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Sensitivity Analysis of Muscle Mechanics-Based Voice Simulator to Determine Gender-Specific Speech Characteristics

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Abstract

The purpose of this study was to investigate the gender differences in voice simulation using a sensitivity analysis approach. A global, Monte Carlo-based approach was employed, and the relationships between biomechanical inputs (lung pressure and muscle activation levels) and acoustic outputs (fundamental frequency, f_0 , and sound pressure level, SPL) were investigated for male and female versions of a voice simulator model. The gender distinction in the model was based on an anatomical scaling of the laryngeal structures. Results showed strong relationships for f_0 and SPL as functions of lung pressure, as well as for f_0 as a function of cricothyroid and thyroarytenoid muscle activity, in agreement with previous literature. Also expected was a systematic shift in f_0 range between the genders. It was found that the female model exhibited greater pitch strength (saliency) than the male model, which might equate to a perceptually more periodic or higher quality voice for females. In addition, the female model required slightly higher lung pressures than the male model to achieve the same SPL, suggesting a possibly greater phonatory effort and predisposition for fatigue in the female voice. The methods and results of this study lay the groundwork for a complete mapping of simulator sound signal characteristics as a function of simulator input parameters and a better understanding of gender-specific voice production and vocal health.

Keywords

voice biomechanics; voice simulation; sensitivity analysis

1 Introduction

There are two basic components necessary for sound production: (1) an object that oscillates at regular intervals, creating a sound wave in the medium surrounding the oscillator; and (2) a power source to set the oscillator into motion and to sustain its vibration. In the case of the human voice, two flaps of tissue known as the vocal folds act as the oscillators, while

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Compliance with Ethical Standards

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aerodynamic power from the lungs serves as the power source. The airspace above the vocal folds, known as the vocal tract, acts as an acoustic filter to selectively amplify and attenuate frequencies of the source sound wave. This filtering of the source sound provides each voice its unique acoustic quality as well as differentiates speech sounds such as vowels and consonants (see Hunter and Ludwigsen 2017, for a review).

The coordination of several muscles of the larynx are responsible for altering the acoustic characteristics of the source sound produced by the vibrating vocal folds. First, three pairs of muscles (IA - interarytenoids, LCA - lateral cricoarytenoids, and PCA - posterior cricoarytenoids) work to adduct and abduct the vocal folds to allow for breath control (valving) which also controls the onset and offset of phonation. Second, the thyroarytenoids (TA), which make up the bulk of the vocal folds, contracts the vocal folds, which shortens and thickens them with the cricothyroid (CT) acting antagonistically to the TA to lengthen and stretch them; together, these two muscles are the primary contributors to vibration frequency control of the vocal folds, perceived aurally as pitch. Amplitude of vibration of the vocal folds, perceived as loudness, is influenced by the air pressure from the lungs (P_L); there are several resources available for a more substantial review of voice production (Titze 2000).

While the laryngeal systems of females and males are very similar during childhood, the differences in hormones during puberty affect the size and shape of the laryngeal system. For example, the influx of testosterone during puberty produces the recognizable male vocal characteristics, including longer, thicker muscles within the vocal folds and the elongation of the male thyroid cartilage which creates the distinctive laryngeal prominence (i.e., Adam's apple). The results of these gender differences in the laryngeal anatomy and physiology can be captured primarily by scaling the human vocal folds in two ways: (1) a 1.6 scale factor in the vocal fold length going from female to male, and (2) a 1.2 scale factor in overall larynx size of male over female (Titze 1989a). The vocal tract also is scaled, though with little effect on vocal production, with the average adult male and female vocal tract length being 15.5 cm and 13.8 cm respectively (Fitch and Giedd 1999).

