# A Sharp Interface Immersed Boundary Method for Flow, FSI & Aeroacoustics II: Application to Biological Flows

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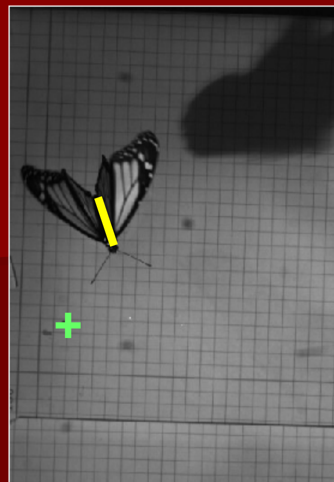
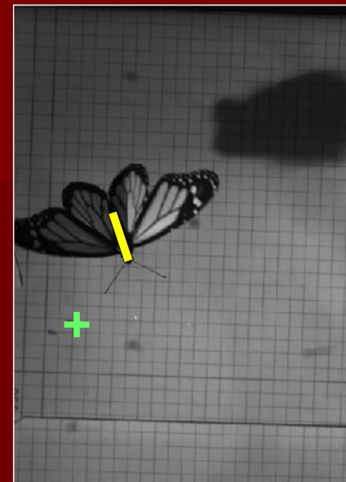
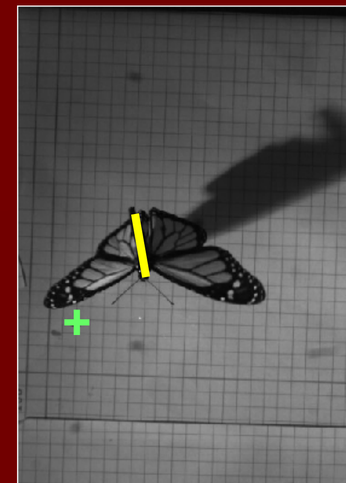
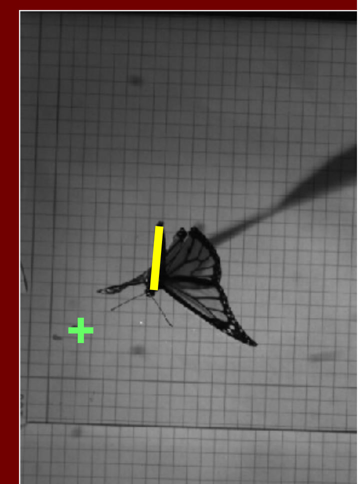
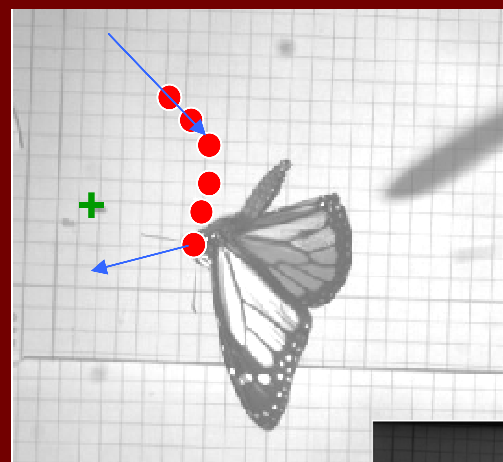
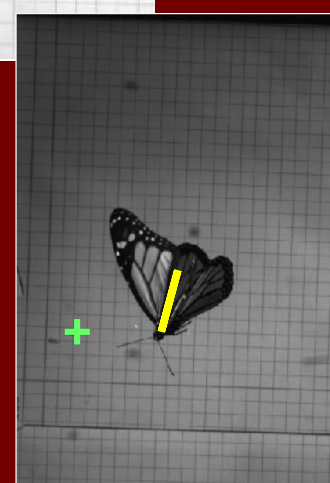
# Outline

- Insect Flight
- Dolphin kick in Olympic swimmers
- FSI of Phonation: Towards a CFD based surgery planning tool
- Cardiovascular Hemodynamics

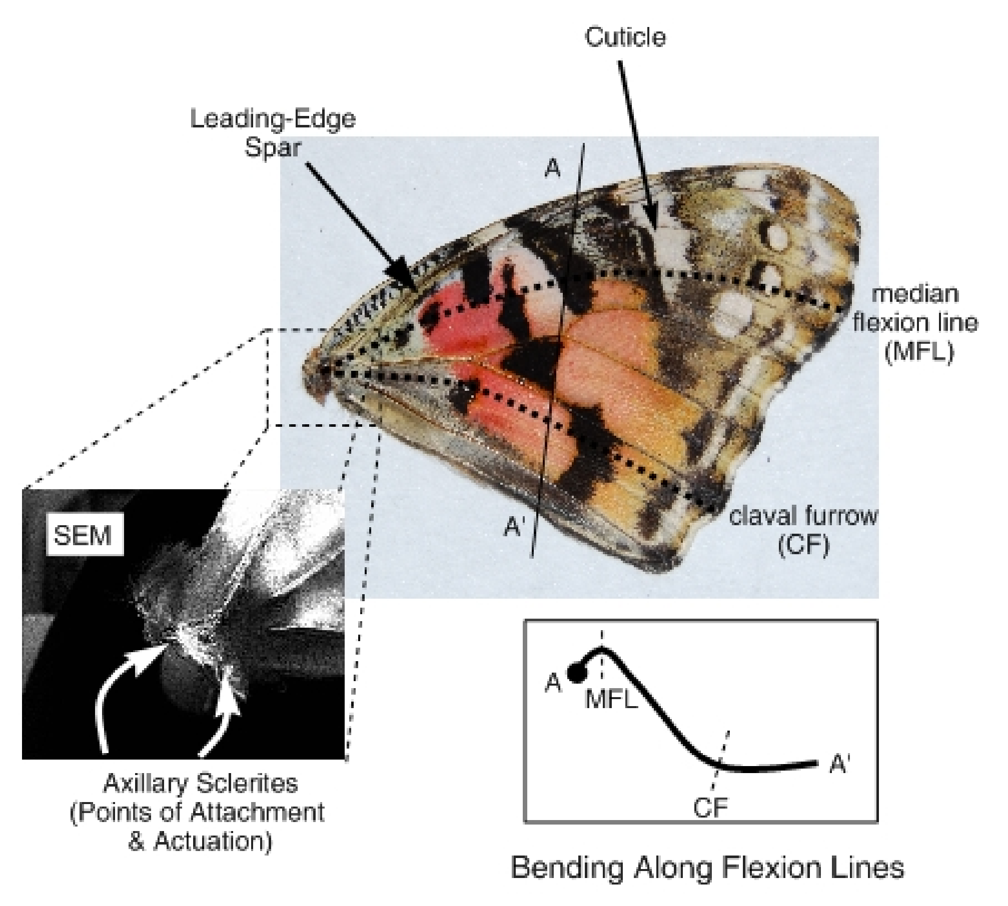






- **Turning in a Monarch Butterfly**
- Sequence shows 1.5 flaps
- >90º change in heading !
- Turning distance < body size
- Turn on a dime!



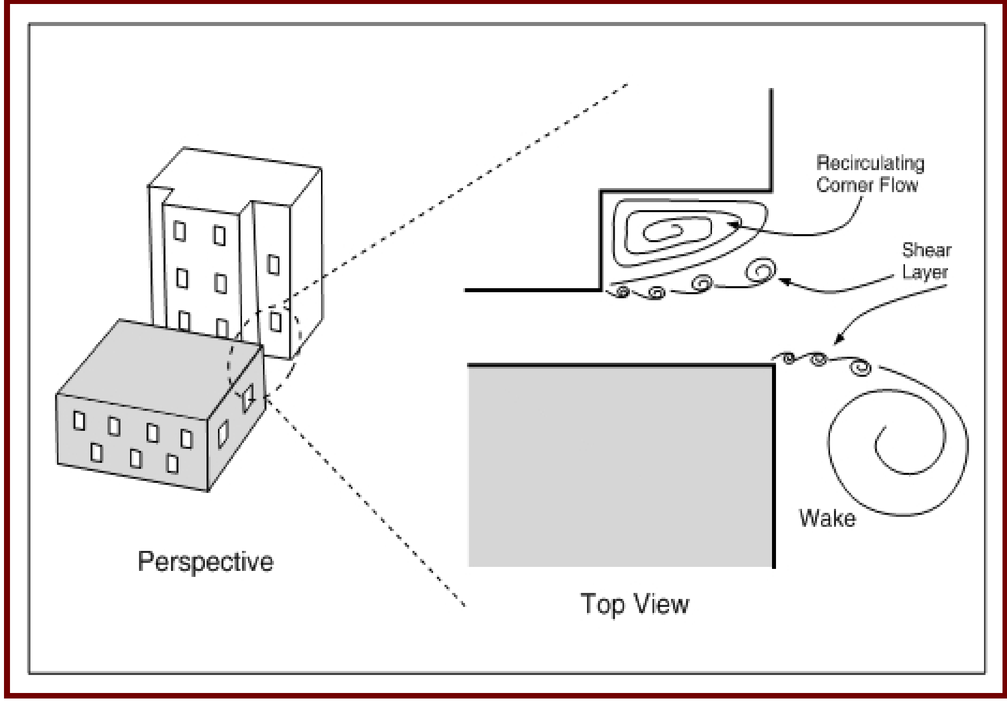

# How does the Butterfly do this ? Deformable Wings

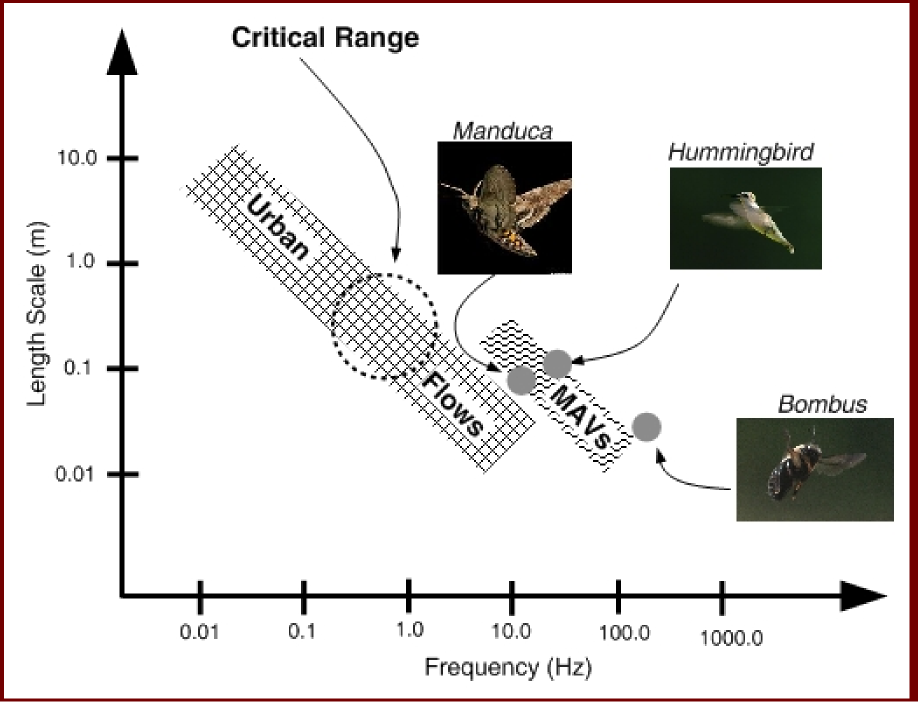
- Wings deform significantly
- Greater repertoire of wing kinematics.
  - Large left-right wing asymmetries
- What causes deformation
  - Flow and inertia induced deformation. (Daniels et al)
  - Also active deformation through action of direct muscles on axillary sclerites (wing joint).
- Perhaps even active control of deformability ??



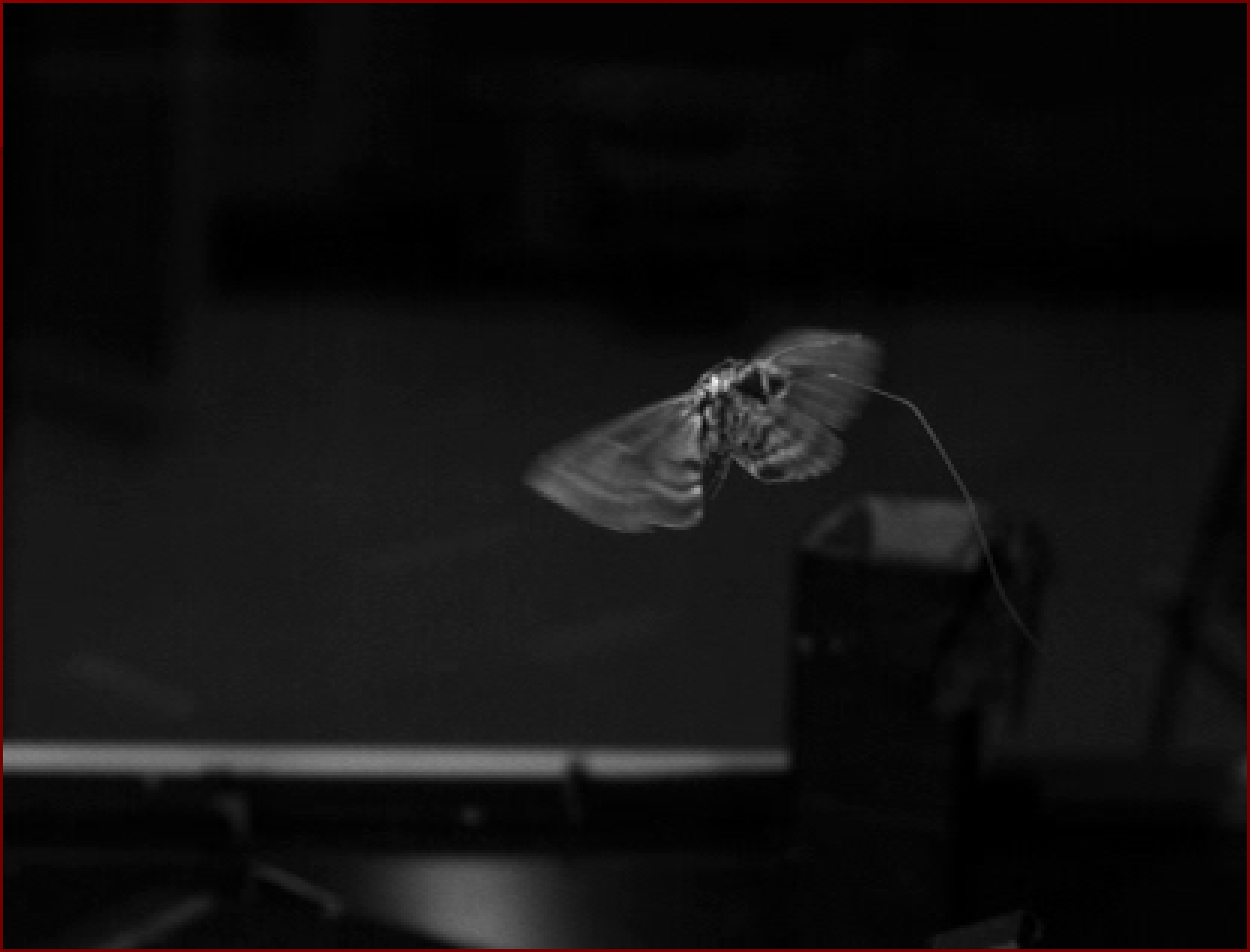
# Flight Stabilization ??

