Computational Study of the Impact of Dehydration-Induced Vocal Fold Stiffness Changes on Voice Production

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Summary: Objective. Systemic vocal fold dehydration is known to increase vocal fold stiffness, which has been hypothesized to have important effect on voice production. However, it remains unclear whether the dehydration-induced vocal fold stiffness changes can have a noticeable impact on phonation, particularly in normal phonation conditions. The goal of this study was to investigate the impact of vocal fold stiffness changes due to vocal fold systemic dehydration and its significance in daily communication.

Methods. Parametric computational simulation using a three-dimensional vocal fold model, in which the vocal fold stiffness was varied as a function of systemic dehydration levels based on previously-reported experimental data.

Results. The results showed that systemic dehydration had significant effects on voice production only at high levels of dehydration, at which dehydration increased the phonation threshold pressure and fundamental frequency, and decreased glottal opening area, vocal intensity and glottal efficiency. The effect depended mainly on the overall dehydration level but was also slightly affected by the dehydration distribution and muscular control. However, for dehydration levels typical of normal phonation conditions, the effect was negligible.

Conclusions. The results indicated that dehydration-induced vocal fold stiffness change likely is not an important mechanism through which vocal fold systemic dehydration affects voice production. Nevertheless, a large decrease in glottal efficiency implies a possible perceived increase of vocal effort under a realistic dehydration condition.

Key Words: Vocal fold systemic dehydration−Stiffness change−Voice production−Computational model.

INTRODUCTION

Since water is a main component of vocal fold tissue and plays an integral role in tissue structure and function,[1-3] vocal fold dehydration, defined as the water loss within the vocal fold tissue (ie systemic dehydration) and on the surface (ie surface dehydration), is considered to have negative effect on vocal function and health.[4,5] For systemic dehydration, many human subject studies have shown its detrimental impacts on voice production (eg increased acoustic perturbation, decreased voice range of pitch and loudness, and increased phonation threshold pressure and phonation effort.[6-10]) However, several studies reported equivocal effects of the vocal fold systemic dehydration on vocal quality.[11-14] The underlying physiological mechanism of how vocal fold dehydration affects voice production is not yet fully understood. In particular, while many different mechanisms have been proposed, it is unclear how large an effect different mechanisms have on voice production. Answering these questions would help us to better clarify the role of vocal fold systemic dehydration in vocal function and related voice disorders.

According to previous theoretical and experimental studies, vocal fold systemic dehydration is believed to directly affect the biomechanical properties of the vocal fold.[15-18] Based on biphasic theory, Zhang et al found that water is as important as the solid component of the vocal fold tissue in providing stress load support.[15] Using excised animal models, Chan et al[16] and Miri et al[17] investigated the biomechanical changes under different hydration conditions and reported significantly increased stiffness and viscosity in dehydrated vocal folds. Furthermore, Yang et al investigated the stress-strain relationships of the vocal fold mucosa at different dehydration levels and quantitatively evaluated the increased stiffness and decreased compression resilience with increasing dehydration levels.[18] Since vocal fold stiffness and viscosity are both important physiologic parameters in controlling vocal fold vibration and voice acoustics,[3,19] it is generally hypothesized that vocal fold systemic dehydration affects voice production mainly through its effect on vocal fold viscoelastic properties.

However, the above hypothesis has not been verified through *in-vivo* and *in-vitro* experiments due to the difficulties in measuring systemic dehydration levels and isolating this effect from that of the surface dehydration. As a result, the impact of dehydration-induced vocal fold viscoelastic changes on voice production is still unclear. More importantly, vocal fold systemic dehydration in normal phonation conditions is generally much lower than that induced in a laboratory setting in previous studies, partially due to water supply from blood circulation and its non-uniform distribution within the vocal fold tissue.[20] It remains unknown whether the vocal fold stiffness and viscosity change related to a realistic, but lower-level and non-uniform systemic

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dehydration is able to cause notable effects on normal voice production.

In this study, we focused on the stiffness aspect of dehydration-induced vocal fold changes, partly due to the lack of quantitative data on the relationship between the viscosity and systemic dehydration. This focus also allows us to better understand the effect of viscosity changes on phonation when such experimental data become available. The objective of this study was to investigate the effect of dehydration-induced stiffness changes on voice production using a three-dimensional vocal fold model. Unlike excised laryngeal models, computational models allow quantitative and independent control of vocal fold systemic dehydration from surface dehydration. In the simulation, the vocal fold stiffness was varied as a function of the dehydration level according to previously-reported experiments, and its effect on selected measures of vocal fold vibration (ie phonation threshold pressure, glottal airflow and opening area, and closed quotient) and voice acoustics (ie fundamental frequency, sound pressure level, and glottal efficiency) were calculated. The details of the computational model and data analysis method are described in the following in Sec. 2. The effect of the systemic dehydration-induced stiffness changes on voice production is analyzed in Sec. 3 and the implication toward practical conditions is discussed in Sec. 4.