These gender differences in voice production result in vocal quality and identification cues (Lass et al. 1976). For example, women speak at a higher fundamental frequency, which comes from more vocal fold vibrations, and potentially more tissue damage because of the vibration (Hunter et al. 2011). Further, in addition to anatomical differences, there seems to be a gender difference in how women and men use their voice in different situations (Hunter et al. 2015). For example, when speaking in a loud environment, all talkers generally respond using the Lombard effect or Lombard reflex (Zollinger and Brumm 2011). However, females appear to respond to a noisy environment with a larger change in loudness, while men respond with a larger change in fundamental frequency (Letowski et al. 1993).

These types of gender differences in laryngeal physiology and voice behavior are likely contributors to the fact women generally having more voice problems than men (Roy et al. 2005). However, while it is accepted that women are at greater risk, the reasons for this difference are still not universally accepted. Numerous studies have been conducted to better

understand both the general differences in voice production between the genders as well as potential risk factors to vocal health that come from how the voice is produced. However, while many biomechanical models have been developed to simulate vocal fold vibration, few biomechanical modeling studies have investigated gender differences.

Traditionally, biomechanical models of the laryngeal system have been used as a sound source for voice simulation and for the study of voice production mechanics (Alipour et al. 2000; Alipour-Haghighi and Titze 1983; Berry et al. 1994; Flanagan and Landgraf 1968; Luo et al. 2009; Sciamarella and Le Quéré 2008; Smith and Thomson 2012; Story and Titze 1995; Zañartu et al. 2014; Zheng et al. 2011). Simulation of the voice is based on modeling physical principles that lead to production of sound (e.g., lung pressure, muscle activation, tissue properties). Previous studies have used biomechanical voice production models to study relevant topics such as pitch control and resonance in humans (Tokuda et al. 2010; Zhang et al. 2009), causes and effects of disorders such as vocal fold lesions and paralysis (Dresel et al. 2006; Gunter 2004), and voice production in other mammals (Riede et al. 2010). Regarding gender differences, Titze (1989a), using a model of vocal fold vibration based on normal modes, showed differences in glottal flow, glottal area, and contact area waveforms due to different laryngeal scaling and medial surface bulging between the genders. Kob et al. (2009) used a multi-mass model to explore the influence of gender-related differences in vocal fold edge shape on impact force during vibration.

Sensitivity analysis, defined as the study of how uncertainty in the output of a model can be attributed to different sources of uncertainty in the model input (Saltelli et al. 2008), is typically performed on biomechanical models to determine model limits and understand overall model behavior in relation to its inputs. It is particularly useful for models that are deterministic yet nonlinear so that the behavior is influenced by the combination of several inputs and cannot be predicted by simple relationships (as is the case for many computational models). A global sensitivity analysis is performed by considering a set of parameters that cover the full ranges and all combinations of model inputs, to explore the variety of possible model behavior. This is often paired with a Monte Carlo approach, where the parameter sets are randomly generated from parameter distributions (Doubilet et al. 1985; Sobol' 2001). Sensitivity analysis can be applied to biomechanical models of the voice to consider a vast range of potential voice states and elucidate where there might be differences in behavior of the male versus female voice. Yet, no studies have employed sensitivity analysis to explore gender-specific voice behavior.

The purpose of this study was to investigate the gender differences in voice simulation using a sensitivity analysis approach. A global, Monte Carlo-based approach is employed, and the relationships between inputs of lung pressure and intrinsic muscle activation and outputs of fundamental frequency and sound pressure level are investigated for male and female versions of a voice simulator model. The methods and results of this study lay the groundwork for a complete mapping of simulator sound signal characteristics as a function of simulator input parameters and a better understanding of gender-specific voice production and vocal health.