- Consider a Flapping Wing MAV in an Urban Environment:
  – Shear layers, wakes, corner flows …
  – Understand flight stabilization in insects



# What can we learn from insects?

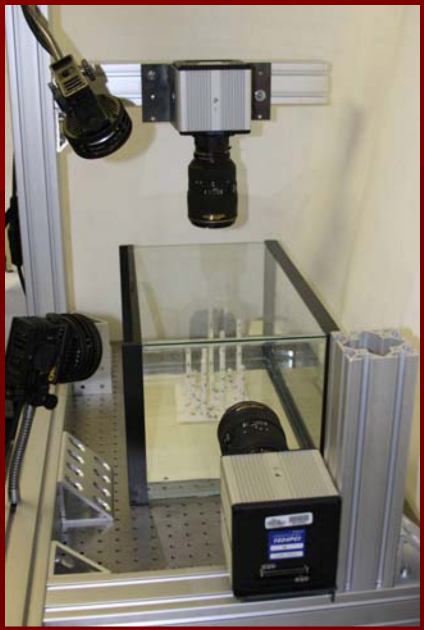


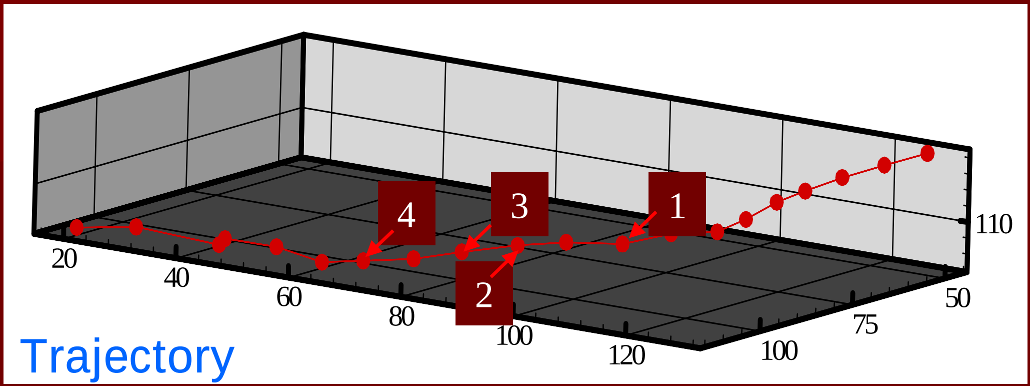
# Integrated Approach

- High Speed Videogrammetry
  - Tyson Hedrick Lab (UNC Chapel-Hill)
- Structural parameterization (Vallance Lab, GWU)
  - Wing
  - Body
- High Fidelity Computational Modeling of Aerodynamics and Aero-Structural Interaction
  - Sharp Interface Immersed Boundary Method
  - Direct and Large-Eddy Simulation
  - Wing deformation modeling using FEM

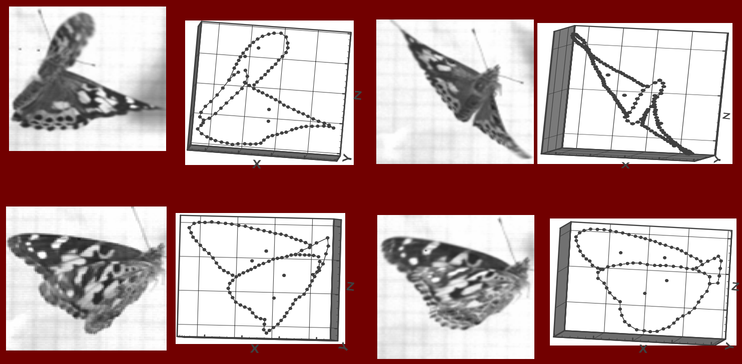
# High-Speed High-Resolution Videogrammetry

COBRE Insect Videogrammetry Lab

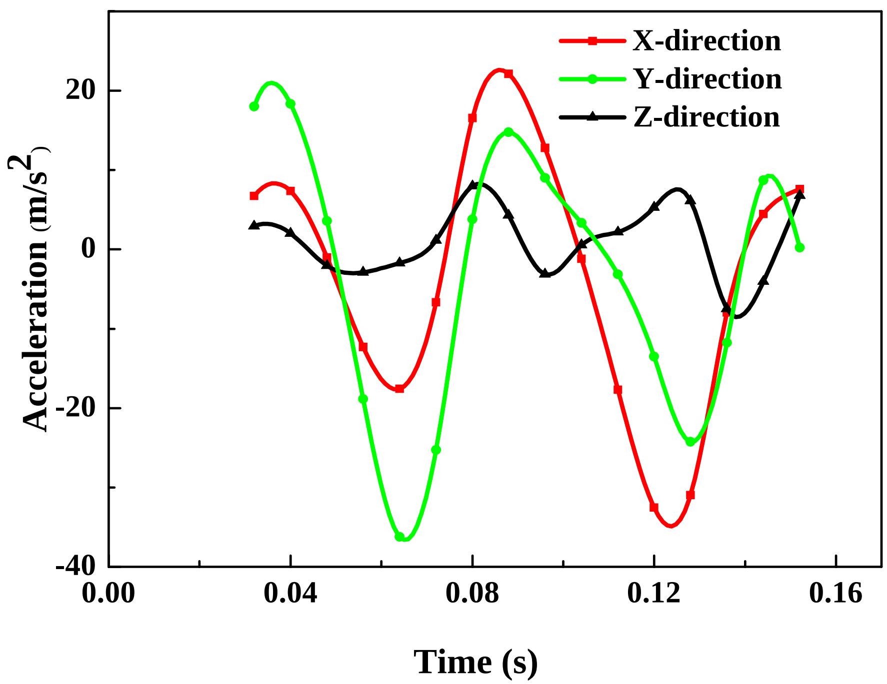





Trajectory



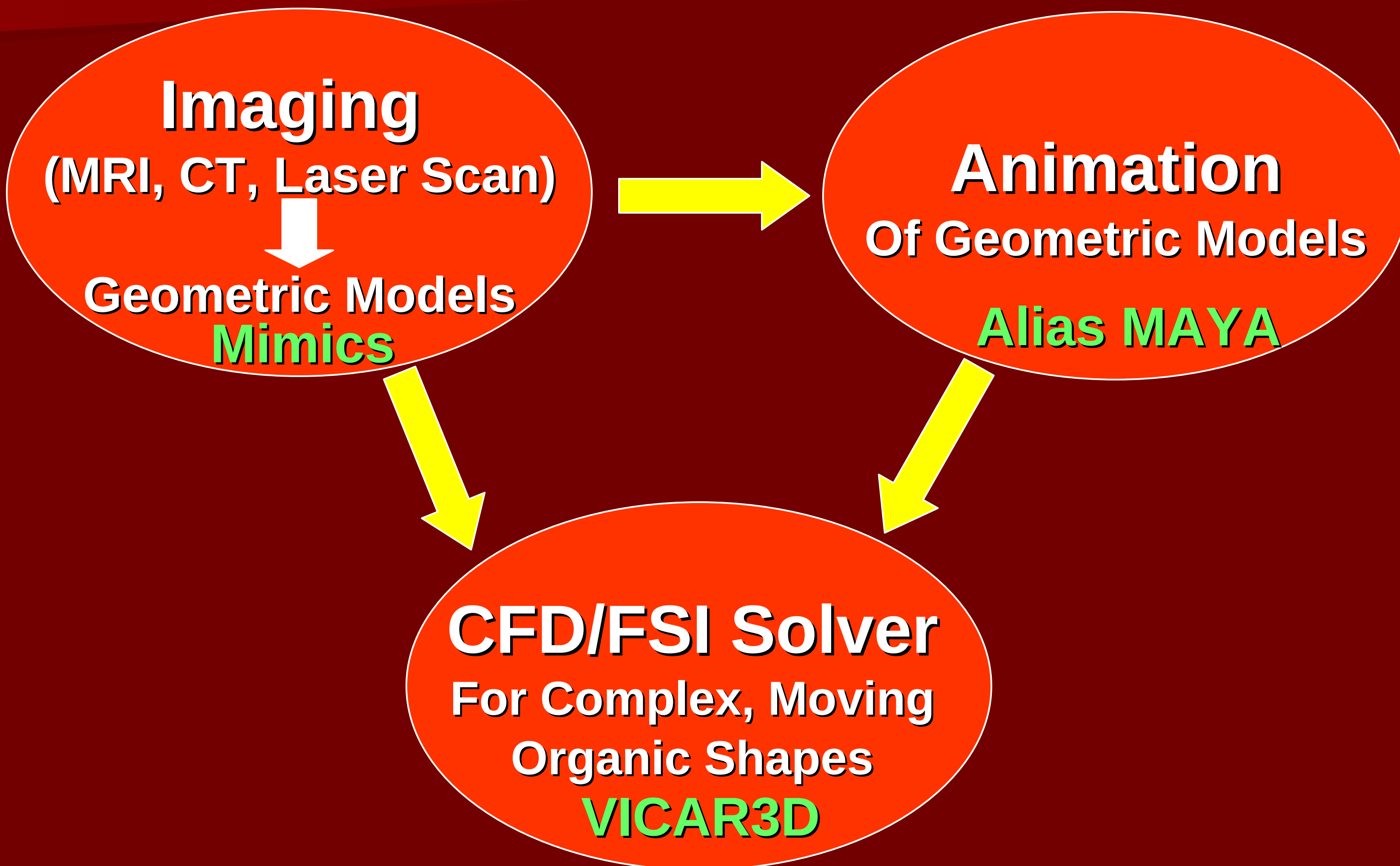
Rendering for CFD



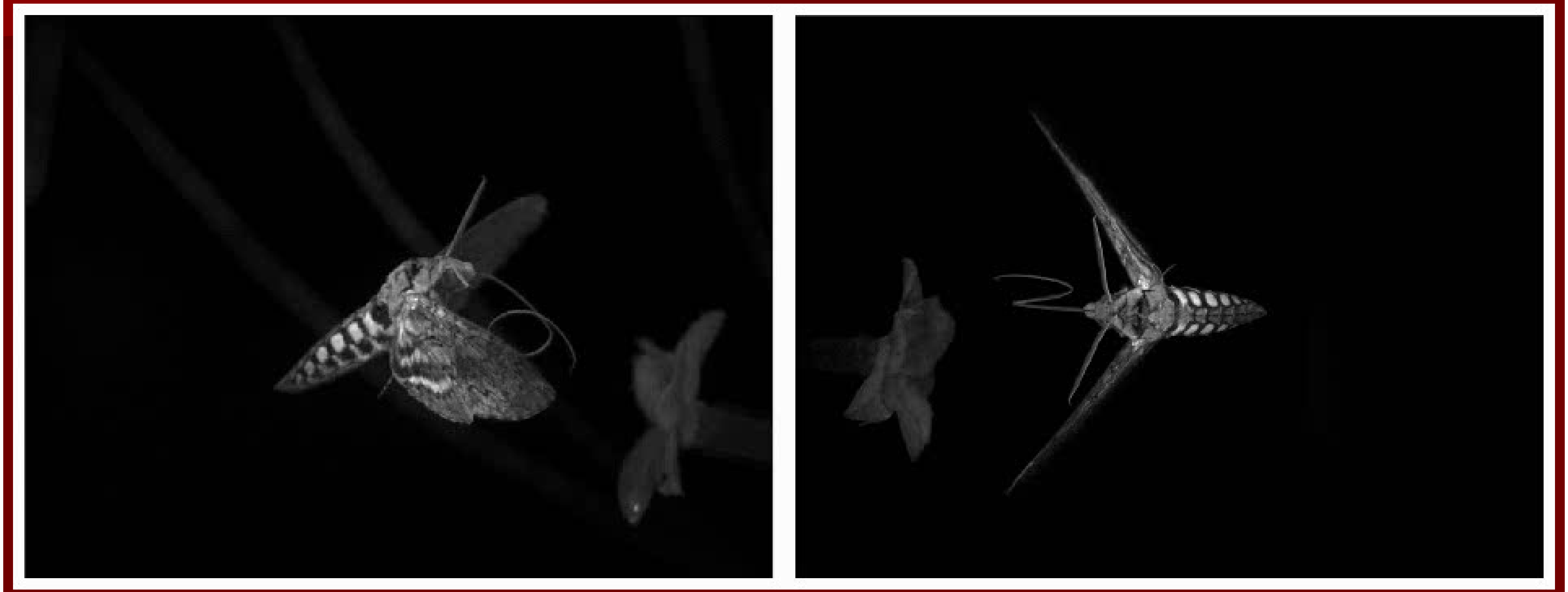

Body Acceleration

Painted Lady

# Closing the Loop for
# CFD in Biology/Biomedical Engineering

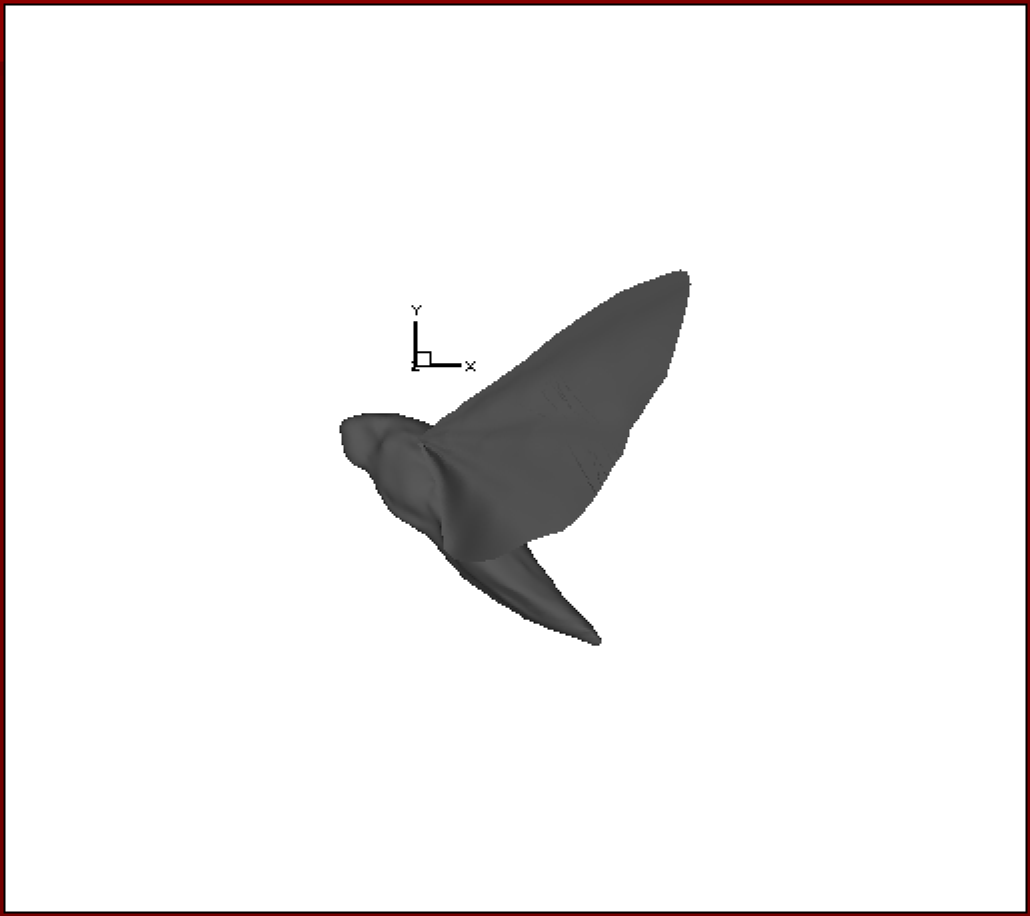


# Hawkmoth in Hover



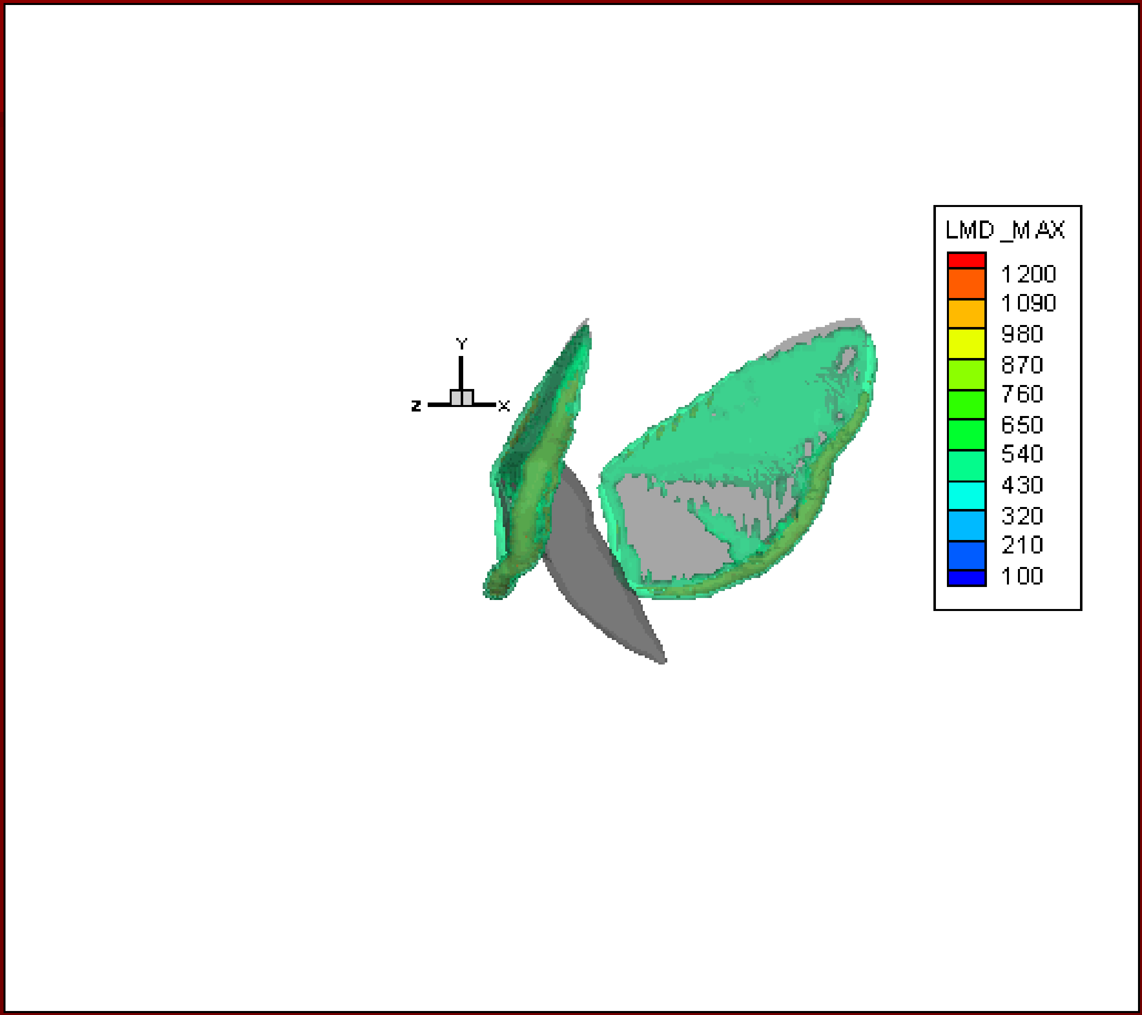
Hedrick Lab (UNC)

# Animated Model Rendered for CFD



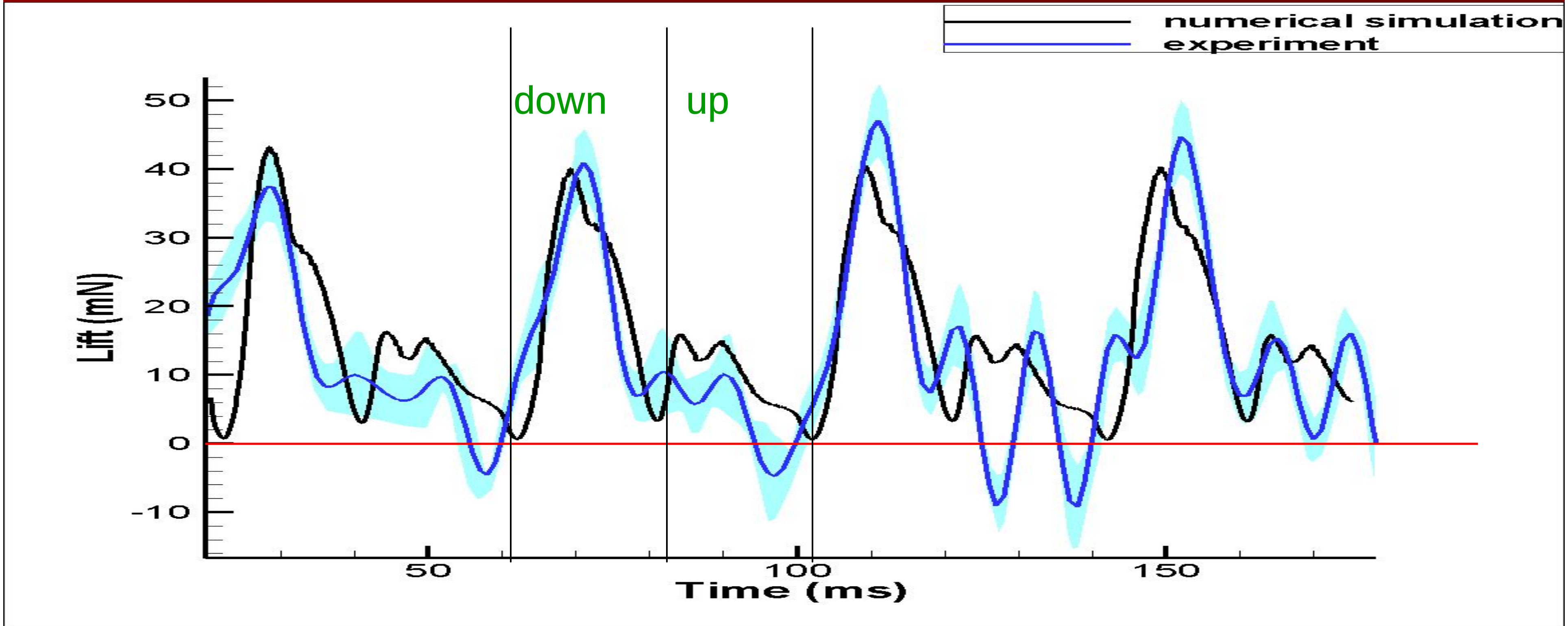

- Moth body based on high-res laser scan.
- Animation created in MAYA by matching high speed video.

