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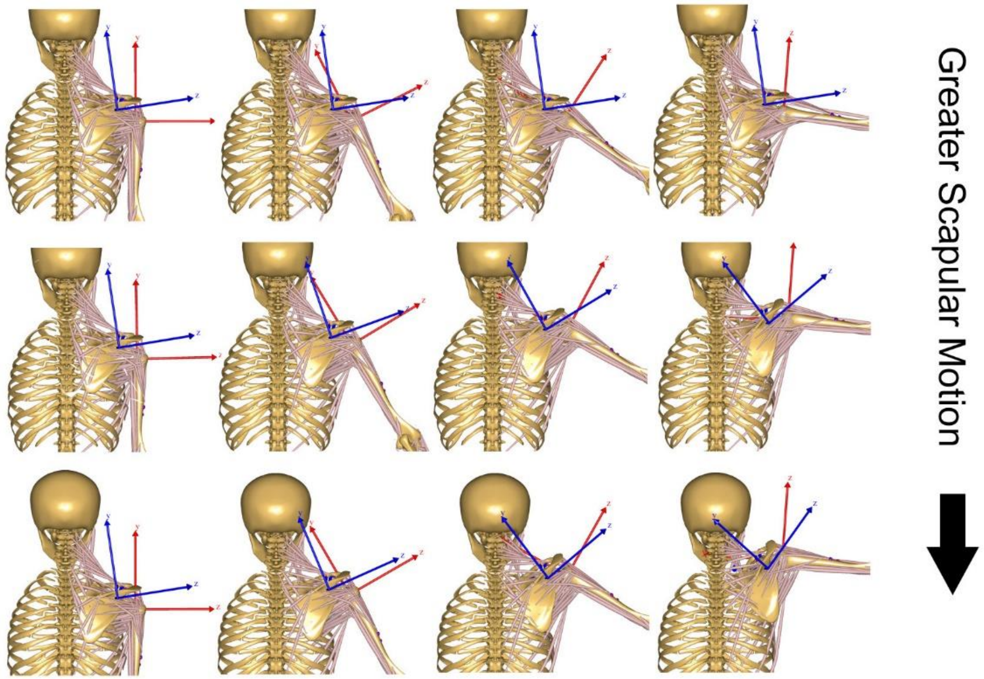


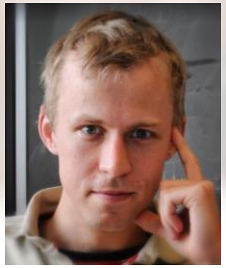
Scapulothoracic Rhythm Affects Glenohumeral Joint Force

A VIRTUAL POPULATION STUDY WITH MUSCULOSKELETAL MODELING

Outline

- General introduction to the modeling system
- Presentation by Cesar Flores
  - Scapulothoracic Rhythm Affects Glenohumeral Joint Force
- Questions and answers

Presenter:
Cesar Flores
Research associate,
Shiley Center for Orthopedic Research and Education,
Scripps Clinic in La Jolla



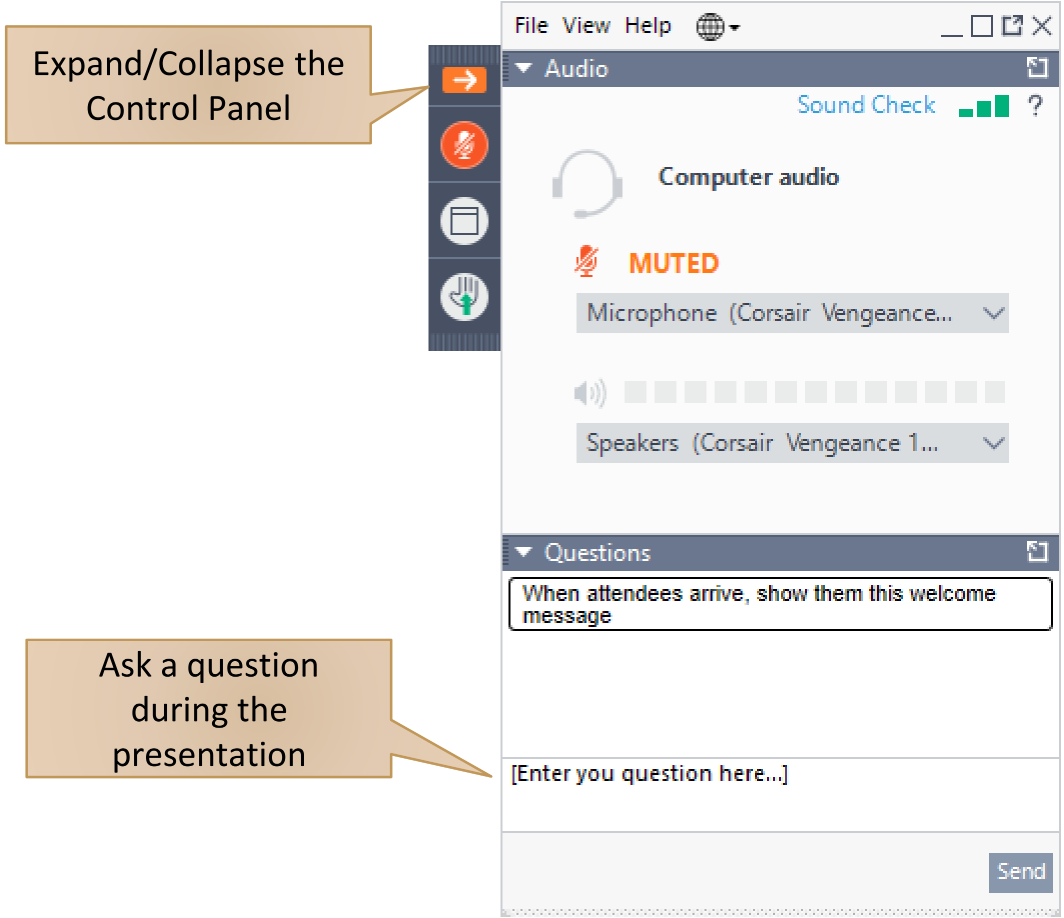
Host:
Morten Enemark Lund
Sr. R&D Engineer

Control Panel

The Control Panel appears on the right side of your screen.

Submit questions and comments via the Questions panel.

Questions will be addressed at the end of the presentation. If your question is not addressed we will do so by email.



Musculoskeletal Simulation

Motion data
Kinematics + Forces

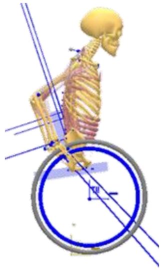
→

AnyBody Modeling System

→

Body Loads
- Joint moments
- Muscle forces
- Joint reaction forces

ANYBODY TECHNOLOGY

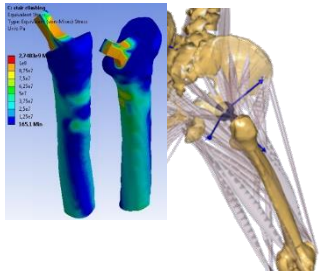


Product Design Optimization

Movement Analysis

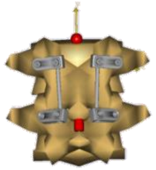
ANYBODY Modeling System

Ergonomic Analysis



Load Cases for Finite Element Analysis

Surgical Planning and Outcome Evaluation



Scapula Motion and Shoulder Biomechanics

Cesar Flores

Shiley Center for Orthopaedic Research & Education
Scripps Clinic, La Jolla, CA

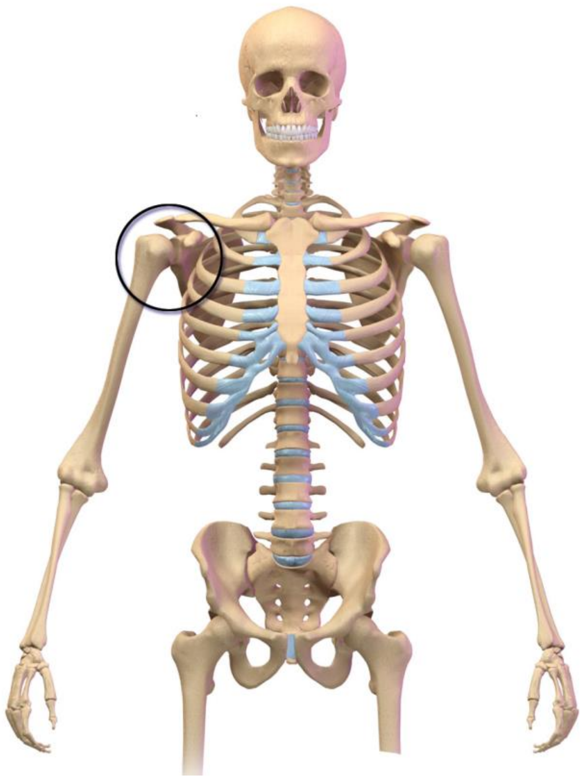
FINDINGS

- Increasing body height increased glenohumeral joint forces.
- Increasing the ratio
  of scapulothoracic to glenohumeral elevation also increased forces.
- Increasing humeral head radius and acromiohumeral interval decreased forces.
- We found that scapulohumeral rhythm had a significant influence on glenohumeral joint force.

