A SEAWATER-SEABED MODEL OF VOCAL FOLD VIBRATION: *IN-VIVO* MEASUREMENTS OF AMPLITUDE ATTENUATION AND PHASE LAG

Chen-Gia Tsai 1, Jeng-Horng Chen 2, Tzu-Yu Hsiao 3, and Yio-Wha Shau 4

1) Graduate Institute of Musicology, National Taiwan University, Taipei, Taiwan
2) Department of Systems and Naval Mechatronic Engineering, National Cheng Kung University, Tainan, Taiwan
3) Department of Otolaryngology, National Taiwan University Hospital, College of Medicine, National Taiwan University, Taipei, Taiwan
4) Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan

Abstract

Reinke's space comprises loose fibers and interstitial proteins with a high water content. Therefore, the lamina propria of the vocal fold can be regarded as a multilayered liquid-saturated porous medium. A formal approach to physical modeling may be Biot's poroelasticity theory, which accounts for wave propagation in a two-component medium composed of a porous solid frame and a pore fluid. Poroelasticity has a wide range of applications to the study of rocks, soils, and biological tissues. Here we proposed a seawater-seabed model of vocal fold vibration by analogizing Reinke's space and the vocal ligament as seawater and seabed, respectively. Whereas gravity provides the restoring force of a water wave, the restoring forces of liquid motion in Reinke's space are presumably provided by the tensioned epithelium. When water waves propagate over the ocean, they generate stress fluctuations within the seabed and induce its vibration, which is characterized by amplitude attenuation and phase lag. We used medical ultrasound to measure the amplitude attenuation and phase lag across the vocal fold surface and the vocal ligament during modal phonation.

INTRODUCTION

The highly pliable property of Reinke's space is unique to human tissues. This space comprises loose fibers and interstitial proteins with a high water content. Previous studies have emphasized the roles of this strongly hydrated gel in tissue viscosity, shock absorption, and space filling (for a recent review, see Ward et al. 2002). It has been shown that the vocal fold hydration level affects vocal fold vibration in a dramatic manner (e.g., Chan and Tayama 2002). From a viewpoint of biomechanics, the lamina propria of the vocal fold can be regarded as a multilayered liquid-saturated porous medium. A formal approach to physical modeling may be Biot's (1941, 1956) poroelasticity theory, which accounts for wave propagation in a two-component medium composed of a porous solid frame and a pore fluid. Biot's equations are derived from (1) equations of linear elasticity for the solid frame, (2) Navier-Stokes equations for the viscous fluid, and (3) generaized Darcy's law for the interaction between the fluid and the solid frame due to their relative motion. Poroelasticity has a wide range of applications to the study of rocks, soils, and biological tissues (e.g. bones, cartilages, skins, lungs, arterial or myocardial tissues).

The first attemp to include the effects of the liquids in the vocal fold may be a water wave model (Tsai et al. 2006), which assumed that the fibers in Reinke's space are fine and loosely folded, and the wave amplitude in the vocal ligament is small, so that the liquid-like nature dominates vocal fold vibration. We used a water wave theory (Airy 1841) to predict the global vibration of the vocal fold, while the damping effect of the fibrous frames in the lamina propria is discussed as a correction. Given that the the ratio of the water depth H to the wavelength λ of the vocal fold lies between 1/2 and 1/20, its dynamics may be analogous to intermediate water waves. Particles in intermediate water waves follow elliptic orbits with the major axis parallel to the bottom. These ellipses flatten with depth, and particles near the bottom are primarily involved in tangential motion (Fig. 1). Contradicting the assumption of lateral motion of the vocal-fold body in previous models (Hirano 1974, Story and Titze 1995, Titze 1988, Liljencrants 1991), however, this vibration behavior was verified in a specific experiment (Tsai et al. 2006, Chang et al. 2007).