METHODS

Model and simulation

Figure 1 shows schematic diagram of the vocal fold model used in this study. In order to directly apply phonation-induced systemic dehydration distribution from the previous work,[20] we used the same one-layer three-dimensional vocal fold geometry with a uniform cross section along the anterior-posterior (AP) direction. The vocal fold had a 15-mm length in AP direction, a 7.5-mm depth in medial-lateral direction, a 9-mm vocal fold thickness and 2.5-mm medial surface vertical thickness. Although the vocal fold is physiologically a multilayered structure, Yin and Zhang[21] showed that the vocal folds behaved mechanically as one-layer structure for most phonation conditions. The left and right vocal folds were assumed to be symmetric about the glottal midline in geometry, biomechanics, and vibrations, so only one vocal fold was considered in the simulation as shown in Figure 1A.

Figure 1B illustrates the variation of vocal fold stiffness with relation to the systemic dehydration level, which was derived from the experimental data in Yang et al.[18] The curve shows a good fitting with the experimental data and a consistent dehydration effect on the stiffness with the previous studies.[16,17] Furthermore, a non-uniform distribution of the systemic dehydration was observed during normal phonation,[20] and this condition was considered in this model to induce a non-uniform change of vocal fold stiffness as shown in Figure 1C. The highest increase of the vocal fold stiffness occurs at the anterior-posterior midpoint on the inferior edge of the medial surface due to the highest dehydration level. However, the range of the non-uniform dehydration level is small,[20] it is unclear how much of an effect this non-uniform distribution has on voice production. Thus, the conditions with the uniform systemic dehydration were also simulated to compare with the non-uniform distributed conditions.

In order to focus on the effect of vocal fold systemic dehydration on voice production, the dynamic vocal fold dehydration during phonation was ignored, and the voice production under a specific dehydration level was simulated using the same structure-airflow interaction model as described in Zhang.[19,22] The airstream was modeled as a one-dimensional quasi-steady flow with a viscous loss along the glottal channel, and the vocal fold was modeled as a transversely isotropic, nearly incompressible, linear elastic material with an isotropic plane perpendicular to the AP direction. The material was defined by the properties including the transverse Young's modulus E_t, AP shear modulus G_{ap}, and AP Young's modulus $E_{ap} = 4G_{ap}$, AP Poisson's ratio $v_{ap} = 0.495$, and density $\rho = 1030$ kg/m^3. A fixed boundary condition was applied on the anterior surface, the

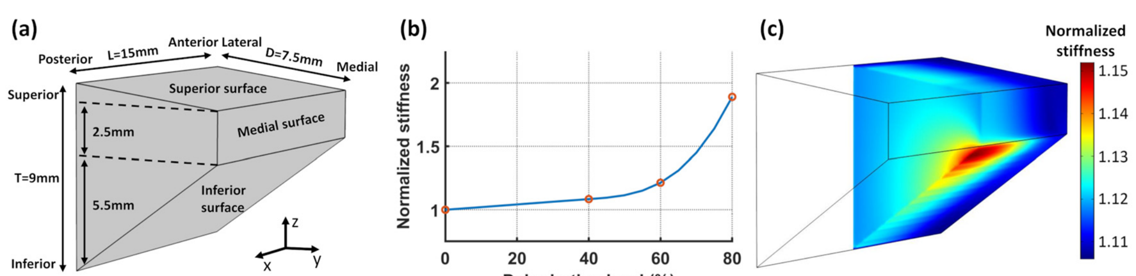

FIGURE 1. Geometry and stiffness setup of the vocal fold model. (**A**) Three-dimensional geometry of the vocal fold model, defined by the length L in the anterior-posterior direction, the depth D in the medial-lateral direction, and the thickness T in the inferior-superior direction. (**B**) Fitting curve of the normalized stiffness across the systemic dehydration level based on experimental data (Red circle) in Yang et al.[18] (**C**) Non-uniform stiffness changes due to unevenly distributed dehydration based on data in Wu and Zhang.[20] In this case, the average level of the systemic dehydration is 50% and the range of the non-uniform dehydration level is 7%. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

posterior surface, and the lateral surface. This model is computationally efficient and has been proved capable of capturing the essential features of the glottal fluid-structure interaction.[23,24] For specific details of the model formulation, please refer to these papers.

