Achieving complete glottal closure during vibration in a physical vocal fold model: -- Influence of fiber locations and epithelium

Zhaoyan Zhang and Yue Xuan

School of Medicine, University of California
Los Angeles, CA, USA

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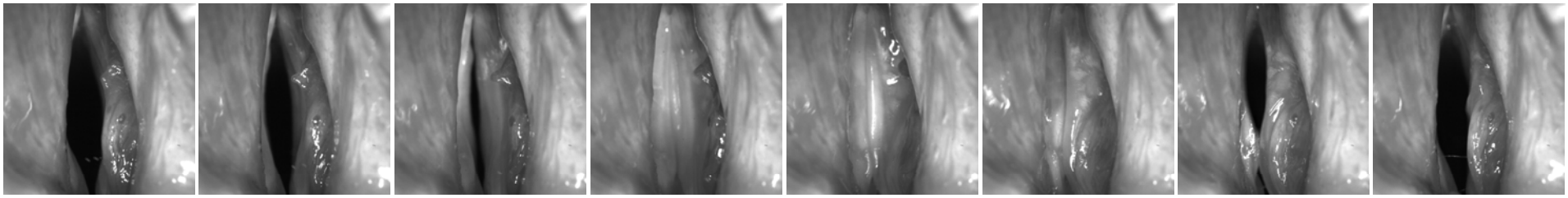
Vocal fold vibration from a superior view

The glottis remains closed for a certain portion of one oscillation cycle

-- closed quotient around 0.5 and as high as 0.8

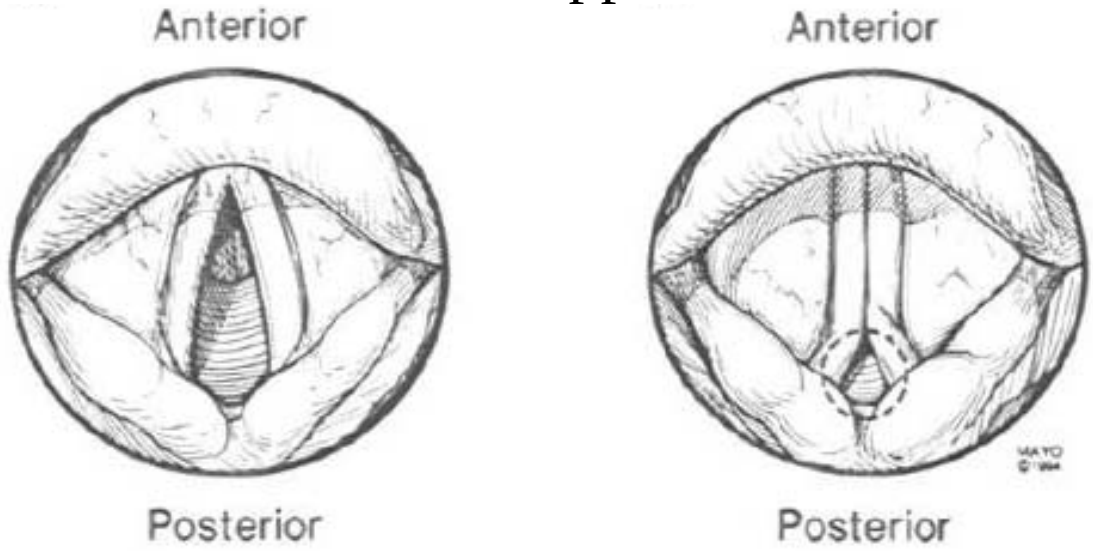


Importance of glottal closure to normal phonation

- Excitation of high-order harmonics
  - leads to strong vocal fold collision and longer glottal closure, and thus richer harmonic structure
  - Bright voice quality
- Ease of phonation
  - facilitates the establishment of sufficient subglottal pressure required to initiate phonation
  - enhances fluid-structure coupling strength

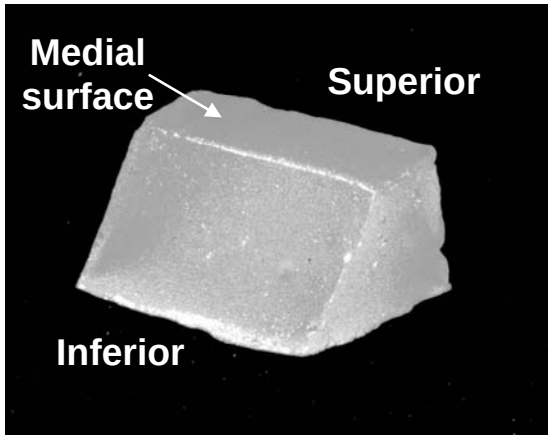
How to achieve glottal closure during phonation?