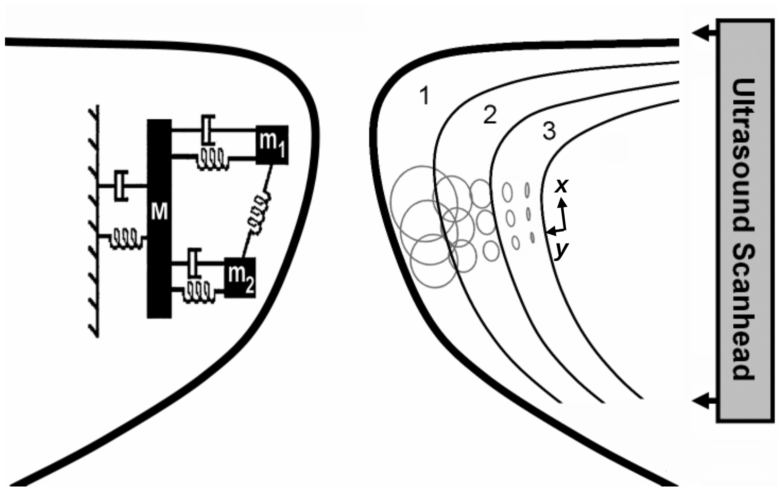

Figure 1: Comparison of the three-mass model (left) and the intermediate water wave model (right). The grey ellipses represent the orbits of tissue particles (clockwise motion) in the three layers of the lamina propria. Whereas the three-mass model assumes lateral motion of the body layer (M), the water wave model predicts dominant vertical motion of the deep lamina propria.

In the present study, we refined the previous model and proposed a seawater-seabed model of vocal fold vibration by analogizing Reinke's space and the vocal ligament as seawater and seabed, respectively. Our theory will deal with the equations of motion and the boundary conditions of the vocal fold. In the experimental study, we used medical ultrasound to measure the amplitude attenuation and phase lag across the vocal fold surface and the vocal ligament during modal phonation. The possible mechanical roles of different layers of the vocal fold were discussed in the light of the seawater-seabed model.

THEORY

Description of the seawater-seabed model is divided into the motion equations and boundary conditions of (1) Reinke's space, and (2) the vocal ligament. In the simplified model, the liquids in Reinke's space are assumed to be homogeneous, incompressible, inviscid, and two dimensional. A mucosal wave is assumed to propagate along the *x*-direction, as shown in Fig. 1. Based on the potential flow theory, the velocity potential of the water waves is governed by Laplace's equation:

$$\nabla^2\Phi(x,y)=0\,, \tag{1}$$

where the fluid velocity is defined as $\nabla\Phi$.

Next, we compare the boundary conditions of seawater waves and the liquids in Reinke's space. The first boundary condition of water waves is the *kinematic condition*, which states that a parcel of fluid at the surface remains at the surface. Obviously, this condition is satisfied at the liquid-epithelium interface during vocal fold vibration:

$$\left.\frac{\partial\Phi(x,y)}{\partial y}\right|_{y=w}=\left.\frac{dw}{dt}\right|_{y=w}=\left(\frac{\partial w}{\partial t}+\frac{\partial w}{\partial x}\Big/\frac{\partial\Phi}{\partial x}\right)_{y=w}, \tag{2}$$

where *w* is the deformation of the water surface.

The second boundary condition of water waves is the *dynamic condition*: the pressure on the surface equals the air pressure $p_a(t)$. This condition can be expressed by the Bernoulli equation

$$\frac{\partial\Phi(x,w)}{\partial t}+\frac{p(x,w)}{\rho_w}+\frac{1}{2}\left|\nabla\Phi(x,w)\right|^2+gw=\frac{p_a}{\rho_w}, \tag{3}$$

where $p(x,y)$ is the liquid pressure, ρ_w is the liquid density, and *g* is the acceleration due to gravity.

A major difference between mucosal waves and water waves is the restoring force: whereas gravity provides the restoring force of a water wave, the restoring forces of liquid motion in Reinke's space are presumably provided by the tensioned epithelium. We assume that the epithelium is composed of parallel strings aligned in the anterior-posterior direction (*z*-direction in Fig.1), with no coupling between adjacent strings. Each string has the shape of a hyperbola when subject to a deformation *w*:

$$w(x,z)=\left(1-\frac{4z^2}{l_e^2}\right)w(x,0)\,, \tag{4}$$

where l_e is the epithelium length, and the $z = 0$ plane is located at the middle-point of the vibrating portion of the vocal fold. This deformation of the epithelium produces a pressure on the water surface p_e:

$$p_e=T_e\tau\frac{d^2w}{dz^2}=-\frac{8T_e\tau}{l_e^2}w(x,0)=-\frac{8T_e\tau}{l_e^2-4z^2}w(x,z)\,, \tag{5}$$

where T_e is the tensile stress on the epithelium and τ is its thickness. The dynamic condition for the liquids in Reinke's space becomes:

$$\frac{\partial\Phi(x,w)}{\partial t}+\frac{p(x,w)}{\rho_w}+\frac{1}{2}\left|\nabla\Phi(x,w)\right|^2=\frac{1}{\rho_w}\left(p_a+p_e\right)=\frac{1}{\rho_w}\left(p_a-\frac{8T_e\tau}{l_e^2-4z^2}w(x,z)\right). \tag{6}$$