Table 1 lists the conditions simulated in this study. Five sets of vocal fold stiffnesses (E_t, G_{ap}) were considered as the initial condition without systemic dehydration, which are in the normal range of vocal fold moduli used in previous numerical studies.[19,25] For each set of initial vocal fold stiffness, a wide range of the systemic dehydration level from 0 to 100% was investigated. Under a specific dehydration level, the vocal fold stiffness (E_t, G_{ap}) was determined according to the stiffness-dehydration relationship (Figure 1B) and non-uniform dehydration distribution (Figure 1C). For each dehydration condition, the subglottal pressure was varied in a range from 50 to 2400 Pa as in previous studies.[19,22] A total of 3780 conditions (including 5 initial vocal fold stiffness conditions, 21 dehydration levels, 18 subglottal pressures, and 2 dehydration distribution conditions) were investigated, each simulating a 0.5-s voice production at a sampling rate of 44100 Hz.

Data analysis

For each simulation, only the last 0.25-s of the data was used for analysis, because during this time period vocal fold vibration is generally in the steady state or nearly steady state. For vocal fold vibration, the phonation threshold pressure (PTP), mean glottal flow rate (Q_{mean}), mean glottal area (Ag_{mean}), and closed quotient (CQ) were extracted. The PTP was estimated as the minimum subglottal pressure required to initiate vocal fold vibration, while the CQ was calculated as the percentage of the glottal cycle in which glottal flow rate was lower than 10 percent of the glottal flow waveform. For voice acoustic, the fundamental frequency (F0) and sound pressure level (SPL) were extracted. Furthermore, the glottal efficiency (GE) was calculated as the ratio of the acoustic power (ie sound energy radiated at the glottal exit) to the aerodynamic power (ie the product of the mean subglottal pressure and the mean glottal flow rate). In addition, for different dehydration distribution conditions, the relative difference of each paired measures was calculated as a percentage of their absolute difference divided by the value under uniform distribution condition.

RESULTS

Impact of the non-uniform dehydration distribution

Figure 2A shows the comparison of each measure between different dehydration distribution conditions. Except for the glottal efficiency, all the measures had small relative differences (<5%) between the uniform and non-uniform distributed dehydration conditions, indicating a slight impact of the non-uniform distribution of the systemic dehydration on the vocal fold vibration and output voice. Although the glottal efficiency had a large range of relative difference, the GE variations with the dehydration levels in the non-uniform dehydration conditions were similar to those in the uniform dehydration conditions, as shown in Figure 2B, indicating an insignificant effect of the non-uniform distribution in dehydration on voice production. The large relative difference in GE might be due to the small absolute value of the GE, thus leading to high sensitivity to small fluctuations. Consequently, the impact of the non-uniform dehydration distribution is negligible and only the results in the uniform dehydration conditions will be shown in the following figures.

Effect of the systemic dehydration on voice production

Figures 3 and 4 show the effects of the systemic dehydration on different measures of vocal fold vibration and voice acoustics. Overall, all selected measures were influenced by the systemic dehydration of the vocal fold. The phonation threshold pressure is generally stable at a low dehydration level, but when water loss exceeds 60%, the PTP rapidly and noticeably increased by up to 200∼300%. Although the absolute values of the PTP increase are different across initial vocal fold stiffness conditions, the percentage increases of the PTP were quite similar for all initial vocal fold stiffness conditions as shown in Figure 3B.

For the mean glottal flow rate and mean glottal area, a similar decreasing pattern with increasing dehydration levels was shown in Figure 4. Especially in the case with higher

TABLE 1.
Simulation Conditions

	Stiff 1	Stiff 2	Stiff 3	Stiff 4	Stiff 5
Transverse Young's modulus E_t (kPa)	1	1	2	2	4
AP shear modulus G_{ap} (kPa)	10	20	20	40	40
Systemic dehydration level	From 0 to 100% with intervals of 5%				
Subglottal pressure Ps (Pa)	[50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400]				
Dehydration distribution	Uniform/Non-uniform				