2 Methods

2.1 Voice Simulation and Sensitivity Analysis

Simulation of voice production was performed using voice simulator software developed by The National Center for Voice and Speech. In the software, simulated lung pressure drives air flow through an elliptical airway via a wave reflection algorithm, and the air flow in turn drives self-oscillation of a finite element vocal fold model (Hunter et al. 2004; Titze 2006; Titze et al. 2017). Acoustic output and behavior of the finite element model in the simulator have been validated in previous studies (Titze et al. 2014; 2017). A schematic of the vocal fold model, along with posturing parameters, is shown in Figure 1. The simulator relies on muscle activity levels for intrinsic laryngeal muscles, including the cricothyroid (CT), lateral cricoarytenoid (LCA), thyroarytenoid (TA), interarytenoid (IA), and posterior cricoarytenoid (PCA), as inputs to determine prephonatory vocal fold posturing. Posturing parameters of interest include the glottal half-widths at the inferior and superior edges (ξ_{01} and ξ_{02} , respectively), a bulging factor governing curvature on the vocal fold medial surface (ξ_B), vocal fold length (L), and vocal fold thickness (T) (see Figure 1). Relationships between the various muscle activity levels and vocal fold parameters are as follows:

$$\xi_{02} = x_{caj} + x_{adif} - 1.5a_{lca} + .0661a_{ia} + .1894a_{pca} + .0620a_{ct} - .1720a_{ta}$$

$$\xi_B = .05T(1 - a_{ta})$$

$$\xi_{01} = \xi_{02} + .15T(1 - 1.5a_{ta})$$

$$\epsilon = .3(2a_{ct} - a_{ta}) - .4a_{lca}$$

$$L = L_0(1 + \epsilon)$$

$$T = T_0/(1 + \epsilon)$$

In the above equations, muscle activation levels are represented by a_m , where the subscript m denotes each respective muscle abbreviation. The variable x_{caj} is the x-position of the cricoarytenoid joint, and x_{adif} is the x-displacement of the arytenoid cartilage, giving the starting position of the vocal process. Vocal fold length and thickness vary from their *in situ* lengths (L_0 and T_0 , respectively) with anterior-posterior strain (ϵ). Vocal fold depth is held constant.

Outputs produced by the simulator are various waveforms of interest to voice analysis, including transglottal pressure, glottal flow rate, glottal flow derivative, oral pressure, oral flow, and radiated sound pressure. The default model uses a generic shaped vocal tract based on MRI measurements with a typical male anatomical scale. For the female model, the larynx and airway dimensions are scaled to 62.5% of the male configuration (Titze 1989a).

The sensitivity analysis employed a Monte Carlo based method, considering the full range of possible input values and combinations to the simulator for both male and female cases. This was accomplished through random sampling of input parameters across uniformly distributed ranges. Input parameters to the model included lung pressure (P_L) and activation level of four of the intrinsic muscles: CT (a_{ct}), LCA (a_{lca}), TA (a_{ta}), and IA (a_{ia}). Parameter ranges were 0 – 23 cm H₂O for P_L and 0 – 100% for each of the muscle activation levels, except LCA, which ranged from 15 – 100%, based on previous simulations that have shown no vibration to occur below a certain threshold of LCA activity. A total of 2000 randomly sampled parameter sets were created, and voice production was simulated for 0.500 sec based on each set. Radiated sound pressure and glottal flow waveforms from each simulation were output, saved, and used to calculate the desired output parameters. This was repeated for both male and female models, using the same random parameter sets for each gender. A MATLAB script was written to run the batch of simulations and save the required data. The analysis was performed on a Windows-based desktop computer, with a 3.20 GHz Intel Core i7 processor and 16 GB RAM. Each simulation required approximately 36 seconds to complete, resulting in a total computation time of 40 hours for both male and female simulations.

2.2 Data Analysis

Outputs of specific interest for the sensitivity analysis were fundamental frequency (f_0) and sound pressure level (SPL). While there are numerous acoustic metrics, f_0 and SPL could be thought of as primary production variables in speech output, that of vocal pitch and loudness. In an attempt to capture the quality of a vibration, pitch strength was also estimated (Camacho and Harris 2008). Pitch strength is a psychoacoustic construct of the pitch saliency of a sound (the degree that a tone can be heard in a sound) which is similar to a periodicity measure and correlates to perceptual voice quality (Kopf et al. 2017). Fundamental frequency (f_0) and pitch strength were calculated from the glottal flow waveform for each signal using the Aud-SWIPE pitch estimation algorithm (Camacho 2012) in MATLAB. Sound pressure level was found in the voice simulator software from the calculated radiated sound pressure signal for all simulations, using the following equation:

$$SPL = 20 \log_{10} \frac{\mathcal{P}}{\mathcal{P}_0} \text{dB},$$

where $\mathcal{P}$ is the mean radiated output power of the sound signal and $\mathcal{P}_0$ is a reference power of 1.0 E-7.

