely because of the reduced vibration amplitude.

C. Comparison to previous studies

This study shows that the effect of semi-occlusion on voice production depends on the degree of vocal fold adduction. This differential effect may explain the large variability in SOVTE effects reported in previous studies. For example, in this study, phonation threshold pressure increased significantly for conditions of weak vocal fold adduction, but the increase was smaller for conditions of strong vocal fold adduction or the large-diameter tube. Although previous studies often reported a slightly decreased phonation threshold pressure (e.g., Apfelbach and Guzman, 2024),

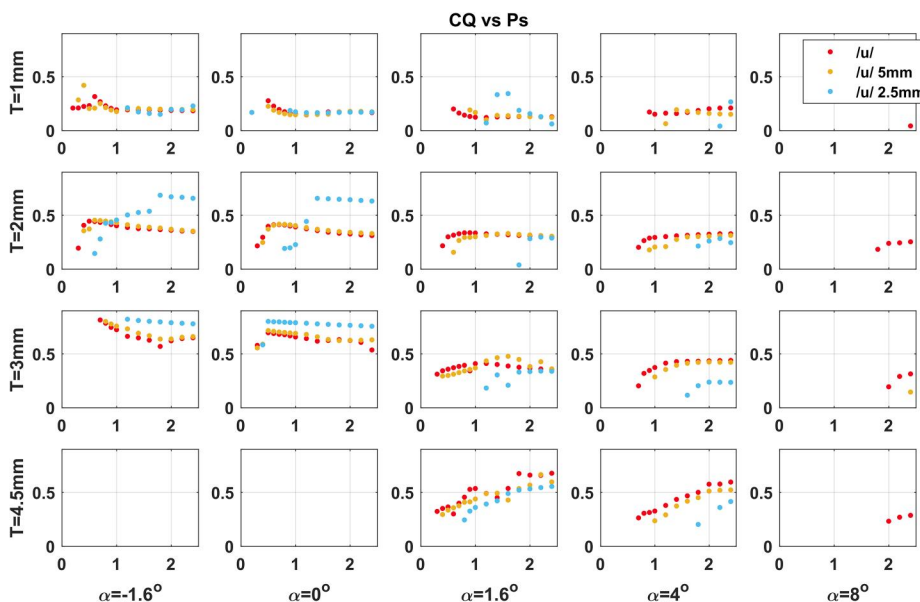


FIG. 4. The CQ as a function of the subglottal pressure P_s (kPa) for different conditions of thickness T , initial glottal angle α , and vocal tract semi-occlusion. With semi-occlusion, it is difficult to phonate with large initial glottal angles. For other conditions, semi-occlusion tends to increase CQ for the most constricted vocal folds but decrease CQ for the less constricted vocal folds.

significant increase in phonation threshold pressure has been reported in previous experimental studies. For example, Horacek *et al.* (2019a) showed that the phonation threshold pressure was significantly higher for phonation into a tube submerged in water than in phonation without a tube. Horacek *et al.* (2019b) showed that the phonation threshold pressure with a /u/ vocal tract was lower than that in phonation with a tube submerged in water but higher than phonation with a tube in air. The lower phonation threshold pressure with a tube in air was probably because of the fact that the fundamental frequency was very close to the first vocal tract resonance for phonation with a tube in air. Tangney *et al.* (2021) showed that although phonation threshold pressure slightly decreased for phonation with a large-diameter tube, more than half of the larynges (17 of 29) did not phonate with a 3 mm-diameter tube, indicating a significantly increased phonation threshold pressure in these larynges. It is possible that the conditions without phonation in their experiment corresponded to the weak adduction conditions in the present study, whereas the conditions with phonation observed corresponded to the strong adduction conditions in the present study. Conroy *et al.* (2014) showed that the phonation threshold pressure decreased slightly by about 120–140 Pa with large-diameter tubes (diameters of 6.5 and 17.5 mm), which is consistent with the smaller effects observed in the present study for the larger diameter tube.

In this study the CQ can either increase, decrease, or remain the same with semi-occlusion, depending on the specific vocal fold condition. This may explain the contradictory findings in humans on the effect of SOVTE on CQ (Laukkanen, 1992; Guzman *et al.*, 2013b; Guzman *et al.*, 2016; Dargin and Searl, 2015; Hampala *et al.*, 2015; Mills *et al.*, 2018). The variability in the changes in CQ in humans is likely further increased by the potential variability in how individual speakers adapt to SOVTE, which was not modeled in this study.

IV. DISCUSSION

This study showed that the effect of semi-occlusion at the lips on voice production depends on the degree of vocal fold adduction. For conditions with weak vocal fold adduction (i.e., large glottal angles or thin folds), semi-occlusion with a narrow straw significantly increased phonation threshold pressure. In contrast, for conditions with tight vocal fold adduction (i.e., large thickness and small/negative glottal angle), the effect on phonation threshold pressure was smaller. However, semi-occlusion in these conditions resulted in a tighter vibratory pattern with an increased duration of vocal fold contact and glottal closure, as demonstrated by the reduced mean glottal area and increased CQ.

Although this study did not investigate how speakers adapt to semi-occlusion during SOVTE, the findings of this study suggest two possible adaptation mechanisms through which speakers may adopt a more efficient and healthier phonatory configuration in response to semi-occlusion at the lips. For speakers with hypofunctional voice, the

results showed that semi-occlusion substantially increased phonation threshold pressure. This may lead to an *effort-driven* adaptation that encourages speakers to increase vocal fold adduction, especially when explicitly instructed to avoid excessively high effort.