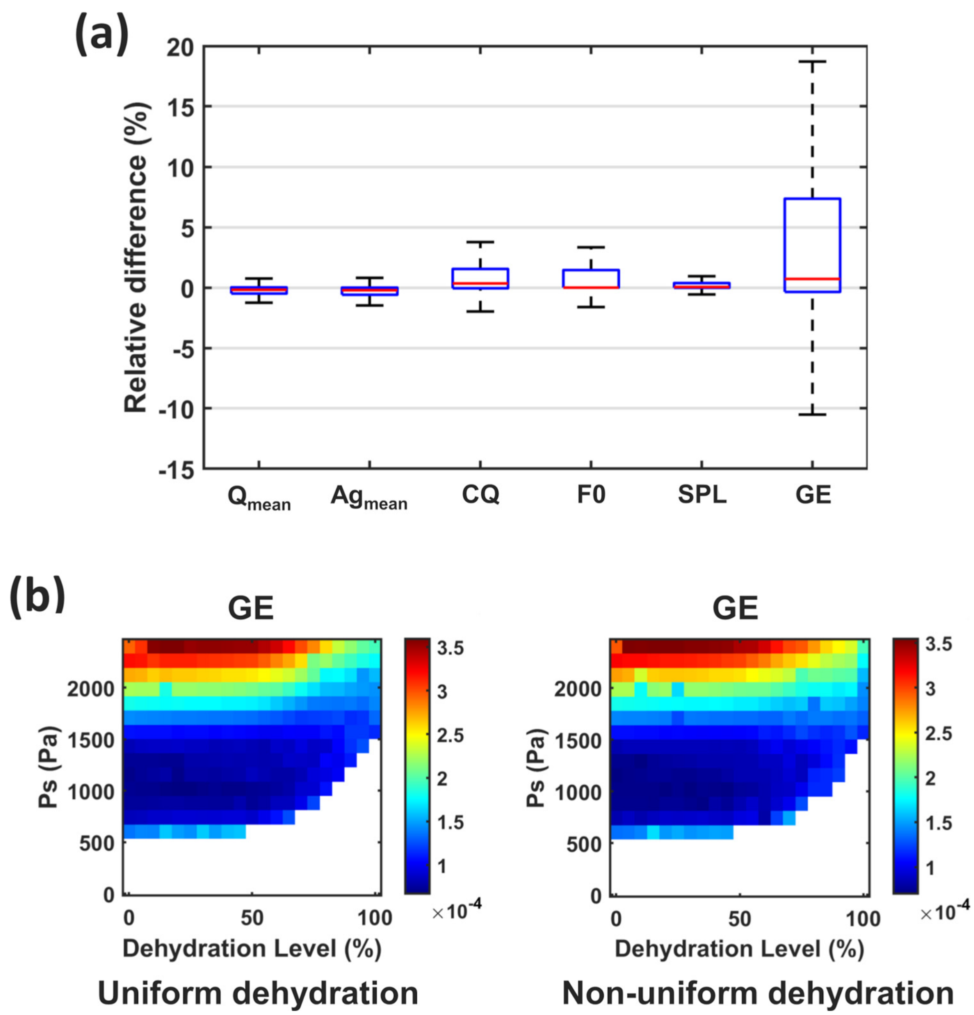

FIGURE 2. (**A**) Relative differences of the selected measures between the conditions with uniform and non-uniform distributed dehydration. Box plots mark the minimum, first quartile (25% percentile), median (50% percentile), third quartile (75% percentile), and maximum values of the data. (**B**) The variations of the glottal efficiency (GE) with the increasing dehydration levels under different dehydration distribution conditions. In this figure, the initial vocal fold stiffness condition is Stiff 3 (E_t = 2kPa and G_{ap} = 20kPa).

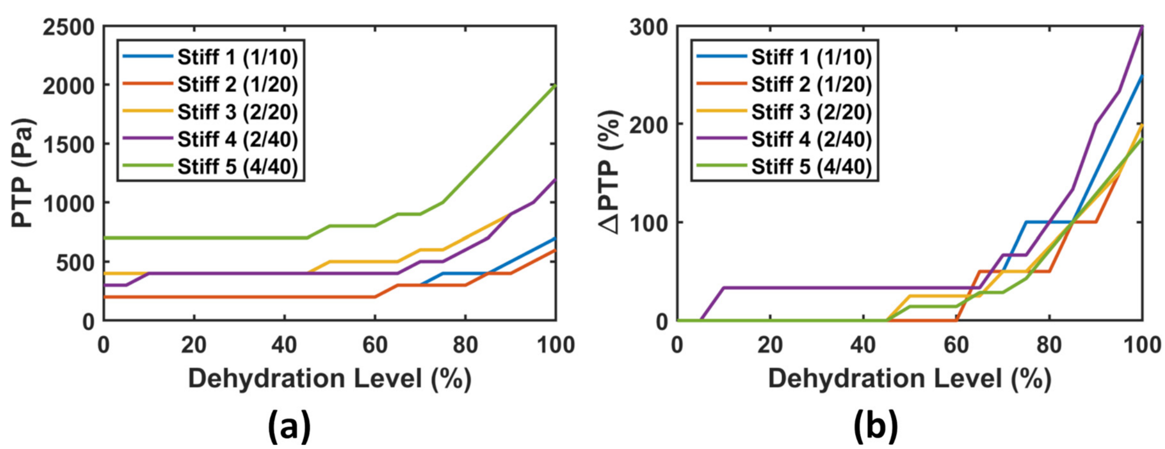

FIGURE 3. (**A**) Phonation threshold pressure PTP and (**B**) percentage change of the phonation threshold pressure ΔPTP with the increasing dehydration levels under different initial vocal fold stiffness conditions. In this case, the dehydration distribution is uniform. The values in the parentheses represent the transverse Young's modulus E_t and AP shear modulus G_{ap} of the vocal fold. AP, anterior-posterior.