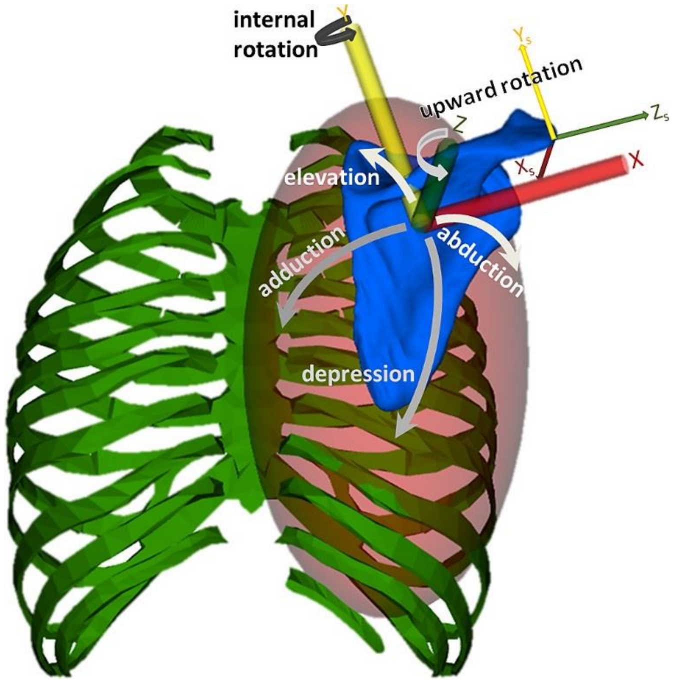
What is Scapula Motion?

Shoulder is not jus one joint.

- Glenohumeral Joint



- Scapulothoracic Joint



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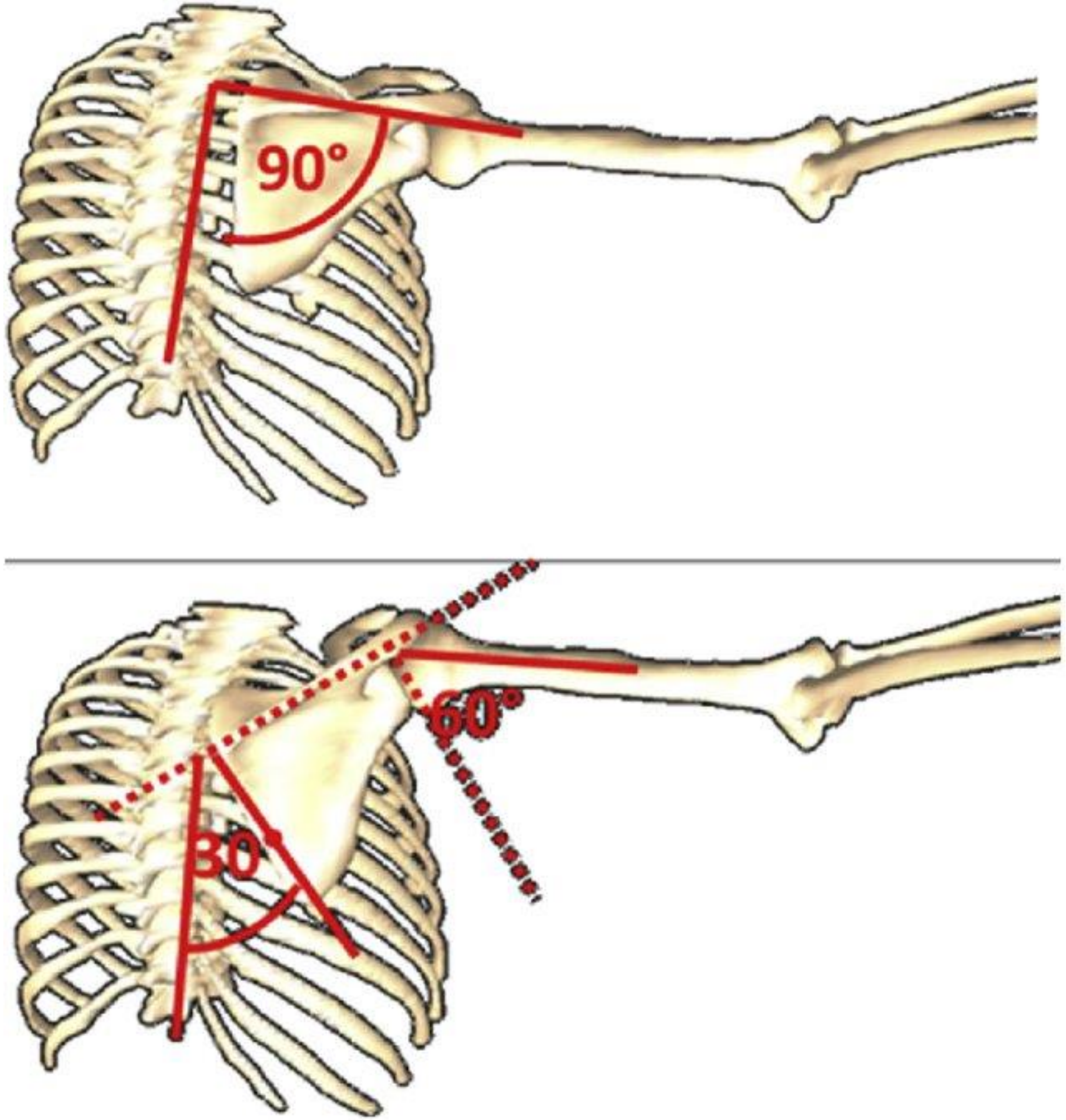
What is Scapula Motion?

- **Scapulohumeral Rhythm**: The ratio of humeral elevation with respect to the scapular elevation. The humerus elevates relative to the scapula. The scapula elevates relative to the thorax.
- **The normal rhythm is 2:1** but it can vary due to disease. Frozen shoulder patients have an inverted rhythm of 1:2



