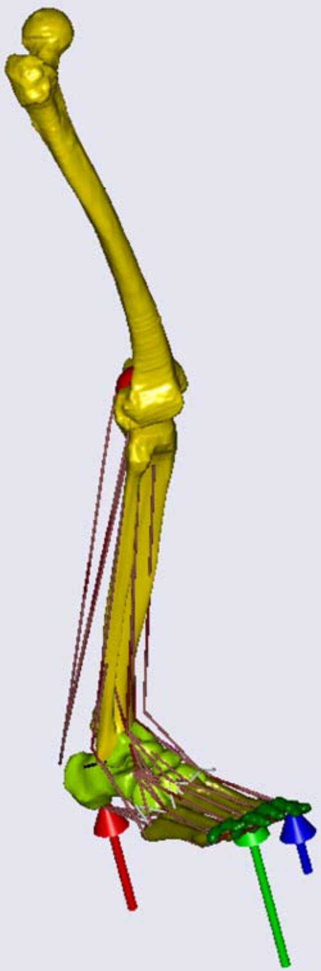
Foot Model for Clinical Gait Analysis



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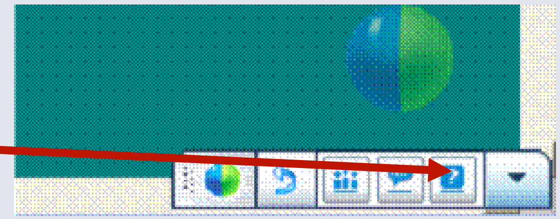
Q&A Panel



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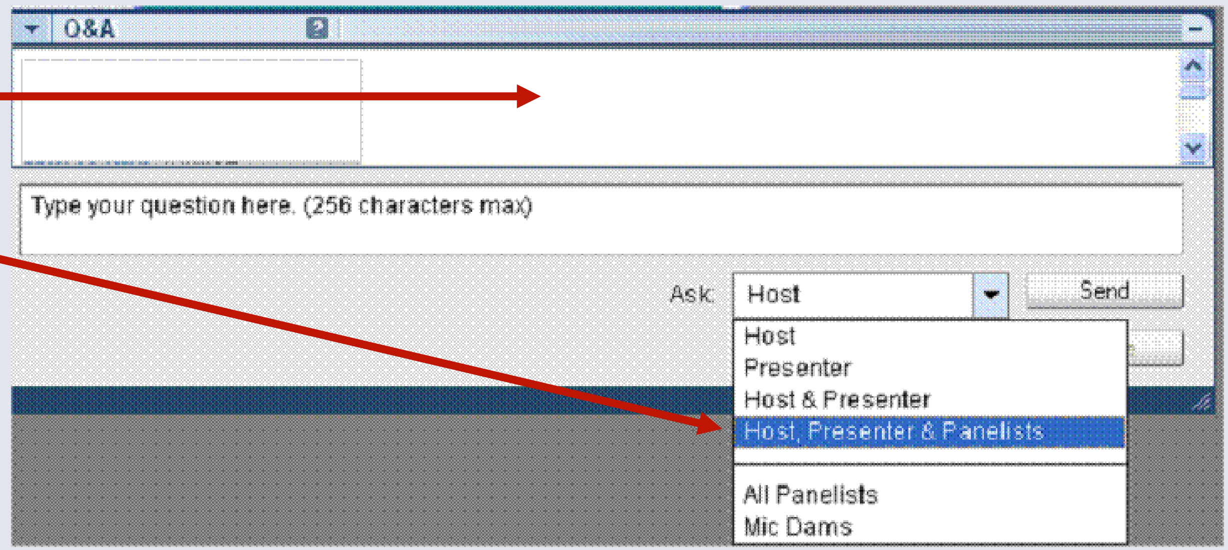

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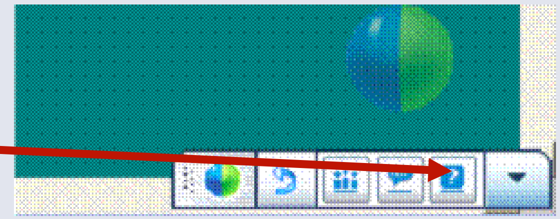

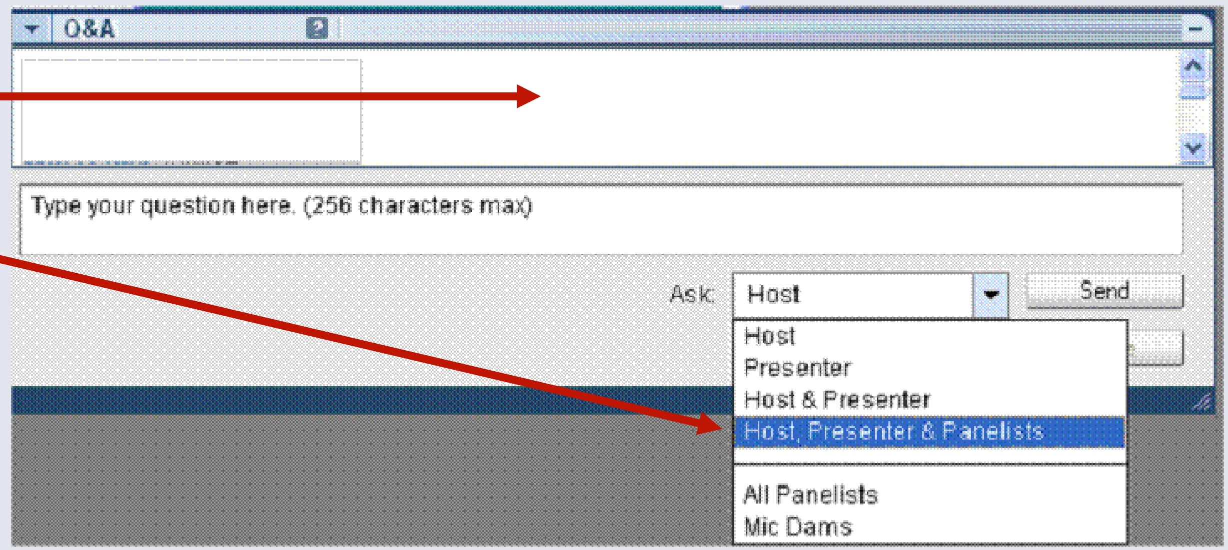

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Outline

1. Brief Introduction of Gait Analysis & need for a foot model

2. Development of the Base Model

3. Adaptation of the model for subject-specific application

4. Model Outcomes

5. Q&A

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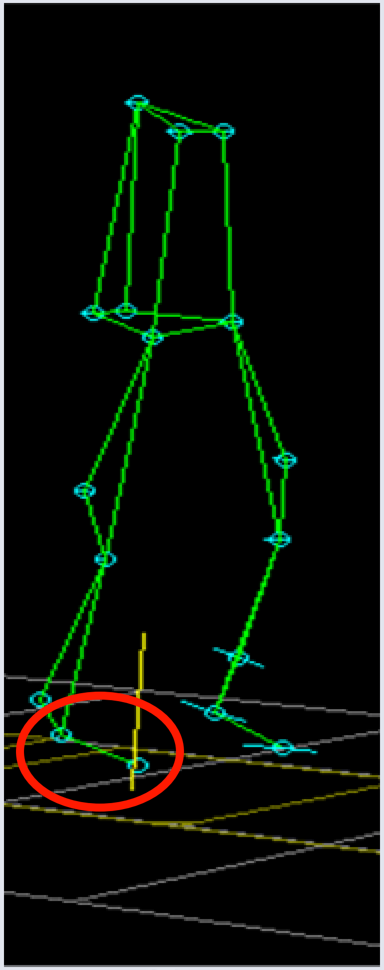
Clinical Gait Analysis

- Tool for clinical decision making since 1980
- Quantitative assessment of surgical outcomes
- Typically used in
  1) Children with neuromuscular disease
     a) Cerebral palsy
     b) Spina bifida
  2) Adults with stroke
  3) Prosthetics



