Vocal Fold Movement Prediction from Neural Inputs:

Building the Model

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Research Question

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

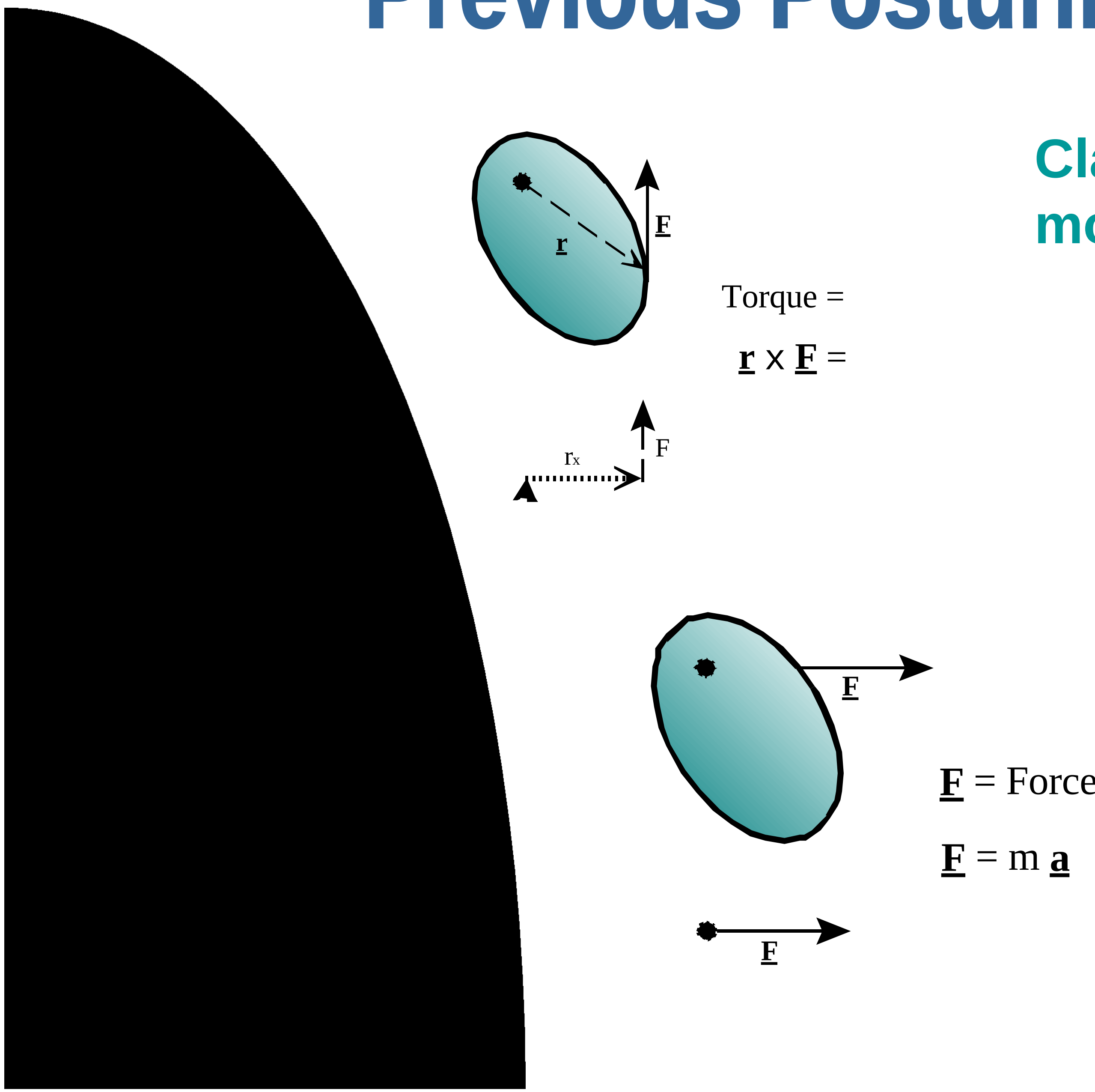
Myoelastic-Aerodynamic Theory of Phonation

- Vocal-tract acoustics
- Laryngeal aerodynamics
- Tissue mechanics

Configuration of the tissue is key to phonation. (Murry, *et al*, 1998)