# Vortex Dynamics




- Strong spiral LEV on downstroke.
- Vortex ring shed at the end of downstroke from each wing.
- Weak LEV on upstroke

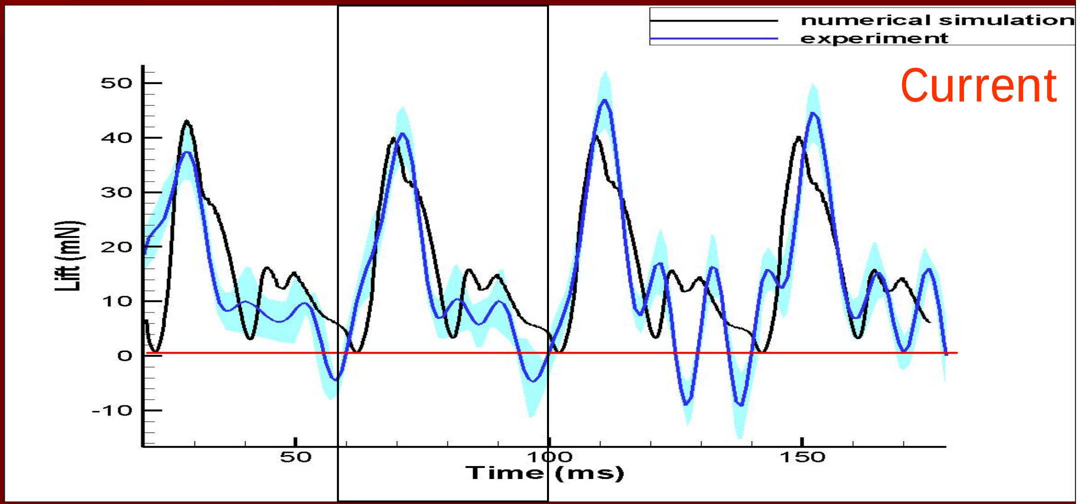
# Lift Prediction



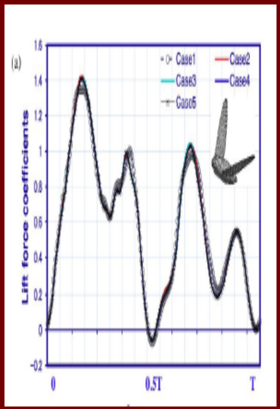

- Fairly good prediction of peak thrust during downstroke.
- Some mismatch during upstroke
  - Larger cycle-to-cycle variations in upstroke
- Interestingly, upstroke is found to be quite ineffective!

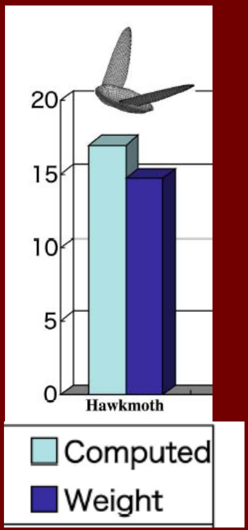
# Comparison with Past Models

- Liu et al (Chiba University)
- Hawkmoth in hover
- Rigid wings
- Kinematics based on Ellington's data.
- Average lift is comparable




- However simulations show significant lift generation during up (back) stroke.




Liu et al.

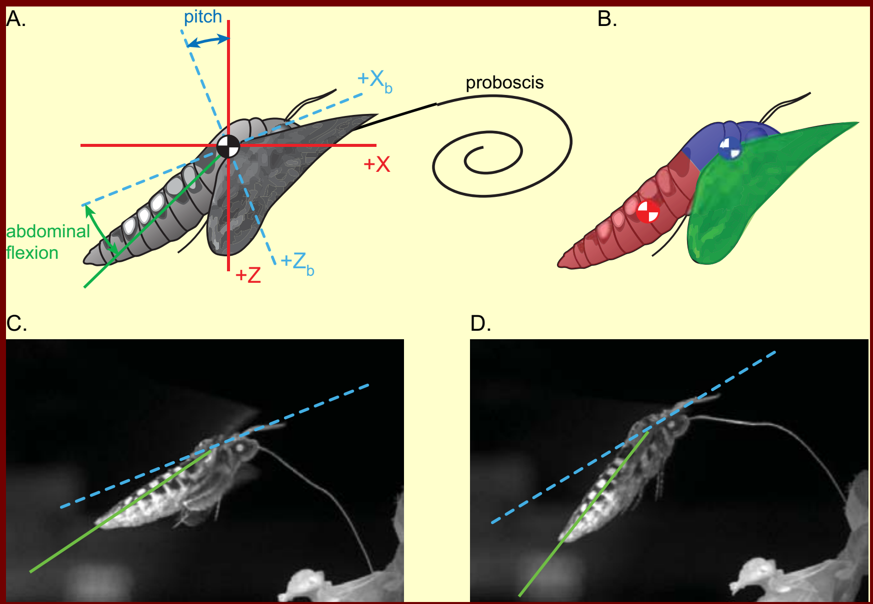
- Possibilities?
  - Discrepancy in kinematics
  - Rigid versus deformable?

# Insect Flight Stability in Unsteady Environments

- $$\left[I^{body}+I^{wing}\right]\{\dot{\omega}\}=\left\{r_{cp}^{wing}\right\}\times\left\{F^{wing}\right\}+\left\{r_{cp}^{body}\right\}\times\left\{F^{body}\right\}$$
$$-\left[\dot{I}^{body}+\dot{I}^{wing}\right]\{\omega\}$$

- Conventional View: Stabilization achieved by changes in $\left\{F^{wing}\right\}$

- Many large insects seem to also change
  - $\left[I^{wing}\right]$
  - $\left[I^{body}\right]$




- Role of $\left\{F^{body}\right\}$ ?

# How to study gust response in insects?

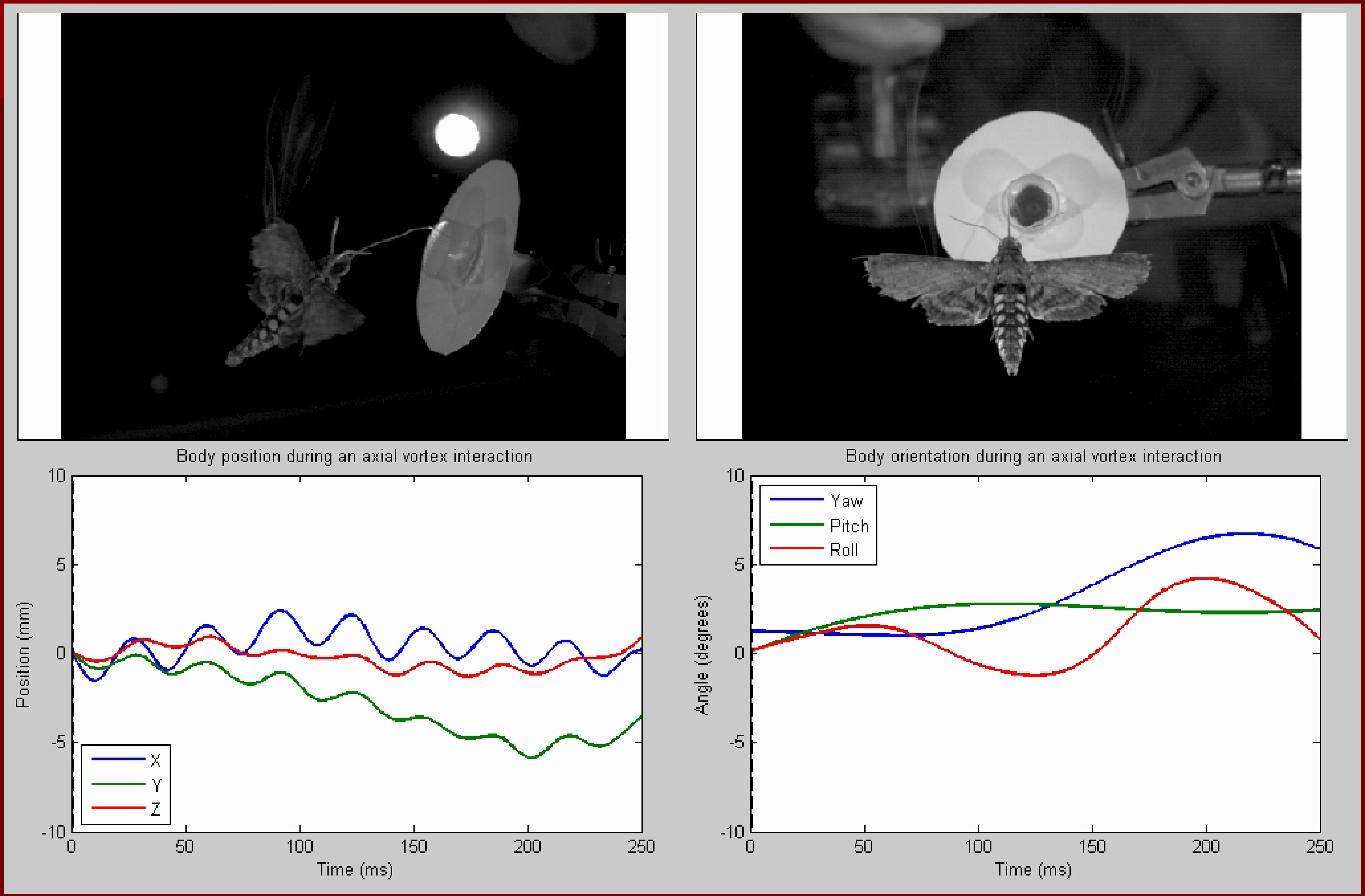
- Controlled experiments with freely flying insects are challenging!

- Need experimental assays that are
  - For untethered free flight
  - Predictable (to enable high-speed-rez videography)
  - Repeatable
  - Provide a variety of (and calibrated) gust perturbations.

# Approach

- Work with Hawkmoths (*Manduca Sexta*)
  - Large insect (~4” span)
  - Easy to culture/maintain.
  - Excellent hoverer.
  - Can be conditioned to approach and hover in front of nectar source.
- Hovering flight perturbed by incident vortex rings
  - Can control magnitude of impulse, energy and vorticity of the incident vortex ring.
    - Small/large/massive perturbation.
  - Control size of ring and location/orientation of impact
    - Pitch, roll, yaw moments can be generated.