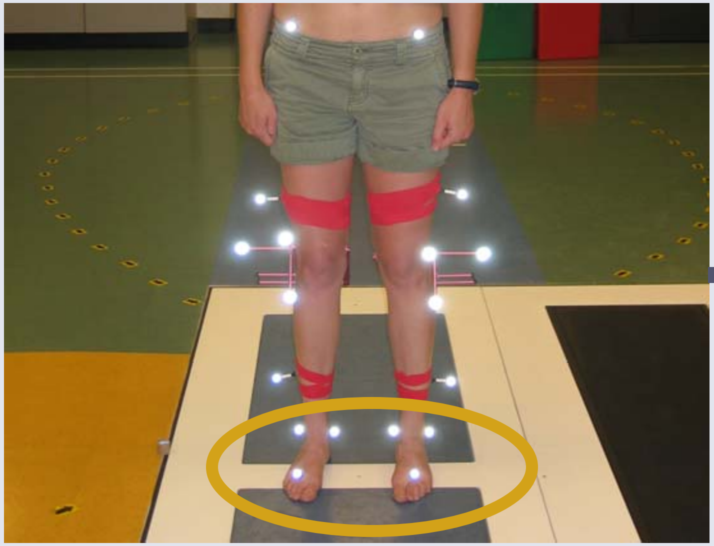
Need for detailed model of Foot

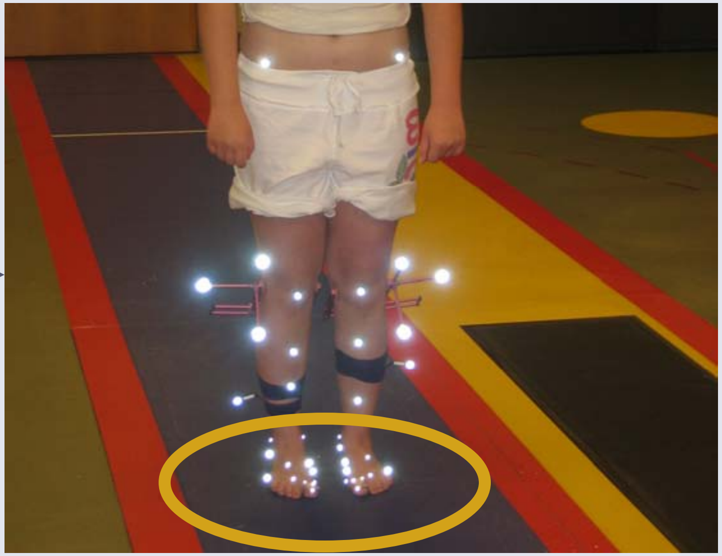
- Most CP patients seen in Salt Lake Ctiy (SLC) motion analysis lab have foot deformities
- Traditional gait model can not measure these offsets

Flatfoot

Ankle Valgus

Progress in Kinematic Gait Model





- Traditional Model-
  - Single segment of the foot
- Current Model
  - 3 segment of the foot

- Musculoskeletal model needs to be updated for these changes.

Musculoskeletal Model as a Clinical Tool

- Current Gait Analysis
  - Kinetics (Total Joint moments)
  - Which muscle are active to produce moments?

- Understand normal muscle activation pattern of foot muscles during walking

- Potential Model Applications
  - Detect muscle imbalance before deformity
  - Simulate the surgical procedure
    - Calcaneal Lengthening
    - Tendon transfer

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Musculoskeletal foot model

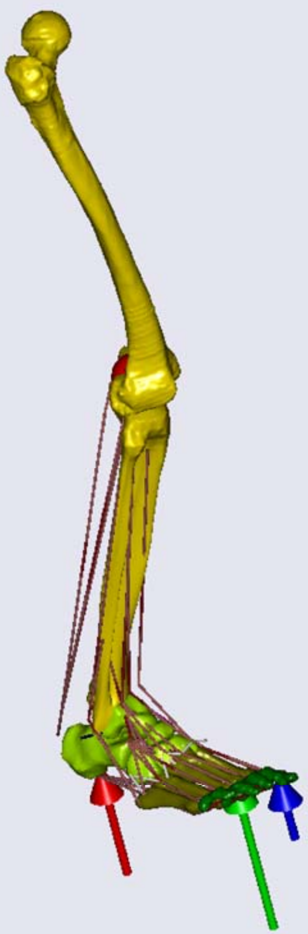
- Model Geometry (Right Foot)
  - Segments
    - Femur
    - Shank
    - Hindfoot
    - Forefoot
    - Toes
  - 16 Muscles
  - 14 Ligaments

Necessary to define muscle origin points

Ankle Joint (Spherical)

Forefoot Joint (Spherical)

Toe Joints (Revolute)



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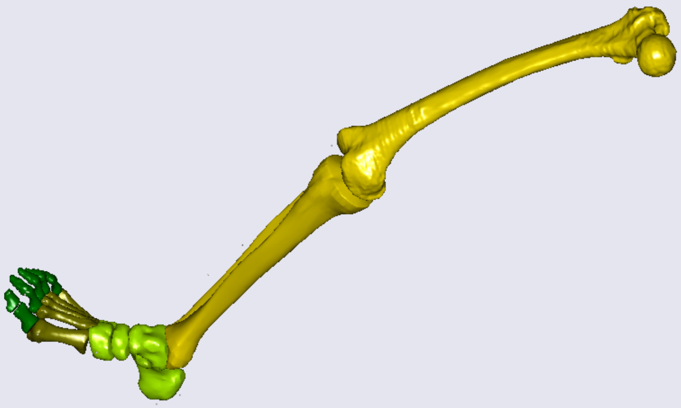
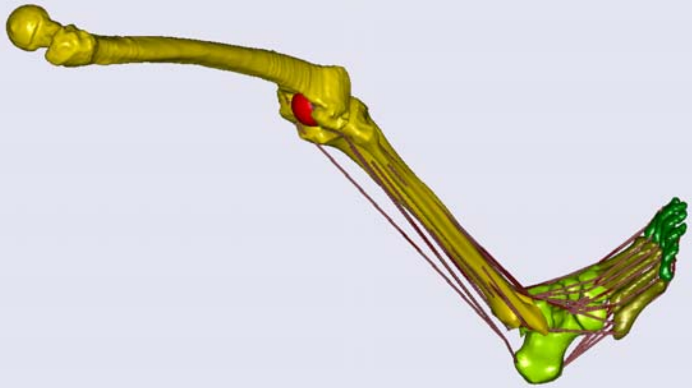
Base Model Development: Geometry

- Segment Inertia
  - Assume each bone to be cylindrical
  - Add the inertia of all bones attached in a single segment
  - Attach CT scan image to give a graphical representation



- Muscle, Ligament Geometry
  - Insertion, via points

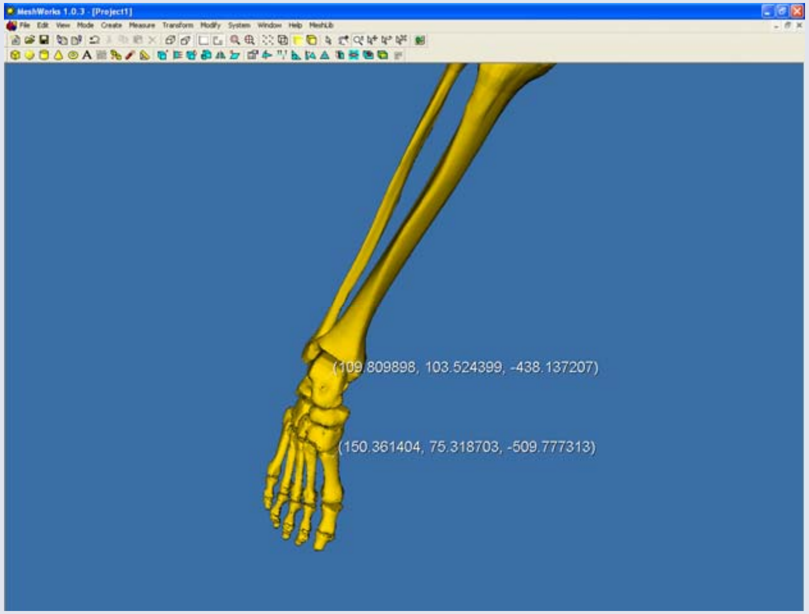


Base Model Development: Extracting via points from CT scan

- Find the position of anatomical landmark (through which the muscle pass) in CT scan image [Meshworks]

