JASA ARTICLE

Contribution of laryngeal size to differences between male and female voice production

Zhaoyan Zhang[a)]
Department of Head and Neck Surgery, University of California, Los Angeles, 31-24 Rehabilitation Center, 1000 Veteran Avenue, Los Angeles, California 90095-1794, USA

ABSTRACT:
In this study we investigated the effect of sex- and age-related differences in vocal fold length, thickness, and depth on voice production in a three-dimensional vocal fold model. The results showed that the cause-effect relationships between vocal fold physiology and voice production previously identified in an adult male-like vocal fold geometry remained qualitatively the same in vocal folds with geometry representative of adult females and children. We further showed that the often-observed differences in voice production between adult males, adult females, and children can be explained by differences in length and thickness. The lower F0, higher flow rate, larger vocal fold vibration amplitude, and higher sound pressure level (SPL) in adult males as compared to adult females and children can be explained by differences in vocal fold length. In contrast, the thickness effect dominated and contributed to the larger closed quotient of vocal fold vibration, larger normalized maximum flow declination rate, and lower H1-H2 in adult males as compared to adult females and children. The effect of differences in vocal fold depth was generally small. When targeting a specific SPL, adult males experienced a lower peak vocal fold contact pressure during phonation than adult females and children. https://doi.org/10.1121/10.0009033

(Received 17 August 2021; revised 21 November 2021; accepted 24 November 2021; published online 28 December 2021)

[Editor: James F. Lynch] Pages: 4511–4521

I. INTRODUCTION

This study aimed to investigate how voice production is affected by sex- and age-related differences in vocal fold length, thickness, and depth. This study was part of a series of large-scale parametric computational studies (Zhang, 2016a, 2017, 2020) in an effort to understand the cause-effect relationships between vocal fold physiology and voice production. In these previous studies, the cause-effect relationships were investigated in vocal folds with geometry based largely on adult male larynges. In humans, the vocal fold length, thickness, and depth are known to differ significantly between adult males and adult females and vary with age in children (Kahane, 1978; Hirano *et al.*, 1983; Titze, 1989; Hirano and Kakita, 1985). The goal of this study was thus to investigate whether the cause-effect relationships between vocal fold physiology and voice production identified in our previous studies remain the same in vocal folds with geometry more representative of adult females and children.

A related question of this study was whether differences in laryngeal size alone (length, thickness, and depth) are able to produce the often-reported differences in voice production between adult males, adult females, and children. Notable differences in fundamental frequency, aerodynamics, vocal efficiency, and voice quality have been observed between adult males, adult females, and children (Hirano *et al.*, 1983; Holmberg *et al.*, 1988; Stathopoulos and Sapienza, 1993; Tang and Stathopoulos, 1995; Patel *et al.*, 2015; Patel and Ternström, 2021). Compared to the adult female and children's voice, the adult male voice generally has a lower fundamental frequency (F0), higher vocal intensity, uses higher glottal flow, and has a larger vocal fold vibration amplitude. Adult male vocal folds often vibrate with a relatively longer period of glottal closure and a higher normalized maximum flow declination rate. Children often use higher subglottal pressures during phonation and have lower vocal efficiency than adults. While these differences are often attributed to the underlying physiological differences between adult males, adult females, and children in previous studies [e.g., Titze and Talkin (1979), Titze (1989), Lucero and Koenig (2005), and Hunter *et al.* (2011)], there have been few systematic investigations on how differences in vocal fold length, thickness, and depth affect voice production. In particular, few studies have attempted to isolate the effect of individual changes in vocal fold length, thickness, and depth on voice production, due to difficulties in isolating the effects of individual geometric parameters in humans or animal models in which vocal fold geometry often co-varies with vocal fold stiffness (Hirano and Kakita, 1985; Zhang, 2016b).

In this study, by performing voice production simulations with parametric variations in vocal fold geometry, we hoped to provide a better understanding of what voice differences can be expected from sex- and age-related size differences alone. Such an understanding would allow us to better differentiate variability in voice production related to physiological differences (e.g., laryngeal size differences

a)Electronic mail: zyzhang@ucla.edu, ORCID: 0000-0002-2379-6086.

related to sex or age) from those resulting from behavioral differences in the use of vocal mechanisms [e.g., adult females may make greater use of breathy voice quality with a wider glottal angle and often have a larger dynamic pitch range and make sharp pitch modulation; Titze (1989), Kreiman and Sidtis (2011), and Zimman (2018)]. This may help to develop better computer programs for speaker gender recognition (Shue and Iseli, 2008; Bishop and Keating, 2012) and voice production inversion (Zhang, 2020b). A better understanding of the size-related differences in voice production would also provide insight into the development of vocal production and control in children. For example, while the higher values of subglottal pressures in children as compared to adults during phonation are often attributed to the high flow resistance associated with the small airway, it may also be that the small larynx size poses more restricted phonation threshold conditions (Lucero and Koenig, 2005), or that children may have a comfortable speaking level that is higher than adults (Stathopoulos and Weismer, 1985).

Understanding the effect of laryngeal size on voice production is also of clinical importance. Adult females are more likely than adult males to experience vocal health problems, in particular vocal fold mass lesions such as nodules (Miller and Verdolini, 1995; Roy *et al.*, 2004). The underlying mechanisms remain unclear. Titze (1989) argued that if the impact velocity were not very different across sex, the high F0 and thus high frequency of collision in adult female and children's voices would predispose them to have higher incidence of vocal fold injury. It is possible that other size-related differences in the vocal fold vibratory pattern may also play a role. For example, Xuan and Zhang (2014) showed that shorter vocal folds often vibrated with more complete closure than longer vocal folds, implying higher vocal fold contact pressure in shorter vocal folds. In addition to the length difference, adult male vocal folds generally are thicker than adult female vocal folds in the vertical direction, although the thickness effect on vocal fold injury is less clear. The thinner vocal folds in adult females are often hypothesized to provide less tissue to damp or absorb vibratory forces and thus increase risk of vocal fold injury in adult females (Roy *et al.*, 2004; Hunter *et al.*, 2011). However, more recent simulations showed that thinner vocal folds generally experience lower vocal fold contact pressure during phonation (Zhang, 2019, 2020). The parametric simulation design of this study would allow us to evaluate both the individual and combined effect of these geometric differences, which would provide a clearer picture of whether differences in laryngeal size alone predispose a specific sex or age group to vocal health problems.

In this study, individual effects of changes in vocal fold length, thickness, and depth were first investigated in simulations with parametric variations in vocal fold length, thickness, and depth. Findings from this parametric study provided a foundation to better understand voice production differences due to combined changes in vocal fold length, thickness, and depth, as in cases of larynges of different sex and age. In this study, this combined effect was considered in three geometric conditions representative of adult males, adult females, and children, in order to evaluate the contribution of laryngeal size differences to the often-reported sex- and age-related voice differences between adult males, adult females, and children.

II. METHOD

A. Computational model and simulation conditions

The three-dimensional body-cover vocal fold model used in this study has been described in detail in our previous studies (Zhang, 2016a, 2017, 2019, 2020). The reader is referred to these previous studies for details of the model. A sketch of the vocal fold model is shown in Fig. 1. Left-right symmetry in vocal fold properties (geometry, material properties, and position) about the glottal midline is imposed so that only one vocal fold is modeled. The vocal fold is geometrically parameterized by five control parameters, including the vocal fold medial surface vertical thickness T, vocal fold length L, body- and cover-layer depths D_b and D_c, and initial glottal angle α which controls the degree of vocal fold approximation. 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, the AP Young's modulus E_{ap}, the AP shear modulus G_{ap}, and density. 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).