- Generally it occurs naturally once vocal folds are approximated and airflow is applied

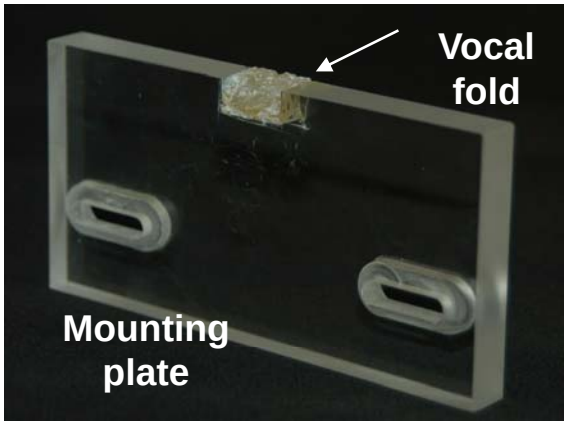


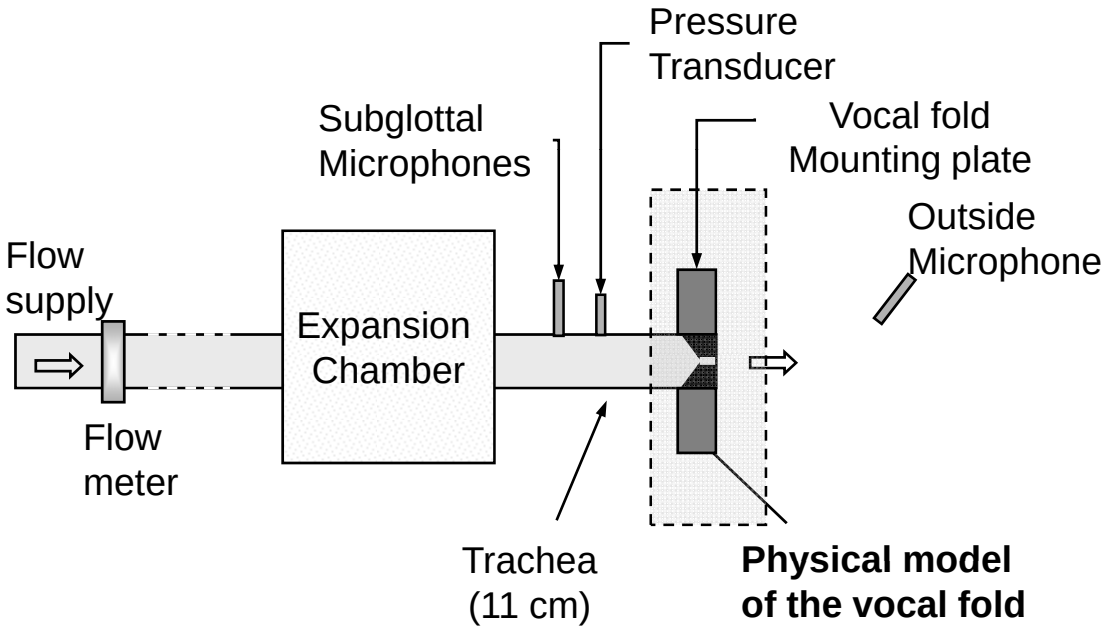
- *Is vocal fold approximation ALONE sufficient to achieve complete glottal closure?*
  - *What other biomechanical conditions are required?*
- *How humans control the closed quotient?*

Self-oscillating silicone-based vocal fold model



Young's modulus: ~2.5 kPa
Density: ~1000 kg/m3



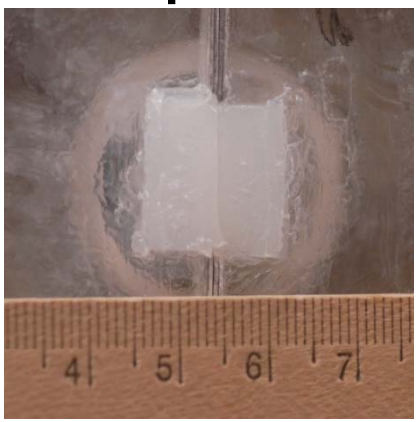


* Thomson, S., (2004), "Ph.D. Thesis, Purdue University, West Lafayette, Indiana.