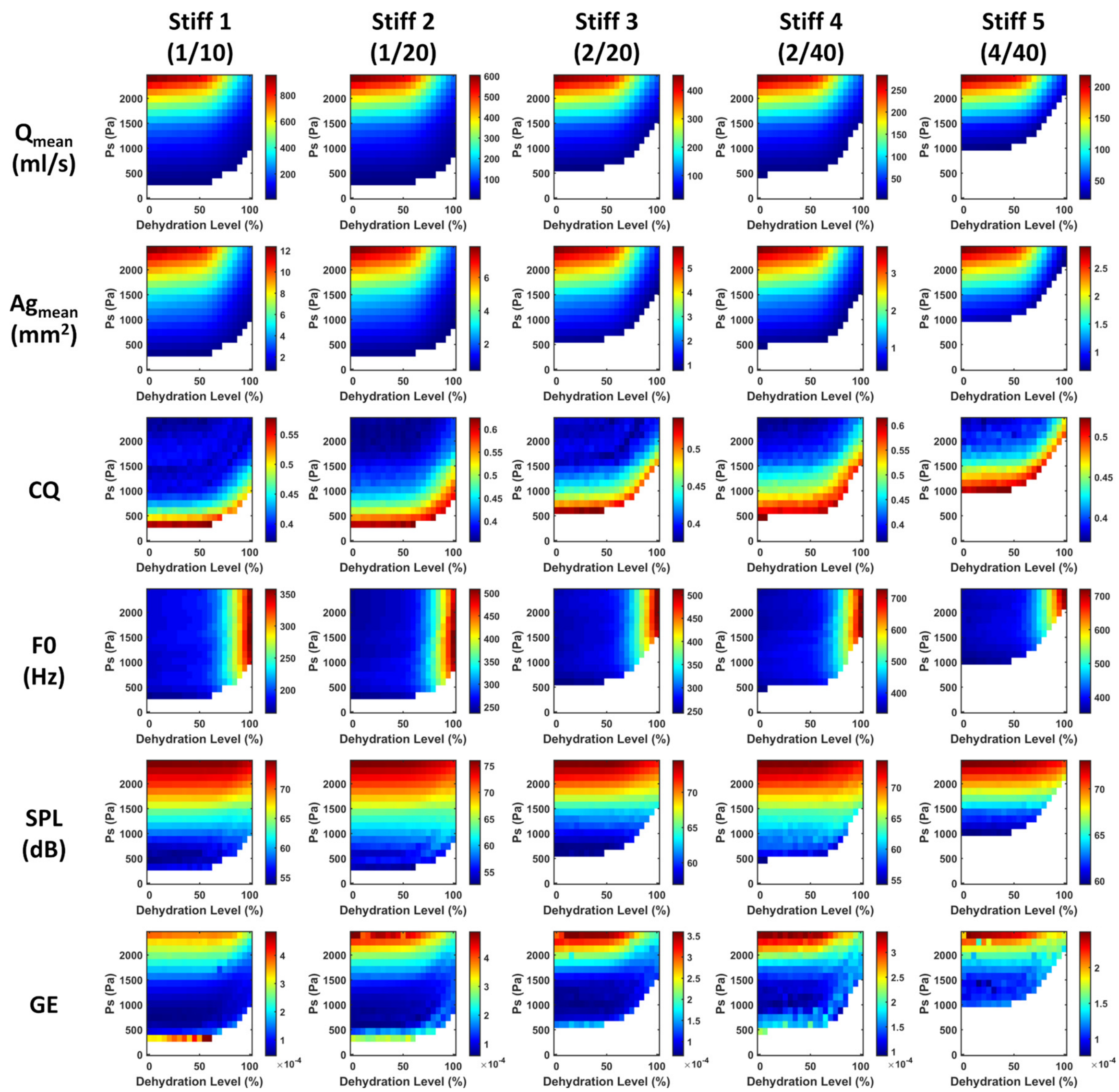

FIGURE 4. Effect of the systemic dehydration on the selected measures for different vocal fold stiffness conditions. The selected measures include the mean glottal flow rate Q_{mean}, mean glottal area Ag_{mean}, closed quotient CQ, fundamental frequency F0, sound pressure level SPL, and glottal efficiency GE. For all cases, the dehydration distribution is uniform in the vocal fold. The values in the parentheses represent the transverse Young's modulus E_t and AP shear modulus G_{ap} of the vocal fold. AP, anterior-posterior.

