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Uncertainty, Validation and Sensitivity Analyses of the OpenSim Muscle Model for Pre- and Post-flight Strength Predictions

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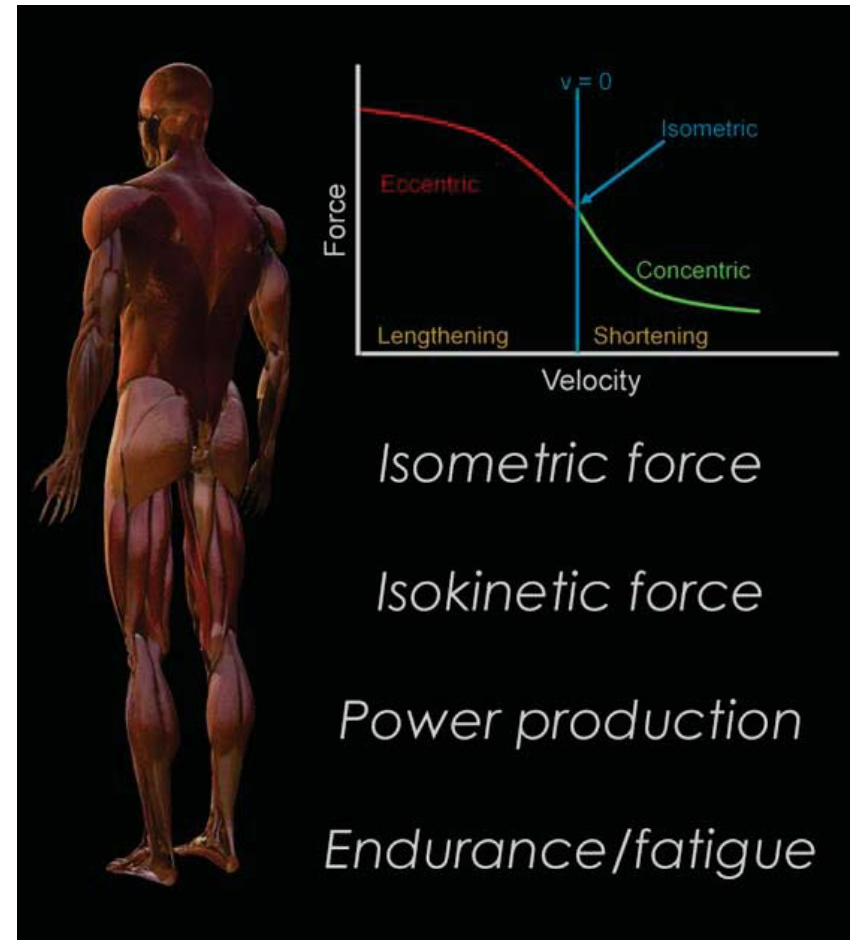
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Topics to Cover

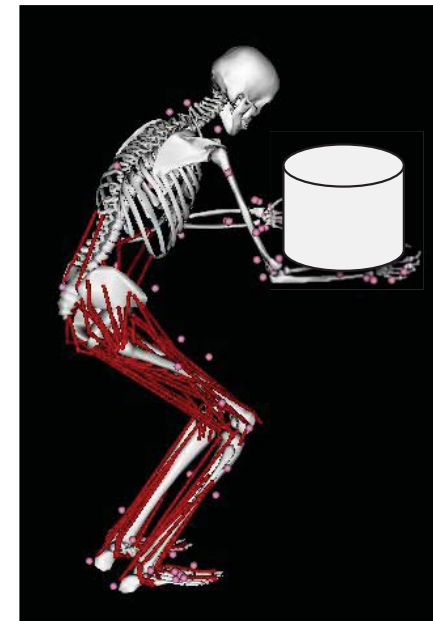
- **Digital Astronaut Project (DAP) Muscle Model Background**
- **The Plantar Flexion Model**
- **Uncertainty Analysis**
- **Sensitivity Analysis**
- **Validation Analysis**
- **Future Work**





DAP Muscle Model Background

- **The DAP muscle model is a computational model describing muscle structure and function as a function of time in space**
 - The DAP muscle model is based upon the OpenSim Thelen 2003 muscle model
 - Tendon force equation
 - Force vs. length relationship
 - Force vs. velocity relationship
 - Passive muscle force vs. length relationship
 - At first, the model will consist of simplified models of the OpenSim muscle model parameters as a function of time in space, based on spaceflight data
 - Later versions of the DAP muscle model will be based upon two functions:
 - Muscle degradation vs. time in microgravity
 - Muscle generation/maintenance as a function of muscle contraction and stretch during the mission
- **The DAP muscle model will be incorporated into OpenSim and used in biomechanical modeling of exercise countermeasures and spaceflight tasks to:**
 - Develop site specific bone loading input to the DAP Bone Adaptation Model
 - Predict astronaut performance of spaceflight tasks
 - Inform effectiveness of new countermeasure concepts