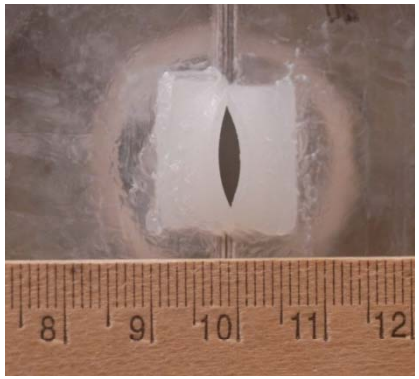
Isotropic one-layer physical models vibrated with incomplete glottal closure

Top view

No airflow

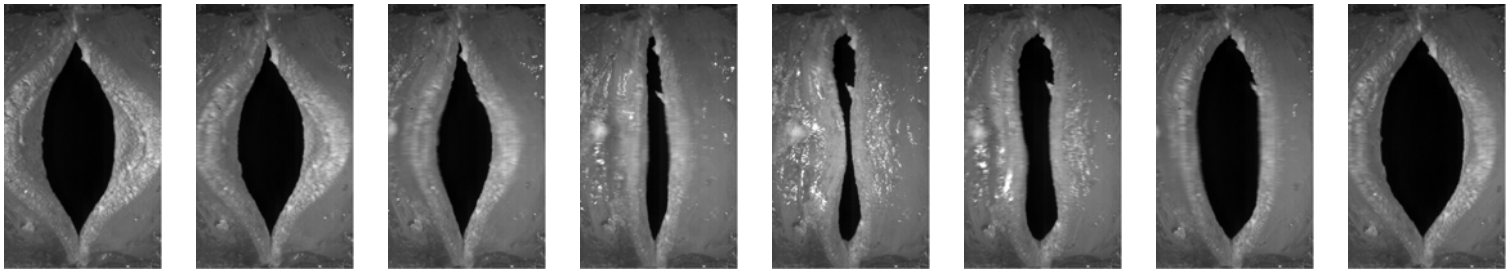


Top view

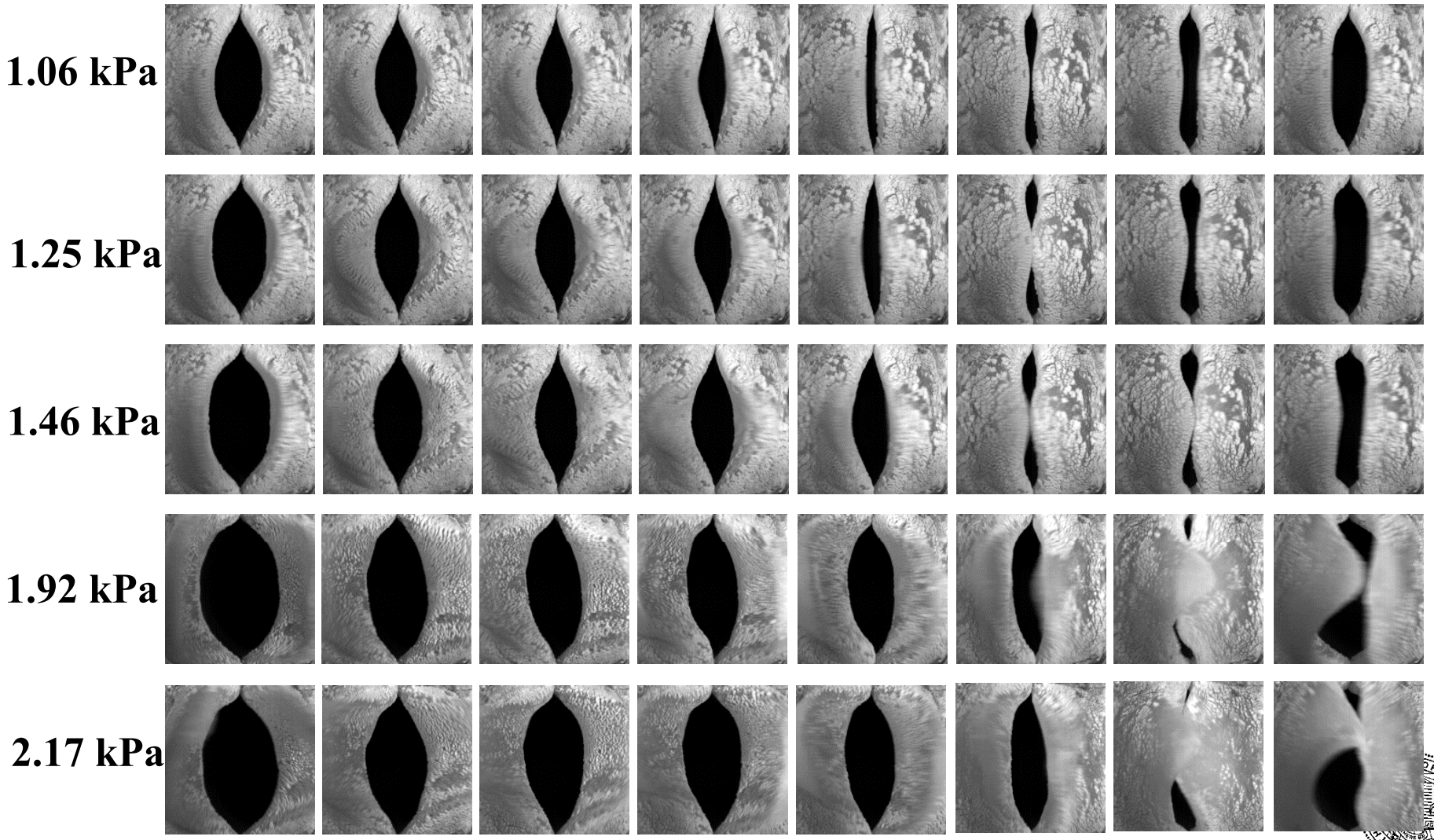


With airflow

Isotropic vocal folds were pushed open despite that they were brought into contact at rest

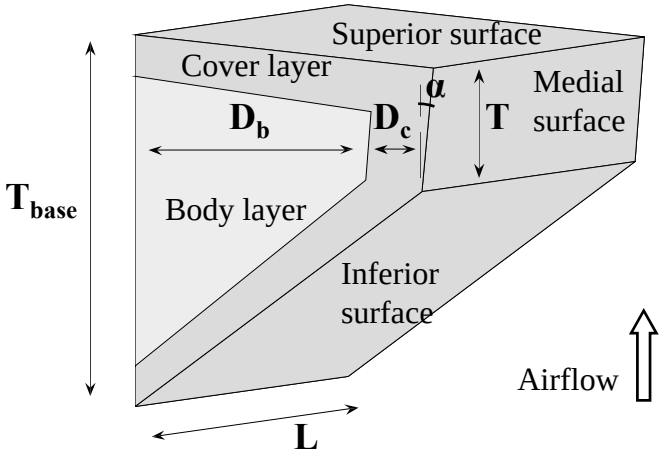


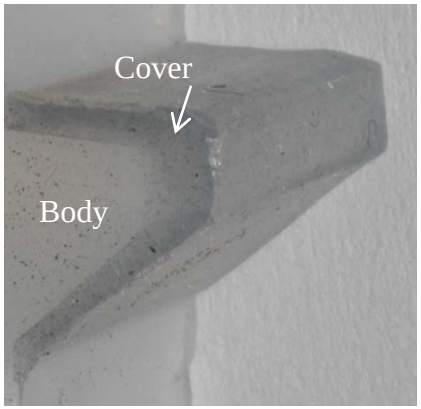
Increasing subglottal pressure is insufficient to achieve complete glottal closure



Stiffening the body layer: simulating contraction of the thyroarytenoid muscle

- *Rationale*: stiffening the body will reduce the mean glottal opening, thus shifting the equilibrium position towards the glottal midline, and may facilitate complete closure.