# Vortex Ring Impingement: Low Impulse Impact



# High Impulse Impact

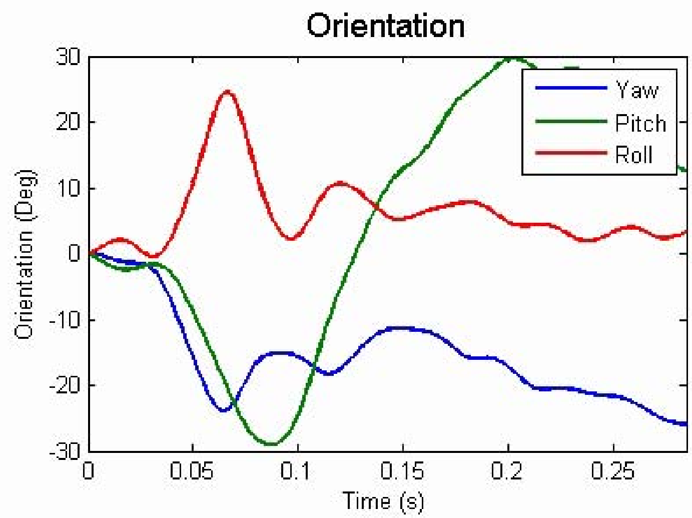
Axial

Lateral

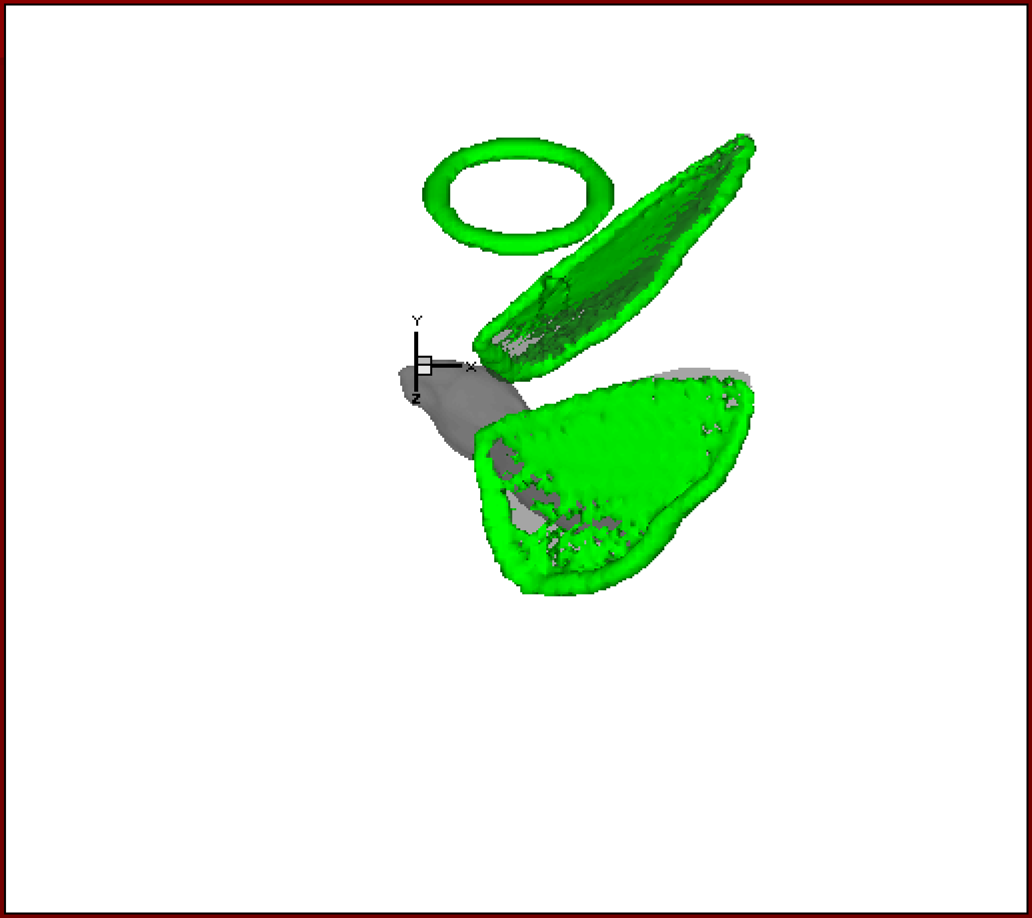
**Also track**

- **Head-thorax- abdomen**
- **Multiple points on wing**
- **Body / Wing CoM**

Overhead

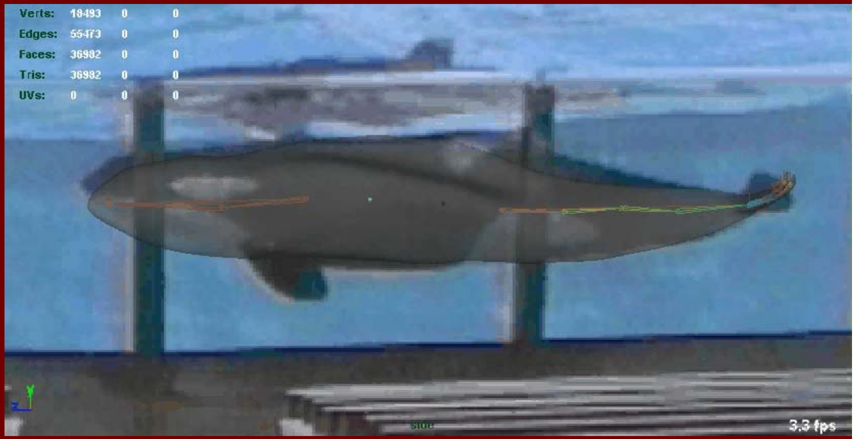


# Vortex Ring Impingement: CFD

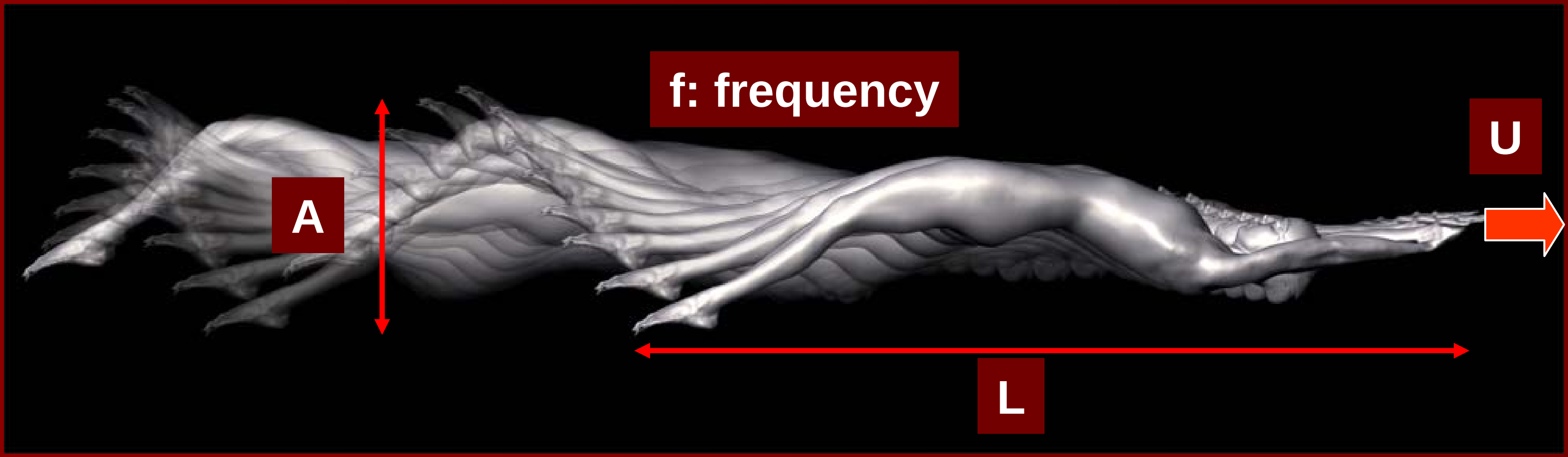


# Hydrodynamics of the Dolphin Kick

- Introduced in 1980, no regulation
- David Berkoff and Daichi Suzuki swim half the race using the dolphin kick, prompting FINA regulation
- Subsequently allowed for 15 meters after the start and every turn
- Undulatory wave travels down the length of the body, smallest amplitude at the fingertips, largest amplitude at the toes



# The Dolphin Kick: Key Parameters



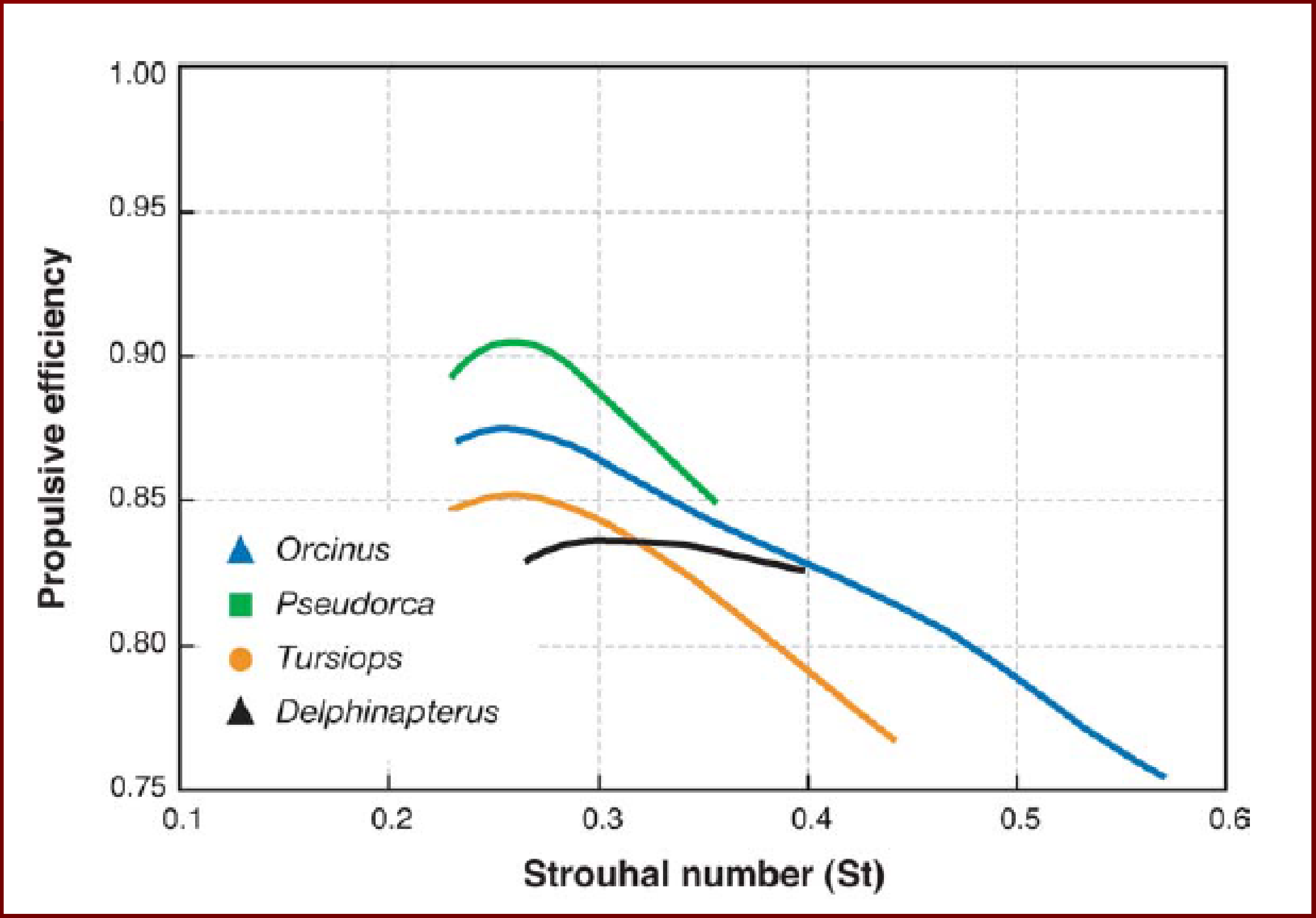

$$Re = \frac{LU}{\nu}; \quad St = \frac{f\ A}{U}; \quad \frac{A}{L}; \ slip : \frac{C}{U}$$

**Re: Reynolds number**
**St : Strouhal Number**

# Issues that we hoped to address:

- What is the mechanism of thrust production in the human dolphin kick?
  - No specific adaptation for swimming
  - Significant anatomical asymmetry → stroke asymmetry
  - What part of the body contribute thrust/drag etc
  - “active drag” versus passive drag
- How does thrust and power consumption scale with St and A/L
  - Optimality?
  - Wake vortex topology?
- Are certain “gaits” more effective than others?