- Vibration
- Posturing

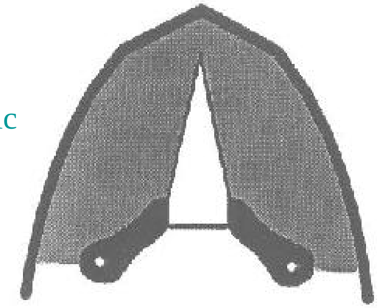
Previous Posturing Models



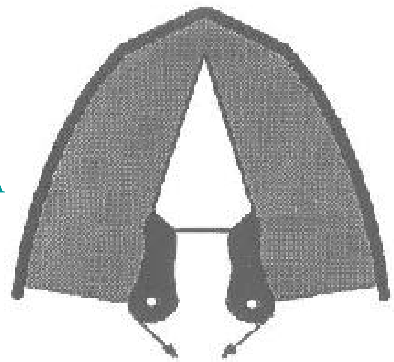
Classical analytical model

- Ridged body mechanics
- Tissue compressibility
- Two dimensions
- Vocal fold medial shape

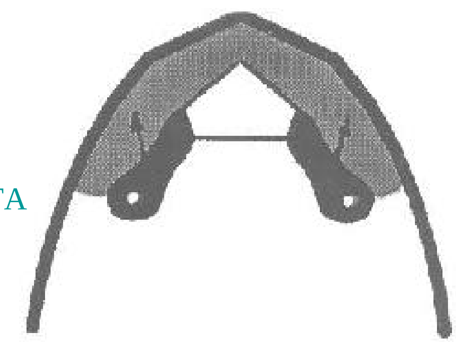
Cadaveric



Full LCA



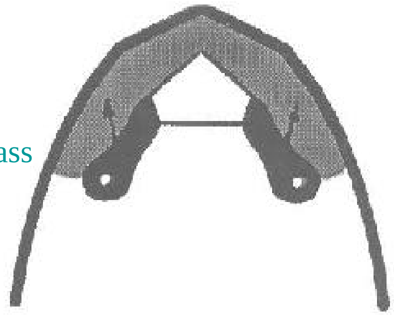
Full TA



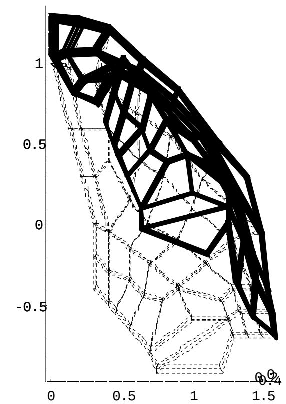
Classical analytical model

- Ridged body mechanics
- Tissue compressibility
- Two dimensions
- Vocal fold medial shape

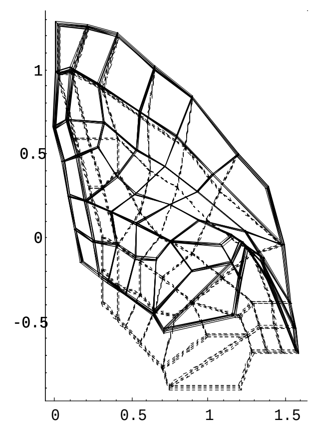
Full TA
point mass



Full TA
compressible



Full TA
incompressible



Classical analytical model

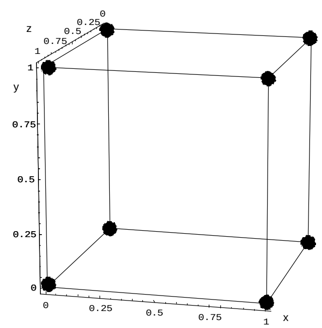
- Ridged body mechanics
- Tissue compressibility
- Two dimensions
- Vocal fold medial shape

Finite Elements

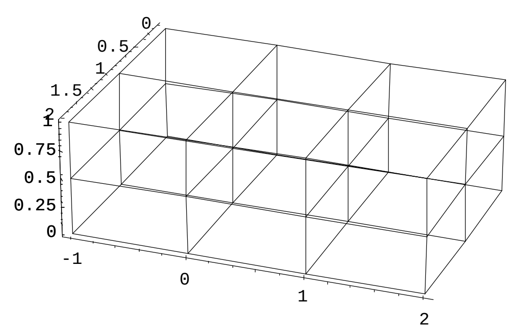
Continuum mechanics through finite elements