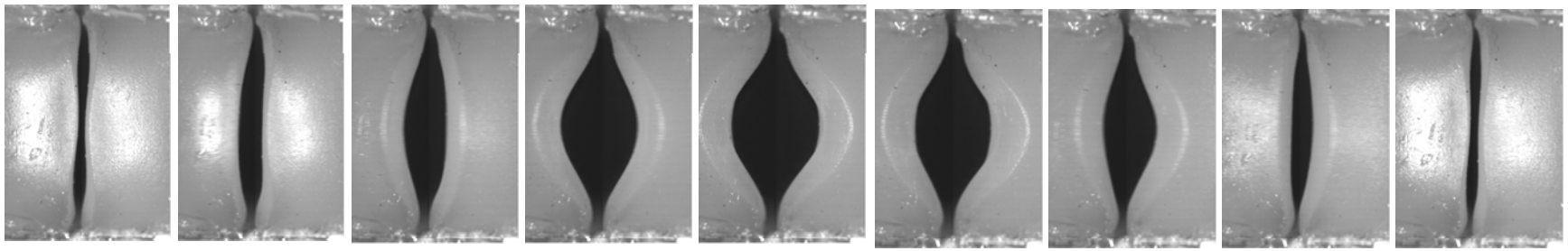




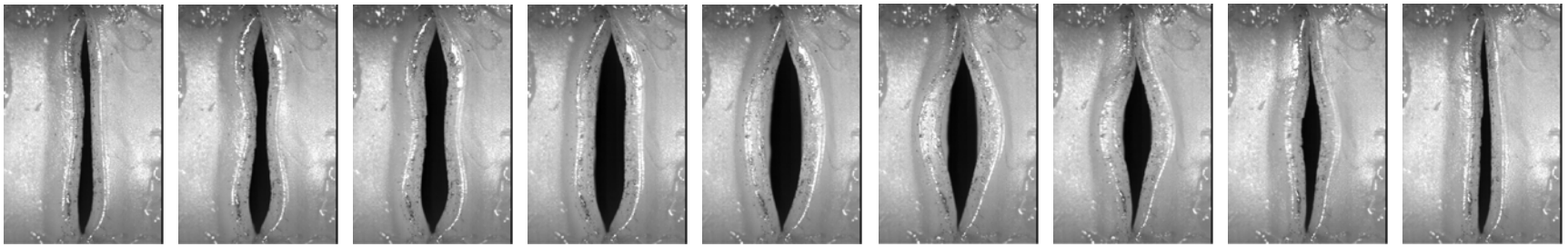
Two vocal folds were in contact at rest

Body-stiffening isotropic model

One-layer isotropic physical model



Body-stiffened two-layer isotropic physical model



Mean glottal opening reduced, but:

- **Vibration amplitude was reduced as well**
- **complete closure achieved only briefly for very large body stiffness**
- **Out-of-phase motion along the anterior-posterior direction**

Problems:

- One-layer isotropic models
  - Do not close complete
  - Zero closed quotient
- Body-stiffening isotropic model
  - Glottal closure improved but was brief
  - almost zero closed quotient
  - Reduced vibration amplitude
  - Strong anterior-posterior out-of-phase motion

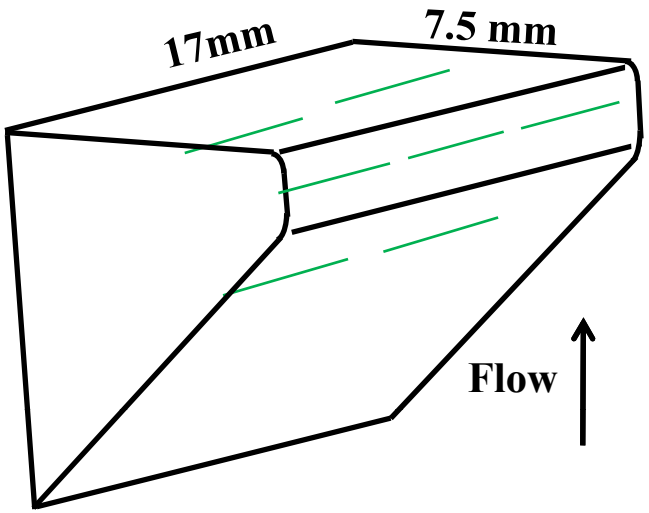
- Maybe human vocal folds have some inherent structural features that facilitate complete glottal closure?

Inherent structural or material features of the vocal folds?

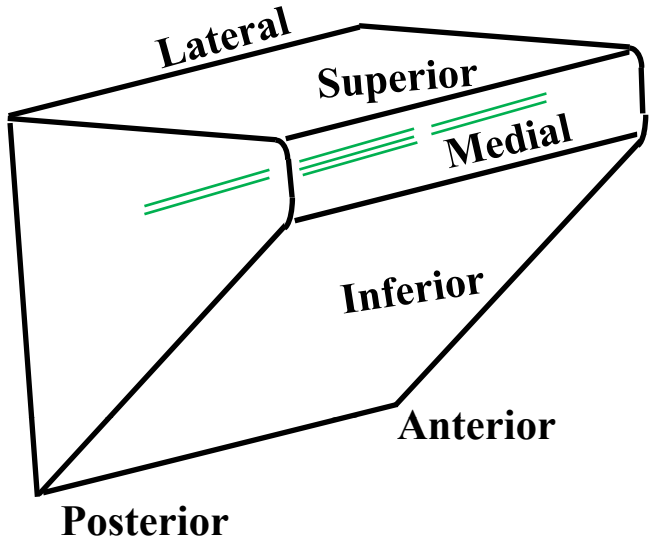
- Vocal fold anisotropy due to the presence of collagen and elastin fibers aligned along the anterior-posterior direction
  - vocal fold elongation (which increases the degree of anisotropy) improves glottal closure in excised larynx experiments (Zhang, 2011)
  - A higher stiffness in the AP direction would also suppress the AP out-of-phase motion