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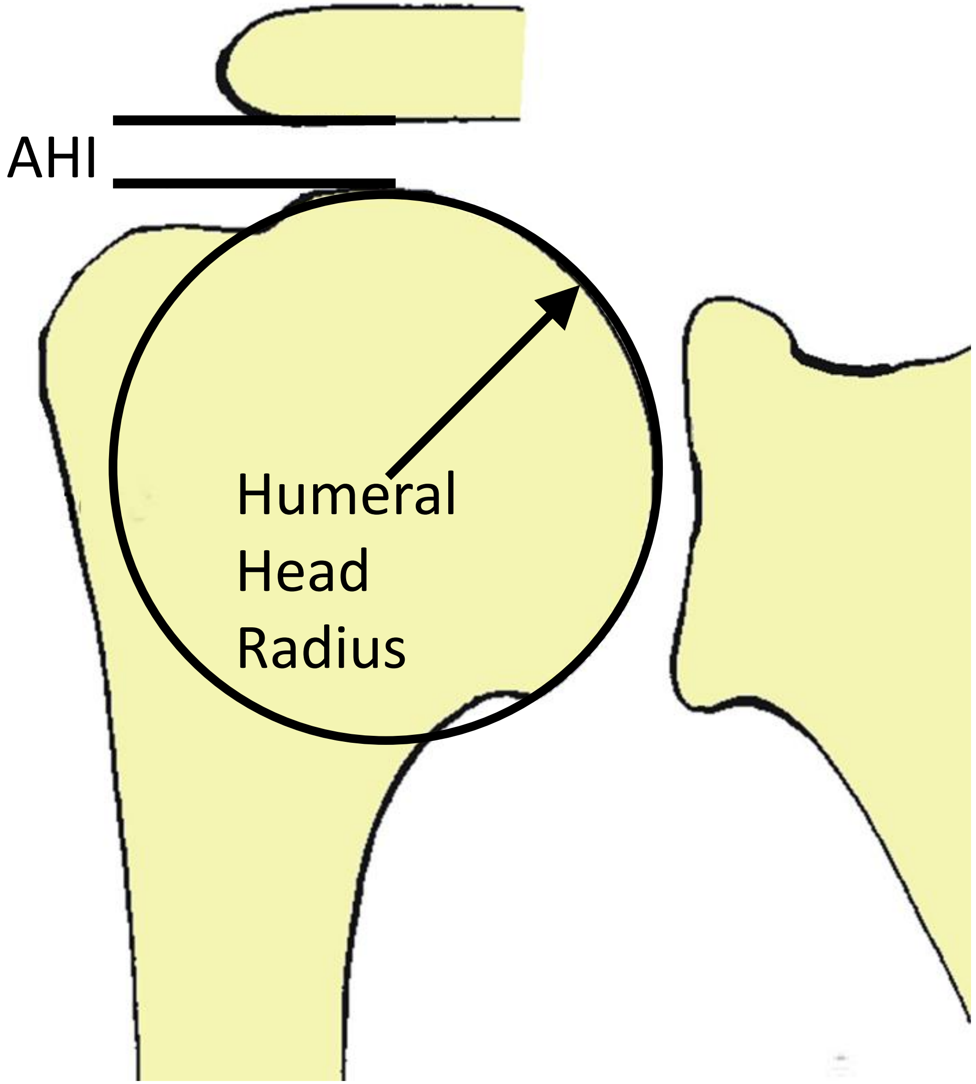
- Lack of Confidence in Model Predictive Ability has prevented adoption of models practically.
- In vivo measurements for validation improve the confidence
- In shoulder it’s important to assess robustness of the model to uncertainties in the inputs and assumptions.
- Need better inputs for models. Uncertainty about important inputs ->motivation for study
- What are the most important inputs? How important is scapula motion compared to other input variables?

?

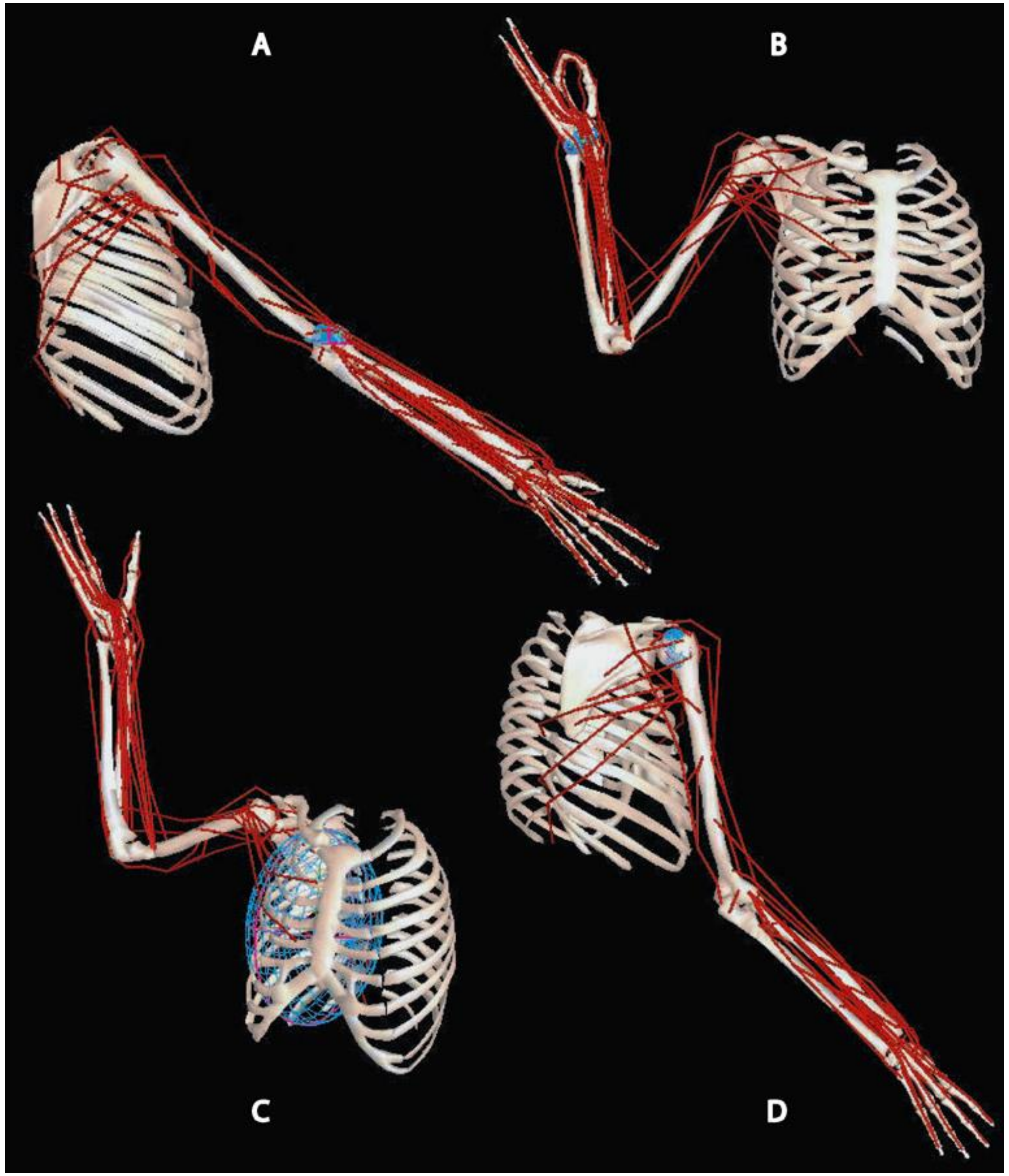
INPUTS

- The goal of our study was to quantify the sensitivity of the shoulder model predictions to important model input parameters.
- A sensitivity analysis using the Anybody Modeling System
- Input Parameters Investigated
    - Height
    - Body Mass
    - Humeral Head Radius
    - Acromiohumeral Interval
    - **Scapular Motion**



Previous Computational Models

- Delft Shoulder and Elbow Model
  - Scapula motion is prescribed but not varied
- UK National Shoulder Model – Charlton and Johnson 2006
- Garner and Pandy Model (2001)
- Swedish Shoulder Model
- Stanford-VA Model
  - Regression based scapula motion



But…

- Scapulothoracic kinematics are important component of shoulder kinematics
- These are hard to measure in vivo
  - fluoroscopy or insertion of pins
  - Noninvasive methods like motion tracking with skin markers are not accurate
- Most models now prescribe scapula motion as a function or ratio of glenohumeral motion and are based on healthy subject populations.
- Scapula motion is highly variable even in normal subjects – fatigue also affects the scapula’s motion
- Determines moment arms AND muscle lengths

We set out to analyze the relative importance of scapulohumeral rhythm, using an Anybody model, compared to other more obvious shoulder input variables like humeral head radius and limb lengths, etc.