# Optimal Strouhal Number in Mammals that Swim Using Dolphin Kick

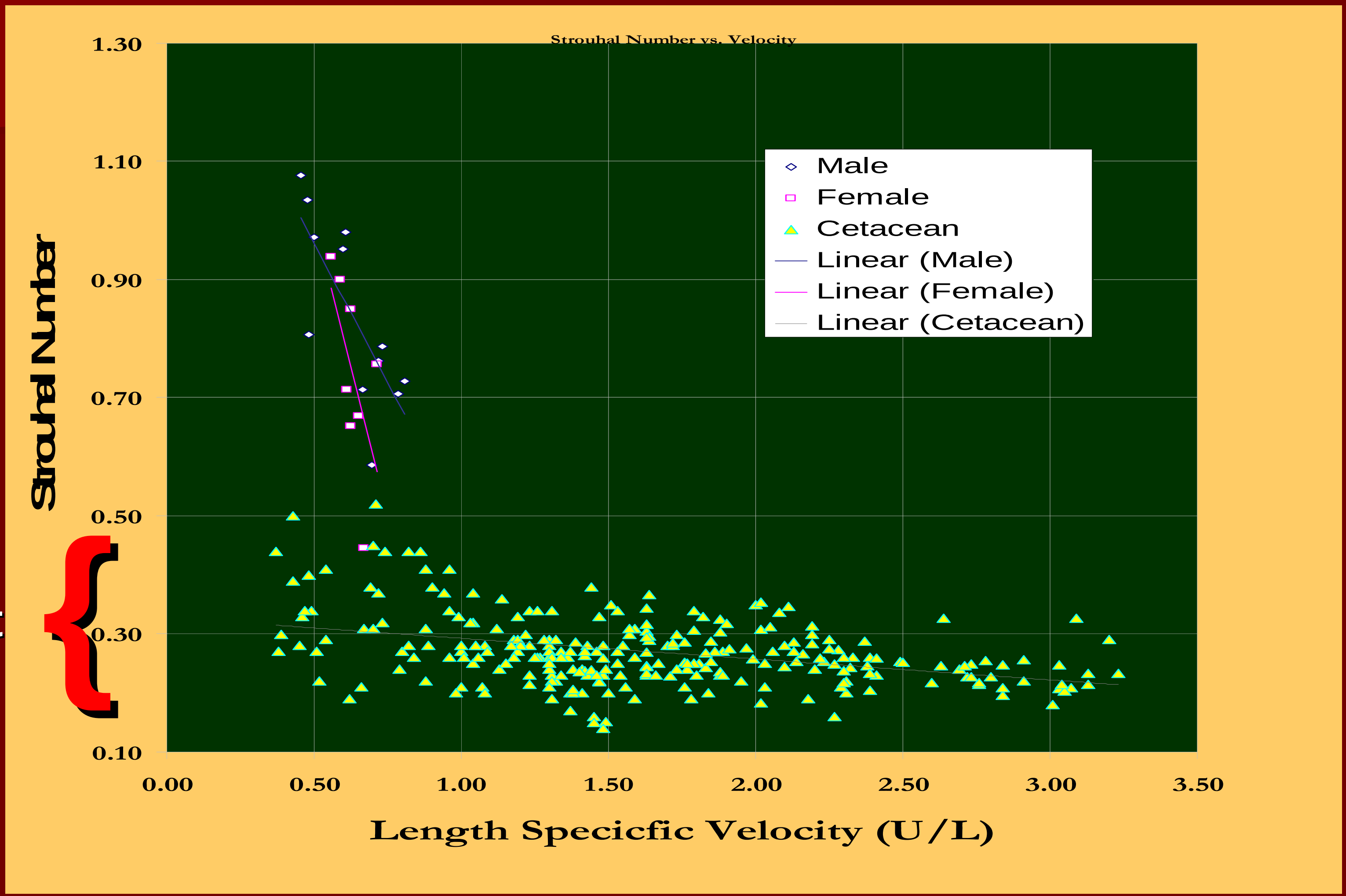



**Courtesy: Dr. Frank Fish**
**Westchester University**

# Olympic Swimmers Versus Dolphins?

$$St = \frac{f\ A}{U}$$

**Range for most efficient swimming**



# The CFD Process
## Laser Body Scan

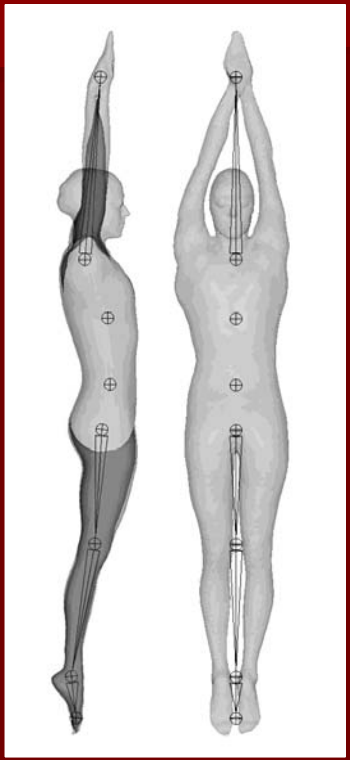
Lenny Krayzelburg

Gabrielle Rose

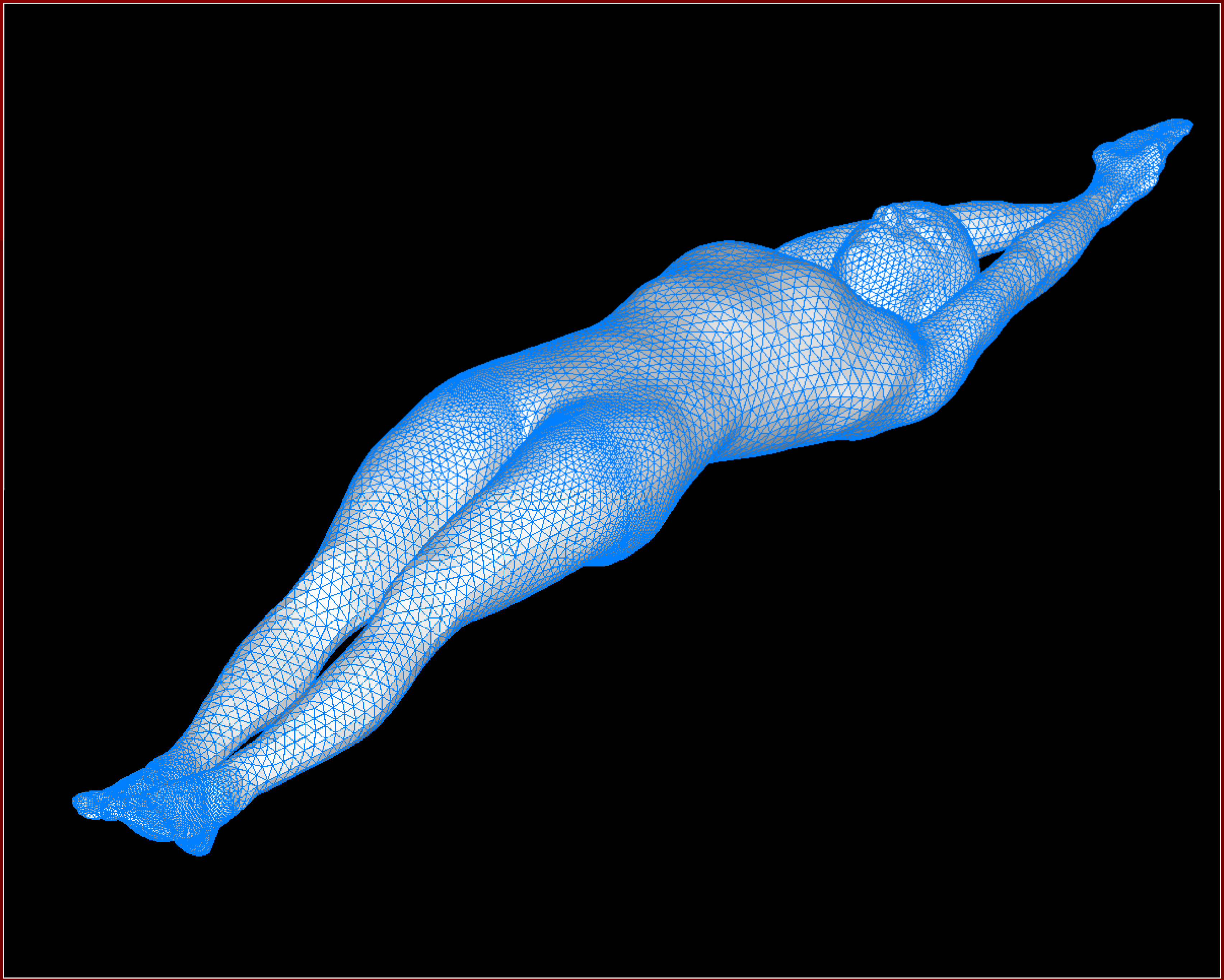
**Courtesy USA Swimming**

# Static Geometric Body Model

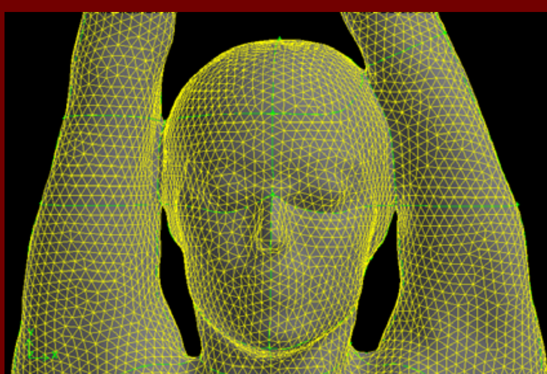
# Model Animation

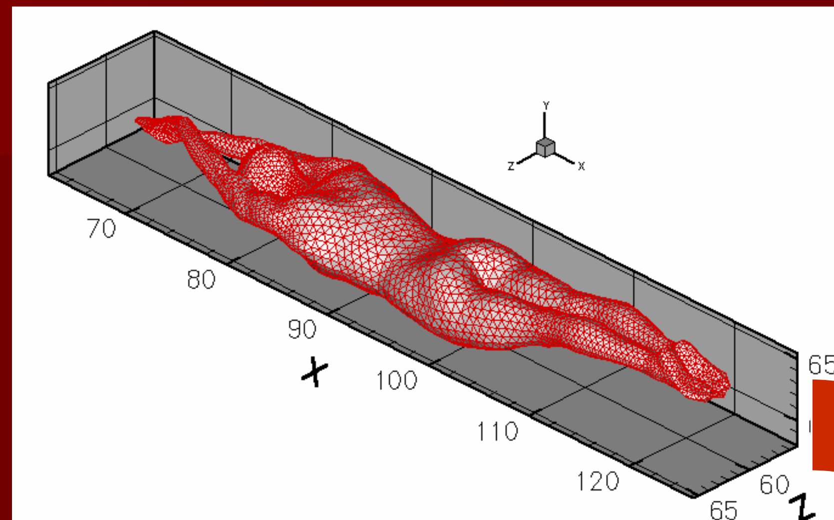


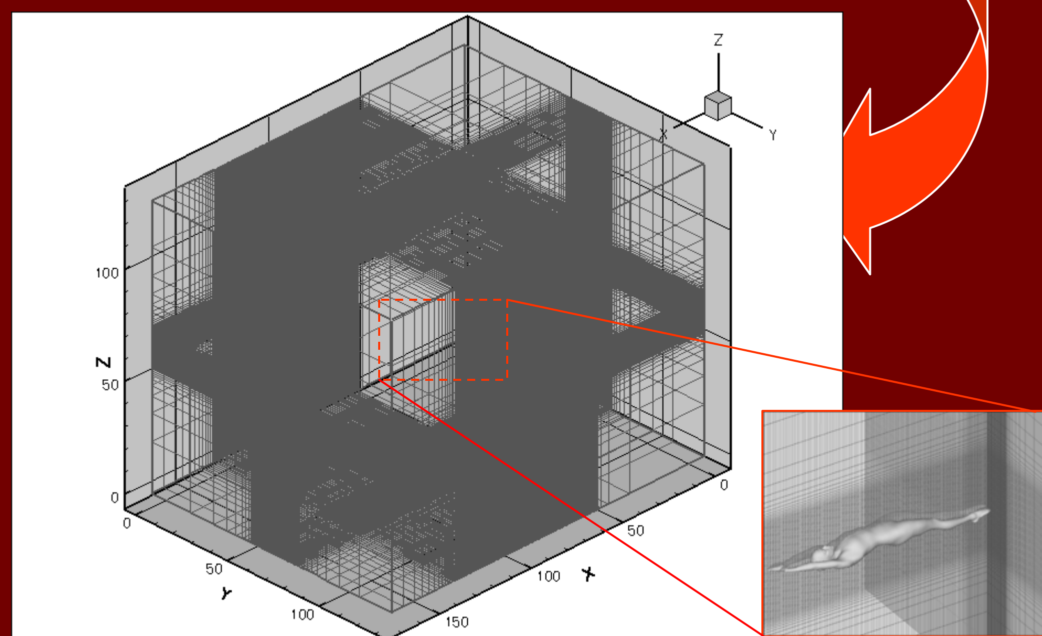
Typical Joint Structure



# Interface with CFD...
## ViCar3D

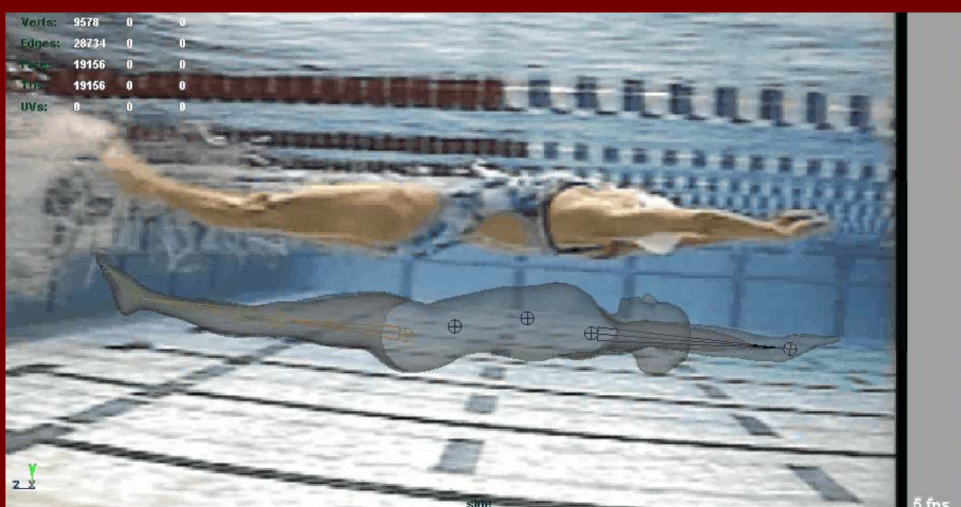


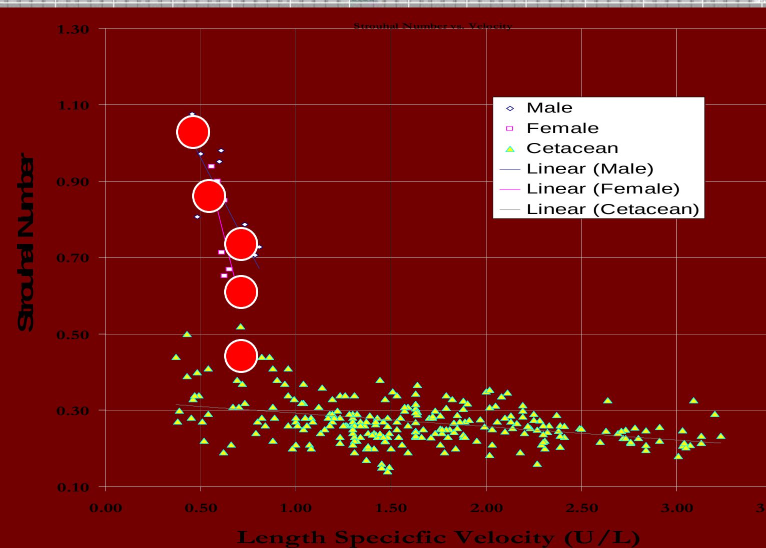


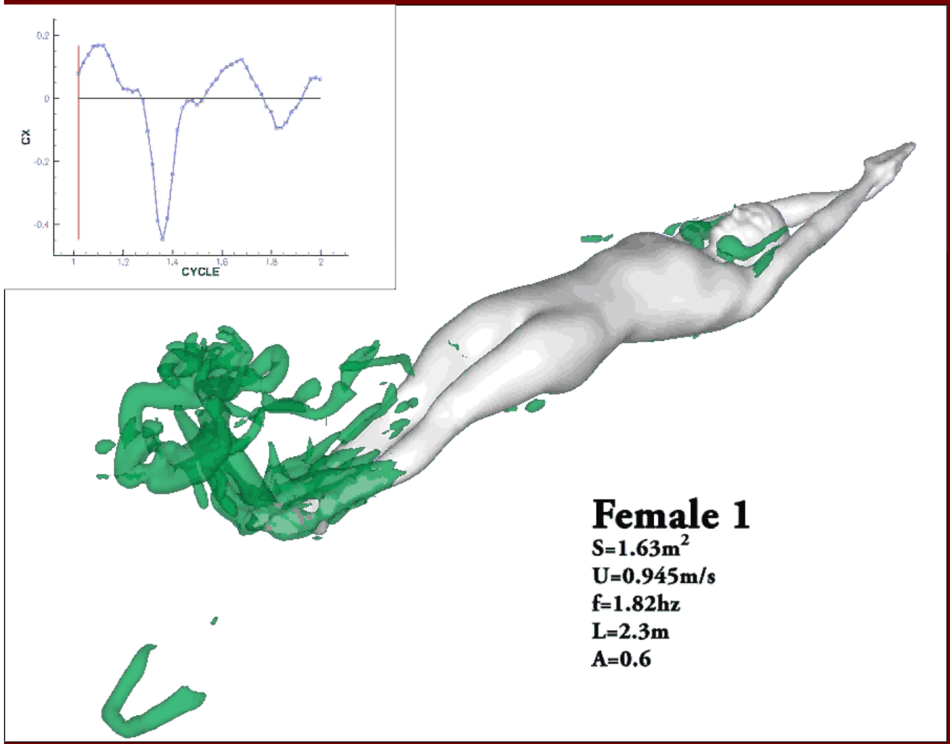
# Strokes Modeled

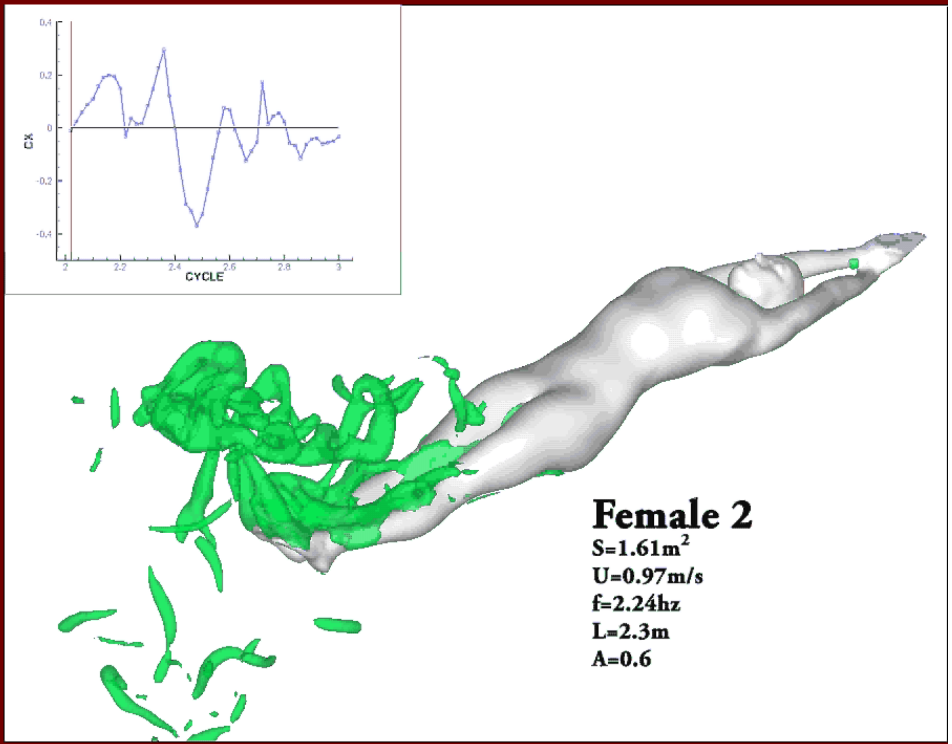




# Vortex Structures and Thrust - Dolphin Kick

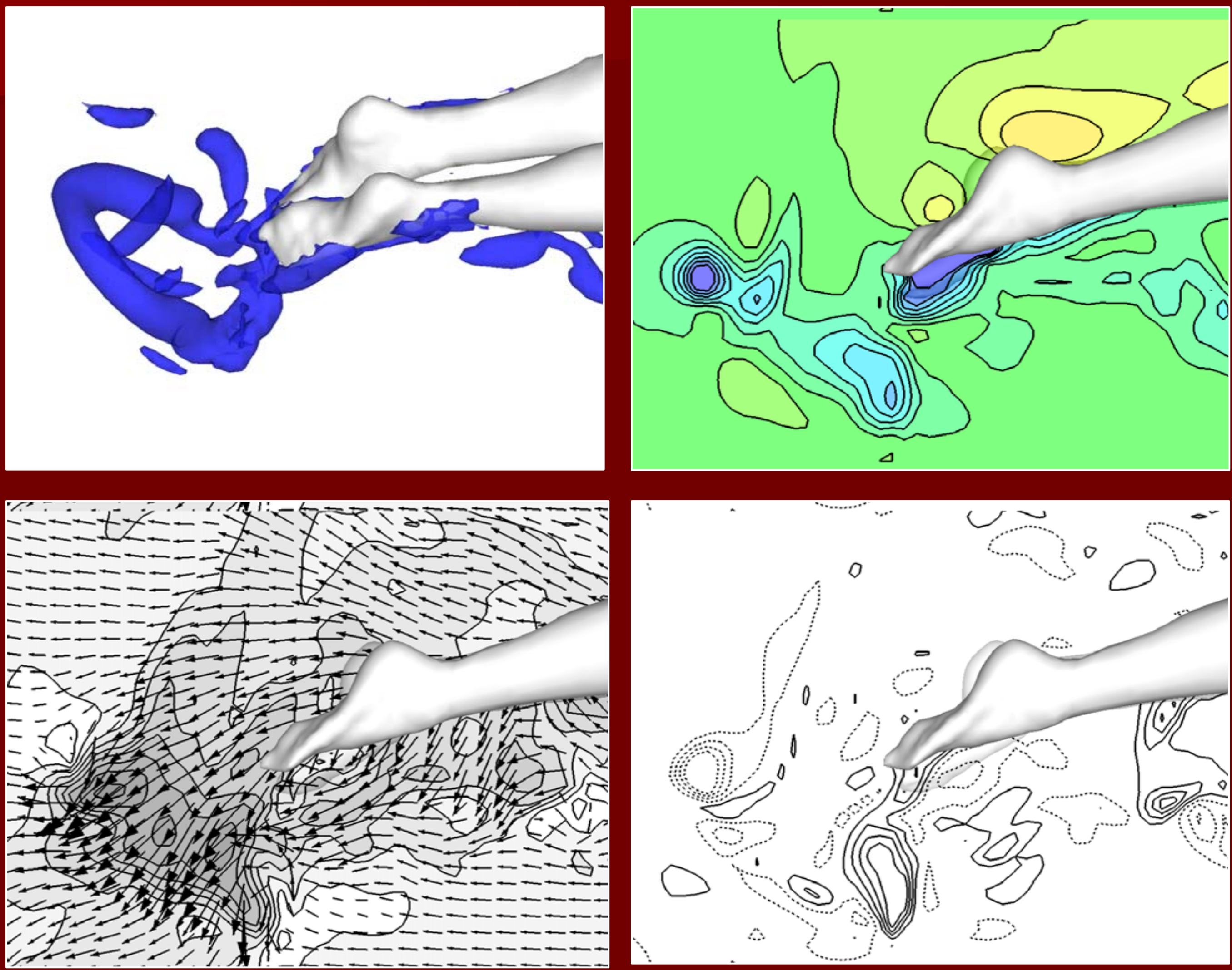


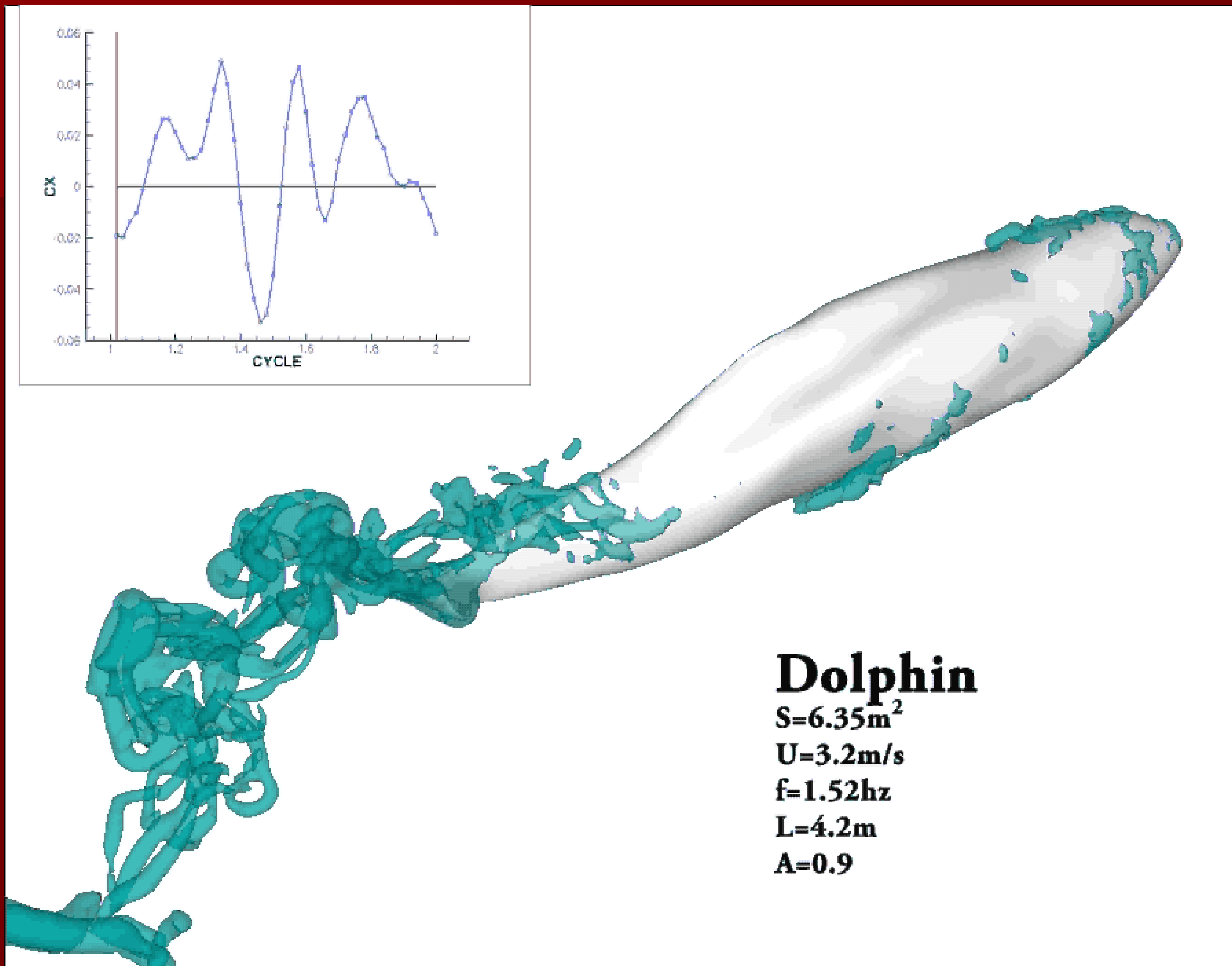

Slow kick

Fast kick

# Vortex Ring Formation

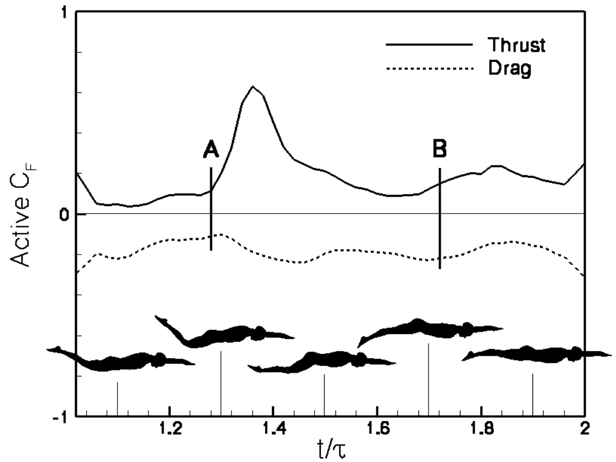


# The Ultimate Olympic Swimmer !

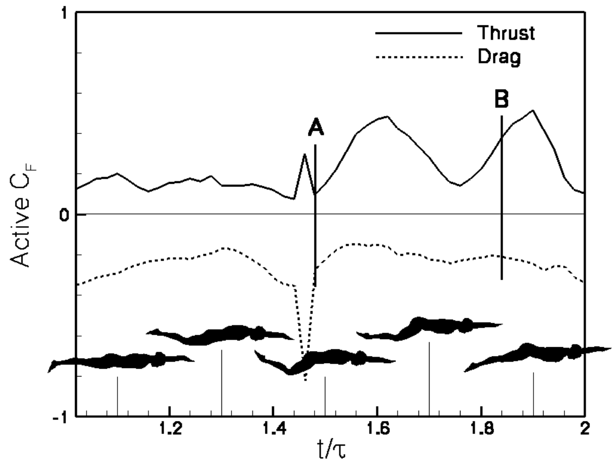


# Active Drag and Thrust

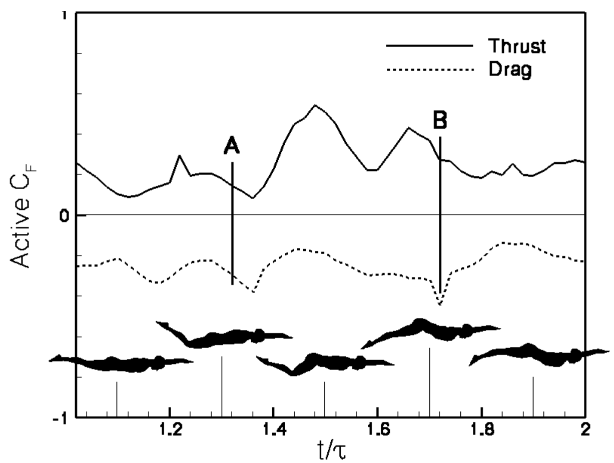
Female 1



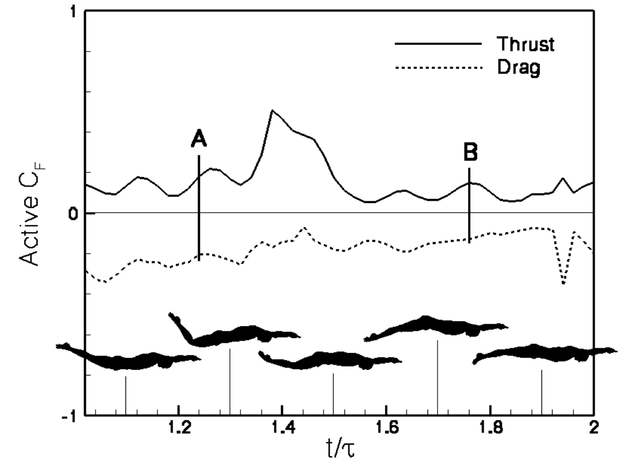

Female 2



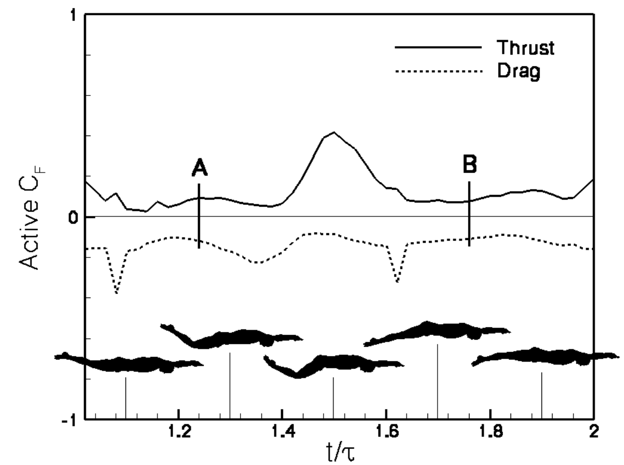

Female 3




Male 1




Male 2



# Work, Power & Efficiency

Froude Propulsive Efficiency

$$\eta = \frac{W_{Useful}}{W_{Total}}$$

Ideal Froude Efficiency
(Lighthill Slender Body Theory)

$$\eta_F = \frac{c + U_\infty}{2c}$$

Actual Froude Efficiency

$$\eta = \frac{\int_0^\tau \sum_{n_{Usefull}} T_n (U_{nX} - U_\infty) dt}{\int_0^\tau \sum_n \vec{F}_n \cdot (\vec{U}_n - \vec{U}_\infty) dt}$$

# Work, Power & Efficiency

| | Mean Useful Power [Watts] | Mean Total Power [Watts] | Useful Work [J] | Total Work [J] |
|---|---|---|---|---|
| Female 1 | 42.5 | 290.4 | 23.4 | 159.7 |
| Female 2 | 85.1 | 289.8 | 32.1 | 109.3 |
| Female 3 | 77.6 | 416.3 | 34.9 | 187.4 |
| Male 1 | 71.8 | 639.0 | 37.3 | 332.3 |
| Male 2 | 141.7 | 482.7 | 59.9 | 204.2 |
| Cetacean | 1912.7 | 3426.4 | 1262.4 | 2261.4 |

| | Actual Efficiency $\eta$ [%] | Ideal Efficiency $\eta_F$ [%] |
|---|---|---|
| Female 1 | 14.6 | 62.2 |