- Transform the position to model segment coordinate system

- Define muscles & Ligaments to pass though these points



Base Model Development: Model Parameters

- Muscle
  - Maximum Force*
    - Proportional to muscle cross-sectional area if unknown **
  - Fiber Length & Pennation Angle*, **
  - Fiber Ratio***
    - Set as 0.5 if not known
- Ligament
  - Yield force, Yield strain, slack length****

* Brand-1986, Friedrich-1990, Wickiwicz-1983

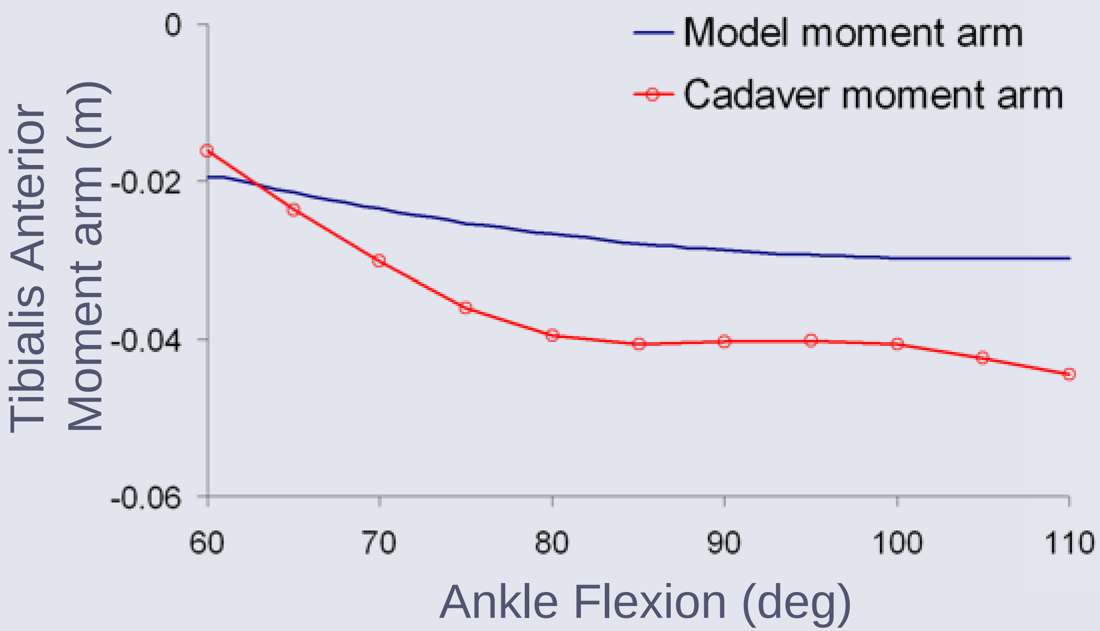
** Kura- 1997

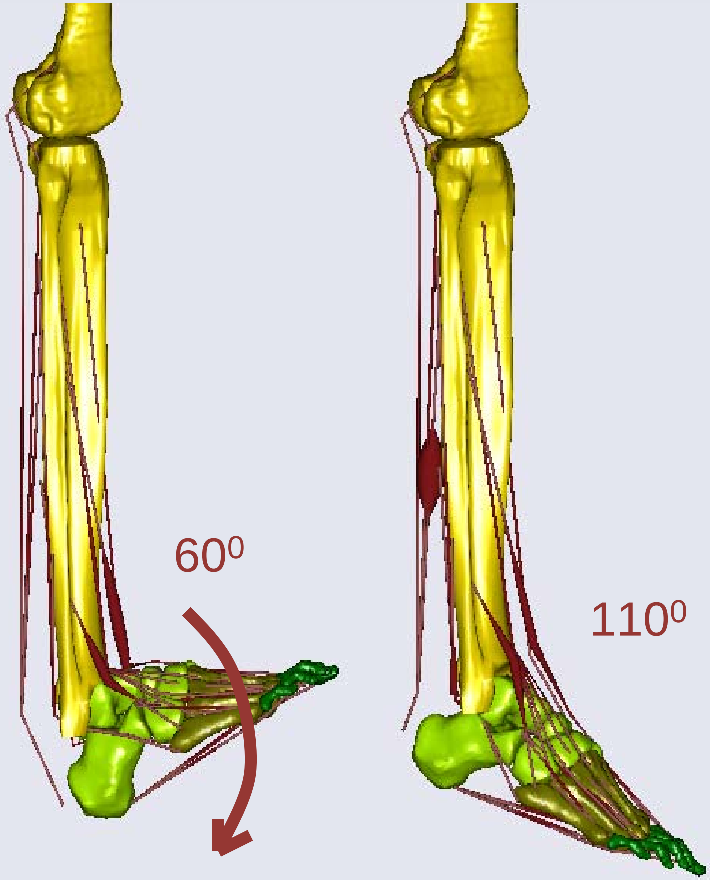
*** Johnson, 1973

**** Siegler-1988, Wright-1964

Base Model Development: Moment Arm Calculations

- Ankle joint moves through the range of motion
- Moment Arm = $\frac{\Delta L}{\Delta \theta}$

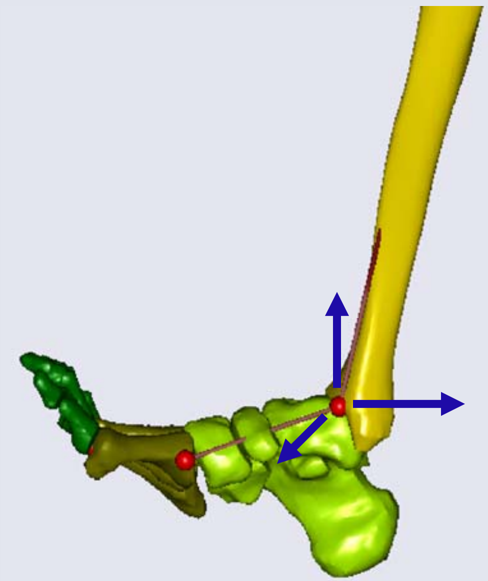




* Cadaver Data- Spoor et. al. 1990

Base Model Development: Moment Arm Optimization

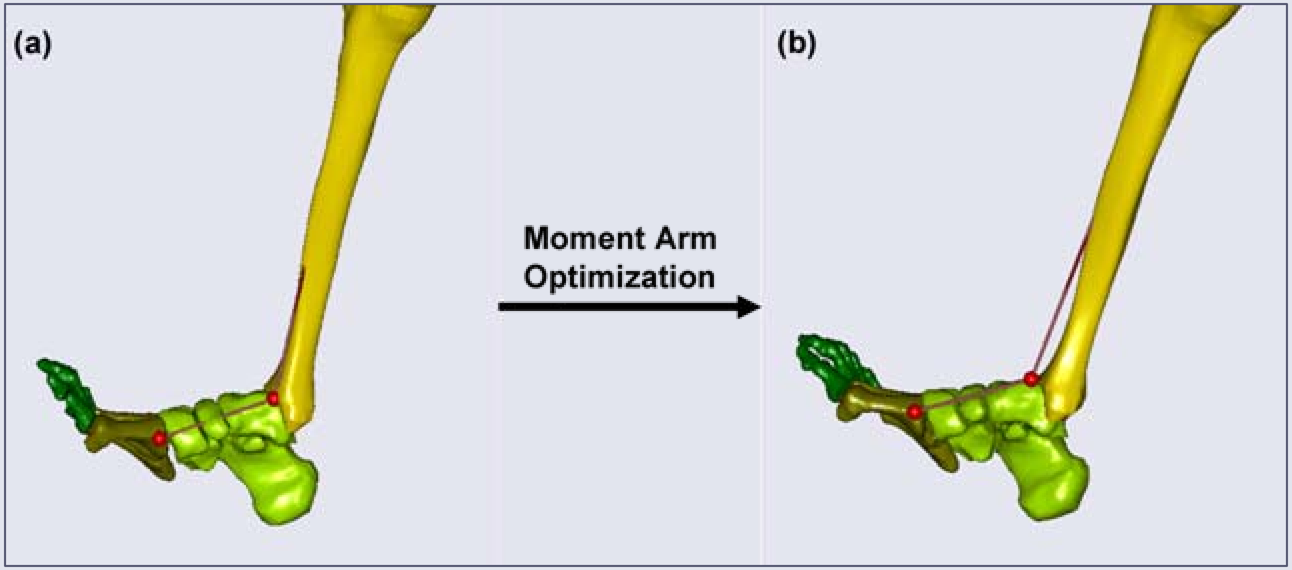
- How to make sure that the model reflects the normal anatomy?
- Function used- 'AnyOptStudy'
- AnyDesVar- Muscle via-points
  - allowed to move ±1 cm in 3 directions
- AnyDesMeasure-