- geometry
- mechanical properties
- boundary conditions
- discretization

Hexahedral element

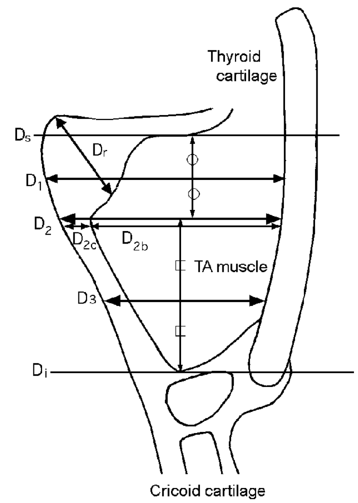


Simple structure

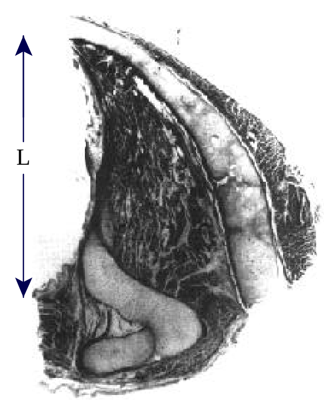


Geometry

Rostra
caudal



Simple
structure



- 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

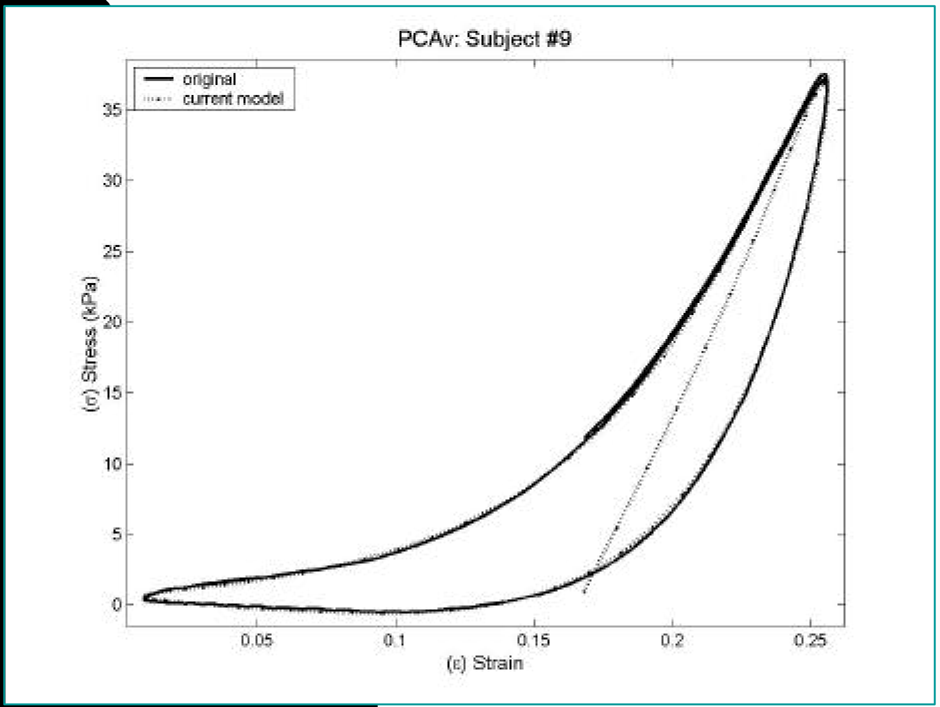
Defining Mechanical Properties

- 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

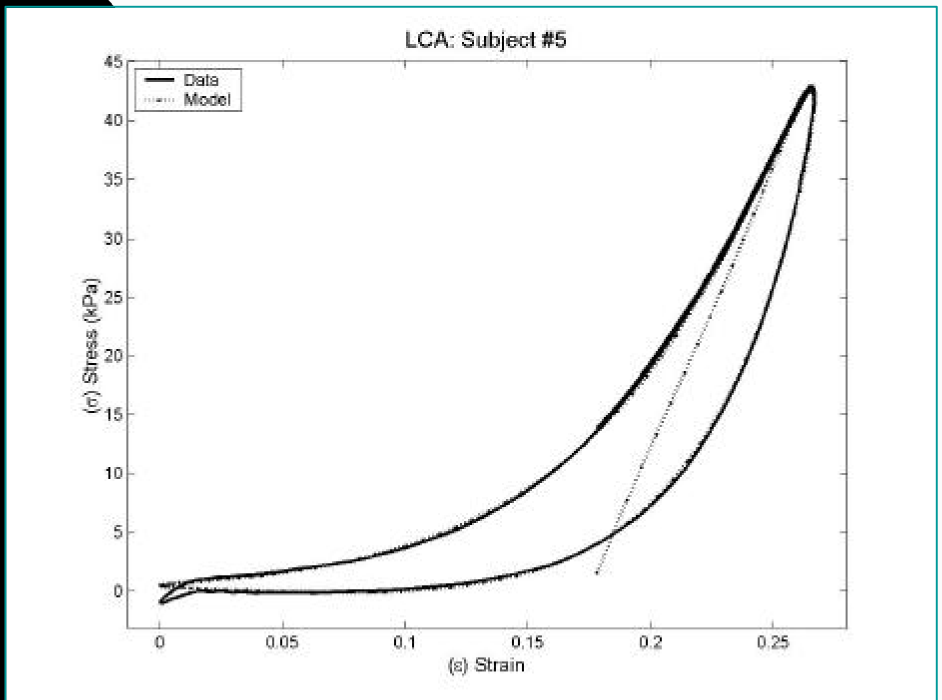
- All tissues have passive properties
- Dynamic stress-strain of IA, LCA, PCAv, PCAo