Materials and Methods

Anybody Modeling System

The model was taken from the Anybody Managed Mode Repository and is based on the Dutch Shoulder Model. F.C.T. van der Helm, Journal of Biomechanics 1994

- Seven Segments
  - Thorax
  - Scapula
  - Humerus
  - Clavicle
  - Ulna
  - Radius
  - Hand

Six Joints

- Ground to Thorax
- Sternoclavicular
- Acromioclavicular
- Glenohumeral
- Elbow
- **Scapulothoracic Joint**

Grey - Rigid
Blue – Spherical Joints
The scapulothoracic joint was modeled by constraining the inferior angle of scapula and scapula Y point to an ellipsoid approximating the ribcageThe grey were rigid

Modifications to the AMMR shoulder model

- Allow for variation in scapula motion
  - Default anybody scapulohumeral rhythm based on paper by Groot and Brand.
- Deltoid wrapping allow varying humeral head radius

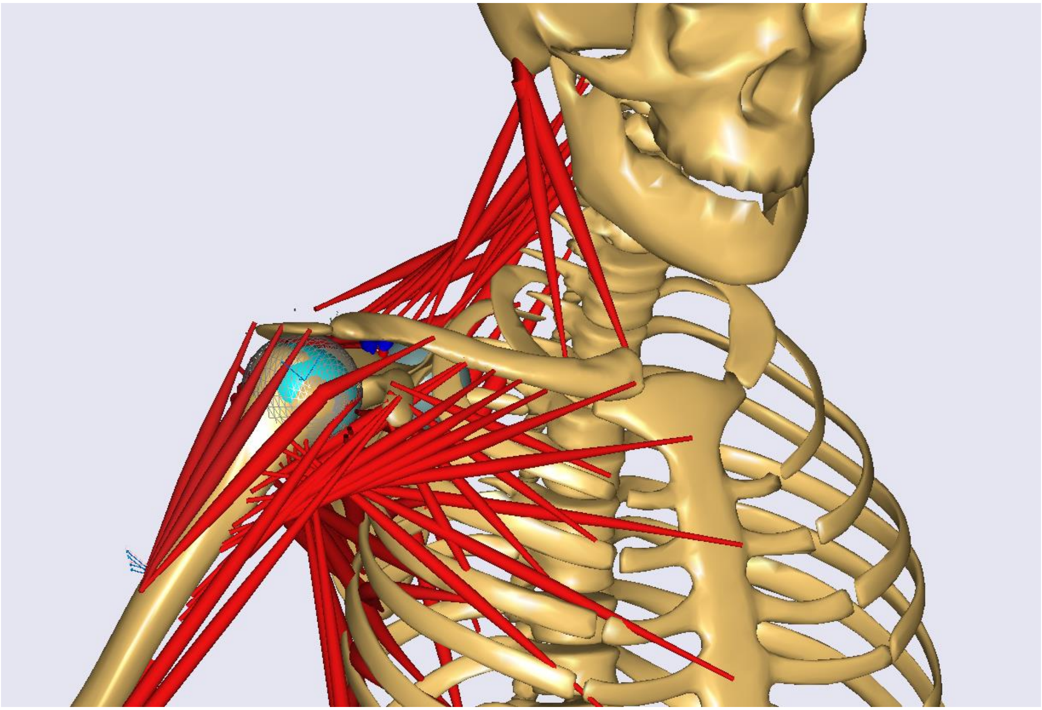


Table II
Ranges of inputs for sensitivity analysis

Parameter	Minimum	Maximum
Scapulohumeral rhythm	No scapular rotation	1:2
Humeral head radius	20 mm	37 mm
Acromiohumeral interval	0 mm	25 mm
Body height	1.4 m	2 m

- Base Model
- Limb lengths and masses derived from height and weight
- Previously published ranges for humeral head radius and acromiohumeral interval values
- Uniform distributions for each parameter

- Simulation Approach
  - Inverse dynamics used to compute muscle and joint reaction forces during a simulated shoulder elevation
  - Static optimization to minimize activations of muscles

- **Sensitivity Analysis**
  - General outline:
    - Quantify the uncertainty in each input (ranges, probability distributions)
    - Identify the model output to be analyzed
    - Ran the model 1000 times with different inputs.
    - Use the resulting model outputs to calculate the sensitivity of the output to each input

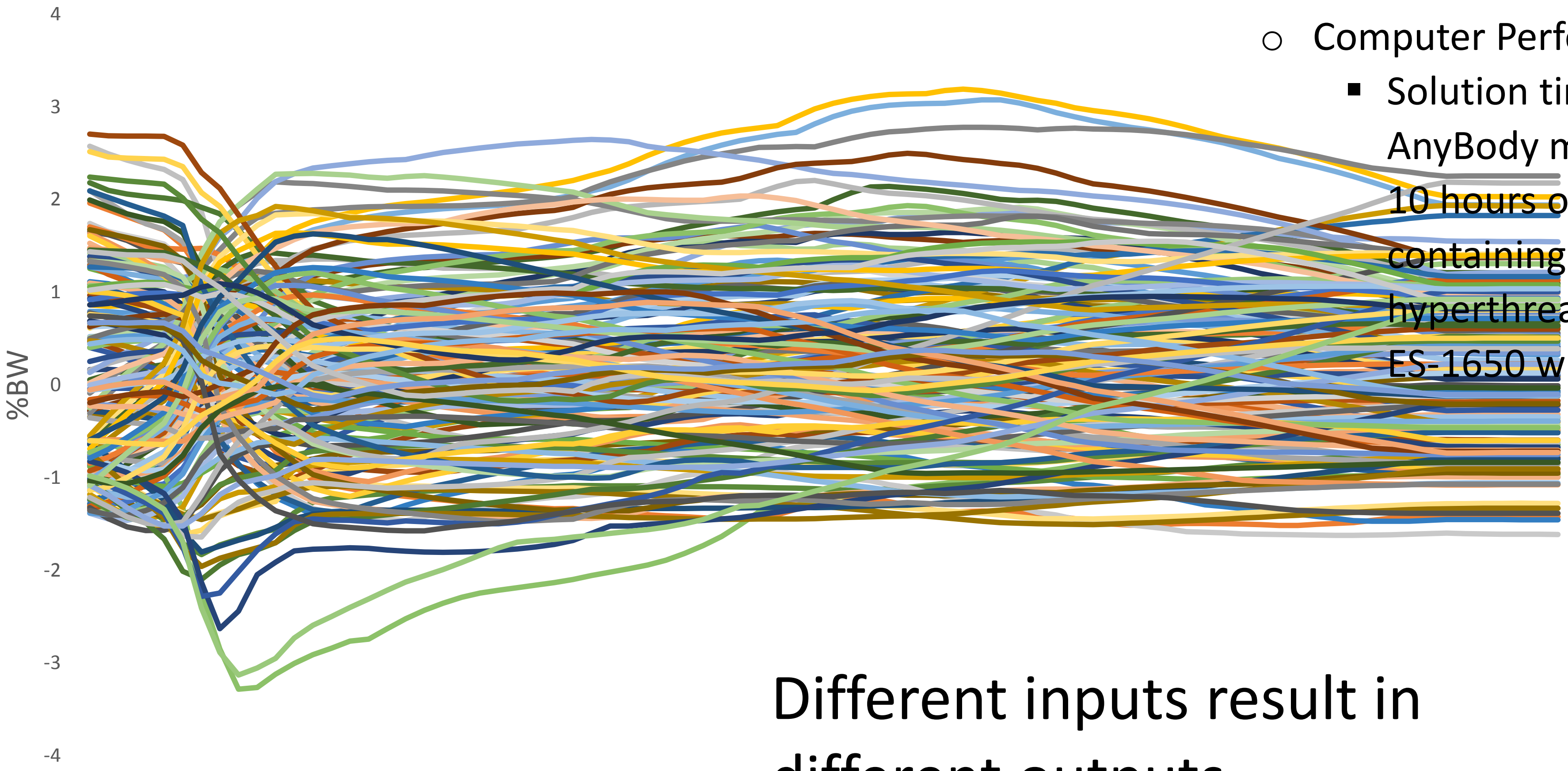
- The power of Anybody. Build a Virtual Population of shoulders
- Python script leveraging Anybody Console Application
- 1000 different models with random values for the inputs
  - Each parameter value was from a uniform distribution
  - Interactions between different inputs
- Python script running Anybody Console

automaticShoulder_005.py - E:_ONGOING\ANYBODY_SHOULDER_MODEL\AMMR\Application\Validation\Bergman