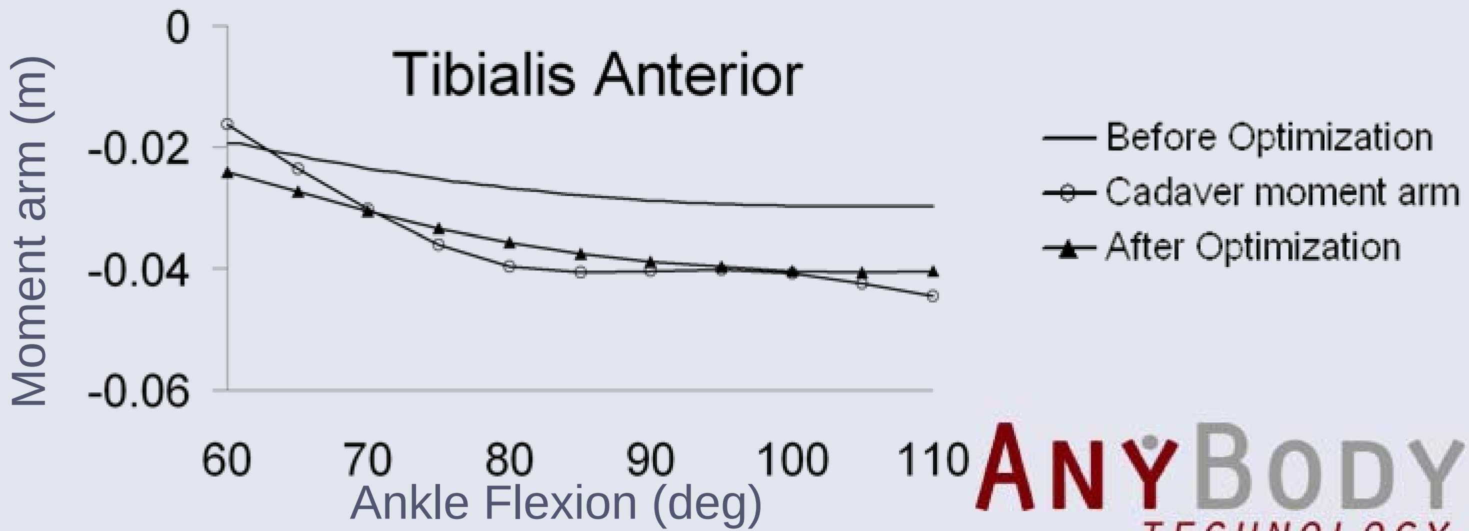


$$\sum (\text{Model moment arm} - \text{cadaver moment arm})^2$$

over ankle flexion range of motion

Base Model Development: Muscle moment arm optimization

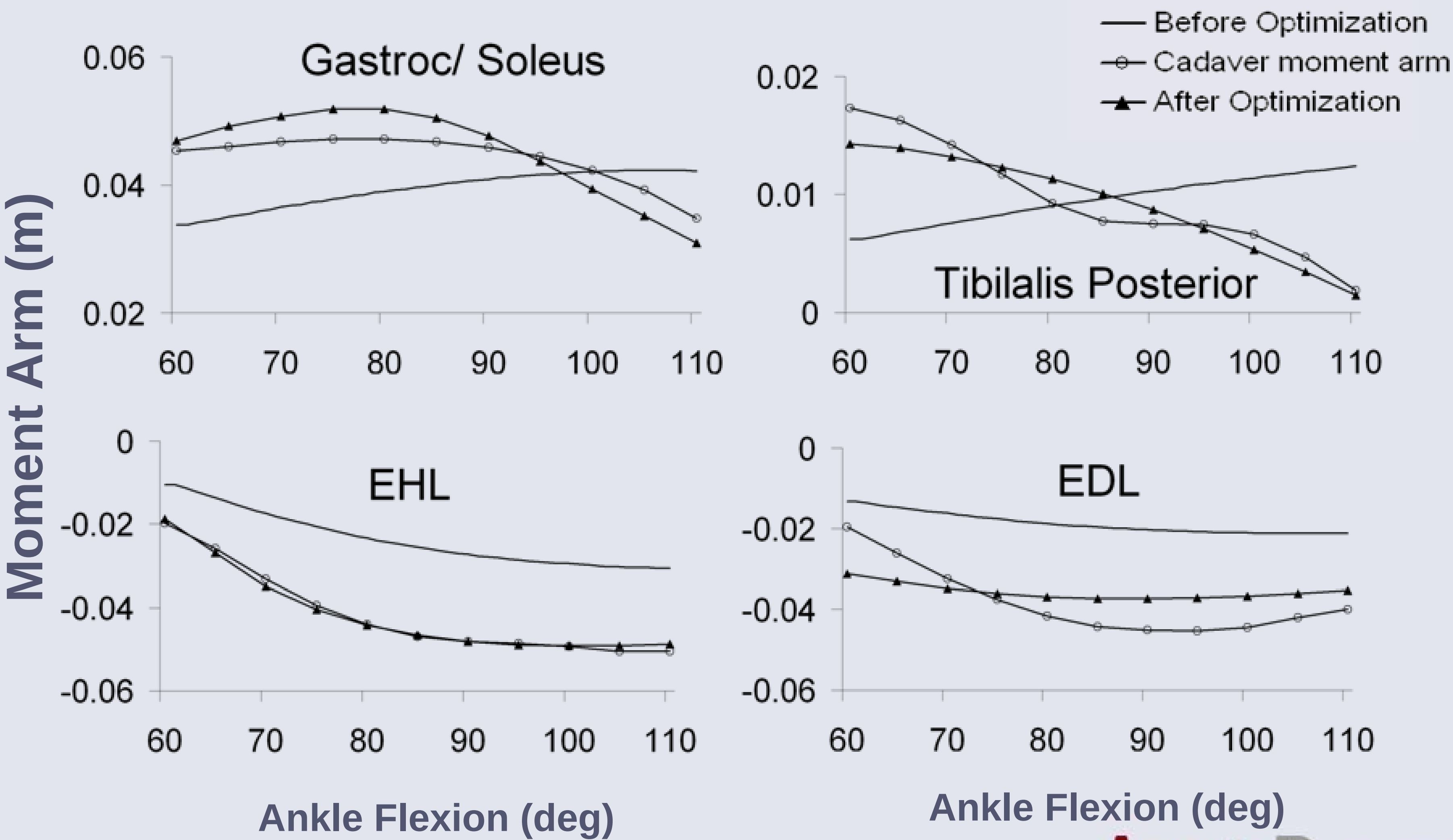




Base Model Development: Muscle moment arm optimization

- Initially defined via points do not account for tendon thickness or soft tissue surrounding tendon
- Optimization adjusts for those offsets according to cadaver tested moment arm data
- Model reflects normal anatomy

Base Model Development: Moment arm optimization results



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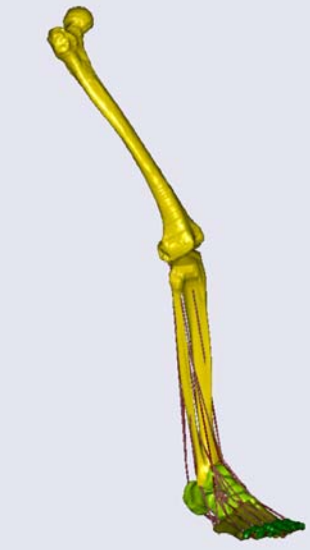
Model Application