A comparison between the first and second 1000 simulations was performed to determine convergence. Convergence measures were average f_0 and average pitch strength for both

male and female simulations. All convergence measures were within less than 0.75% between the first and second 1000 simulations, except for female f_0 , which was within 2%. Thus, the results were considered to be converged and sampling was considered adequate.

Only steady, periodic vibration was considered; damped or chaotic signals were filtered out by using a pitch strength cutoff value of 0.16 (pitch strength ranges from 0 to 1.0) to set f_0 to zero for all signals below the cutoff. Analysis was performed in MATLAB using all signals with a nonzero f_0 . Histograms of pitch strength were plotted for both male and female simulations. Relationships between model inputs and outputs were quantified by curve fitting (e.g., lung pressure versus vocal fundamental frequency). Inputs were plotted against outputs, and curves, along with 95% confidence bounds, were fit to both the male and female data using built-in functions in MATLAB's curve fitting toolbox. For all but the power law curves (which used simple least squares method), we utilized the bisquare weights method, a robust least squares approach that minimizes a weighted sum of squares, where the weight assigned to each point decreases with increasing distance from the fitted curve, in order to reduce the influence of outliers. This provided better fits than the simple least squares method.

To give more insight into the relationship quantified by the curve fits, density contours were also found for all simulations, to visualize the areas in the analysis space with the highest likelihood of periodic vibration. Density of the plotted points was calculated based on an 18×18 grid in the plot space, 75th and 95th density percentiles were found, and contours were plotted for each percentile using built-in MATLAB functions. The 75th percentile may include situations where voicing is less consistent, such as vocal fry, soft voice/whisper, or yell, while the 95th percentile is likely associated with regions where more consistent phonation occurs and, thus, where most normal voicing is focused. Pitch strength histograms, curve fits showing relationships of input parameters to output variables, and periodic vibration density contours were compared between male and female simulations.

3 Results

3.1 Pitch strength

Estimated pitch strength values (between 0 and 1, where 1 is the most salient or “periodic”) were compared between male and female simulations via histograms for all cases of periodic vibration (0.16 and above). Male and female pitch strength histograms are shown in Figure 2. Bin size was 0.02. Both male and female results showed left-skewed distributions. Average and median for male were 0.3013 and 0.3082, respectively. Female average and median were slightly higher, at 0.3314 and 0.3423, which was clear from observation of the histograms. Additionally, the male distribution is broader compared to the female distribution. Maximum pitch strength value was higher for female (0.4739) than male (0.4561).

3.2 f_0 and SPL curve fits

The relationships via curve fits of input parameters to fundamental frequency (f_0) and sound pressure level (SPL), for both male (black) and female (red), are shown in Figure 3. Solid

lines show curve fits, while dashed lines represent the 95% confidence bounds. Equations and adjusted R^2 values for the curve fits are also provided in Table 1. Plots are only shown for lung pressure and CT and TA activity. Activity of the LCA and IA muscles showed only insignificant f_0 and SPL trends and so were not considered further.

3.2.1 Lung pressure—The best fit for the influence of lung pressure on f_0 showed a first-order (linear) relationship for both male and female cases, where f_0 increased with increasing PL. This relationship appeared to be slightly more positive for the male simulations than for female (i.e., male line is steeper). The 95% confidence bounds were wider for the female curve than the male, reflecting a larger spread in the data. R^2 was relatively high for these relationships and was similar between male and female cases (0.5304 and 0.5183, respectively). The most distinct difference between the genders was a systematic increase in f_0 for the female cases over the male. The difference was approximately 32 Hz on average over the whole pressure range.