File Edit Format Run Options Window Help

```python
from anypytools.macro_commands import Load, OperationRun, Dump, SetValue, UpdateValues
import numpy as np
import csv
#from itertools import izip

#The names of the files that will be used
inputFileName = "input_d"
ghcfHistoriesFileName = inputFileName +  '_ghcfTestFile'
maxGHCFfileName = inputFileName + '_maxGHCF'
momentArmHistoriesFileName = inputFileName + '_momentArms'

data=np.genfromtxt(inputFileName + ".txt", unpack=True)

simulationIteration = data[:][0].tolist()
scapulaMotionCoefficient = data[:][1].tolist()
humeralHeadRadius = data[:][2].tolist()
acromioHumeralInterval = data[:][3].tolist()
myBodyWeight = data[:][4].tolist()
myBodyHeight = data[:][5].tolist()

# This cell writes the various macros in the parametric study
macro = [Load('BergmannGHTest_IlanShoulderModel.Main.any'),
         SetValue('Main.simulationIteration', simulationIteration),
         SetValue('Main.scapulaMotionCoefficient', scapulaMotionCoefficient),
         SetValue('Main.humeralHeadRadius', humeralHeadRadius),
         SetValue('Main.acromioHumeralInterval', acromioHumeralInterval),
         SetValue('Main.myBodyWeight', myBodyWeight),
         SetValue('Main.myBodyHeight', myBodyHeight),
         UpdateValues(),

         OperationRun('Main.Study.InverseDynamics'),
         Dump('Main.simulationIteration'),
         Dump('Main.scapulaMotionCoefficient'),
         Dump('Main.humeralHeadRadius'),
         Dump('Main.acromioHumeralInterval'),
         Dump('Main.myBodyWeight'),
         Dump('Main.myBodyHeight'),
         Dump('Main.Study.Output.Y_i.Val'),
         Dump('Main.Study.Output.GHJFmagnitude.Val')]
parameter_study_macro = AnyMacro(macro, number_of_macros = 2)
parameter_study_macro
```

Shoulder Joint Force For Many Different Iterations of Shoulder Model



- Computer Performance
  - Solution time for 1000 AnyBody models was about 10 hours on a desktop PC containing a 6 core hyperthreaded Intel Xeon ES-1650 with 64 GB of RAM

Different inputs result in different outputs

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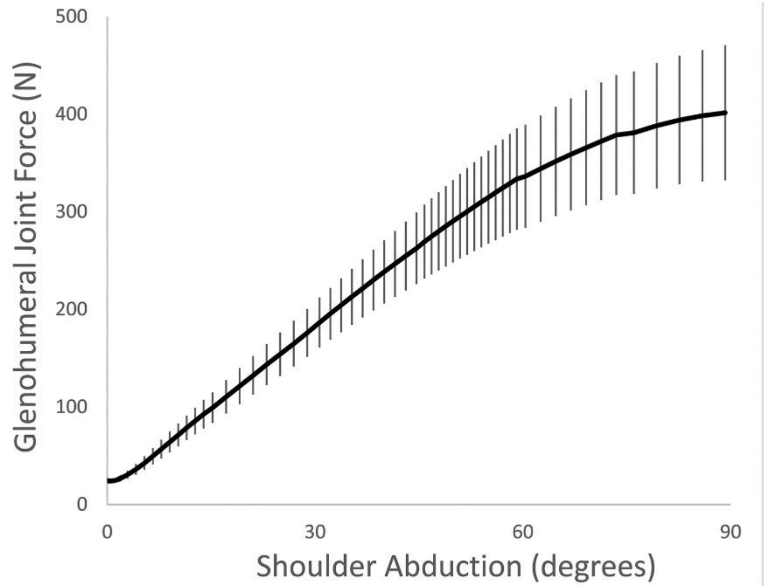
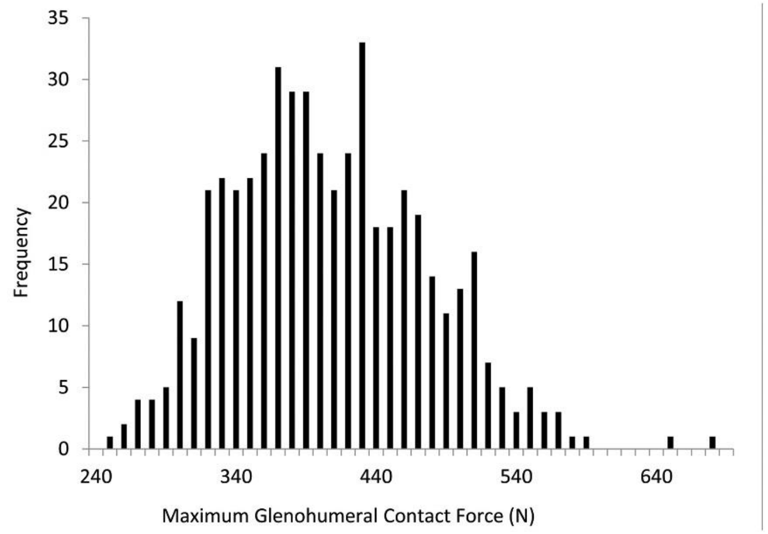
- Data Analysis
  - Linear Regression
    - Normalized the inputs and the outputs by the middle value and performed a linear regression. The output was the joint force between the glenoid and the humerus.
      - Why uniform distribution for inputs.
      - If we do normal distribution too many samples close to the average. Sampling problem. Represent the entire range evenly.
      - Don’t care about probability of input value
    - The analysis took the form Y = C0 + C1*X1 + C2*X2 …
    - We repeated this analysis for 30, 40, 70, and 90 degrees of arm elevation
    - Assumed linearity but this was valid because the R^2 values of the analysis were well north of .8

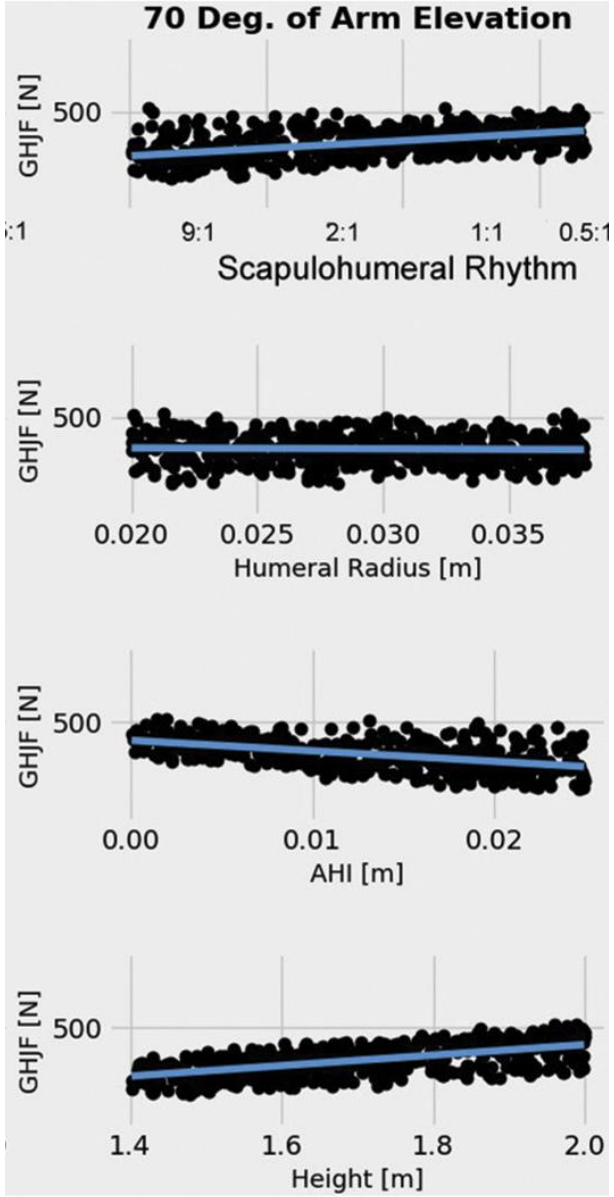
- Results
  - Average peak joint force = 400N



  - Although inputs were uniformly distributed the predicted glenohumeral joint forces were normally distributed
    - Combinations of extreme inputs will result in extreme outputs but can also cancel each other