  (5 canine laryngeal specimen)
- Modeling these curves using a 7-parameter model

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

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

Passive Properties



$$ERR = \sum_n \left(\sigma_d(n) - \sigma_m(n)\right)^2$$

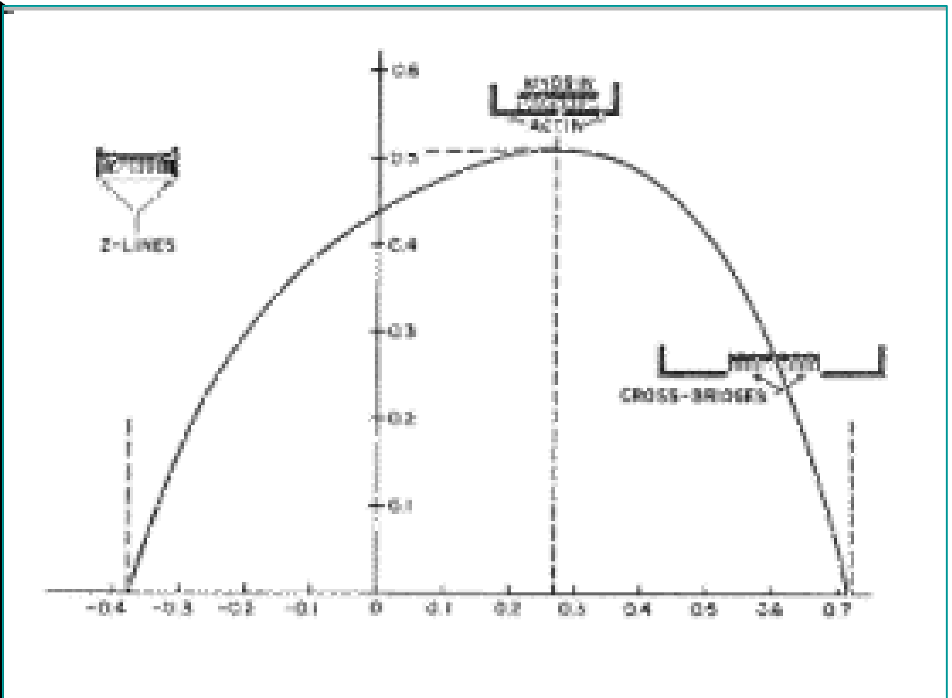
- Nelder and Mead Simplex method of optimization
- Tolerances to end optimization attempt set to 1 percent
  - trial-to-trial difference between parameters
  - trial-to-trial summed square of measured vs modeled stress

