THREE DIMENSIONAL BIOMECHANICAL MODEL OF VOCAL FOLD POSTURING

Eric J. Hunter, M.S.
Doctoral Candidate
National Center for Voice & Speech
Department of Speech Pathology & Audiology
University of Iowa

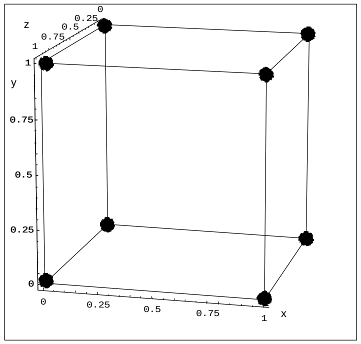
Funded through:
National Institute on Deafness and Other Communication Disorders

Research Question

To what degree can a three-dimensional biomechanical vocal fold model predict the dynamics of a posturing gesture?

Finite Elements

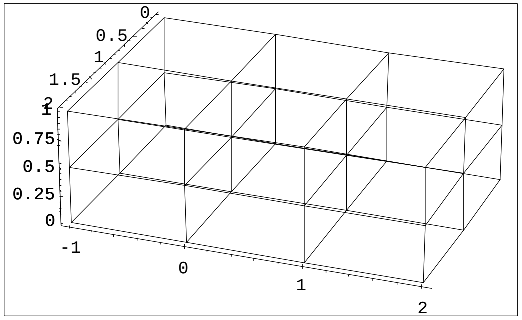
Hexahedral element



Continuum mechanics through finite elements

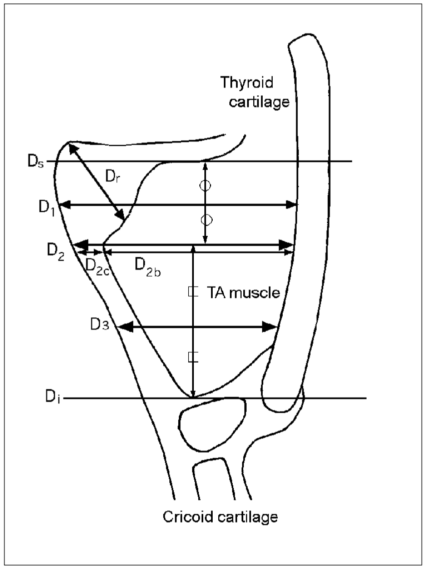
- geometry
- mechanical properties
- boundary conditions
- discretization

Simple structure

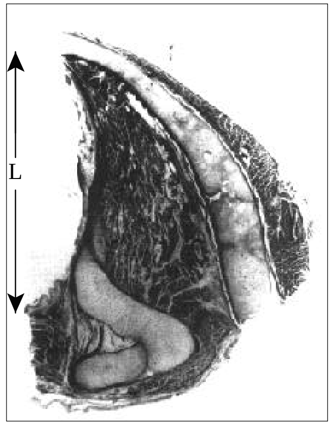


Geometry

Sagittal

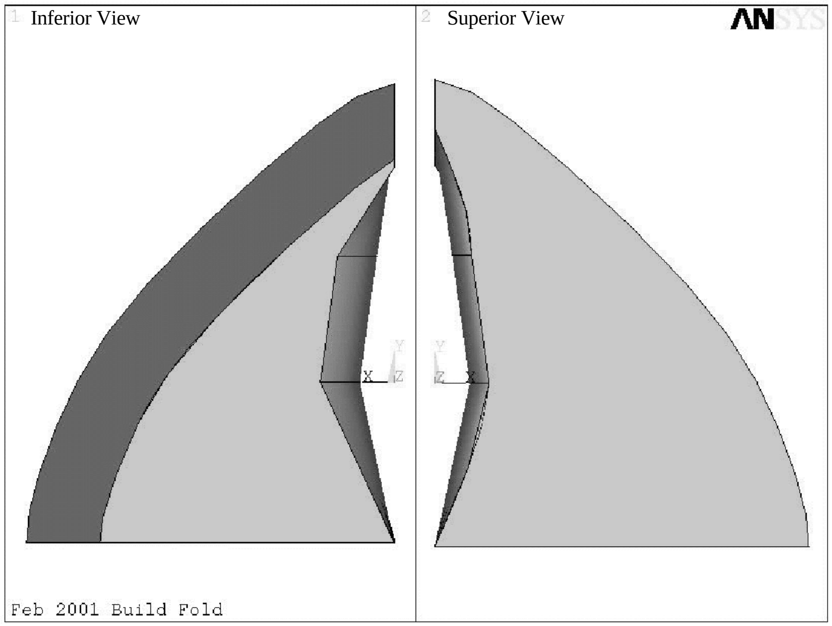


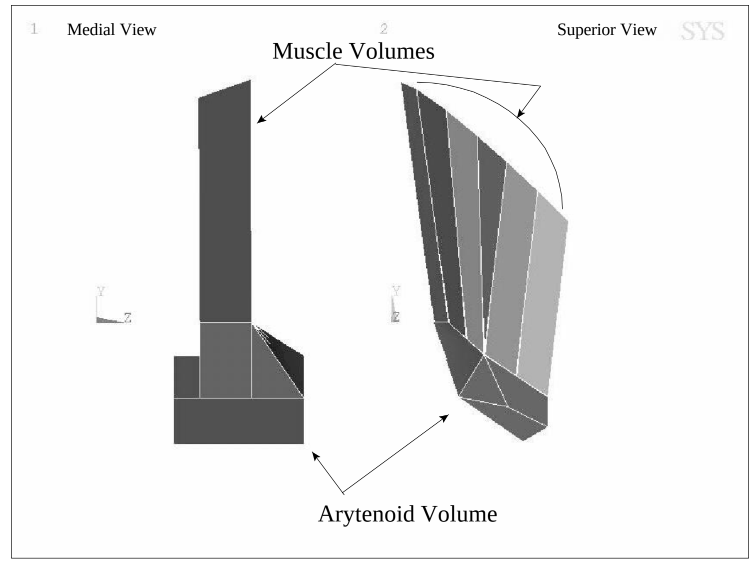
Transverse



- Use existing *in vitro* data of laryngeal specimens (Eckel *et al*, 1994) and VABL data (Tayama *et al*, 1999)
- Simplify geometry of all tissue inside thyroid cartilage, including arytenoid cartilage

Geometry





- Simplified Vocal fold (*left*) inferior view (*right*) superior view
- Arytenoid Cartilage and fiber volumes.