subglottal pressure, the absolute decreasing values of the Q_{mean} and Ag_{mean} were much larger than those with a lower *Ps*. It is noted that there is not much difference in the patterns of the ΔQ_{mean} and ΔAg_{mean} under different subglottal pressures [see Figure 5]. The similar result was observed in the comparison of the Q_{mean} and Ag_{mean} across different initial vocal fold stiffness conditions, that is, the absolute changes of the Q_{mean} and Ag_{mean} largely decreased with increasing initial vocal fold stiffness whereas the pattern of the percentage changes (ie ΔQ_{mean} and ΔAg_{mean}) were consistent. On the contrary, the closed quotient generally increased as the dehydration level went up, and the large increases mostly occurred in the conditions with low subglottal pressures [see Figures 4 and 5], showing an impact of the subglottal pressure on the dehydration-related CQ variation pattern.

With regard to voice acoustic measures, Figure 4 shows a big difference of the variation patterns between the fundamental frequency and sound pressure level. With increasing dehydration level, the F0 significantly varied in a wide range (0∼250 Hz) and could increase up to as high as 100% in the conditions with high dehydration levels, showing an important impact of vocal fold systemic dehydration on the F0. In contrast, the SPL had a slight change (<5%) with increasing dehydration levels, and the SPL variation pattern was heavily dependent on the subglottal pressure. As the dehydration level went up, the SPL increased at a low Ps (<1500Pa) but decreased at a high Ps [see Figure 5]. The glottal efficiency had a similar variation pattern as the SPL but a much larger variation range (60%), indicating a significant but inconsistent effect of vocal fold systemic dehydration on the GE. Even so, the SPL and GE decreased in the