- Scaling the Base Model by subject's height and weight
  - Uniform Scaling law

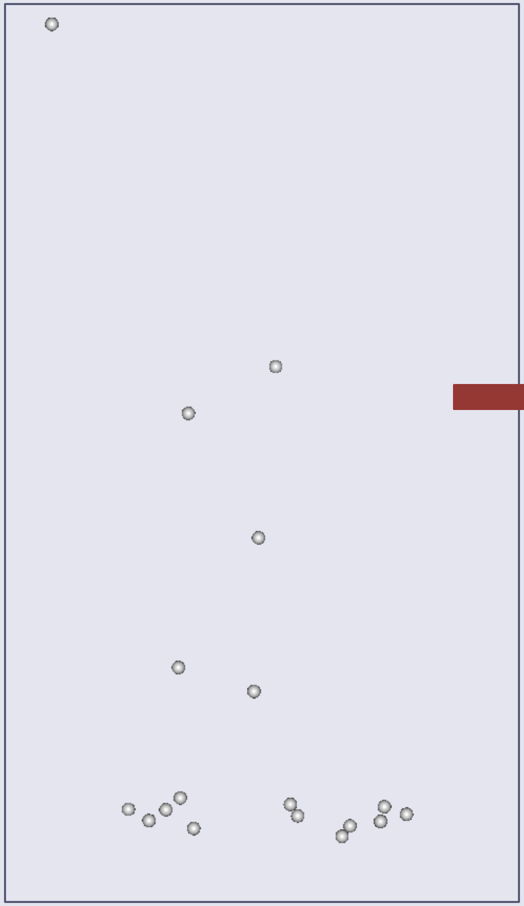
$$S = \begin{bmatrix} K_L & 0 & 0 \\ 0 & K_L & 0 \\ 0 & 0 & K_L \end{bmatrix} \qquad F = F_o k_m^{2/3}$$



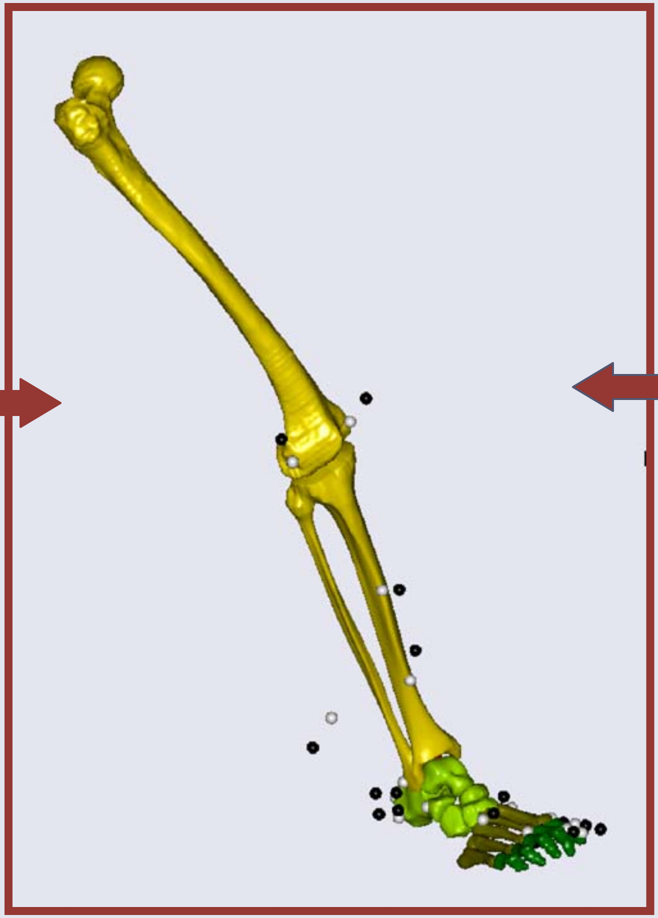
- Driving inputs
  - Marker data from camera system
  - Ground reaction force

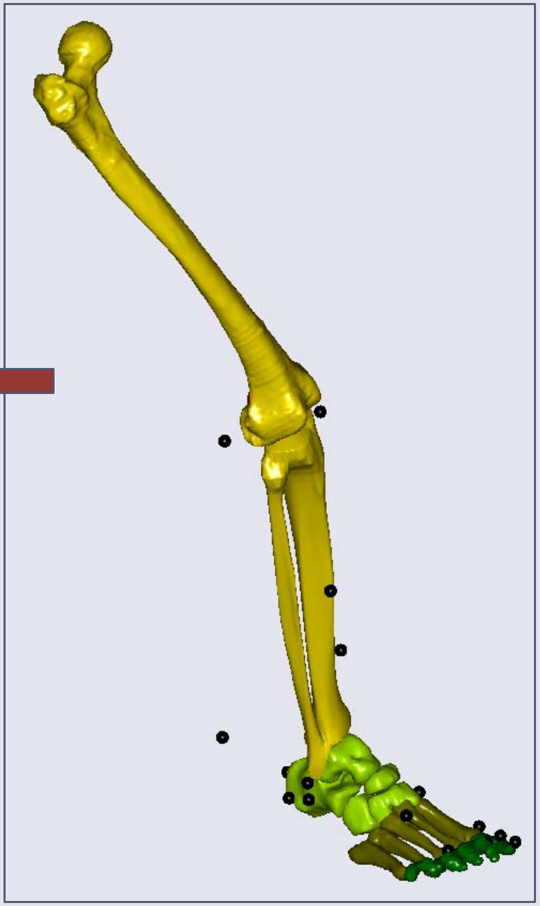
Model Adaptation:

Driving the model with marker trajectories



Marker Data collected by motion camera system



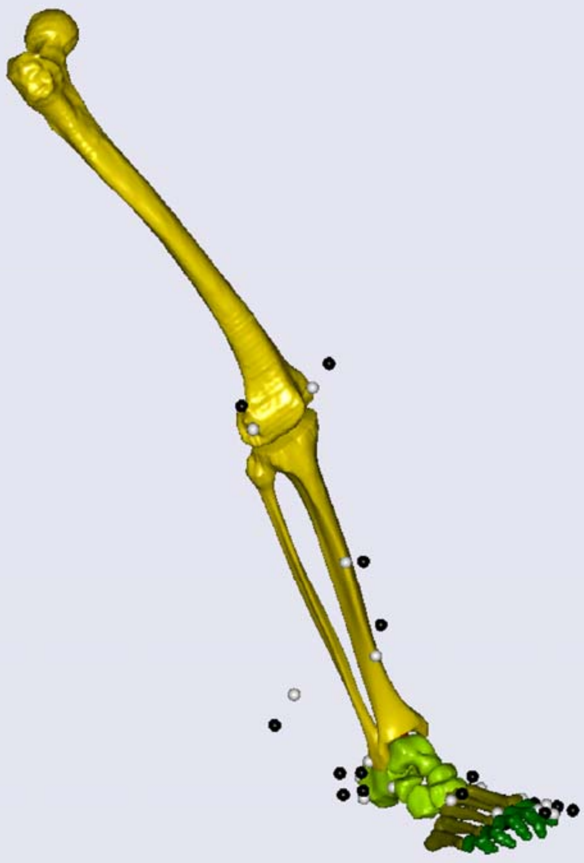


Marker position attached to model segments

Model Adaptation:

Driving the model with marker trajectories

- After applying uniform scaling
  - Marker from camera system (Black) do not match with marker fixed to the model segment (White)
- Reason
  - Over-determinacy
  - Marker placement error
  - Model Joint constraints
  - Uniform scaling does not apply



Model Adaptation:

Driving the model with marker trajectories

- The usual AnyBody approach
  - Over-determinacy is handled by excluding some marker coordinates from consideration
- Method used
  - Over-determinacy is handled by using optimization
    - Developed by Dr. Michael Skipper Andersen

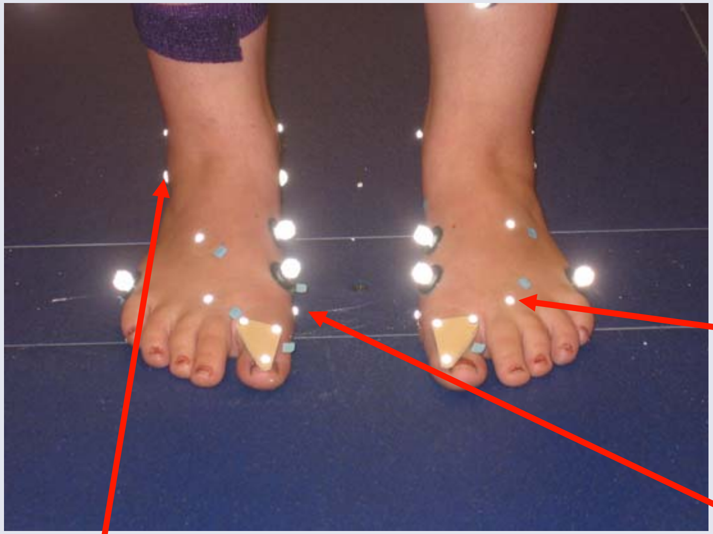
Model Adaptation: Marker Position Optimization

- Enforce joint constraints
- Optimize
  - Segment length
  - Marker position
- Minimize

$$\sum (\text{Markers}_{\text{Camera System}} - \text{Markers}_{\text{Model}})^2$$

over a walking trial

Model Adaptation: Marker optimization settings



- Optimization settings are set according to expected marker placement error

{Off, Off, Off}

Marker placement error is NOT expected

{Off, Off, On}

Marker placement error is expected in Z- direction

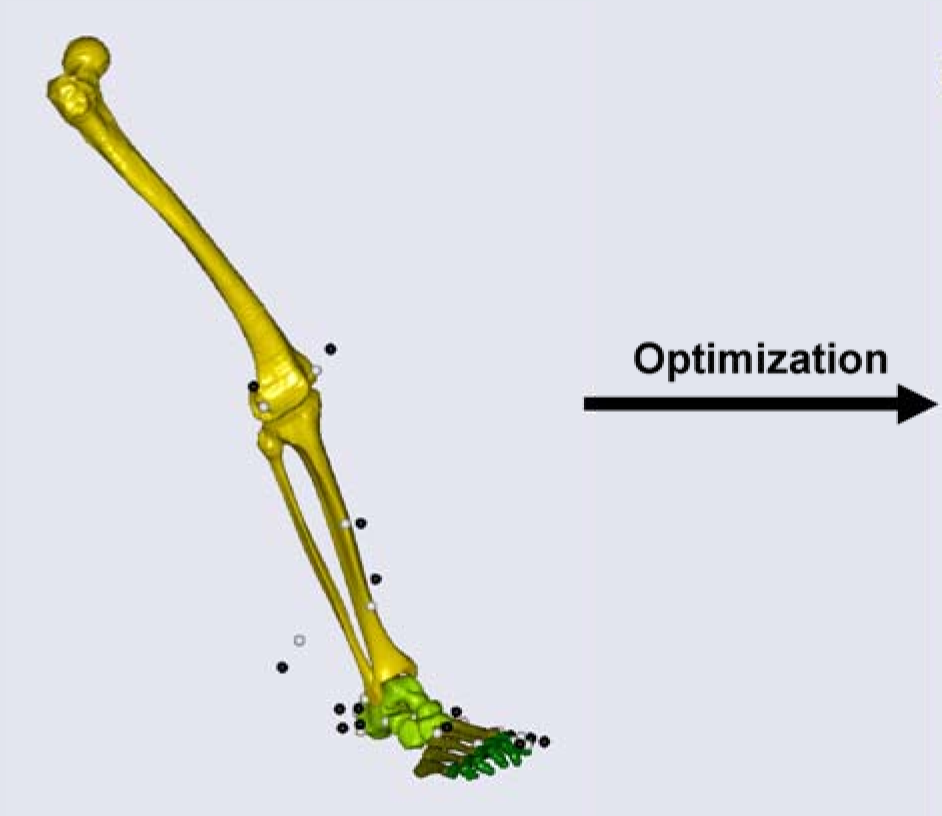
{On, On, On}

Anatomical landmark is hard to find: Optimized in all directions

Off → Not Optimized   On → Optimized

Model Adaptation:

Marker position and Segment Scaling Optimization



Black Markers: Collected by motion camera system

White Markers: Fixed to model segments

Model Application

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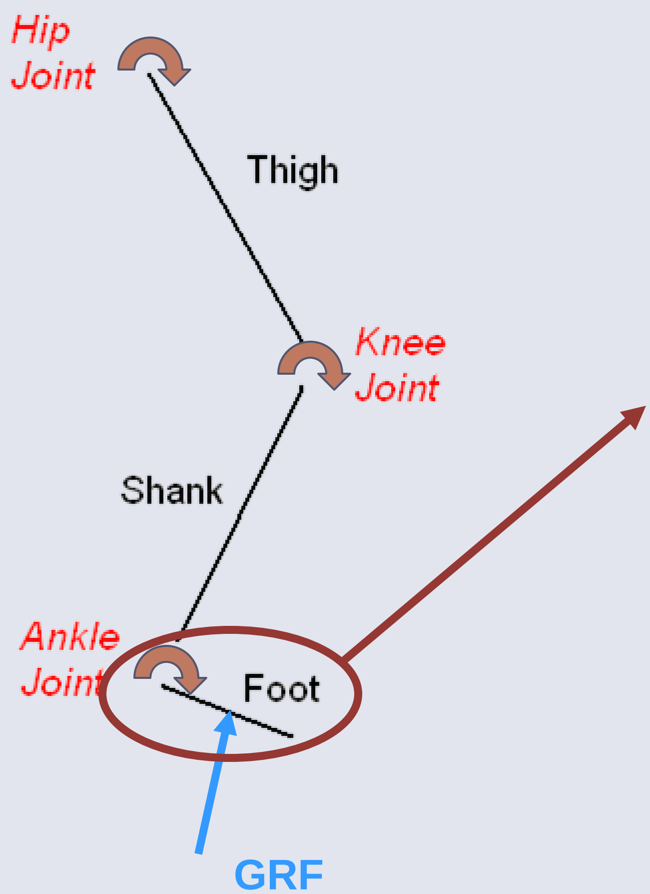
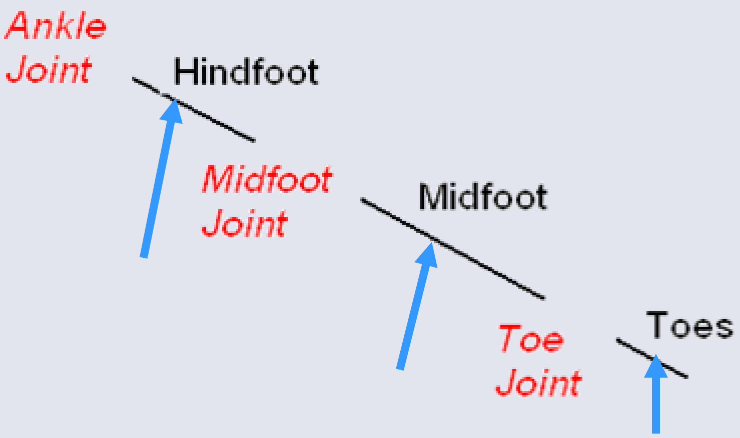
$$S = \begin{bmatrix} K_L & 0 & 0 \\ 0 & K_L & 0 \\ 0 & 0 & K_L \end{bmatrix} \qquad F = F_o k_m^{2/3}$$

- Driving inputs
  - Marker data from camera system
  - Ground reaction force

Model Application: Ground Reaction Force



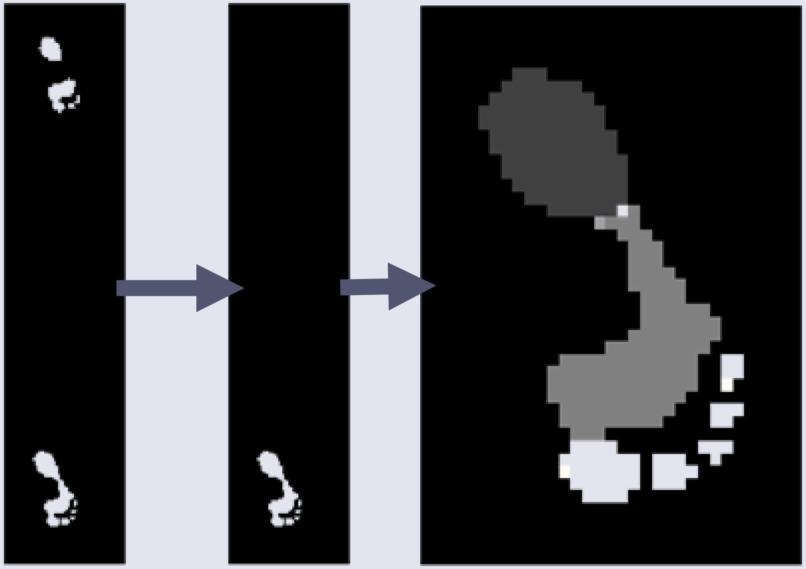
Traditional Model

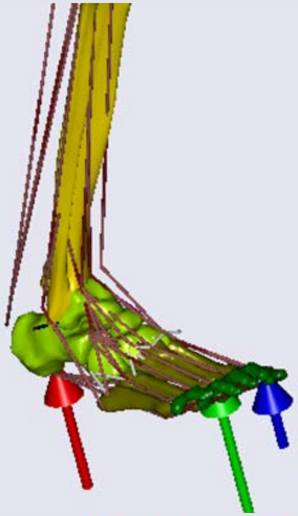


- All three segments are in contact with the ground in stance phase.
- Need Ground Reaction Force for three segments.
- Not possible with single Force plate.

Model Application: GRF Distribution

- Coupled Force Plate & Pedobarograph
  - Pedobarograph mounted on top of Force plate
  - Synchronized
- Pressure Segmented
- Ground reaction force vector & COP are computed for each segment





Model Adaptation: Tendon, Ligament length Calibration

- Two methods
  - Static
    - Joint positions are defined
    - Tendon/Ligament length at this model position is set to be the slack length
  - Dynamic ✓
    - Tendon/ Ligament length is measured as the model segments go through a range of motion (one gait cycle)
    - Mean of this range is set as the slack length

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Muscle force calculations

- Min/Max Algorithm
  - minimize maximum muscle activity

$$\min_{f} \quad \max\left(\frac{f_i^{M}}{N_i}\right), i \in \{1,\ldots,n^{M}\}$$

$$\text{s.t.} \quad \begin{aligned} Cf &= r \\ f_i^{(M)} &\geq 0 \end{aligned}$$

f^{M}: Muscle force

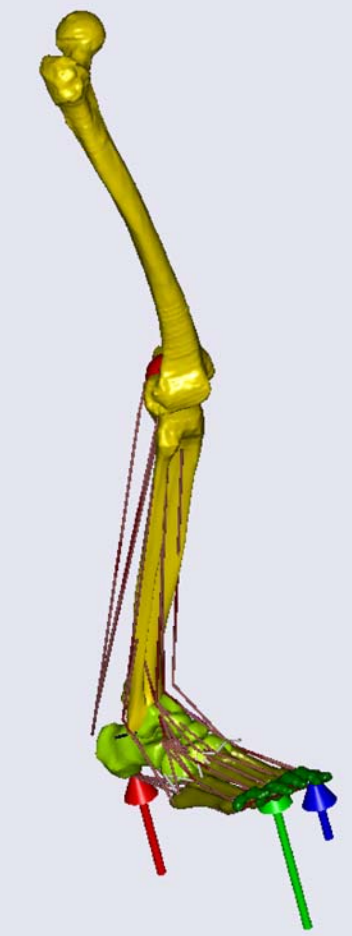
N_i : Normalization factor: instantaneous muscle strength

C : Matrix of coefficient depending on current position of segments

f : Unknown forces, r :external forces (GRF, inertia)

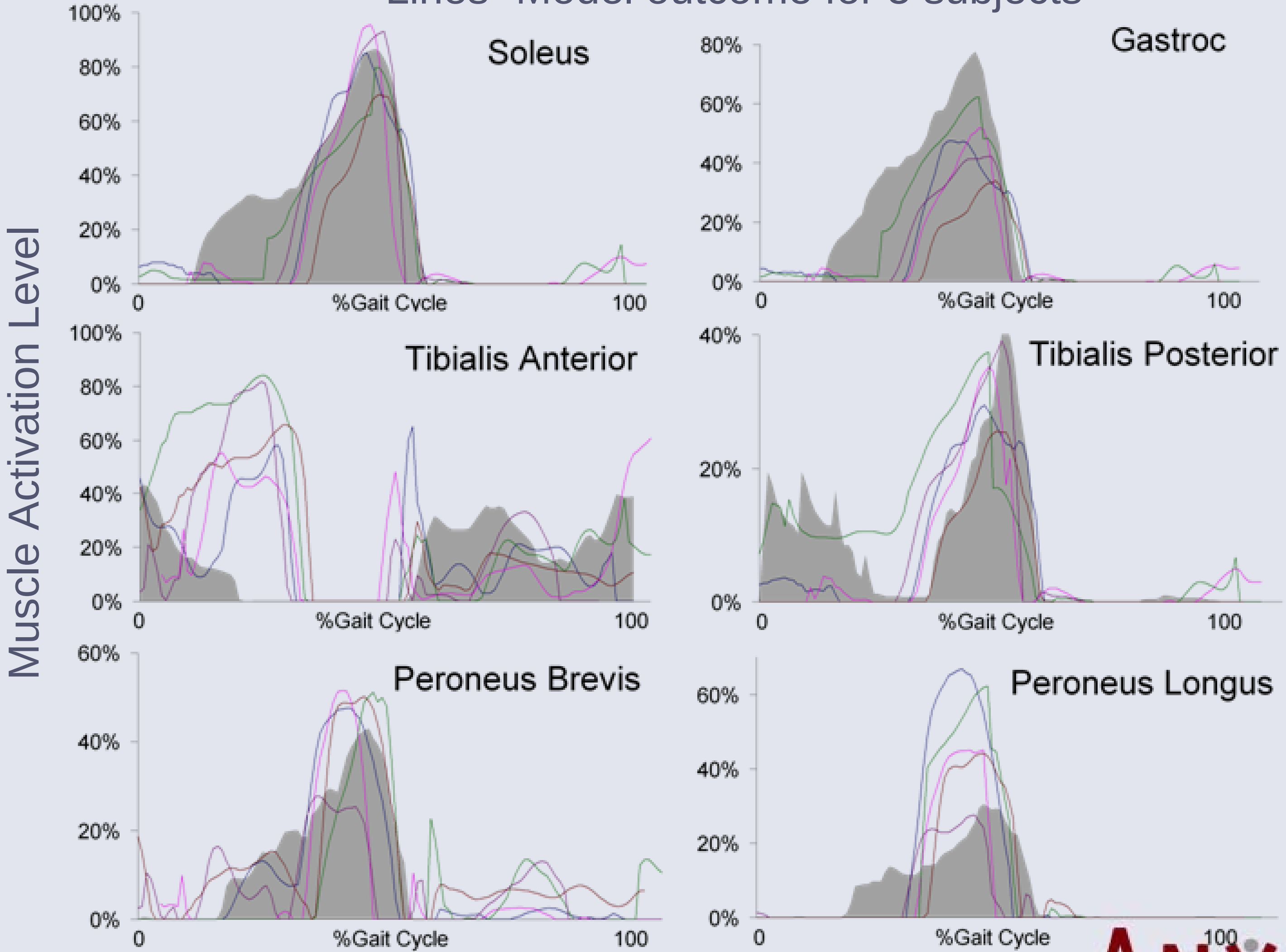
Subject-specific Application: Steps

- Marker Data collected on 5 control pediatric subjects
  - Age 10.6±1.57 years
- Compute GRF for each segment
- Apply optimization routine for marker position and model scaling
- Tendon/Ligament Length Calibration
  - Dynamic (One gait cycle)
- Compute muscle activation level during walking

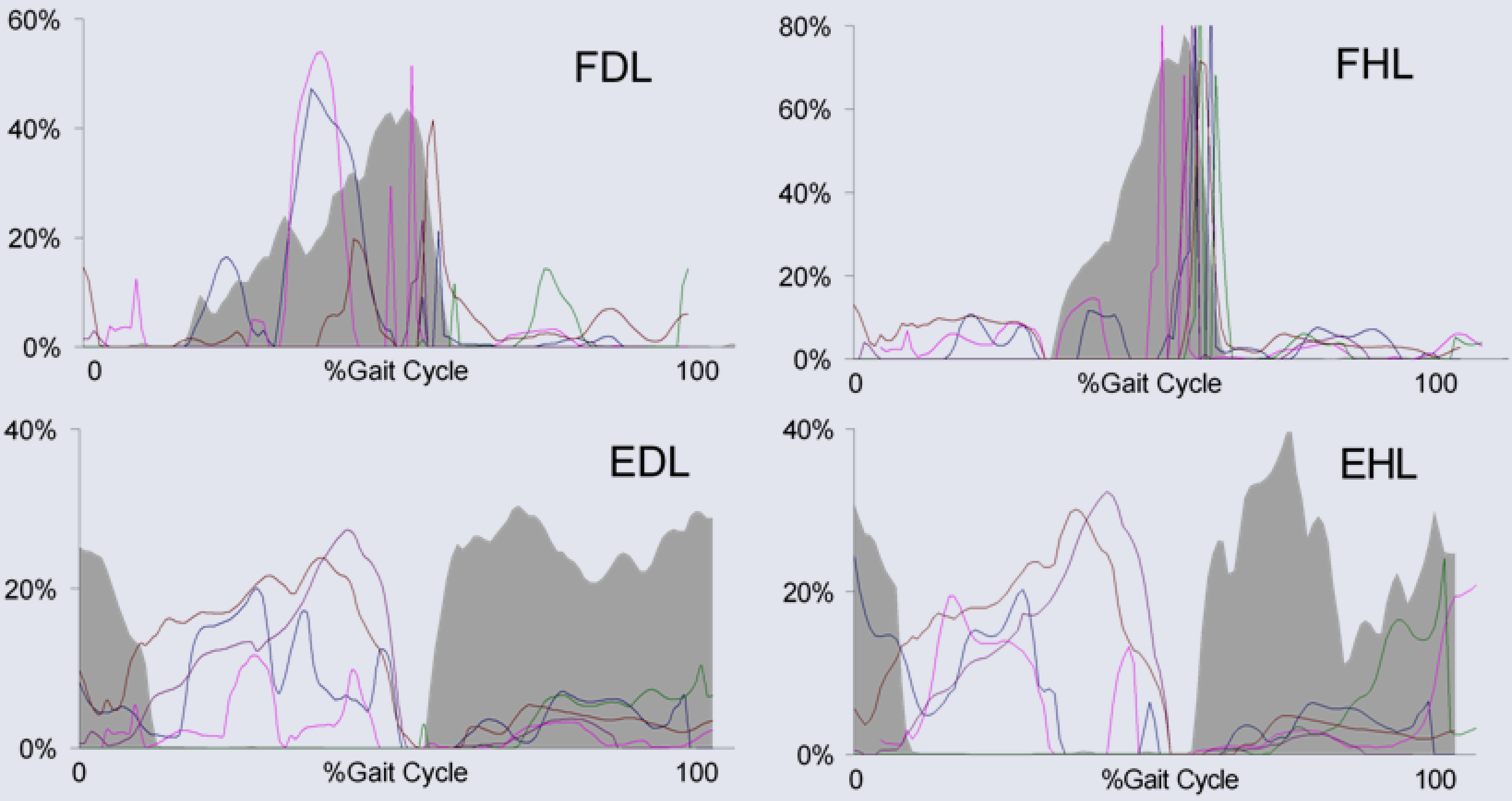


Muscle activation pattern

Shaded- EMG activation pattern from the literature (Perry J, 1992)
Lines- Model outcome for 5 subjects

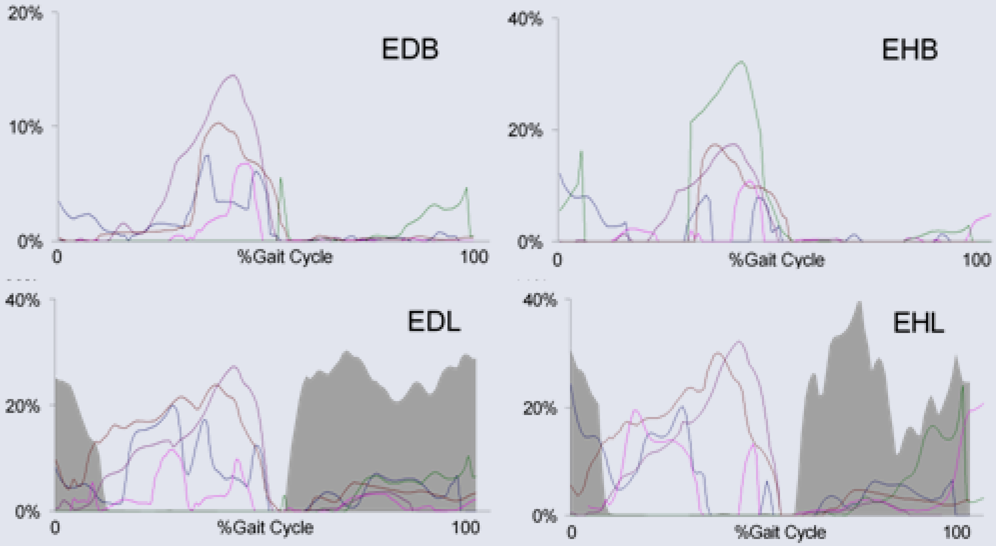


Toe Flexor/Extensor Activation

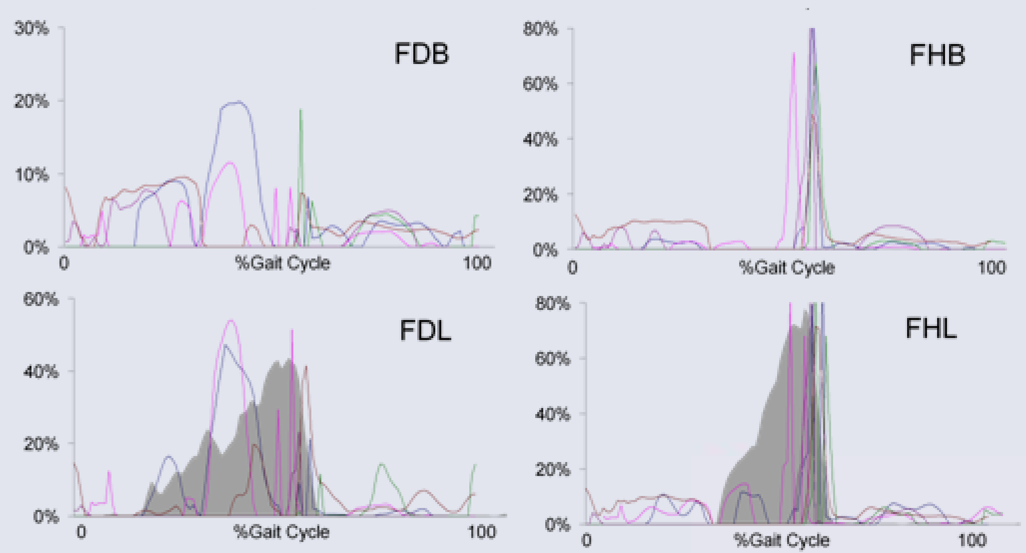


Muscle were recruited to drive sagittal plane motion only

Brevis muscle activation pattern



Similar to Longus Muscle activity



Similar to Longus Muscle activity

Conclusion

- First step towards developing multi-segment foot model for clinical application
- Moment arm optimization improves anatomical accuracy
- Marker position optimization demonstrates adaptability for subject-specific application
- Model outcomes match the EMG activation qualitatively
- More cadaver testing data is needed for moment arm optimization in non-sagittal plane.

Questions?

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