Defining Mechanical Properties

- Develop governing equations that apply to all tissue

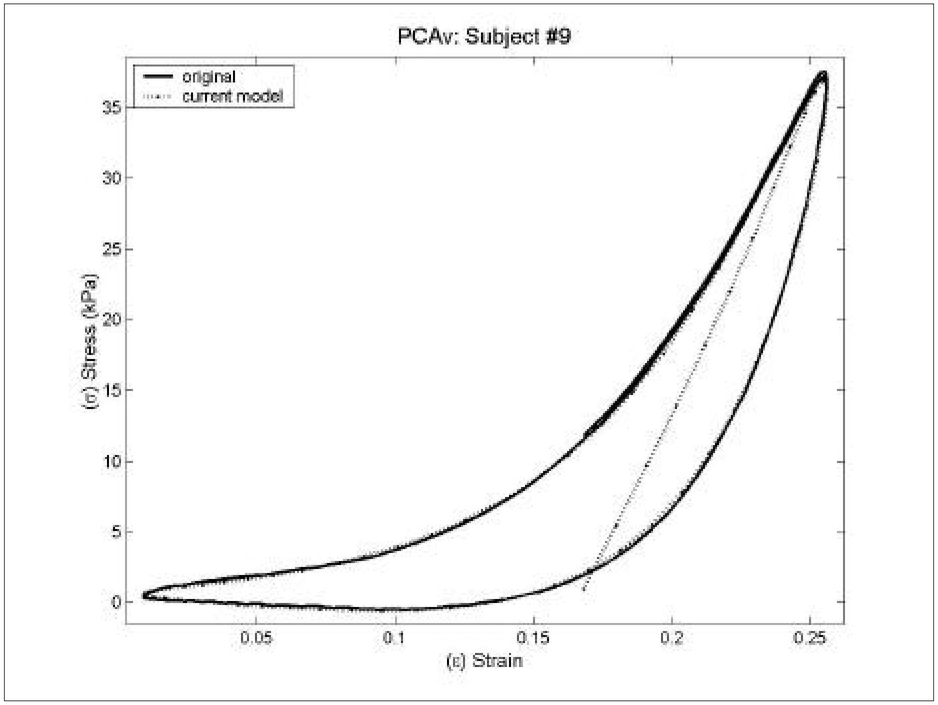
  $\sigma = E\,\epsilon$ (linear example)

- Identify material properties of individual tissues

  Passive properties

  Active properties

Passive Properties



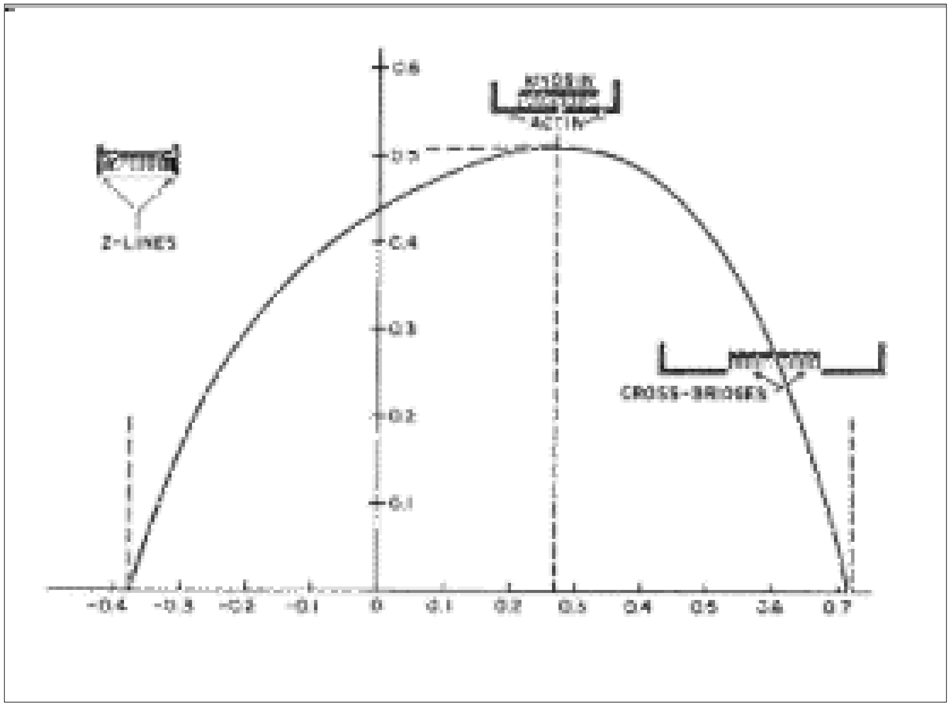
PCAv at 1hz elongation cycle

- All tissues have passive properties
- Six tissues: five canine intrinsic muscles and human vocal ligament
- Axial model with seven parameter

$$t_s\dot{\sigma} + \sigma = \sigma_i + \sigma_p + Et_p\dot{\varepsilon}$$

$$\sigma_p = -\frac{\sigma_o}{\varepsilon_1}(\varepsilon - \varepsilon_1) - B\sigma_2(\varepsilon - \varepsilon_2) + \sigma_2[e^{B(\varepsilon - \varepsilon_2)} - 1], \quad \varepsilon > \varepsilon_2$$

Active Tissue Properties



- Only muscle tissues have active properties
- Assumption: total stress of muscle is superposition of its active and passive properties

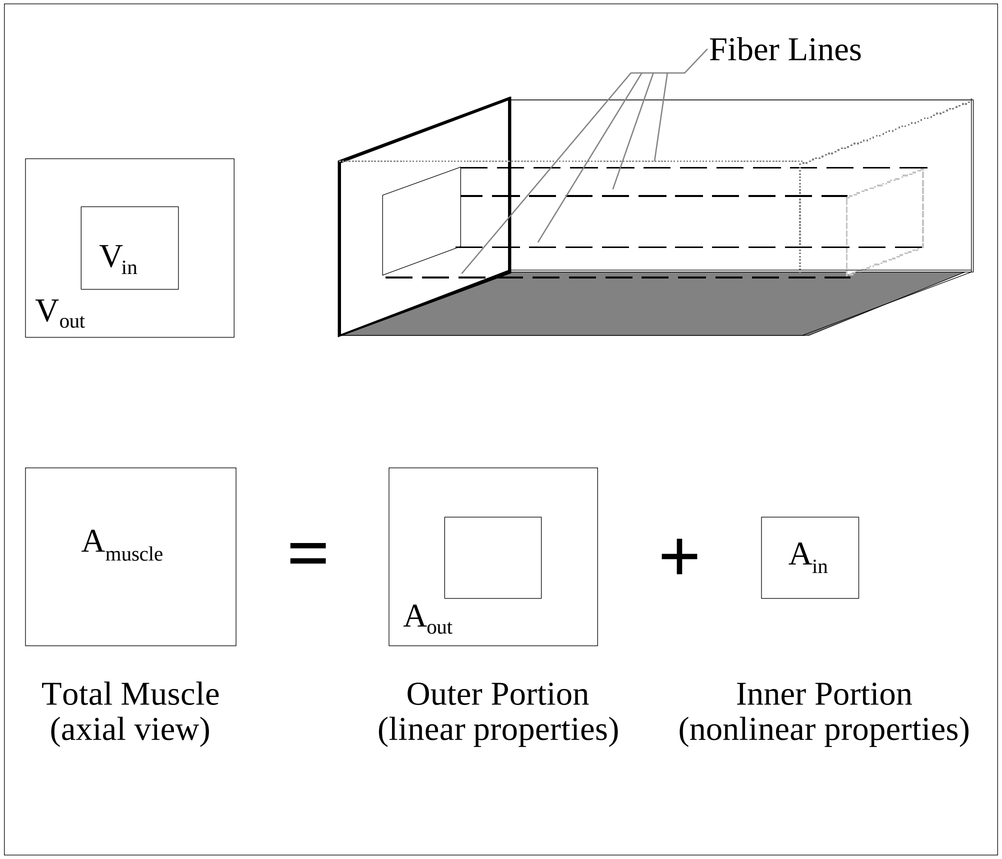
$$\sigma_a = a\,\sigma_m f(\xi_y)\,g(\xi_y)$$

$$g(\varepsilon) = Max\left[0, \frac{\varepsilon/\varepsilon_m + 1}{1 - 3\varepsilon/\varepsilon_m}\right] \quad \varepsilon \le 0$$

$$= \frac{9\varepsilon/\varepsilon_m + 1}{5\varepsilon/\varepsilon_m + 1} \quad \varepsilon > 0$$