Eqs. (3) and (6) become identical if we define the "equivalent gravity acceleration" of mucosal waves as

$$g = \frac{8T_e\tau}{\rho_w\left(l_e^{\;2} - 4z^2\right)}. \tag{7}$$

Although there is little evidence that the epithelium provides restoring forces, a recent study showed an intertwined network arrangement immediately below the epithelium (Madruga de Melo et al. 2003). The authors suggested that this basket-like configuration explained how the epithelium was able to stretch even though it contained nonstretchable fibers.

The last boundary condition of seawater waves is the mass conservation of the pore fluid at the seawater-seabed interface (i.e., the interface between Reinke's space and the vocal ligament) $y = y_0$:

$$\left.\frac{\partial\Phi}{\partial y}\right|_{y=y_0} = \left(\frac{\partial u_y}{\partial t} + \frac{\partial v_y}{\partial t}\right)_{y=y_0}, \tag{8}$$

where u and v are the seabed displacement and the relative dispalcement between pore fluid and the solid, respectively.

The seabed is considered as a porous elastic medium. Based on Biot's (1956) poro-elastic theory, four generalizing formulations have been used as the governing equations, including: constitutive law, overall equilibrium equation, equilibrium of pore fluid flow, and mass balance (see, e.g., Jeng 2003). These equations contains two parameters characteric to a liquid-saturated porous medium: the porosity of the solid frame and the permeability coefficient. To solve the motion equations of the seabed, the boundary conditions at the seawater-seabed interface and the bottom are required (see, e.g., Jeng 2003). In the case of the vocal ligament, however, the intermedaite and deep layers of lamina propria have different elastic properties. Due to anisotropy of the layered lamina propria, the permeability coefficient may be replaced with the permeability matrix.

EXPERIMENT

Since analytical solutions or simulation of the seawater-seabed model is difficult, we focused on its general dynamic properties. According to Jeng's (2003) review, two mechanisms of the seawave-induced seabed response have been observed in the laboratory and field measurements. One appears at the initial stage of cyclic water-loading, and therefore plays a role in voice onset. The other is generated by the oscillatory pore pressure, which is accompanied by the amplitude damping and phase lag in the pore pressure. The goal of the present experiment was to measure the amplitude attenuation and phase lag across the vocal fold surface and the vocal ligament during modal phonation. Instead of measuring the pore pressure in the vocal fold, we estimated the phase lag in the pore pressure across the vocal fold surface and the vocal ligament from their motion pattern, as illustrated in Fig. 2.

Methods

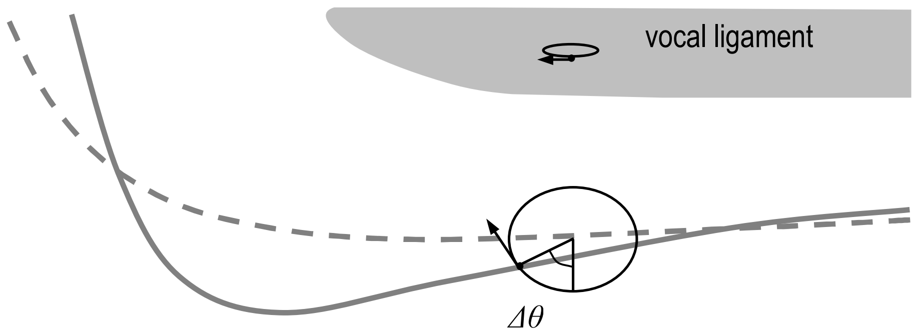

Figure 2: Phase difference between the right vocal fold surface and the vocal ligament during phonation. The grey dashed line represents the static position of the vocal fold surface, whereas the grey solid line represents its temporal position during vibration. The glottal flow induces surface vibration of the vocal fold, and the liquid motion in Reinke's space drives the vocal ligament to also vibrate. Due to relative motion between the fluid and the elastic frame in the lamina propria, the oscillatory pore pressure on the surface and in the ligament is characterized by a phase difference. This is manifested in the elliptic motion of tissue particles on the surface and in the ligament.