Passive Properties- Results

Parameters’ mean values, their standard deviations, and the number of contributing specimens

	IA			LCA			PCAo			PCAv		
	mean	**s.d.**	**N**	**mean**	**s.d.**	**N**	**mean**	**s.d.**	**N**	**mean**	**s.d.**	**N**
Iteration	1364	364	5	2770	1150	4	1431	480	5	3602	2249	4
ó$_0$ (Pa)	1333	242	5	751	114	4	1551	396	5	818	263	4
ó$_2$ (Pa)	7099	2105	5	329	224	4	6019	4754	5	28	17	4
å$_1$	-0.5	0	5	-0.5	0	4	-0.5	0	5	-0.5	0	4
å$_2$	0.00439	0.02581	5	-0.0231	0.04809	4	0.03999	0.04075	5	-0.182	0.01834	4
B	5.947	0.776	5	14.908	1.565	4	10.842	2.898	5	16.10	0.310	4
t_p (sec)	0.09038	0.00308	5	0.09931	0.01860	4	0.08443	0.01417	5	0.1154	0.01279	4
t_s (sec)	0.05058	0.00236	5	0.05429	0.01237	4	0.04843	0.00899	5	0.0612	0.00674	4

Active Tissue Properties



$$\sigma_a = a\,\sigma_m f(\varepsilon_y)\,g(\dot{\varepsilon}_y)$$

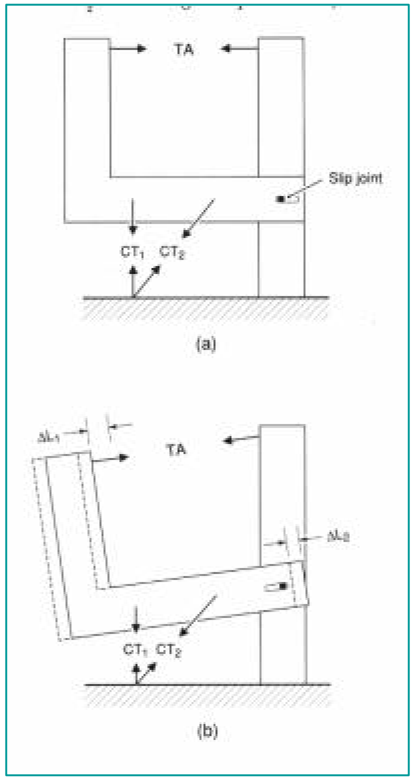
$$g(\varepsilon) = Max\left[0, \frac{\varepsilon/\varepsilon_m + 1}{1 - 3\varepsilon/\varepsilon_m}\right] \quad \varepsilon \le 0$$

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

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

- Only muscle tissues have active properties
- Assumption: total stress of muscle is superposition of its active and passive properties
- Optimize to twitch response using same scheme as before

Boundary Conditions

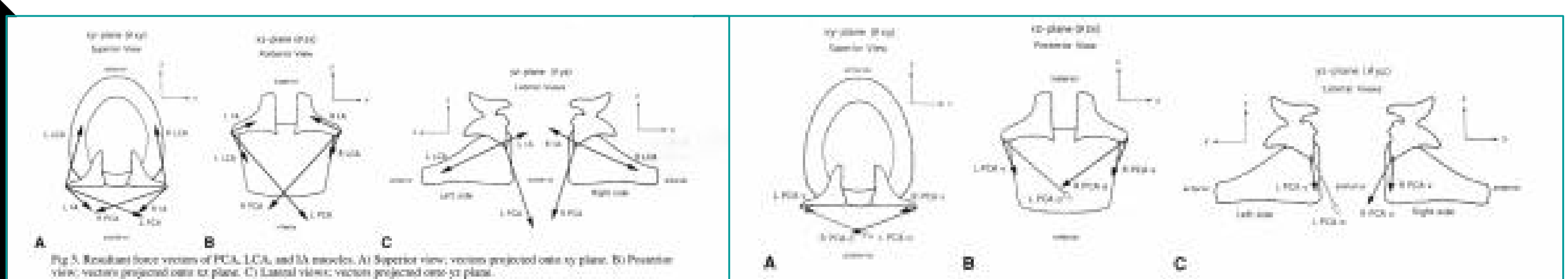


$$\varepsilon = G(R\,a_{ct} + a_{ta}) + \varepsilon_o$$

- Thyroid cartilage
  - CTJ mechanics
    (Titze, 1994)
- Arytenoid cartilage
  - Rocking
  - Sliding
  - Rotation
    (Sellars & Vaughan, 1983)
- Free medial boundary

