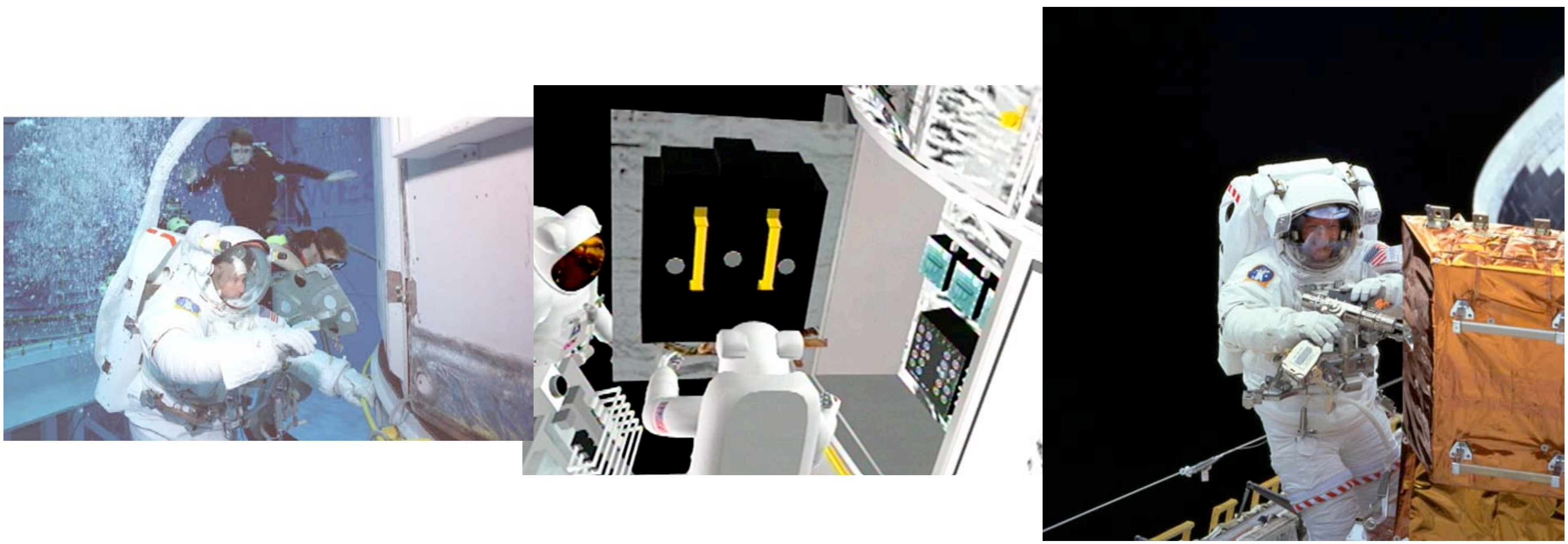
An Investigation of Space Suit Mobility with Applications to EVA Operations

Patricia Schmidt
Doctoral committee members:
Prof. Dava Newman, Chair

Motivation

- Planning and rehearsal for extravehicular activity (EVA)
  - ➢ Physical simulation
  - ★ EVA human performance modeling

- Current models do not include space suit mobility



Overview

	Thesis Chapter
Background	1, 2
Methods and results	
Experiment	3
Modeling	4
Work envelope	5
Discussion	3-5
Conclusions	6

Background and Contributions

Space Suit Mobility Experiments	Space Suit Mobility Modeling	Model Applications
Empty space suits •Dionne, 1991 •Abramov, 1994 •Menendez, 1994	**Structural mechanics** •Fay and Steele, 2000 •Main, Peterson, and Strauss, 1994	**Space suit affects dynamic sim results** •Rahn, 1997
Human Subjects •Morgan et al., 1996	**Descriptive Model** •Rahn, 1997	**ISS worksite analysis** •Anderson, 1999 •Hagale and Price, 2000 •Dischinger, 2001

Space suit mobility database → **Comparison to experimental data**

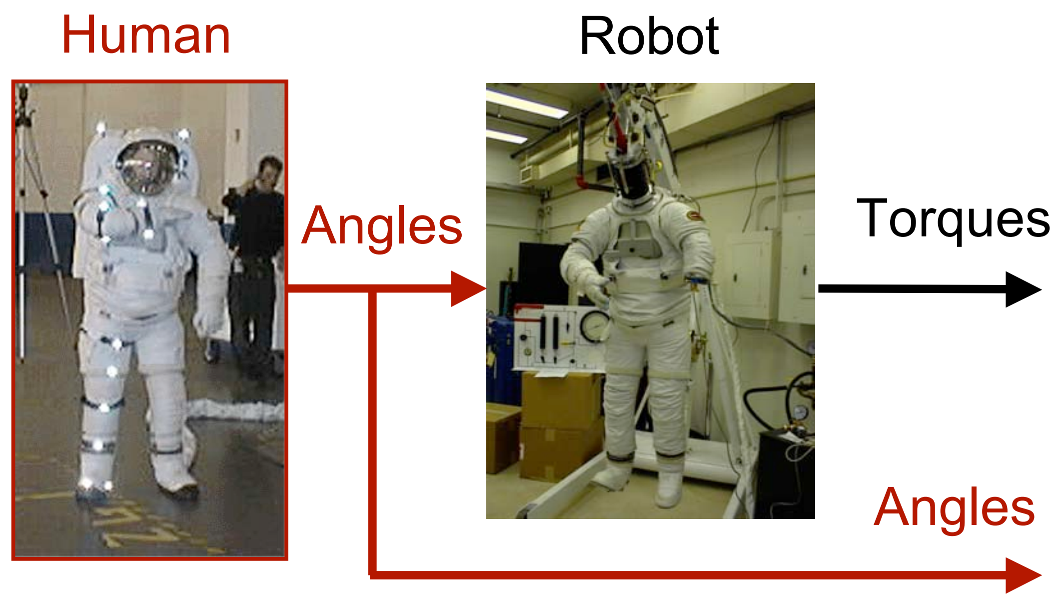
Space suit mobility database → **Mathematical model** → **Work envelope analysis**

Experiment Methods

<u>Goal</u>: Joint torque and angle data in realistic human motions

Human testing

- 4 human test subjects
- 11 simple motions isolating individual degrees of freedom
- 9 complex motions:
  - Overhead reach
  - Cross-body reach
  - Low reach
  - Locomotion
  - Step up 15 cm (6 in)

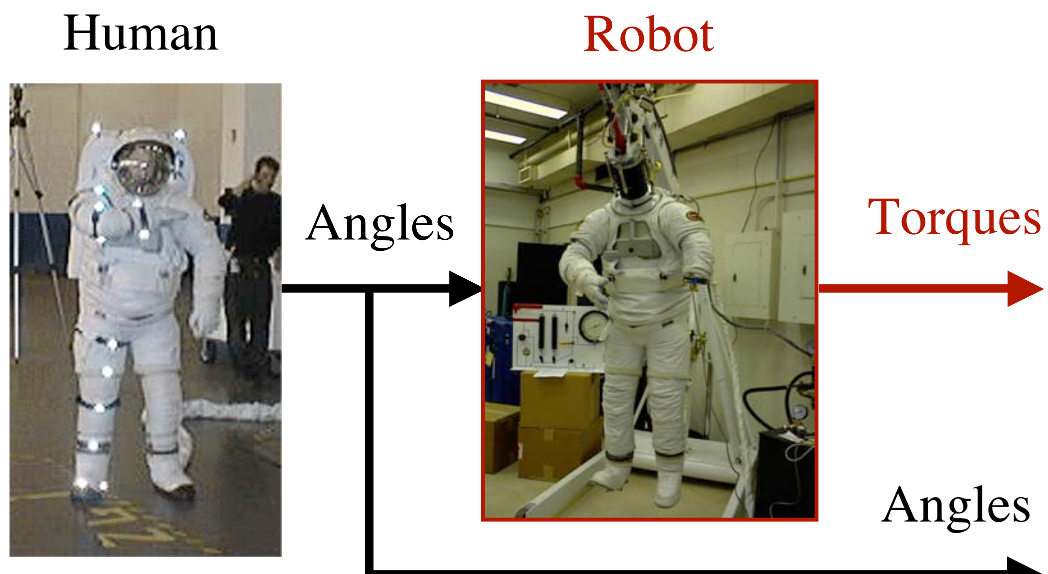


Experiment	Modeling	Work Envelope

Experiment Methods

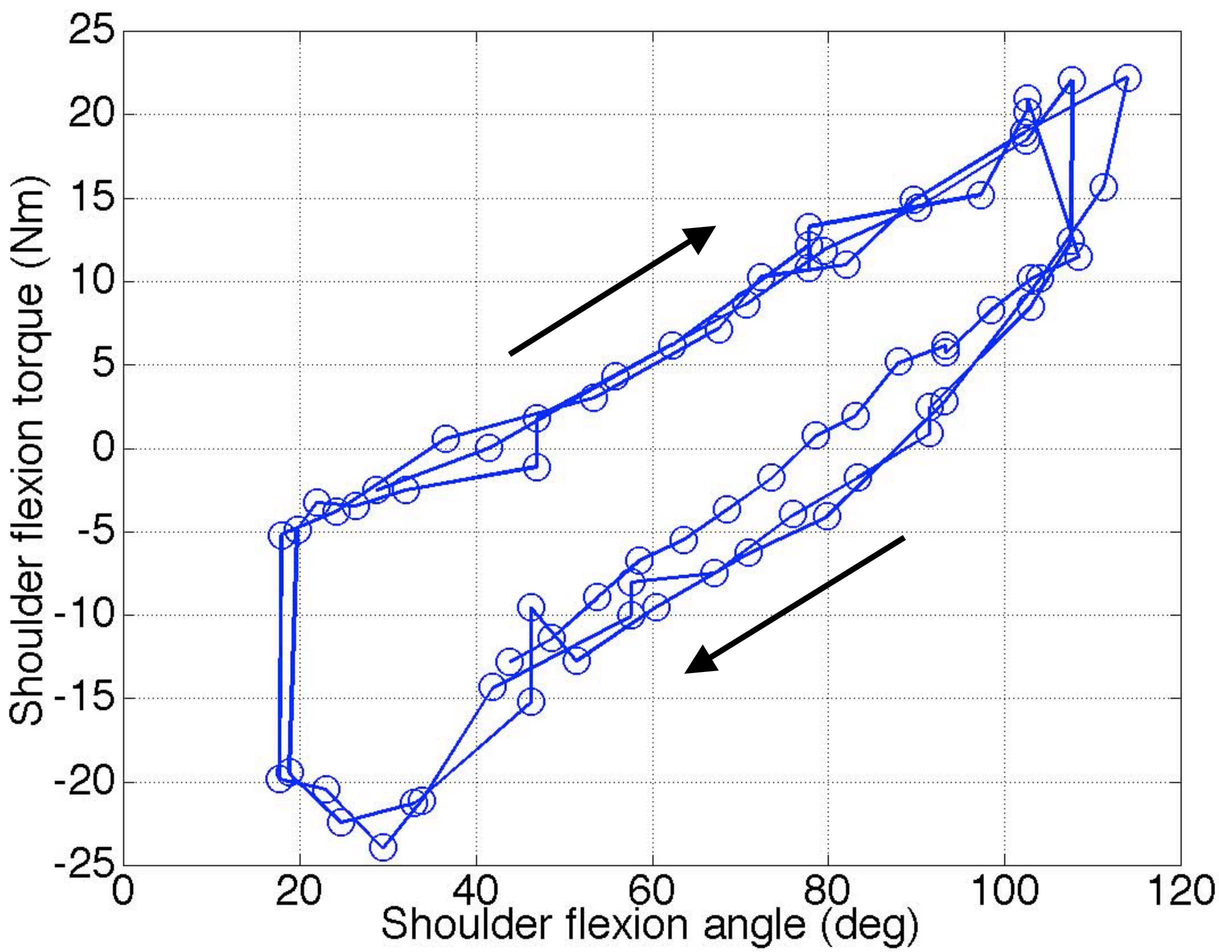
Robot testing

- Motion data from human subjects drives robot
- Torques at 11 joints recorded
- Space suit installed and pressurized to 4.3 psi
- Unsuited, to measure torque due to robot's weight
- Full speed and half speed, for best robot performance



