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Vocal tract adjustments to minimize vocal fold contact pressure during phonation

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ABSTRACT:
This computational study aims to identify vocal tract adjustments that minimize the peak vocal fold contact pressure during phonation and thus should be targeted in voice therapy treating phonotraumatic vocal hyperfunction. The results showed that for a given subglottal pressure, the effect of vocal tract adjustments on the peak vocal fold contact pressure was generally small except when such adjustments caused noticeable changes in the glottal flow amplitude. In this study, this occurred mainly when the lip opening was reduced and at conditions of large initial glottal angles or high subglottal pressures, which decreased the peak contact pressure but also significantly reduced the output sound pressure level (SPL). On the other hand, increasing lip opening significantly increased sound radiation efficiency from the mouth and reduced the subglottal pressure required to produce a target SPL. Because of the large effect of the subglottal pressure on the peak contact pressure, increasing lip opening thus was able to significantly reduce the peak contact pressure in voice tasks targeting a specific SPL. In contrast, the effect of pharyngeal expansion alone had only a small effect on the peak contact pressure, whether controlling for the subglottal pressure or targeting a specific SPL.
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I. INTRODUCTION

Phonotraumatic vocal hyperfunction is among the most frequently occurring voice disorders. While the underlying pathophysiology varies, this voice disorder involves vocal fold injury due to repeated, excessive mechanical stress sustained by vocal folds during voice production, particularly the contact pressure between the vocal folds when they collide. In the clinic, voice therapy attempts to modify the adducted hyperfunction generally acknowledged to underlie phonotraumatic lesions (Hillman *et al.*, 1989) through different techniques or exercises. It is generally believed that these approaches lead to adjustments in the larynx and vocal tract that improve vocal efficiency and economy, thus reducing vocal fold contact pressure (Titze, 2006). However, the specific adjustments induced by voice therapy and the scientific rationale for how these adjustments reduce vocal fold contact pressure remain unclear.

The long term goal of this research was to identify laryngeal and vocal tract adjustments that minimize vocal fold contact pressure and thus should be targeted in voice therapy treating phonotraumatic vocal hyperfunction. This study was a follow up to our recent numerical studies (Zhang, 2019, 2020), which investigated the effect of laryngeal adjustments on the vocal fold contact pressure during phonation. These studies showed that the peak vocal fold contact pressure can be minimized by adopting a barely-abducted, thin vocal fold configuration, as often promoted in voice therapy (e.g., resonant voice therapy, Verdolini-Marston *et al.*, 1995) and some approaches of voice training. In this study, we focused on the effect of vocal tract adjustments on vocal fold contact pressure.

There have been no systematic studies on how vocal fold contact pressure is impacted by different vocal tract adjustments, despite the fact that voice therapy often emphasizes vibratory sensations in certain parts of the vocal tract. Indeed, Grillo and Verdolini (2008) showed that resonant voice involves a perceptual quality that is not fully distinguished by measures of integrated respiratory/laryngeal parameters, indicating an important role of vocal tract adjustments. Previous imaging studies also reported more consistent and prominent changes in vocal tract configuration than vocal fold configuration after voice therapy (Hampala *et al.*, 2015). It is generally hypothesized that voice therapy results in vocal tract adjustments that enhance source-tract interaction. Titze (2006) argued that enhanced source-tract interaction, through increased vocal tract inertance or improved impedance matching between the voice source and the vocal tract, allows the supraglottal pressure to have an increased influence on glottal flow and vocal fold vibration, which would maximize vocal economy or the ratio between the output acoustic pressure and the vocal fold contact pressure during phonation.

However, these hypotheses are not always consistent with observations in recent imaging and simulation studies. For example, epilaryngeal narrowing is considered an

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important adjustment that enhances source-tract interaction and minimizes vocal fold contact pressure. While epilaryngeal narrowing has been observed during semi-occluded vocal tract exercises (SOVTE) in some studies (e.g., Guzman *et al.*, 2013a), some other imaging studies reported no noticeable epilaryngeal narrowing, and some even observed epilaryngeal expansion (e.g., Vampola *et al.*, 2011; Laukkanen *et al.*, 2012; Guzman *et al.*, 2013b; Guzman *et al.*, 2017; Hampala *et al.*, 2015; Patel *et al.*, 2019; Lulich and Patel, 2021). Our recent simulation study (Zhang, 2021) also showed that epilaryngeal narrowing does not always reduce the peak vocal fold contact pressure as previously hypothesized. However, these imaging studies also reported pharyngeal expansion, and it has been speculated that widening the pharynx may have the same effect as epilaryngeal narrowing (Titze and Laukkanen, 2007). Additionally, oral cavity expansion, increased mouth opening, and reduced velopharyngeal opening have been observed to occur consistently after SOVTEs (Vampola *et al.*, 2011; Guzman *et al.*, 2013b; Guzman *et al.*, 2017). It is possible that these additional vocal tract changes may reduce vocal fold contact pressure, although their effect on vocal fold contact pressure has not been investigated.

In this study, using an experimentally-validated three-dimensional voice production model, we manipulated vocal tract shape and observed how it affected the peak vocal fold contact pressure during phonation. To ensure that we manipulated the vocal tract in a realistic way as in humans, we manipulated the vocal tract based on computed tomography data of vocal tract changes before and after SOVTE as reported in Vampola *et al.* (2011). Specifically, seven vocal tract configurations were investigated. The first four configurations were vocal tract shapes before and after SOVTE reported by Vampola *et al.* (2011), with the post-SOVTE vocal tract showing expansion in the pharynx, oral cavity, and lip opening compared with the pre-SOVTE vocal tract. The other three vocal tract configurations were manipulations of the pre-SOVTE vocal tract, with expansion in the pharynx, oral cavity, and lip opening, respectively. These three additional vocal tracts were included to isolate and investigate the effect of volume expansion in individual regions of the vocal tract. Our previous studies (Zhang, 2020, 2021) showed that some adjustments reduce the peak contact pressure at the cost of reduced output sound pressure level (SPL), and thus are not practical in voice tasks with a desired SPL. Thus, in this study, we investigated the peak contact pressure in both tasks controlling for the subglottal pressure and tasks targeting a specific output SPL.

Our hypothesis was that vocal fold contact pressure and risk of vocal fold injury can be minimized by adopting vocal tract configurations that minimize the subglottal pressure required to produce a desired SPL. This was based on the finding from our recent computational simulations (Zhang, 2019, 2020, 2021) that the subglottal pressure has the most dominant effect on the peak vocal fold contact pressure compared with other controls of the vocal system. By comparison, the effect of laryngeal and vocal tract adjustments on vocal fold contact pressure is often smaller and sometimes inconsistent (i.e., may increase or decrease contact pressure depending on interaction between other laryngeal parameters and subglottal pressure; Zhang, 2021). Thus, effort targeting at minimizing vocal fold contact pressure should aim at minimizing the subglottal pressure, the most dominant determining factor of vocal fold contact pressure. Specifically, when targeting a specific SPL, we hypothesized that the vocal fold contact pressure can be reduced by vocal tract adjustments that maximize vocal efficiency, which would minimize the subglottal pressure required to produce the target SPL, thereby minimizing vocal fold contact pressure.