Table I shows the parametric values for the geometric and mechanical properties of the vocal fold and the subglottal pressure P_s investigated in this study. In our previous studies, the vocal fold length L, body-layer depth D_b, and cover-layer depth D_c were kept constant at 17, 6, and

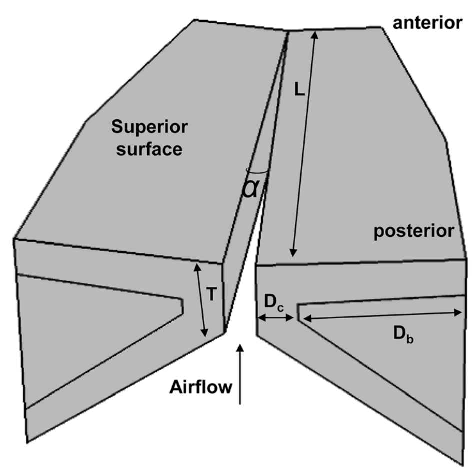

FIG. 1. The three-dimensional vocal fold model and key geometric control parameters, including the vocal fold length L along the anterior-posterior direction, vertical thickness of the medial surface T, body-layer and cover-layer depths D_b and D_c, and the initial glottal angle α.

TABLE I. Ranges of model control parameters. For all conditions, the vocal fold density was 1030 kg/m^3, the AP Poisson's ratio was 0.495, and $E_{ap} = 4G_{ap}$ was assumed.

Transverse Young's modulus	$E_t = [1, 2, 4]$ kPa
Cover AP shear modulus	$G_{apc} = [1, 10, 20, 30, 40]$ kPa
Body AP shear modulus	$G_{apb} = [1, 10, 20, 30, 40]$ kPa
Vertical thickness	$T = [1, 2, 3, 4.5]$ mm
Cover layer depth	$D_c = [1, 1.5]$ mm
Body layer depth	$D_c = [4, 6, 8]$ mm
Vocal fold length	$L = [6, 10, 17]$ mm
Initial glottal angle	$\alpha = [0°, 1.6°, 4°, 8°]$
Subglottal pressure	P_s = 200–1800 Pa (13 steps)

1.5 mm, respectively. In this study, three values of the vocal fold length L (6, 10, and 17 mm) were considered, each representing a typical length for the membranous vocal fold for children [about 8–10 years old; Titze (1989)], adult female, and adult males. Note that our model currently does not include the cartilaginous component of the vocal fold, inclusion of which should be straightforward and will be addressed in a future study. Two values were used for the cover layer depth D_c (1 and 1.5 mm), based on data reported in Hirano and Kakita (1985). The range of the body-layer depth D_b (4, 6, and 8 mm) was based on our recent measurements using magnetic resonance imaging of human larynges (Wu and Zhang, 2016, 2019; Zhang *et al.*, 2020). The initial glottal angle α was varied between 0° and 8°, corresponding to adduction conditions ranging from normal to breathy phonation.

The subglottal pressure was varied between 200 and 1800 Pa, which covers the range in normal phonation as well as some pathological conditions (Holmberg *et al.*, 1988; Gillespie *et al.*, 2013; Desjardins *et al.*, 2021). The ranges for the other control parameters were the same as in our previous studies [e.g., Zhang (2017)], which were based on previous experimental and computational studies (Hollien and Curtis, 1960; Titze and Talkin, 1979; Hirano and Kakita, 1985; Alipour-Haghighi and Titze, 1991; Alipour *et al.*, 2000; Zhang *et al.*, 2017).

The density of the vocal fold was assumed to be 1030 kg/m^3. The AP Poisson's ratio was assumed to be 0.495. As in previous studies (Zhang, 2017), to reduce the number of conditions to be investigated, the AP Young's modulus E_{ap} was assumed to be four times the AP shear modulus G_{ap}, and the transverse Young's moduli of the two layers were assumed to be identical in the present study. For both layers, a constant loss factor of 0.4 was used, similar to Zhang (2016a). No vocal tract was included in the simulations in order to focus on laryngeal mechanisms alone. Source-tract interaction will be addressed in future studies.

In total, 216 000 conditions were simulated. For each condition, a half-second of voice production was simulated at a sampling rate of 44 100 Hz, with the subglottal pressure linearly increased from zero to a target value in 30 time steps and then kept constant.

B. Data analysis

For each phonating condition, data analysis was performed using the last 0.25 s of each simulation, by which time vocal fold vibration had either reached steady state or nearly steady state. For each condition, the fundamental frequency F0, A-weighted SPL, and cepstral peak prominence (CPP) (Hillenbrand *et al.*, 1994) were extracted from the output acoustics as described in Zhang (2016a). Spectral shape measures H1-H2, H2-H4, and H1-H2k were also extracted from the output acoustics (Zhang, 2016a). The closed quotient (CQ) of vocal fold vibration was calculated as the fraction of the cycle in which the glottal area function falls within the lower 10% between the minimum and maximum glottal area. The mean (Ag0) and peak-to-peak amplitude (Agamp) of the glottal area waveform were extracted. These two measures were further divided by the vocal fold length to estimate the mean glottal width (Ag0/L) and the vocal fold vibration amplitude (Agamp/L). From the glottal flow waveform, the mean glottal flow rate (Qmean), the peak-to-peak amplitude (Qamp), and normalized amplitude quotient (NAQ, ratio between Qamp and the product of the maximum flow declination rate and period of vocal fold vibration) (Alku *et al.*, 2002) were extracted. The peak vocal fold contact pressure P_c was calculated as the maximum contact pressure over the medial surface within the last 0.25 s of each simulation.

C. Statistical analysis

A multi-factorial analysis of variance (ANOVA) was performed to quantify the effect sizes of the nine model control parameters on selected output measures of voice production. Multiple comparisons with Bonferroni correction were made to further evaluate the general trends of variation of these output measures at different steps of individual control parameters. While interactions between control parameters were observed in our initial analysis, the main effects generally dominated in the analysis. Considering the complex interaction between the many control parameters and for clarity of presentation, in the following results are presented from the ANOVA analysis including only main effects. Interactions will be further explored in a future study.

In this study, the effect size η^2 was calculated as the ratio between the variance explained by each control parameter and the total variance. It should be noted that due to the relatively large number of control parameters, the effect sizes were usually small. This was particularly the case since our simulation conditions included a large range of the subglottal pressure, which had a large effect on many output measures of voice production. Thus, small effect sizes may still present as significant effects, especially when considering a smaller range of subglottal pressures. In the analysis of similar datasets in our previous studies, an effect size of 0.1 often represented a large effect that was dominant across a large range of conditions. For this reason, all results from the ANOVA analysis were presented below with effect sizes above 0.1 highlighted in bold.

III. RESULTS

Although this study focused on the effect of vocal fold length, thickness, and depths, results are presented for the effects of all nine control parameters for completeness, which also provided the context in which the length, thickness, and depth effects were interpreted.

A. Vocal fold vibration, glottal flow, and output acoustics

Table II shows the effect sizes of the nine control parameters on selected vibratory and aerodynamic measures. Table III shows the effects on selected acoustic measures. The inequality symbols in these two tables also show the general trends of variation for selected output measures at different levels of the control parameters. For example, Table II shows that the mean glottal area Ag0 varied with thickness T monotonically, with Ag0 being the highest at $T=1$ mm and lowest at $T=4.5$ mm. The mean values of selected measures of voice production averaged over the entire data set are also shown in Fig. 2 as a function of vocal fold length.

