DEVELOPMENT OF THE NASA DIGITAL ASTRONAUT PROJECT MUSCLE MODEL

B.E. Lewandowski[1], J.A. Pennline[1], W.K. Thompson[1], B.T. Humphreys[2], J.W. Ryder[3], L.L. Ploutz-Snyder[3], L. Mulugeta[3]
[1]NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135
[2]ZIN Technologies, 6745 Engle Road, Airport Executive Park, Cleveland, OH 44130
[3]Universities Space Research Assoc., Div. of Space Life Sciences, 3600 Bay Area Blvd., Houston, TX 77058

National Aeronautics and
Space Administration

BACKGROUND

NASA's Digital Astronaut Project (DAP) Vision

The Digital Astronaut Project implements well-vetted computational models to predict and assess spaceflight health and performance risks, and enhance countermeasure development

HRP Risks/Gaps Addressed by This Effort

Risk of Muscle Atrophy: Impaired performance due to reduced muscle mass, strength and endurance
M2 - Characterize in-fight and post-flight muscle performance
M7 - Develop the most efficient exercise program for the maintenance of muscle fitness
M24 - Characterize the time course of changes in muscle protein turnover, muscle mass and function during long duration space flight

Musculoskeletal Modeling Objectives

Use an integrated musculoskeletal modeling approach to support the bone remodeling model efforts and provide muscle performance prediction capabilities:

- Provide bone loading information from biomechanical models of exercise that incorporate muscles that reflect spaceflight atrophy
- Develop algorithms which equate mechanical stimulus from in-flight exercise to muscle maintenance
- Predict the minimal amount of stimulus needed to maintain required performance levels
- Predict if the stimulus be achieved by performing in-flight exercise on the available exercise devices
- Predict task performance after a specified time in space
- Predict the minimum amount of muscle strength and power to perform a task

OPERATIONAL CONCEPT

Support Advanced Exercise Countermeasures Project

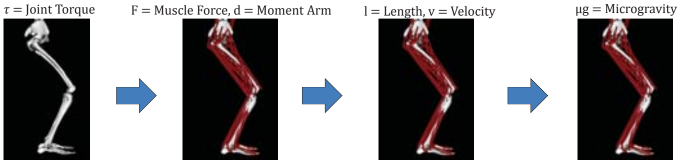
Advance from prediction of joint torque to muscle force to muscle force as a function of muscle length and velocity to incorporation of muscular changes due to spaceflight

τ_{Net}
τ = Joint Torque

$\tau = Fd$
F = Muscle Force, d = Moment Arm

$\tau = F(l,v)d$
l = Length, v = Velocity

$\tau = F(l,v,\mu g)d$
μg = Microgravity



General information about active muscle groups

Individual muscle force comparison between and within exercises

Muscle length and power production predictions and comparison of muscle performance between and within exercises

Mechanical stimulus related to muscle function maintenance and predict changes in muscle performance due to spaceflight

Inform questions such as:

How does muscle performance differ between different exercise devices, types of exercises and exercise configurations?

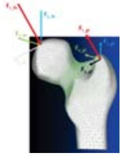
Does the limited volume and power requirements affect the muscle forces generated during prescribed exercises?

Does that affect the ability of the countermeasure device to maintain muscle performance?

How does that affect the astronauts ability to perform required tasks?

Support Bone Remodeling Modeling Efforts

Increase the fidelity of the input force to the FEM which provides bone strain input to the bone remodeling model



A full representation of muscle attachment points will likely change the stress distribution in the cortical bone

Important for modeling the whole proximal femur rather than only the femoral neck and for modeling the periosteal surface as well as cortical bone

Incorporate decreases in muscle force due to spaceflight atrophy into bone loading predictions

MUSCLE MODEL CONCEPT

DAP Muscle Model Concept

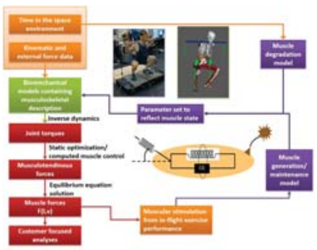
Version 1.0 (Target completion, 9/2016) model input includes time spent in space and qualitative level of exercise use (low, average, high)

The model uses spaceflight and Earth based analog data to perform a parameter fit for the OpenSim muscle model parameters

Model output is an OpenSim muscle model parameter set that reflects the state of the muscle after the specified amount of time in space and exercise use

Version 2.0 (Target completion, 9/2019) based upon two functions:
1) Muscle degradation vs. time in microgravity

2) Muscle generation/maintenance as a function of muscle contraction and stretch during the mission

