Self-Oscillating Vocal Fold Model Mechanics: Healthy, Diseased, and Aging

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BACKGROUND AND MOTIVATION

- The vocal folds (Figure 1.1) are comprised of muscle and tissue layers that stretch across the airway and are initially abducted (open). The vocal folds adduct (close) in preparation for speech.
- Voiced speech is produced when a critical lung pressure is achieved, forcing air through the vocal folds. The aerodynamic forces then impart energy to the VF tissues and induce self-sustained oscillations [Titze, 1988].
- Physiological vocal folds (Figure 1.2) have non-linear stress-strain relationships and exhibit mucosal wave motion.

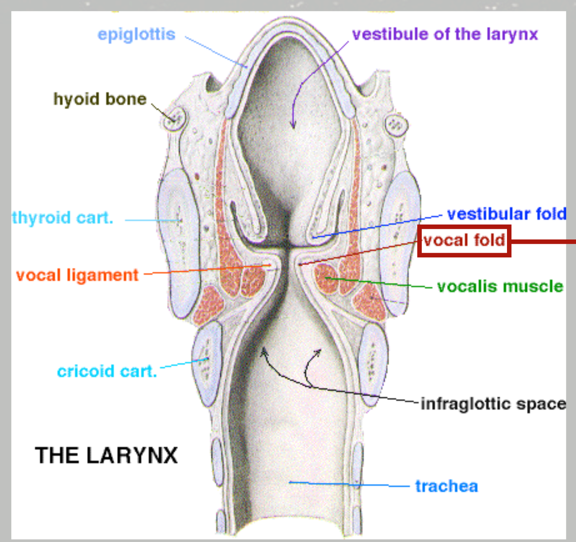


Figure 1.1 - Vocal Fold Schematic [www.yorku.ca]

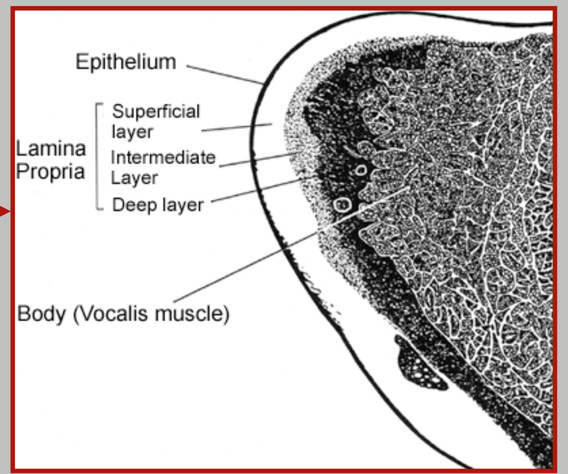


Figure 1.2 - Vocal Fold Layers [http://www.british-voice-association.com/voice-information_vocal-nodules.htm]

- Certain types of growths on the VF surfaces, such as nodules and polyps, can result from the repeated and prolonged collision between the tissues of opposing vocal folds, and can be devastating to one's daily life.
- 30% of people will suffer from a voice disorder at some point in their lives [Roy et al., 2005].
- Replicating physiological properties of human VFs will enable bench-top scientific speech investigations using synthetic, self-oscillating vocal fold models which are made from 3D-printed molds (Figures 1.3 and 1.4).

Figure 1.3 - Silicone Self-Oscillating VF Model

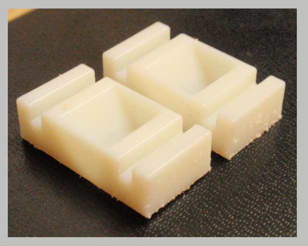


Figure 1.4 - VF Model Molds Created In 3D Printer

- A tensile tester was designed and used to measure stress-strain relationships of Smooth-On EcoFlex silicone samples and the corresponding modulus of elasticity values.

OBJECTIVE

The objective of this research is to study and improve synthetic vocal fold (VF) models by evaluating their ability to replicate physiological vocal fold motion and characteristic parameters of human speech within a life-size experimental setup in the Biofluid Dynamics Laboratory, and compare the experimental results with clinical results from the GWU Department of Speech and Hearing Sciences. This study will guide the development and improvement of self-oscillating vocal fold models for scientific investigations of voiced speech, and is funded by GWU IBE and COBRE.