Joint Force is a Function of the Inputs with varying sensitivity



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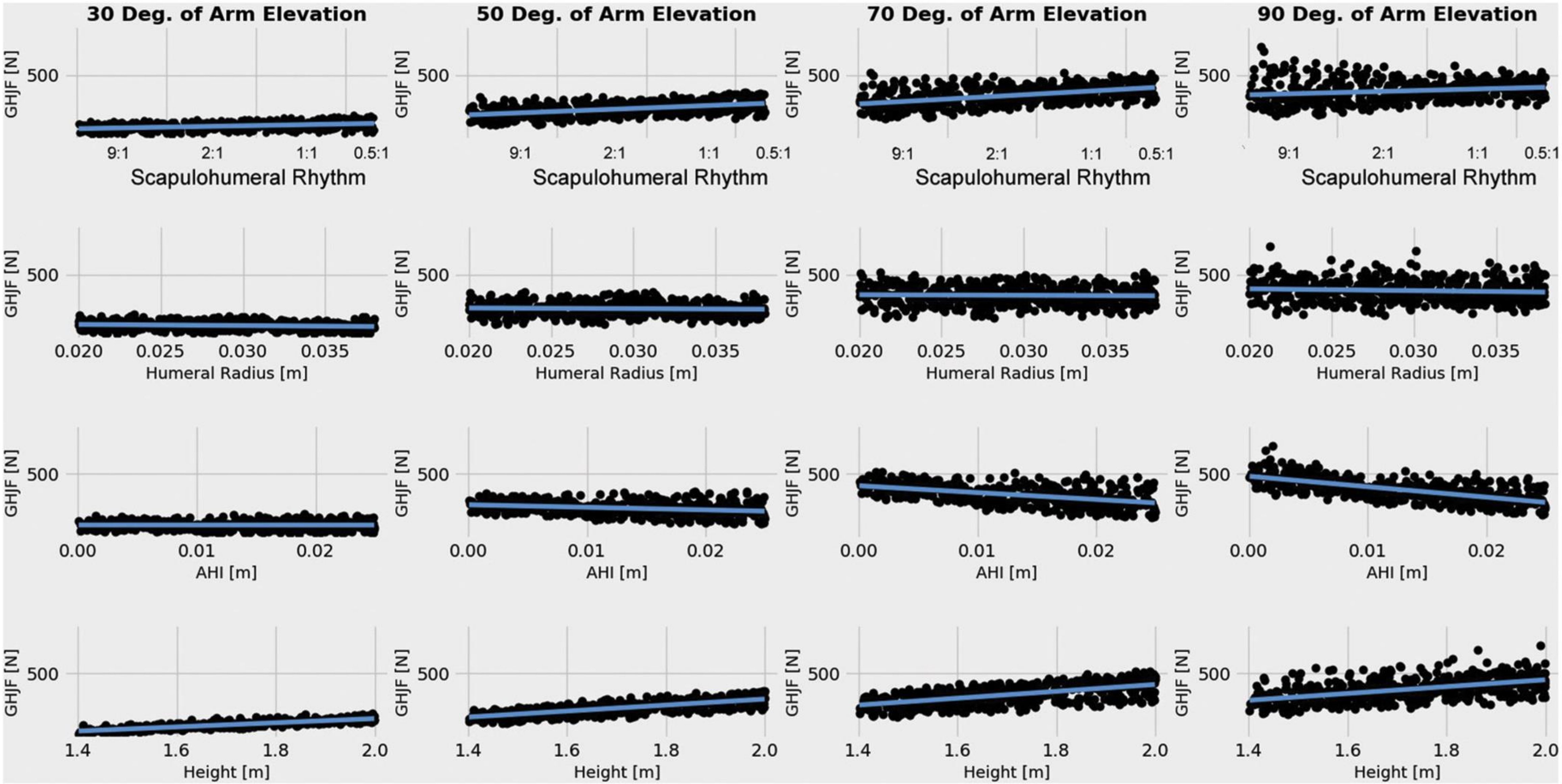
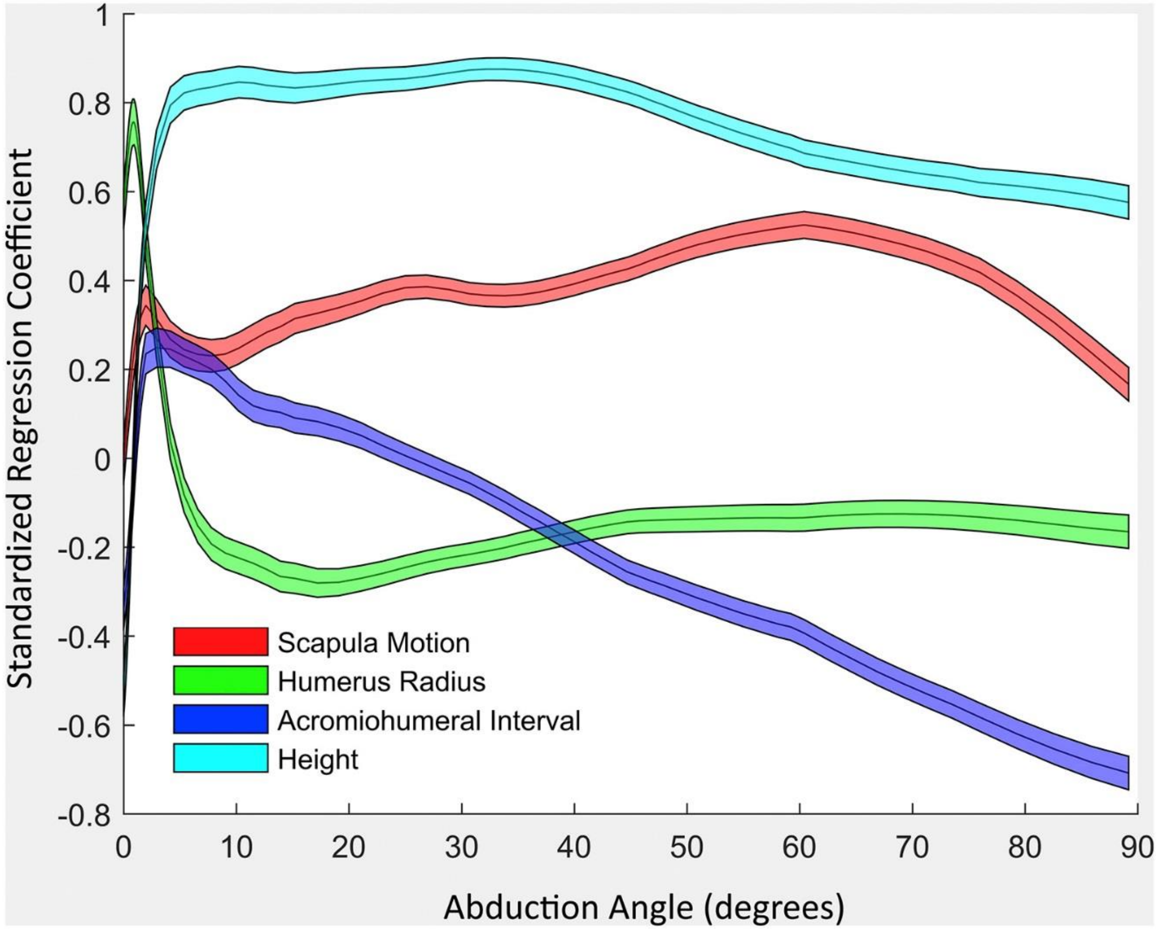


Figure 4 The range of the effect of each input parameter on joint force is depicted for different angles of arm elevation. Height and scapular humeral rhythm have the most effect on glenohumeral joint force (*GHJF*). Note that scapular elevation is 0 at the origin of the x-axis and that the entire shoulder elevation occurs at the glenohumeral joint. Humeral head radius and acromiohumeral interval (*AHI*) have a smaller negative influence on joint force.