| Female 2 | 29.4 | 59.9 |
| Female 3 | 18.7 | 60.9 |
| Male 1 | 11.2 | 70.5 |
| Male 2 | 29.4 | 62.9 |
| Cetacean | 55.8 | 75.3 |

# What have we learnt?

- Propulsive efficiency of dolphin kick in humans varies from about 10-30% .  (>55% for dolphins).
- Human dolphin kick constrained by anatomy
  - Small "fluke"
  - Discrete joints that preclude smooth wave (active drag)
  - Anterior-posterior asymmetry (up and down stroke)
- Almost all the thrust comes from foot (beyond ankle)
- Down stroke produces most of the thrust
- Upstroke effectiveness can be improved by increasing ankle flexibility
  - "Floppy" ankles are the best for the dolphin kick

# Biophysics of Phonation

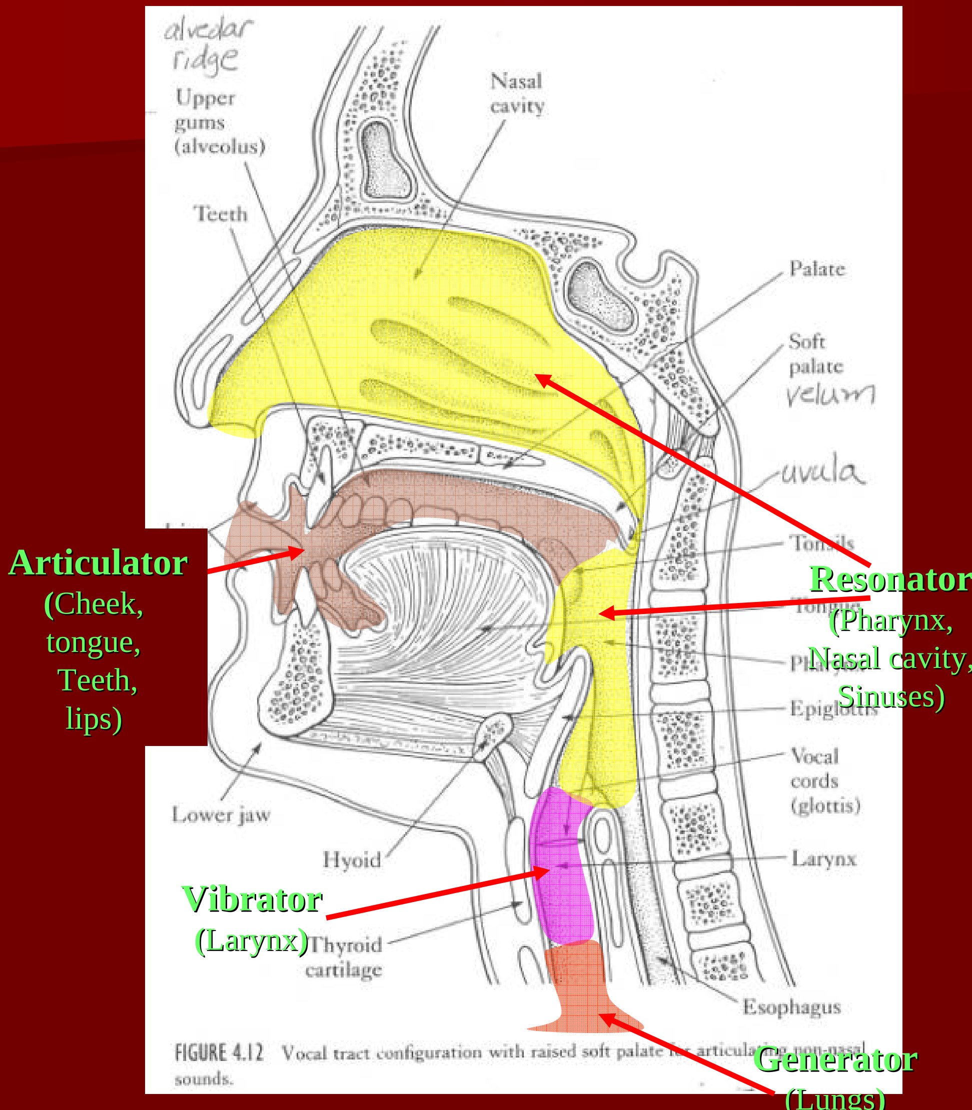
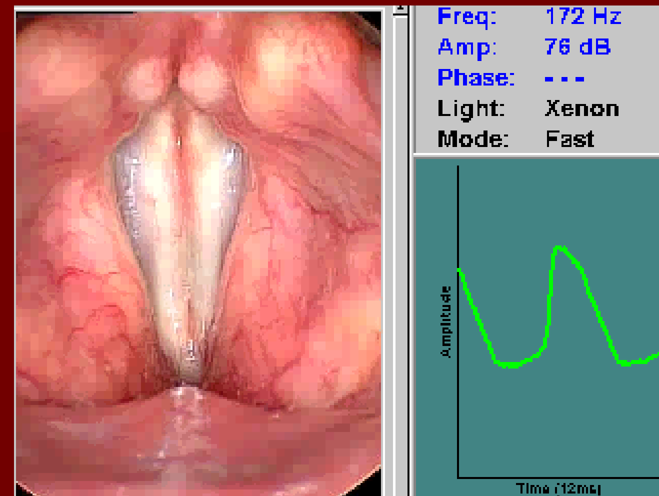


FIGURE 4.12 Vocal tract configuration with raised soft palate for articulating non-nasal sounds.

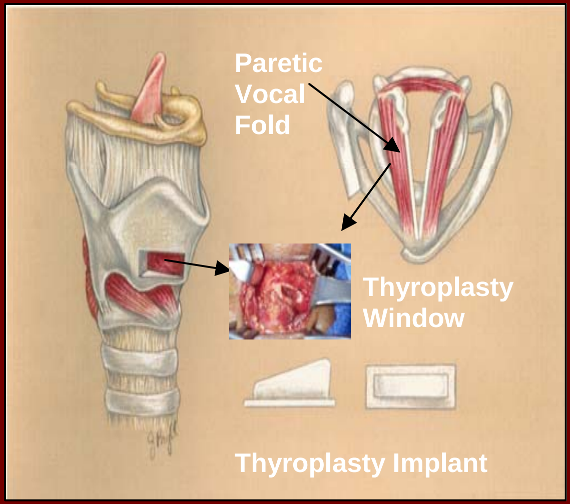


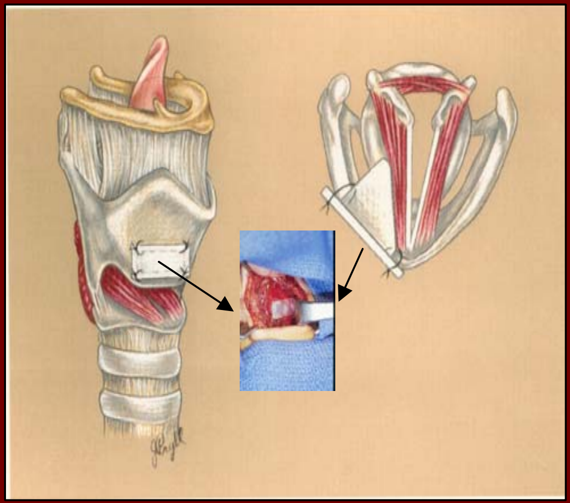

- NIH R01 grant focused on flow-structural interaction in larynx
- Understand the FSI mechanisms
- Apply knowledge to enhance laryngeal surgical procedures.

# Medialization Laryngoplasty

- **Surgical procedure of choice for unilateral VF paralysis**
  - Cord injection
  - Synthetic implant inserted to medialize paretic VF
- **Surgical outcome highly sensitive to implant shape and placement**
  - **Requires mm level precision**
  - **Intra-operative trial-and-error procedure**
- **Relatively high revision rate for this surgery in the USA.**
- **Surgeons have no means of predicting the effects of the implant on the vibratory characteristics of the paralyzed vocal fold**

**Can a surgical planning tool based on a computational biomechanical model of the larynx improve the surgical outcome ??**



**Current Thyroplasty Procedure**

# Structural Dynamics of VF

- Governing equations

$$\frac{\partial \sigma_{ij}}{\partial x_j} + b_i = \rho \frac{\partial v_i}{\partial t} = \rho \frac{\partial^2 u_i}{\partial t^2}$$

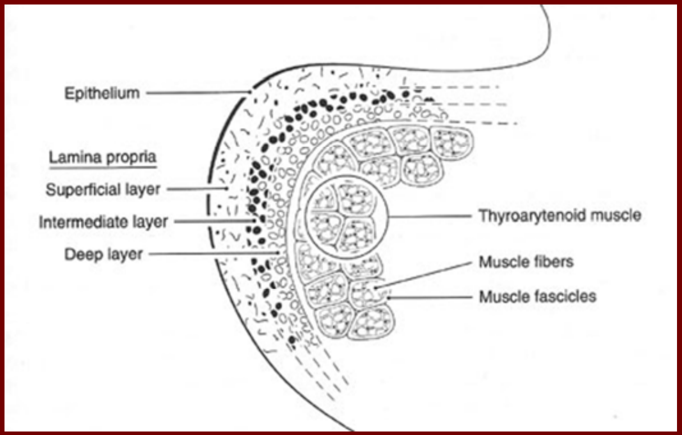
$$\sigma_{ij} = C_{ijmn} e_{mn}$$

$$u_i = u_{b_i} \qquad \sigma_{ij} n_j = T_i$$

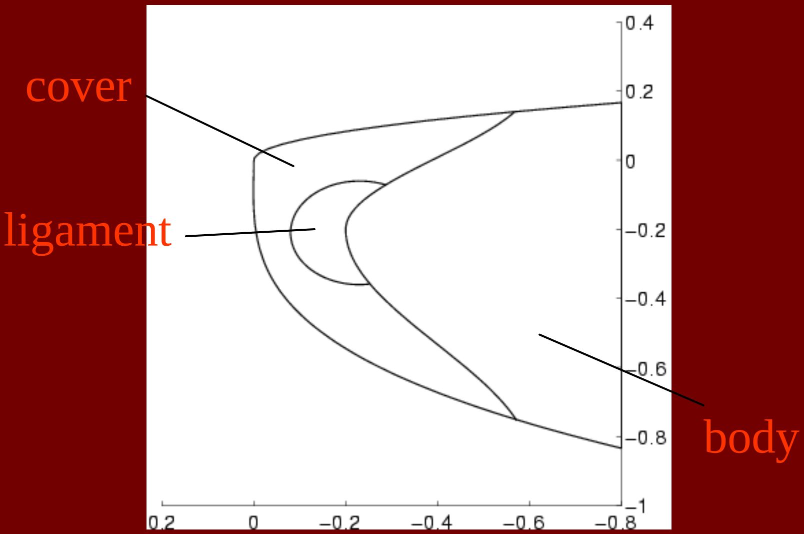
•The tissue materials are assumed to be transversely isotropic.

•Material properties are obtained from experiments (e.g., Titze *et al* 2000).