Axis	X (mm)	Y (mm)	Z (mm)
Rocking	4.9	-3.8	-5.6
Sliding	9.2	-5.9	-10.8
Twisting	14.0	-21.7	23.2

Boundary Conditions



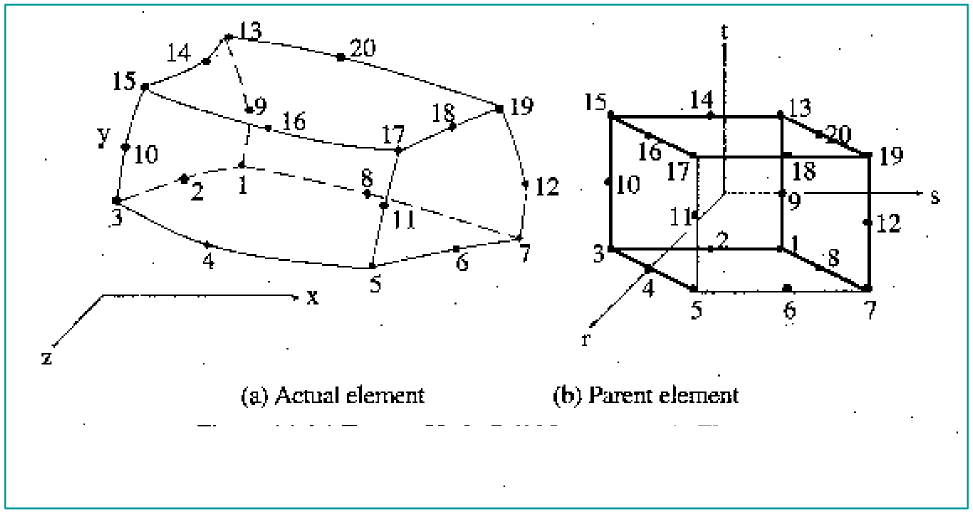
- Apply muscle stresses to origin and insert points on cartilages in appropriate directions (Mineck, *et al*, 1999)

- Quantify CAJ stiffness (Berry *et al*,1999)

Translational Stiffness	k_x (N/m)	k_y (N/m)	k_θ (Nm/rad)
	91	254	0.0120

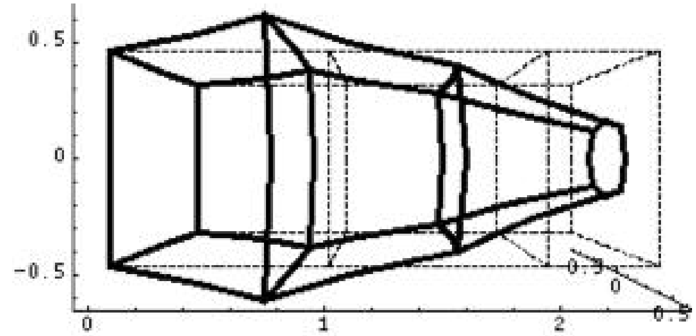
Discretization

- Finite element analysis divides the continuum into small elements.
- Simple continuum mechanic equations approximate solutions over these small elements.