II. METHOD

A. Computational model and simulation conditions

The same three-dimensional body-cover vocal fold model as in our previous studies (Zhang, 2019, 2020, 2021) was used in this study. The reader is referred to these previous studies for details of the model (Zhang, 2017, 2019, 2020). The vocal fold geometry is parameterized by various geometric and mechanical properties of the vocal folds (Zhang, 2020). Previous studies (Berry *et al.*, 2001; Horáček *et al.*, 2009; Zhang 2020, 2021) showed that the initial glottal angle and the medial surface vertical thickness are two geometric measures with a large impact on the peak vocal fold contact pressure. In this study, due to the large number of vocal tract conditions, we considered parametric variation only in the initial glottal angle α ($-1.6°$, $0°$, $1.6°$, $4°$, and $8°$). The negative initial glottal angle corresponds to a pressed vocal fold configuration, whereas the $0°$–$1.6°$ and $4°$–$8°$ initial glottal angles roughly correspond to a barely-abducted and breathy vocal fold configuration, respectively. The vertical thickness was set to 3 mm, which has been shown to minimize both the peak contact pressure and the respiratory effort required to produce a target SPL (Zhang, 2021). The vocal fold model is fixed at the lateral surface and the two side surfaces at the anterior and posterior ends. 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 material control parameters for each vocal fold layer include the transverse Young's modulus E_t, AP Young's modulus E_{ap}, AP shear modulus G_{ap}, and density. The effect of these mechanical properties on vocal fold contact pressure has been investigated in detail in our previous studies (Zhang, 2019, 2020). In this study, the body and cover layers had identical mechanical properties, with E_t, G_{ap}, and E_{ap} set to 4, 10, and 40 kPa, respectively. 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 along the medial-lateral direction into the vocal fold is applied to the contact surface of the vocal fold (Zhang, 2019). The parameters of the penalty pressure model were 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). This voice production model has been able to qualitatively and quantitatively reproduce experimental observations (Zhang *et al.*, 2002; Zhang and Luu, 2012; Farahani and Zhang, 2016).

B. Vocal tract data and manipulations

The vocal tract is modeled as a one-dimensional waveguide coupled with a yielding vocal tract wall (Story, 1995). The effective mass, stiffness, and damping of the vocal tract wall was set to 16.3 kg/m^2, 2187.0 kN/m^3, and 13 980 N.s/m^3, respectively (Milenkovic and Mo, 1988). The vocal tract area functions were based on data reported in Vampola *et al.* (2011), which include vocal tract area functions of a single subject before, during, and after SOVTE. Specifically, four vocal tract area functions, two each before and after SOVTE, were used in this study. These are labeled as B1 and B2 for the two pre-SOVTE area functions, and A1 and A2 for the two post-SOVTE area functions, as shown in Fig. 1.

Since the post-SOVTE vocal tracts showed expansion in the pharynx, oral cavity, and mouth opening compared with the pre-SOVTE vocal tracts, three additional vocal tract configurations were considered in this study to isolate the effect of these individual vocal tract changes. These three configurations, labeled BP, BO, BL, were the same as the pre-SOVTE B1 vocal tract, but each with expansion in the pharynx, oral cavity, and mouth opening, respectively, to the same degree as in the post-SOVTE vocal tract A2, as shown in Fig. 1. Note that the post-SOVTE vocal tracts were also longer than the pre-SOVTE vocal tracts. This vocal tract lengthening effect was included in the BO vocal tract.

Vampola *et al.* (2011) also showed a reduced velopharyngeal opening after SOVTE. Because data on the nasal cavity were not available, no nasal tract was considered in this study, and the velopharyngeal port was closed for all seven vocal tract configurations.

For each vocal tract, the impulse response was obtained by exciting the vocal tract with an impulse input to the vocal tract entrance. The vocal tract transfer function, defined as the ratio between the vocal tract output and input acoustic volume velocities, and the vocal tract input impedance were then calculated from the impulse response. The vocal tract input impedance was further divided by the angular frequency to obtain the vocal tract input inertance. Note that the vocal tract inertance is defined only if the input reactance is positive.

C. Simulation conditions and data analysis

For each vocal tract condition, a half-second of voice production was simulated for 18 values of the subglottal pressure ranging from 50 Pa to 2.4 kPa, similar to Zhang (2020, 2021). From each simulation, the peak vocal fold contact pressure P_c over the medial surface was calculated using the last 0.25 s of each simulation, by which time vocal fold vibration had either reached steady state or nearly steady state. Note that although the peak contact pressure often occurred at the mid-membranous region, it may also occur at a more anterior or posterior location, depending on the specific vocal fold conditions (for detailed analysis, see Zhang, 2019, 2020). The A-weighted SPL was extracted from the output acoustics as described in Zhang (2016). An oral SPL was also calculated using the acoustic pressure inside the oral cavity at a location 8 mm from the lips. The mean (Ag0) and peak-to-peak amplitude (Agamp) of the glottal opening area and the maximum area declination rate (MADR; the most negative peak of the time derivative of the glottal area waveform) were extracted from the glottal area waveform. From the glottal flow waveform, the mean glottal flow rate (Qmean), the peak-to-peak amplitude (Qamp), and the maximum flow declination rate (MFDR; the most negative peak of the time derivative of the glottal flow waveform) were extracted. The MFDR and MADR measures have been used in previous studies (e.g., Titze, 2006) as indirect measures of the output SPL and vocal fold contact pressure, respectively. To isolate changes in MFDR/MADR associated with changes in waveform shape from those associated with amplitude changes, two normalized measures of the two declination rates, MFDRN and MADRN, were calculated by normalizing the MFDR and MADR values by (πF0·Qamp) and (πF0·Agamp), respectively, so that they are equal to one for a sinusoidal waveform.

III. RESULTS

A. Effect on vocal tract transfer function and input inertance

Figure 1 shows the vocal tract input inertance and vocal tract transfer function for different vocal tract conditions. The top three panels of Fig. 1 compare the pre-SOVTE vocal tract configuration B1 and the other three vocal tract configurations reported in Vampola *et al.* (2011). In general, post-SOVTE changes in vocal tract inertance were small except near vocal tract resonances where large changes in inertance occurred due to a slight shift in resonance frequencies. Such shift in resonance frequencies brought the first and second vocal tract resonances (R1 and R2) closer to each other, and also led to a clustering of R3, R4, R5, and R6 in the vocal tract transfer function for the post-SOVTE vocal tracts. As a result, the vocal tract transfer functions of A1 and A2 were shifted upward in the frequency range up to 6 kHz. The energy boost was particularly noticeable in the 3–5 kHz range.

The next three panels in Fig. 1 further show that R1 and R2 were brought closer to each other by a combined effect of the increased mouth opening and oral cavity expansion. The clustering of R3-R6 appeared to result from a combined effect of expansion in the oral cavity and pharynx (Sundberg, 1974): pharyngeal expansion increased R3 (compare B1 and BP), whereas oral cavity expansion decreased R3-R6 (compare B1 and BO). Note that pharyngeal expansion

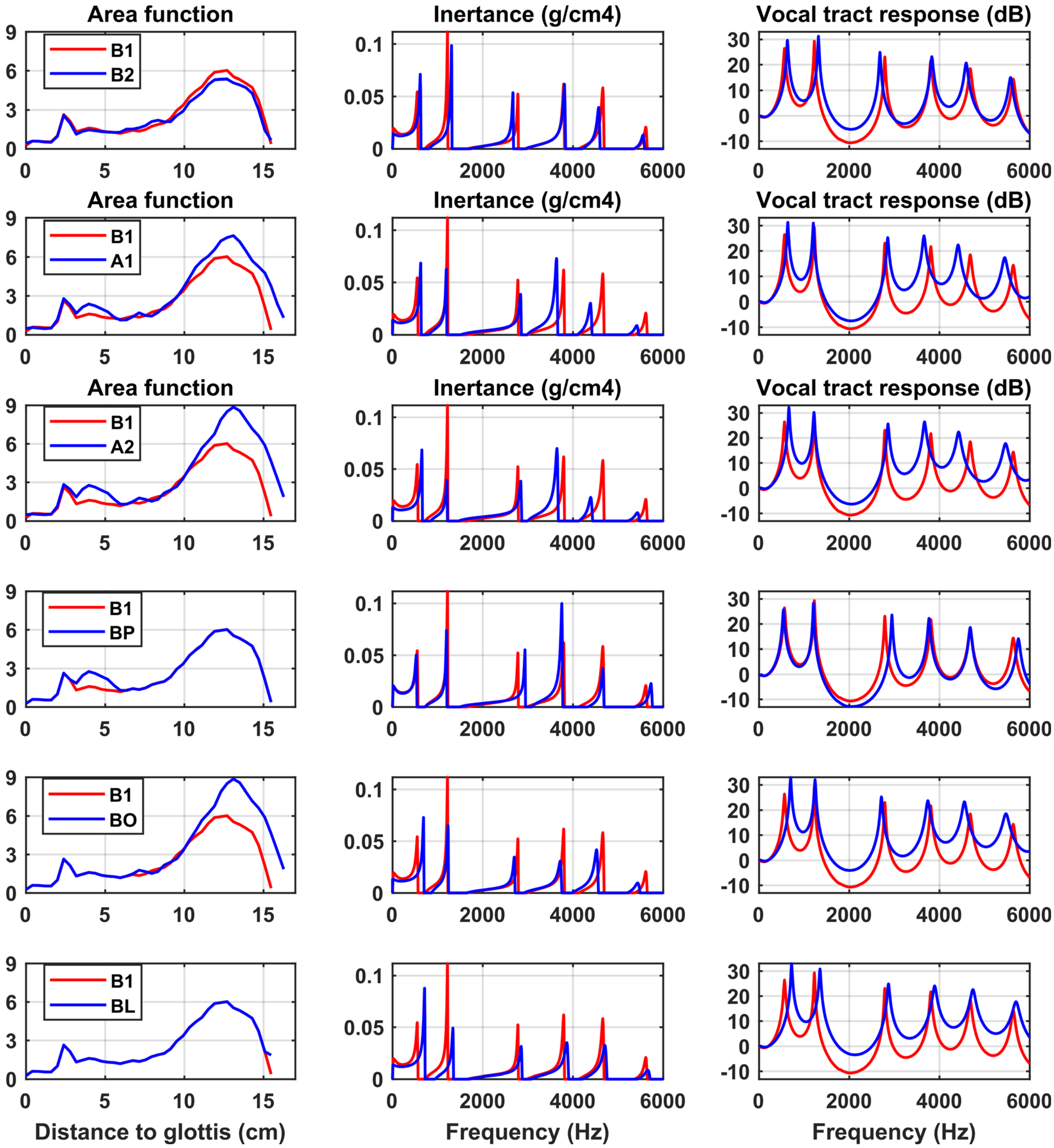

FIG. 1. (Color online) Comparison in the vocal tract area function, inertance, and vocal tract transfer function between the pre-SOVTE vocal tract B1 and the other six vocal tract configurations considered in this study. Vocal tract B1, B2, A1, and A2 are the two pre-SOVTE and two post-SOVTE vocal tract shapes reported in Vampola *et al.* (2011). The three additional vocal tract shapes are manipulations of the vocal tract B1 and A2 (BP: B1 with pharyngeal expansion; BO: B1 with oral expansion and increased mouth opening; BL: B1 with increased mouth opening). Notable post-SOVTE changes in the vocal tract include pharyngeal expansion, oral expansion, increased mouth opening, and vocal tract lengthening.

alone was not able to significantly boost energy in the vocal tract transfer function.

B. Effect on the produced acoustics

The upper-left panel of Fig. 2 compares the voice source spectra before and after SOVTE. The other panels in the figure show the output acoustic spectra and the corresponding voice source spectra for all seven vocal tract configurations. The data shown were for a subglottal pressure of 1.2 kPa and an initial glottal angle of 1.6°.

There was no noticeable difference in the voice source spectra across the four vocal tract configurations, indicating a negligible effect of vocal tract adjustments on the voice source for this particular initial glottal angle condition. The post-SOVTE vocal tract configurations provided better amplification of the voice source harmonics, particularly in the 3–5 kHz. In this frequency range, the B1 vocal tract

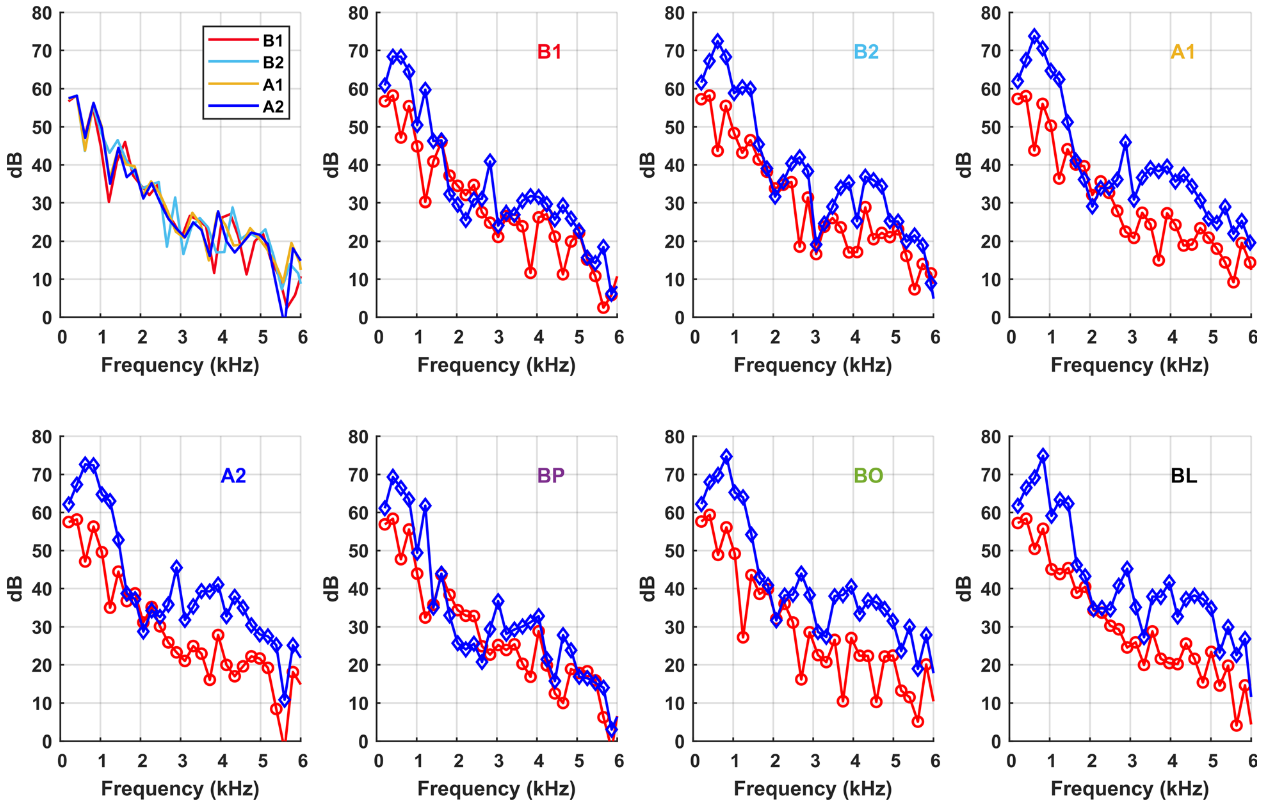

FIG. 2. (Color online) The upper-left panel compares the voice source spectra between vocal tract configurations before (B1 and B2) and after (A1 and A2) SOVTE. The rest of the panels compare the voice source spectra and output sound spectra for the seven vocal tract configurations (see Fig. 1 for the corresponding vocal tract area functions).

provided the least amplification of the voice source. B2 was slightly better than B1, likely due to the slightly larger mouth opening (Fig. 1). Pharyngeal expansion in the BP vocal tract did not lead to much improvement over the B1 vocal tract. The other four vocal tract (A1, A2, BO, and BL) all provided noticeable amplification of the voice source in the 3–5 kHz range. Compared with B1, these four vocal tract configurations also provided more energy boost in the frequency range below 2 kHz. These observations are consistent with those from the analysis of the vocal tract transfer function.

Figure 3 (bottom row) shows that the B1 and BP configurations consistently produced the lowest output SPL among all vocal tract configurations, whereas the BO and BL configurations generally produced the highest SPL. In general, the output SPL was positively related to the lip opening area, indicating a strong effect of the lip opening on the SPL. An increased lip opening improved radiation efficiency and led to an upward shift of the vocal tract transfer function, particularly in the regions of R1 and R2, as shown in Fig. 1. In contrast, the SPL inside the oral cavity was the highest for the two pre-SOVTE vocal tracts, and the lowest for the two post-SOVTE vocal tracts. This was probably due to the smaller lip opening in the pre-SOVTE configurations, which reduced sound radiation from the lips and allowed sound pressure to build up inside the oral cavity.

C. Effect on aerodynamics and vocal fold vibration

Figure 3 compares different measures of voice production and the peak vocal fold contact pressure. In general, the effect of vocal tract adjustments on the mean glottal flow and mean glottal area was small. The same was true for the peak-to-peak amplitudes of the glottal flow and area waveforms, except for the B1 and BP vocal tract configurations at the largest initial glottal angle where there was a noticeable decrease in both the glottal flow and area amplitudes. Note that the main difference between the B1 and BP configurations and the other configurations was the degree of mouth opening. This suggests that this effect on the glottal flow amplitude was likely due to the small mouth opening in the B1 and BP configurations. Indeed, this small mouth opening led to a notably higher vocal tract impedance in B1 and BP at the $F0$ of vocal fold vibration compared with other vocal tract configurations (Fig. 4, left panel). Note that this effect of increasing vocal tract impedance on reducing the glottal flow amplitude was the largest at large initial glottal angles (top row, Fig. 3), which provided an improved impedance matching between the voice source and the tract (Fig. 4, middle panel) and allowed a greater influence of vocal tract acoustics on the glottal flow amplitude. In general, the effect of vocal tract configuration on the mean and amplitude of the glottal area was smaller than that for the glottal flow, similar to that in Zhang (2021).

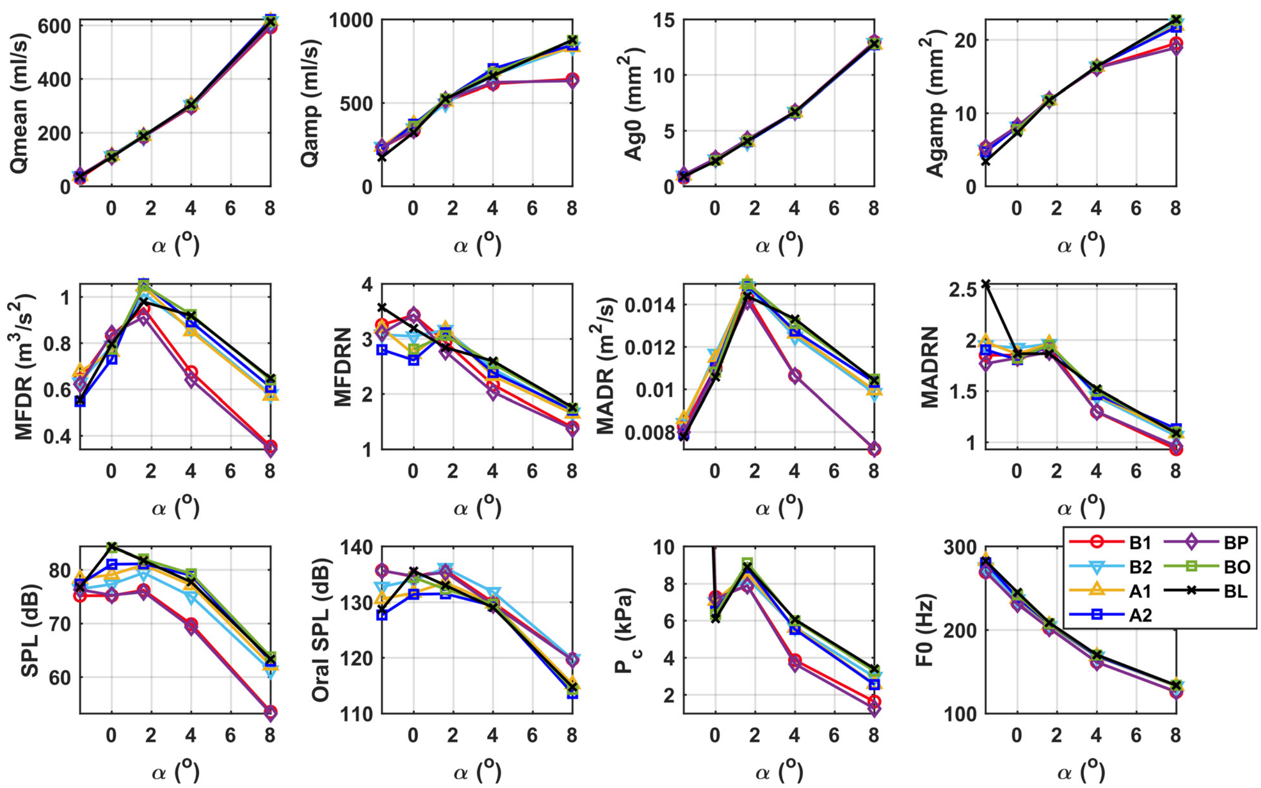

FIG. 3. (Color online) Measures of voice production for the seven vocal tract configurations and a subglottal pressure of 1.2 kPa, including the means and peak-to-peak amplitudes of the glottal flow (Qmean, Qamp) and glottal area (Ag0, Agamp), MFDR, and its normalized value (MFDRN), MADR and its normalized value (MADRN), output SPL, SPL within the oral cavity (oral SPL), peak contact pressure (P_c), and fundamental frequency ($F0$). See Fig. 1 for the seven vocal tract configurations.

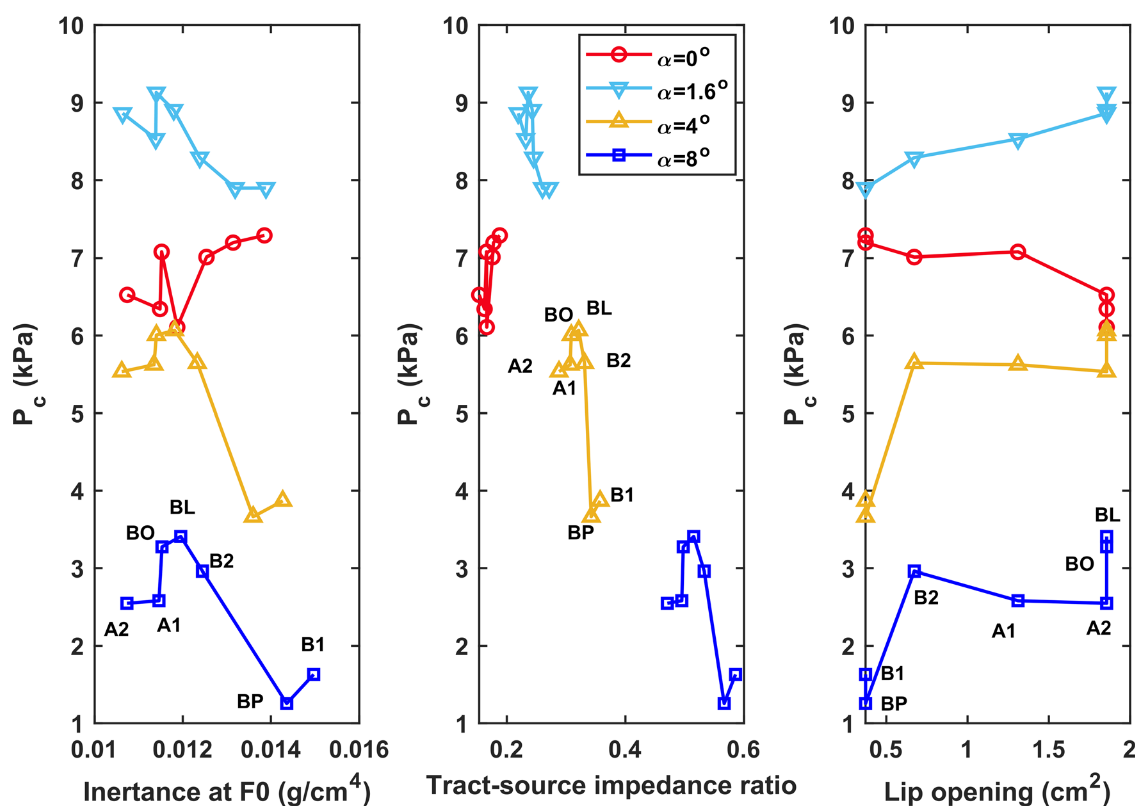

FIG. 4. (Color online) The peak vocal fold contact pressure as a function of the vocal tract inertance at the $F0$ (left), tract-source impedance ratio (middle), and lip opening area (right), for a subglottal pressure of 1200 Pa.

Due to the reduced amplitudes of the glottal flow and area waveforms, the MFDR and MADR were noticeably lower for the B1 and BP configurations at large initial glottal angles. After normalization for these amplitude changes, the effect of vocal tract configuration on the MFDRN and MADRN was generally small. This is consistent with the small effect of vocal tract adjustments on the voice source spectra discussed above at small initial glottal angles. It seems that the MFDRN and MADRN were noticeably lower for the B1 and BP configurations at large initial glottal angles, but this trend appeared to be reversed for MFDRN at small and negative initial glottal angles.

D. Effect on peak vocal fold contact pressure

A multiple linear regression was performed to relate the peak vocal fold contact pressure and the model control parameters, including the subglottal pressure, initial glottal angle, lip opening area, pharyngeal expansion, and oral cavity expansion (left side of Table I). Although the two variables representing pharyngeal expansion and oral cavity expansion were binary in nature, they were treated as numerical variables with values 1 for vocal tracts with volume expansion and 0 for vocal tracts without volume expansion. The analysis showed that the peak vocal fold contact pressure was primarily determined by the subglottal pressure, similar to our previous observations (Zhang, 2020, 2021), followed by the initial glottal angle and then the lip opening area. No statistically significant effect was observed for pharyngeal or oral cavity expansion. When vocal tract adjustments were collectively represented by vocal tract inertance (right side of Table I), the regression also showed a statistically significant effect of vocal tract inertance, with the peak contact pressure decreasing with increasing vocal tract inertance.

Figure 3 shows that the peak contact pressure was the highest for the negative initial glottal angle, decreased with increasing initial glottal angle, reached a local maximum at the initial glottal angle of 1.6°, then decreased rapidly with further increase in the initial glottal angle. This is consistent with the findings in Berry *et al.* (2001) and Zhang (2020).

In comparison, the effect of vocal tract adjustments was generally smaller. For large initial glottal angles (1.6°–8°), the peak vocal fold contact pressure was the highest for the BL and BO configurations, followed by A1, A2, and B2, and was the lowest for the B1 and BP configurations. Note that the B1 and BP configurations had the highest inertance at the $F0$ frequency range (around 125–210 Hz). This seems to indicate that the peak vocal fold contact pressure is lowered by increasing inertance. However, this trend was reversed for conditions of small and negative initial glottal angles (–1.6°–0°), with the B1 and BP configuration producing the highest peak vocal fold contact pressure.

This complex relationship is more clearly illustrated in Fig. 4 (left panel), which shows the peak contact pressure as a function of the vocal tract inertance at the $F0$. While the figure appears to show an inverse relationship between the peak contact pressure and the inertance at large initial glottal angles, a closer look shows that this inverse relationship was largely due to the much lower peak contact pressures for vocal tracts B1 and BP. When these two vocal tracts were excluded, the effect of the inertance on the peak contact pressure was much smaller and no clear patterns can be observed.