•Multi-property, non-homogeneous structure

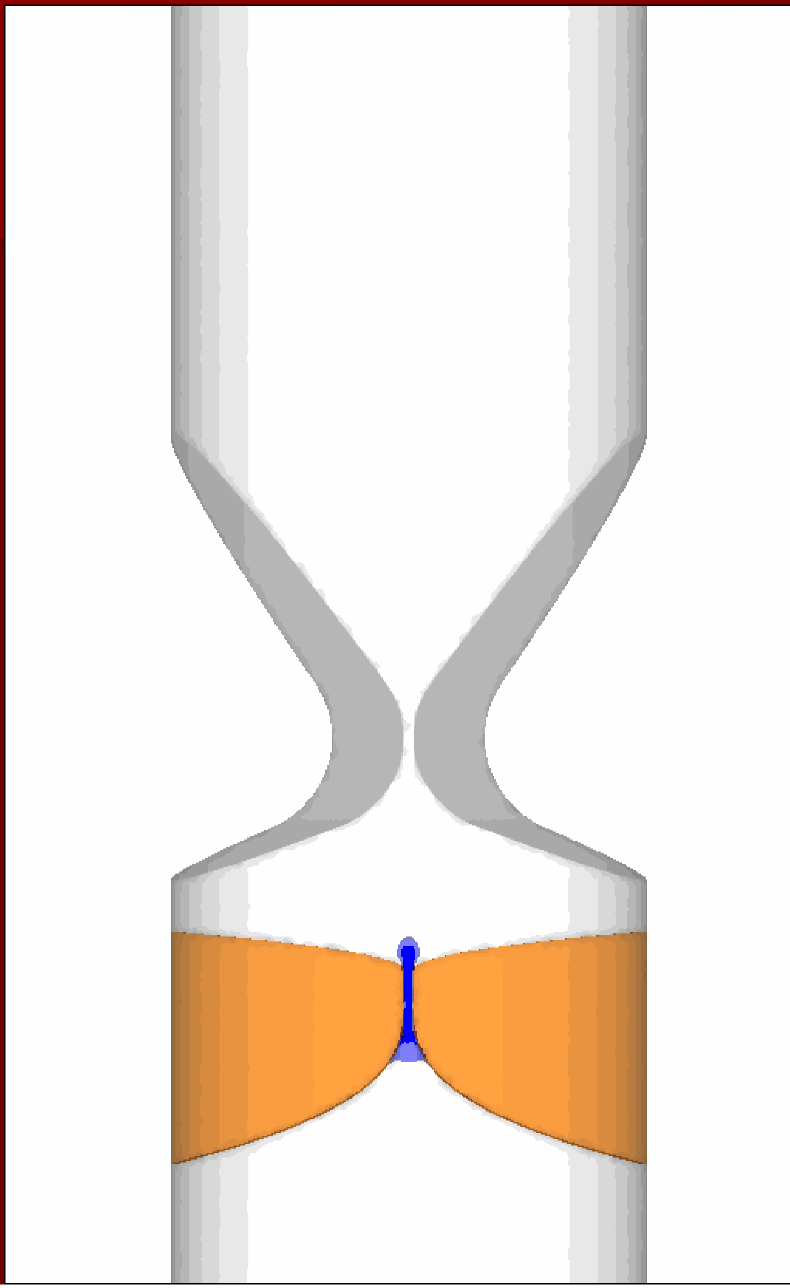


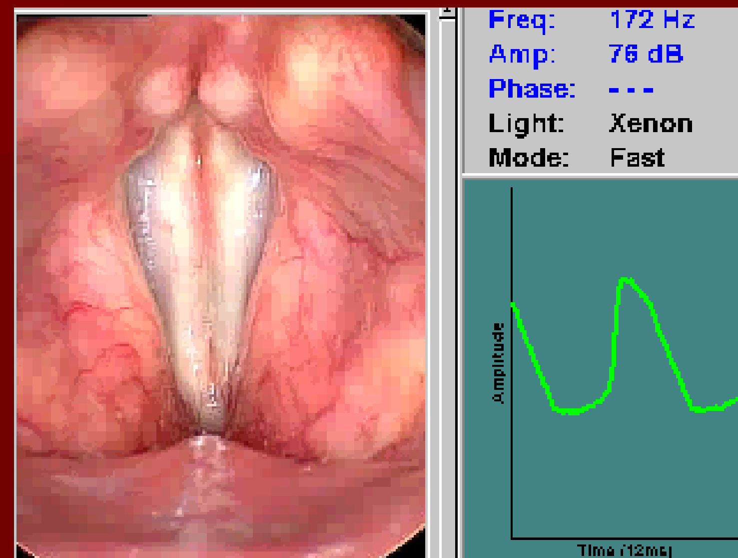

Schematic showing VF substructure

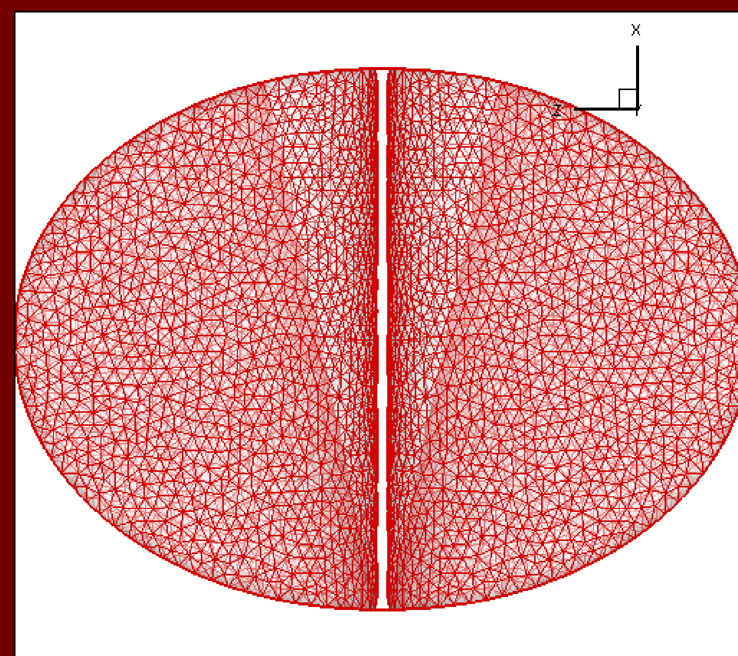



Model assumed in current study

# 3D Vocal Fold Model

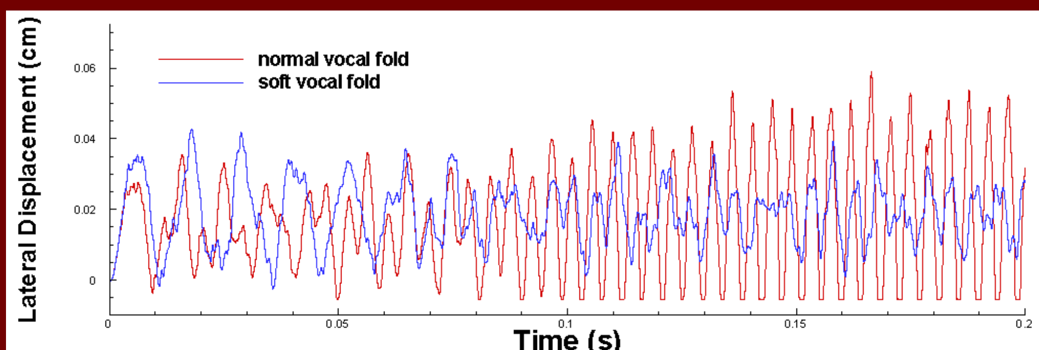


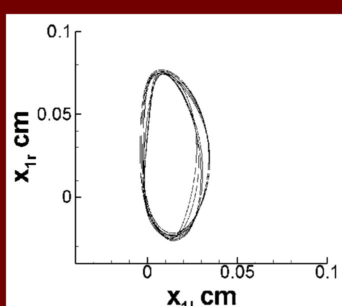


# Effects of Tension Imbalance on Phonation

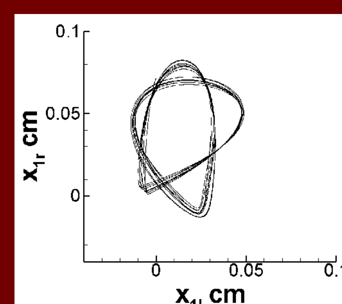
- Smaller VF vibration amplitude
- Lack of full glottal closure leads to leakage flow
  - "Breathy" voice
- Multiple incommensurate frequencies
  - Chaotic vibration