$$f(\varepsilon) = \max\left[0, 1 - b(\varepsilon - \varepsilon_m)^2\right]$$

Gel-Fiber Muscle

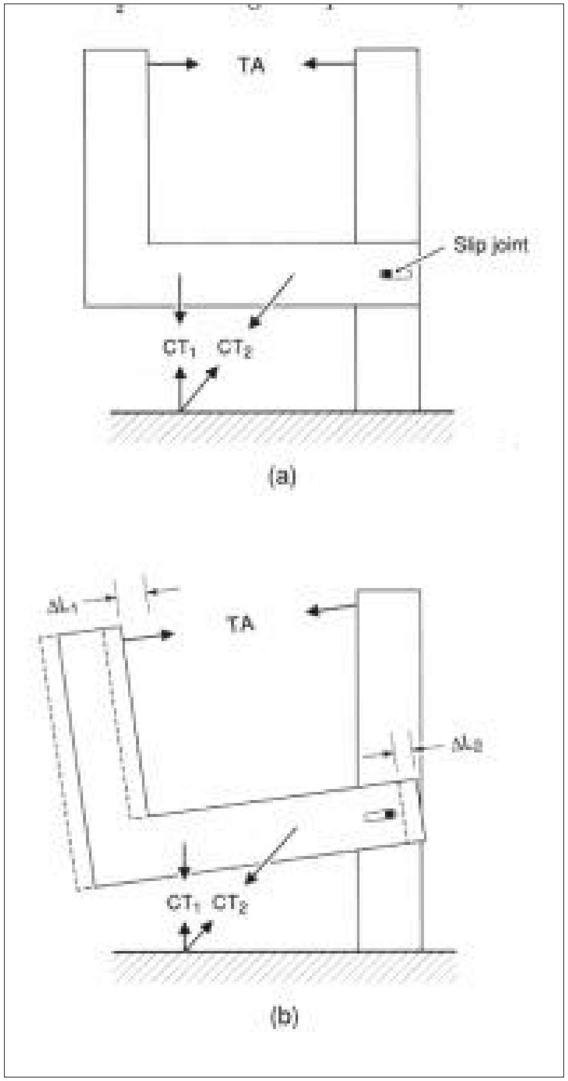


- Inner Volume has nonlinear lossless passive properties.
- Outer Volume is linear lossless passive properties.
- Active properties and viscous passive stress are superimposed on fiber lines.

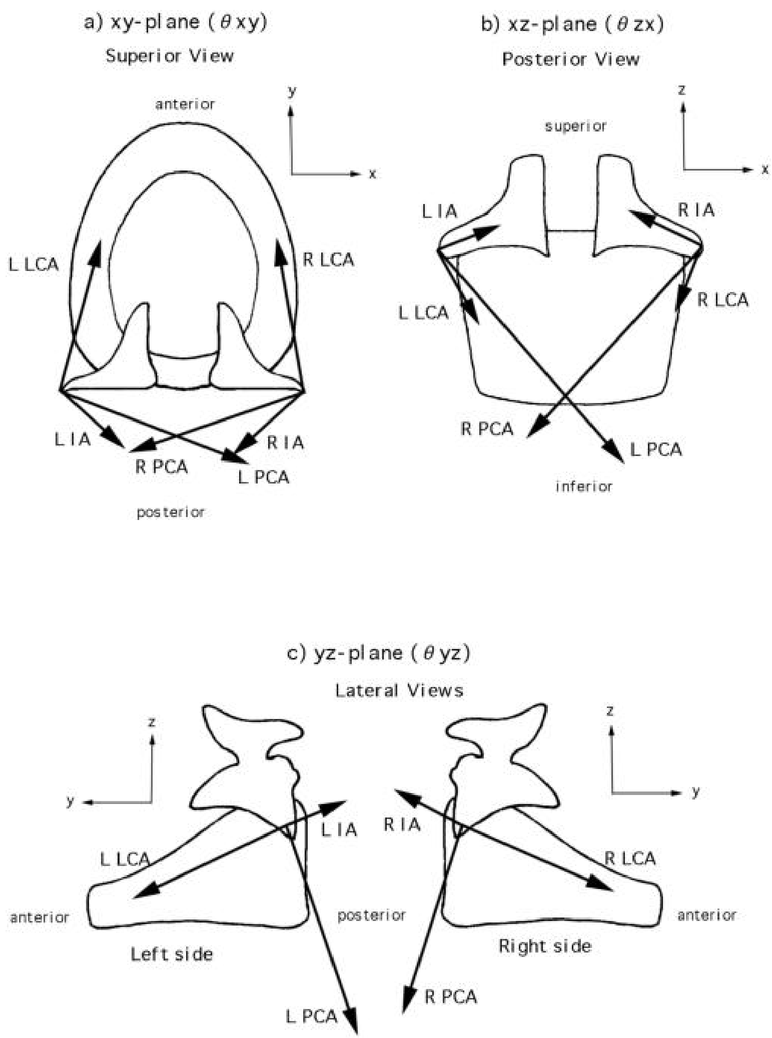
Boundary Conditions

- Thyroid cartilage
  - CTJ mechanics (Titze, 1994)
- Free medial boundary
- Arytenoid cartilage
  - Rocking
  - Sliding
    - *in terms of direction cosines* (Selbie *et al.*, 1998)