FACILITY AND METHODS

- Homogeneous, wool additive, and two-layer synthetic, self-oscillating VF models are fabricated both with and without a polyp-like structure, a pathology that has been shown to produce rich viscous flow structures not normally observed.
- The experimental setup provides flow from a compressed air line that feeds into an adjustable volume, acoustically-treated, constant pressure chamber which mimics the role of human lungs (Figure 2.1).

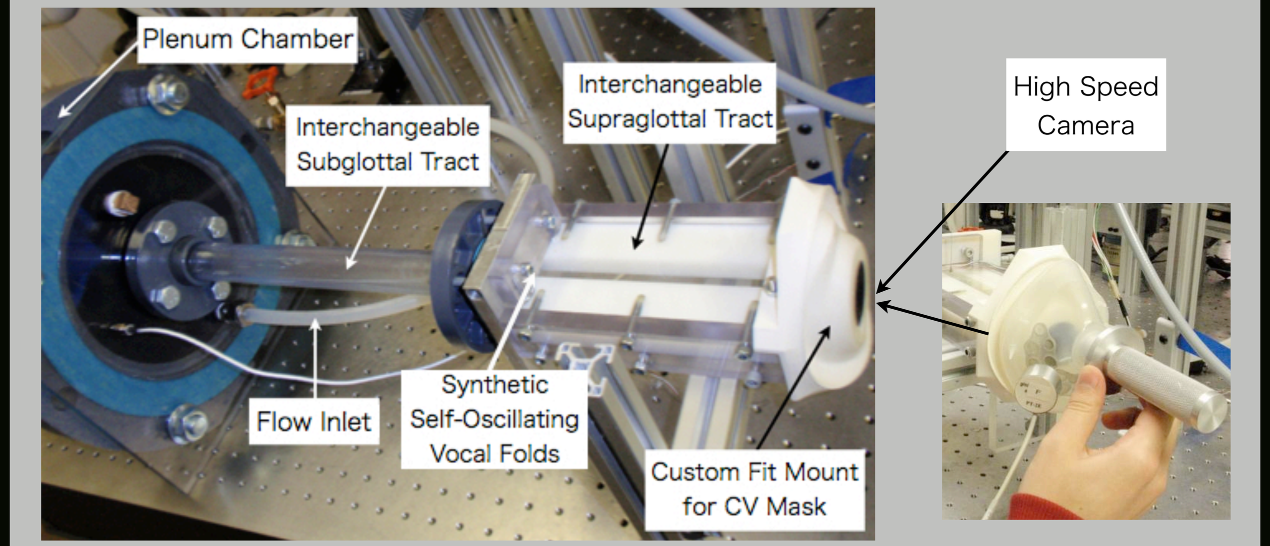


Figure 2.1 - Experimental Setup

- Pressure measurements are taken in the subglottal chamber (lung), the subglottal channel, and the supraglottal tract.
- High speed images (2500 fps) are captured at varying flow rates during VF oscillation to facilitate an understanding of the characteristics of healthy and diseased vocal folds.
- Clinical parameters are calculated from the volume-velocity output of a circumferentially vented (CV) pneumotachograph (Rothenberg) mask and compared to human data collected from two groups of males aged 18-30 and 60-80 in order to validate the synthetic VF models.

ROTHENBERG MASK RESULTS

- The waveform outputs collected with the CV mask for both the male subjects and the experimental setup were analyzed and compared using an extensive MATLAB algorithm (Figure 3.1).

