Mathematical Modeling of the Medial Surface of the Vocal Fold for the Study of Chest and Falsetto Registers

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Introduction

Experimental data suggest that the shape of the medial surface plays in important role in the change of laryngeal register between chest and falsetto [1]. The thyroarytenoid plays a large role in determining the shape of medial surface, but only in conjunction with the cricothyroid [1,2,3] and lateral cricoarytenoid muscles [3]. The chest register is associated with increased medial surface bulging relative to the falsetto register [1]. This project explored whether medial surface bulging resulting from the activation of the thyroarytenoid muscle could cause change in the spectral slope of the acoustic output.

Questions

- How do laryngeal muscle activations change the medial surface?
- Do the changes in the medial surface produce acoustic spectra consistent with different registers?

Methods

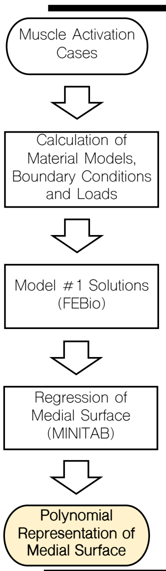
This project used two different finite element models to answer the two questions. The first model defined the medial surface as a function of muscle activation. The second model used the medial surface shape from the first and was solved for a vibratory response that generated the acoustic output.

Model #1:

The geometry for the finite element model was based on the typical male geometry defined in VoxInSilico [4], a voice simulation program written by Drs Ingo Titze and Fariborz Alipour. Modeling was performed in FEBio using a transverse-isotropic Mooney-Rivlin model for the muscle tissue and Neo-Hookean models for the mucosa and ligament. The length of the vocal fold was adjusted by motion of the thyroid cartilage relative to a fixed posterior surface. The muscle tissue was divided into vocalis and muscularis portions to allow variation in fiber orientation and activation. The FE model was solved for 36 cases of muscle activations that covered the expected range of muscle activations for the chest and falsetto registers. The muscle activations defined the amount of bulging in the muscle tissue as well as the change in the length of the vocal fold, which was set by the displacement of the thyroid cartilage. The change in vocal fold length was calculated by VoxInSilico for each set of muscle activations. The muscle activations also altered the stiffnesses of the mucosa and the ligament. The medial displacements of the medial surface were extracted from each of those solutions. The extracted medial surface displacement data was regressed into a polynomial function of muscle activations and position on the medial surface using the MINITAB statistical software package..

Model #2:

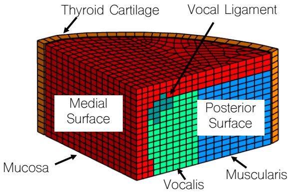
The regressed polynomial function was inserted into VoxInSilico to calculate the shape of the medial surface for the finite element model in VoxInSilico. The VoxInSilico model used transverse isotropic properties for the mucosa, ligament and muscle. Posturing calculations in VoxInSilico, described in detail in [5], modified the longitudinal (Y direction below) stiffness for each material model. A sample chest and falsetto case were then run in VoxInSilico. The spectral slope of the resulting acoustic output was calculated by fitting the amplitudes of the spectral peaks to a base 2 logarithmic fit.



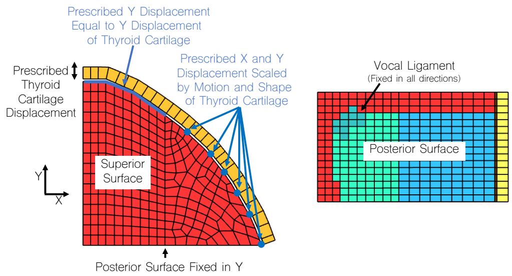
Muscle Activation Levels

Muscle	Activation Levels (%)				
Cricothyroid	1	25	50	75	100
Lateral Cricoarytenoid	20	30			
Thyroarytenoid	1	25	50	75	100

Model #1



Model #1 Boundary Conditions



Model #1 Muscle Material Model

$$W = C_1(\bar{I}_1 - 3) + C_2(\bar{I}_2 - 3) + \frac{1}{2}K(\ln J)^2 + F_2(\tilde{\lambda})$$

$$\text{where } \tilde{\lambda}\frac{\partial F_2}{\partial \tilde{\lambda}} = \begin{cases} 0, & \tilde{\lambda} \le 1 \\ C_3\left(e^{C_4(\tilde{\lambda}-1)} - 1\right), & 1 < \tilde{\lambda} < \lambda_m \\ C_5\tilde{\lambda} + C_6 & \lambda_m \le \tilde{\lambda} \end{cases}$$