l	***m***	***n***
0.6092	0.6192	-0.4954



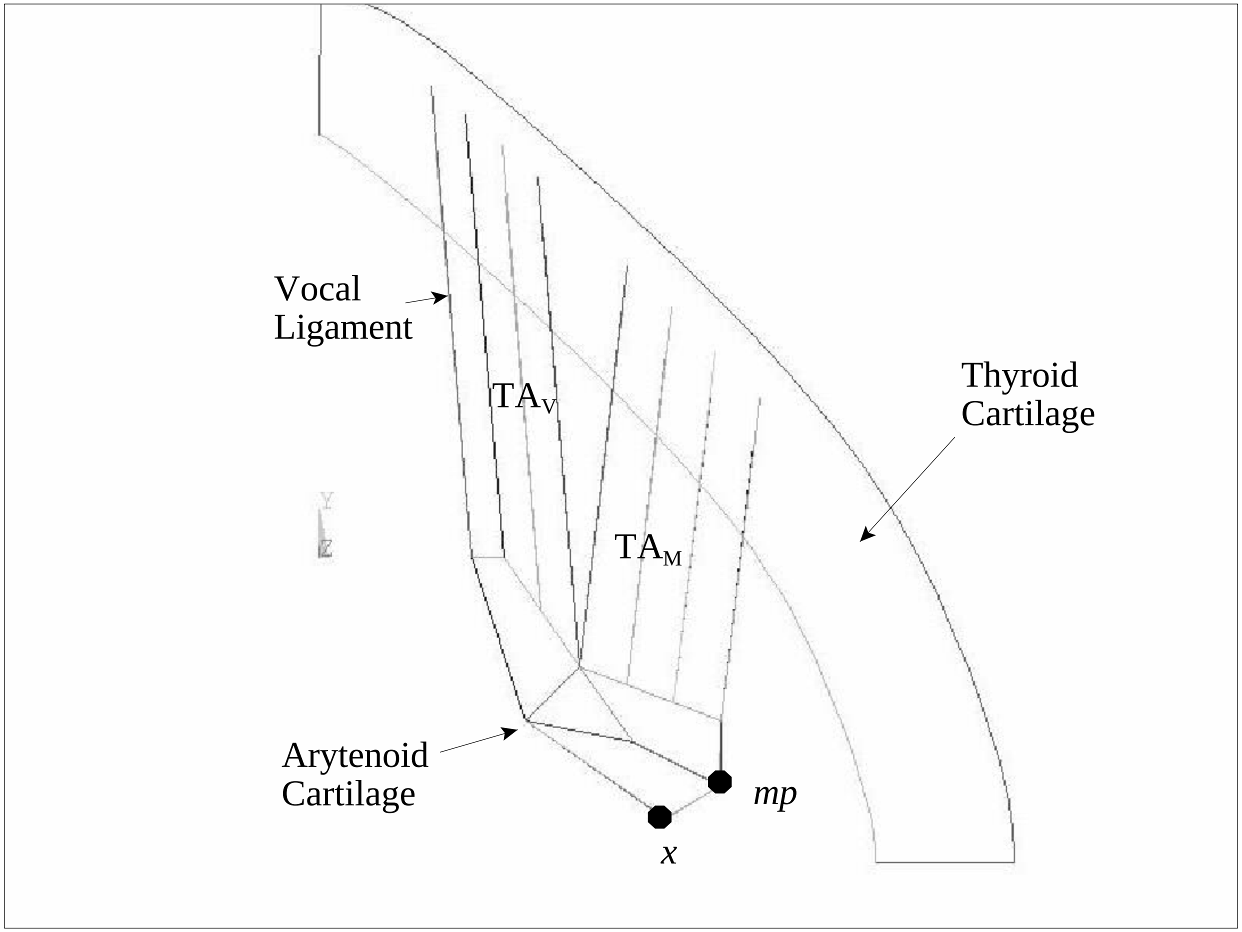
Boundary Conditions



Apply LCA, IA and PCA muscle stresses to the arytenoid catilage in appropriate directions.

(after Mineck *et al*., 1999)

Boundary Conditions

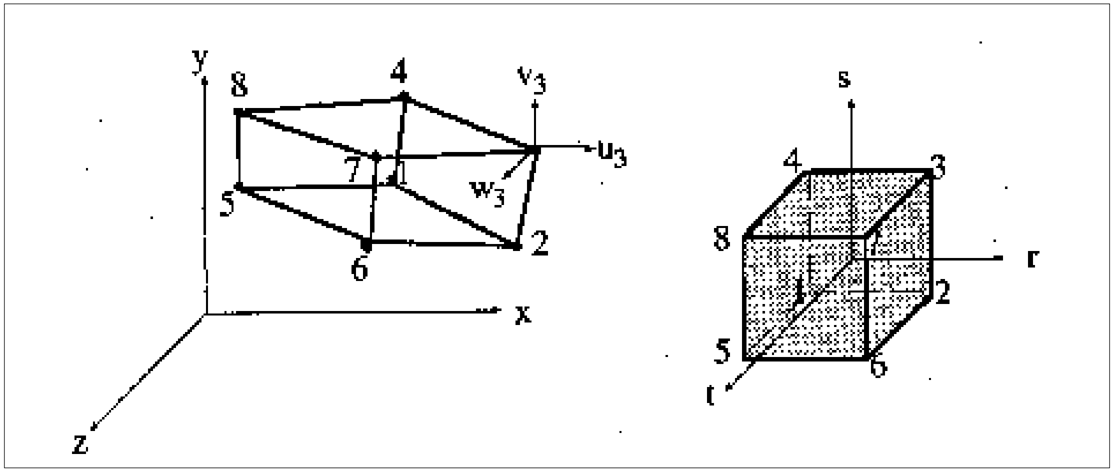


Apply the vocal ligament and the TAm and TAv as grouped fibers (Cox *et al*., 1999).

Discretization

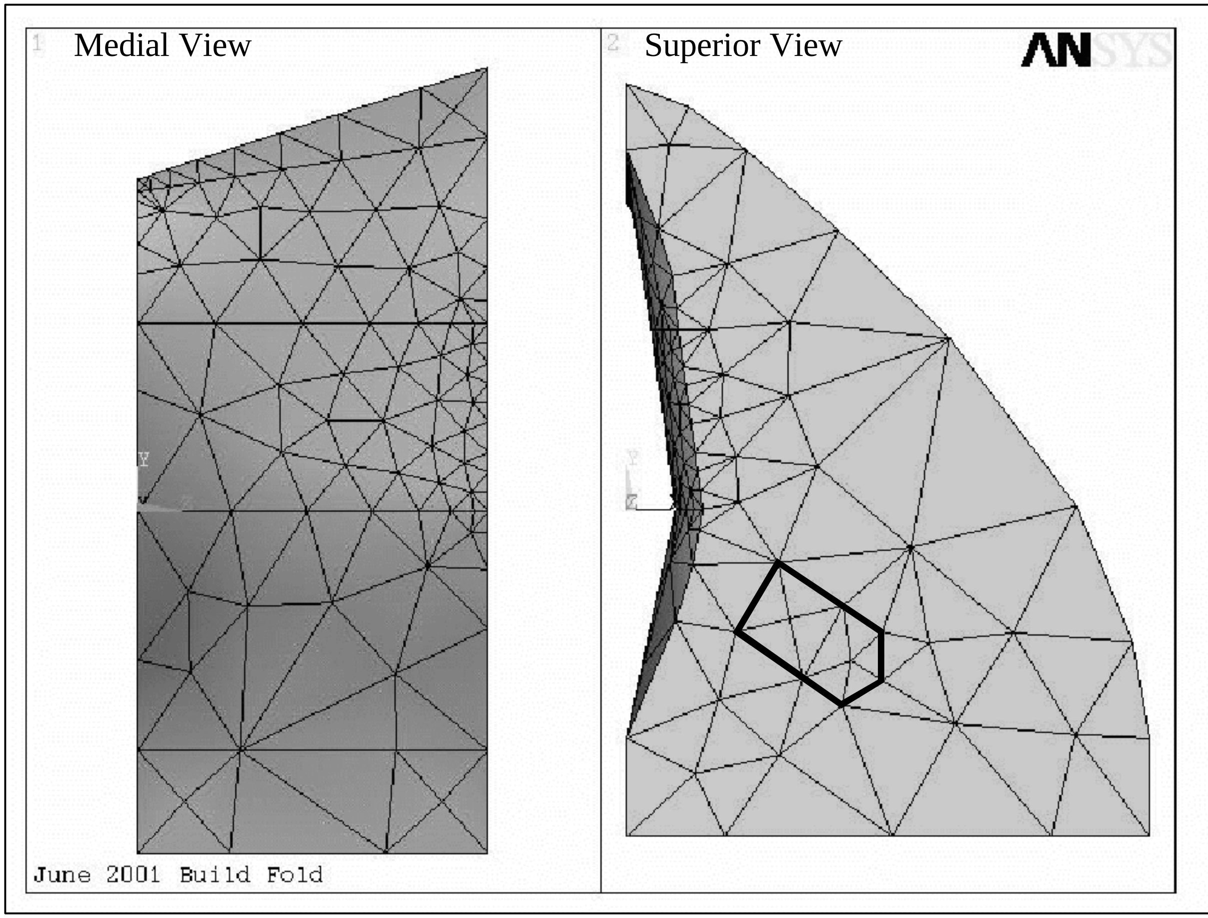
- Finite element analysis divides the continuum into small elements.

- Simple continuum mechanic equations approximate solutions over these small elements.