- Sensitivity Note the wide variation in sensitivity for different arm elevation angles.
  - This shows the dynamic nature of the biomechanics of arm elevation

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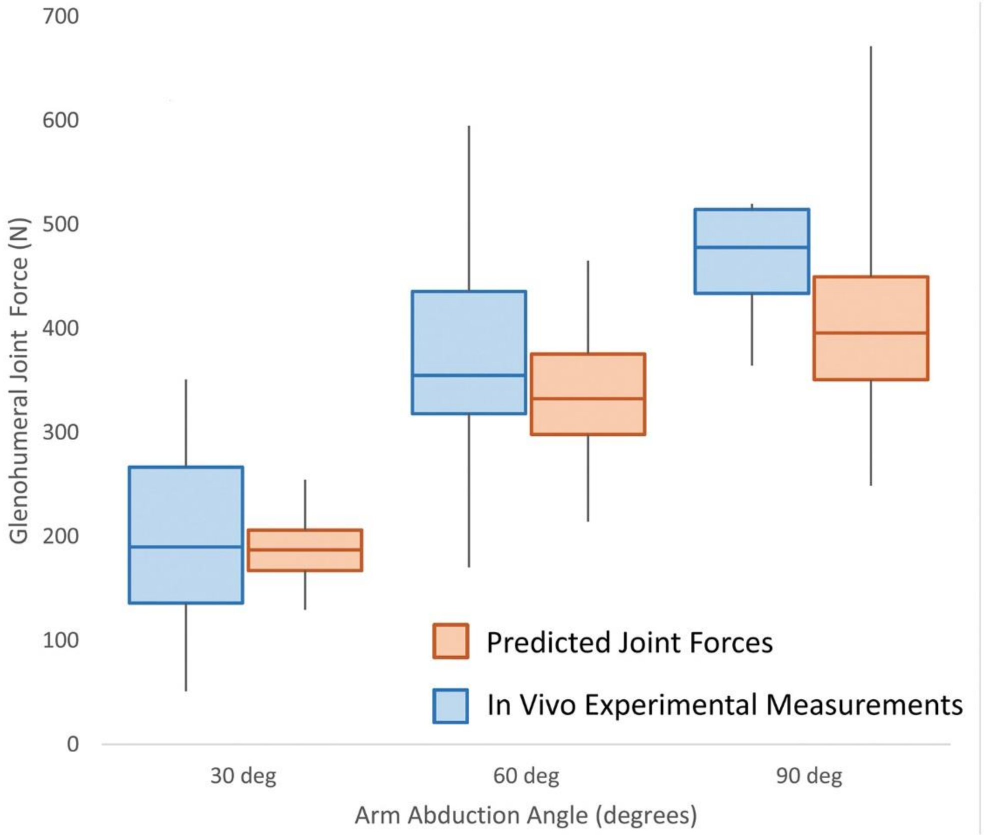
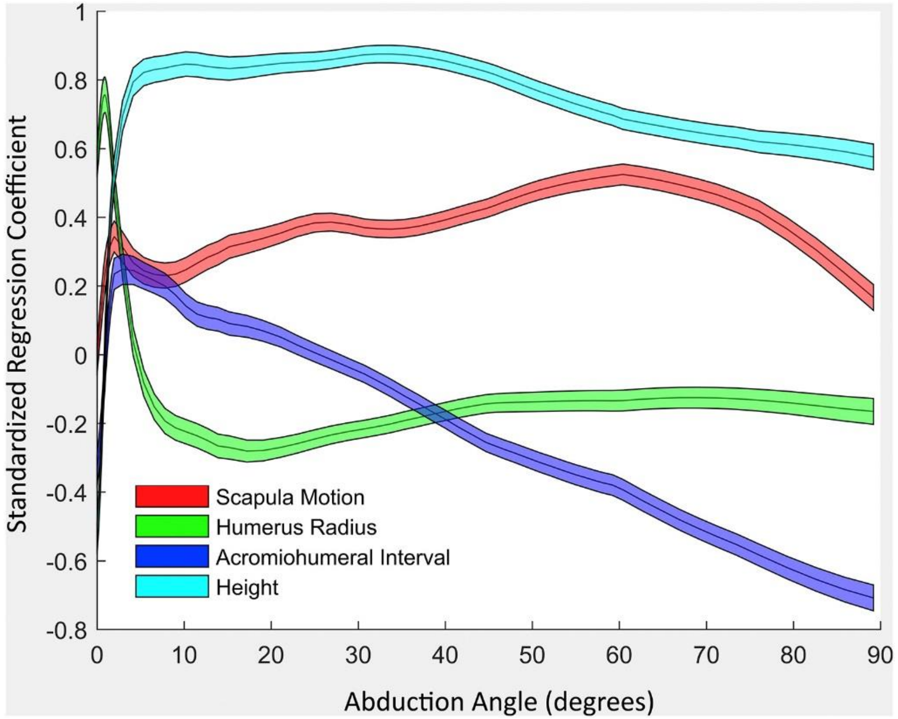
- Validation
  - We compared the range of predicted glenohumeral joint forces with in vivo measurements published for the same activity.
  - Bergmann et al, J Biomechanics 2011
  - The joint forces predicted at 30, 60, and 90 were well within the ranges predicted for our model population.



- Discussion
    - The complexity of the shoulder girdle – modeling challenges
    - Scapula a floating bone whose motion is controlled by scapulothoracic muscles and scapulohumeral muscles.
    - scapulohumeral rhythm is an important feature of shoulder function and is often disrupted during disease Restoring this rhythm major goal of physical therapy and rehabilitation after injury, disease, or surgery.
    - We built a population of 1000 virtual shoulders to assess the importance of the scapula rhythm to the glenohumeral
    - We then compared the impact of scapula rhythm to other important shoulder parameters like limb length and mass, humeral head radius and acromiohumeral interval width
    - The subject's height which correlated with limb lengths had strongest effect on joint force. This may be an artifact because the muscle attachment points were not updated only the lengths of the bones increased with height. Muscle moment arms may increase with height as well as limb lengths but this effect was not modeled.

- Scapula motion is an important input throughout the range of arm elevation, peaking in importance around 60 degrees of elevation
- Height is always important and positively correlated to joint force
- Acromiohumeral Interval width rises in importance as the arm reaches 90 degrees of elevation but is inversely correlated to joint force.
    - The greater the AHI width the lower the joint force and vice versa.
- While not as important as some of the other inputs the radius of the humeral head was a factor. Inversely proportional to joint force



- Alternative Sensitivity Analyses
  - One at a time – Simpler but does not account for interactions between the input variables.
  - Variance-based approaches. Fortunately the response of our model with respect to the inputs was linear and thus we could use linear regression method.
  - Local Methods, taking the partial derivative of the output with respect to each input near a fixed value of the input – Does not assess the effects of the input over a wide range of its possible values.
  - Scatter Plots – Not as quantitatively
  - Emulators or metamodels.
    - Modeling the model
    - The challenge is to find an emulator
  - Fourier Amplitude Sensitivyt Test (FAST)
    - Fourier series representation of the model in the frequency domain. Univariate resulting in computational savings.
  - We chose Regression Analysis because the regression was linear with respect to the data. The coefficient of determination was large at .82.

- Why such a limited number of inputs? Computational expense. These were the inputs deemed essential and we wanted to minimize the number of inputs tested since the number of sample simulations grew exponentially with the number of inputs.
- Why choose glenohumeral joint force?
  - joint force very correlated with the sum of muscle force – taken as a proxy for effort
  - correlated with stress which is correlated with wear in both anatomic condition and implanted condition.
- Why a population of 1000? Is this enough? Is this too much? Judging by the very narrow 95th percentile confidence intervals in figure 5 1000 models may have been overkill.
  - Computationally feasible
  - Smooth regression coefficient curves vs. elevation angle
  - R^2 over .8
  - Narrow 95th percentile confidence bands.