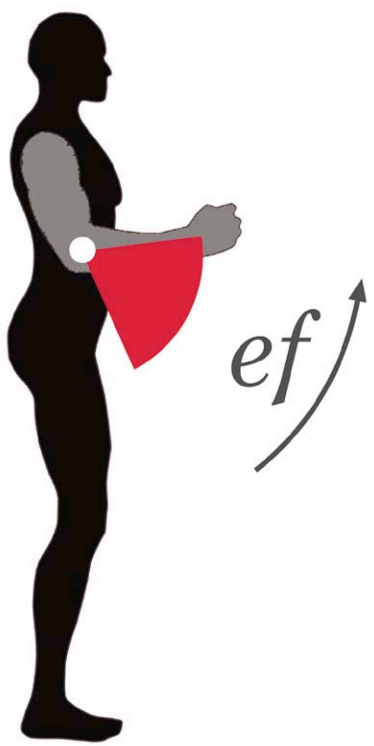
Experiment	Modeling	Work Envelope

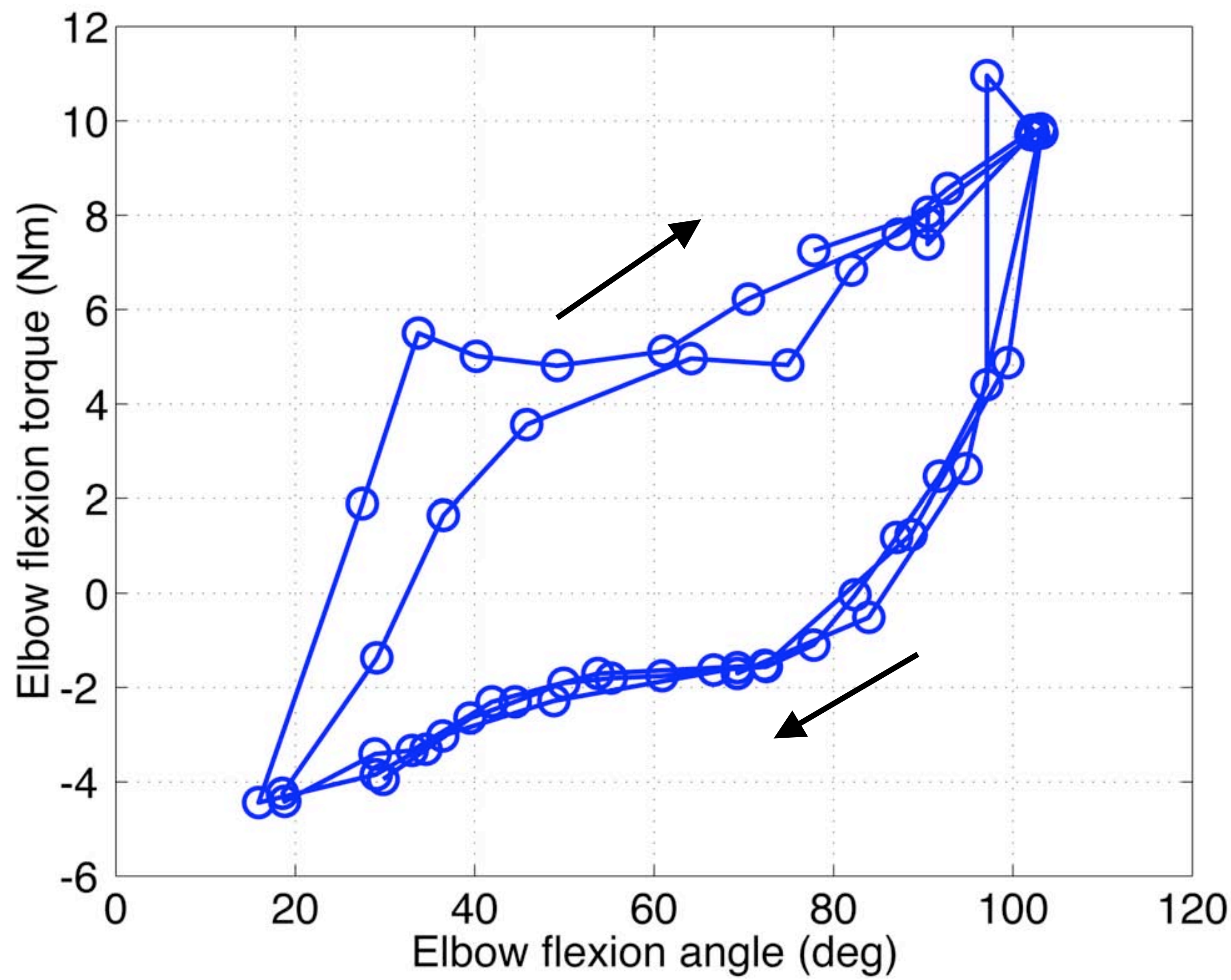
Experiment Results



Experiment	Modeling	Work Envelope

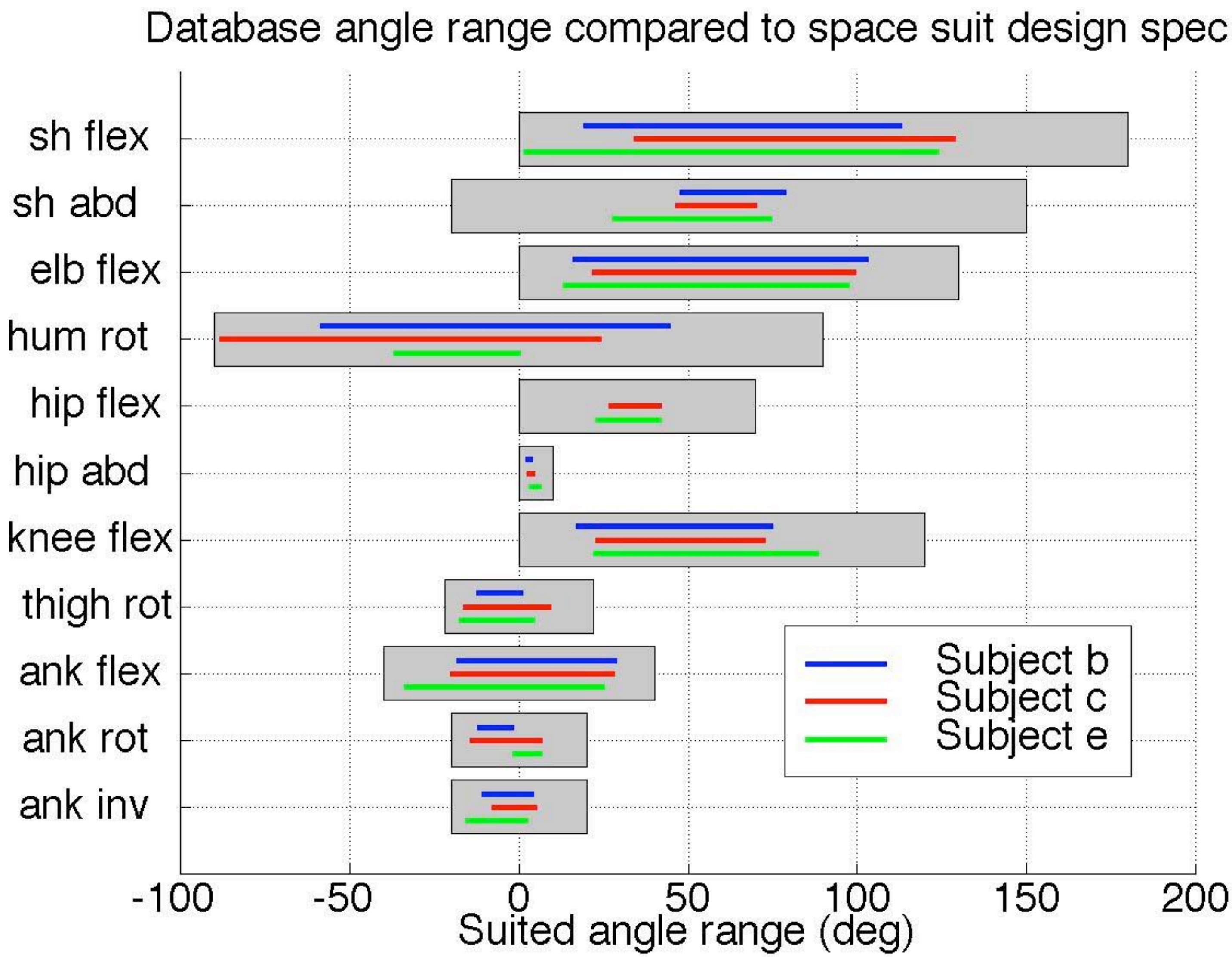
Experiment Results





Experiment	Modeling	Work Envelope

Experiment Results



Experiment	Modeling	Work Envelope

Modeling Overview

Mathematical model

Goal: Numerically calculate torque needed to bend space suit joint, for any angle history.

Method

- Preisach hysteresis model
- Coefficients fit to data for 5 joints
- New error analysis method

Physics-based model

Goal: Understand physical processes that govern space suit joint mobility.

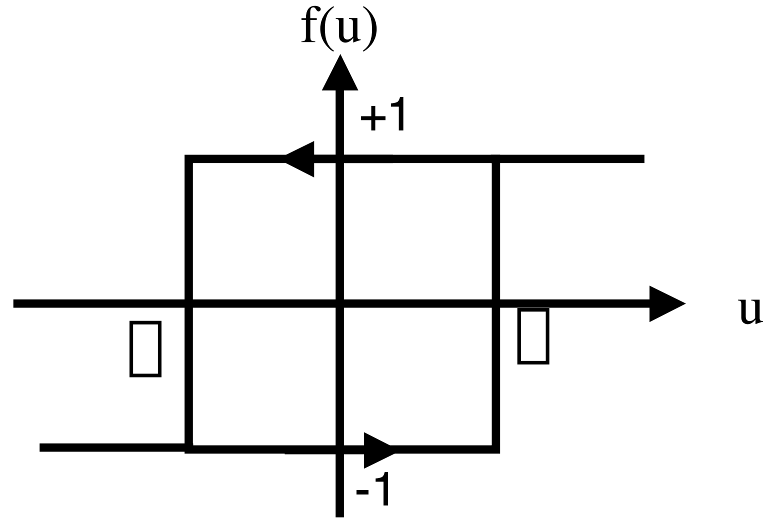
- Gas compression vs elasticity

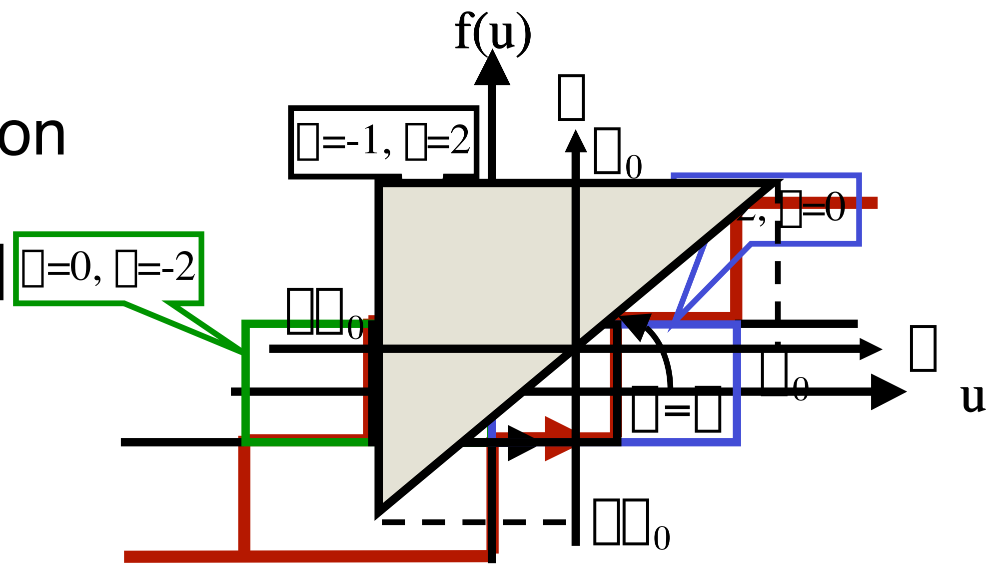
Method

- Compare two approximate models of bending inflatable structures to experimental data.
- Beam model (Main, Peterson and Strauss, 1995)
  - Elasticity only
- Membrane model (Fay and Steele,1999)
  - Gas compression only

Preisach model overview

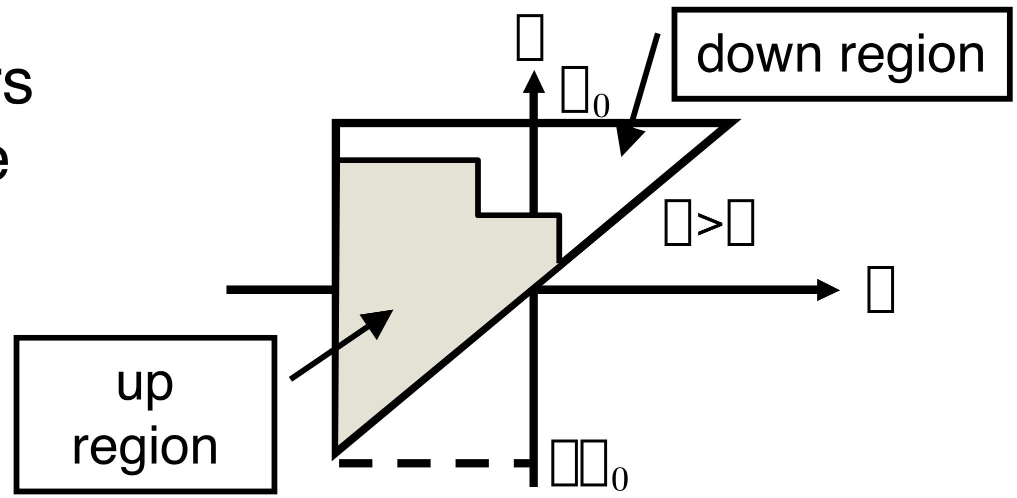
- Weighted sum of simple hysteresis transducers
- Weighting coefficients □(□,□) defined as function of switching thresholds □ and □
- Graphical representation plots weighting coefficients vs □ and □
  - □ > □
  - □□$_0$ <□ < □$_0$
  - -□$_0$<□ < □$_0$





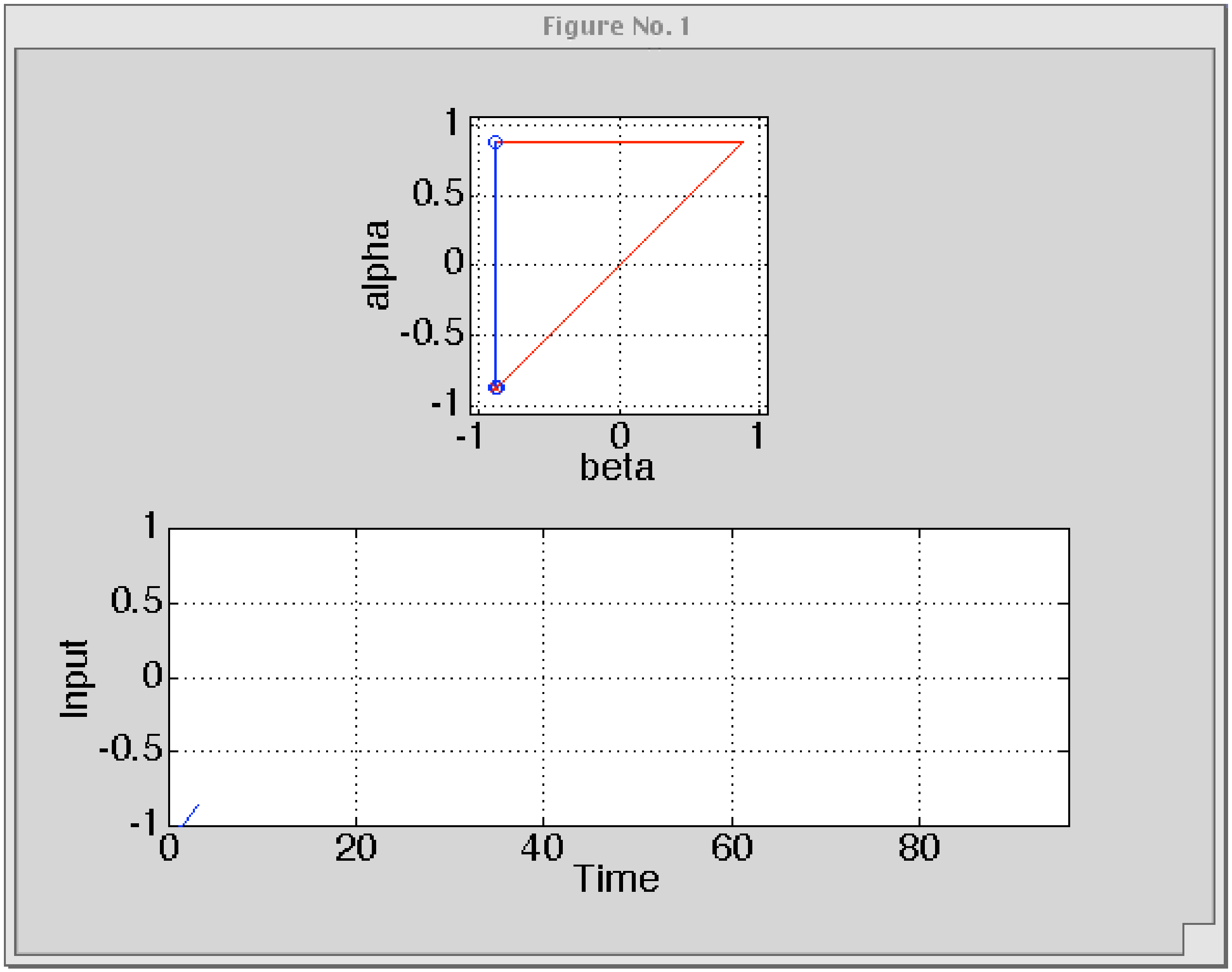
Preisach model implementation

- To calculate output, want to know which transducers are up (+1) and which are down (-1)
- Draw boundary in α-β plane according to rules
  - segment moves up for increasing input
  - segment moves left for decreasing input
- Integrate coefficients in up region, subtract integral of coefficients in down region