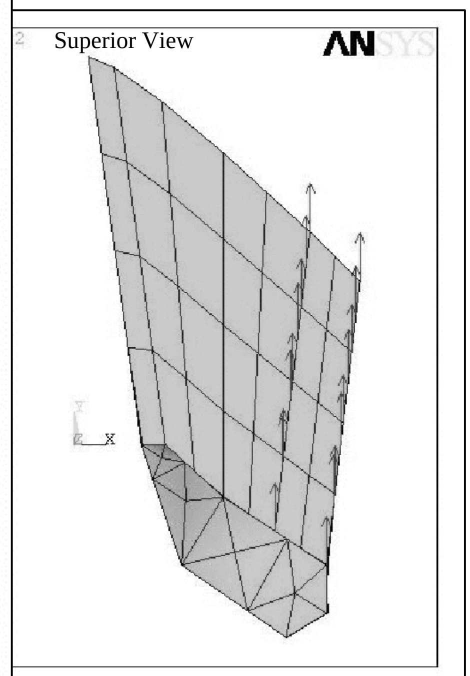


eight-node hexahedral element

Discretization

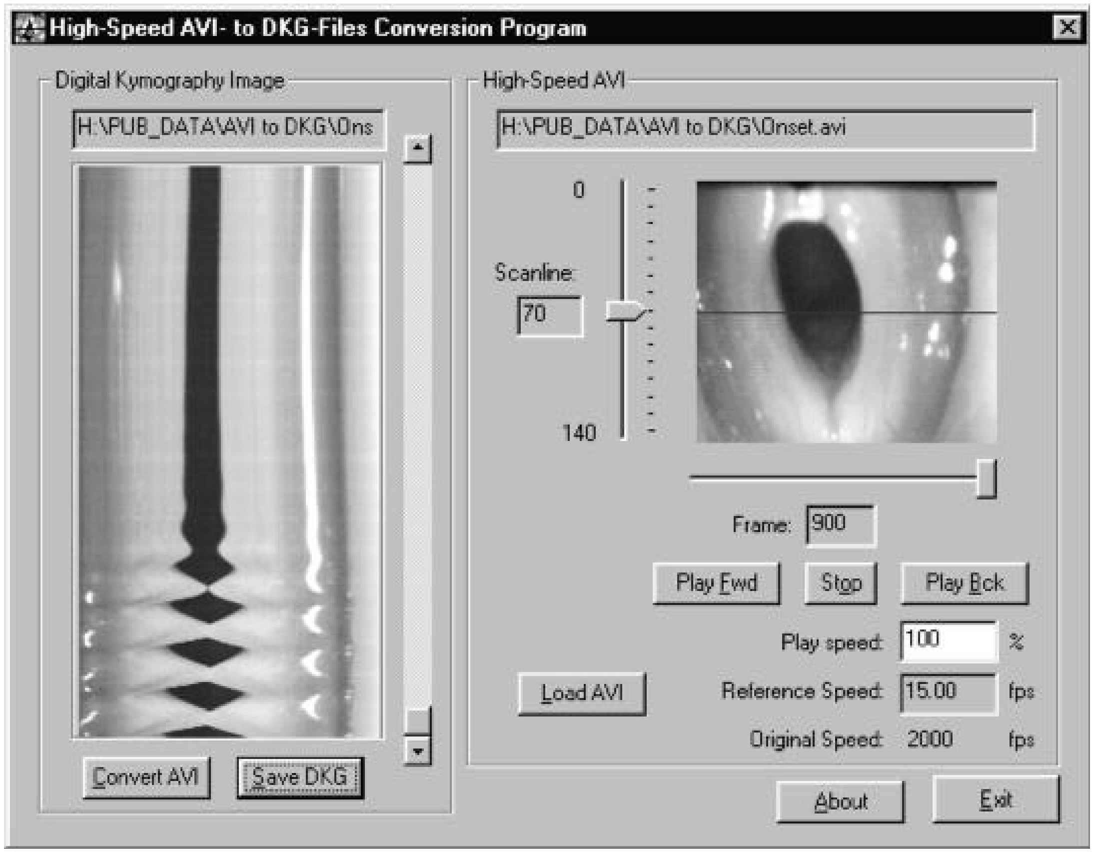


Full model in two views



Arytenoid & muscles with TA_M fiber nodes marked

Subjects and Tasks



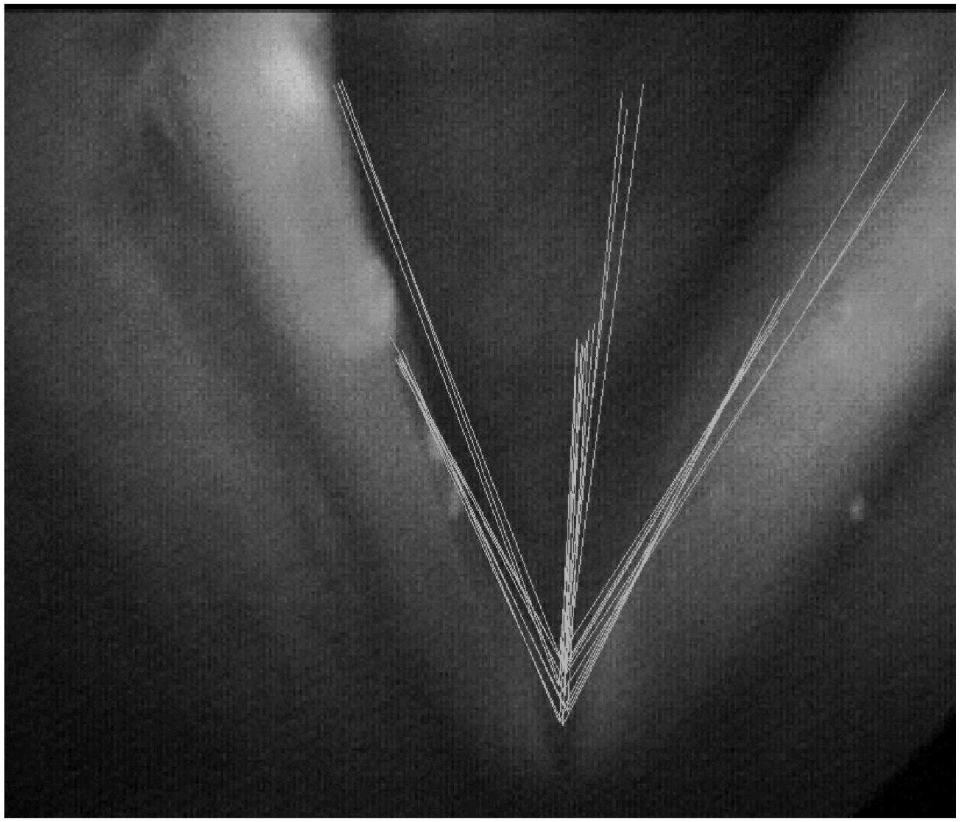
- Tasks

  Deep inhalation (1)

  / hi / - / hi / (5)

- Three male subjects (age: 35) were recorded using high-speed endoscopy at 500 frames/second.
- Frames were converted to a single kymographic image.