DAP Muscle Model Background

- In this work, analyses were performed to assess OpenSim's default muscle model capabilities and to begin formulation of the DAP muscle model:

- Uncertainty Analyses

- Quantification of OpenSim's calculation error

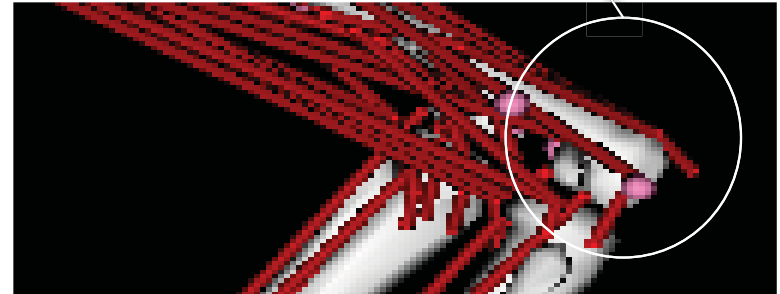
- Sensitivity Analyses

- Identification of OpenSim's most sensitive parameters
- Determination of focus areas for DAP muscle model development

- Validation Analyses

- Using spaceflight data, OpenSim muscle parameters were adjusted according to time in space
- Simulated results were compared to measured data to quantify how well the muscle parameter changes described changes in muscle function due to spaceflight

$$\vec{\tau}_J = \sum_{n=1}^N R_n(\vec{q}) \vec{F}_n$$



$$F_n = F_{PE} + A(t) F_{Max} f_H(v_r) f_L(l_r)$$

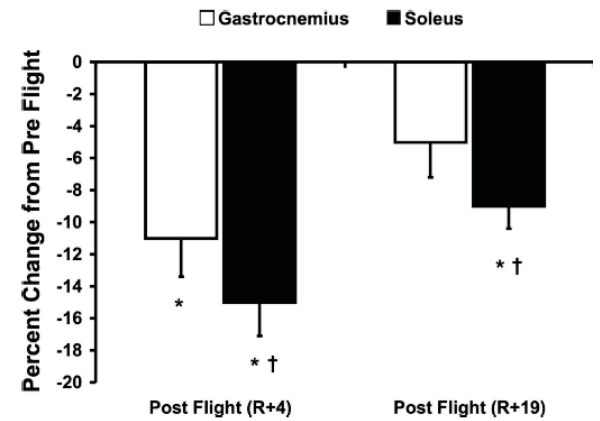
Joint torque (τ_J) is the sum of the N muscle forces (F_n) multiplied by their corresponding muscle moment arms (R_n). Muscle force (F_n) consists of the passive muscle force (F_{PE}) and the active muscle force, which is dependent on the excitation $A(t)$, maximum isometric force (F_{max}), velocity dependent force ($f_H(v_r)$) and length dependent force ($f_L(l_r)$).



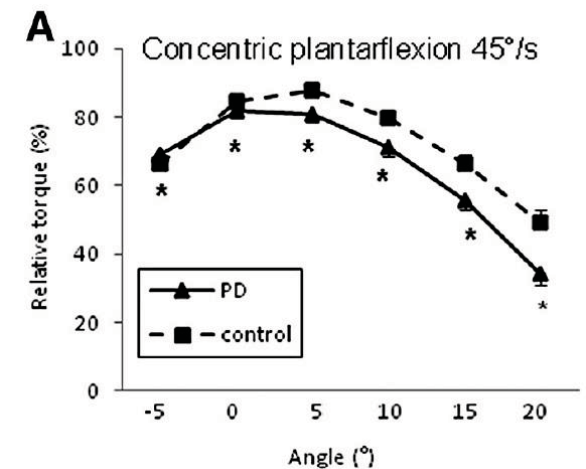
The Plantar Flexion Model



- Based upon isometric and isokinetic plantar flexion strength measurement tests [1-4]
- The OpenSim full body model was used [5]
- Computed muscle control analyses
 - Ankle joint angles described in a kinematics file
 - Ankle torque described in an applied force file
 - Muscle excitations calculated and used as input to forward dynamics analyses
- Joint torque calculation:
 - Lower leg musculotendon forces calculated with forward dynamics analyses
 - Muscle forces multiplied to their corresponding moment arms and the products summed to obtain simulated ankle torque