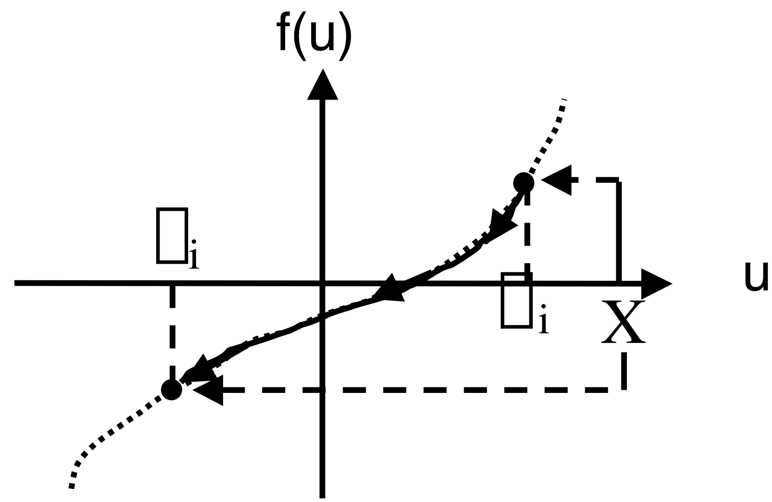
$$f(u) = \iint_{up} \mu(\alpha,\beta)\, d\alpha\, d\beta - \iint_{down} \mu(\alpha,\beta)\, d\alpha\, d\beta$$

Preisach model implementation

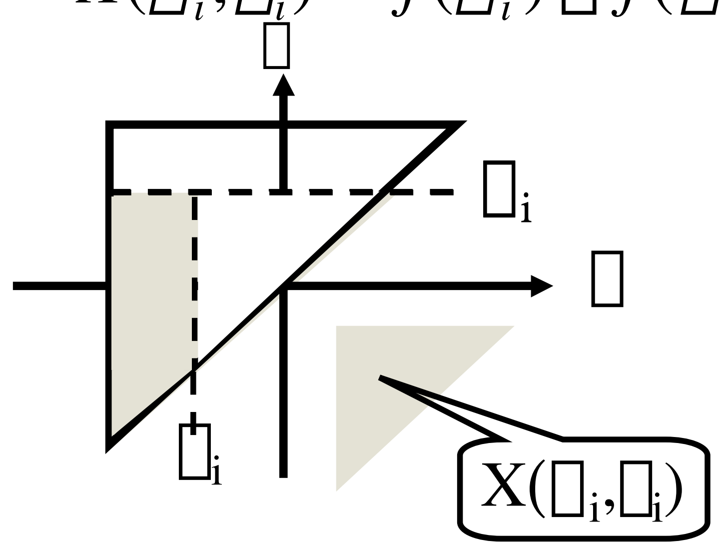


Preisach model identification

- Find weighting coefficients from experimental data
- Since coefficients are integrated, find integral of coefficients over known area instead: X(□,□)
- Get integral over triangular region from output differences



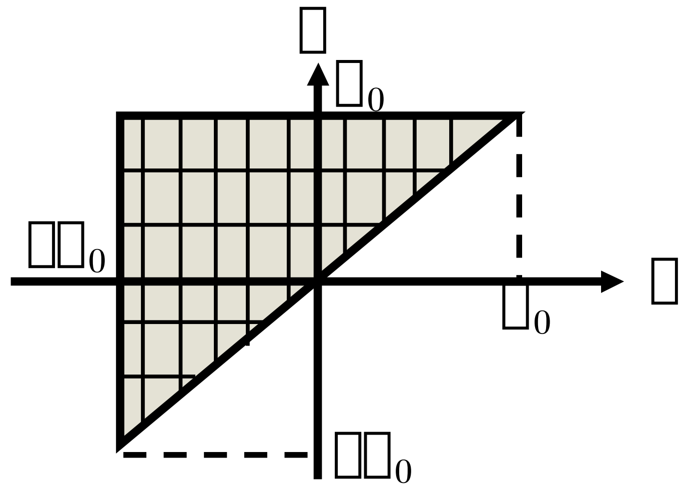
$$X(\square_i,\square_i) = f(\square_i) \square f(\square_i)$$



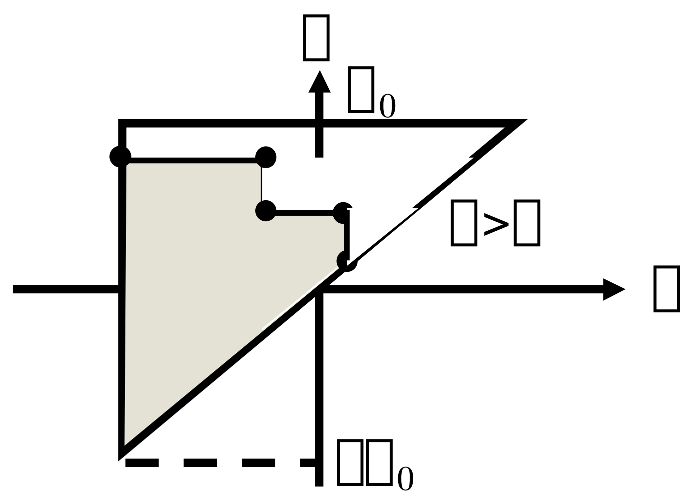
Numerical implementation

Doong and Mayergoyz, 1985

- Find coefficient integrals for mesh of points in □□□ plane
- Build staircase shapes from summing and differencing triangles



$$f(u) = X(\square_0, \square\square_0) + \sum_{i=1}^{n} (\square 1)^{i+1} X(\square_i, \square_i)$$



Error analysis

Output f(u) is sums and differences of triangle integrals

$$f(u) = X(\theta_0, -\theta_0) + \sum_{i=1}^{n} (-1)^{i+1} X(\theta_i, \phi_i)$$

Sum variances of errors in $X(\theta_i, \phi_i)$ values to obtain variance of error in output

$$\sigma_f^2 = \sum_{i=1}^{n} \sigma_{X(\theta_i, \phi_i)}^2$$

Errors in $X(\theta, \phi)$ depend on errors in experimental data

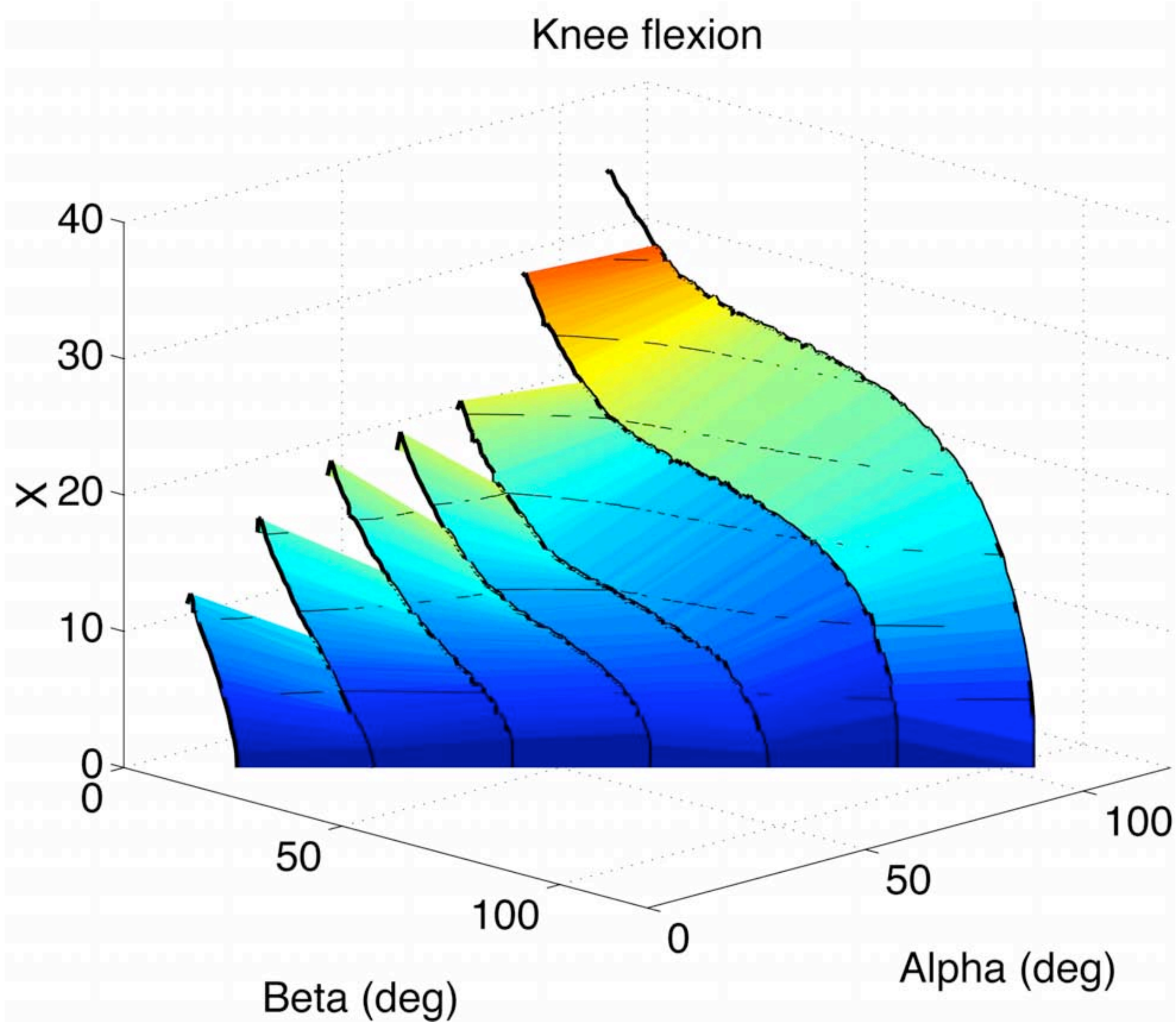
$$\sigma_{X(\theta,\phi)}^2 = 2\sigma_T^2 + \sigma_A^2 \left[\frac{\partial X(\theta,\phi)}{\partial \theta} + \frac{\partial X(\theta,\phi)}{\partial \phi} \right]^2$$

Torque

Angle

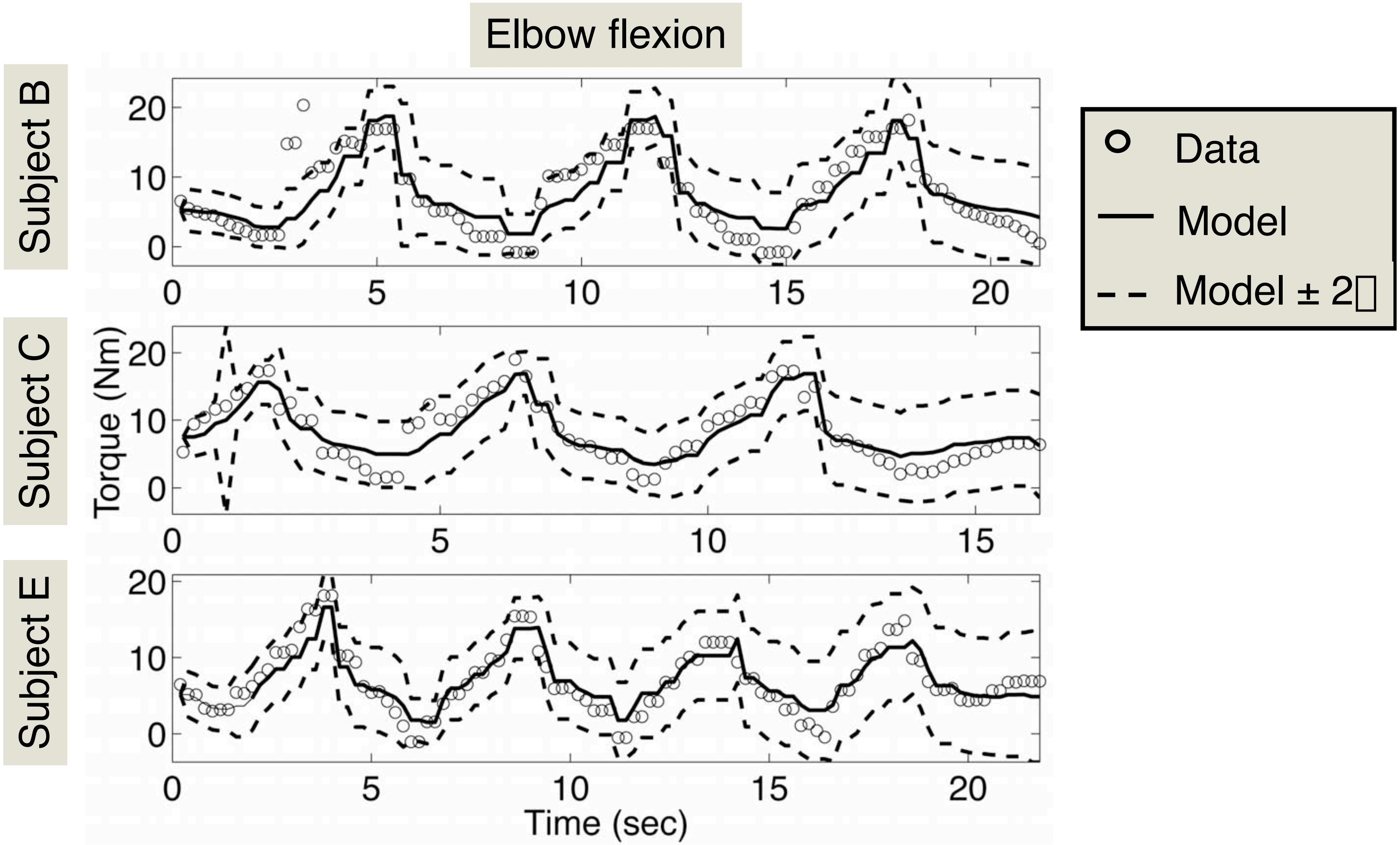
$$\sigma_{f(u)}^2 = 2n\sigma_T^2 + \sigma_A^2 \sum_{i=1}^{n} \left[\frac{\partial X(\theta_i,\phi_i)}{\partial \theta_i} + \frac{\partial X(\theta_i,\phi_i)}{\partial \phi_i} \right]^2$$