Tables II and III show that the major cause-effect relationships previously identified in an adult male-like vocal fold geometry (Zhang, 2016b, 2017, 2020; Desjardins *et al.*, 2021) were still valid for larynges with geometry more representative of adult females and children. For example, similar to our previous studies, Tables II and III show that the vertical thickness T of the vocal fold medial surface played a dominant role in regulating the closed quotient (CQ) of vocal fold vibration, the normalized amplitude quotient of the glottal flow (NAQ), and the spectral shape of the produced acoustics. Vocal fold thickness T, together with the initial glottal angle α, played an important role in controlling the mean and peak-to-peak amplitude of the glottal area and flow waveforms. The subglottal pressure P_s and transverse stiffness E_t remained the two important factors in determining the peak vocal fold contact pressure P_c. The effect of the AP stiffnesses (G_{apc} and G_{apb}) of the vocal folds on the spectral shape of the produced voice remained small.

In general, the effects of differences in vocal fold depths on voice production were small, whereas differences in vocal fold length L did produce noticeable differences in voice production. As expected, longer vocal folds produced a larger mean glottal opening area Ag0 and a higher mean glottal flow rate Qmean (Table II). Longer vocal folds also had a larger mean glottal width during phonation, as quantified by the mean glottal area divided by vocal fold length (Ag0/L), and vibrated with a larger vocal fold vibration amplitude, as measured by the peak-to-peak glottal area amplitude divided by length (Agamp/L). Although not shown, longer vocal folds also exhibited larger vertical displacement. In other words, longer vocal folds were relatively easier to be pushed apart and upward by the subglottal pressure, thus less able to maintain adduction against the subglottal pressure. While the subglottal pressure tends to push the vocal folds apart and upward, this glottis-opening effect is resisted by the fixed boundary condition at the anterior and posterior ends. This restraining effect of the fixed boundary conditions gets weaker with increasing distance from the anterior or posterior ends. Thus, the longer the vocal folds, the weaker is this restraining effect at the mid-membranous portion of the vocal folds, and the more open

TABLE II. F values/effect sizes η^2 and multiple comparison results from ANOVA analysis of selected measures of vocal fold vibration and glottal flow. All effects were significant for $p<0.001$ unless denoted by N.S. Control parameters with an effect size larger than 0.1 are highlighted in bold. The inequality symbols (<, >) indicate significant multiple comparison results with $p<0.001$. Conditions in parentheses indicate no statistically significant differences between these conditions.

	Ag0	Qmean	Ag0/L	Agamp/L	CQ	NAQ	P_c
P_s	562/0.021, increase w/ P_s	2094/0.089, increase w/ P_s	781/0.024, increase w/ P_s	**2827/0.150, increase w/ P_s**	661/0.050, increase w/ P_s	392/0.021, increase w/ P_s then plateaus	**9193/0.429, increase w/ P_s**
T	**15898/0.146, 1>2>3>4.5**	**12260/0.130, 1>2>3>4.5**	**26499/0.205, 1>2>3>4.5**	4114/0.055, 1>2>3>4.5	**15195/0.290, 1<2<3<4.5**	**39360/0.518, 1>2>3>4.5**	2939/0.034, 1<2<3<4.5
α	**20927/0.192, 0<1.6<4<8**	**14199/0.151, 0<1.6<4<8**	**35507/0.275, 0<1.6<4<8**	4894/0.065, 0<1.6<4<8	4707/0.090, 0>(1.6,4)>8	4447/0.059, 0<8<(1.6,4)	**16108/0.188, 0>1.6>4>8**
E_t	913/0.006, 1>2>4	653/0.005, 1>2>4	1075/0.006, 1>2>4	8254/0.073, 1>2>4	4369/0.056, 1>2>4	483/0.004, 1<2<4	**19247/0.150, 1>2>4**
G_{apc}	519/0.006, 1>10>20>30>40	458/0.006, 1>10>20>30>40	1070/0.011, 1>10>20>30>40	2931/0.052, 1>10>20>30>40	422/0.011, 1<40<30<20<10	70/0.001, (1,10)>20>30>40	2040/0.032, 1<10<20<(30,40)
G_{apb}	953/0.012, 1>10>20>30>40	642/0.009, 1>10>20>30>40	1761/0.018, 1>10>20>30>40	490/0.009, 1>10>20>30>40	547/0.014, 1<10<20<(30,40)	213/0.004, 1>10>(30,40), 1>20>40	68/0.001, 1<(10,20,30,40)
D_c	N.S.	N.S.	N.S.	N.S.	N.S.	138/0.001, 1>1.5	N.S.
D_b	125/0.001, (4,6)>8	75/0.001, (4,6)>8	145/0.001, (4,6)>8	211/0.002, 4>6>8	117/0.001, 4>8>6	97/0.001, (4,6)>8	514/0.004, 4>6>8
L	**37352/0.229**, 6<10<17	**24966/0.177**, 6<10<17	**29542/0.153**, 6<10<17	**14498/0.128**, 6<10<17	1560/0.020, 6>10>17	4834/0.042, 6<10<17	1754/0.014, 6>10>17

https://doi.org/10.1121/10.0009033

TABLE III. *F* values/effect sizes η^2 and multiple comparison results from ANOVA analysis of selected acoustic measures. All effects were significant for $p < 0.001$. Control parameters with an effect size larger than 0.1 are highlighted in bold. The inequality symbols (<, >) indicate significant multiple comparison results with $p < 0.001$. Conditions in parentheses indicate no statistically significant differences between these conditions.

	SPL	F0	H1-H2	H2-H4	H1-H2k	CPP
P_s	**11697/0.490, increase w/ P_s**	581/0.022, increase w/ P_s	235/0.022, decrease w/ P_s	99/0.009, decrease w/ P_s	595/0.029, decrease w/ P_s	393/0.040, decrease w/ P_s
T	1222/0.013, 2>1>3>4.5	5804/0.056, 1>2>3>4.5	**10478/0.249, 1>2>3>4.5**	**13553/0.297, 1>2>3>4.5**	**23177/0.278, 1>2>3>4.5**	**6825/0.172, 1<2<3<4.5**
α	952/0.010, 0<8<1.6<4	9655/0.093, (0,1.6)>4>8	1142/0.027, 0<4<(1.6,8)	1063/0.023, 0<(4,8)<1.6	7777/0.093, 0<1.6<4<8	810/0.020, 0>4>1.6>8
E_t	4951/0.035, 1>2>4	2393/0.015, 1<2<4	1109/0.018, 1<2<4	2108/0.031, 1<2<4	741/0.006, 1<2<4	18/<0.001 (1,2)>4
G_{apc}	439/0.006, 1<40<30<20<10	5245/0.067, 1<10<20<30<40	221/0.007, 10<(20,1)<30<40	46/0.001, (1,10,20)>(30,40)	1009/0.016, 1>10>20>30>40	62/0.002, (1,10)>20>(30,40)
G_{apb}	214/0.003, 1<10<(20,30,40)	1291/0.017, 1<10<20<30<40	663/0.021, 1>10>20>30>40	674/0.020, 1>10>20>30>40	4277/0.068, 1>10>20>30>40	228/0.008, 1<10<(20,30,40)
D_c	48/<0.001, 1>1.5	N.S.	N.S.	N.S.	36/<0.001, 1>1.5	314/0.003, 1>1.5
D_b	454/0.003, 4>6>8	83/0.001, 4<8<6	N.S.	170/0.002, 4<(6,8)	109/0.001, 6>4>8	45/0.001, 6>(4,8)
L	13916/0.097, 6<10<17	**47847/0.306, 6>10>17**	370/0.006, 6<10<17	1323/0.019, 6<10<17	**27019/0.216, 6<10<17**	N.S.

the mid-membranous glottis will be, which is consistent with the observation in our previous experiment (Xuan and Zhang, 2014).