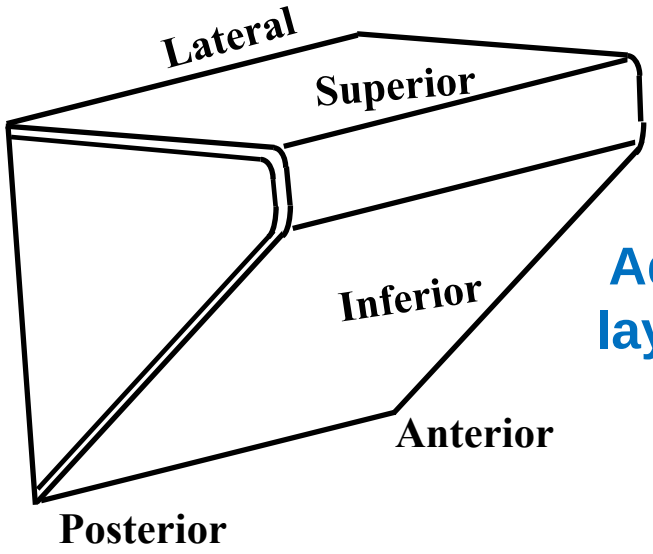
- The epithelium layer
  - A water-filled latex tube mode of the vocal fold was able to vibrate with complete glottal closure (Ruty et al., 2007; Krebs et al., 2010)
  - The presence of an epithelium layer combined with soft inner layers led to a more convergent-divergent motion of the vocal fold (Murray and Thomson, 2012)

Fibers embedded in the cover layer



Fibers embedded in the body layer





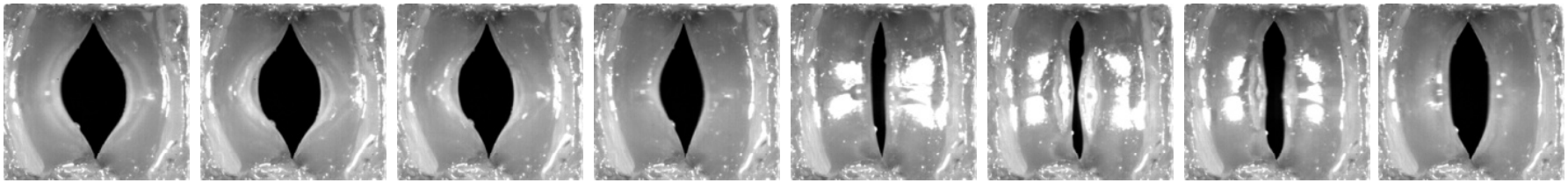
Addition of an epithelium layer (Young's modulus of about 60 kPa)

Six physical models

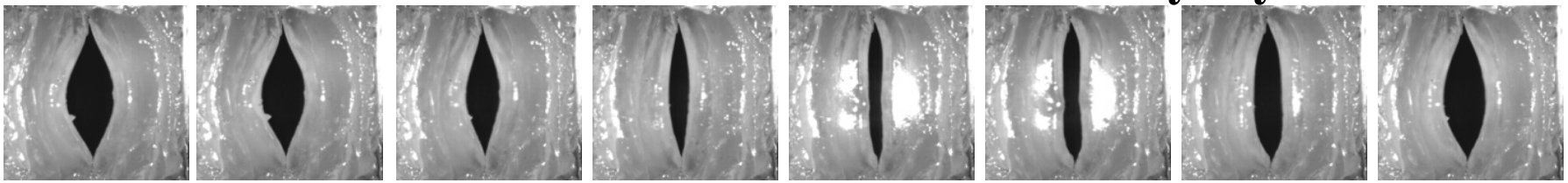
Model	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
Epithelium	No	No	No	Yes	Yes	Yes
Fiber	No fibers	Body	Cover	No fibers	Body	Cover