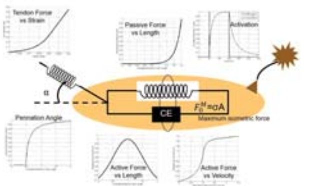


MUSCLE MODEL COMPONENTS

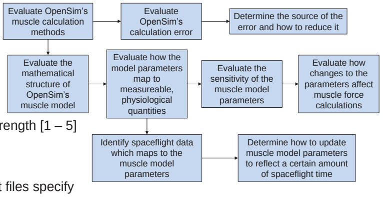
Tendon Force - Muscle Force Equilibrium Equation

$$F_T = F_{M0} = (af_L f_v + f_{PE})\cos \propto$$

F_T = Tendon force vs strain
F_{M0} = Maximum isometric force
a = Neuromuscular activation
f_L = Active force vs length curve
f_v = Active force vs velocity curve
f_{PE} = Passive force vs length curve
α = Pennation angle



UNCERTAINTY, SENSITIVITY AND VALIDATION ANALYSES



Evaluate OpenSim's muscle calculation methods

Evaluate OpenSim's calculation error

Determine the source of the error and how to reduce it

Evaluate the mathematical structure of OpenSim's muscle model

Evaluate how the model parameters map to measureable, physiological quantities

Evaluate the sensitivity of the muscle model parameters

Evaluate how changes to the parameters affect muscle force calculations

Identify spaceflight data which maps to the muscle model parameters

Determine how to update muscle model parameters to reflect a certain amount of spaceflight time

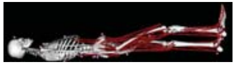
Objectives

- Use simplified exercise models to gain a sufficient understanding of the OpenSim modeling environment and to determine how to augment OpenSim in order to model spaceflight induced muscle atrophy

Methods

- OpenSim models of exercises used to assess post-flight strength [1 – 5]
  - Isometric and isokinetic plantar flexion exercises [6 – 9]
  - Isometric and isokinetic knee flexion and extension exercises [10]
  - Leg press exercise to obtain maximum explosive power [11]
- Kinematics input files specify joint angles and kinetics input files specify joint torques/ground reaction forces
- Muscle excitations obtained with a Computed Muscle Control analysis
- Muscle forces calculated with a forward dynamics analysis
- Analyses performed:
  - Calculated joint torques/ground reaction forces compared to prescribed values to find calculation error
  - Muscle parameters adjusted systematically to determine sensitivity
  - Muscle parameters modified to reflect spaceflight data in order to quantitatively compare preflight and post-flight conditions

OpenSim plantar flexion model



OpenSim knee flexion/extension model

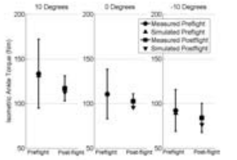
OpenSim leg press model

Results

- Calculation error typically ranged from 1 – 10%, submaximal cases tended to be higher
  - In some cases, calculation error is larger than the differences due to spaceflight and must be reduced for meaningful comparison of 1g to spaceflight conditions
- Tendon slack length and optimal fiber length identified as the most sensitive model parameters
  - Allows prioritization of parameters when addressing parameters for which data is lacking
- Post-flight predictions when changing only the maximum isometric force parameter was successful for isometric and low velocity isokinetic strength predictions, but not for high velocity isokinetic cases
  - Spaceflight data suggests that a reduction in force cannot be explained by reduction in volume alone
  - Neuromotor control, morphology, specific tension, stiffness properties, etc. may also be important
  - These preliminary results suggest that they need to be accounted for in the model

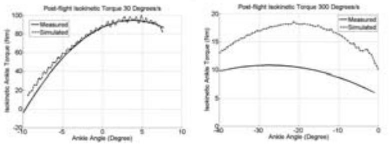
Plantar flexion analysis results

Measured vs simulated comparisons of preflight and post-flight strength measurements



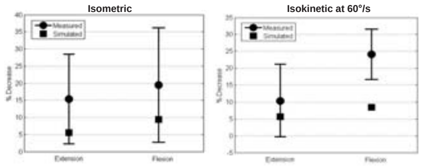
Future Work

- Complete leg press analysis, with particular focus on error due to unknown kinematics
- Determine and develop strategies to minimize the main sources of calculation error in OpenSim
- Take further advantage of the OpenSim optimization methodologies and capabilities
- Complete sensitivity analysis with parameters that are constant across all muscles
- Develop ranges for muscle model parameters which reflect
  - Uncertainty due to individuality
  - Change due to spaceflight as a function of
    - Time in space
    - Level of in-flight exercise performed
- Explore alternative optimization methods for fitting parameters to address [12]:
  - The interdependency of the parameters
  - The lack of quantitative data for all parameters



Knee flexion/extension analysis results

Measured vs simulated changes in muscle strength from preflight to post-flight



Isometric

Isokinetic at 60°/s

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