$$Active\ Stress = T_{max}\frac{Ca_0^2}{Ca_0^2 + ECa_{50}^2} Activation\ Level$$

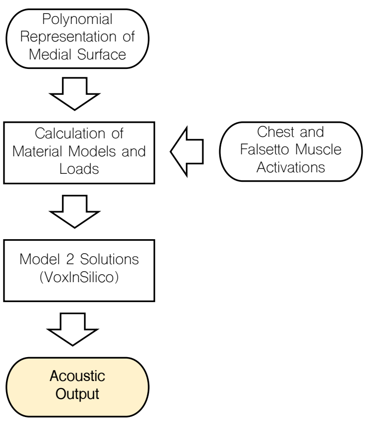
$$\text{where } ECa_{50}^2 = \frac{Ca_0}{\sqrt{B(\lambda l_r - l_0)}}$$

Matrix and Passive Fiber Properties	
Parameter	Value
C_1	3152 Pa
C_2	0
C_3	0.5037 Pa
C_4	31.7
λ_m	1.3
K	10 MPa

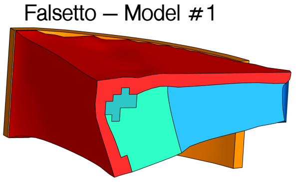
Active Fiber Stress Properties	
Parameter	Value
Ca_0	4.35 μM
Ca_{0max}	4.35 μM
B	2.9456 mm^{-1}
l_0	1.58 μm
l_r	1.617 μm
T_{max}	105 kPa

Polynomial Representation of Medial Surface (from MINITAB)

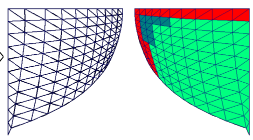
Medial Surface = (1.224E-03) + (4.148E-05)*CT - (2.259E-05)*TA - (3.248E-04)*Y - (2.479E-03)*Z - (4.502E-07)*CT*CT - (5.630E-08)*TA*TA - (7.412E-04)*Y*Y + (4.337E-04)*Z*Z + (2.408E-07)*CT*TA + (1.108E-05)*CT*Y - (5.136E-05)*CT*Z + (3.117E-07)*TA*Y + (3.246E-05)*TA*Z + (3.779E-03)*Y*Z + (2.332E-09)*CT*CT*CT - (1.300E-03)*Y*Y*Y + (8.263E-04)*Z*Z*Z - (1.013E-09)*CT*CT*TA - (1.278E-07)*CT*CT*Y + (1.737E-07)*CT*CT*Z + (2.751E-10)*CT*TA*TA + (1.052E-08)*CT*TA*Y - (1.233E-07)*CT*TA*Z - (5.454E-06)*CT*Y*Y + (1.213E-05)*CT*Y*Z + (1.601E-05)*CT*Z*Z + (1.219E-08)*TA*TA*Z + (9.799E-06)*TA*Y*Y - (1.332E-05)*TA*Y*Z - (8.421E-06)*TA*Z*Z + (6.875E-04)*Y*Y*Z - (2.534E-03)*Y*Z*Z



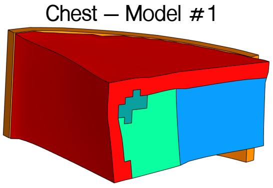
Falsetto – Model #1



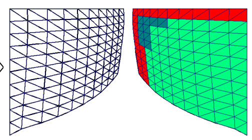
Falsetto – Model #2

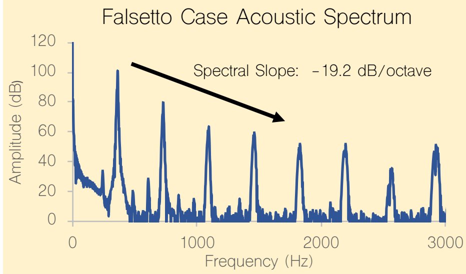


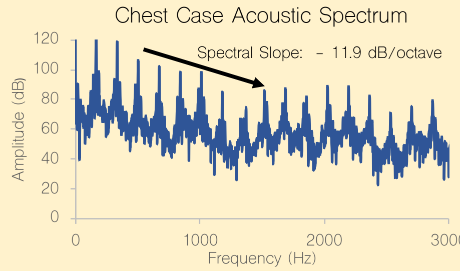
Chest – Model #1



Chest – Model #2







Discussion

The higher muscle activation of the chest case did result in more medial surface bulging and a shallower spectral slope. Future work will include identifying additional chest and falsetto cases to further exercise the regression model.

References

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[5] Titze, I.R. (2006). *Myoelastic Aerodynamic Theory of Phonation.* Iowa City, IA. National Center for Voice and Speech.