Mathematical Model Results



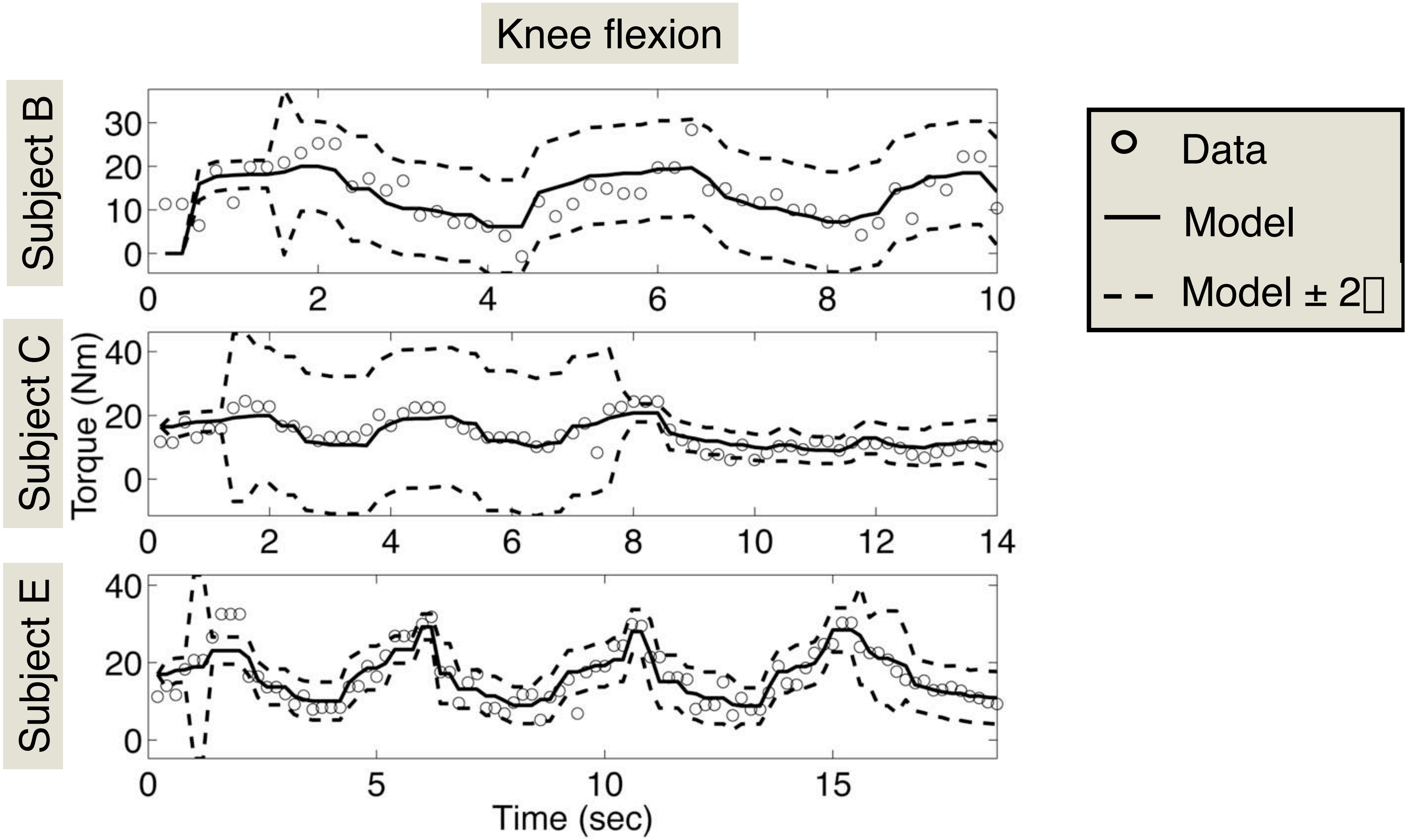
Experiment	Modeling	Work Envelope

Mathematical Model Results



Experiment	Modeling	Work Envelope

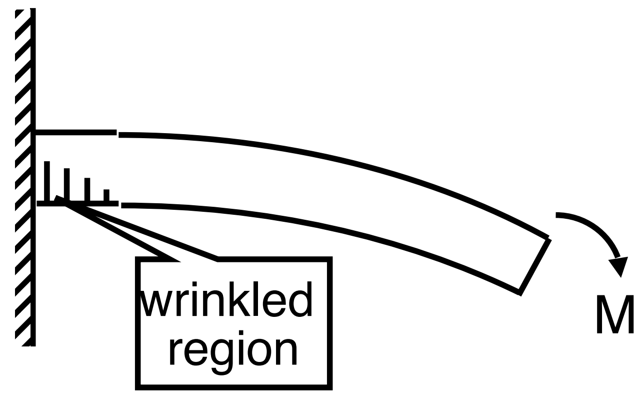
Mathematical Model Results



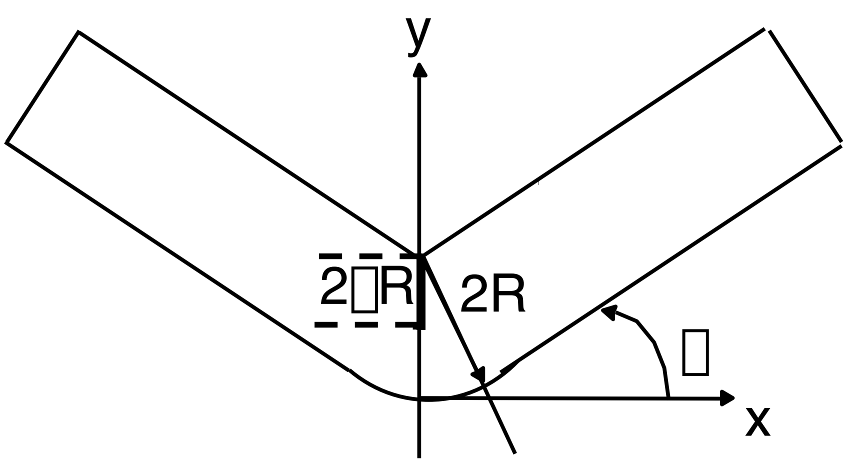
Experiment	Modeling	Work Envelope

Physics-based Model

<u>Beam model</u>:
- Pressurized fabric cylinder remains cylindrical when bent
- All deformations due to fabric wall stretching; no volume change
- Fabric wrinkles when compressed and does not contribute to rigidity

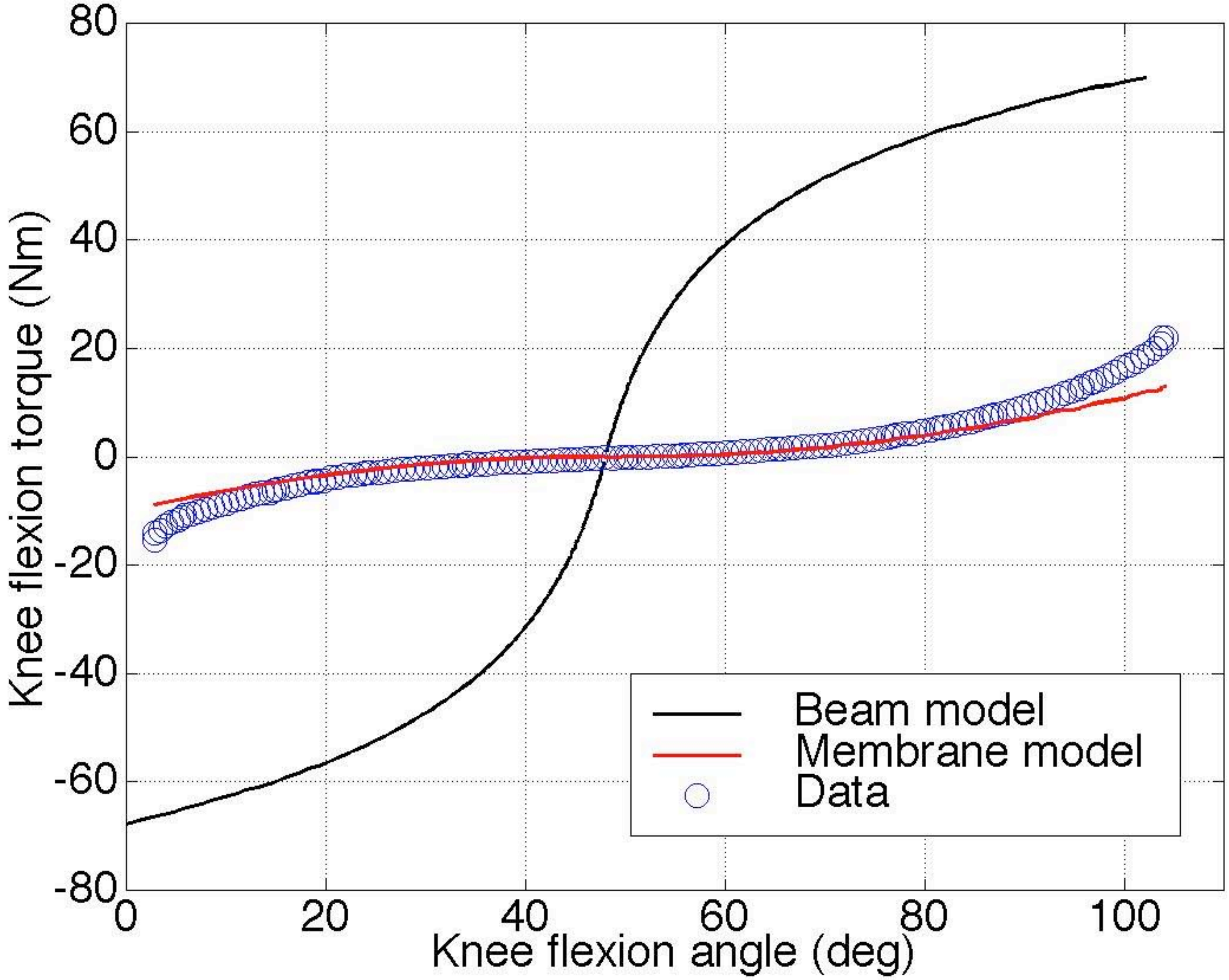


Elasticity — Gas compression



<u>Membrane model</u>:
- Fabric cylinder walls are inextensional
- Shape and internal volume change when cylinder bent
- Moment needed to bend cylinder due to gas compression only

Physics-based Model Results



Experiment	Modeling	Work Envelope

Work Envelope

Work Envelope: Volume in space in which a person can comfortably work

Computational inverse kinematics approach

- Reconfigurable for different individuals or populations
- Indicate areas to avoid
- ★ Determine good worksite locations

<u>Work envelope criteria</u>
1. Visibility
2. Joint torques required to hold position
3. Boundary shape

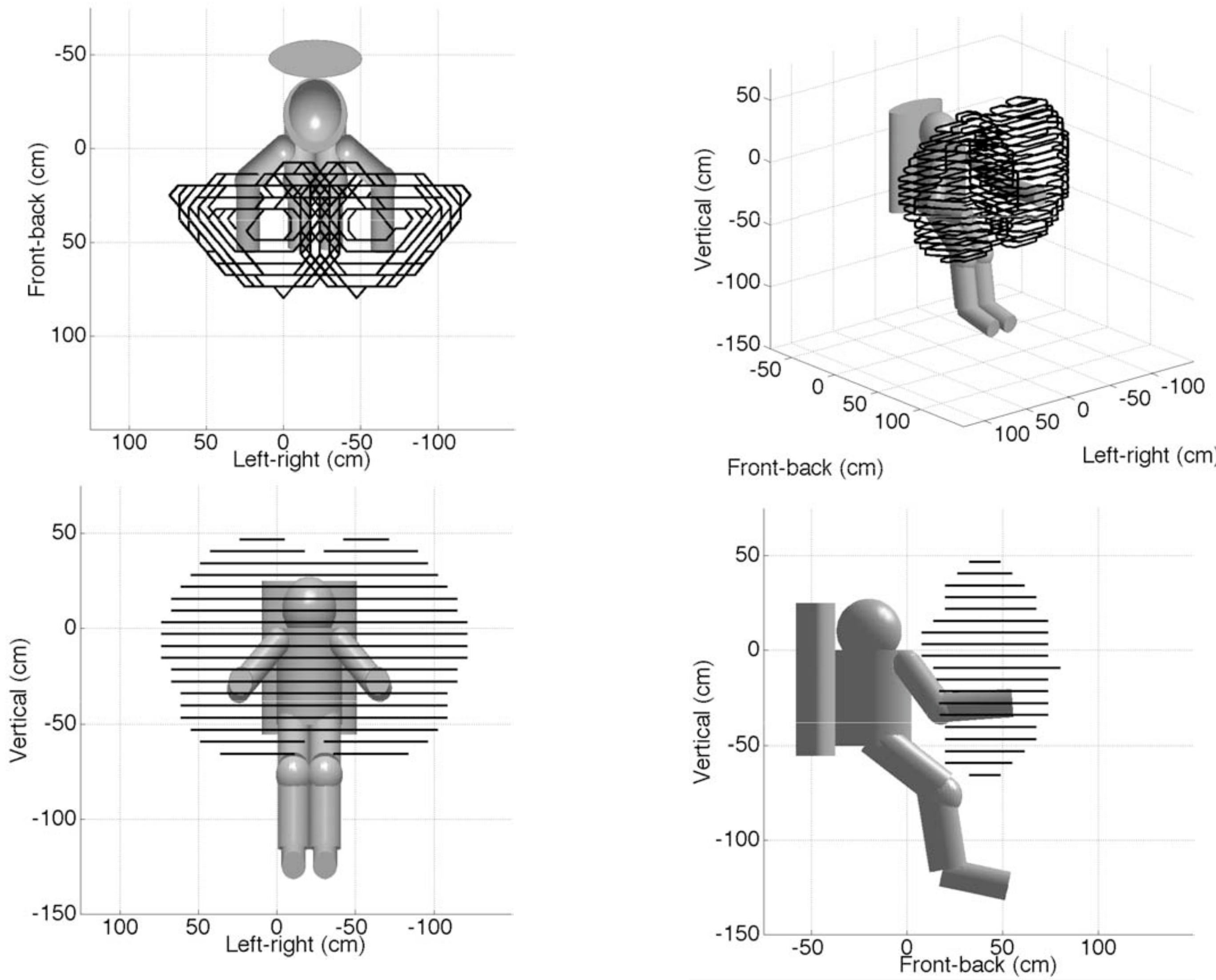
Work Envelope Methods

- Eliminate non-visible areas (NSTS-07700)
- Inverse kinematics gives arm joint angles
  - Several arm configurations place the hand on target
- Calculate required torques from space suit model
- Difficulty metric
  - Choose "easiest" configuration
  - Indicates best worksite locations

$$M = \sum_{4\ \text{joints}} \frac{\text{Required torque}}{\text{Available Torque}}$$

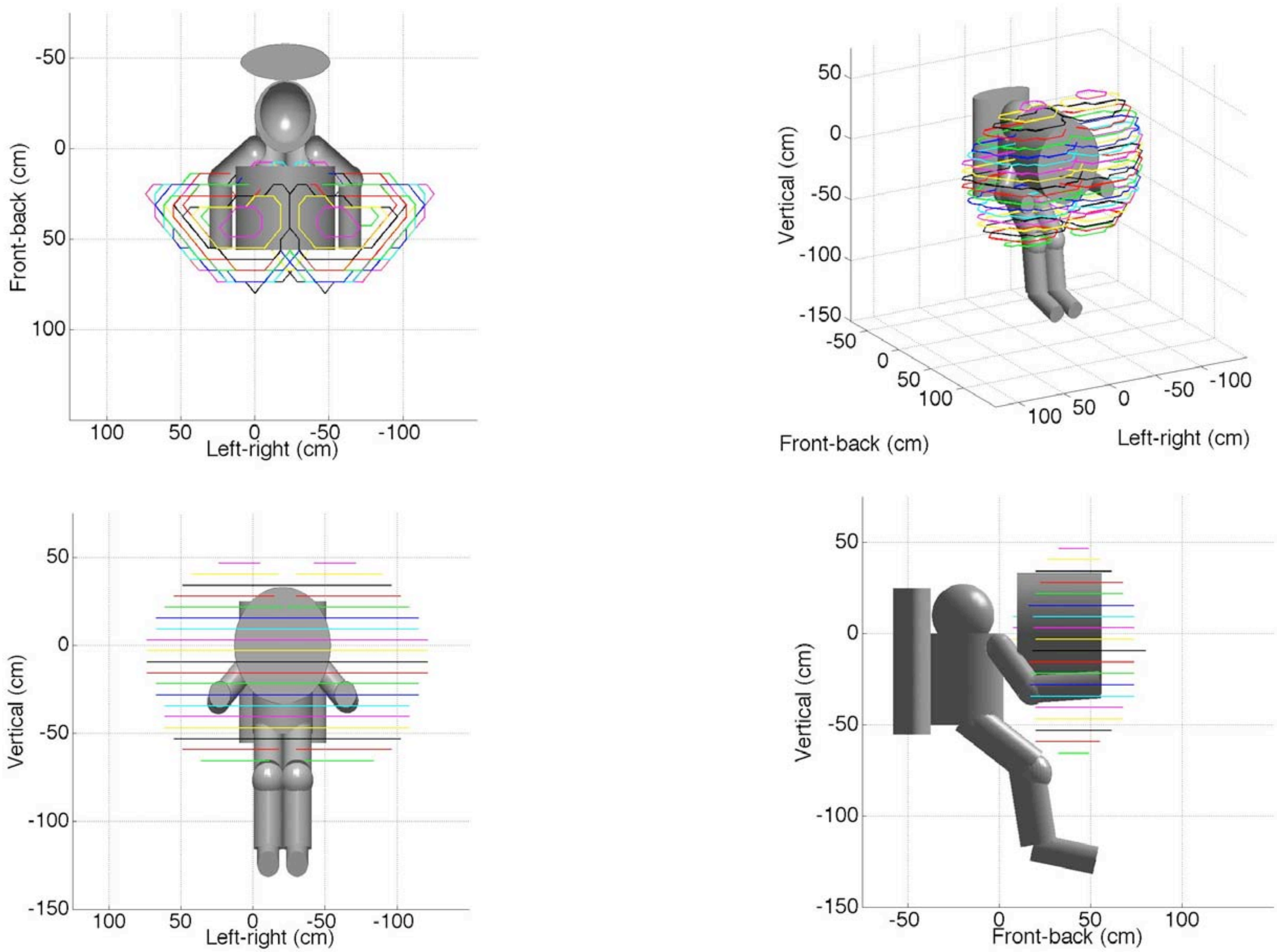
- Evaluate torque limits: No joint may exceed specified percentage of maximum torque
- Blend 15% and 30% limits to set practical workspace boundaries

Work Envelope Results

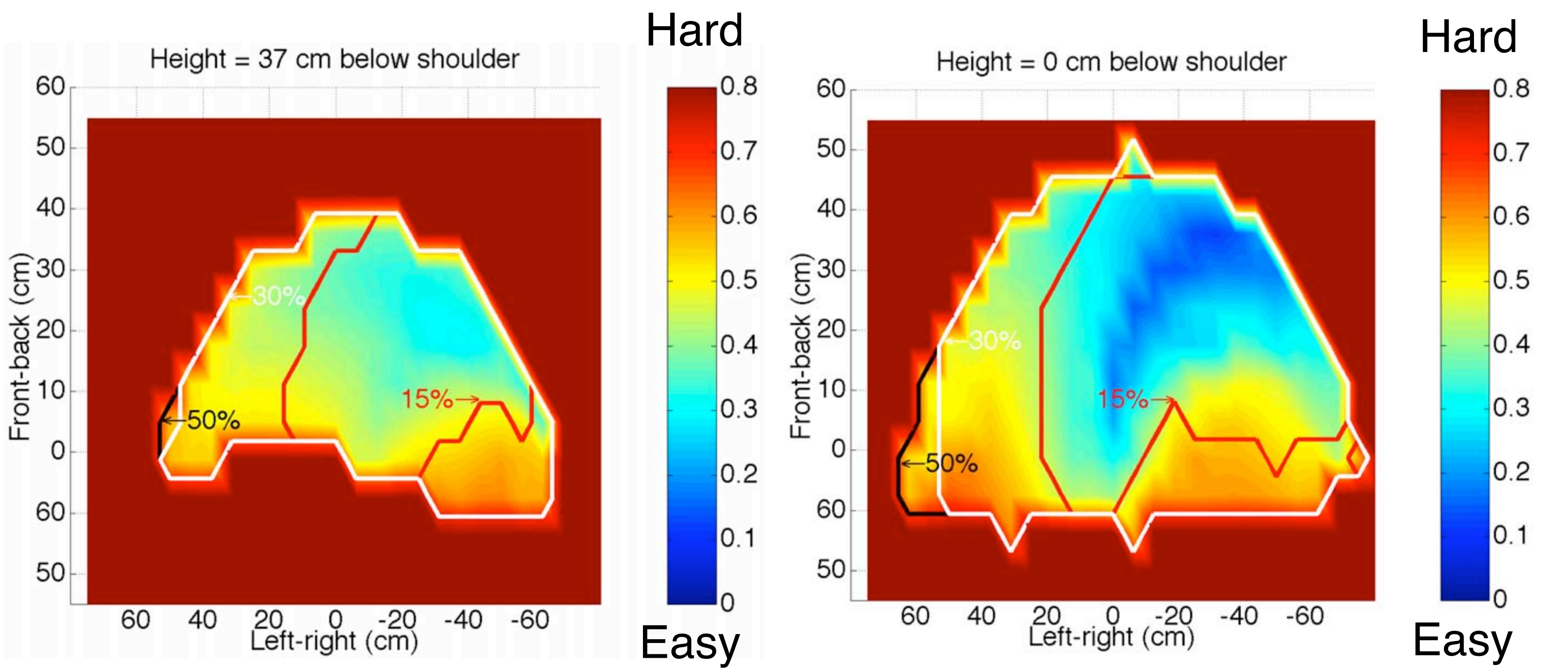


Experiment	Modeling	Work Envelope

NASA work envelope

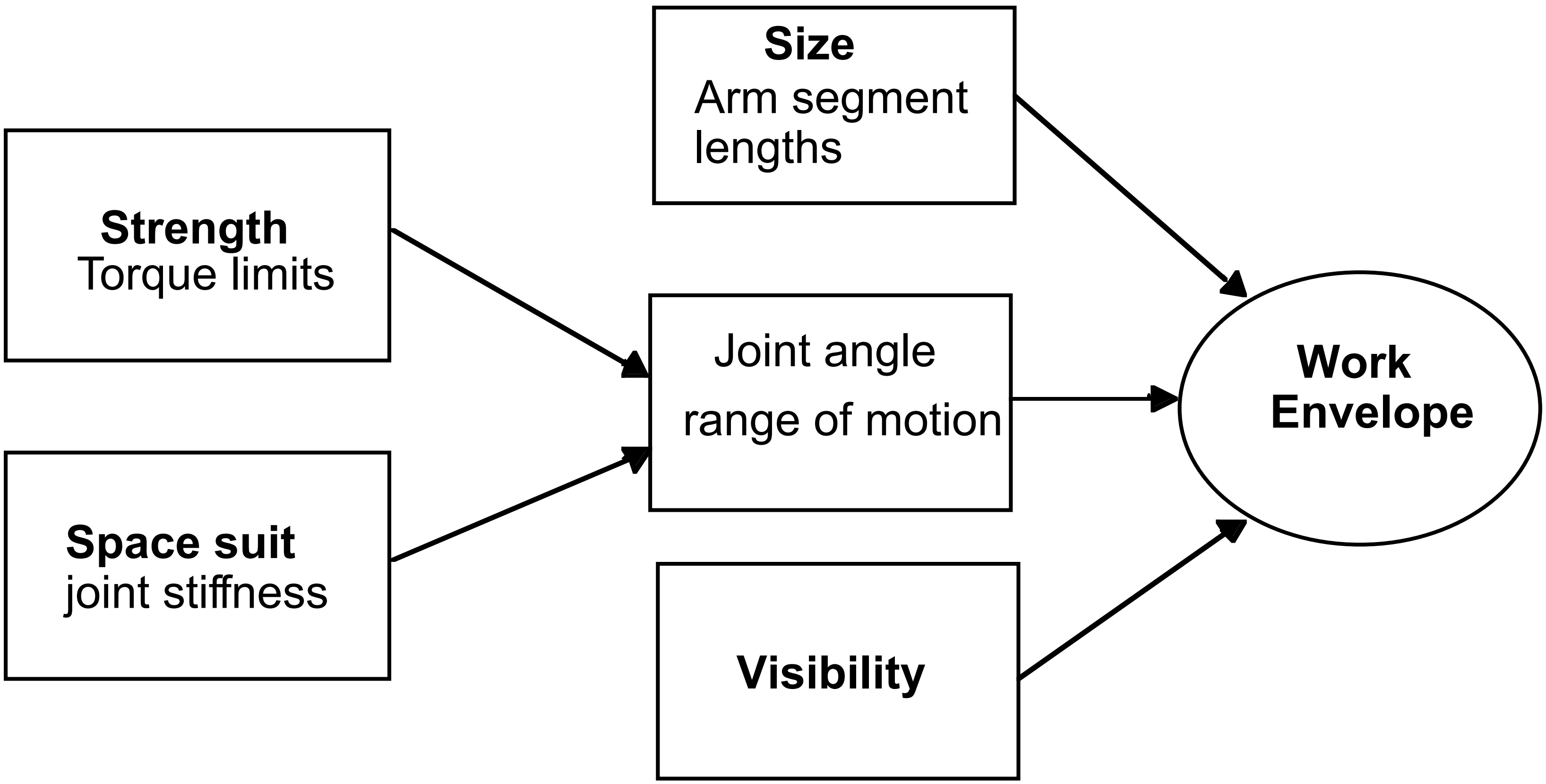


Work Envelope Results



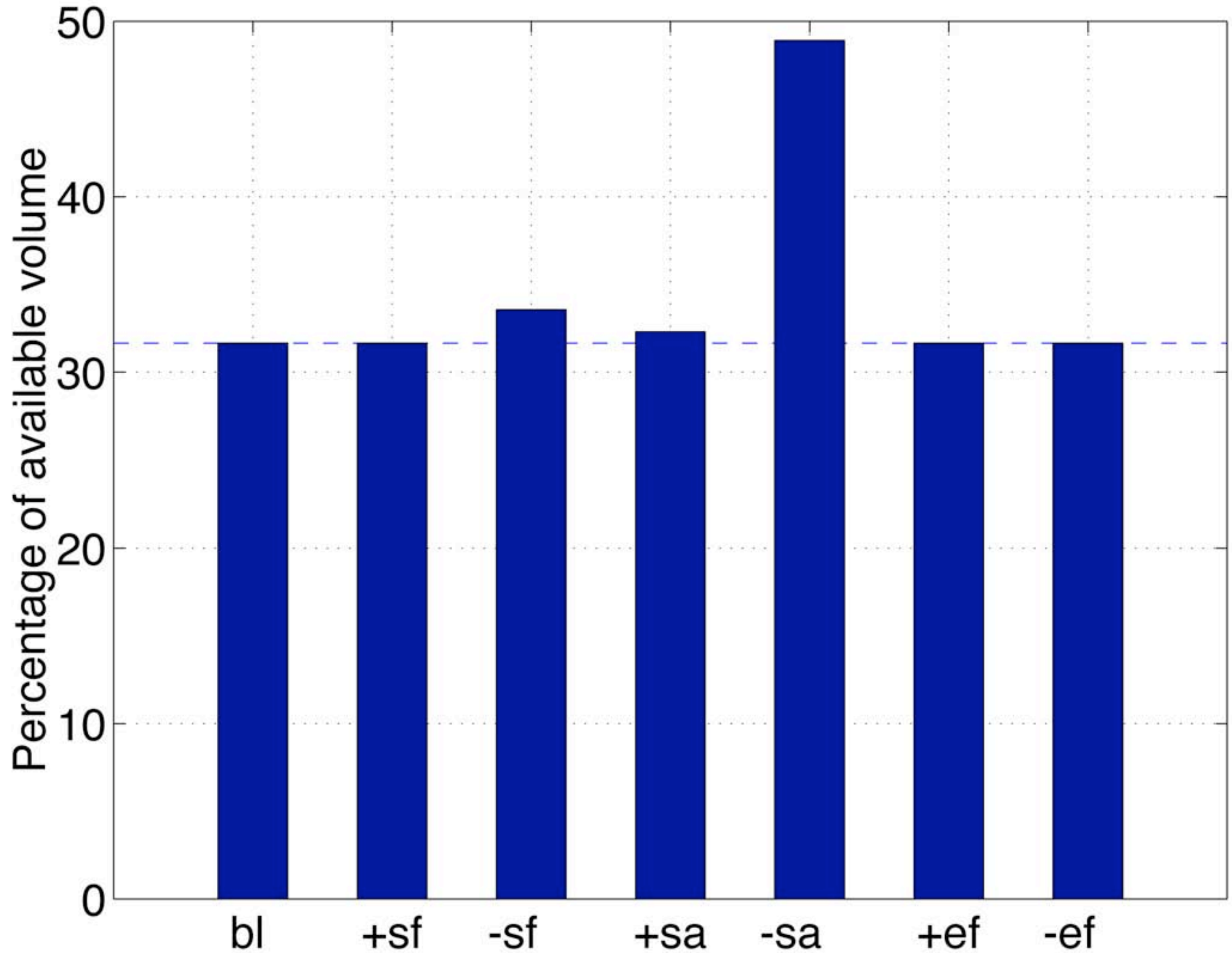
Experiment	Modeling	Work Envelope

What affects work envelope size?



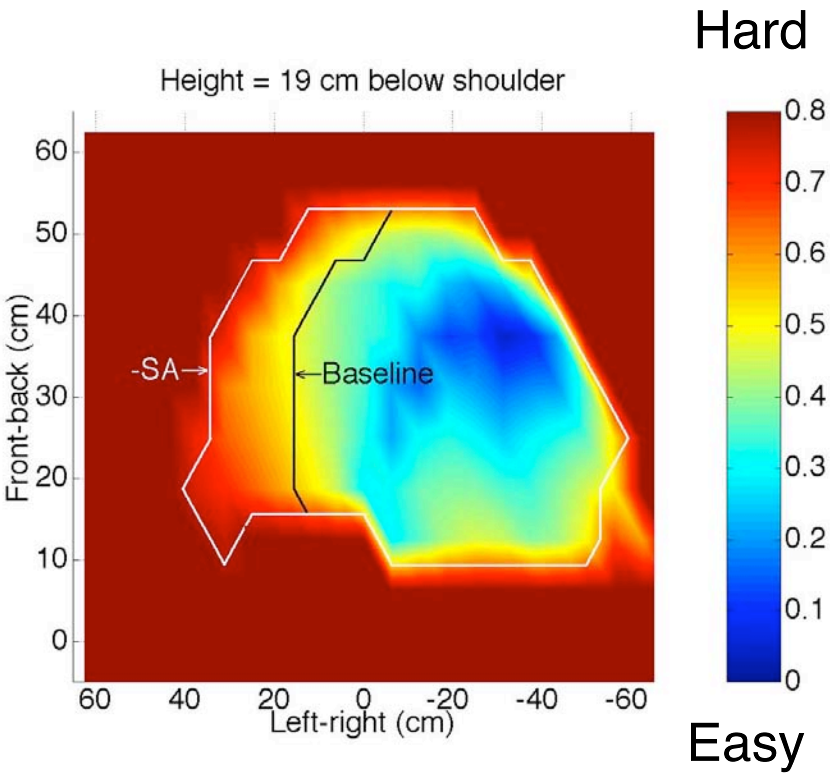
Experiment	Modeling	Work Envelope

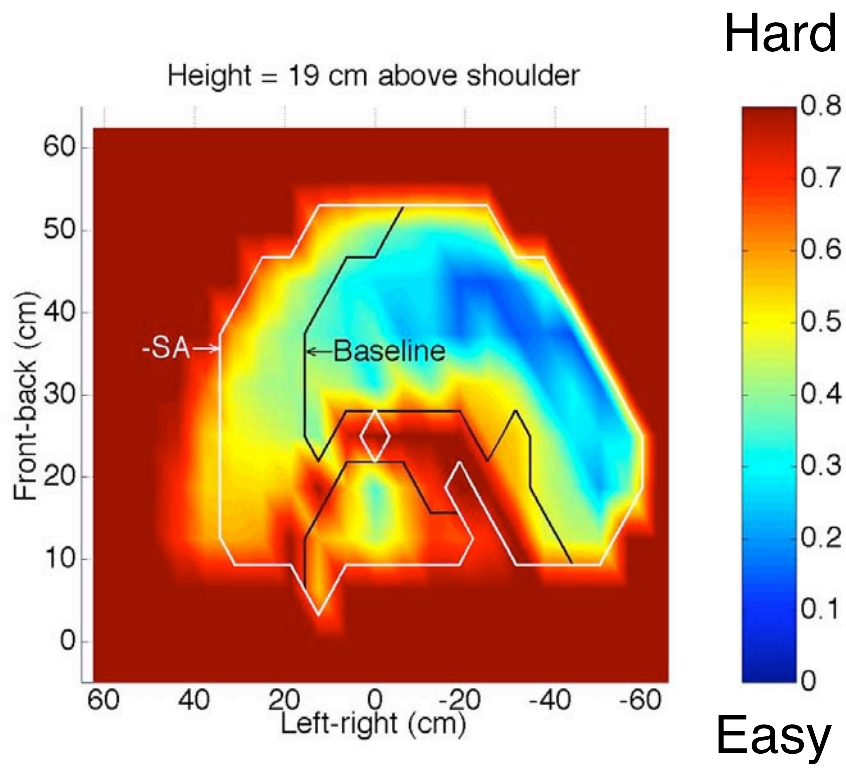
Joint range of motion



Experiment	Modeling	Work Envelope

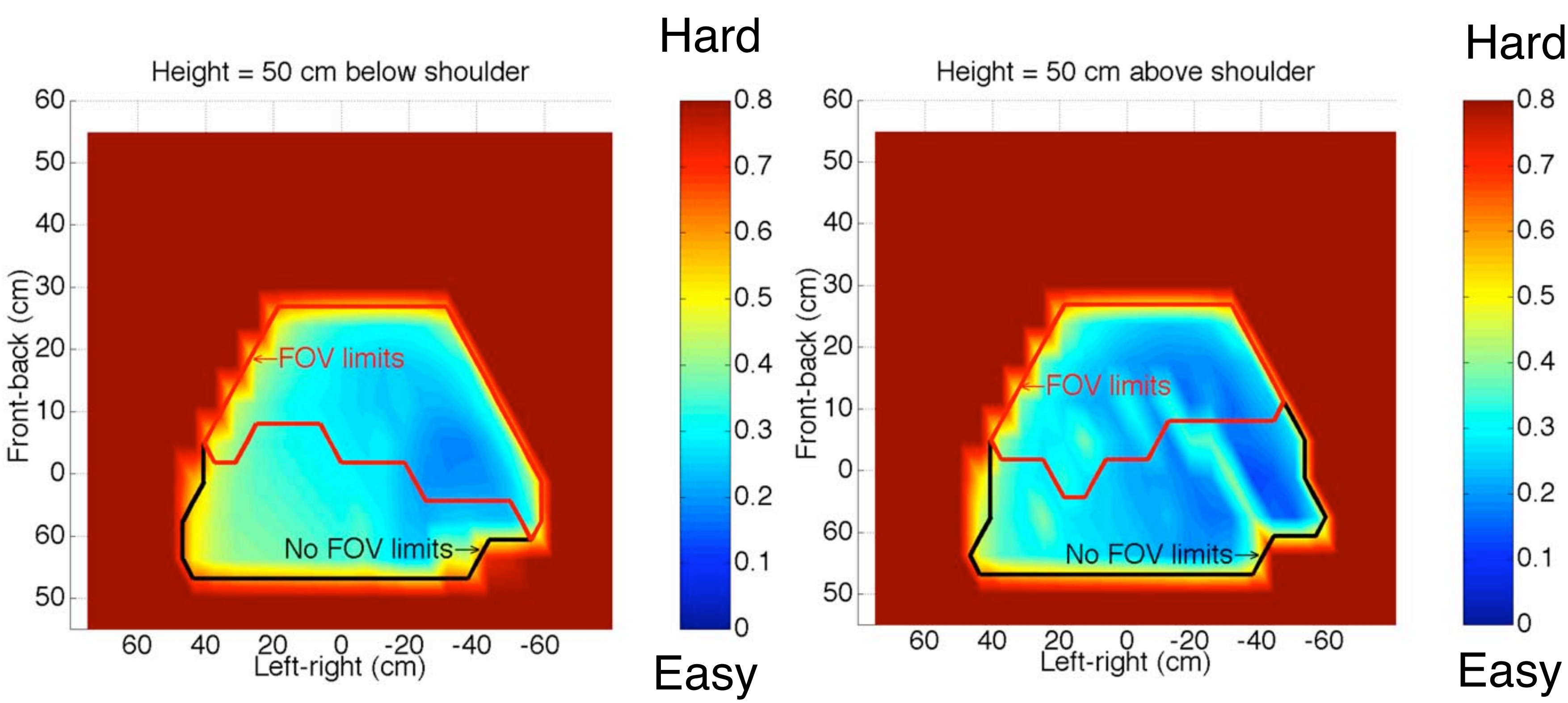
Joint range of motion





Experiment	Modeling	Work Envelope

Visibility



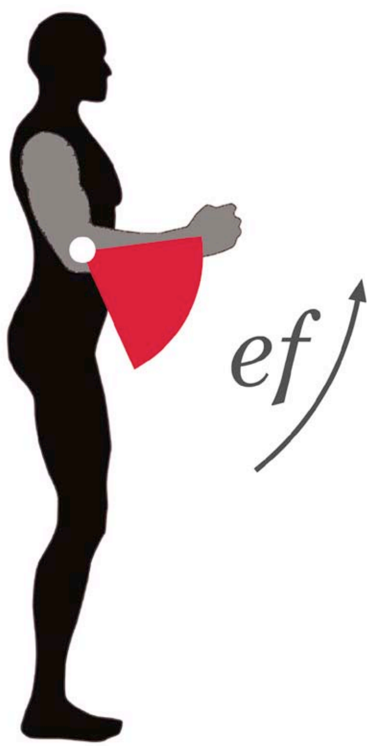
Experiment	Modeling	Work Envelope

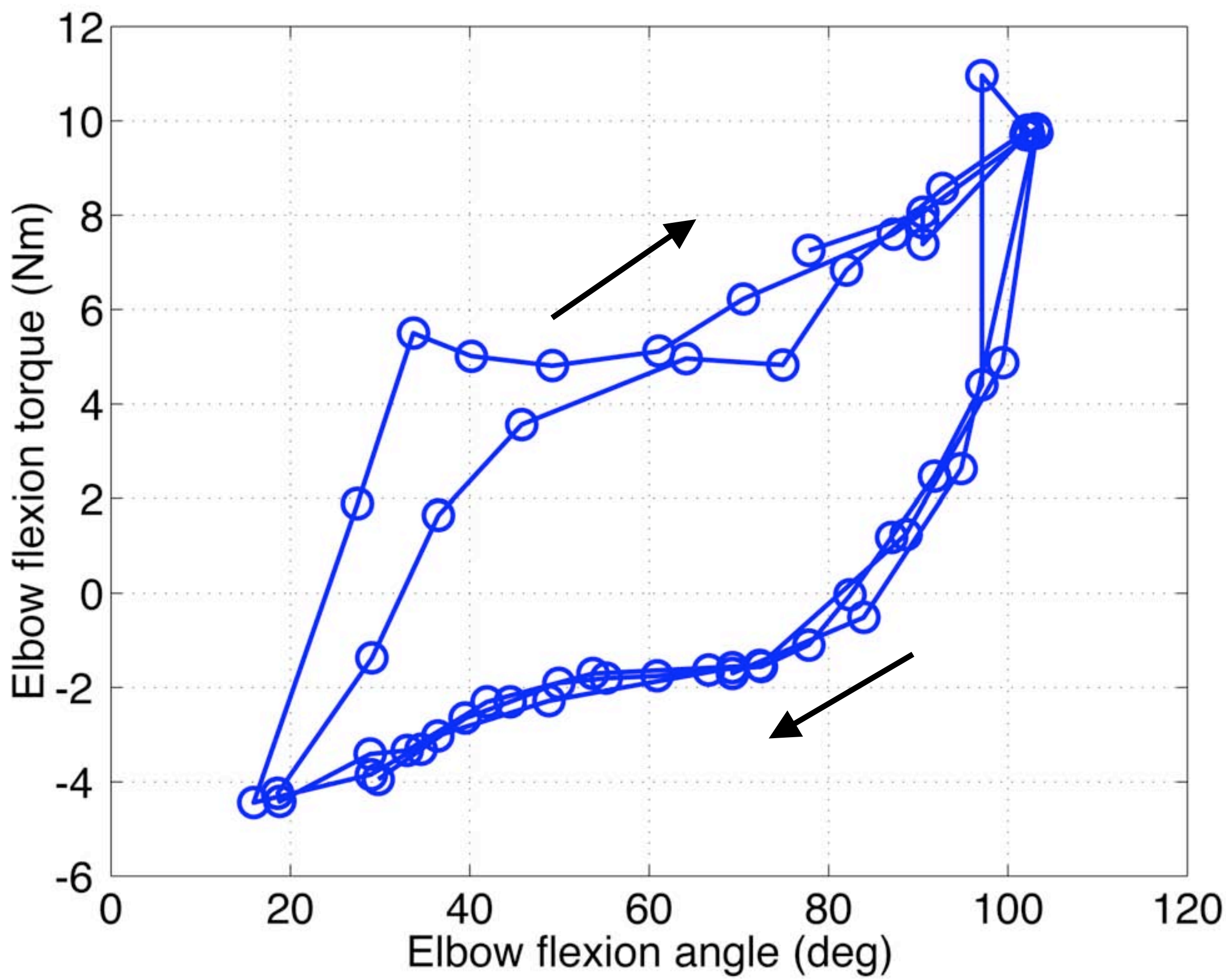
Discussion: Experiment

- Angles accurate to 2-5 degrees, torques accurate to 0.1 Nm
- Torque-angle data exhibits hysteresis
- Stiffness increases with increasing deflection--hardening
- Torque magnitudes greater than “empty-suit” studies
- Space suit mobility database is more extensive in number of joints and range of motion than other published data sets

Study	Dionne	Menendez	Abramov	Morgan et al.	Current study
Methods	EMU, empty suit	Prototype segments, empty	Orlan-DMA, 4.3 psi, empty	EMU, human subjects	EMU, human subjects and robot
Knee, 72 deg	3.2 Nm	NA	6.0 Nm	8.1 Nm	14.6±0.136 Nm
Elbow, 80 deg	2.0 Nm	2 Nm	2.2 Nm	3.4 Nm	3.74±0.0676 Nm

Experiment Results





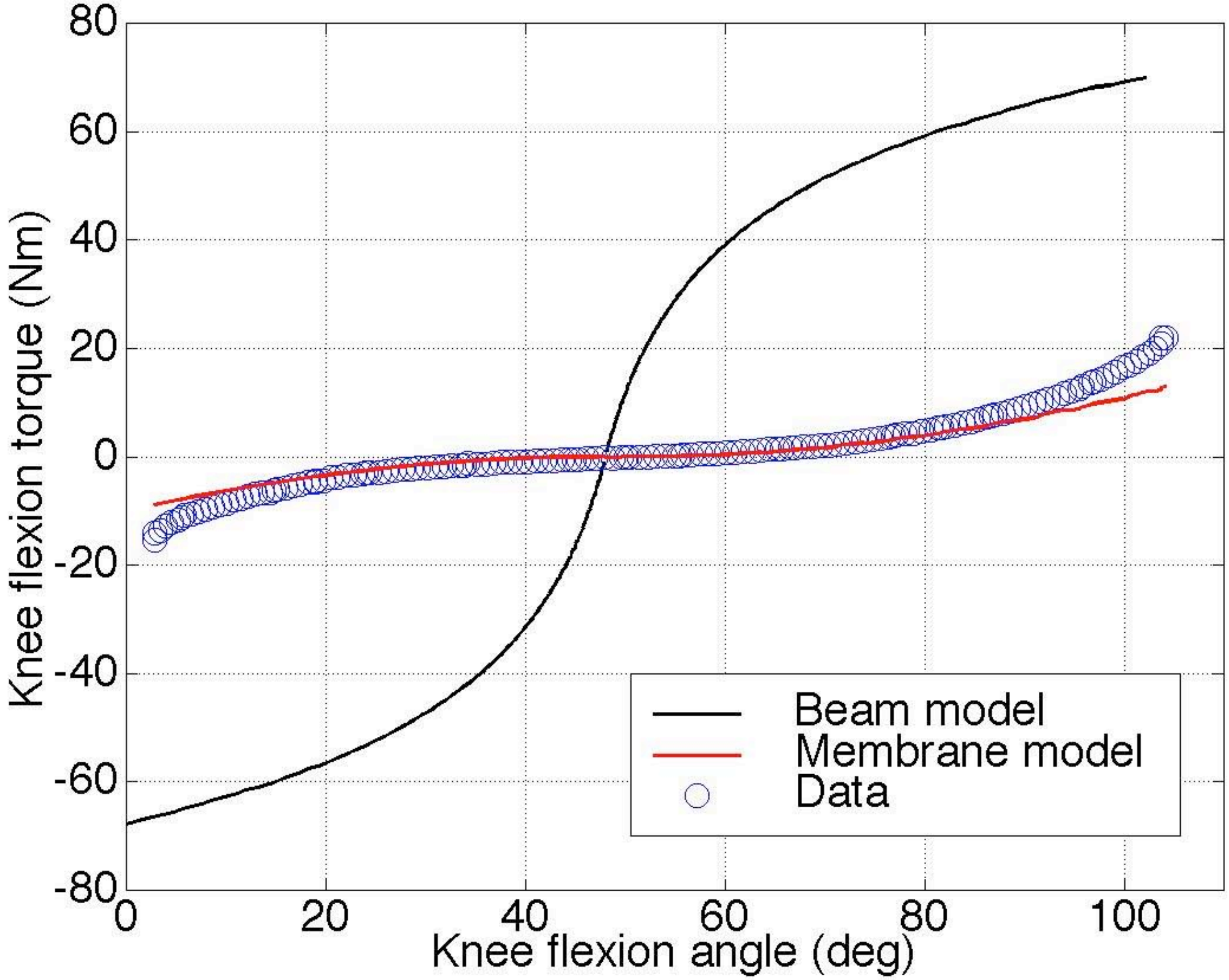
Experiment	Modeling	Work Envelope

Discussion: Modeling

- Mathematical model
  - Hysteresis model agrees with data in human-generated motions for elbow flexion, knee flexion, and hip abduction
  - Proper choice of input angles in experiment is critical to fit quality
  - Hysteresis model is implementable in real time for dynamic simulation