The much lower peak contact pressure in vocal tracts B1 and BP compared with other vocal tract configurations was likely due to the reduced amplitude of the glottal flow waveform, which resulted from the high vocal tract impedance in B1 and BP (Fig. 4). Note again that this effect was the largest at large initial glottal angles when the tract-source impedance ratio was the highest, thus allowing greater influence of vocal tract adjustments on the voice source. Figure 4 also explains why vocal tract B2 produced a glottal flow amplitude and peak contact pressure comparable to those in A1 and A2, despite a vocal tract shape similar to vocal tract B1: the vocal tract inertance for B2 was much closer to A1 and A2 than B1 and BP (Fig. 4, left panel).

That the low peak contact pressure in B1 and BP at large initial glottal angles was due to the reduced glottal flow amplitude was further supported by Fig. 5, which shows the peak contact pressure and other relevant measures at low and high subglottal pressures (800 and 1800 Pa, respectively). The reduction in the peak contact pressure for vocal tracts B1 and BP was closely correlated with the reduction in the glottal flow amplitude for both subglottal pressures. Note that the glottal area amplitude remained almost the same while the glottal flow amplitude was reduced for Ps = 1800 Pa. This suggests that vocal fold vibration was less susceptible to vocal tract influence, but on the other hand, this also means that the reduced peak contact pressure was related to subtle changes in vocal fold vibration that were not quantified by the glottal area amplitude.

In summary, our results showed that the effect of vocal tract adjustments on the peak vocal fold contact pressure was generally small except when the adjustments led to significant changes in the glottal flow amplitude. In this study, this occurred at large initial glottal angles or high subglottal pressures when the lip opening area was noticeably altered. As a result, the pre-SOVTE configuration B1 (and vocal tract BP) produced lower peak vocal fold contact pressure

TABLE I. Standardized coefficients of multiple linear regressions between the peak contact pressure and two sets of model control parameters.

	Peak contact pressure		Peak contact pressure
Ps	0.939[a]	Ps	0.934[a]
α	−0.097[a]	α	−0.085[a]
Lip opening area	0.079[a]	Inertance	−0.078[a]
Pharynx expansion	−0.031		
Oral expansion	0.007		

[a]Denotes parameters with $p < 0.005$ and thus statistically significant.

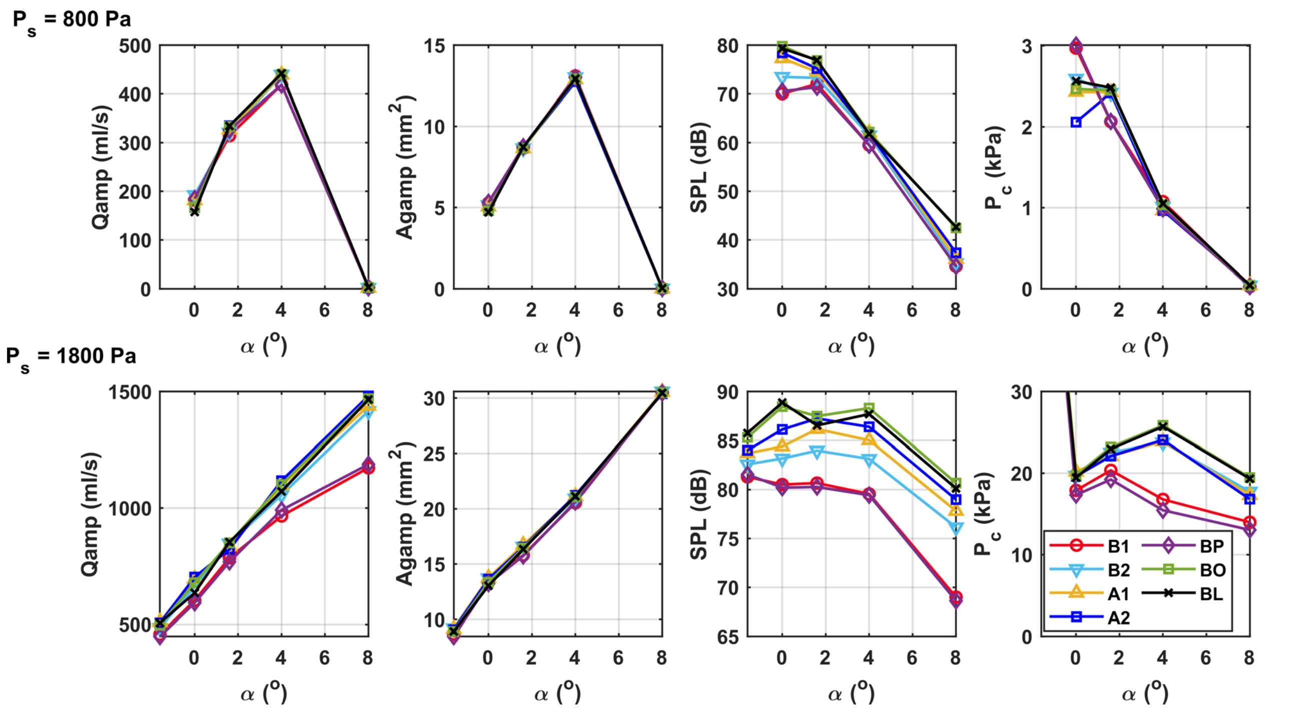

FIG. 5. (Color online) The glottal flow amplitude (Qamp), glottal area amplitude (Agamp), SPL, and peak vocal fold contact pressure (P_c) as a function of the initial glottal angle for the seven vocal tract shapes at a subglottal pressure of 800 Pa (top) and 1800 Pa (bottom).

than the post-SOVTE vocal tract configurations (and vocal tract B2) at high subglottal pressures or large initial glottal angles. However, this reduction in the peak contact pressure due to reduced lip opening also significantly reduced the output SPL, and thus may not be practical in voice tasks with a desired SPL.

E. Effect on peak contact pressure when producing a target SPL level

In this section, we considered voice tasks targeting a specific output SPL. Figure 6 shows the peak vocal fold contact pressure and the subglottal pressure required to produce an output SPL within ±3 dB of a target 80 dB SPL. The

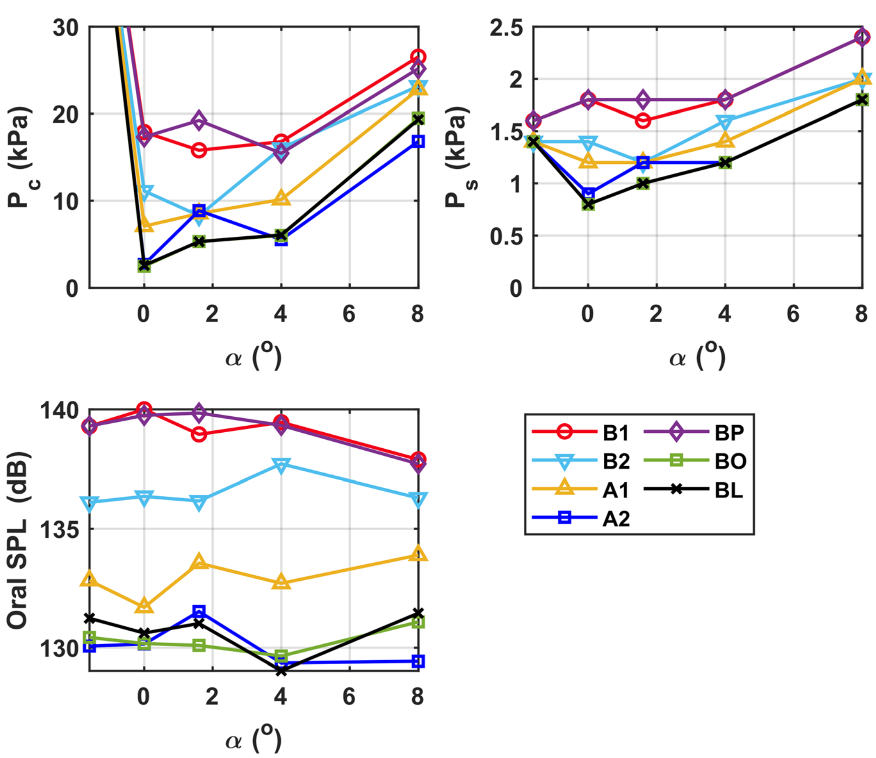

FIG. 6. (Color online) The peak vocal fold contact pressure and subglottal pressure required to produce an 80 dB SPL for the seven vocal tract configurations as a function of the initial glottal angle. The bottom panel shows the SPL within the oral cavity.