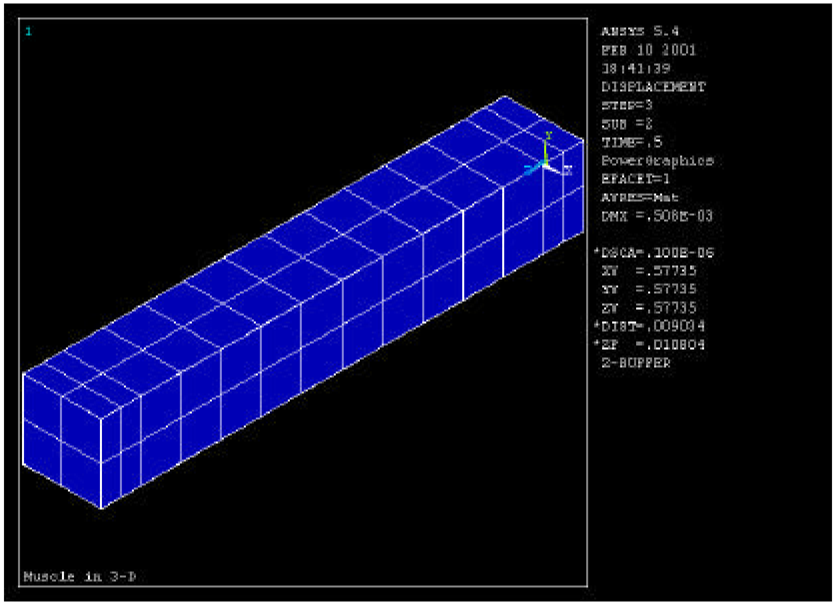


twenty node isoparametric element

Sample Muscle

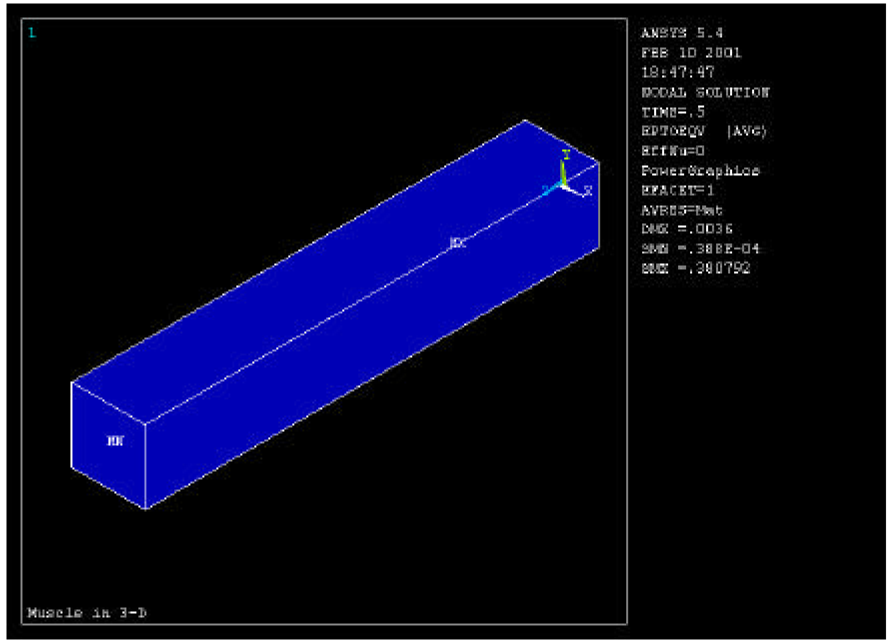


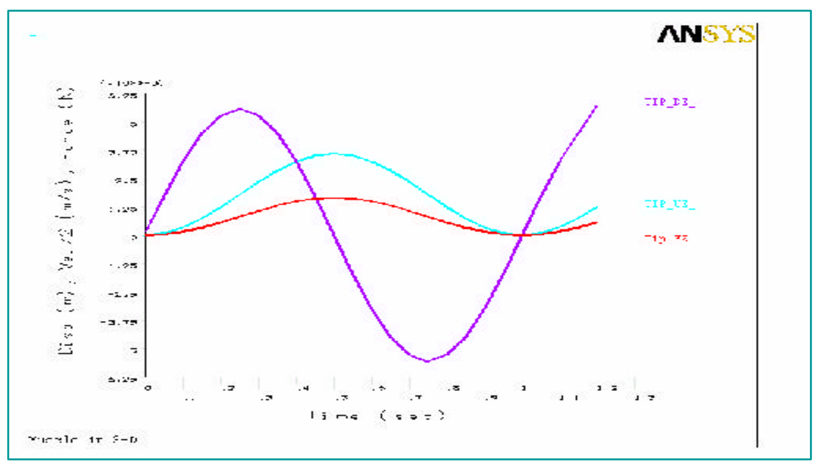
Contracted Muscle



Sample Muscle 2

Elongated muscle



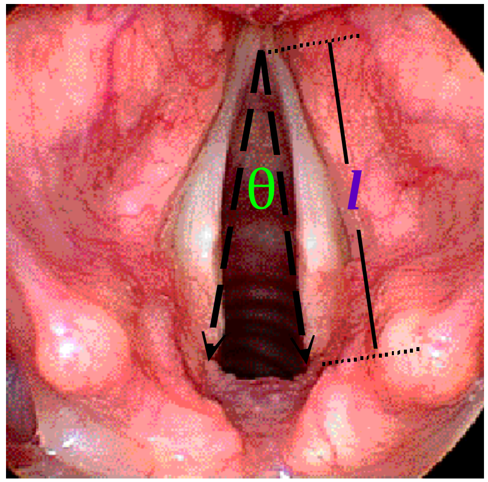


Testing the Model

- Using a high-speed endoscope, vocal fold length glottal angle will be measured for specific postures

Posture	Assumed Muscle Activity
A quick sniff or inhalation (sniff-/i/-sniff-/i/)	the PCA will be assumed at maximum activity
A low-to-high pitch glide (fold lengthening in non-falsetto register)	CT and TA are both nearly maximum for a high pitch if the vibration is not considered a falsetto register (Titze, Luschei, and Hirano, 1989)
alternating low and high pitches	Sundberg, J. (1977), Sundberg, J. (1987).