Inhalation

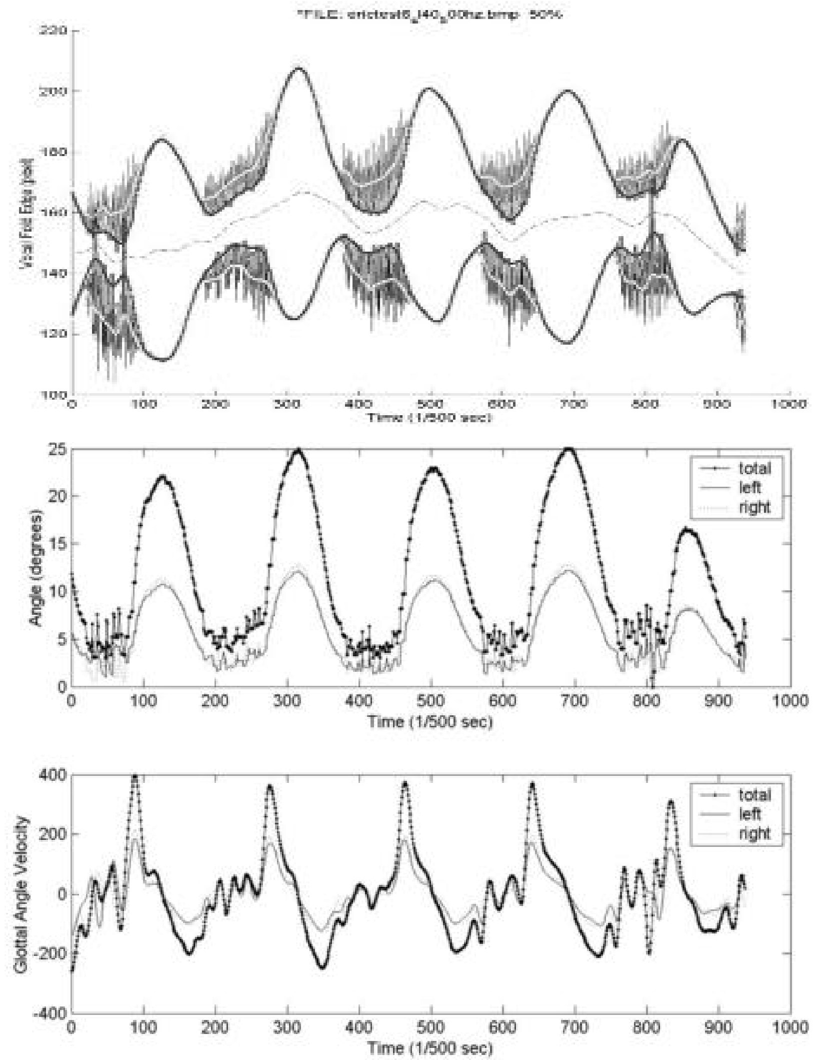


- Subject 2 is shown
- All three subject average of 51.2+/-16.7 degrees
- Note the difficulty in choosing the vocal fold edge.

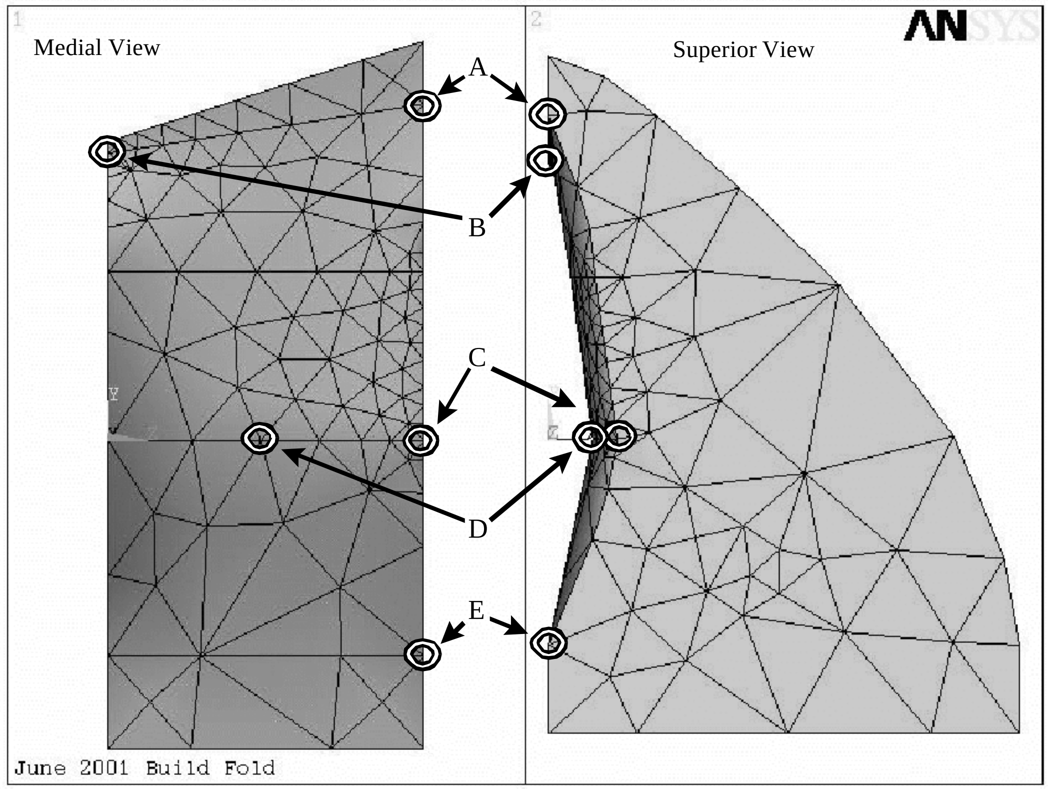
/ hi / - / hi /

Glottal angle and velocity were obtained from kymographic image

- **Upper** -
  Vocal fold edges
- **Middle** -
  Calculated Glottal Angle
- **Lower** -
  Glottal angle velocity