Despite this increased mean glottal width, the effect of vocal fold length on the closed quotient CQ was small, with longer vocal folds having only a slightly lower CQ. This small effect on the CQ was probably because the length effects on the mean glottal width and vibration amplitude partially canceled out each other. However, longer vocal folds exhibited a moderately higher NAQ, implying a lower normalized maximum flow declination rate in longer vocal folds. Longer vocal folds also experienced a smaller peak vocal fold contact pressure P_c. Although the effect size was small, the difference in the mean values of the peak contact pressure was considerable in absolute values as shown in Fig. 2. This small effect on the peak vocal fold contact pressure P_c was likely the result of multiple competing effects: while longer vocal folds had a larger vibration amplitude, which tends to increase contact pressure, the increased mean glottal width tends to reduce the degree of vocal fold contact. In addition, the lower F0 associated with longer length implied a lower rate of momentum change and a longer time for vocal fold contact, which also decreases the peak contact pressure.

Acoustically, differences in vocal fold length had significant effects on both the output SPL and F0 (Table III). For SPL, vocal fold length had the second largest effect size, only smaller than that of the subglottal pressure. This is expected as for a given subglottal pressure and vocal fold position, longer vocal folds allow more airflow through the glottis to be modulated by vocal fold vibration and thus stronger sound production. Thus, for a given subglottal pressure, longer vocal folds are more efficient in voice production, although at the cost of higher airflow expenditure (Table II).

Vocal fold length also had the largest effect size on F0, with F0 lower in longer vocal folds. This effect size was as large as the combined effect size of all other control parameters. This explains why the F0 is generally higher in adult females and children than adult males despite the relatively large F0 range for individual speakers.

The initial glottal angle had the second largest effect size on F0. This was likely because decreasing initial glottal angle α increases vocal fold contact, which provides additional restoring force in the vocal folds, thus increasing the F0 (Zhang, 2016b). Indeed, multiple comparison analysis showed significant differences in F0 when the initial glottal angle α was reduced from a large value, as vocal fold vibration transitioned from without contact to with contact, but not between the two smallest initial glottal angles for which vocal fold contact was already established. The contribution of vocal fold contact to F0 increase was further supported by a similar pattern observed for the peak vocal fold contact pressure P_c, which showed significant yet small differences between the three smaller initial glottal angles but was much lower for the largest initial glottal angle.

The AP stiffness in the cover layer G_{apc} had a moderate effect on F0. A notable effect on F0 was also observed for the transverse stiffness E_t and body-layer AP stiffness G_{apb}. Since both the cover-layer AP stiffness and transverse stiffness increase with elongation (Zhang *et al.*, 2017), this suggests that for an individual speaker, the most effective means to increase F0 is to elongate the vocal folds, which increases both the AP stiffness and transverse stiffness in the cover layer.

The vocal fold vertical thickness *T* also had a moderate effect on F0, with F0 increasing with decreasing thickness (Fig. 3). Since adult female vocal folds are generally thinner than adult male vocal folds, this thickness effect may also contribute in some part to the higher F0 in adult female voices.

In comparison, the effect of vocal fold length *L* on the voice spectra was smaller. Table III shows that longer vocal folds produced a slightly larger H2-H4. Although Table III shows a large effect size of vocal fold length on H1-H2k, this large effect was likely due to the large effect of vocal

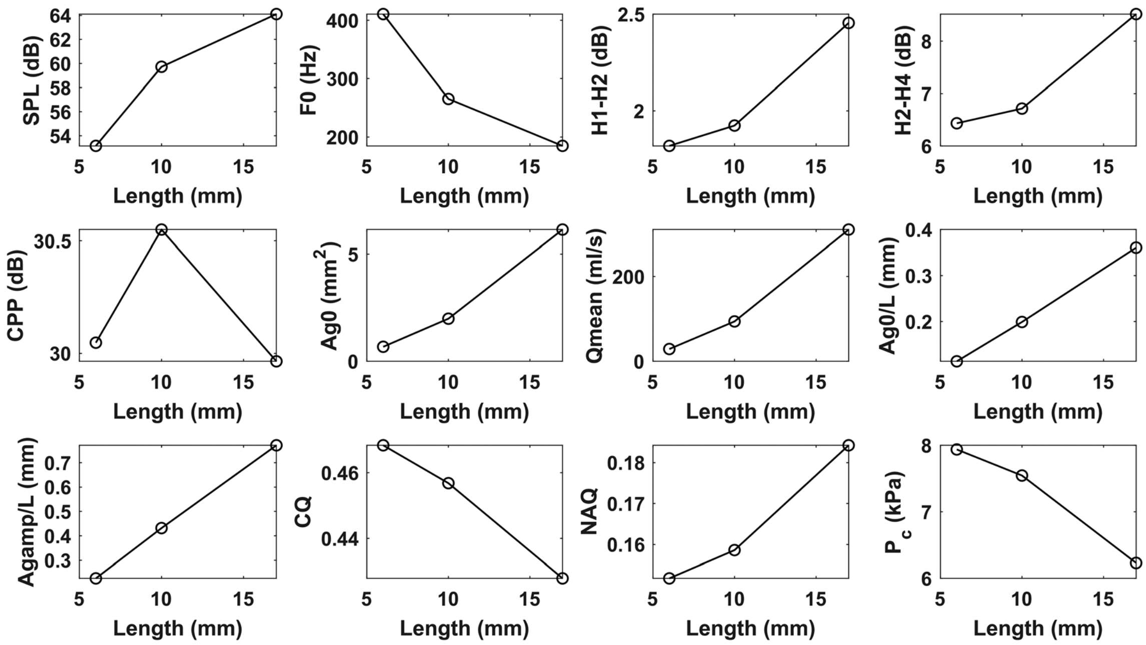

FIG. 2. The mean values of selected output measures as a function of vocal fold length.

fold length on F0. Shorter vocal folds produced a higher F0, which reduced the frequency difference between the fundamental and 2 kHz, thus decreasing H1-H2k. Table III also shows that vocal fold length L had a negligible effect on H1-H2 and CPP, both of which were primarily controlled by the vertical thickness T.

B. Vocal fold contact pressure when producing a target SPL

Our previous studies (Zhang, 2020) showed that in voice tasks targeting a specific output SPL, the peak vocal fold contact pressure can be minimized by adjustments that minimize the subglottal pressure required to produce the target SPL. While Table II shows only a small effect of vocal fold length on the peak vocal fold contact pressure P_c, increasing vocal fold length had a moderate effect on the output SPL (Table III). Thus, differences in vocal fold length are expected to have a larger impact on the peak contact pressure in voice tasks targeting a specific output SPL. Additional ANOVA analysis was performed for vocal fold conditions producing a target SPL of 60, 70, and 75 dB. In this analysis, the subglottal pressure was no longer considered an independent variable. Instead, the subglottal pressure was considered a dependent variable that needs to be adjusted according to other model control parameters in order to produce the target SPL.