Embedding fibers in the cover layer improved glottal closure

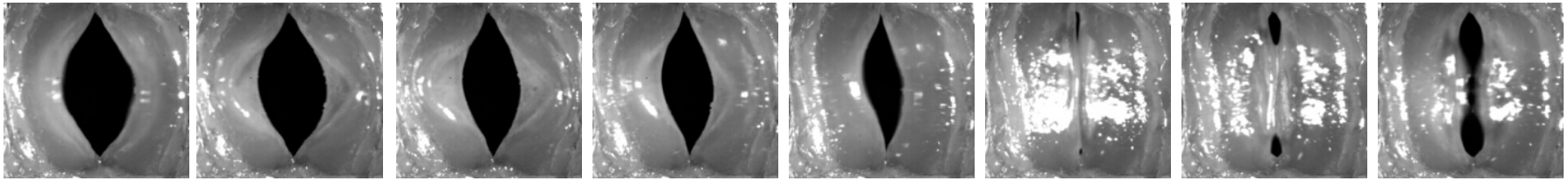
M1: No fibers



M2: Fibers embedded in the body layer

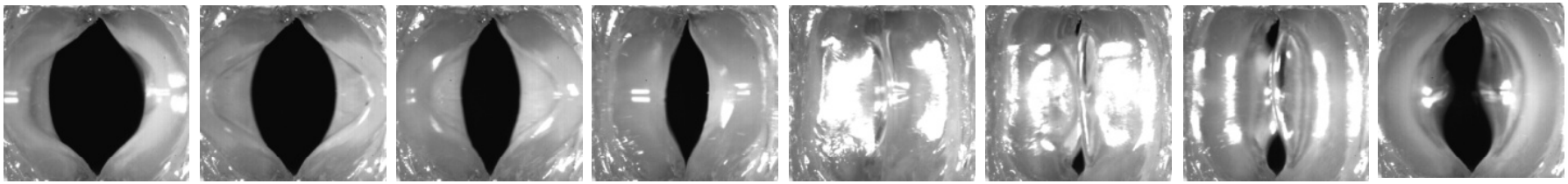


M3: Fibers embedded in the cover layer

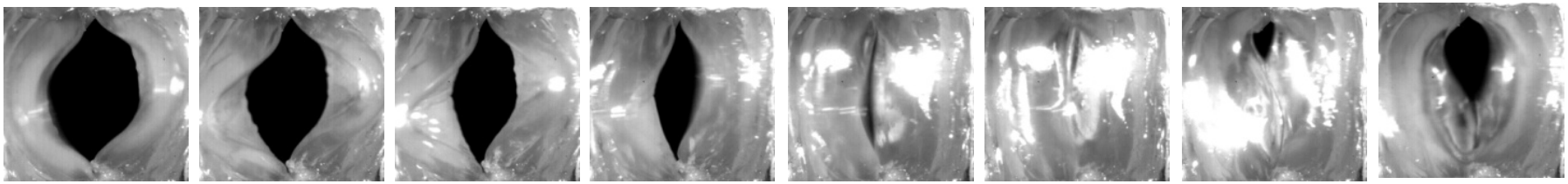


Presence of an epithelium layer led to non-zero closed quotient

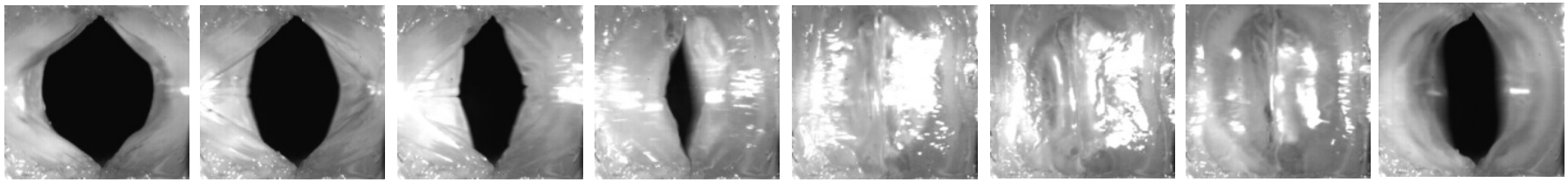
M4: Epithelium only, no fibers (closed quotient 0.13)



M5: Epithelium, fibers in body (closed quotient 0.14)

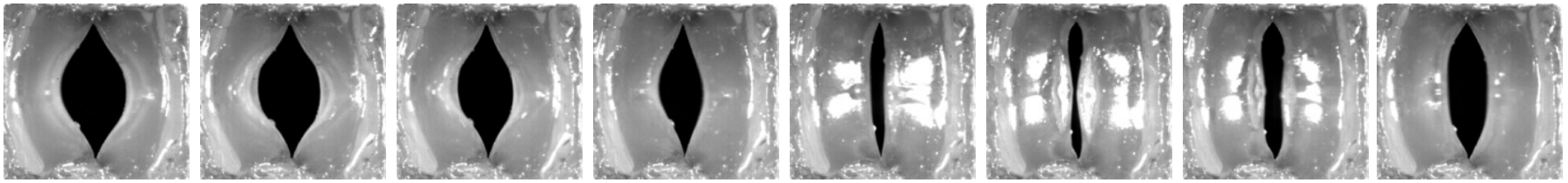


M6: Epithelium, fibers in cover (closed quotient 0.29)

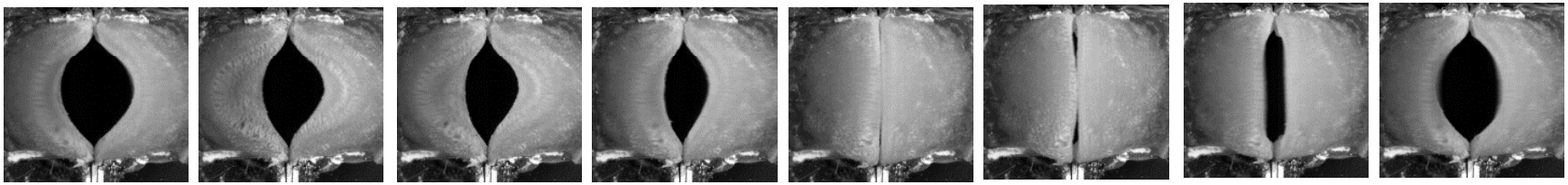


Reduced vocal fold length suppressed AP out-of-phase motion, and improved glottal closure