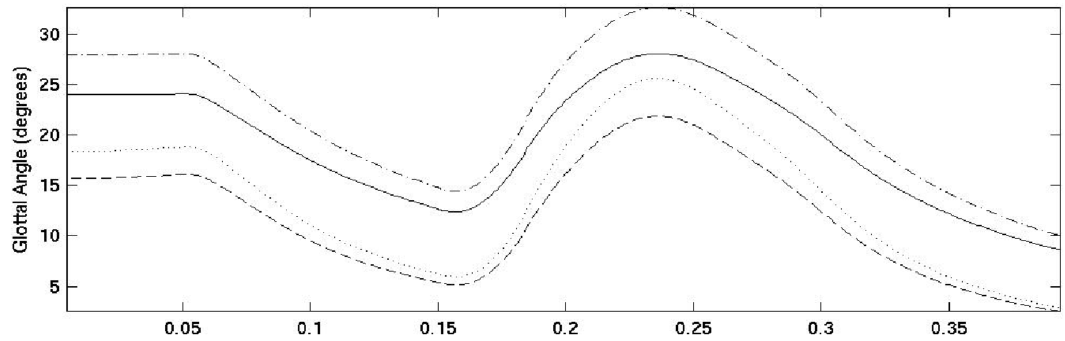


Glottal Angle

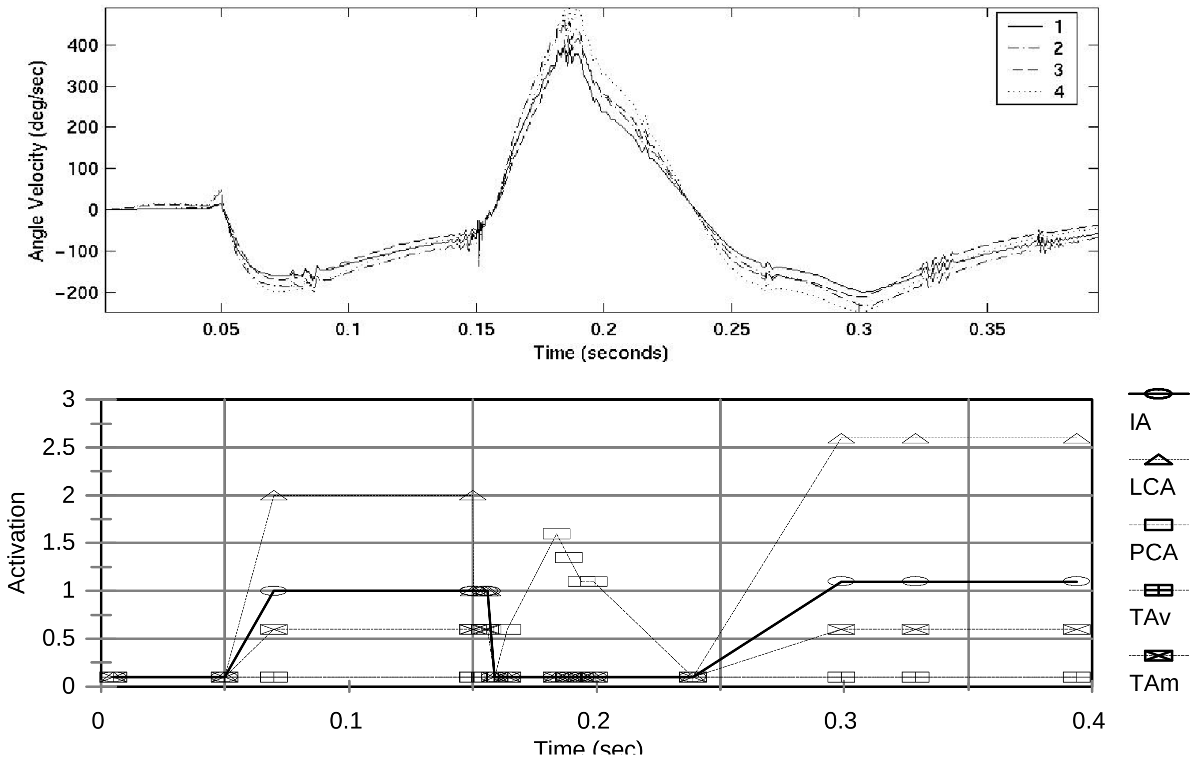


Four unilateral glottal half angles were measured to account for measurement variability.

Simulated */ hi / - / hi /*

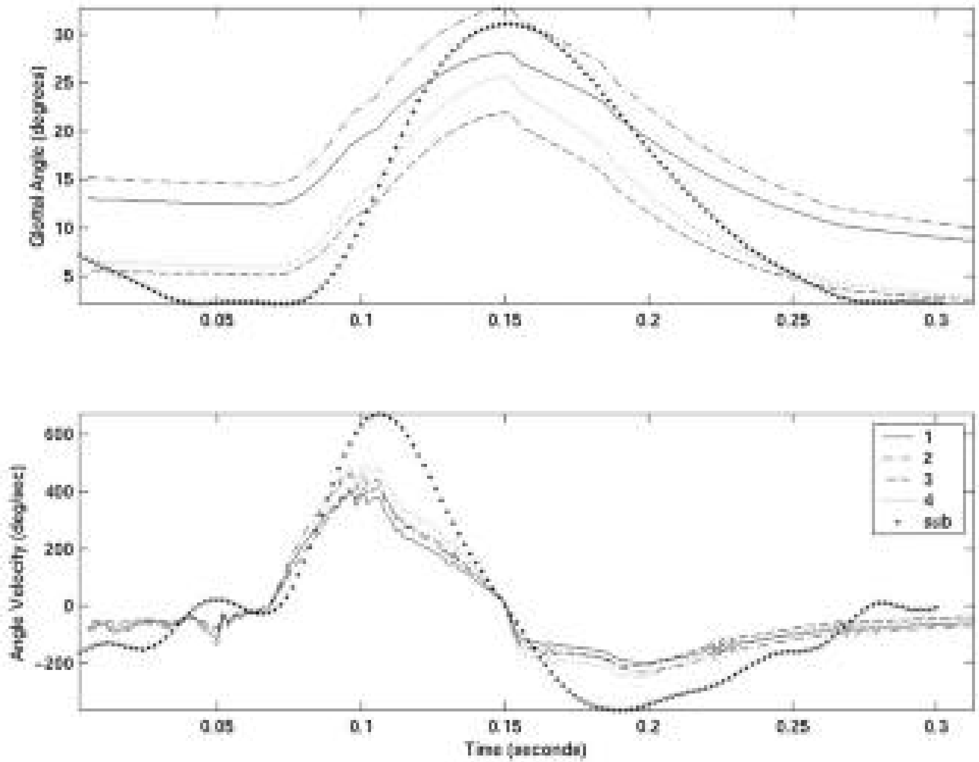


a. Glottal angles of posture.



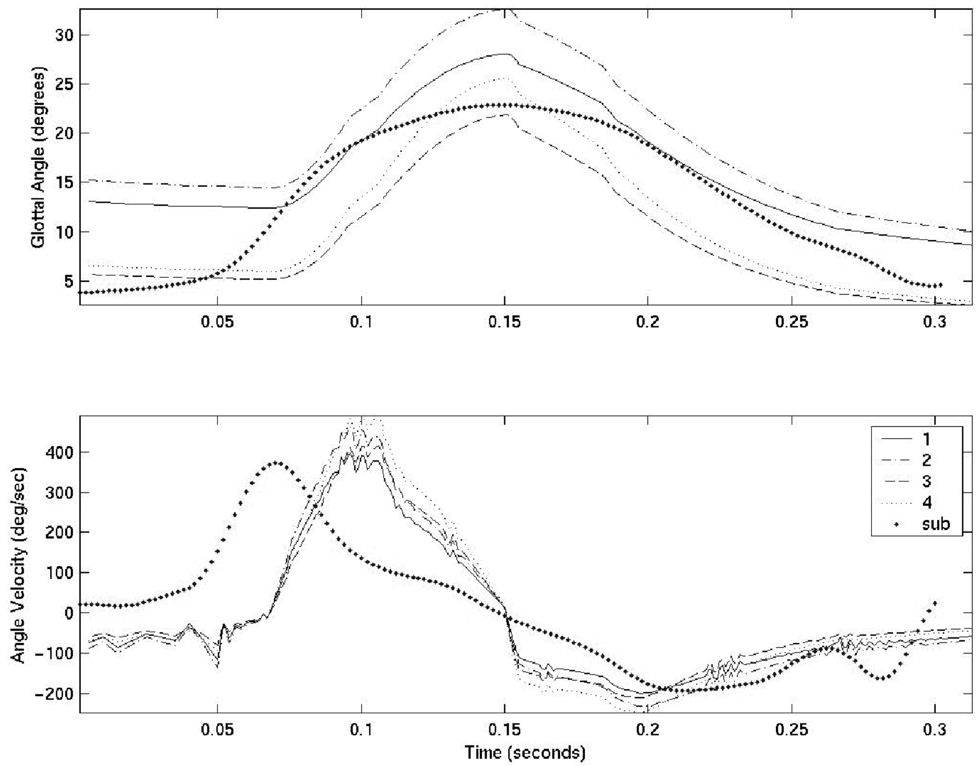
Four unilateral glottal half angles were measured to account for measurement variability.