The best fit for the effect of lung pressure on SPL was a power law curve. R^2 values for these relationships were high and similar for both male (0.6869) and female (0.6832). Male and female average curve fits were very similar to one another, with the female curve being slightly lower than the male curve (about 3.3 dB on average). The 95% confidence interval was similar for both male and female cases.

3.2.2 CT activity—Activity of the CT (a_{ct}) muscle exhibited a concave-up, second-order relationship to f_0 , where f_0 stayed almost the same (minimal decrease) with increasing CT activity up to around 30%, and then increased exponentially as a_{ct} was increased further. Both male and female curves were similar in shape, but the female curve exhibited a steeper slope at higher a_{ct} values. The same systematic shift in frequency between male and female cases was apparent. The confidence interval for the female curve was again wider than the male, as with the lung pressure plot. Both had similar and relatively high R^2 values (0.7806 and 0.7311 for male and female, respectively).

For the effect of a_{ct} on SPL, the best curve fits were slightly increasing (more so for male cases) lines. Over the range of the muscle activation, SPL had roughly a 10 dB change. No significant male or female trend was observed in the data points (not shown), resulting in R^2 values that were low and dissimilar for these fits (male – 0.3342; female – 0.1957).

3.2.3 TA activity—The best fits for f_0 as a function of TA activity (a_{ta}) were increasing, linear relationships for both male and female cases. Aside from the shift in f_0 that was also seen with previously presented results, the difference between male and female curves was a noticeably steeper slope for the female line. There was a distinct trend in the data points, evident from high (highest among the relationships considered) adjusted R^2 values for both genders (male – 0.8200; female – 0.8006). Confidence intervals were also somewhat tighter than for the P_L and a_{ct} plots. The confidence interval for the female cases was once again wider than for the male.

The curve fits for $SPL(a_{ta})$ were second-order, concave-up curves. Plotting the data points, however, showed that no notable trends were present, as with $SPL(a_{ct})$. This was supported by the low and dissimilar adjusted R^2 values (male – 0.2075; female – 0.1210).

3.3 Density contours

Figure 4 presents density contours for male and female data distributions, for relationships between input parameters P_L , a_{ct} , and a_{ta} , and simulation outputs f_0 and SPL. Contours for the male simulations are plotted with solid lines, while contours for the female simulations are shown with dotted lines. Two contours are given, representing 95th (black) and 75th (gray) percentiles of phonation occurrence density. For example, the 95th percentile line shows the boundaries within which the highest 5% of the density lies. Thus, these plots compare the most concentrated regions in the data between the male and female simulations.

Two notable trends were observed from the density contour plots. First, the same frequency shift was still apparent between male and female cases. Second, the trends between male and female were similar, in that the number of regions, location, and area covered for each contour were reasonably comparable. Some minor exceptions were as follows: 1) for f_0 as a function of P_L , the shape of the 95th percentile contours differed below 7.5 cm H₂O, in that the male contour appeared to be more linear and extended further toward 0 cm H₂O; 2) for f_0 as a function of a , the female 95th percentile contour possibly extended to a higher a_{ct} value than the male contour. While these minor differences exist, distinctly or remarkably different trends between the genders in the phonation occurrence density plots were not identified.

4 Discussion

The results indicate phonation regions in the model that are in line with generally accepted and observed phonation styles in humans. Additionally, gender differences in the model are also generally in line with human vocalization.