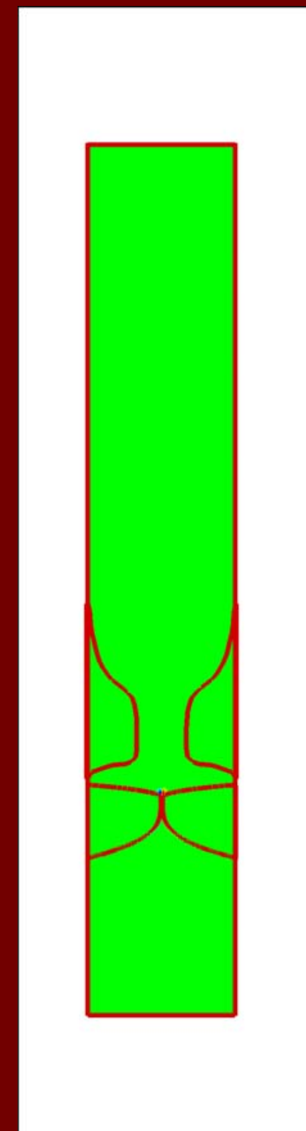


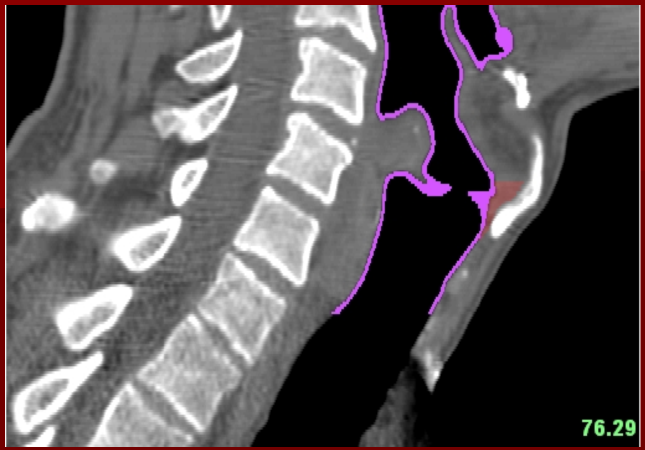

**Period Doubling**

**Bifurcation**

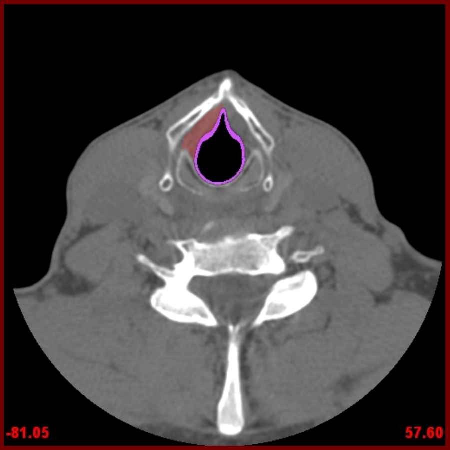


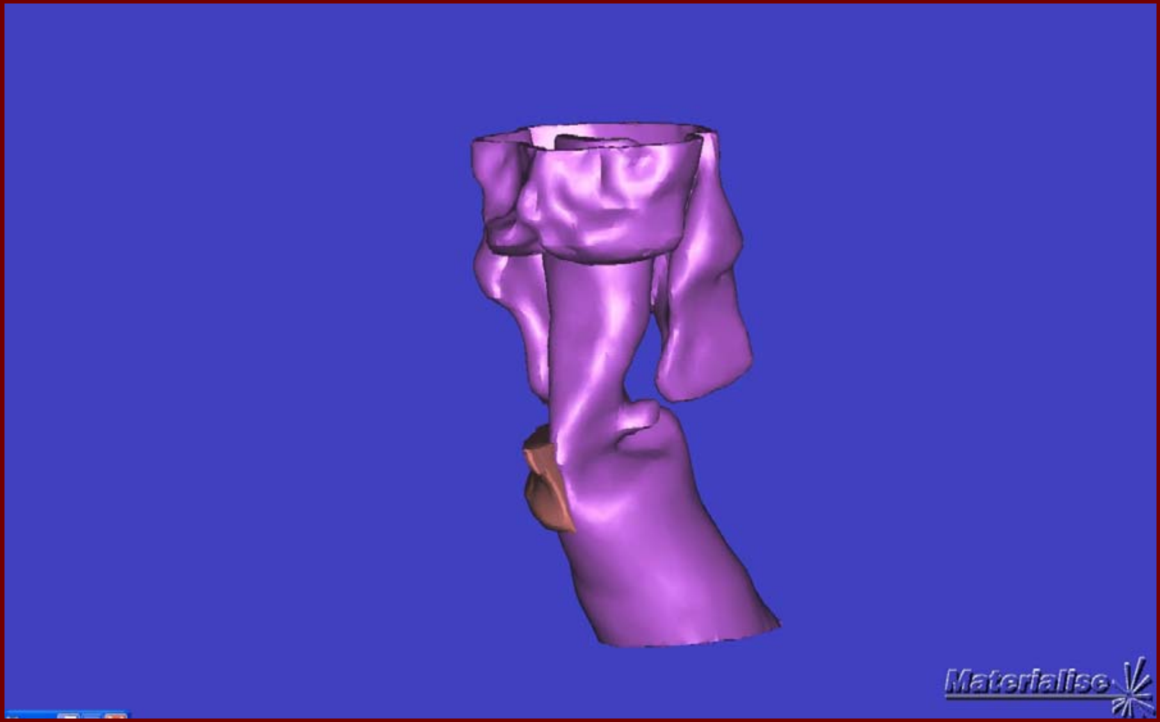
# Towards Patient-Specific Models



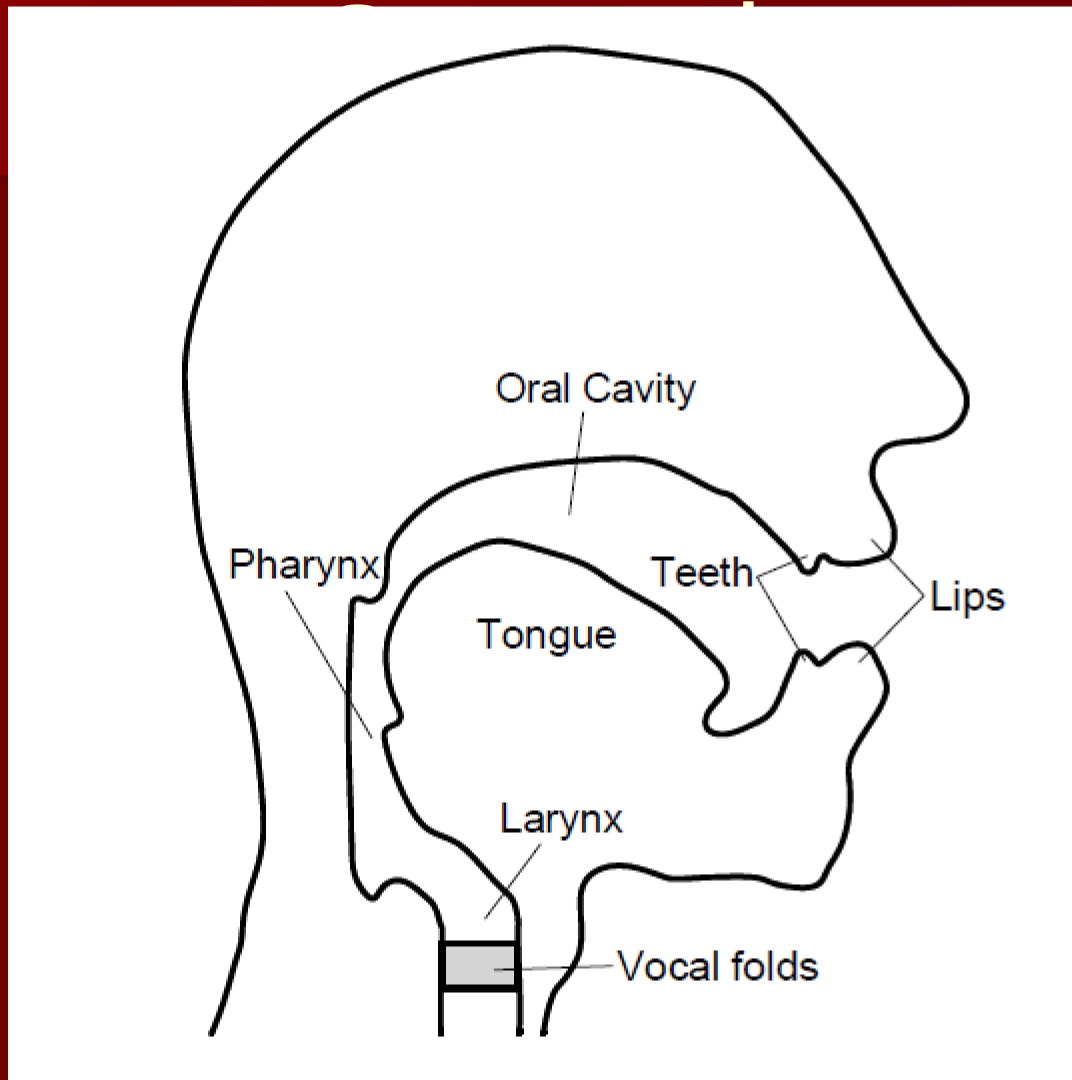

Sagittal View



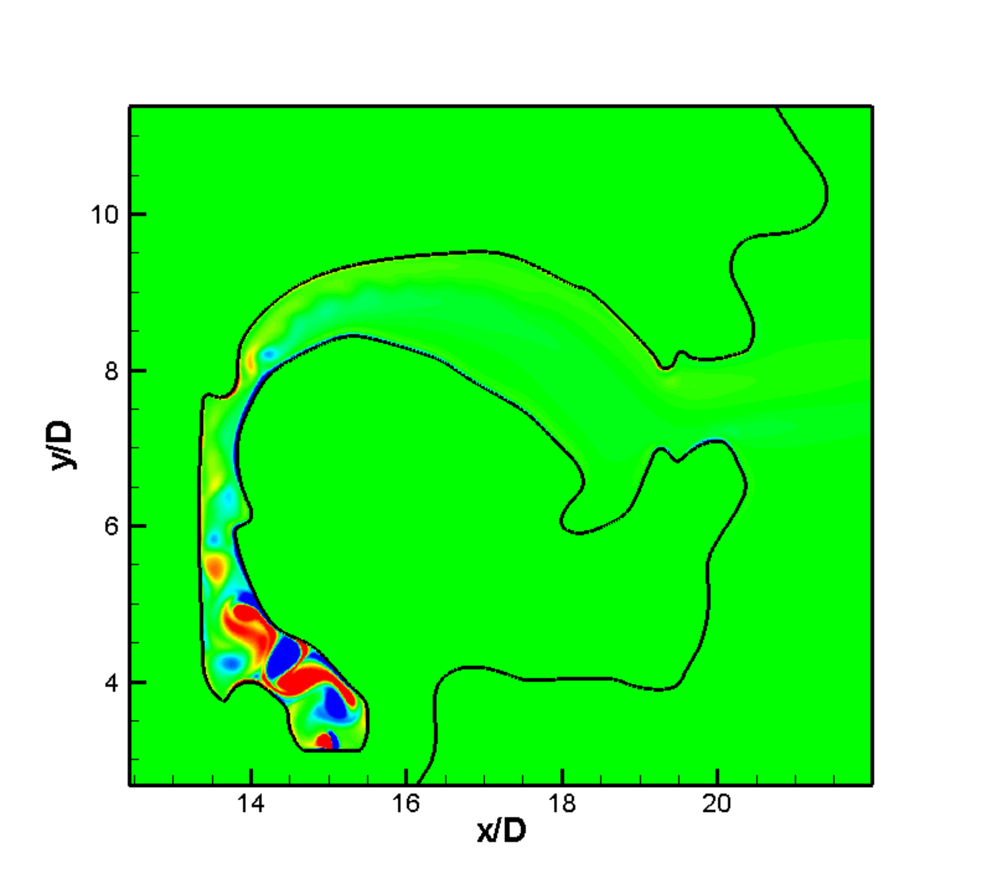

Axial View



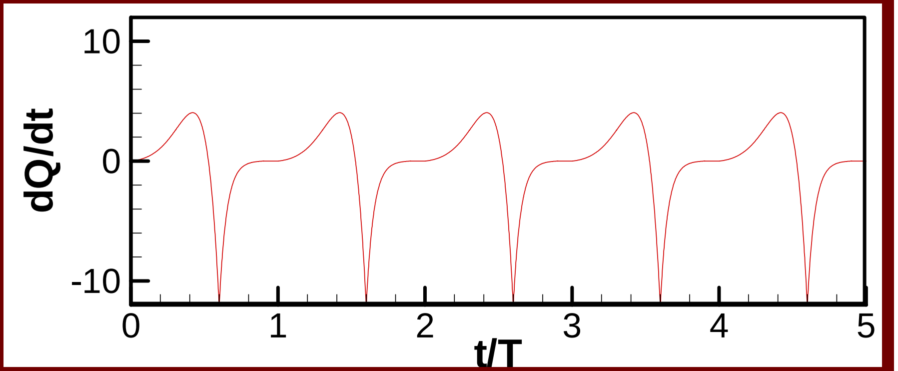
# Computation of Voiced Sound



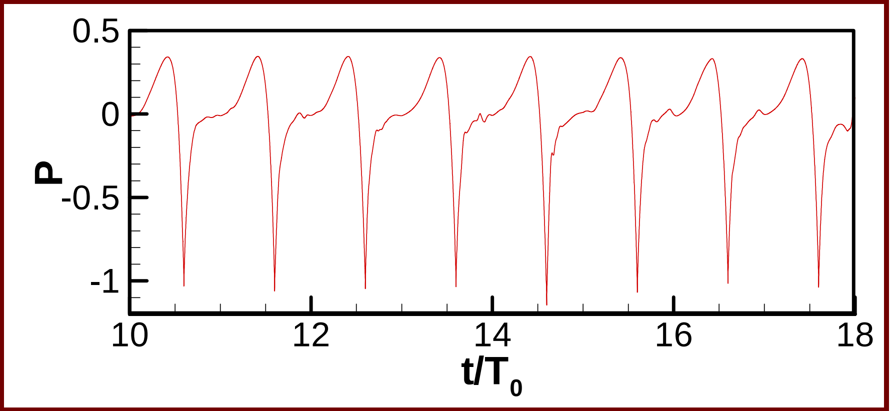
# Flow field in Vocal tract




**Time derivative of glottal flow rate**

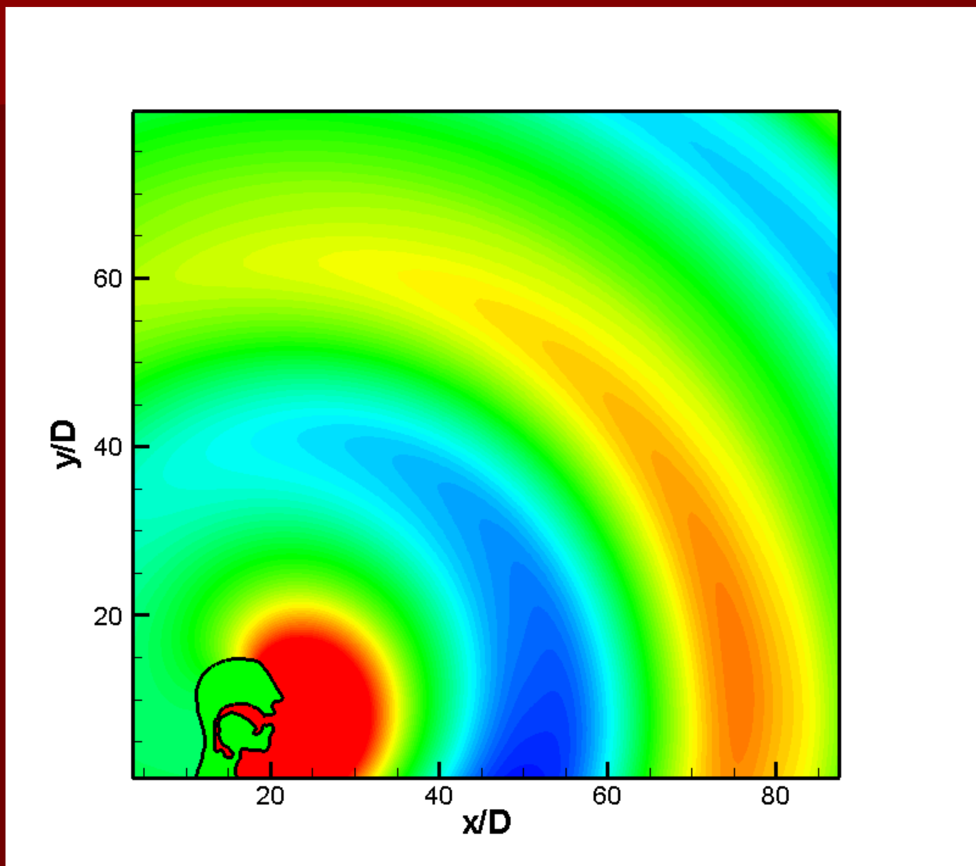


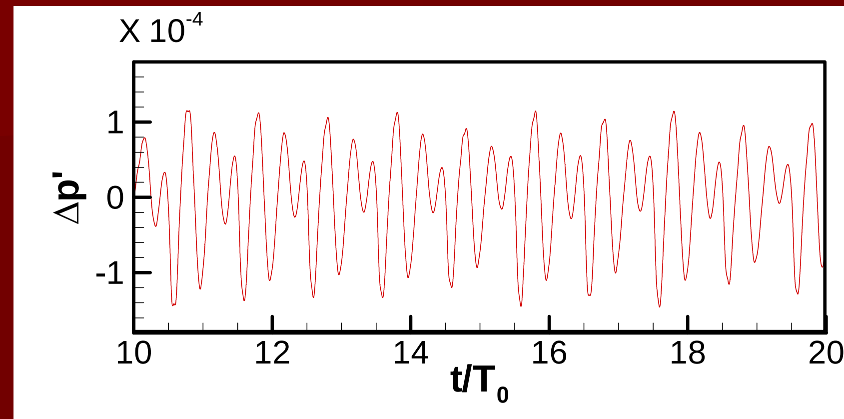

**Hydrodynamic pressure near the vocal tract inlet**

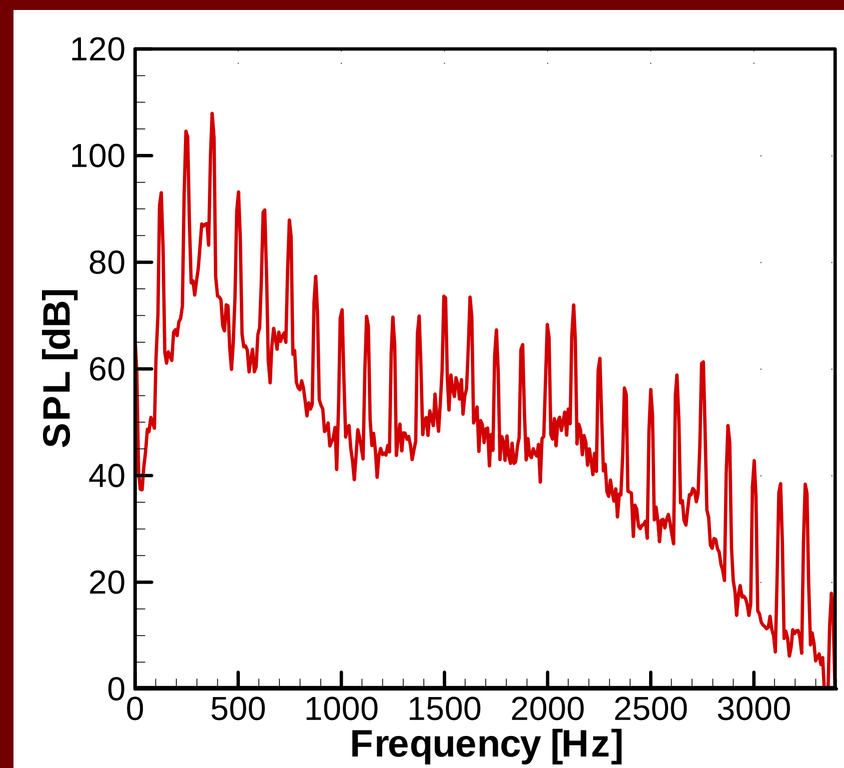


# Acoustic field

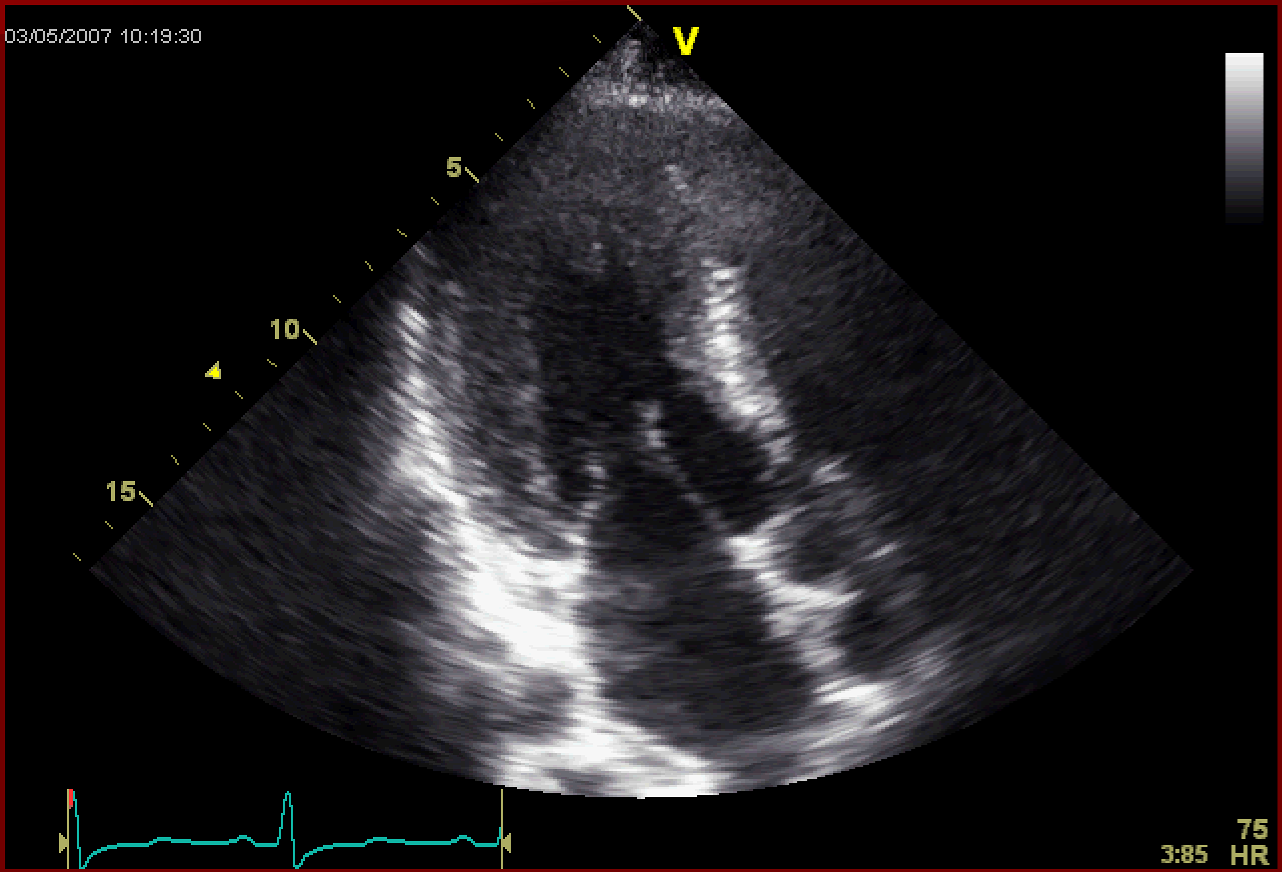
**Acoustic pressure at 60 cm from the mouth**



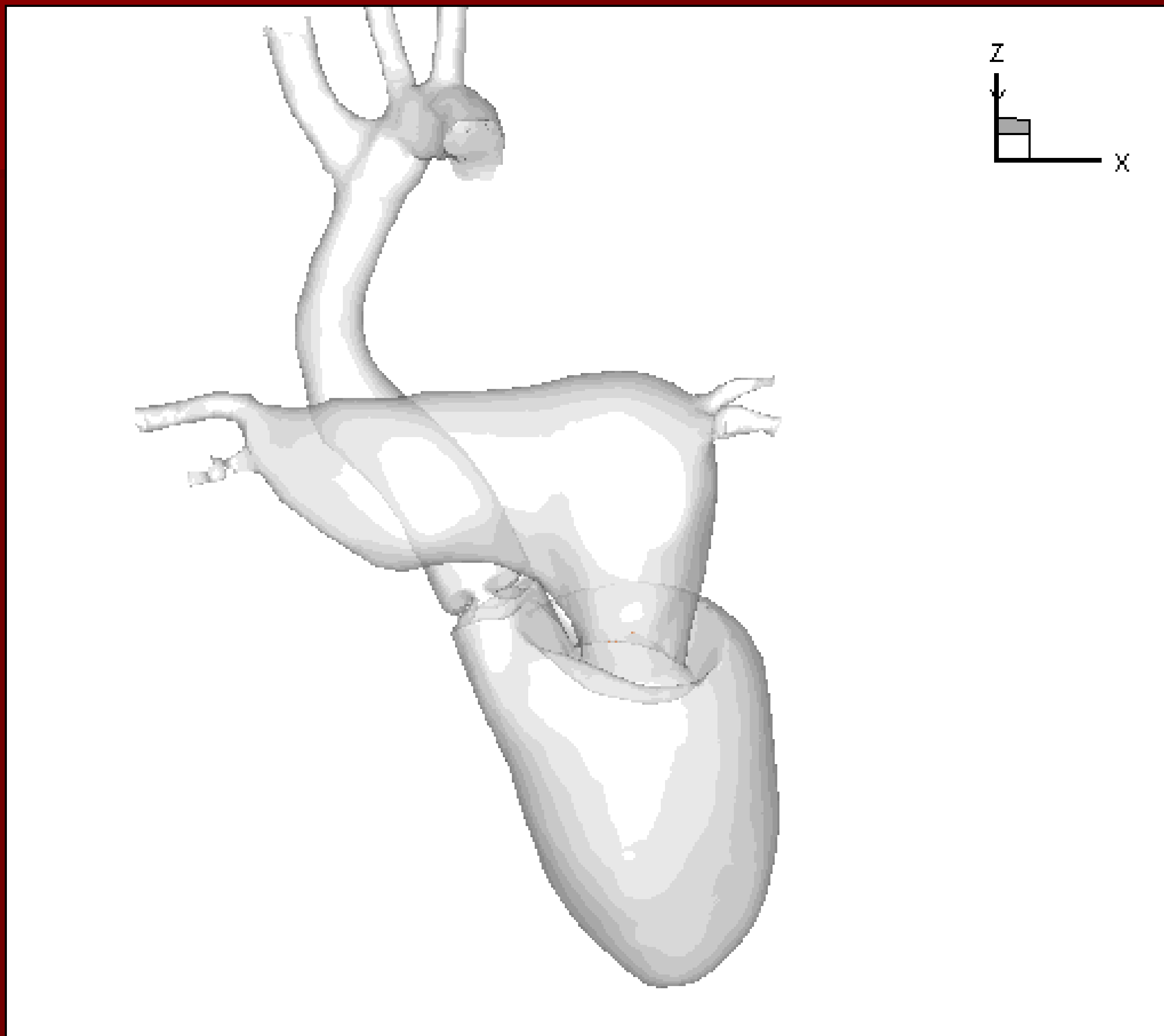



# New Initiative in Cardiovascular Flows




Forty years after the seminal work of Peskin!

# Simulation of Left-Ventricle Flow



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- Collaborators

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Questions?