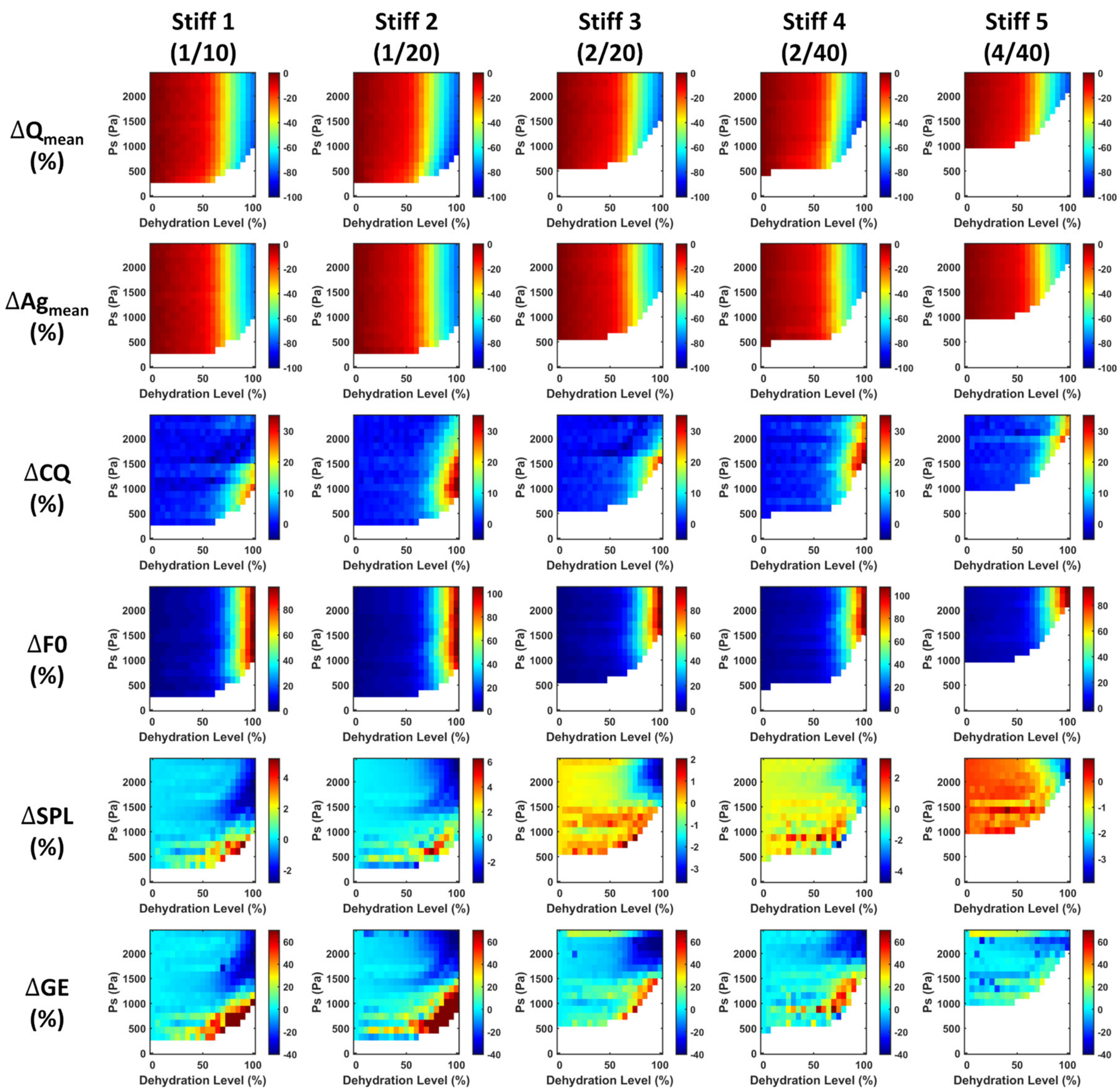

FIGURE 5. Percentage changes of the mean glottal flow rate ΔQ_{mean}, mean glottal area ΔAg_{mean}, closed quotient ΔCQ, fundamental frequency ΔF0, sound pressure level ΔSPL, and glottal efficiency ΔGE with the increasing dehydration levels under different vocal fold stiffness conditions. For all cases, the dehydration distribution is uniform. The values in the parentheses represent the transverse Young's modulus E_t and AP shear modulus G_{ap} of the vocal fold. AP, anterior-posterior.

most dehydrated conditions. In addition, the variation patterns of the F0, SPL, and GE were stable across different initial vocal fold stiffness conditions.

DISCUSSION AND CONCLUSIONS

Vocal fold systemic dehydration occurs frequently during the phonation, which is believed to directly change the vocal fold stiffness and finally affect voice production, but the relationship between the dehydration-induced vocal fold stiffness and the corresponding vocal fold vibration has not been investigated. The goal of this study was to quantitatively evaluate the impact of the systemic dehydration on vocal fold vibration and voice acoustics using a computational model. Based on the experimental data of the dehydration-related vocal fold stiffness changes, the simulations showed that changes in vocal fold stiffness due to systemic dehydration only have small effect on voice production in typical dehydration conditions.

Compared with the conditions without systemic dehydration, the stiffness increase due to water loss within the vocal fold tissue would increase the resistance of glottal opening, thus weakening the vocal fold vibration with a smaller mean glottal opening area and a lower mean glottal flow rate. Furthermore, the reduced glottal opening increased the vocal fold contact and decreased the vocal intensity, but the effect of the systemic dehydration on the CQ and SPL was small and inconsistent. As the systemic dehydration was over a certain level (~60%), the phonation threshold pressure noticeably increased and the glottal efficiency considerably decreased, especially for a loud speaking task (at a high Ps), indicating a possible increase in energy consumption and vocal effort. These outcomes are consistent with the previous findings regarding the effect of vocal fold stiffness on voice production[19] and the experimental observations of increased perceived phonatory effort.[4,5] In addition, the fundamental frequency was significantly affected by the systemic dehydration as expected, because changes in vocal fold stiffness play a leading role in F0 control.[19] Regarding the two factors, that is the initial vocal fold stiffness before dehydration and non-uniform dehydration distribution, the results showed negligible difference in the variation pattern of each measure between different conditions. These outcomes indicate that impact of the systemic dehydration on voice production is mainly determined by the average dehydration level and is insignificantly affected by vocal fold stiffness control under muscular activations and small range of non-uniform distribution in water loss (<10%).[20]

This work has confirmed that the systemic dehydration is able to affect voice production through changing the vocal fold stiffness, but this effect seems to be insignificant in normal phonation conditions. Our previous study showed that the systemic dehydration level is generally no more than 10% even for a loud speaking or without water resupply,[20] which is consistent with clinical experiences.[4,26] According to the results of the present study, 10% systemic dehydration cannot cause a more than 5% change in Q_{mean} (-22 mL/s, -4.4%), Ag_{mean} (-0.3 mm^2, -3.5%), CQ (0.01, 2%), F0 (8.6 Hz, 3.4%), and SPL (-0.4 dB, -0.6%). As shown in Figure 6, for most of the measures, the variations at a dehydration level of 10% are too small to be observed in the vocal fold vibration or be perceived in the produced voice. For example, the just noticeable differences of closed quotient and sound intensity are 0.1 and 1.5 dB, respectively,[27,28] which can be reached in the conditions with more than 85% systemic dehydration. But it is notable that the just noticeable difference of pitch (about 1.5 to 8 Hz[29,30]) is comparable to the F0 change induced by 10% systemic dehydration, meaning that a perceptible tonal variation may be produced in normal phonation. In contrast, the GE has a larger decrease (4.7-11.5%) by 10% systemic dehydration, indicating a potential increase of vocal effort under realistic dehydration conditions, which is consistent with the observations in human researches.[8-10]