For speakers who habitually phonate with tight vocal fold adduction, the results of this study showed that semi-occlusion at the lips had only small effect on the phonation threshold pressure, which does not provide much incentive for speakers to modify their vocal fold configuration. However, semi-occlusion with a narrow tube did result in an even tighter vocal fold adduction and longer duration of vocal fold contact and glottal closure. This may lead to a modified mechanosensory feedback that is stronger than phonation without semi-occlusion. Mechanoreceptors are highly concentrated in the glottal area (see, e.g., Andreatta *et al.*, 2002; Hernández-Morato *et al.*, 2023), and somatosensory feedback, including mechanosensory feedback, has been shown to play an important role in vocal control (e.g., Sorensen *et al.*, 1980; Larson *et al.*, 2008). Thus, a second possible adaptation mechanism is *mechanosensory-driven* compensations in which speakers reduce vocal fold adduction in response to a modified mechanosensory cue during SOVTE.

Together, these two adaptation mechanisms may facilitate adoption of an intermediate vocal fold adductory position, with a balance between thickness and initial glottal angle, as illustrated in Fig. 5. An intermediate adductory configuration has been known to be vocally efficient, have a low phonation threshold pressure, and be of reduced risk of vocal fold injury, which may explain the often-observed immediate effect of SOVTE, including ease of phonation and improved voice quality.

Although these two adaptation mechanisms require experimental verification, they are consistent with findings reported in the literature. For example, Laukkanen *et al.* (1995) and

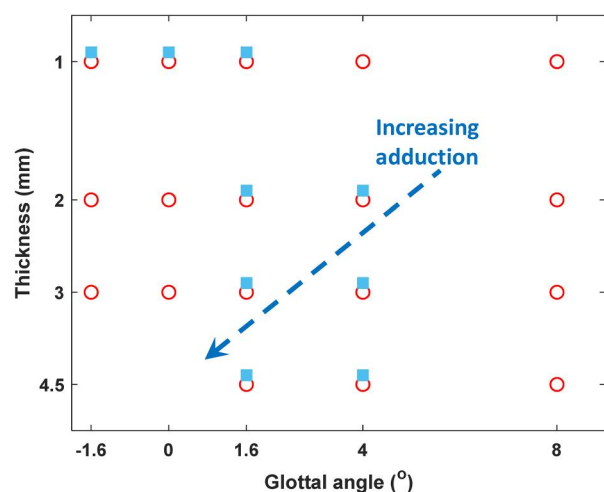


FIG. 5. With the hypothesized adaptations, semi-occlusion at the lips facilitates adoption of an intermediate vocal fold adductory configuration. Circles indicate conditions that are possible for phonation without semi-occlusion, and squares are conditions likely adopted by speakers if they were to avoid excessively high subglottal pressure and compensate for the modified mechanosensory feedback.

Laukkanen *et al.* (1996) showed that SOVTE led to decreased glottal resistance in most subjects with normal voices, whereas in subjects with glottal insufficiency the glottal resistance and efficiency increased. They also reported reduced adductory muscle activity during and after SOVTE, “at least when the voice quality before the exercise is normal or more or less pressed and not breathy.” Similar findings were also reported in Mills *et al.* (2018) and Dargin and Searl (2015), both of which showed significantly decreased glottal resistance.

Previous studies have shown that speaker adaptation to perturbed auditory feedback is relatively automatic and is not easily modified by conscious strategies to resist compensation (e.g., Munhall *et al.*, 2009; Kim and Max, 2021). If speakers do adapt in response to perturbed mechanosensory feedback, such adaptation is likely also automatic, which may explain why an immediate effect during SOVTE is often observed in most speakers, as long as they are able to phonate during SOVTE. Although the effects on the phonation threshold pressure and the CQ disappear immediately after the semi-occlusion is removed, the adaptation toward an intermediate adductory configuration may persist and carry over even after the semi-occlusion is removed. Similar to observations in experiments involving perturbed auditory feedback (e.g., Burnett *et al.*, 1998), the carry-over effect likely fades with time after the mechanosensory feedback returns to the original state.

The results of this study also showed that the effects of semi-occlusion were noticeable only when the semi-occlusion tube was sufficiently narrow (2.5 mm diameter or 5 mm²). This is consistent with the observation in previous studies. For example, Bickley and Stevens (1987) showed that constrictions with area greater than 20 mm² had little effect on the open phase duration of vocal fold vibration. This reduced effectiveness of wide tubes is probably because wide tubes at the lips do not provide additional semi-occlusion beyond the natural, internal semi-occlusion in the epilarynx and/or oral constrictions to allow noticeable increase in back pressure buildup, as demonstrated in Fig. 3.

A main limitation of this study is the relatively limited range of vocal conditions simulated. In particular, the simulations did not include variations in vocal fold stiffness or vocal tract shape. Although the main findings of this study, namely, increased phonation threshold pressure under conditions of weak vocal fold adduction and increased vocal fold contact duration under conditions of strong vocal fold adduction, are likely generalizable to a broader range of phonatory conditions, this possibility requires further verification through simulations incorporating a wider range of vocal fold properties and vocal tract shapes and through human studies.

V. CONCLUSION

Computational simulations of SOVTE showed that semi-occlusion significantly increased phonation threshold pressure under conditions of weak vocal fold adduction and increased vocal fold contact duration under conditions of strong vocal fold adduction. These findings suggest that speakers may respond to these changes by adopting an intermediate vocal

fold adduction configuration, thereby reducing phonatory effort under weak adduction conditions and compensating for altered mechanosensory cues associated with increased vocal fold contact under strong adduction conditions. Although these hypothesized adaptations are consistent with previous observations in humans, further human studies are needed to validate these proposed mechanisms.

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AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the author upon reasonable request.

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