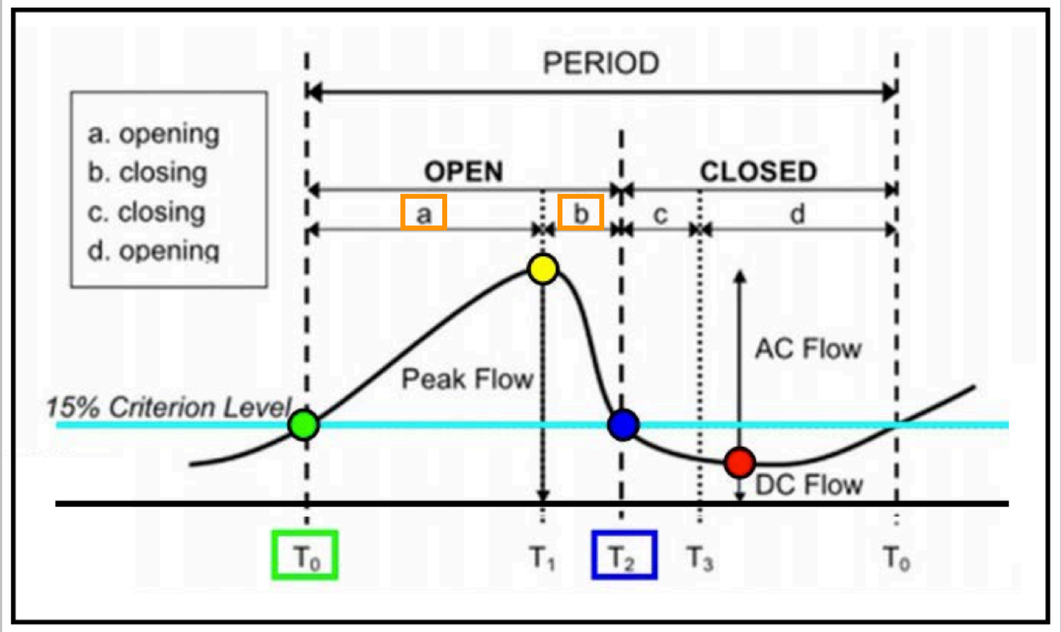


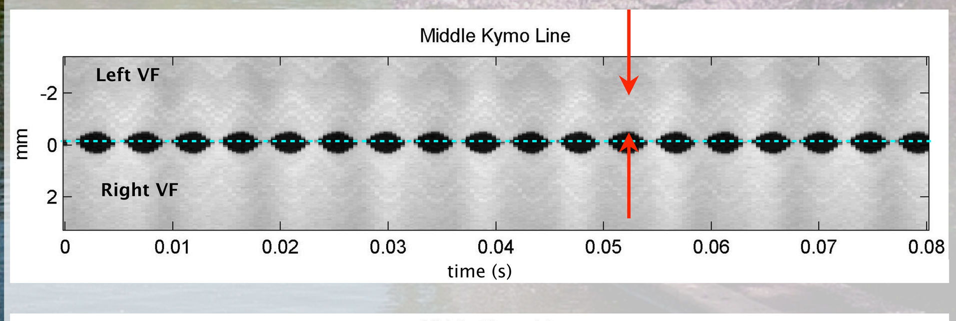
Figure 3.1: Glottal Airflow Signal After Inverse Filtering [Hancock 2011]

Parameter	Ages 18-30 Mean (SD)	Ages 60-80 Mean (SD)	B&O values Mean (SD)
F0 (Hz)	113 (19.1)	125 (14.1)	112 (11.8)
Peak Flow (L/s)	0.36 (0.11)	0.47 (0.23)	0.41 (0.09)
AC/DC (ratio)	0.67 (0.21)	0.89 (0.42)	0.65 (0.18)
Open Quotient (%)	45.7 (6.58)	48.7 (7.43)	57.0 (10.7)
Speed Quotient (%) a / b	1.46 (0.32)	1.38 (0.24)	1.52 (0.35)
MFDR (L/s²)	320 (134)	444 (322)	337 (127)

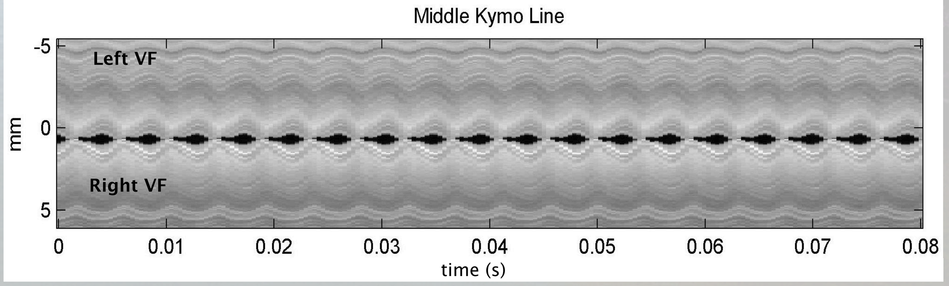
Healthy Vocal Fold Model	Mean Speed Quotient
Homogeneous (10.6 kPa)	1.13
Homogeneous (15.5 kPa)	1.17
Two-Layer (less stiff cover)	0.85
Two-Layer (stiffer cover)	1.27