Overall, the impact of dehydration-induced vocal fold stiffness changes on voice production is real but so small in daily communication conditions that it can be ignored. We can further conclude that vocal fold stiffness changes caused by water loss is not the principal physiological mechanism of systemic dehydration effect on voice production. Since human phonation experiments observed significant voice changes resulted from vocal fold systemic dehydration,[4,5] there must be some other ways for the systemic dehydration to affect voice production, like reducing the muscle functions.[31] Future studies are required to evaluate the muscle function changes due to the systemic dehydration and its effect on the voice production control.

One of the limitations in this work was the lack of dehydration-induced viscosity changes in the model, which is also an important aspect affecting voice production.[3,18] Because the research on mechanical properties of vocal fold tissue under dehydration conditions is limited, more experimental data about the quantitative variation of vocal fold viscosity as systemic dehydration increasing is required. Furthermore, the curve of the vocal fold stiffness change with the dehydration level was derived from the experimental data of vocal fold mucosa. It is unclear whether the vocal fold muscle like thyroarytenoid muscle has a similar dehydration-related stiffness variation as the vocal fold mucosa. If not, a two-layer model may be needed to investigate the effect of dehydration-induced different stiffness changes of muscle and mucosa on voice production. In addition, this study mainly focused on the effect of vocal fold systemic

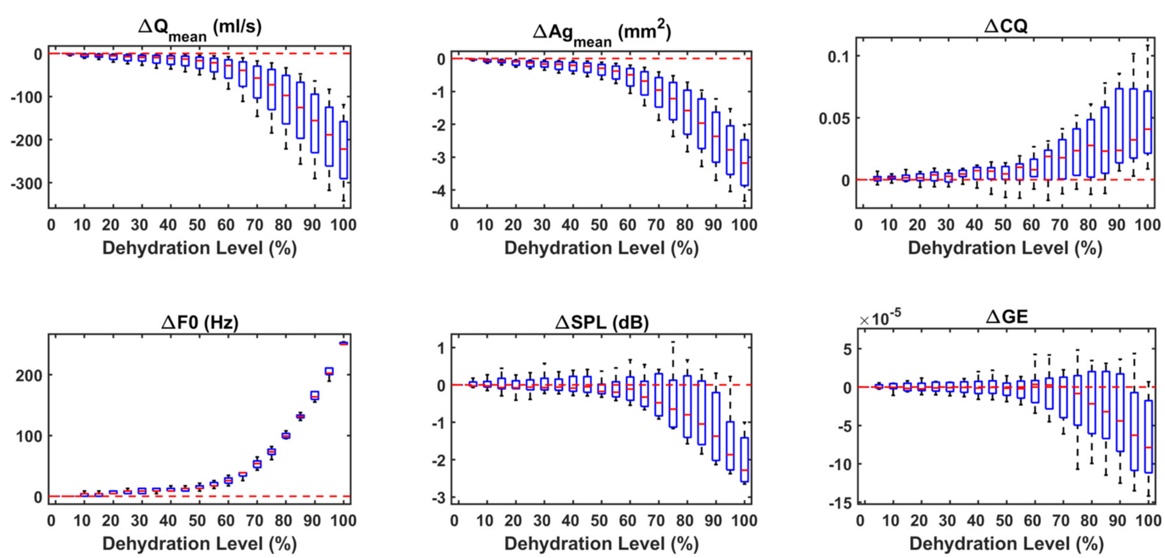

FIGURE 6. Statistic changes of the measures with the increase of the systemic dehydration level in the initial vocal fold stiffness condition of Stiff 3 (E_t = 2kPa and G_{ap} = 20kPa). Box plot shows the minimum, first quartile (25% percentile), median (50% percentile), third quartile (75% percentile), and maximum values of the data, while the dashed line shows the zero value.

dehydration but ignored the vocal fold surface dehydration, because the surface dehydration has a different physiological mechanism on voice production through affecting lubrication and adhesion during vocal fold contact,[32,33] which will be studied in the future work.

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