Comparison with S1



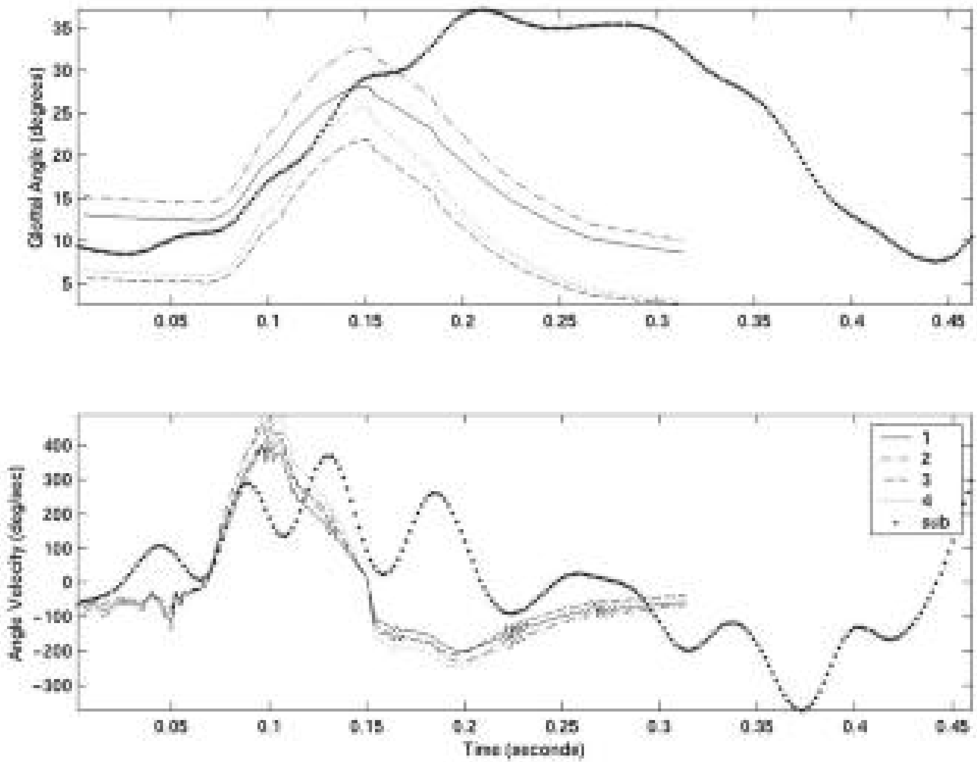
Timing is similar, but range and speed are not matched.

Comparison with S2



Range and speed are similar.

Comparison with S3

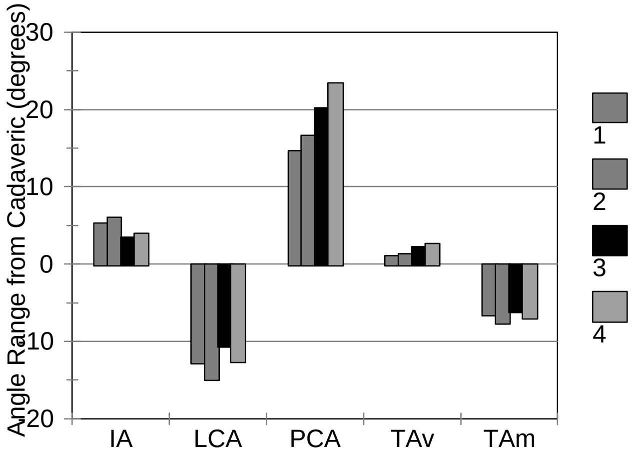


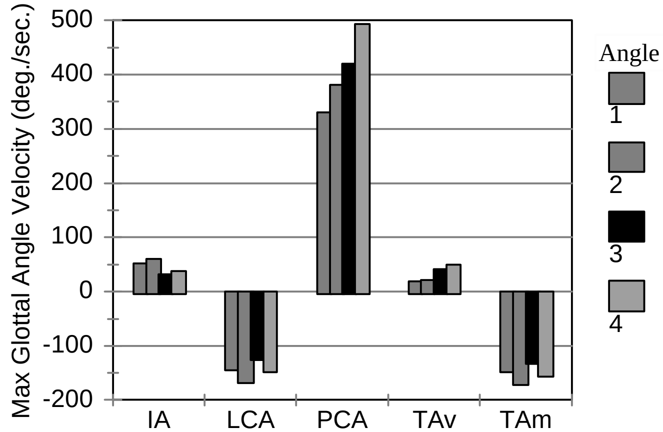
Model does not match range but is similar to speed.

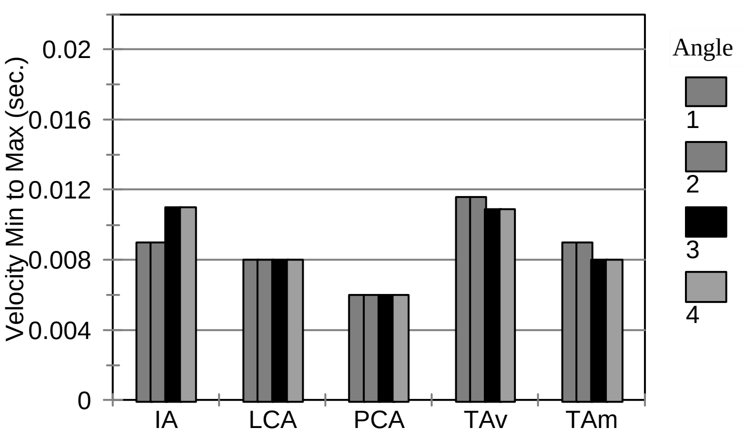
Comparison of Measures

	Combined Subject			**Model**			
	mean	**s.d.**	**N**	**Angle 1**	**Angle 2**	**Angle 3**	**Angle 4**
Glottal Angle (Ł) ***degrees***	27.2	5.9	15	28.1	32.6	21.9	25.6
Half Glottal Angle (Left) ***degrees***	12.1	3.6	15				
Half Glottal Angle (Right) ***degrees***	15.3	3.4	15				
Abduct Angle Velocity (***dŁ / dt*** **)** ***deg/sec***	403.80	153.3	15	398.2	463.4	417.1	490.6
Time minimum to maximum (*sec*)	0.044	0.012	15	0.038	0.038	0.038	0.038
Half Glottal Angle Velocity - Left ***deg/sec***	184.57	61.66	14				
Time minimum to maximum (*sec*)	0.036	0.013	14				
Half Glottal Angle Velocity-Right ***deg/sec***	241.17	96.59	14				
Time minimum to maximum (*sec*)	0.043	0.018	14				
Adduct Angle Velocity (***dŁ / dt*** **)** ***deg/sec***	235.9	82.0	14	190	220	200	240

Individual Muscles







Conclusions:

6 Key Findings

- The model was able to produce a posture comparable to the subjects in range and speed
- The model showed that certain characteristics of the posture seem to be inherent to the vocal system mechanics and not just input-related
- The model verified that the PCA is the main abductor by showing that the PCA on its own could obtain the glottal angle range and speed of the subjects.
- The model verified that the IA is needed to close the posterior glottis
- The rocking-sliding simplification of the CAJ was found to simulate the type of motion seen in the larynx.
- The model showed that the TA_v and the TA_m have significantly different roles in posturing, the TA_m having the more important role.

Bibliography

- Berry, D. A., Montequin, D. W., Titze, I. R., Hoffman, H. T. (1997). An investigation of cricoarytenoid joint mechanics using simulated muscle forces, in press.
- Cox, K. A., Alipour, F., and Titze, I. R. (**1999**), "Geometric structure of the human and canine cricothyroid and thyroarytenoid muscles for biomechanical applications," Ann. Otol. Rhinol. Laryngol. **108**(12), 1151- 8.
- Murry T., Xu JJ., Woodson GE. (1998) Glottal configuration associated with fundamental frequency and vocal register. Journal of Voice. 12(1):44-9.
- Tayama, N., Chan, R.W., Kaga, K, and Titze, I.R. (in review). Functional Definitions of Vocal Fold Geometry for Laryngeal Biomechanical Modeling. Ann. of Oto, Rhino, & Lary.
- Titze, I.R. (1994). *Principles of Voice Production*. Englewood Cliffs: Prentice Hall.
- Titze I.R & Alipour, F. (in progress), The Myoelastic-Aerodynamic Theory of Phonation.

A special thank you to Ingo Titze and

The National Center for Voice and Speech