Healthy Vocal Fold Model	Mean Speed Quotient
Homogeneous (10.6 kPa)	1.13
Homogeneous (15.5 kPa)	1.17
Two-Layer (less stiff cover)	0.85
Two-Layer (stiffer cover)	1.27

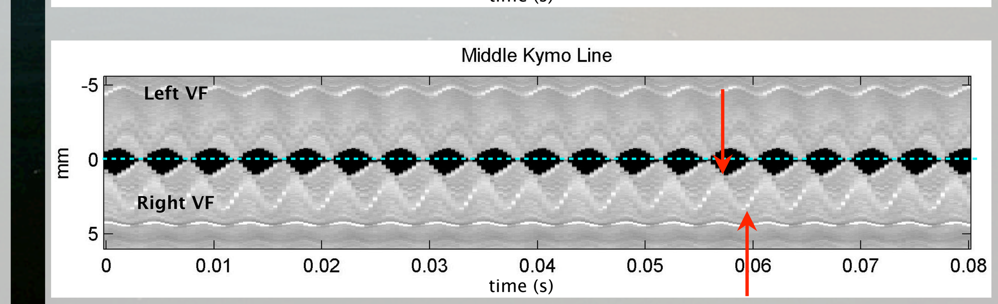
HIGH-SPEED IMAGE RESULTS



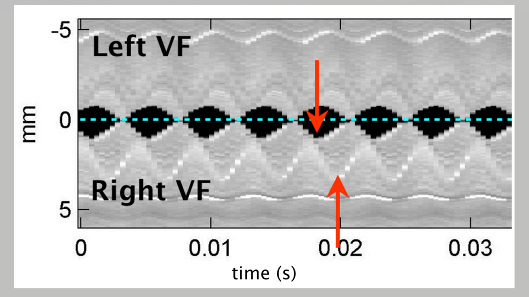
Homogeneous
E = 15.5kPa
- symmetric
- no offset: no mucosal wave

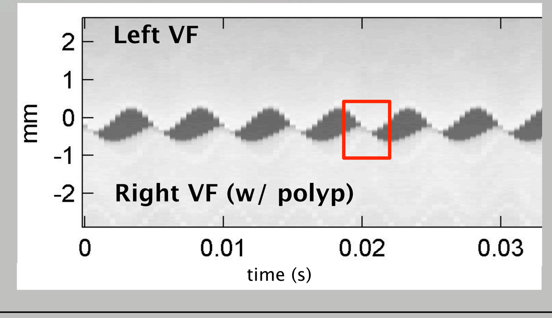


Wool Additive
E_{Base} = 15.5kPa with 1/8 inch wool added
- asymmetric
- slight offset: slight mucosal wave



Two-Layer
E_{Base} = 15.5kPa,
E_{Cover} < 5.4kPa
- slight asymmetry
- offset: mucosal wave





Healthy Two-Layer (Non-Pathological)
E_{Base} = 15.5kPa, E_{Cover} < 5.4kPa
- Asymmetric
- Mucosal Wave (offset)

Diseased Two-Layer (Pathological)
E_{Base} = 15.5kPa, E_{Cover} < 5.4kPa
- Stronger asymmetry
- Temporal shift in left and right VF opening and closing
- Partial closure on either side of the polyp

DISCUSSION AND CONCLUSIONS

- Synthetic silicone-based, self-oscillating VF models were able to replicate key behaviors and clinical parameters of both non-pathological and pathological *in vivo* vocal folds, such as: modulus of elasticity values, mucosal wave motion, asymmetry, partial closure, fundamental frequency ranges, and speed quotient values.
- The kymograph and CV mask results show that the wool additive and two-layer VF models more accurately replicate physiological characteristics of VF motion.
- This study integrates speech science with engineering and flow physics to overcome current limitations of synthetic VF models to properly replicate normal phonation in order to better understand resulting flow features, progression of pathological conditions, and medical techniques.