One of the authors (C.G. Tsai), a healthy man aged 35 years without voice disorders, was the subject of this study. A standard medical high-resolution ultrasound scanner (HDI-5000, ATL, Bothell, WA) with a linear-array transducer (CL10-5 25 mm, ATL) was used to record 2D sonography. The scanhead was placed in the coronal plane at the midline of the thyroid cartilage lamina on the right side during sustained loud modal phonation (Fig. 1). The frame rate of ulatrsound was 40 Hz. Dynamic sonography was recorded at the phnation frequencies of approximately 122 Hz, and 202 Hz. Consequently, the vibration frequency evident from sonography was approximately 2 Hz, and slowly-traveling waves can be seen on the vocal fold surface and in the vocal ligament. This is known as *aliasing effect*. The vibration displacement and phase relation of tissue particles in a medial portion of the vocal fold were extracted from dynamic sonography.

Results

Fig. 3 displays the measurements of amplitude attenuation in the vocal fold. The depths of vibrating tissues were approximately 5.0 mm and 3.6 mm at phonation frequencies 122 Hz and 202 Hz, respectively. This reflects the thinning of the lamina propria as the phonation frequency increases. The lateral displacements on the vocal fold surface were 1.8 ± 0.3 mm.

For the phonation frequency 122 Hz, the theoretical curve predicted by the water wave model is slightly higher than the measured displacements in the vocal ligament, reflecting its damping effect as a seabed. The phase difference across the vocal fold surface and the vocal ligament was estimated as 20°–80°.

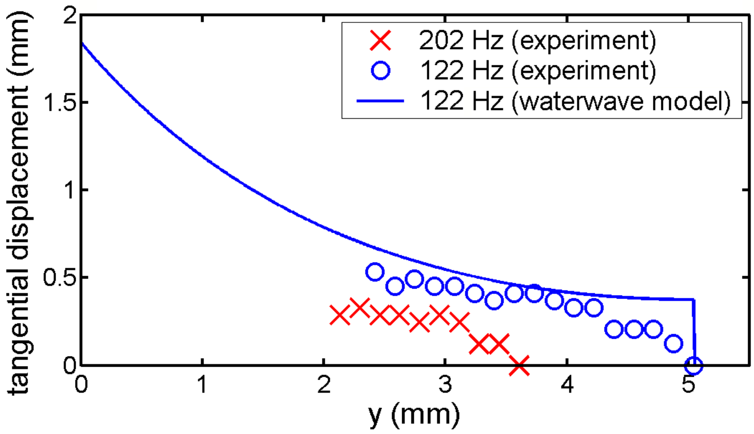

Figure 3: Comparison of the experimental data of the amplitude attenuation across the vocal fold surface and the vocal ligament during modal phonation.

DISCUSSION

Particle displacements of the vocal fold were estimated from sonographic data obtained during modal phonation. Although the imaging quality was only moderate, it allowed to confirm the existence of the phase difference between the vocal fold surface and the vocal ligament. Tsui and Helfrich (1983) conducted experiments for loose and dense sands, discovering that the maximum phase lag might reach 120°. In our experiment, the phase lag was estimated as 20°–80° at the phonation frequency of 122 Hz. We regard this measurement as supportive evidence for the seawater-seabed model of vocal fold vibration.

The seawave-seabed model of vocal fold vibration may provide new insight into the mechanical roles of the vocal ligament. First, the elasticity of the vocal ligament might be responsible for attenuating the water wave near the bottom. In oceanography, friction with the seabed increases as waves approach intermediate/shallow water, and sometimes leads to problems of erosion and sedimentation, because water particles move forth and back at the bottom. In the vocal fold, the displacement of tissue particles may attenuate rapidly in the tensioned vocal ligament. In the other word, the vocal ligament may serve to match the impedances of Reinke's space and the vocalis muscle, thereby minimizing viscous losses due to velocity differences in the vocal fold. For loud phonation, this effect may be important for preventing tissue damage.