Table IV shows the results of the ANOVA analysis. When targeting a specific SPL, the vocal fold length now had the largest effect size on the peak contact pressure P_c (except for the highest target SPL). Thus, the peak vocal fold contact pressure was much lower in longer vocal folds when producing a target output SPL. A large effect on the peak contact pressure was observed also for the initial glottal angle α, vertical thickness T, and transverse stiffness E_t. The relative dominance of these parameters appeared to vary depending on the target SPL value, similar to the observations in Zhang (2020). In general, vocal folds that were longer, thinner, and stiffer (large E_t) experienced smaller peak contact pressure when producing a target output SPL.

C. Phonation threshold pressure

Previous studies showed that children often use higher subglottal pressures than adults during voice production. While this higher use of the subglottal pressure has been attributed to higher airway resistances in children (Stathopoulos and Sapienza, 1993), some other studies

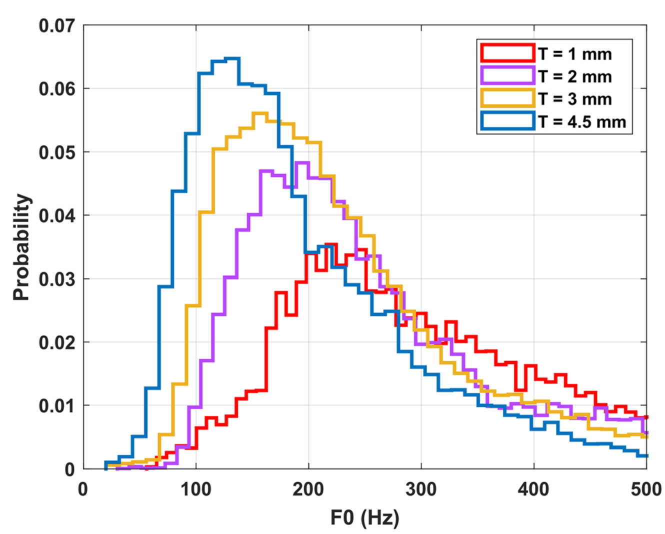

FIG. 3. (Color online) Probability of the F0 at different values of vertical thickness T. Thinner vocal folds generally produced higher F0.

TABLE IV. F values and effect sizes η^2 of the eight laryngeal control parameters on the peak contact pressure, and multiple comparison results from ANOVA analysis for conditions producing a target SPL of 60, 70, and 75 dB. All effects were significant for $p < 0.001$ unless denoted by N.S. The inequality symbols (<, >) indicate significant multiple comparison results with $p < 0.001$. Conditions in parentheses indicate no statistically significant differences between these conditions.

	60 dB	70 dB	75 dB
T	**1014/0.165, 1<2<3<4.5**	590/0.067, 1<2<3<4.5	636/0.085, 1<2<3<4.5
α	**987/0.161, 0>1.6>4>8**	**2500/0.284, 0>1.6>4>8**	**2326/0.310, 0>1.6>4>8**
E_t	517/0.056, 1>2>4	**911/0.069, 1>2>4**	**1425/0.127, 1>2>4**
G_{apc}	159/0.034, 1<10<(20,30,40)	235/0.036, 1<10<(20,30,40)	223/0.040, 1<10<20<30<40
G_{apb}	7/0.001, 1<(20,30)	30/0.005, 1>(10,20,30,40)	30/0.005, 1>(10,20,30,40)
D_c	N.S.	N.S.	N.S.
D_b	N.S.	24/0.002, (4,6)>8	42/0.004, (4,6)>8
L	**2504/0.272, 6>10>17**	**3214/0.244, 6>10>17**	**1229/0.109, 6>10>17**

suggested that the smaller laryngeal size may lead to more restricted phonation threshold conditions (Lucero and Koenig, 2005). Table V shows the results from the ANOVA analysis of the phonation threshold pressure P_{th}. All main effects were significant with $p < 0.001$ except for the cover-layer depth D_c.

Overall, the initial glottal angle α and transverse stiffness E_t had the largest effect sizes. For the initial glottal angle, the phonation threshold pressure was the lowest at the intermediate value of 1.6°, and increased as the initial glottal angle deviated from this value. The phonation threshold pressure P_{th} increased with increasing transverse stiffness E_t. This large effect of E_t is consistent with the finding in the literature that the phonation threshold pressure generally increases with pitch (Verdolini-Marston *et al.*, 1990; Solomon *et al.*, 2007).

The vertical thickness T had the largest effect among the three geometric control parameters. The phonation threshold pressure was the highest for the thinnest vocal fold condition, reached minimum at the intermediate thicknesses, and increased again at the thickest vocal fold condition, similar to the observation in our previous study Zhang (2017). In comparison, the effect of vocal fold length or depth on the phonation threshold pressure was smaller, with P_{th} increasing with an increase in either vocal fold length L or body-layer depth D_b. A small effect was also observed for the AP stiffness in the cover layer G_{apc}, although this effect was noticeable only between the softest condition ($G_{apc} = 1$ kPa) and the other stiffer conditions ($G_{apc} > 1$ kPa).

TABLE V. F values/effect sizes η^2 and multiple comparison results from ANOVA analysis of the phonation threshold pressure (P_{th}). All effects were significant for $p < 0.001$ unless denoted by N.S. The inequality symbols (<, >) indicate significant multiple comparison results with $p < 0.001$. Conditions in parentheses indicate no statistically significant differences between these conditions.

	P_{th}		P_{th}
T	232/0.041, 1>4.5>(2,3)	G_{apb}	15/0.004, 1>(10,20,30,40)
α	**896/0.158, 1.6<4<0<8**	D_c	N.S.
E_t	**1227/0.144, 1<2<4**	D_b	120/0.014, 4<6<8
G_{apc}	124/0.029, 1>(10,20,30,40)	L	135/0.016, 6<10<17

Thus, our results showed that the phonation threshold pressure could be very high for very thin vocal folds, implying that children with thin vocal folds may have to adopt higher subglottal pressures than adults in order to initiate phonation. This appears to be consistent with the findings in Lucero and Koenig (2005) that the phonation threshold pressure increased with decreasing laryngeal size. However, in their study, a decrease in laryngeal size was accompanied by an increase in vocal fold stiffness, which may further increase the phonation threshold pressure in small larynges.

D. Contribution of laryngeal size differences to sex- and age-related voice differences

In general, male vocal folds are longer and thicker than female vocal folds. Vocal folds in children are shorter than adult vocal folds. The results above showed that these differences in length and thickness had opposite effects on voice production. Specifically, while the longer vocal folds in adult males increased the mean glottal area and mean glottal flow, slightly reduced the CQ, and slightly increased the normalized amplitude quotient NAQ, the larger thickness had an effect of decreasing the mean glottal area and glottal flow, increasing the CQ, and decreasing the NAQ. In this section, we explored the combined effect of differences in length, thickness, and depth on voice production. The goal was to investigate whether differences in voice production between children, adult females, and adult males as often reported in the voice literature can be explained by differences in laryngeal size alone.

Three geometric conditions representative of children, adult females, and adult males were selected from our simulations. For the condition representative of children, $L = 6$ mm, $T = 1$ mm, $D_b = 4$ mm, and $D_c = 1$ mm. For adult females, $L = 10$ mm, $T = 2$ mm, $D_b = 6$ mm, and $D_c = 1$ mm. For adult males, $L = 17$ mm, $T = 3$ mm, $D_b = 8$ mm, and $D_c = 1$ mm. Despite that our simulations were performed for only a limited number of values for each of the geometric control parameters, these conditions were selected to represent the geometric differences between adult males, adult females, and children as close as possible to data reported in previous studies (Hollien and Curtis, 1960; Hollien, 1960; Titze, 1989).