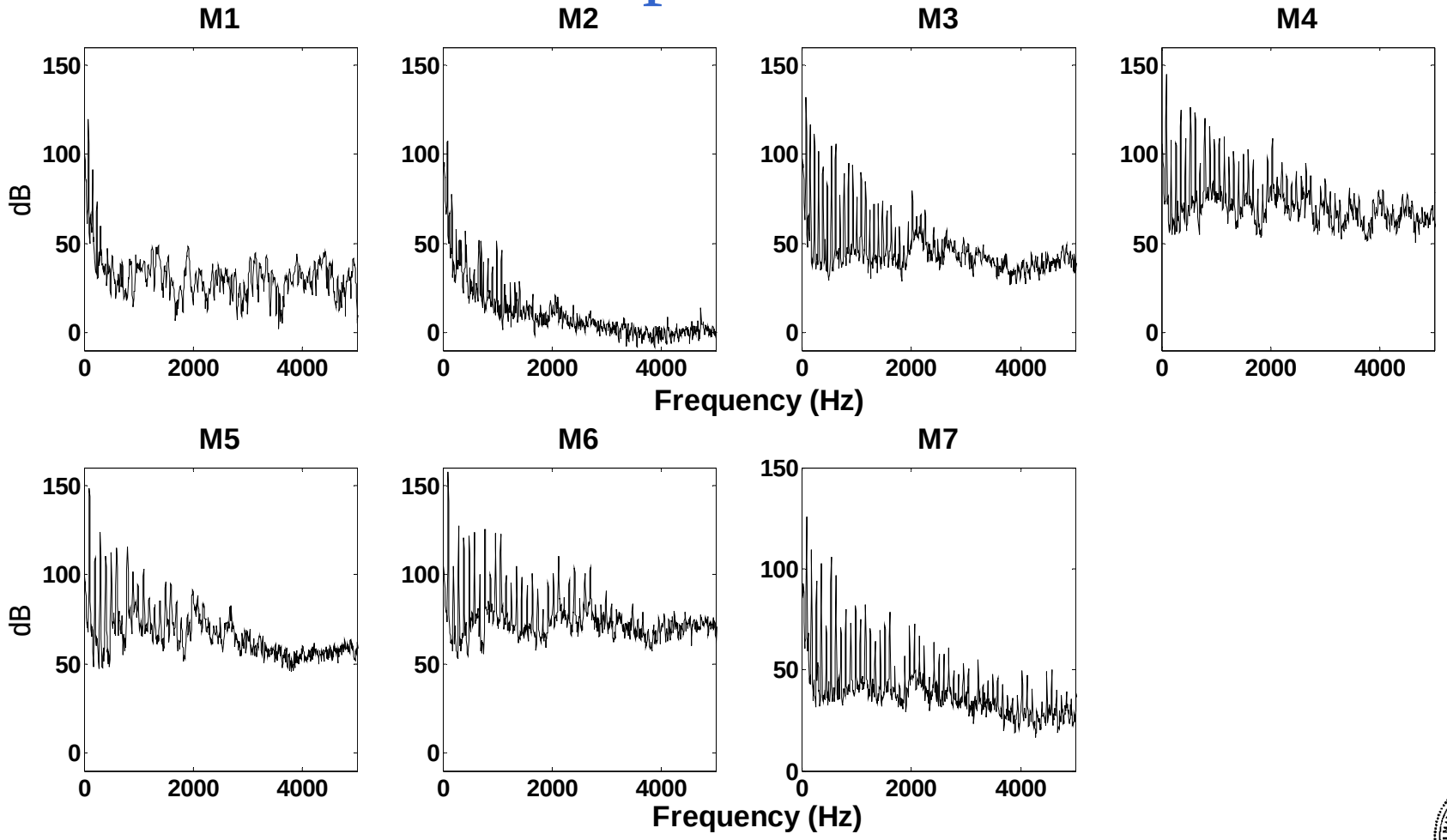
M1: Isotropic one-layer mode, 17-mm long



M7: Isotropic one-layer mode, 12-mm long



Complete glottal closure increased harmonic sound production, but also led to increased noise production



Summary

- Vocal fold approximation alone does not guarantee complete glottal closure in phonation
- Isotropic vocal fold models often vibrated with incomplete glottal closure
  - Stiffening the body-layer or increasing subglottal pressure did not improve it much
- Some inherent features of the vocal fold may facilitate complete glottal closure
  - Vocal fold anisotropy due to presence of collagen and elastin
  - The epithelium layer

- More studies needed to understand
  - The distribution of collagen fibers within the vocal folds
  - how such features affect the fluid-structure interaction during phonation