Another role of the vocal ligament may be as an energy-saving mechanism. Whereas intermediate/shallow water waves lose energy through friction at the bottom, the strings in the vocal ligament (aligned in the *z*-direction in Fig.1) are able to convert a portion of kinetic energy into potential energy when displaced from their equilibrium positions. While these strings move to their equilibrium positions, they accelerate the liquids in Reinke's space, and thereby supply energy to water waves. This effect may improve the efficiency of loud vocalization. It is interesting to note that energy-saving springs can be found in numerous oscillation systems in animals, such as legs of mammals, insect flight, and dolphin/jellyfish/scallop swimming (for a recent review, see Alexander 2003).

The water wave model may shed new light on the function of the incompressible liquids in Reinke's space. Motion of the epithelium induces the liquid motion in

Reinke's space and, since this layer is thin, the stiff wall of the vocalis muscle stops the impinging liquid and deflects the flow in the tangential direction. The liquid-like nature of Reinke's space might be responsible for the conversion between the circular motion on the surface to the tangential motion in the vocal ligament. A comparison between the water wave model and a solid finite-element model (Alipour et al. 2000) may highlight the importance of the liquids in Reinke's space. The lateral displacements on the inferior-medial surface predicted by that finite-element model were small, and the predicted particle orbits were more flattened than those measured experimentally (Baer 1975, Saito et al. 1985, Berry et al. 2001). This discrepancy may stem from the liquid-like nature of Reinke's space. It is interesting to note that the vibration behavior of the lips of brass players (Yoshikawa and Moto 2003) shares some common features with the solid finite-element model of the vocal fold (Alipour et al. 2000).

Lateral motion of the vocal fold plays a key role in absorbing the kinetic energy from the airflow, and therefore determines the vocal efficiency. We suggest that the liquid-like nature of Reinke's space is essential to produce significant lateral motion on the inferior-medial surface of the vocal fold.

CONCLUSIONS

This paper proposes a seawater-seabed model of vocal fold vibration. The epithelium may provide the restoring forces of the water waves, whereas the vocal ligament may serve as a wave damper, an impedance matcher, and an energy saver. The liquids in Reinke's space play a key role in the conversion between the circular motion on the vocal-fold surface to the tangential motion in the vocal ligament.

Because the measurements of porosity and permeability matrix of the vocal fold are unavailable at present, our experimental study has focused on two properties of a seawater-seabed system: amplitude damping and phase lag across the vocal fold surface and the vocal ligament. For the phonation frequency of 122 Hz, the the wave amplitude in the vocal ligament is slightly smaller than predicted by the water wave model. This reveals the damping effect of the seabed. For the phonation frequency of 202 Hz, the lamina propria becomes thinner and this damping effect is more significant. Although the imaging quality of sonography was only moderate, we have confirmed the existence of the phase lag. In the near future, the measurements of amplitude damping and phase lag will be performed in more subjects.

REFERENCES

Airy, G.B. (**1841**). "Tides and waves," in *Encyclopaedia Metropolitana* (1817–1845), Mixed Sciences, Vol. 3, edited by H. J. Rose, et al.

Alexander, R.M. (**2003**). "Functions of elastomeric proteins in animals," in *Elastomeric Proteins: Structures, Biomechanical Properties, and Biological Roles*, edited by P. R. Shewry, A. S. Tatham, and A. J. Bailey (Cambridge University Press), pp. 1–14.

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

Berry, D.A.; Montequin, D.W.; Tayama, N. (**2001**). "High-speed digital imaging of the medial surface of the vocal folds," *J. Acoust. Soc. Am.* 110, pp. 2539–2547.

Biot, M.A. (**1941**). "General theory of three dimensional consolidation," *Journal of Applied Physics* 12, pp.155–164.

Biot, M.A. (**1956**). "Theory of propagation of elastic waves in a fluid-saturated porous solid, Part I: Low frequency range," *J. Acoust. Soc. Am.* 28, pp. 168–177.

Chan, R.W.; Tayama, N. (**2002**). "Biomechanical effects of hydration in vocal fold tissues," *Otolaryngol Head Neck Surg.* 126(5), pp. 528–537.