Multi-factorial ANOVA analysis was performed using data corresponding to the three geometric conditions, with length, thickness, and depths lumped into a new variable named laryngeal size. Table VI shows the F values and effect sizes of laryngeal size on selected output measures and their trends of variation across the three laryngeal size groups. Figure 4 shows the averaged values of selected output measures of voice production for the three laryngeal size groups corresponding to children, adult females, and adult males. Note that these values were averaged over conditions of different initial glottal angles, AP and transverse stiffnesses of the vocal folds, and subglottal pressures. Thus, Fig. 4 shows the trends related to laryngeal size differences alone, and does not reflect the effects of potential differences in vocal fold stiffness or the use of the vocal mechanism (i.e., the initial glottal angle and subglottal pressure) between children, adult females, and adult males.

The results showed that voice production in adult males generally had a larger mean glottal opening area Ag0, higher airflow Qmean, and a higher CQ than adult females, which were higher than children. Voice production in adult males produced lower F0, H1-H2, and NAQ than adult females, which again were lower than children. Laryngeal size differences also led to moderate but statistically significant differences in SPL, H2-H4, vibration amplitude (Agamp/L), mean glottal width (Ag0/L), and CPP, and a small difference in peak vocal fold contact pressure P_c. These observations are generally consistent with the differences between children, adult females, and adult males as reported in the literature regarding the F0, H1-H2 (Iseli *et al.*, 2007), CPP (Awan *et al.*, 2012), glottal flow (Holmberg *et al.*, 1988), CQ (Holmberg *et al.*, 1988; Patel and Ternström, 2021), NAQ [Alku *et al.* (2002) for normal and pressed voices], risk of vocal fold injury (Miller and Verdolini, 1995; Roy *et al.*, 2004). Table VI also includes a new measure Agamp/L^2, which quantifies the vibration amplitude normalized by vocal fold length. This measure was the highest in children, followed by adult females and adult males, which is consistent with the finding in Patel *et al.* (2015).

The results from Tables II and III allowed us to further determine which geometric parameter had a more dominant contribution toward the observed differences between children, adult females, and adult males in Table VI and Fig. 4.

TABLE VI. *F* values/effect sizes η^2 of the laryngeal size variable on selected measures of voice production and multiple comparison results between the three laryngeal size groups representative of children (C), adult females (F), and adult males (M). All effects were significant for $p < 0.001$. The inequality symbols (<, >) indicate significant multiple comparison results with $p < 0.001$.

SPL	561/0.051, M>F>C	Ag0/L	690/0.046, M>F>C
F0	**11302/0.555, M<F<C**	Agamp/L	976/0.096, M>F>C
H1-H2	**1185/0.228, M<F<C**	Agamp/L^2	199/0.022, M<F<C
H2-H4	259/0.064, M<F<C	**CQ**	**945/0.174, M>F>C**
CPP	292/0.068, M>F>C	**NAQ**	**1081/0.194, M<F<C**
Ag0	**4100/0.353, M>F>C**	P_c	199/0.017, M<F<C
Qmean	**2875/0.261, M>F>C**		

The differences in SPL, F0, Ag0, Qmean, Agamp/L, and peak contact pressure P_c appeared to be dominated by the effect of vocal fold length, whereas the differences in H1-H2, H2-H4, CPP, CQ, and NAQ was consistent with the effect of the vertical thickness. Both the length and thickness appeared to have a significant effect on Ag0/L.

While laryngeal size by itself had only a small effect on the peak vocal fold contact pressure P_c, it also had a moderate effect on the output SPL. This suggests a potentially larger effect of laryngeal size on the peak vocal fold contact pressure in voice tasks targeting a specific SPL, as shown similarly in Sec. III B. Following a similar procedure described in Sec. III B, ANOVA analysis was performed to compare the peak vocal fold contact pressure across the three laryngeal size groups in vocal fold conditions producing a target SPL. The results showed that the effect size of the laryngeal size variable on the peak vocal fold contact pressure was 0.165, 0.213, and 0.106 for a target SPL of 60, 70, and 75 dB, respectively. Thus, laryngeal size had a large effect on the peak contact pressure in voice tasks targeting a specific output SPL, with the peak vocal fold contact pressure the lowest in adult males, followed by adult females and children.

IV. DISCUSSION AND CONCLUSIONS

Our results showed that the major cause-effect relationships identified in an adult male-like geometry in our previous studies remained the same in larynges with geometry more representative of adult females and children. In particular, the vertical thickness of the medial surface remained the dominant parameter in regulating the glottal closure pattern (both CQ and NAQ) and the spectral shape of the produced voice. However, differences in vocal fold length did lead to significant differences in voice production. Longer vocal folds produced lower F0, used more airflow, and had a larger mean glottal width and vocal fold vibration amplitude, resulting in a higher SPL and a reduced normalized maximum flow declination rate (increased NAQ) during phonation. In contrast, the effect of differences in vocal fold depth was generally small.

This study showed that the often-observed differences between adult males, adult females, and children can indeed be explained by differences in vocal fold length and thickness alone. The lower F0, higher glottal flow rate, larger vocal fold vibration amplitude, and higher SPL in adult males can be directly explained by the longer vocal fold length. Although longer vocal folds in adult males had the tendency to reduce the normalized flow declination rate, this effect was dominated by that of the thicker vocal folds, which increased the normalized maximum flow declination rate (lower NAQ) as well as the closed quotient CQ. Overall, the male voices had a larger closed quotient and a higher normalized maximum flow declination rate, which decreased H1-H2 and H2-H4. Interestingly, both H1-H2 and H2-H4 have been shown to have a weak but notable contribution to gender perception (Shue and Iseli, 2008; Bishop and Keating, 2012).

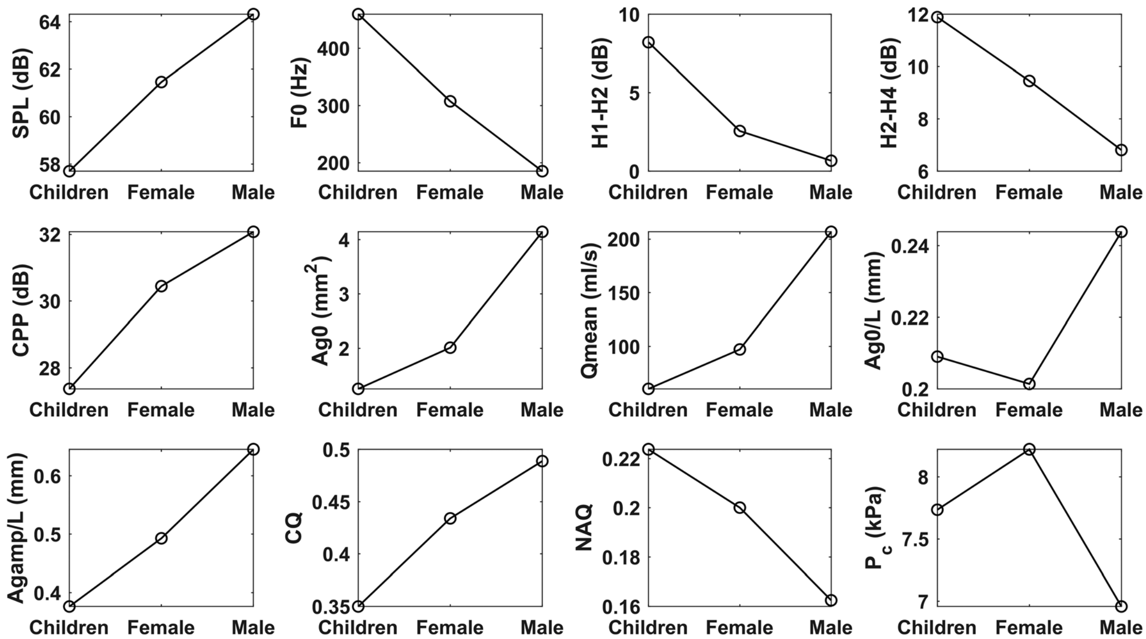

FIG. 4. The mean values of selected output measures for vocal fold conditions representative of children, adult females, and adult males (see text for details of these vocal fold conditions).