Pressed Phonation, Cough	
A valsalva (a hard closure)	the LCA and IA will be assumed maximum

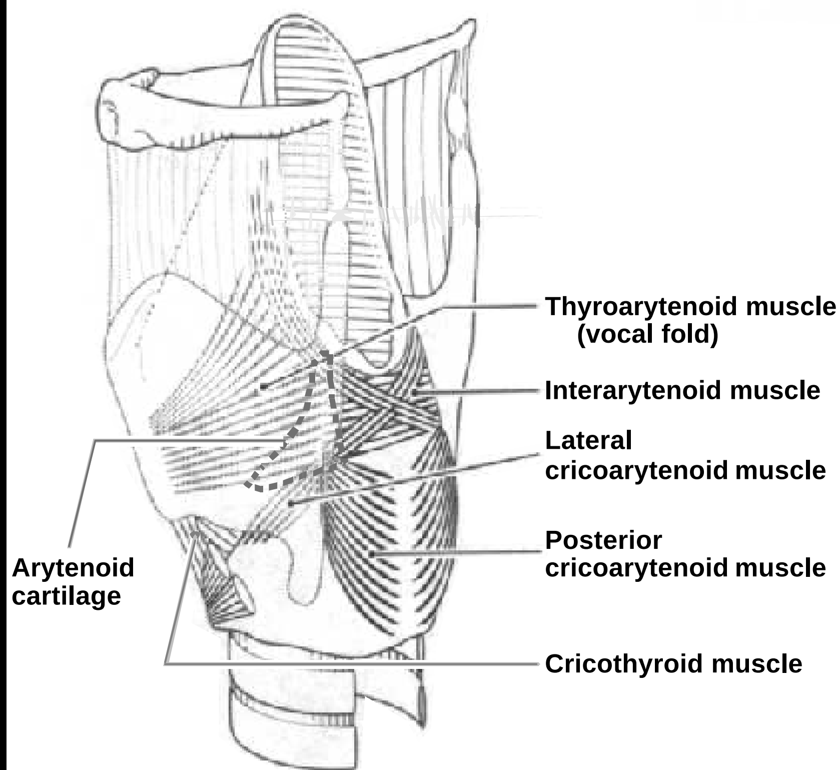
Neurological Projections



- Muscle activities *a* will be obtained by fitting the results of the model to the results of the high speed endoscopy measures.

Name	Symbol	Calculation
Glottal Angle	è	
Range of Glottal Angle	Äè	(è$_2$ -è$_1$)/2
Glottal Angle Rate of Change	Äè/Ät	(è$_2$ -è$_1$)/(2 Ät)
Vocal Fold Length Change	Ý	$(l-l_o)/l_o$
Vocal Fold Length Rate of Change	Ý/Ät	$(l-l_o)/(l_o$ Ät)

What is still to be done?



- Active properties are still being optimized
- High-speed endoscopic data is being taken TODAY
- *The Future?*

Bibliography

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