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peak vocal fold contact pressure remained low at small initial glottal angles but increased significantly at the largest initial glottal angle, which is consistent with the observation in our previous studies (Zhang, 2020, 2021).

In general, the B1 and BP vocal tract configurations produced the highest peak contact pressure across all initial glottal angles, whereas the BO and BL configurations produced the lowest peak contact pressure. The other three vocal tract configurations produced a peak contact pressure somewhere in between, with the B2 vocal tract generally producing a higher peak contact pressure than the A1 and A2 vocal tract configurations. The trends of the peak vocal fold contact pressure across different vocal tract configurations were similar to those for the subglottal pressure required to produce an 80 dB output SPL, and was negatively related to the lip opening area (Fig. 4, right panel). This indicates that the observed effect of vocal tract adjustments on the peak contact pressure was largely determined by how these adjustments affected the subglottal pressure required to produce the target SPL, similar to observations in our previous studies (Zhang, 2020, 2021). Specifically in this study, how these adjustments affected the required subglottal pressure appeared to depend largely on the lip opening area.

Figure 7 shows the spectra of the voice source and output acoustics for the seven vocal tract configurations when producing an 80 dB output SPL, for an initial glottal angle of 0°. Although the output sound spectra generally had similar spectra shape, the energy level in the source spectra was noticeably higher for pre-SOVTE vocal tract configurations (B1 and B2) than the other vocal tract configurations. In particular, the source spectra for A2, BO, and BL were about 10 dB lower than the source spectrum for the B1 vocal tract. This reduced energy level in the voice source spectra was responsible for the reduced peak contact pressure.

IV. DISCUSSION

This study showed that for a given subglottal pressure, the effect of vocal tract adjustments on the peak vocal fold contact pressure was generally small except when the adjustments led to significant changes in vocal tract impedance and the glottal flow amplitude. Specifically in this study, this occurred when the lip opening was reduced and at conditions of high subglottal pressures or large initial glottal angles, which reduced the peak contact pressure but also the output SPL. At low subglottal pressures and small initial glottal angles, such adjustment increased the peak contact pressure but the effect was generally small.

Our results also showed that vocal tract adjustments had a much larger effect on the output SPL, and were able to significantly reduce the subglottal pressure required to produce a target SPL. Thus, when targeting a specific SPL, the peak contact pressure can be more effectively reduced by adopting vocal tract adjustments (e.g., increasing lip opening) that minimize the subglottal pressure required to produce the

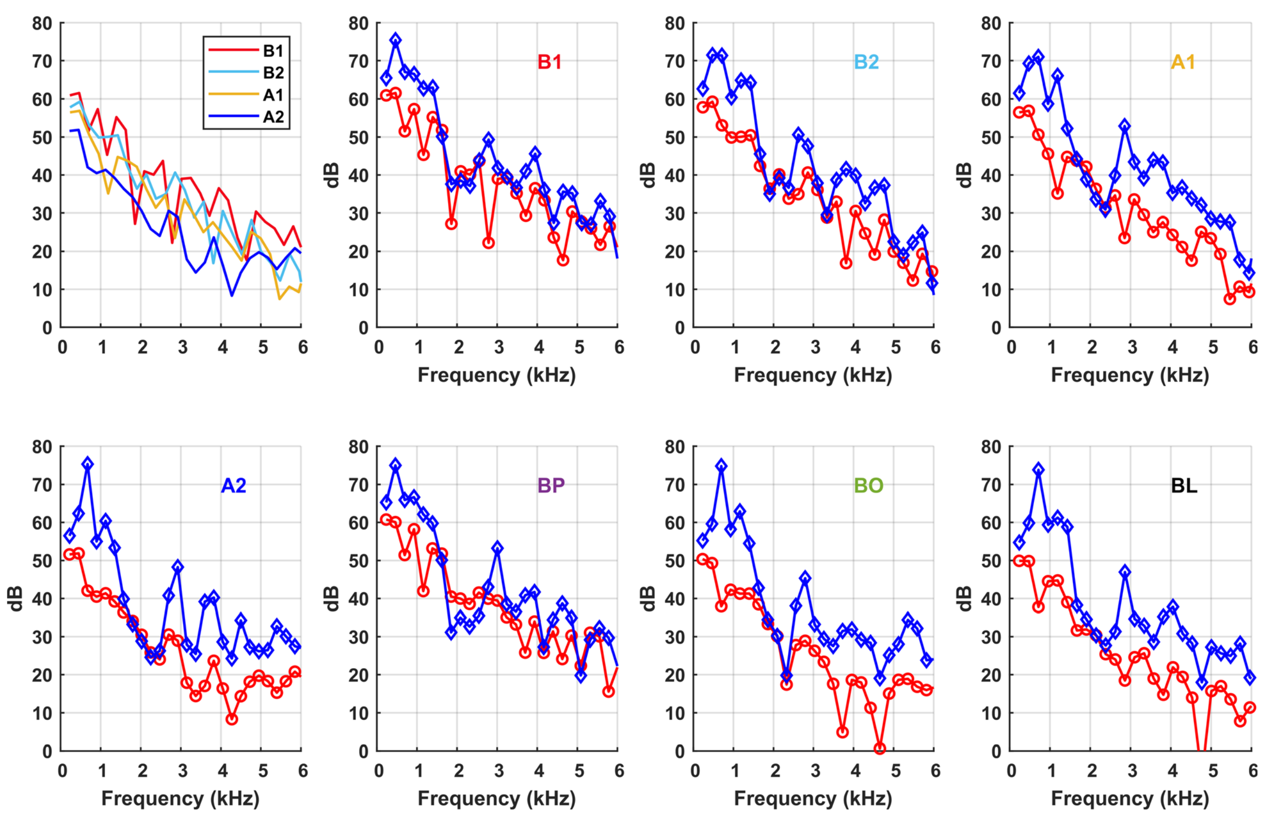

FIG. 7. (Color online) The upper-left panel compares the voice source spectra between pre-SOVTE (B1 and B2) and post-SOVTE (A1 and A2) vocal tracts when producing an 80 dB output SPL. The rest of the panels compare the voice source spectra and output sound spectra for the seven vocal tract configurations producing an 80 dB SPL.

target SPL, due to the much larger effect of the subglottal pressure on the peak contact pressure (Zhang, 2020).