Our results showed that by itself, laryngeal size only had a statistically significant, but small effect on the peak vocal fold contact pressure. However, in voice tasks targeting a specific output SPL, the peak vocal fold contact pressure was much lower in adult males than adult females or children. This may explain the clinical observation that adult females are more likely than adult males to experience vocal health problems such as vocal fold mass lesions. It should be noted that this conclusion was reached without consideration of potential differences in vocal fold stiffness and initial glottal angles between adult males, adult females, and children. The less developed vocal ligament in younger vocal folds may weaken their ability to maintain adductory positions against the subglottal pressure, which may result in a less tight glottal condition than observed in this study and thus reduce the overall peak vocal fold contact pressure in children. There seems to be no perceivable difference between adult males and adult females in stiffness along the AP direction (Titze, 1989). As to the transverse stiffness, human data are scarce (Zhang *et al.*, 2017). It has been reported that adult females have less hyaluronic acid in the superficial layer than adult males (Hunter *et al.*, 2011), which may imply a lower transverse stiffness in adult females (Chan *et al.*, 2001). If this is indeed the case, the lower transverse stiffness would lead to even higher peak vocal fold contact pressure and further increase risk of vocal fold injury in adult females. On the other hand, the wider spreading of the vocal processes in adult females (Titze, 1989) may reduce the peak vocal fold contact and thus risk of vocal fold injury in adult females. The effects of these factors on vocal health risks need to be further investigated.

While vocal fold length and depth had only a small effect on the phonation threshold pressure, the results showed that the phonation threshold pressure may become very high for very thin vocal folds. This, together with the lower vocal efficiency in small vocal folds, may partially explain why children often use higher subglottal pressures than adults during phonation.

In general, vocal fold length had the most dominant effect on F0, which explains why F0 is generally lower in adult males than in adult females or children, despite the large F0 range for individual speakers. The effect of vocal fold thickness on F0 remains controversial in the voice literature (Colton *et al.*, 2011; Titze, 2011). In this study, we observed a notable effect of vocal fold thickness on F0, with F0 increasing with decreasing thickness (Table III and Fig. 3). This shows that the F0 of vocal fold vibration is determined by not only vocal fold length and stiffness along the AP direction, as assumed in the string model of vocal fold vibration, but also the dimensions of the coronal cross section of the vocal folds. The vocal folds have finite cross-sections across which vibration modes are excited, often manifested as a mucosal wave propagating upwards on the vocal fold medial surface. A larger thickness reduces the eigenfrequency of these vibration modes within the coronal cross-section and the overall frequency of vocal fold vibration or F0, in the same way that longer vocal folds produce lower F0. Thus, larynx size does play an important role in determining F0, with longer, thicker folds producing a lower F0. This relatively large effect of the vertical thickness on F0 also provides a theoretical rationale for surgical interventions targeting the vertical thickness in voice feminization surgery (Koçak *et al.*, 2010; Kim, 2020). In contrast, the same reasoning does not seem to apply to the medial-lateral vocal fold depth. The effect of vocal fold depth of either the body or cover layer on F0 was small, with the F0 decreasing slightly with decreasing body-layer depth, which is consistent with the observation in the experiment of Mendelsohn and Zhang (2011). This small effect was likely due to an interaction effect between vocal fold depth and vocal fold stiffness in determining the effective vocal fold depth of vibration: depending on the stiffness condition, a larger vocal fold depth does not always lead to a larger effective depth of vibration.

Finally, it is worth noting that no vocal tract was included in this study. Source-tract interaction is known to affect voice production and perception. In particular, our previous studies have shown that vocal tract configurations (with vs without, and different vocal tract shapes) have significant effect on the dependence of the peak vocal fold contact pressure on vocal fold properties (Zhang, 2019, 2020). The effect of laryngeal size in the presence of different vocal tract shapes and degrees of source-tract coupling will be addressed in future studies.

ACKNOWLEDGMENTS

This study was supported by research Grant Nos. R01DC009229 and R01DC001797 from the National Institute on Deafness and Other Communication Disorders, the National Institutes of Health.

Alipour, F., Berry, D. A., and Titze, I. R. (**2000**). "A finite-element model of vocal-fold vibration," J. Acoust. Soc. Am. **108**(6), 3003–3012.

Alipour-Haghighi, F., and Titze, I. R. (**1991**). "Elastic models of vocal fold tissues," J. Acoust. Soc. Am. **90**(3), 1326–1331.

Alku, P., Bäckström, T., and Vilkman, E. (**2002**). "Normalized amplitude quotient for parametrization of the glottal flow," J. Acoust. Soc. Am. **112**(2), 701–710.

Awan, S. N., Giovinco, A., and Owens, J. (**2012**). "Effects of vocal intensity and vowel type on cepstral analysis of voice," J. Voice **26**(5), 670.e15–670.e20.

Bishop, J., and Keating, P. (**2012**). "Perception of pitch location within a speaker's range: Fundamental frequency, voice quality and speaker sex," J. Acoust. Soc. Am. **132**(2), 1100–1112.

Chan, R. W., Gray, S. D., and Titze, I. R. (**2001**). "The importance of hyaluronic acid in vocal fold biomechanics," Otolaryngology-Head and Neck Surgery **124**(6), 607–614.

Colton, R. H., Casper, J. K., and Leonard, R. (**2011**). *Understanding Voice Problems: A Physiological Perspective for Diagnosis and Treatment* (Lippincott Williams and Wilkins, Baltimore, MD), Chap. 13.

Desjardins, M, Verdolini Abbott, K., and Zhang, Z. (**2021**). "Computational simulations of respiratory-laryngeal interactions and their effects on lung volume termination during phonation: Considerations for hyperfunctional voice disorders," J. Acoust. Soc. Am. **149**(6), 3988–3999.

Gillespie, A. I., Gartner-Schmidt, J., Rubinstein, E. N., and Abbott, K. V. (**2013**). "Aerodynamic profiles of women with muscle tension dysphonia/aphonia," J. Speech Lang. Hear. Res. **56**(2), 481–488.

Hillenbrand, J. M., Cleveland, R. A., and Erickson, R. L. (**1994**). "Acoustic correlates of breathy vocal quality," J. Speech Hear. Res. **37**(4), 769–778.

Hirano, M., and Kakita, Y. (**1985**). "Cover-body theory of vocal fold vibration," in *Speech Science: Recent Advances*, edited by R. G. Daniloff (College-Hill Press, San Diego), pp. 1–46.