The simulation results show that there was a strong relationship for f_0 and SPL productions as a function of lung pressure, and a strong relationship between f_0 as a function of CT and TA activity. Relationships between SPL and CT and TA activity can be considered non-significant and LCA and IA had no remarkable influence on f_0 or SPL. These relationships were not unexpected given previous lab bench studies. For example, both modeling (Titze 1989b) and excised laryngeal studies (Titze et al. 2010) have shown that increased subglottic pressure will increase both the vibratory frequency of the vocal folds and the radiated dB level. Additionally, the increase in f_0 with CT activity has been well documented *in vivo* (Atkinson 1978; Baer et al. 1975; Chhetri and Park 2016), as well as predicted with a body-cover model of phonation (Titze 2000). Moreover, the positive correlation between a_{ta} and f_0 has been shown in the literature (Nasri et al. 1995; Titze 2000). The density contour plot provides additional insight into the relationship, where the 95th percentile contour reveals this positive relationship between a_{ta} and f_0 in the densest region, which then drops off, in agreement with previously observed phenomena (Nasri et al. 1995). Also as would be expected, the simulation results in differentiated f_0 ranges in a similar way as is seen in male and female humans, confirming that the general model geometrical differences are

reasonable approximations of reality (Titze 1989a). Taken as a whole, these results indicate the validity of the current simulations.

The results of the simulator add some insight into the potential differences in the perception of vocal effort and vocal risk in females. For example, the results indicate that female larynx (as simulated) has a slight disadvantage (3.3 dB) when considering the lung pressures needed to make phonation occur. Therefore, if this indicates actual human phonation, to match the vocal output, females would require a slightly higher lung pressure than the males. The $SPL(P_L)$ plot in Figure 3 suggests that at low lung pressure (start of the curve) an additional roughly 1 cm H₂O would be required for females to achieve the same SPL as males, and that difference would become greater at higher lung pressures because of the nonlinear curve. However, due to nonlinear physics in the model, such a superficial estimate is unreliable. Future work requiring additional simulations would need to be performed in order to know the exact physiological requirements to account for the disadvantage. Along with the requirement for increased lung pressure comes an increase in phonatory effort. This corresponds with previously discussed reasons why female occupational voice users may experience more voice problems (Hunter et al. 2011). This observation could have an even larger effect when considering more than just a set lung pressure input but where the lung pressure comes from. Hixon and Morgan (1989) measured that, when controlling for age, female maximum expiratory lung pressures are smaller in magnitude compared to males. Thus, not only do the females not generate the same pressure but more pressure may be needed. If, therefore, this simulated situation were realized in a human, it would imply that the female would require more effort for similar production and would predispose that person to more fatigue.

The results of the pitch strength gender differences has not been discussed in the literature for human phonation. Considering that pitch strength has a correlate to perceived voice quality, the model results indicate that the female model has a higher average pitch strength (saliency) yet the male distribution is broader. While it is unclear why there would be this difference, it would indicate that, per the pitch strength estimation, the female simulated voice would be more perceptibly pitch salient than the male voice, perhaps perceived as more periodic or even at a higher vocal quality (Kopf et al. 2017).

The slope of the $f_0(a_{ct})$ curve was slightly steeper at high a_{ct} , and the $f_0(a_{ta})$ slope was steeper overall, for the female cases than for the male cases. A likely explanation for this is that the female vocal fold model is more sensitive to changes in CT and TA activity because of its smaller scale. In the simulator, changes in a_{ct} and a_{ta} affect vocal fold length (via strain, ϵ) which then determines vocal fold stiffness. Natural (fundamental) frequency is proportional to (k/m) , where k is material stiffness and m is mass. Thus, the smaller mass of the female vocal folds naturally results in a higher fundamental frequency for the same stiffness, but this relationship also results in a steeper slope in f_0 as a function of k with smaller mass.

It is important to note that the current results are due solely to differences in anatomical scale between male and female models, as this is the only difference that the simulator currently includes. Although it is highly beneficial to isolate and study the influence of an

individual parameter, and, for the current study, it provided useful insights into gender-related differences in voice simulations due to size differences, the results are nonetheless limited. Other differences between the male and female phonatory system are known to exist, such as differences in material properties of male and female vocal folds, as well as morphology (e.g., different angle between left and right laminae of thyroid cartilage). These would also influence results, perhaps more so than what was observed here. Thus, the current study provides a partial and preliminary picture, and the effects of other gender-specific features must also be investigated, individually and together, in the future. This can be accomplished with the current simulator, which has the capability to include several of the other input differences. Nevertheless, illustrating that the anatomical scale alone captures several known differences seen in human gender phonation is a finding of note.