Thus, our results showed that compared with the pre-SOVTE vocal tract B1, the post-SOVTE vocal tract configurations reported by Vampola *et al.* (2011) actually increased the peak contact pressure for a given subglottal pressure. However, these post-SOVTE configurations were able to significantly reduce the peak contact pressure in voice tasks targeting a specific SPL.

Our results further showed that the observed changes in the peak contact pressure were largely due to changes in the lip opening area. The effect of an increased lip opening is twofold. First, increasing lip opening reduces the input impedance of the vocal tract and increases the amplitudes of the glottal flow waveform (Fig. 3), thus increasing peak contact pressure for a given subglottal pressure (compare vocal tract BL with vocal tract B1). On the other hand, increasing lip opening increases the efficiency of sound radiation from the mouth, thus increasing the output SPL. This reduces the subglottal pressure required to produce a target SPL and the corresponding peak contact pressure in voice tasks targeting a specific SPL. In contrast, adding oral cavity expansion to the vocal tract BL did not produce much difference in the peak vocal fold contact pressure (compare vocal tracts BL and BO). This indicates that oral cavity expansion alone, without increasing lip opening, had only a small effect on the peak contact pressure.

It has been hypothesized that widening the pharynx may have the same effect of epilaryngeal narrowing and may increase vocal economy (Titze and Laukkanen, 2007). However, our results showed that pharyngeal expansion alone (compare vocal tracts B1 and BP), without simultaneous expansion in the oral cavity or lip opening, had almost no effect on the SPL and the peak vocal fold contact pressure. Only at high subglottal pressures and large initial glottal angles did pharyngeal expansion lead to a noticeable but small reduction in the peak contact pressure (Fig. 5). This small effect was consistent with the observation in Fig. 1 that pharyngeal expansion had little effect on the low-frequency inertance or vocal tract transfer function other than a slight shift of the third vocal tract resonance frequency.

Overall, the results are consistent with findings from previous studies. In particular, the relatively small effect of vocal tract adjustments is consistent with our previous finding that the effect of vocal tract acoustics on voice production is small except when the $F0$ approaches one of the vocal tract resonances (Zhang *et al.*, 2009). The small yet complex effect of vocal tract adjustments on the peak contact pressure was similar to that of epilaryngeal narrowing in Zhang (2021). Titze (2006) showed that a narrow-wide vocal tract with a wide lip opening had the highest efficiency and economy. This is consistent with our finding that compared with pre-SOVTE vocal tract configurations, the post-SOVTE vocal tracts (with a wider lip opening) produced higher SPL for a given subglottal pressure and had lower peak contact pressure when producing a target SPL. Titze (2006) also noted that maximization of efficiency and economy in this configuration required fine tuning of the initial glottal angle in a restricted range around a 0 mm glottal gap. This contrasts with the finding of our study that the low peak contact pressure can be maintained in a relatively wide range of initial glottal angles (Fig. 6). Note that different vocal fold models were used in the study by Titze (2006) and our study. This discrepancy may also result from the different settings of vocal fold properties. For example, our previous studies (Zhang, 2020, 2021) have shown that the range of initial glottal angels producing low peak contact pressure is generally wider for thinner vocal folds.

The results of this study support our hypothesis that when targeting a specific SPL, the peak vocal fold contact pressure can be more consistently lowered by adopting laryngeal and vocal tract strategies to minimize the subglottal pressure required to produce the target SPL. Although vocal tract adjustments by themselves have some effect on the peak vocal fold contact pressure and sometimes even increase the contact pressure, this effect is much smaller than that of the subglottal pressure. Thus, the overall effect of vocal tract adjustments is still determined by how these adjustments affect the subglottal pressure required to produce a target SPL, as shown in Fig. 6. Taken together, this study and our previous studies (Zhang, 2020, 2021) showed that when targeting a specific SPL, the peak vocal fold contact pressure can be lowered by adopting a barely-abducted, thin vocal fold configuration, epilaryngeal narrowing, and widening lip opening whenever possible.

Our results showed that the SPL within the oral cavity was higher for the pre-SOVTE vocal tracts than the post-SOVTE vocal tracts, when either controlling for the subglottal pressure or targeting a specific output SPL. This is likely due to the smaller lip opening in the pre-SOVTE vocal tracts, which reduced sound radiation from the mouth and allowed sound pressure to build up more easily in the oral cavity. Thus, semi-occlusion at the lips enhances vibratory sensations in the oral cavity. However, it is unlikely that this reduced lip opening is what is being targeted by vocal exercises focusing on vibratory sensations in the vocal tract. It is more likely that by focusing on vibratory sensations in the vocal tract, these vocal exercises lead to an open larynx configuration. Although vocal tract adjustments had no noticeable effect on the mean glottal opening area (Fig. 3), in vocal exercises involving lip trills, tongue trills, and voiced bilabial fricatives, the speaker has to adopt a more abducted vocal fold configuration in order to establish sufficient oral pressure required to produce these vocal exercises. An open laryngeal configuration may also be achieved passively by increasing intraglottal pressure, for example by phonation into water or a narrow tube that provides sufficient airflow resistance much higher than observed in this study. This needs to be investigated further in future studies.

In this study, while the vocal tract adjustments were based on human data reported in Vampola *et al.* (2011), the vocal fold configuration, both geometry and stiffness, was based on our previous simulations since little information was available on the geometry and stiffness from the same subject. It has been shown that vocal exercises may induce compensatory adjustments in the laryngeal and/or respiratory subsystems, which may change the vertical larynx position, degree of vocal fold adduction, and/or subglottal pressure (e.g., Guzman *et al.*, 2016). It is possible that the subject in the study by Vampola *et al.* (2011) may have made simultaneous laryngeal adjustments (although nothing prominent was observed in Hampala *et al.*, 2015) that allow a much larger effect of the vocal tract adjustments on voice production than observed in this study, due to a better source-tract coupling (e.g., formant tuning). Thus, the findings of this study need to be verified in experiments in which adjustments in both the vocal fold and vocal tract configurations are simultaneously measured, or in simulation studies with parametric variations in both the vocal fold and vocal tract configurations.

V. CONCLUSIONS

Our results showed that for a given subglottal pressure, the effect of vocal tract adjustments on the peak vocal fold contact pressure was generally small, except when the adjustments reduced the glottal flow amplitude. In this study, this occurred when the lip opening was reduced and at conditions of high subglottal pressures or large initial glottal angles, which decreased the peak contact pressure but at the cost of reducing output SPL. On the other hand, while increasing lip opening may increase the peak contact pressure for a given subglottal pressure, it increased vocal efficiency and reduced the subglottal pressure required to produce a target SPL, and thus was able to significantly reduce the peak vocal fold contact pressure in voice tasks targeting a specific SPL. Overall, the findings of this study support the hypothesis that vocal fold contact pressure and risk of vocal fold injury can be minimized by adopting vocal tract configurations (e.g., increasing lip opening or epilaryngeal narrowing) that minimize the subglottal pressure required to produce a desired SPL.

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