- Physics-based model
  - Gas compression vs. elastic deformations in space suit mobility
  - Membrane model agrees with data within 30-50 degrees of equilibrium angle
  - Beam model does not agree with experimental data
  - → Gas compression is dominant process for EMU space suit elbow and knee mobility

Physics-based Model Results



Experiment	Modeling	Work Envelope

Discussion: Work Envelope

- Possible to predict large-scale human factors metric from joint torque-angle models
- Work envelope analysis method is easily reconfigurable for different anthropometrics and strengths
- Sensitivity analysis indicates
  - Improving shoulder mobility adds most volume to work envelope
  - Improving upward and downward visibility enlarges work envelope

Contributions

- Extensive space suit joint torque-angle database
- Real-time numerical predictions of torque needed to bend space suit joints for complicated angle histories
- Comparison of experimental data to approximate theoretical models indicates that gas compression is dominant process in space suit elbow and knee mobility
- Computational work envelope analysis
  - Reconfigurable for individuals of different sizes and strength
  - Indicates both desirable and undesirable areas for worksite placement

Future work

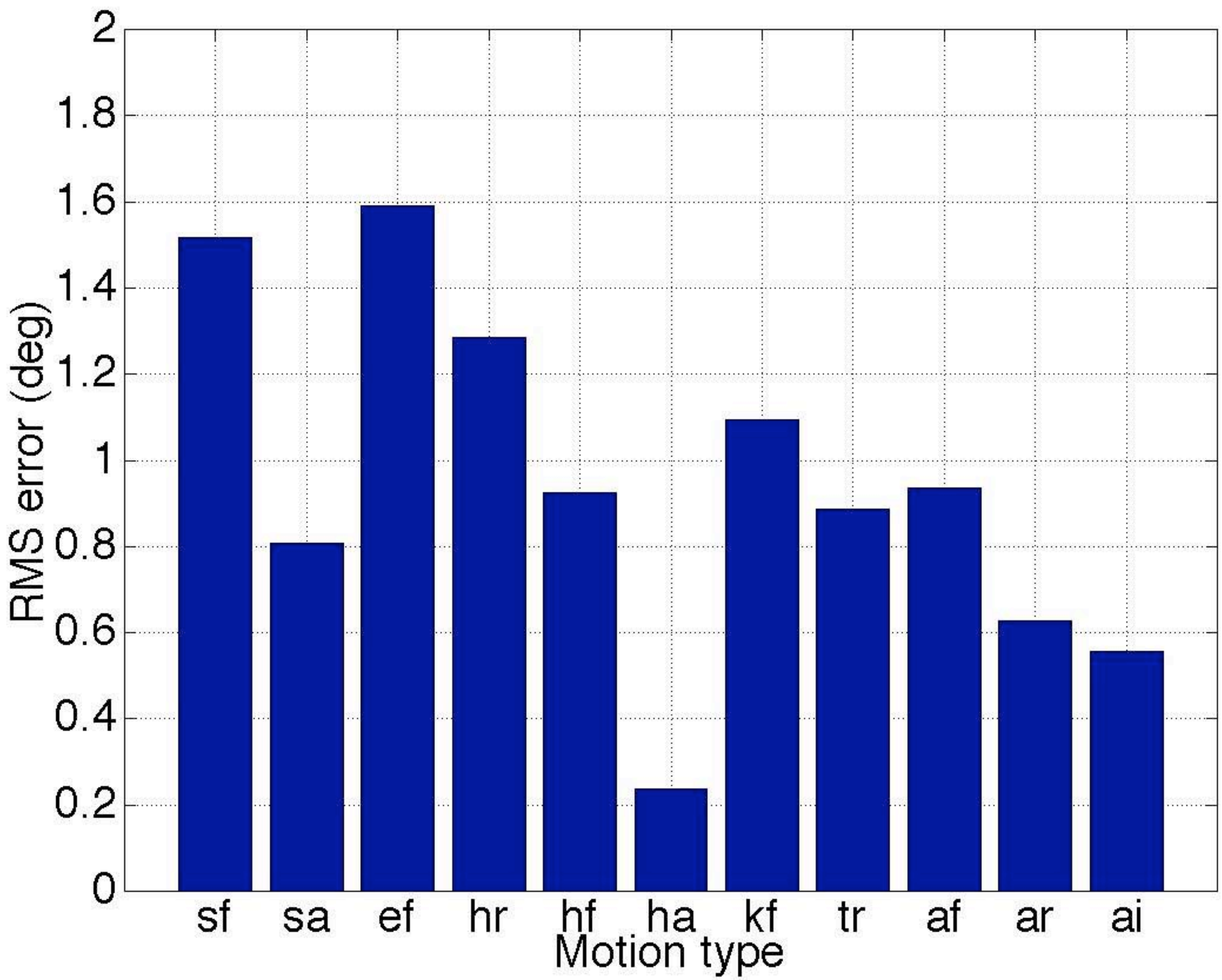
- Experiment
  - Space suit mobility
    - Contact forces between limbs and space suit
    - Space suit motions
  - Validation of computational work envelope predictions
  - Experimentation with space suit joint mockups

- Analysis
  - EVA dynamic simulations should incorporate space suit models
  - More sophisticated physics-based models, including joint design

- NASA EVA operability standards and requirements
  - Currently simple, low accuracy
  - Update to reflect current analytical techniques that can evaluate complicated requirements

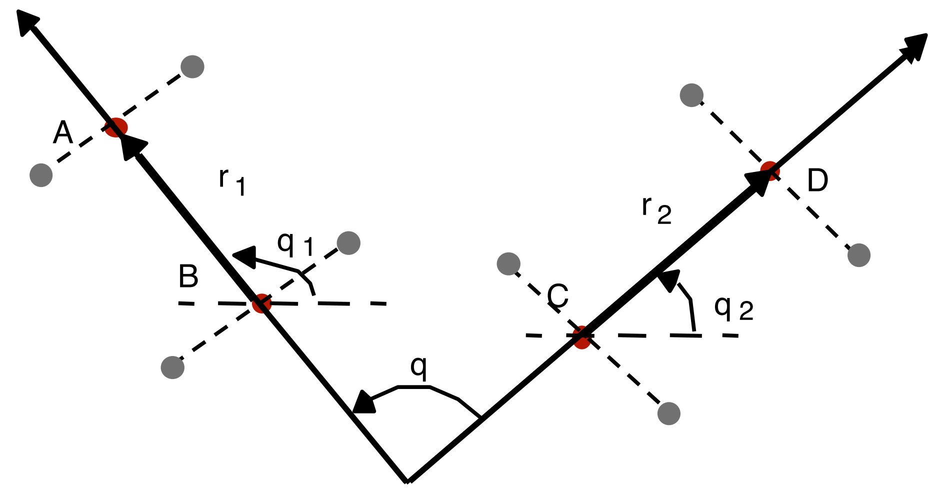
backup slides

Experiment: Robot angle error



Motion capture error

Motion capture system tracks reflective markers on arm and leg



Accuracy depends on
- Marker spacing
- Number of markers visible

Assume that markers are located to 1 cm (1 diameter)

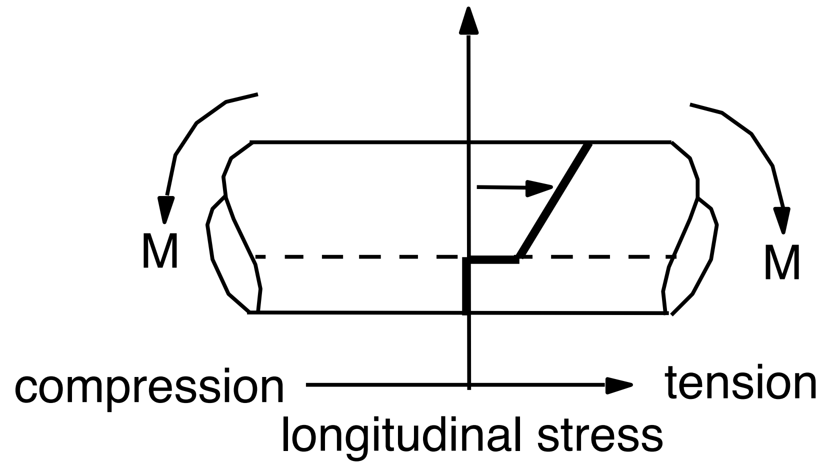
Joint angle error standard deviation (deg)

Joint	8 markers	7 markers	6 markers	5 markers	4 markers
Elbow	3.7	4.2	4.6	5.0	5.3
Knee	2.8	3.3	3.5	3.8	4.0

Beam Model

Main, Peterson, and Strauss, 1994

- Fabric wrinkles when compressed, then does not contribute to flexural rigidity



- Solve numerically for bending angle $\square_0$

$$\frac{M}{pr^3} = \frac{\square/2\left[(\square\square\square_0) + \sin\square_0\cos\square_0\right]\square\square\left[(\square\square\square_0)\sin\square_0\cos\square_0\,\square\,(2\sin\square_0)^2\right]}{\sin\square_0 + (\square\square\square_0)\cos\square_0}$$

- Substitute $\square_0$ into moment-curvature equation

$$K = \frac{M\,\square\,2\square pr^3\sin\square_0}{Er^3\left[(\square\square\square_0) + \sin\square_0\cos\square_0\right]}$$

- Assume cantilever boundary conditions, moment applied distance a from beam root

$$\square = aK$$

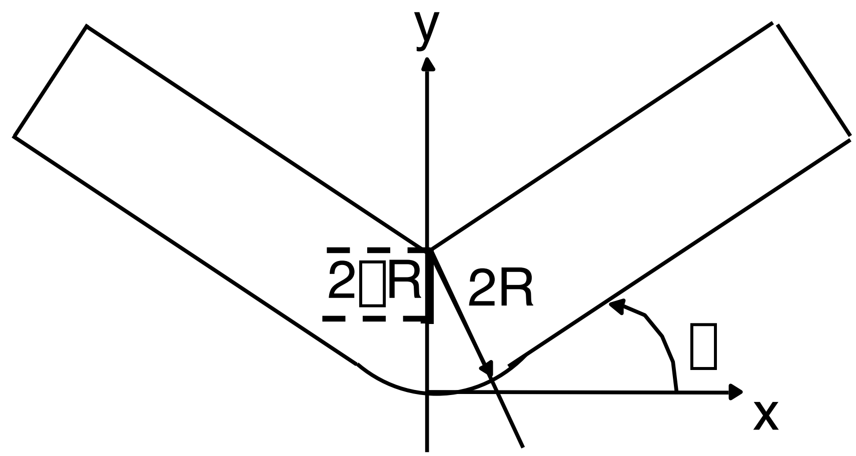
Membrane model

Fay and Steele, 2000

- Energy minimized when

$$M = \square p \frac{\partial V}{\partial \square}$$

- Inextensibility and cylindrical shape provide enough information to specify bent tube shape and obtain V(□)

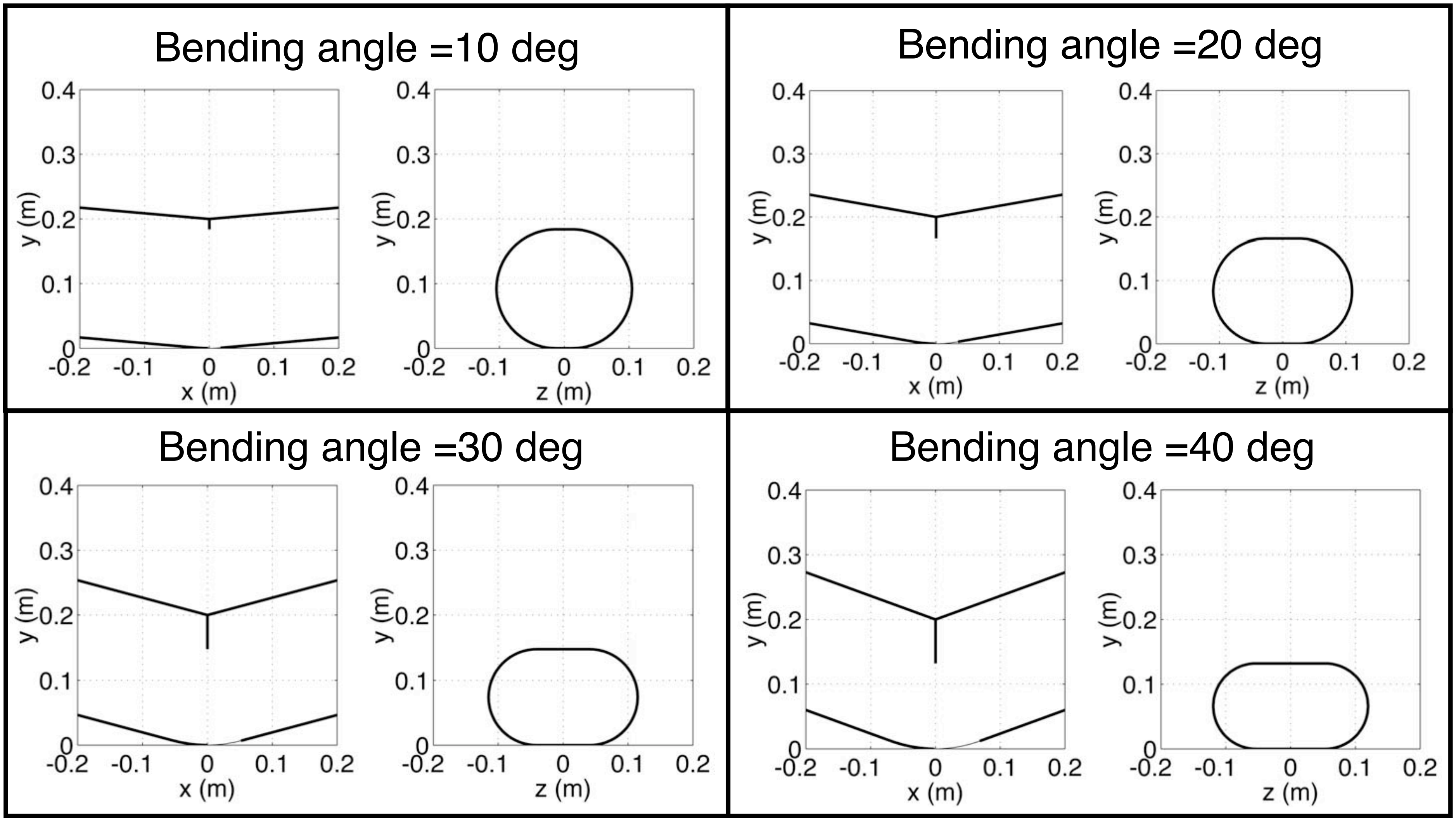


- Numerically integrate cross-sectional area to get V(□)