Hirano, M., Kurita, S., and Nakashima, T. (**1983**). "Growth, development, and aging of human vocal folds," in *Vocal Fold Physiology: Contemporary Research and Clinical Issues*, edited by D. M. Bless and J. H. Abbs (College-Hill, San Diego), pp. 22–43.

Hollien, H. (**1960**). "Vocal pitch variation related to changes in vocal fold length," J. Speech Hear. Res. **3**(2), 150–156.

Hollien, H., and Curtis, F. (**1960**). "A laminagraphic study of vocal pitch," J. Speech Hear. Res. **3**(4), 361–371.

Holmberg, E., Hillman, R., and Perkell, J. (**1988**). "Glottal airflow and transglottal air pressure measurements for male and female speakers in soft, normal, and loud voice," J. Acoust. Soc. Am. **84**(2), 511–529.

Hunter, E. J., Tanner, K., and Smith, M. E. (**2011**). "Gender differences affecting vocal health of women in vocally demanding careers," Logoped. Phon. Vocol. **36**(3), 128–136.

Iseli, M., Shue, Y. L., and Alwan, A. (**2007**). "Age, sex, and vowel dependencies of acoustic measures related to the voice source," J. Acoust. Soc. Am. **121**(4), 2283–2295.

Kahane, J. (**1978**). "A morphological study of the human prepubertal and pubertal larynx," Am. J. Anat. **151**(1), 11–20.

Kim, H. T. (**2020**). "Vocal feminization for transgender women: Current strategies and patient perspectives," IJGM **13**, 43–52.

Koçak, I., Akpınar, M. E., Çakır, Z. A., Doğan, M., Bengisu, S., and Çelikoyar, M. M. (**2010**). "Laser reduction glottoplasty for managing androphonia after failed cricothyroid approximation surgery," J. Voice **24**(6), 758–764.

Kreiman, J., and Sidtis, D. (**2011**). *Foundations of Voice Studies: An Interdisciplinary Approach to Voice Production and Perception* (Wiley-Blackwell, Hoboken, NJ), Chap. 4.

Lucero, J. C., and Koenig, L. L. (**2005**). "Phonation thresholds as a function of laryngeal size in a two-mass model of the vocal folds," J. Acoust. Soc. Am. **118**(5), 2798–2801.

Mendelsohn, A., and Zhang, Z. (**2011**). "Phonation threshold pressure and onset frequency in a two-layer physical model of the vocal folds," J. Acoust. Soc. Am. **130**(5), 2961–2968.

Miller, M. K., and Verdolini, K. (**1995**). "Frequency and risk factors for voice problems in teachers of singing and control subjects," J. Voice **9**(4), 348–362.

Patel, R., Donohue, K. D., Unnikrishnan, H., and Kryscio, R. J. (**2015**). "Kinematic measurements of the vocal-fold displacement waveform in typical children and adult populations: Quantification of high-speed endoscopic videos," J. Speech Lang. Hear. Res. **58**(2), 227–240.

Patel, R., and Ternström, S. (**2021**). "Quantitative and qualitative electroglottographic wave shape differences in children and adults using voice map–based analysis," J. Speech Lang. Hear. Res. **64**(8), 2977–2995.

Roy, N., Merrill, R. M., Thibeault, S., Parsa, R. A., Gray, S. D., and Smith, E. M. (**2004**). "Prevalence of voice disorders in teachers and the general population," J. Speech Lang. Hear. Res. **47**(2), 281–293.

Shue, Y. L., and Iseli, M. (**2008**). "The role of voice source measures on automatic gender classification," in *2008 IEEE International Conference on Acoustics, Speech and Signal Processing*, pp. 4493–4496.

Solomon, N. P., Ramanathan, P., and Makashay, M. J. (**2007**). "Phonation threshold pressure across the pitch range: Preliminary test of a model," J. Voice **21**(5), 541–550.

Stathopoulos, E. T., and Sapienza, C. (**1993**). "Respiratory and laryngeal measures of children during vocal intensity variation," J. Acoust. Soc. Am. **94**(5), 2531–2543.

Stathopoulos, E. T., and Weismer, G. (**1985**). "Oral airflow and air pressure during speech production: A comparative study of children, youths and adults," Folia Phoniatr. **37**(3–4), 152–159.

Tang, J., and Stathopoulos, E. T. (**1995**). "Vocal efficiency as a function of vocal intensity: A study of children, women, and men," J. Acoust. Soc. Am. **97**(3), 1885–1892.

Titze, I. R. (**1989**). "Physiologic and acoustic differences between male and female voices," J. Acoust. Soc. Am. **85**(4), 1699–1707.

Titze, I. R. (**2011**). "Vocal fold mass is not a useful quantity for describing F0 in vocalization," J. Speech Lang. Hear. Res. **54**, 520–522.

Titze, I., and Talkin, D. (**1979**). "A theoretical study of the effects of various laryngeal configurations on the acoustics of phonation," J. Acoust. Soc. Am. **66**(1), 60–74.

Verdolini-Marston, K., Titze, I. R., and Druker, D. G. (**1990**). "Changes in phonation threshold pressure with induced conditions of hydration," J. Voice **4**(2), 142–151.

Wu, L., and Zhang, Z. (**2019**). "Voice production in a MRI-based subject-specific vocal fold model with parametrically controlled medial surface shape," J. Acoust. Soc. Am. **146**(6), 4190–4198.

Wu, L., Zhang, Z. (**2016**). "A parametric vocal fold model based on magnetic resonance imaging," J. Acoust. Soc. Am. **140**(2), EL159–EL165.

Xuan, Y., and Zhang, Z. (**2014**). "Influence of embedded fibers and an epithelium layer on glottal closure pattern in a physical vocal fold model," J. Speech Lang. Hear. Res. **57**(2), 416–425.

Zhang, Z. (**2016a**). "Cause-effect relationship between vocal fold physiology and voice production in a three-dimensional phonation model," J. Acoust. Soc. Am. **139**(4), 1493–1507.

Zhang, Z. (**2016b**). "Mechanics of human voice production and control," J. Acoust. Soc. Am. **140**(4), 2614–2635.

Zhang, Z. (**2017**). "Effect of vocal fold stiffness on voice production in a three-dimensional body-cover phonation model," J. Acoust. Soc. Am. **142**(4), 2311–2321.

Zhang, Z. (**2019**). "Vocal fold contact pressure in a three-dimensional body-cover phonation model," J. Acoust. Soc. Am. **146**(1), 256–265.

Zhang, Z. (**2020**). "Laryngeal strategies to minimize vocal fold contact pressure and their effect on voice production," J. Acoust. Soc. Am. **148**(2), 1039–1050.

Zhang, Z. (**2020b**). "Estimation of vocal fold physiology from voice acoustics using machine learning," J. Acoust. Soc. Am. **147**(3), EL264–EL270.

Zhang, Z., Samajder, H., and Long, J. (**2017**). "Biaxial mechanical properties of human vocal fold cover under vocal fold elongation," J. Acoust. Soc. Am. **142**(4), EL356–EL361.

Zhang, Z., Wu, L., Gray, R., and Chhetri, D. (**2020**). "Three-dimensional vocal fold structural change due to implant insertion in medialization laryngoplasty," PLoS One **15**(1), e0228464.

Zimman, L. (**2018**). "Transgender voices: Insights on identity, embodiment, and the gender of the voice," Lang. Ling. Compass **12**(8), e12284.