Lastly, we emphasize that this study lays the groundwork for further in-depth studies to completely map simulator sound signal characteristics as functions of simulator input parameters. As such, the scope of the current work was limited to exploring differences in model behavior due to gender. However, future work will investigate more general model behavior and the mechanisms behind that behavior.

5 Conclusion

We successfully used sensitivity analysis to draw out phonation relationships between input parameters which match what we see in human speech production. Additionally, we were able to see nuances in these relationships which are difficult to observe in humans (e.g., the relationship between laryngeal muscle activation and vocal output). The results added insight to some of the underlying assumptions on why female occupational voice users have a higher incidence of voice problems, particularly with the slight advantage the simulated male larynx has in producing vocal volume. However, the results indicated that the simulated female vocalization have a higher pitch strength which has shown to correspond with higher vocal quality.

Future steps in this work could move in several directions. First, in the study here, the female larynx was just a smaller scaled version of the male larynx. While this is a valid first approximation, it is possible that more detailed geometric differences and variations could change the results. Also, the material properties of the simulated gender larynx were identical, which, like the geometry, is a valid first approximation; however, the literature has shown that there are slight differences of the material properties. These limitations allow for future work regarding gender-specific behavior in the simulated voice.

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Fig. 1.
Schematic of vocal fold model in voice simulator, displaying posturing parameter definitions

Fig. 2.
Histograms showing probability distributions for pitch strength in male (left) and female (right) simulated voice signals

Fig. 3.

Curve fits with 95% confidence bounds, derived from sensitivity analysis scatter data, for male and female simulated fundamental frequency (f_0) and sound pressure level (SPL) as functions of lung pressure (P_L), CT activation (a_{ct}), and TA activation (a_{ta})

Fig. 4. Contour plots showing 75th and 95th percentiles of scatter data density for male and female simulated fundamental frequency (f_0) and sound pressure level (SPL) as functions of lung pressure (P_L), CT activation (a_{ct}), and TA activation (a_{ta})

Table 1

Equations and adjusted R^2 values of curve fits to sensitivity analysis scatter data for male and female simulated fundamental frequency (f_0) and sound pressure level (SPL) as functions of lung pressure (P_L), CT activation (a_{ct}), and TA activation (a_{ta}).

		Curve Fit	Male Equation	Male R^2
f_0	P_L	Linear	$f_0 = 0.4417P_L + 100.4$	0.5304
	a_{CT}	2 nd Order	$f_0 = 0.008453a_{ct}^2 - 0.1487a_{ct} + 87.36$	0.7806
	a_{TA}	Linear	$f_0 = 0.8083a_{ta} + 70.82$	0.8200
SPL	P_L	Power Law	$SPL = -121.8a_{ta}^{-0.1304} + 38.07$	0.6869
	a_{CT}	Linear	$SPL = 0.1254a_{ct} - 57.07$	0.3342
	a_{TA}	2 nd Order	$SPL = 0.002353a_{ta}^2 - 0.1640a_{ta} - 48.97$	0.2075

Female Equation	Female R^2
$f_0 = 0.3381P_L + 130.7$	0.5183
$f_0 = 0.01289a_{ct}^2 - 0.3810a_{ct} + 114.9$	0.7311
$f_0 = 0.9585a_{ta} + 91.45$	0.8006
$SPL = -95.41a_{ta}^{-0.2098} + 3.705$	0.8682
$SPL = 0.09748a_{ct} - 58.62$	0.1957
$SPL = 0.001263a_{ta}^2 - 0.1518a_{ta} - 50.03$	0.1210