Chang, M.D.; Chen, J.H. Tsai, C.G.; Hsiao, T.Y.; Shao, Y.H. (**2007**). "PIV analysis of ultrasound images of voval fold vibration," *XXI Congress of International Society of Biomechanics*, July 1–5, Taipei, Taiwan.

Chiba, T.; Kajiyama, M. (**1958**). *The Vowel: its Nature and Structure*. Phonetic Society of Japan, Tokyo.

Dean, R.; Dalrymple, R.A. (**1991**). *Water Wave Mechanics for Engineers and Scientists* (World Scientific, Singapore).

Hirano, M. (**1974**). "Morphological structure of the vocal cord as a vibrator and its variations," *Folia Phoniatr.* 26(2), pp. 89–94.

Jeng, D.S.; Lin, M.; Cha, D.H. (**2003**). "Revisit of poroelastic models for wave damping in a porous seabed: Comparison of existing models," *Engineering Mechanics*'03, ASCE, July 16–18, 2003, Seattle, USA.

Liljencrants, J. (**1991**). "A translating and rotating mass model of the vocal folds," *STL Q. Progr. Stat. Rep.*, 1, Speech Transmission Laboratory, KTH, Stockholm, Sweden.

Madruga de Melo, E.C.; Lemos, M.; Aragao Ximenes Filho, J.; Sennes, L.U.; Nascimento Saldiva, P.H.; Tsuji, D.H. (**2003**). "Distribution of collagen in the lamina propria of the human vocal fold," *Laryngoscope* 113(12), pp. 2187–2191.

Saito, S.; Fukuda, H.; Kitahira, S.; Isogai, Y.; Tsuzuki, T.; Muta, H.; Takyama, E.; Fujika, T.; Kokawa, N.; Makino, K. (**1985**). "Pellet tracking in the vocal fold while phonating: experimental study using canine larynges with muscle activity," in *Vocal Fold Physiology*, edited by I. R. Titze and R. C. Scherer (Denver Center for the Performing Arts, Denver, CO), pp. 169–182.

Spilker, R.L.; Maxian, T.A. (**1990**). "A mixed-penalty finite element formulation of the linear biphasic theory for soft tissues," *Int. J. Num. Meth. in Engng.* 30, pp. 1063–1082.

Story, B.H.; Titze, I.R. (**1995**). "Voice simulation with a body-cover model of the vocal folds," *J. Acoust. Soc. Am.* 97, pp. 1249–1260.

Titze, I.R. (**1988**). "The physics of small amplitude oscillation of the vocal folds," *J. Acoust. Soc. Am.* 83, pp. 1536–1552.

Tsai, C.G.; Hsiao, T.Y.; Shau, Y.W.; Chen, J.H. (**2006**). "Towards an intermediate water wave model of vocal fold vibration: Evidence from vocal-fold dynamic sonography," *International Conference on Voice Physiology and Biomechanics*, 12-14 July, 2006, Tokyo, Japan.

Tsai, C.G.; Shau, Y.W.; Hsiao, T.Y. "Laryngeal mechanisms during human 4 kHz vocalization studied with CT, videostroboscopy, and color Doppler Imaging," *J. Voice* (accepted).

Tsai, C.G.; Hsiao, T.Y.; Shau, Y.W.; Chang, M.D.; Chen, J.H. (**2007**). "The in-vivo investigation of vocal fold vibration by dynamic sonography," *19th International Congress on Acoustics*, 2-7 September, 2007, Madrid, Spain.

Tsui, Y.T.; Helfrich, S.C. (**1983**). "Wave-induced pore pressures in submerged sand layer," *J. Geotech. Eng. Div., Am. Soc. Civ. Eng.* 109(4), pp. 603–618.

Ward, P.D.; Thibeault, S.L.; Gray, S.D. (**2002**). "Hyaluronic acid: its role in voice," *J Voice.* 16(3), pp. 303–309.

Yoshikawa, S.; Moto, Y. (**2003**). "Lip-wave generation in horn players and the estimation of lip-tissue elasticity," *Acustica/Acta Acustica* 89, pp. 145–162.

Zhang, K.; Siegmund, T.; Chan, R.W. (**2006**). "A constitutive model of the human vocal fold cover for fundamental frequency regulation," *J Acoust Soc Am.* 119(2), pp. 1050–1062.