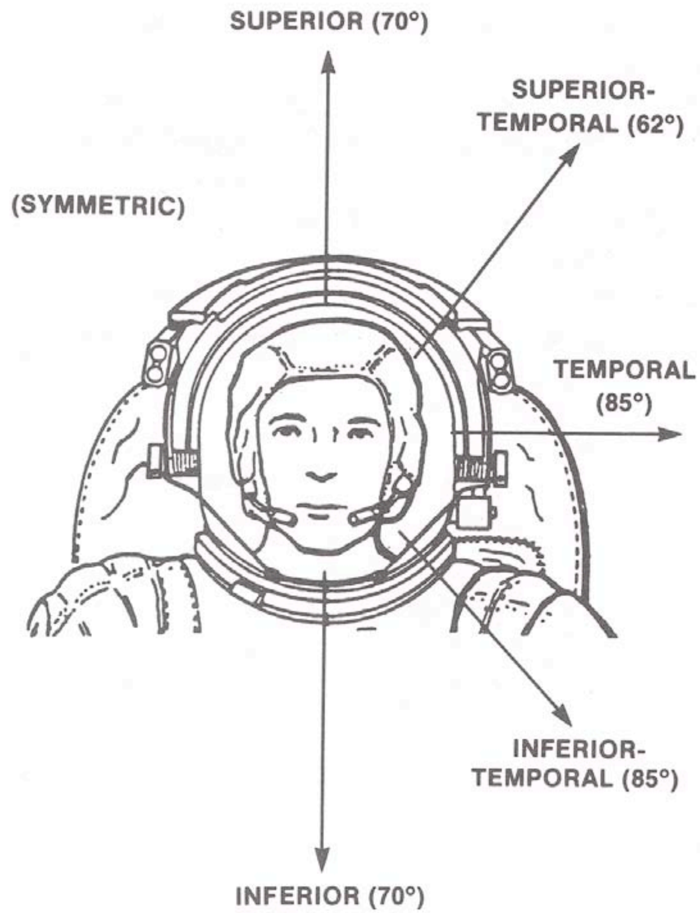
$$A = \square R^2 \square R \square \frac{H}{2} \square^2$$

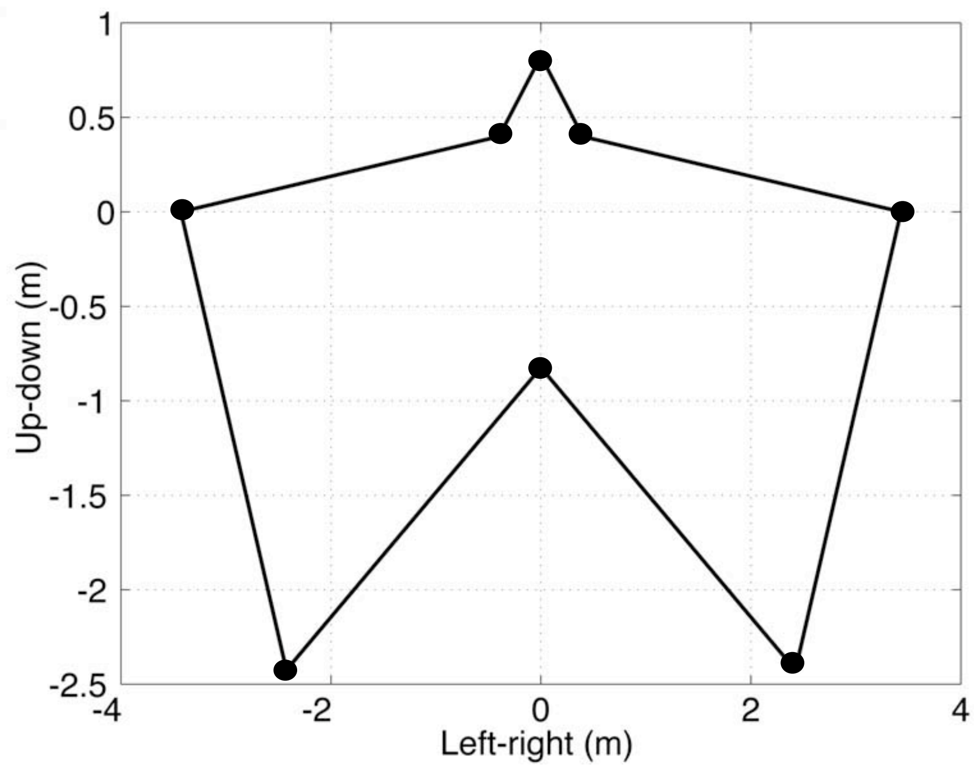
- Differentiate V(□) to get M(□)

Membrane model



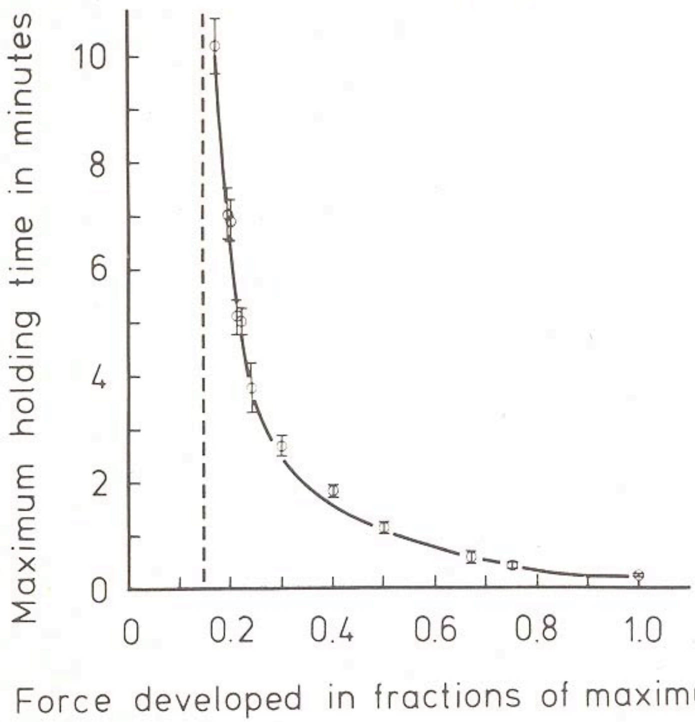
Work Envelope: Visibility





NSTS-07700

Work Envelope: Torque Limits



Astrand, 1977

Motion	50th percentile male (Nm)	95th percentile male (Nm)	50th percentile female (Nm)	95th percentile female (Nm)
Shoulder flexion (+)	71	101	37	57
Shoulder flexion (-)	67	115	30	54
Shoulder abduction (+)	67	103	33	57
Shoulder abduction (-)	92	119	40	60
Elbow flexion (+)	77	111	41	55

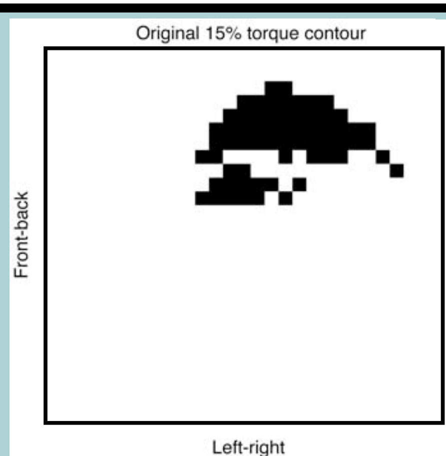
Chaffin, 1984

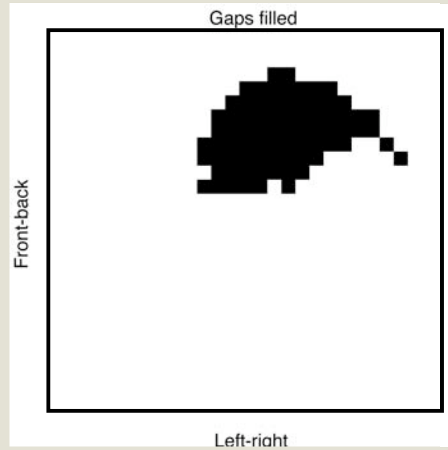
-23 deg < Humerus rotation < 160 deg

NASA STD-3000

Work Envelope: Smoothing

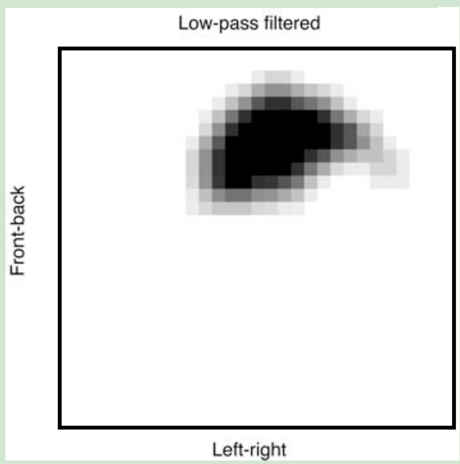
1. Start with 15% torque contour as binary image

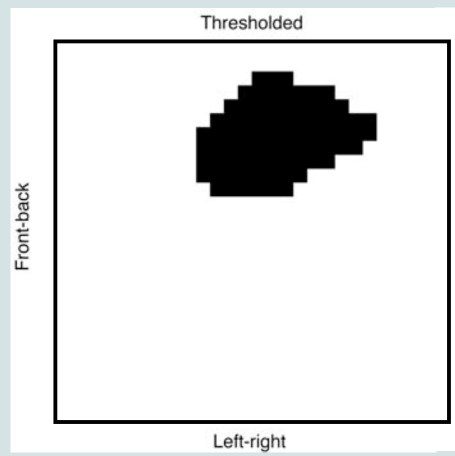




2. Fill holes using morphological operators

3. Low-pass filter



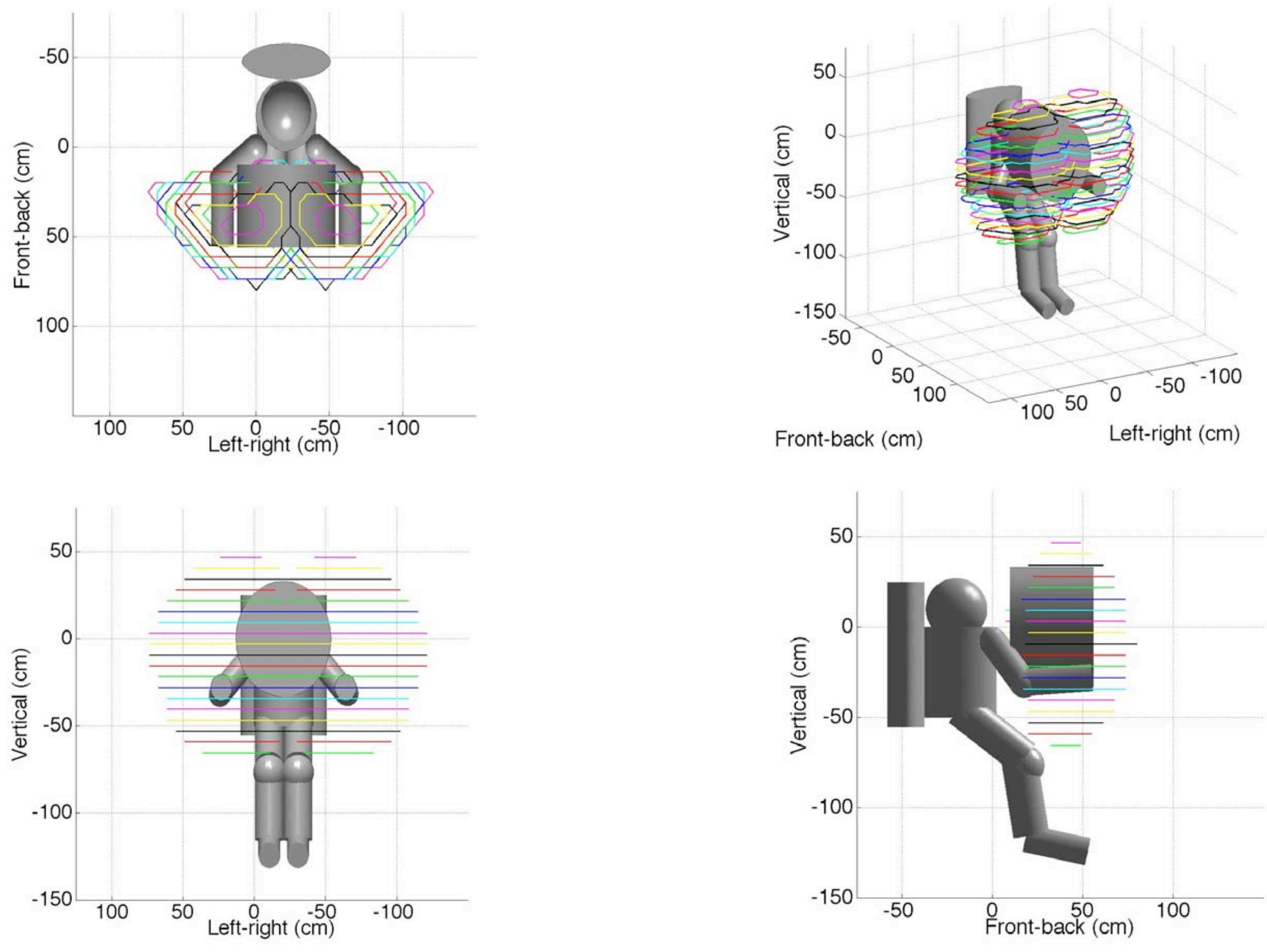


4. Convert back to binary

Set threshold so that

- Less than 30% new points added
- Fewest vertices in contour

NASA work envelope



Work envelope volumes