Conclusion

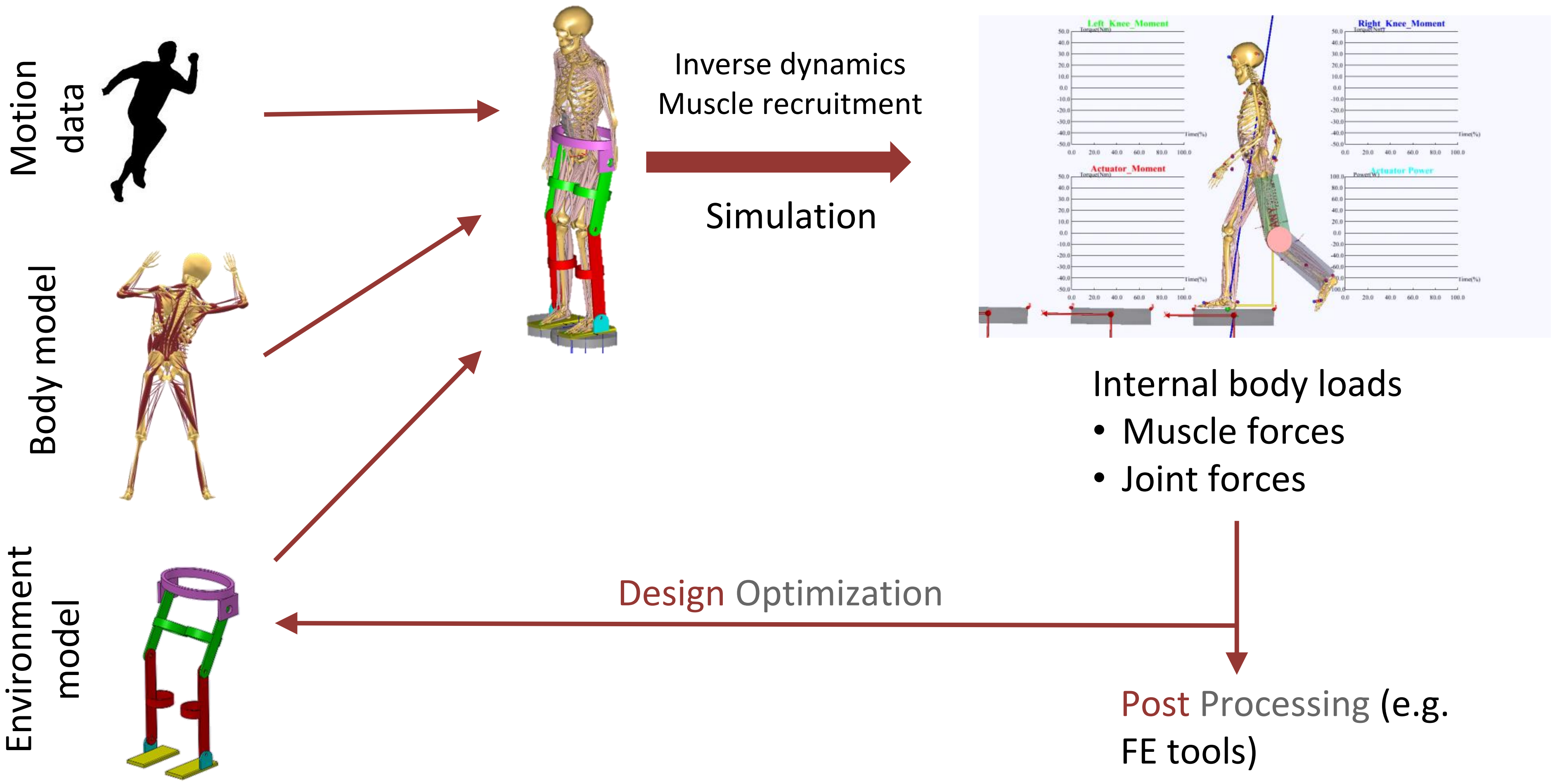
Increasing body height increased **glenohumeral joint forces**. Increasing the ratio of **scapulothoracic** to **glenohumeral** elevation also increased **forces**. Increasing **humeral** head radius and acromiohumeral interval decreased **forces**. ... We found that **scapulohumeral rhythm** had a significant influence on **glenohumeral joint force**.

- The relative importance of each of these input parameters changes with elevation angle, for example AHI.
- Unexpected result that Scapula motion is not only important but that its importance varies with shoulder elevation. sensitivity would vary so greatly with respect to elevation angle and that it was as influential as it turned out to be.
- Shoulder modelers should pay more attention to the modeling the scapula and its motion.
- Models Scapula Motion prediction?
    - Scapulothoracic muscles, contact
- Validation requires clinical measures of Scapulothoracic motion.
    - Only published methods are fluoroscopy and pins.

Would a different model have the same sensitivity profile?

Thank You.

AnyBody Modeling System



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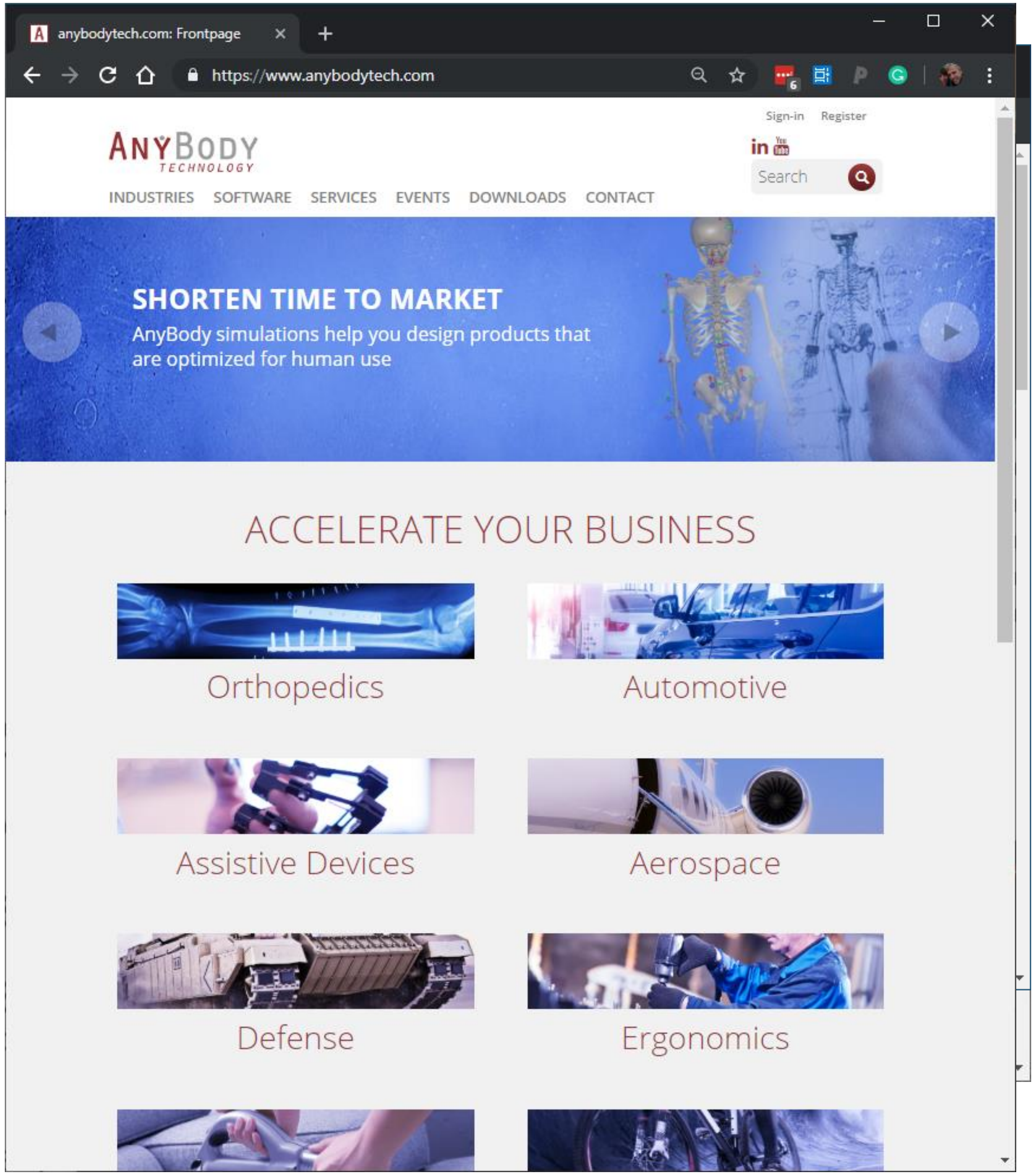

Events:

19-20 Nov: Meet us at the “WearRAcon Europe” exoskeleton event in Stuttgart, Germany

9 Jan: *Webcast:* Prediction of Kinetic Variables during Parkinsonian Gait using Depth Sensor-driven Musculoskeletal Modeling. University of Miami

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Time for questions: