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A Computational Workflow to Determine Saddle Position Effects on Metabolic Energy Expenditure Rate While Cycling

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ME 329

Introduction

How do we make the most efficient mode of transportation even more efficient?

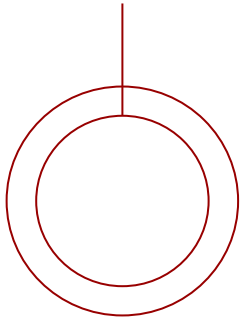
Cycling Efficiency is…

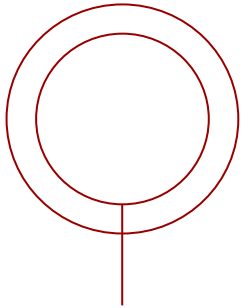
Cycling Efficiency is…

The ratio of power output at the wheels to the metabolic energy expenditure rate of the rider

Metabolic Energy Expenditure Rate (MEER)

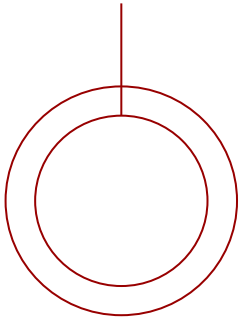
ATP consumption in muscle fibers



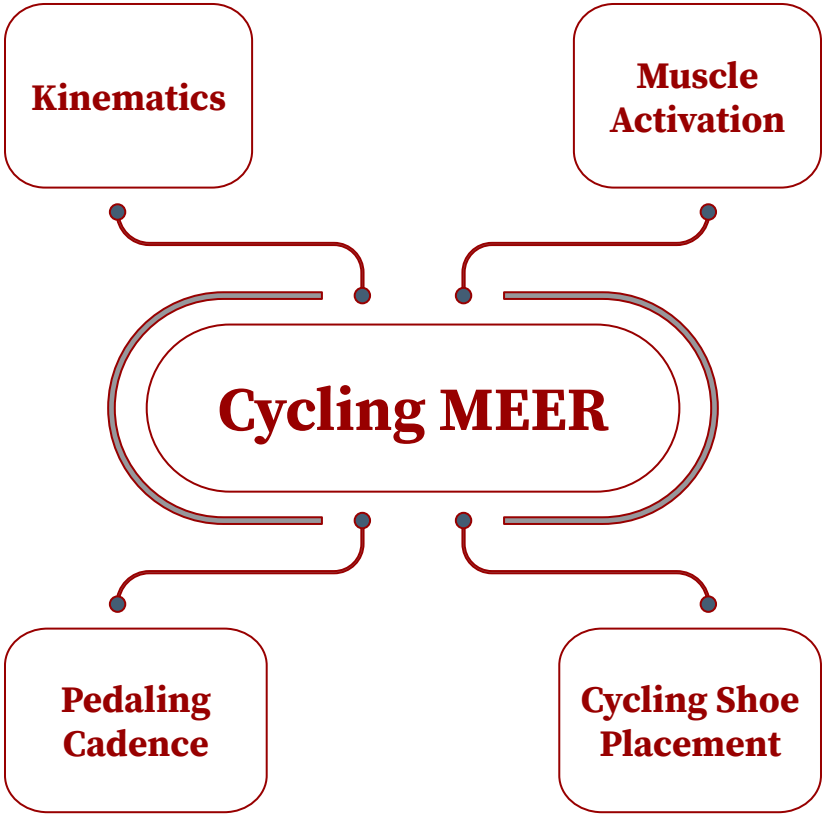


Rate at which **heat is released** and **muscles perform work**

Experimentally measured via **indirect calorimetry**

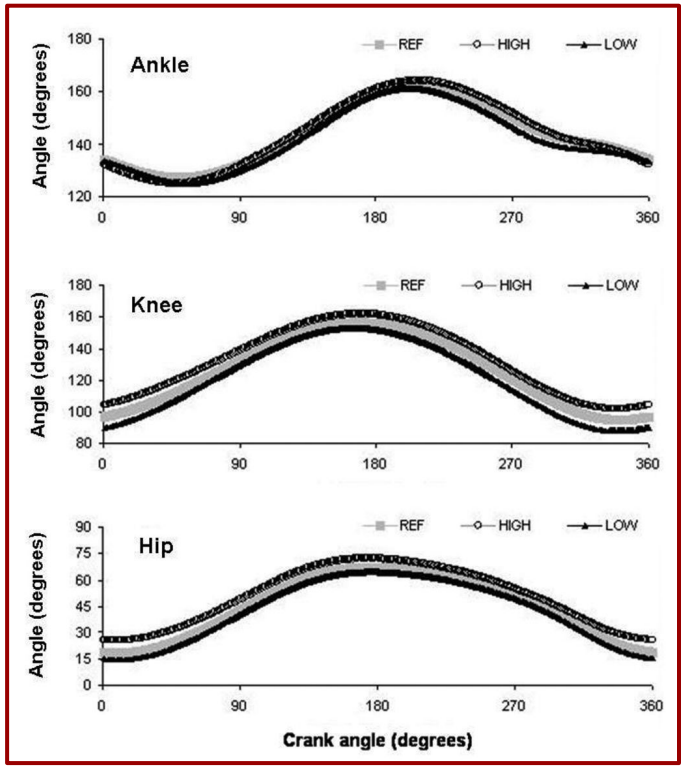


Factors Affecting MEER During Cycling



Related Works & Background

Review: Cycling Research

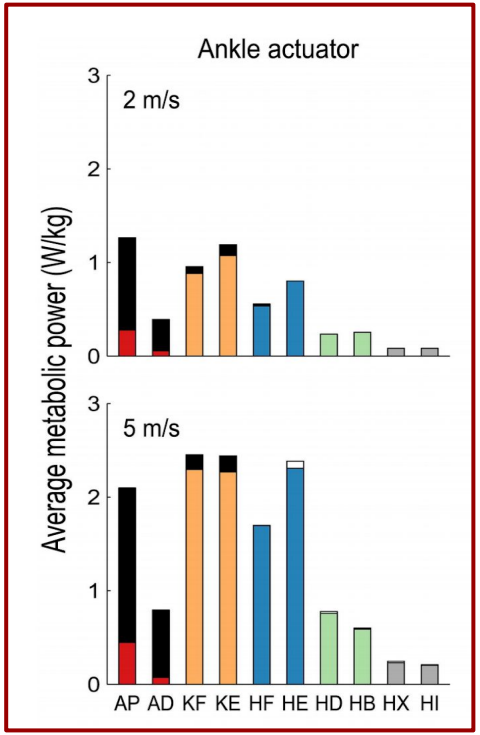


Joint angles for ankle, knee, hip as a function of crank angle (Bini 2010)

- Extensive **cycling research** exists on cycling kinematics, dynamics, and MEER *(Faulkner 2020, Leib 2008, Dembia 2017, Coleman 2007, Hull 1985, Gonzalez 1989, Fonda 2010)*
- Studies often use electromyography (EMG) and motion capture data to acquire **muscle activation** and **joint angle** data

Review: History of OpenSim and MEER

- **OpenSim** was released as an open-source tool by Dr. Scott Delp and team at Stanford in 2007
- OpenSim has been used to study **MEER** of walking and running, making use of the **Computed Muscle Control** (CMC) Tool *(Uchida 2016, Hamner 2013)*
- MEER results are often validated with **indirect calorimetry experimental measurements** *(Uchida 2016, Hamner 2013)*

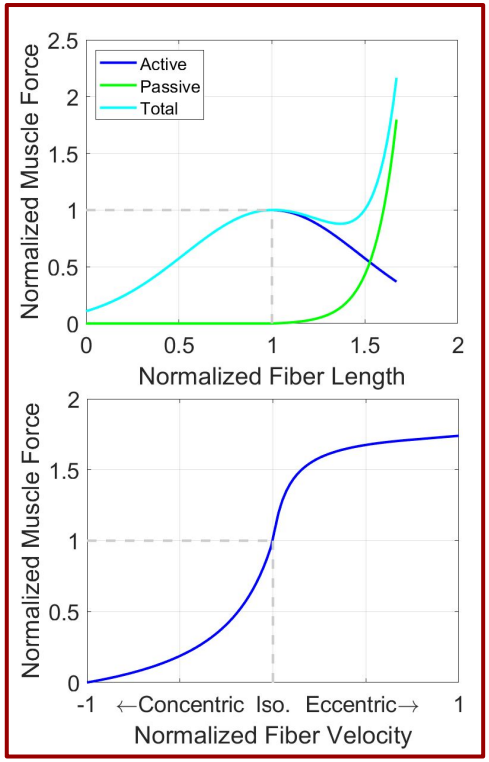


MEER output normalized by body weight for running for each leg muscle (Uchida 2016)

Review: Biomechanical Analysis

- **Muscle states**
  - Muscle fiber length
  - Muscle fiber velocity (speed of contraction)
- **Active force generating capacity** is the product of the active force due to muscle length and the force due to muscle velocity
- If a muscle has a **higher active force generating capacity**, less activation will be required to generate a given motion and the **MEER will be smaller**

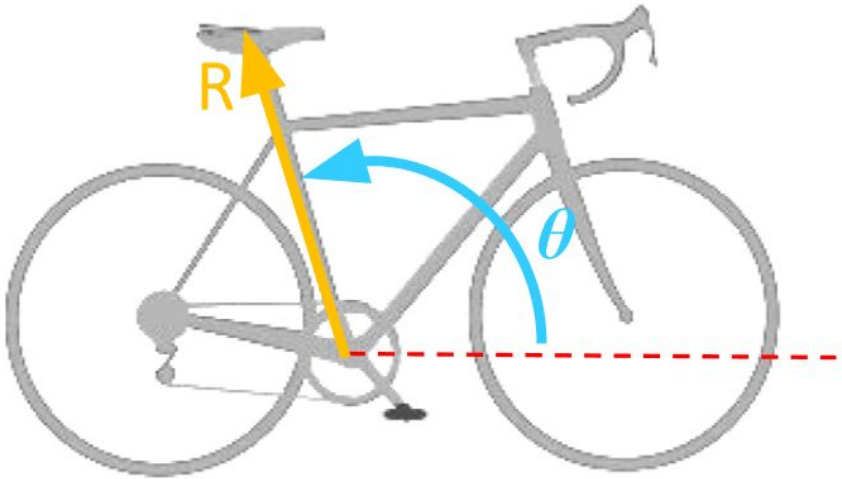
(Bohm 2019, Alcazar 2019)



Active force-length and force-velocity curves for active force generation (OpenSim Documentation)

Problem Definition

Our goal is to **establish a computational workflow** for Specialized to relate MEER and bicycle saddle position (R, θ) to inform bicycle design



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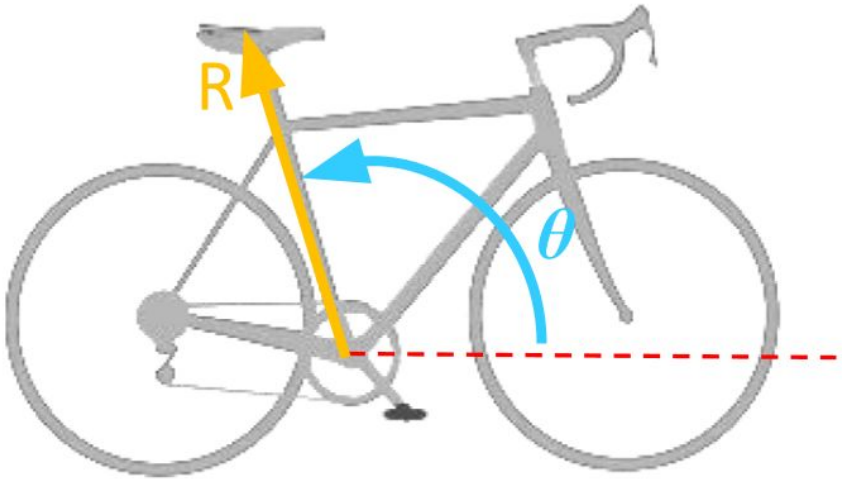
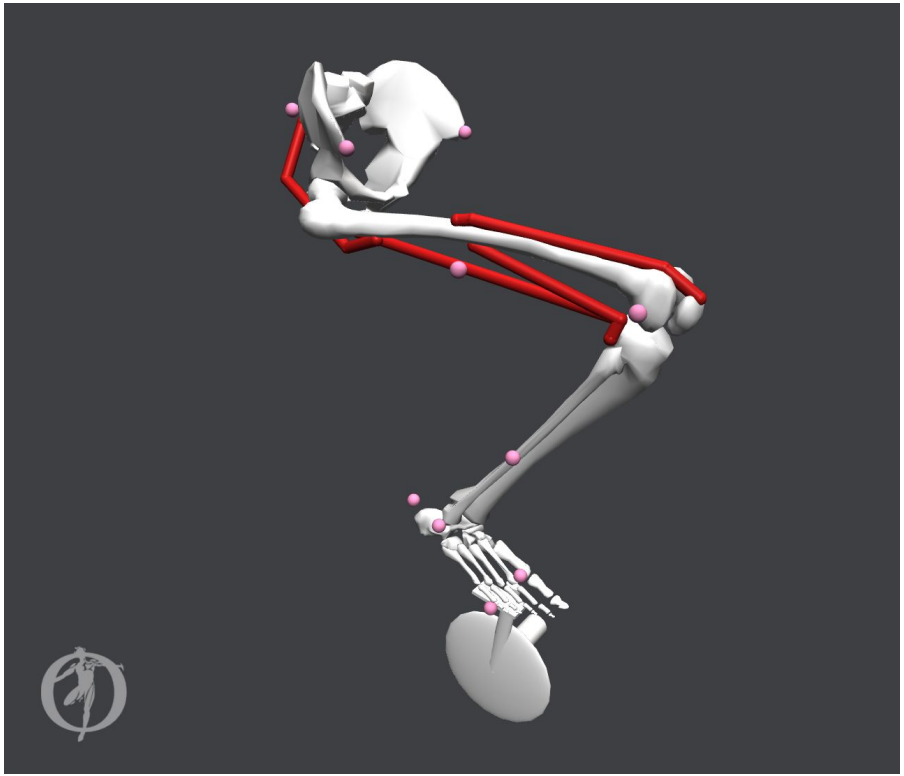


We validated this workflow by relating changes in bicycle saddle position to MEER through simulation in OpenSim

Methods

Methods: Model

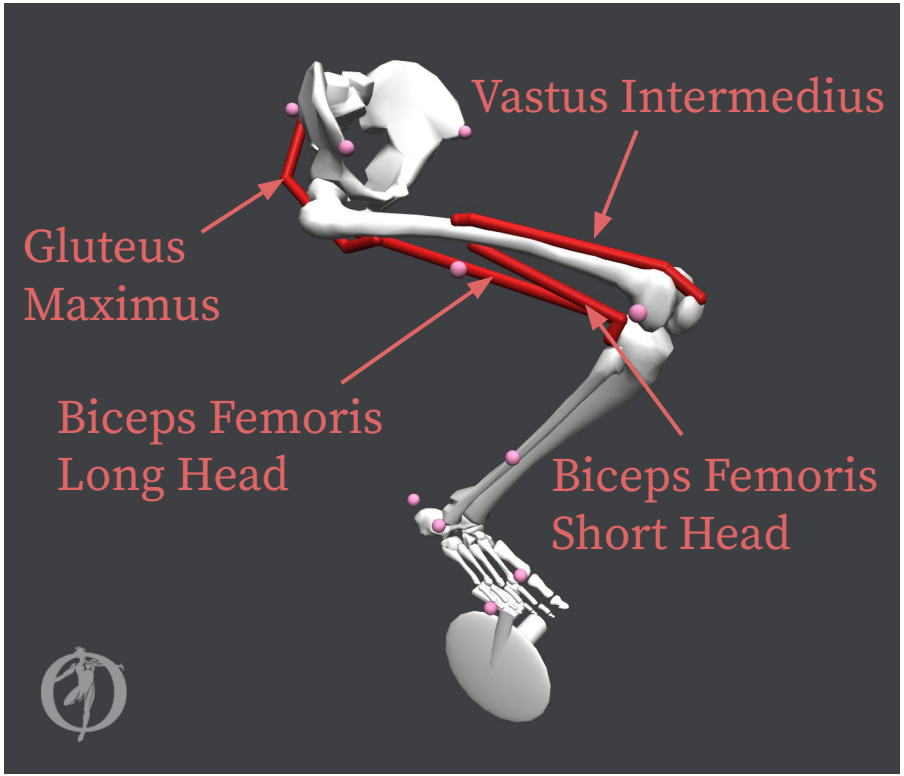
Single leg model



Methods: Model

Single leg model

4 muscles: 1 quadricep, 2 hamstrings, 1 glute



Methods: Model

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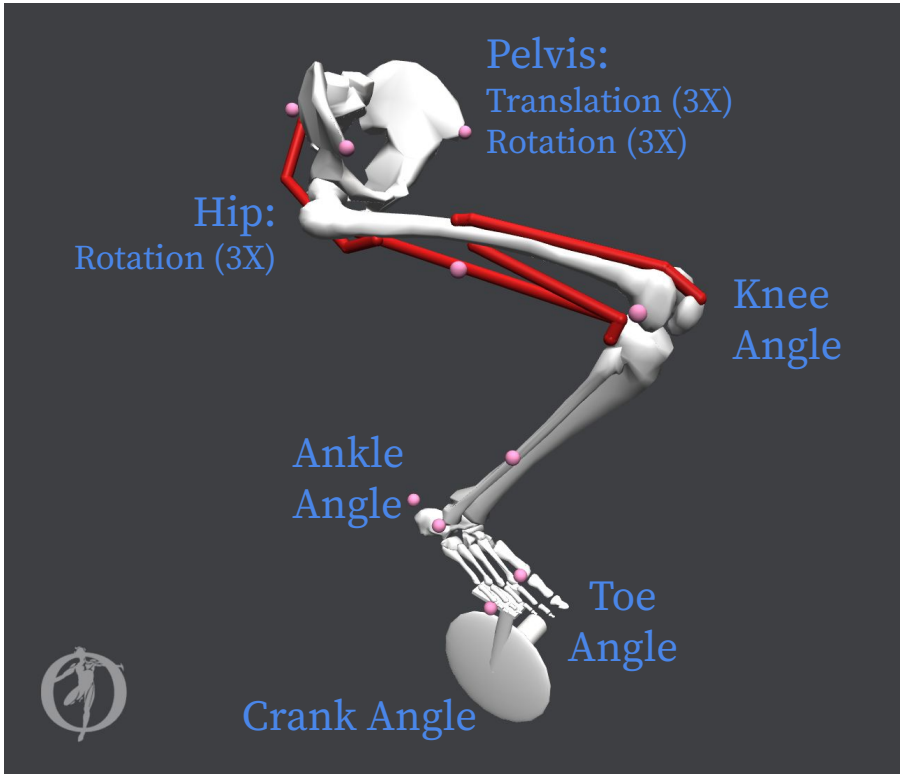
13 Degrees of Freedom (DOF)



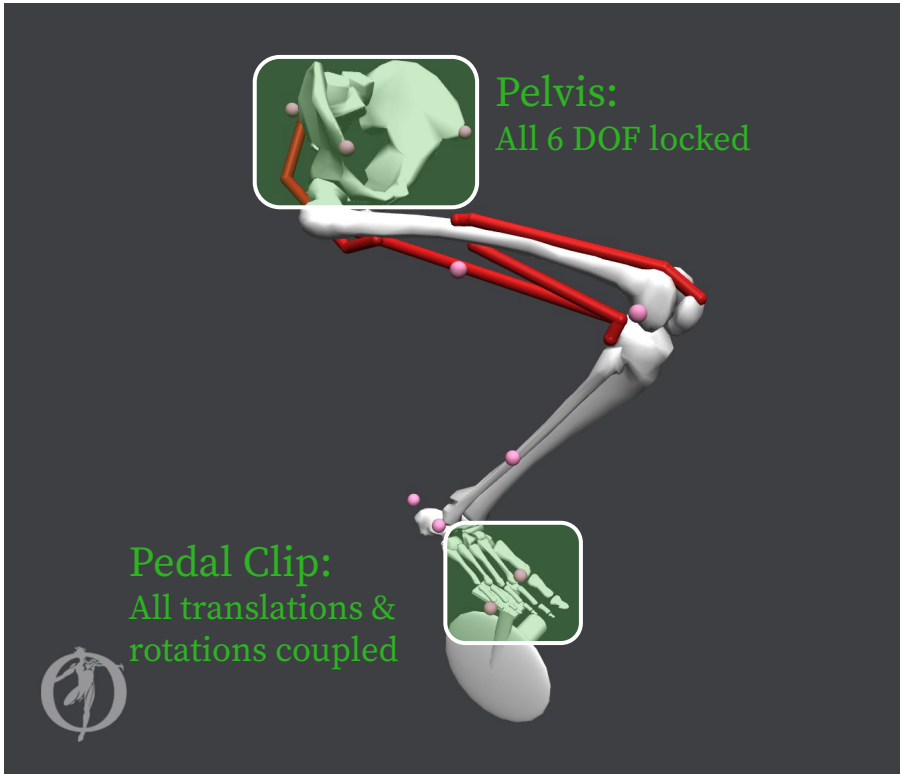
Methods: Model

Single leg model

4 muscles: 1 quadricep, 2 hamstrings, 1 glute

13 Degrees of Freedom (DOF)

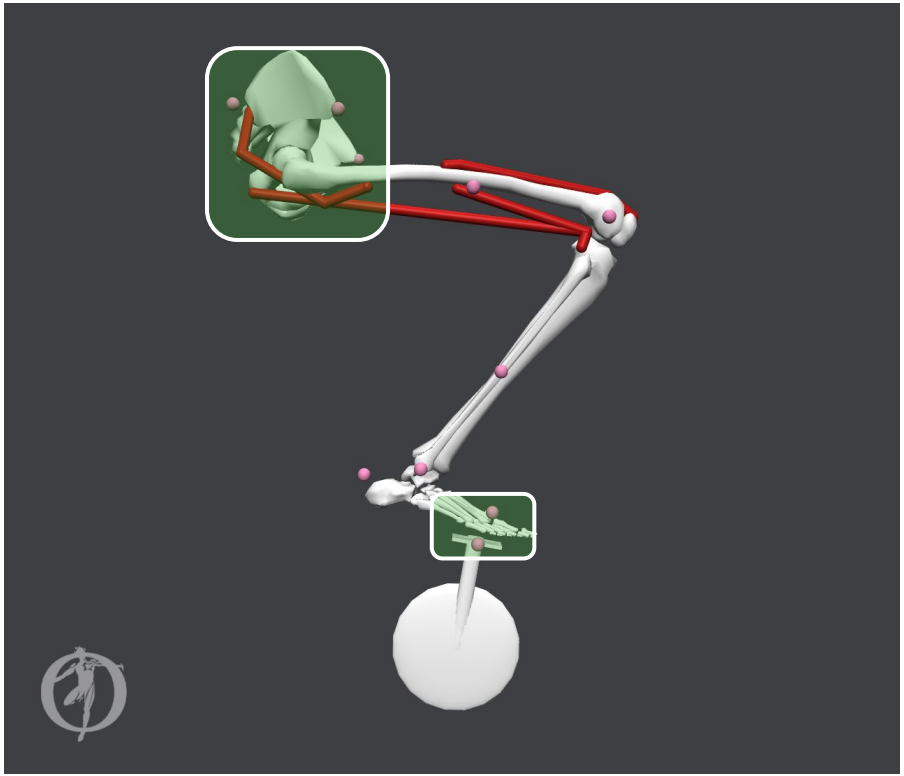
Constraints: pelvis, pedal clip



Methods: OpenSim Tools

Forward Dynamics Tool

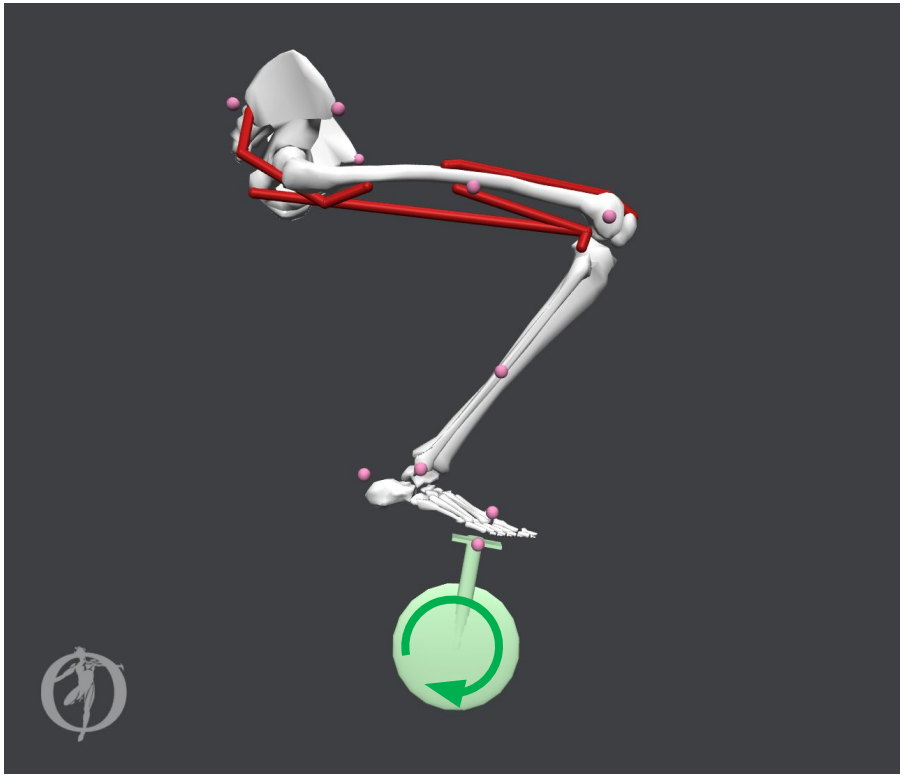
- Given initial position and constraints, determines the motion of the model



Methods: OpenSim Tools

Forward Dynamics Tool

- Given initial position and constraints, determines the motion of the model
- Model DOF(s) can be driven via prescribed function



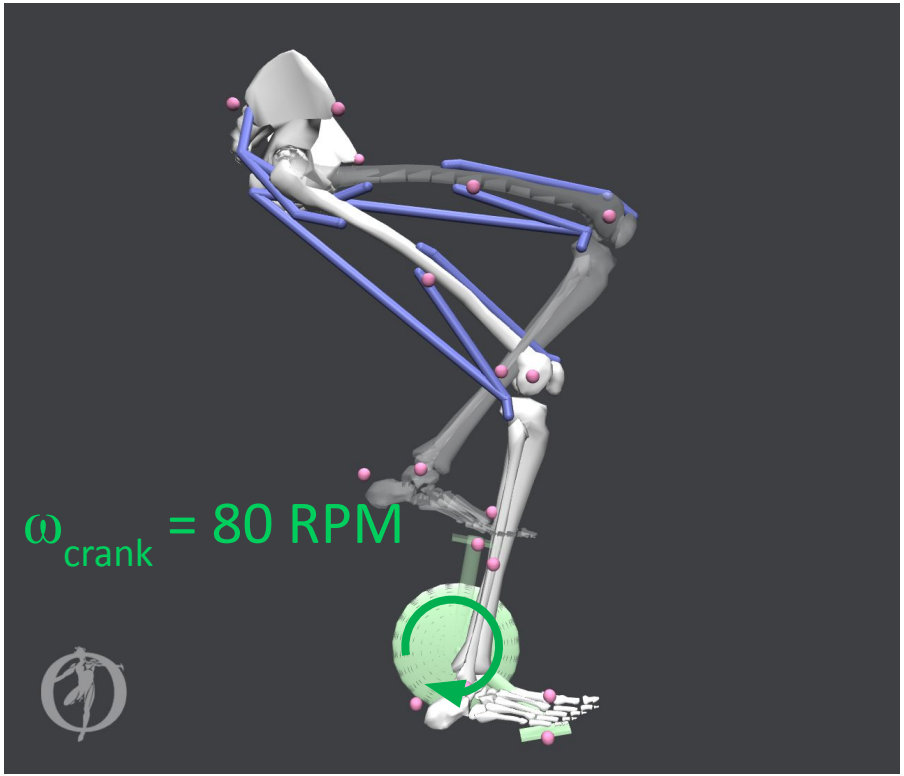
Methods: OpenSim Tools

Forward Dynamics Tool

- Given initial position and constraints, determines the motion of the model
- Model DOF(s) can be driven via prescribed function

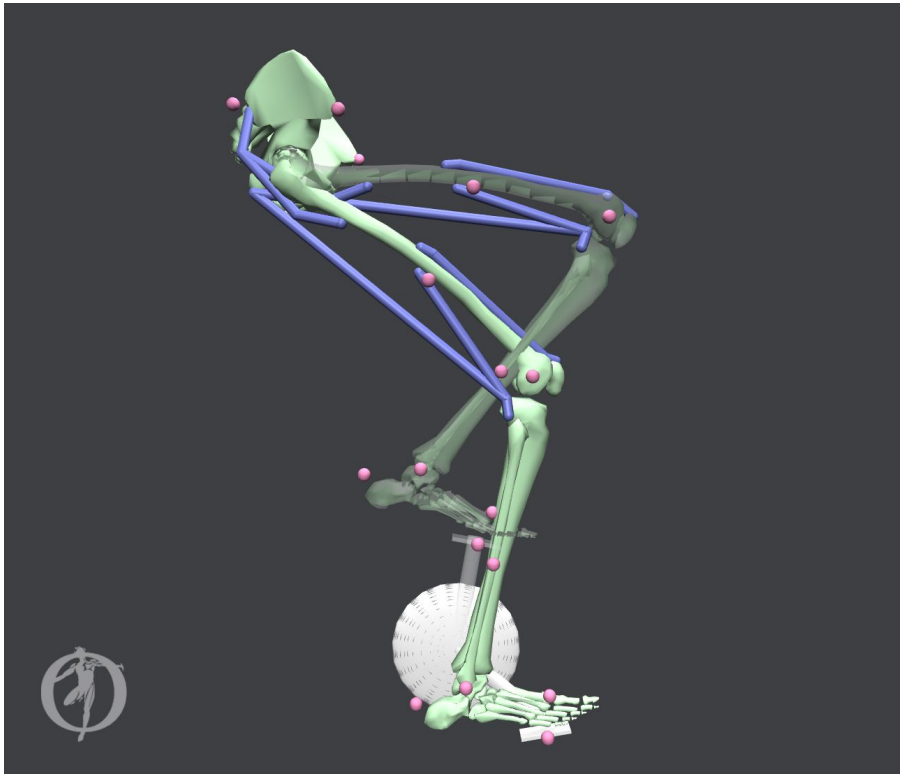
In the Workflow: *Simulated Forward Kinematics (SFK) step*

- Outputs model joint angles, muscle fiber lengths, muscle fiber velocities, and pedal reaction forces at the midfoot



Methods: OpenSim Tools

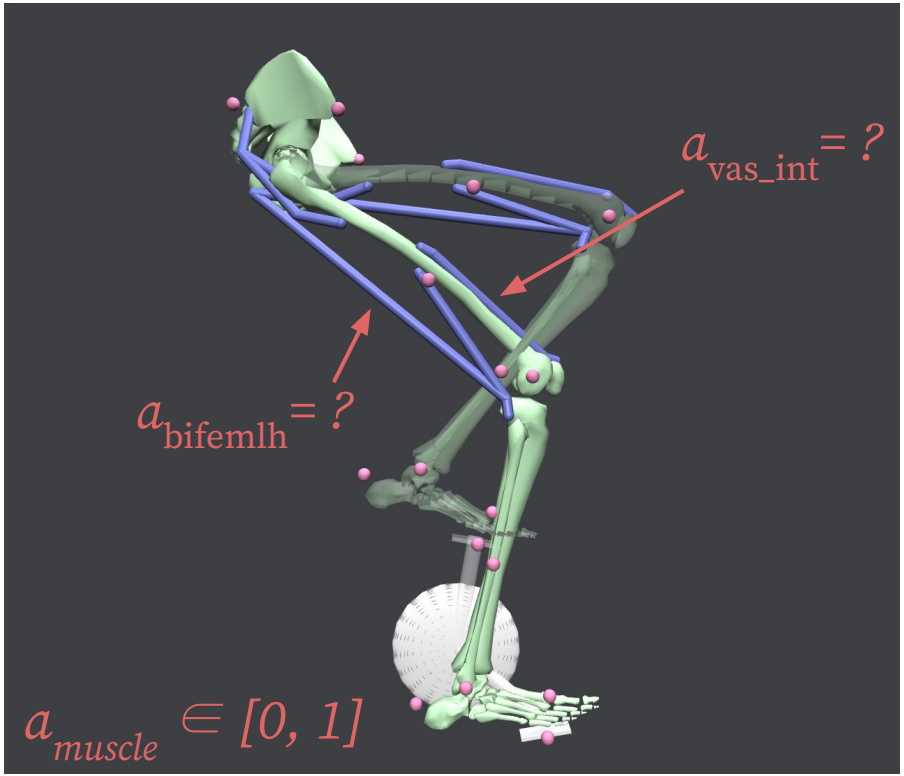
Computed Muscle Control Tool



Methods: OpenSim Tools

Computed Muscle Control Tool

- Given a desired motion and external forces, determines muscle activations needed to reproduce the motion

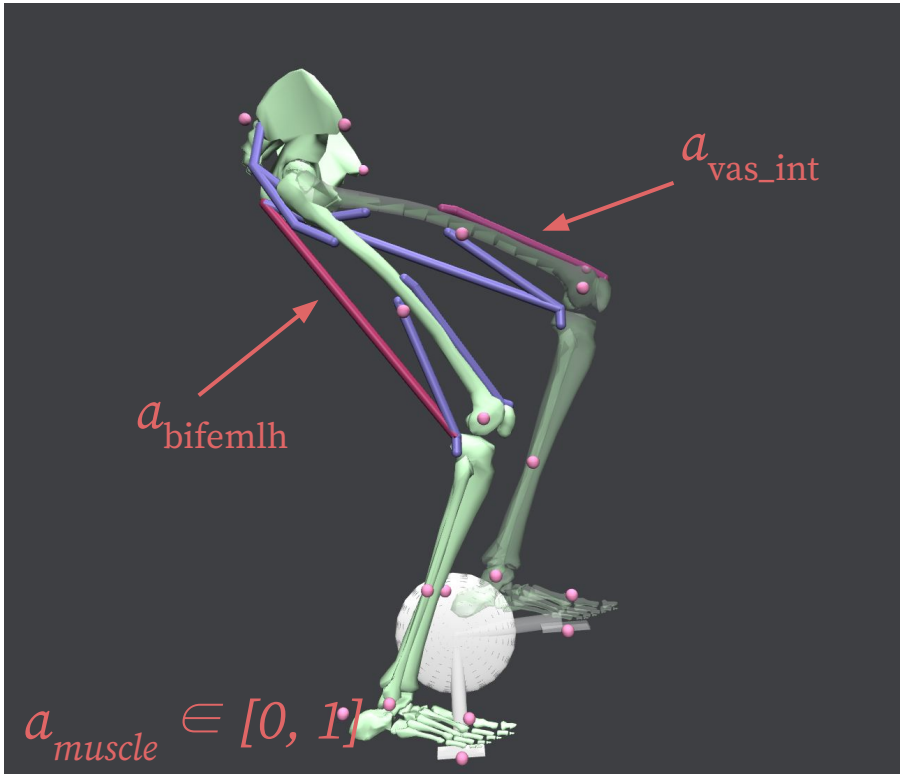


Methods: OpenSim Tools

Computed Muscle Control Tool

- Given a desired motion and external forces, determines muscle activations needed to reproduce the motion
- Optimization minimizes activations and deviations from desired motion

$$J = \Sigma w_i x_i^2 + \Sigma w_j (q''_{j,\,des} - q''_{j,\,CMC})^2$$



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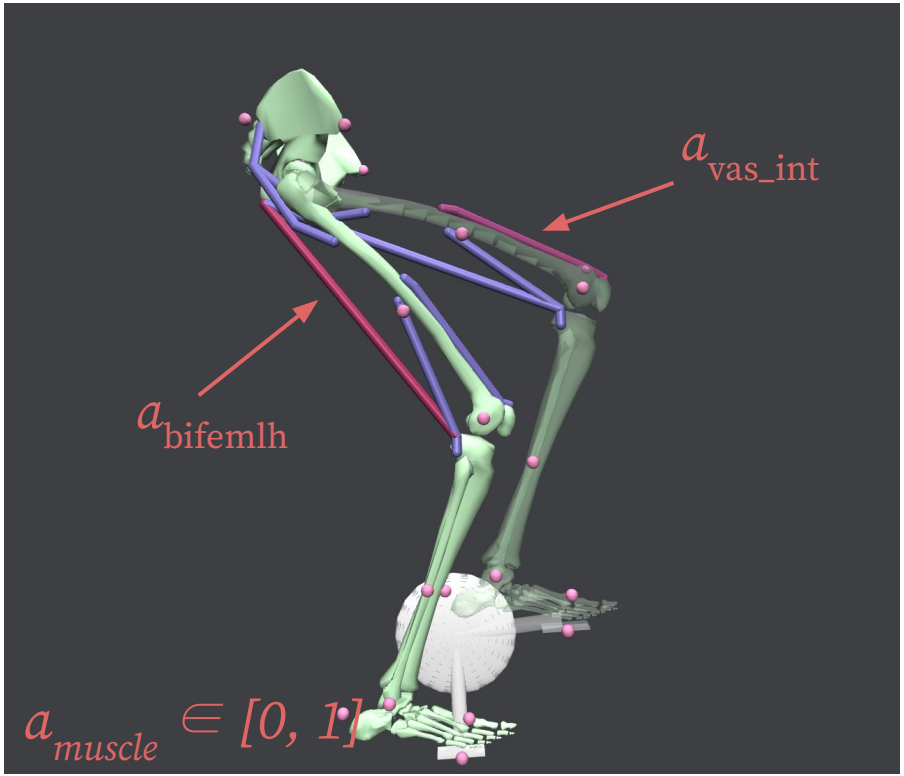
In the Workflow: *CMC Tool step*

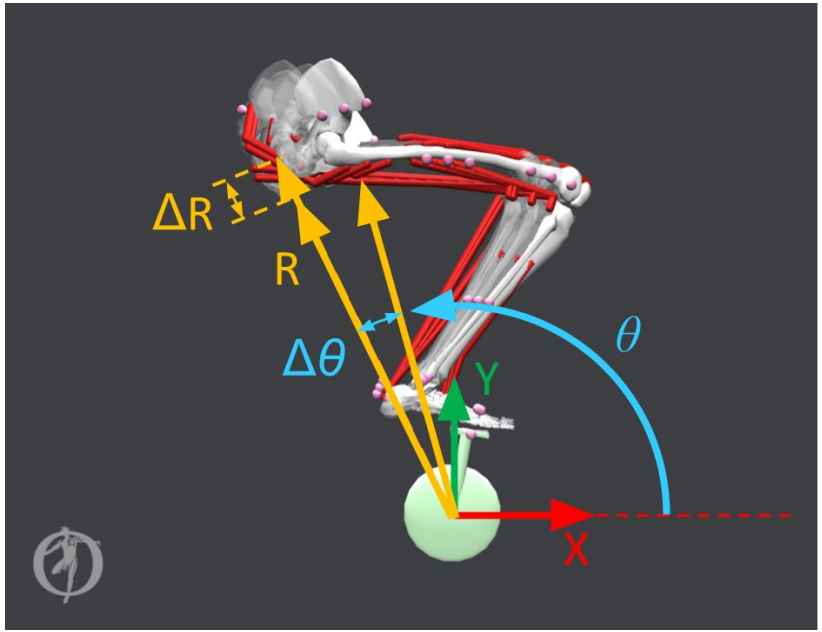
- Activations used to calculate MEER directly



Workflow

Workflow: Inputs

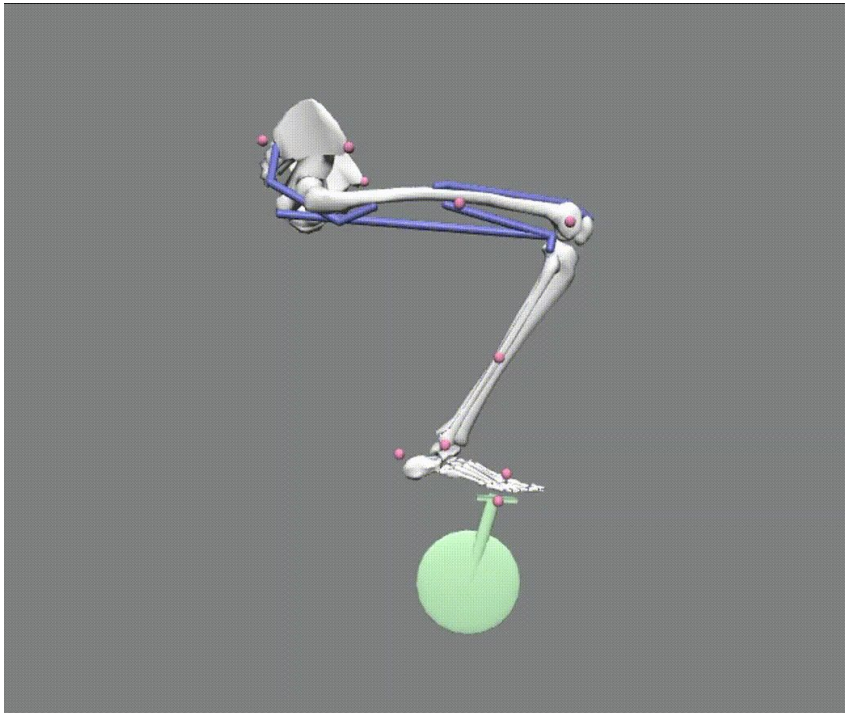
- 6 unique saddle positions
  1. (R,θ) = (0.8196 m, 102°)
  2. (R,θ) = (0.8196 m, 105°)
  3. (R,θ) = (0.8196 m, 108°)
  4. (R,θ) = (0.8396 m, 102°)
  5. (R,θ) = (0.8396 m, 105°)
  6. (R,θ) = (0.8396 m, 108°)
- Saddle positions (R, θ) correspond to locations of the pelvis with respect to the bottom bracket



The parametrized saddle position is defined by:

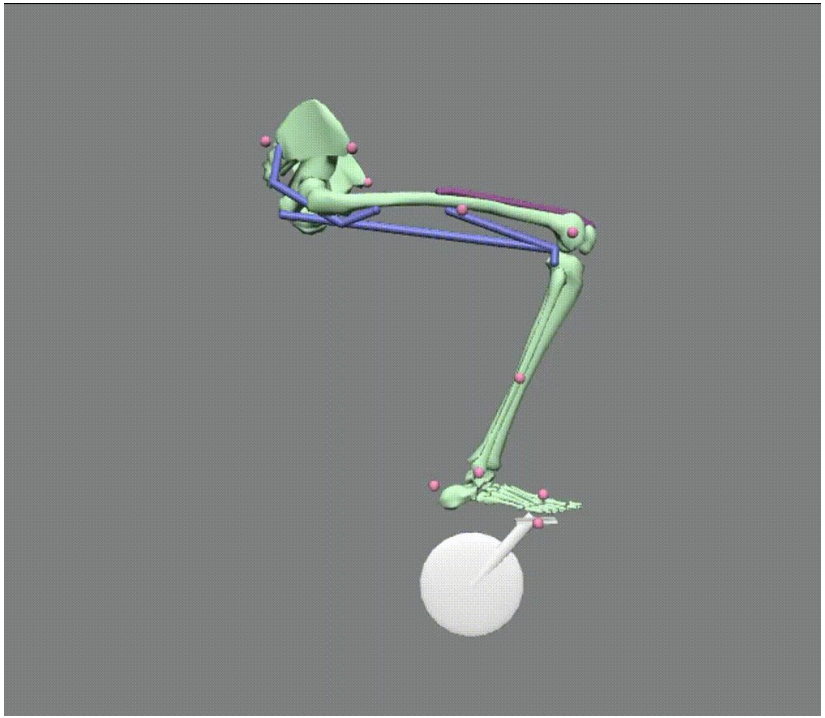
R = seat tube height **&** **θ = seat tube angle**

Workflow: Simulated Forward Kinematics (SFK)



- Constant pedaling speed (80 RPM) was prescribed to the crank angle
- Model passively followed crank via pedal clip constraint
- Joint angles, muscle lengths, muscle velocities, and reaction forces at the pedal clip constraint vs. time were extracted
- Pedal reaction forces were smoothed in MATLAB for each subsequent CMC trial

Workflow: Computed Muscle Control (CMC)



- The CMC Tool generated the muscle activations required for the model's muscles to produce the same motion from the SFK step
  - Minimized:
    $$J = \Sigma w_i x_i^2 + \Sigma w_j (q''_{j,\,des} - q''_{j,\,CMC})^2$$
  - *CMC Tool may find unstable solutions and fail to solve a trial*
- From muscle activations, MEER, was calculated

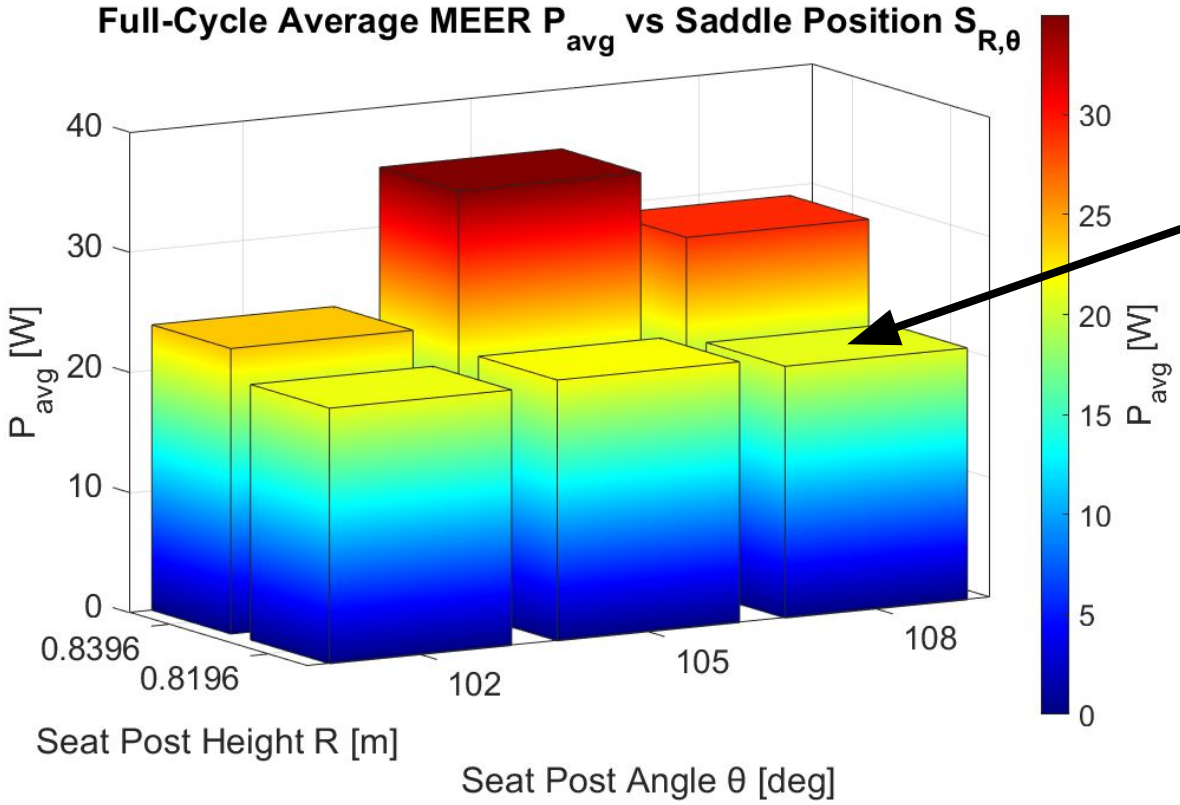
Workflow: Organization of Analysis

- **Metabolic Energy Expenditure Rate (MEER) Analysis**
  - Analysis & comparison of full-cycle averaged MEER for all 6 trials
  - Analysis of MEER of trial with minimum full-cycle averaged MEER: $(R,\theta) = (0.8196\ m, 108°)$

- **Active Force Capacity Analysis**
  - Gain insights & validate MEER results without explicitly calculating MEER
  - Analysis of muscle states of trial with minimum full-cycle averaged MEER: $(R,\theta) = (0.8196\ m, 108°)$

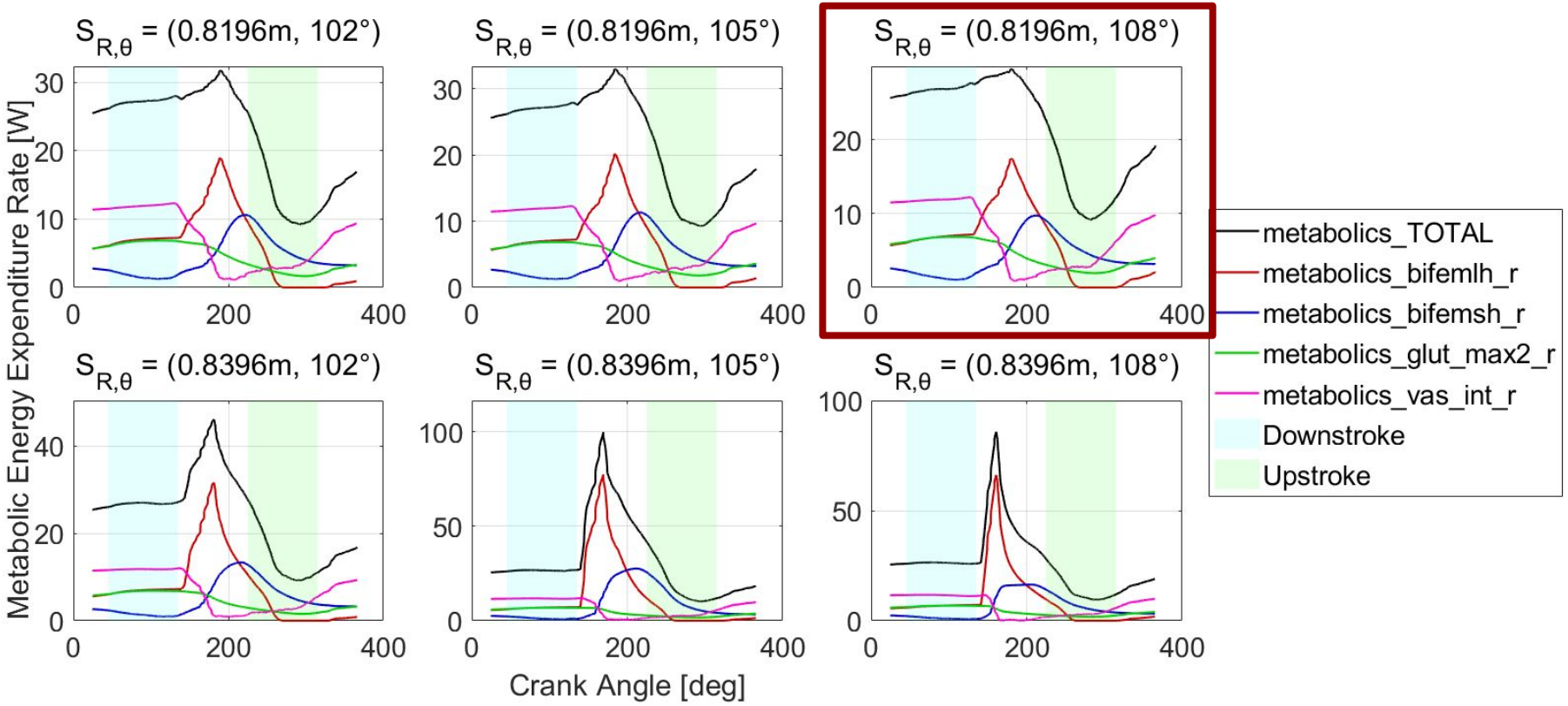
Results & Analysis

Results: Full-Cycle Average MEER vs. Saddle Position

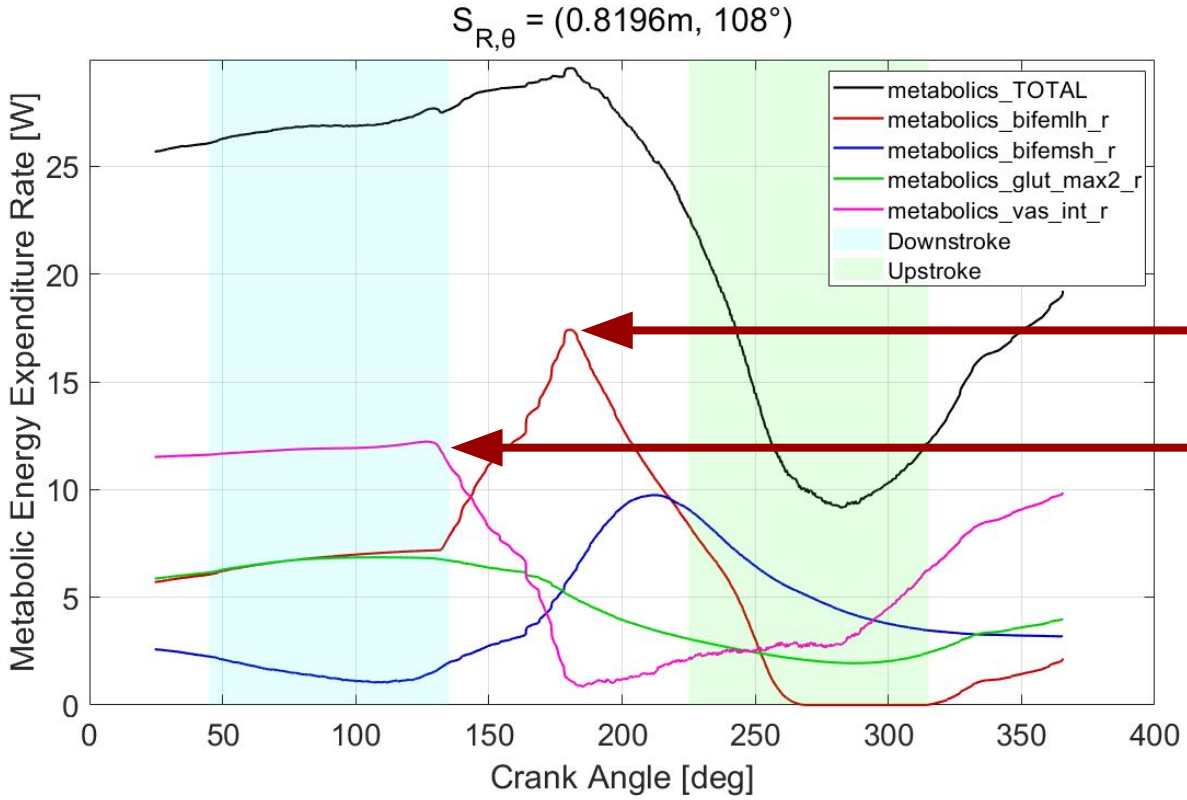


Smallest full-cycle average MEER
(R, θ) = (0.8196 m, 108°)

Results: MEER vs. Crank Angle (all Saddle Positions)



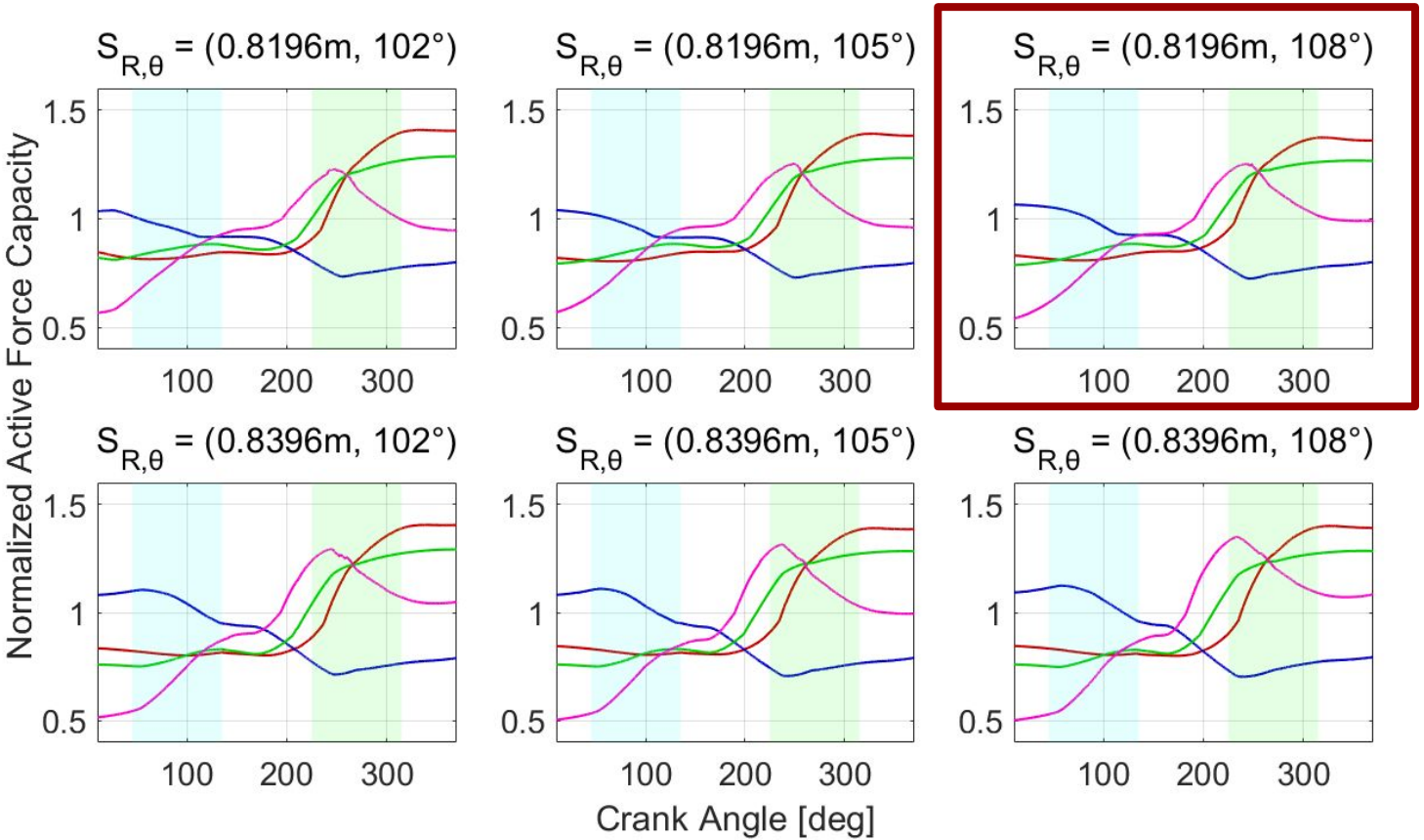
Results: MEER vs. Crank Angle, (R, θ) = (0.8196 m, 108°)



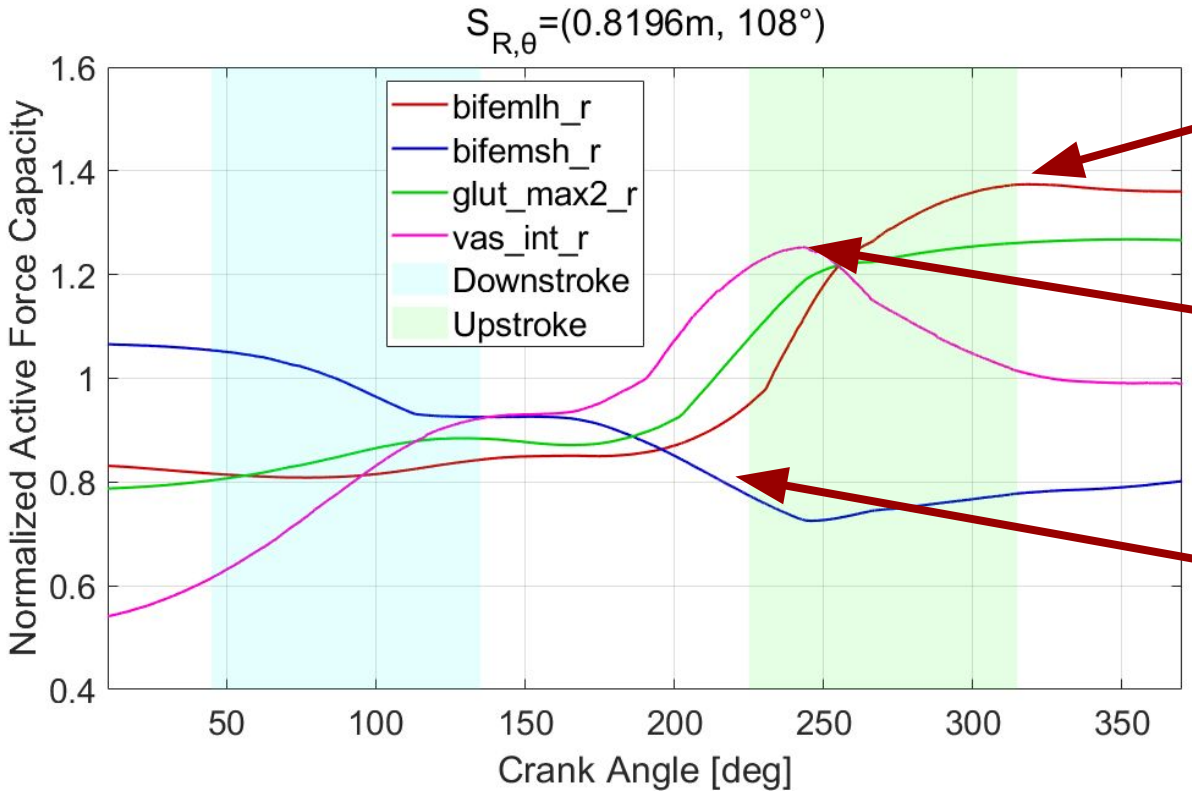
Biceps femoris long head peaks at transition to upstroke

Vastus intermedius peaks in downstroke

Results: Active Force Capacity (all Saddle Positions)



Results: Active Force Capacity, (R, θ) = (0.8196 m, 108°)

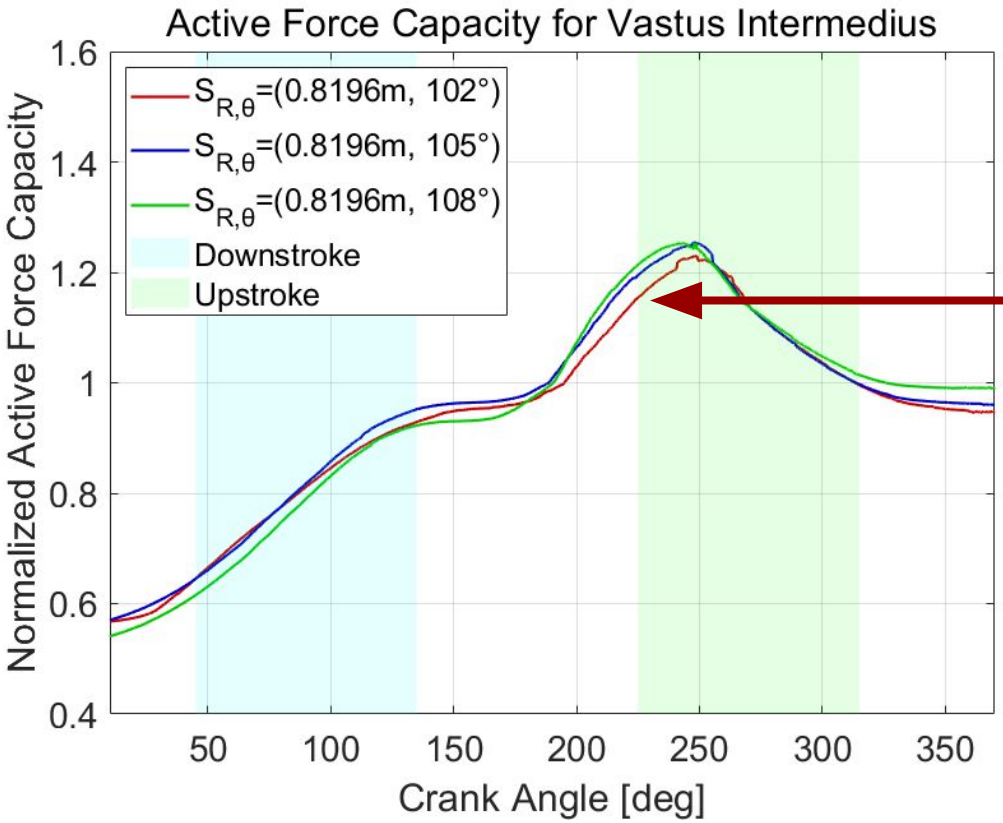


Biceps femoris long head force peaks at maximum eccentric contraction

Vastus intermedius force peaks at maximum fiber length

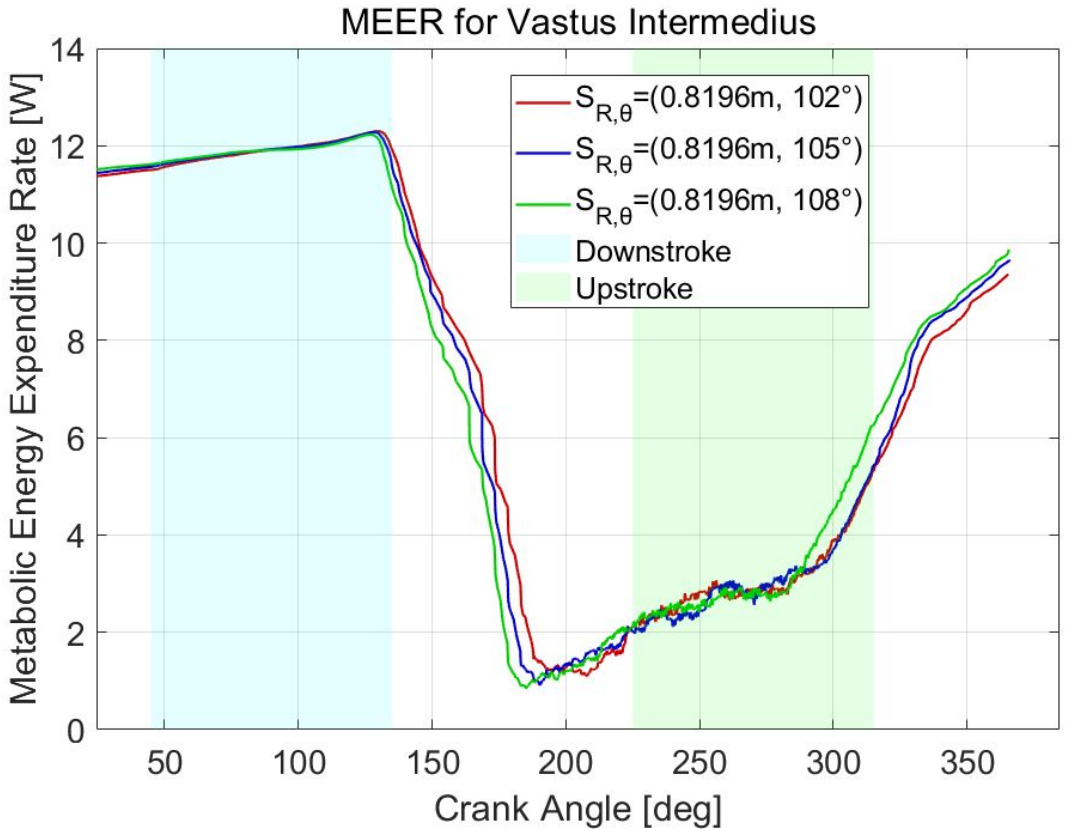
Biceps femoris short head force decreases due to decreasing muscle fiber length

Results: Active Force Capacity for Vastii at R = 0.8196 m



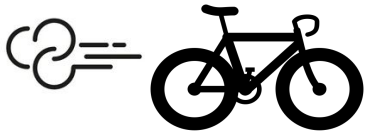
Saddle position at **θ = 102°** has smallest active force capacity

Results: MEER for Vastii at R = 0.8196 m



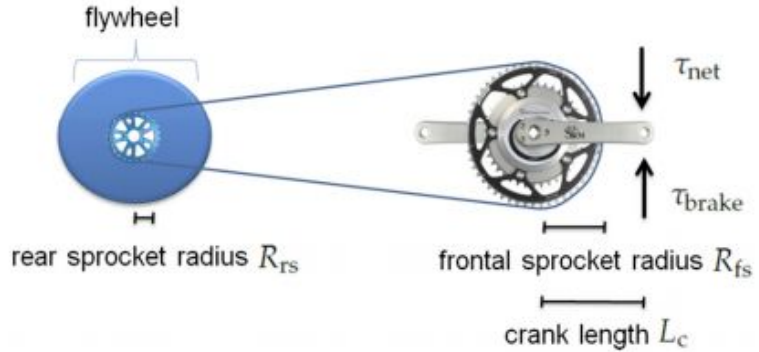
Full-cycle average MEER is highest at **θ = 102°**

Moving Forward



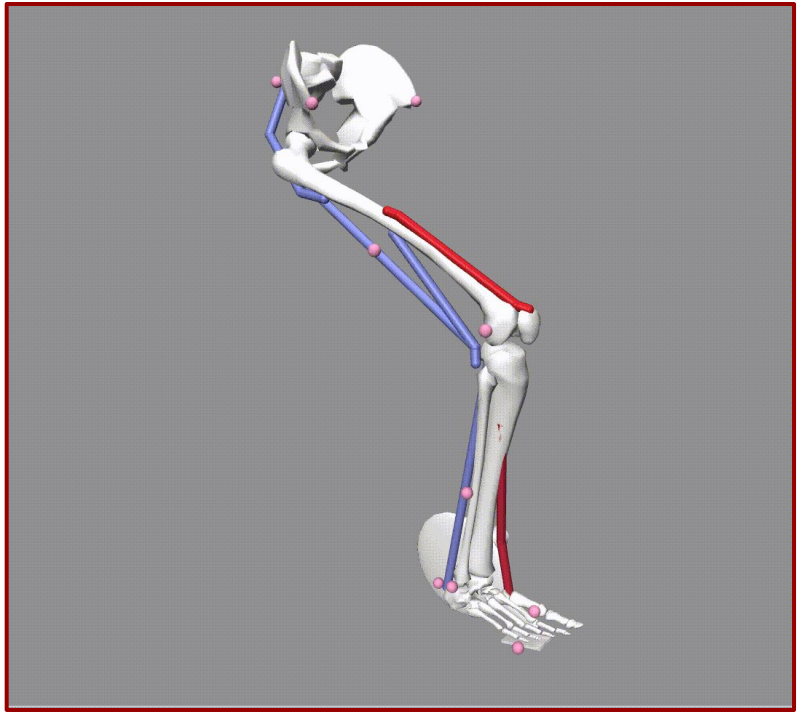
Moving Forward: Adding Model Complexity

Incorporating Resistance Torque

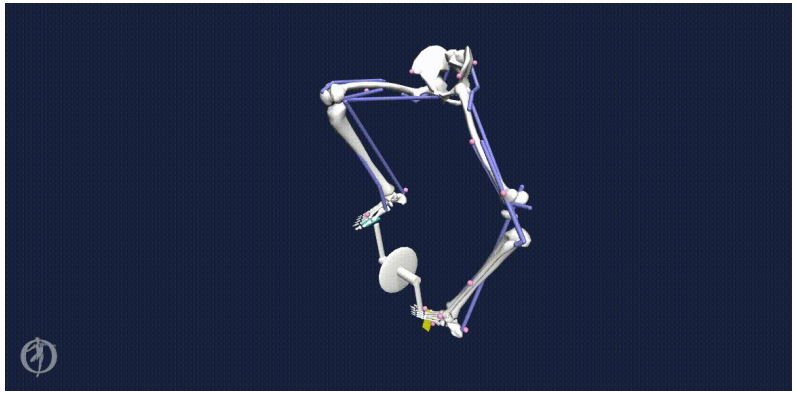


Schematic of brake/resistive torque in relation to crank and sprocket dimensions *(Quintana-Duque 2015)*

Adding Gastrocnemius & Tibialis Anterior



Moving Forward: Two-Legged Model



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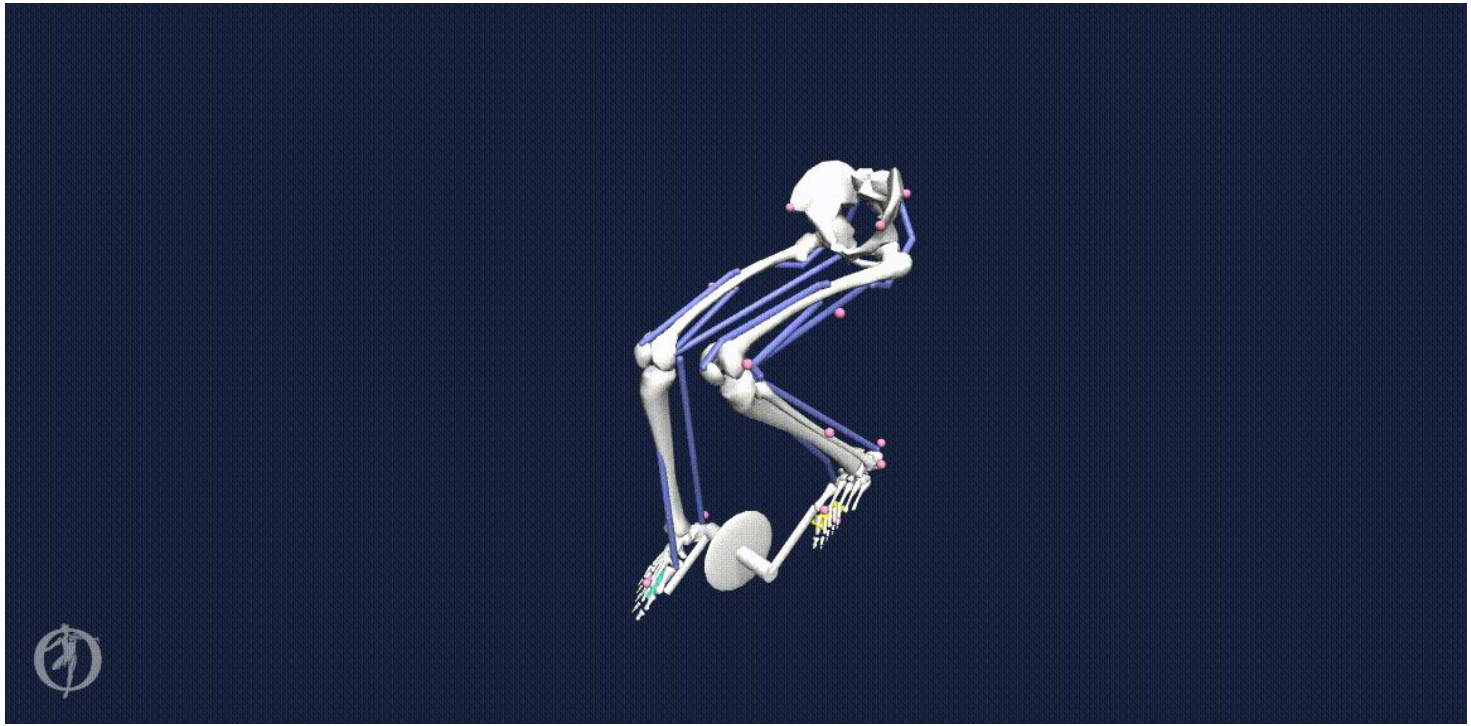

Completed SFK Run of Two-Legged Model for Specialized to Leverage in Future Analysis

Conclusions

Conclusions

- **Developed a computational workflow** to relate cyclist MEER to saddle position
- **Validated this workflow** by obtaining and analyzing the results for a set of saddle positions
  - MEER analysis showed minimum MEER @ (R,θ) = (0.8396 m, 108°)
  - MEER analysis results were validated by biomechanics muscle states analysis
- Specialized can now use this **computational workflow method for quick results turnaround** in their design cycle in place of traditional time-consuming experimental methods

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