1. Percent change in gastrocnemius and soleus muscle volume



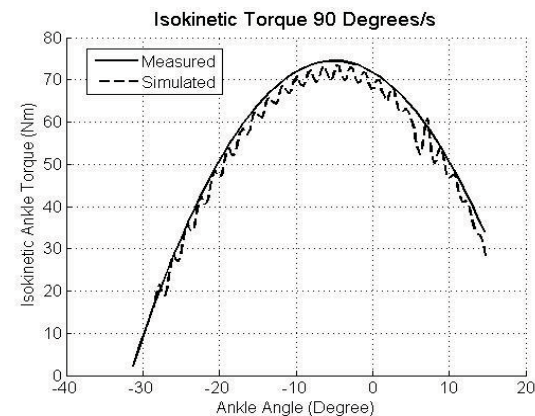
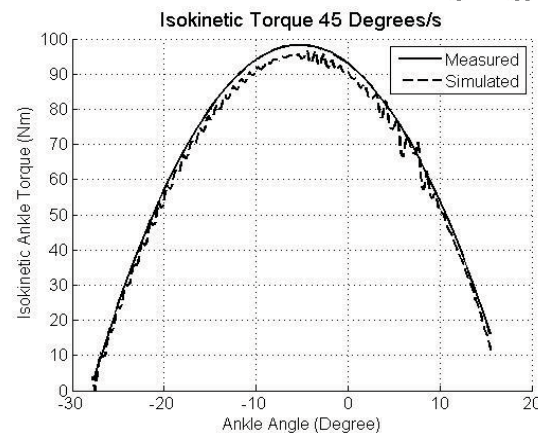
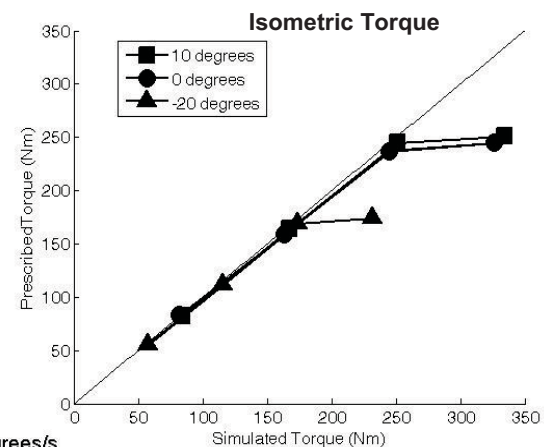
[1] Trappe et al. (2009) *J Appl Physiol*, 106(4) 1159-68
[2] Trappe et al. (2001) *Int J Sports Med*, 22(3) 186-91
[3] Pang et al. (2012) *Arch Phys Med Rehabil*, 93(12) 2352-59
[4] Bobbert et al. (1990) *J Biomech*, 23(2) 105-19
[5] Hamner et al. (2010) *J Biomech*, 43(14) 2709-16



Uncertainty Analysis



- OpenSim calculation error was determined by comparing prescribed torque to simulated torque
- Isometric analyses at ankle angles of 10, 0 and -20° resulted in 1.3 – 3.3% error
- Isokinetic analyses at velocities of 45 and 90°/s resulted in a mean \pm standard deviation percent error of $4.2 \pm 5.1\%$ and $4.8 \pm 4.0\%$ error, respectively
- The calculation error provides a bound on the necessary difference between two conditions before a case can be made that the prediction is due to the phenomenon being modeled





Sensitivity Analyses

- Identification of the most sensitive OpenSim muscle model parameters and determination of focus areas for DAP muscle model development
- Five OpenSim muscle parameters for each of the twelve calf muscles were analyzed in a Monte Carlo sensitivity analysis (Isometric) and in a one-at-time sensitivity analysis (Isokinetic)
 - Maximum Isometric Force
 - Tendon Slack Length
 - Optimal Fiber Length
 - Maximum Shortening Velocity
 - Pennation Angle
- **The top two sensitive parameters were**
 - Soleus Tendon Slack Length
 - Medial Gastrocnemius Tendon Slack Length
- In many cases the other muscles compensated for the change in force of the muscle whose sensitivity was being analyzed

Top 2 sensitive parameters from the Isometric Sensitivity Analysis, w.r.t. ankle torque

Parameter	Correlation coefficient (%)
Soleus Tendon Slack Length	24.50
Med Gastroc Tendon Slack Length	20.77

Top 2 sensitive parameters from the Isokinetic Sensitivity Analysis w.r.t mean % error

Parameter	% Error
Soleus Tendon Slack Length	341
Med Gastroc Tendon Slack Length	240



Validation Analyses



- **Using spaceflight data, OpenSim muscle parameters were adjusted according to time in space [1-3]**
- **The OpenSim full body model was scaled to reflect the average height (176 cm) and weight (81 kg) of the spaceflight study subjects [1]**
- **Default OpenSim muscle parameters were used for the preflight cases due to limited data on absolute muscle parameter values**
- **Simulated results were compared to measured pre- and post-flight ankle torque data to determine how well the muscle parameter adjustments described changes in muscle function due to spaceflight [1]**

[1] Trappe et al. (2009) *J Appl Physiol*, 106(4) 1159-68

[2] Gopalakrishnan et al. (2010) *Aviat Space Environ Med*, 81(2) 91-102

[3] Fitts et al. (2010) *J Physiol*, 588(18) 3567-92



Validation Analyses Methods

- Maximum isometric force (F_{max}), maximum shortening velocity (V_{max}) and the force-velocity curve shape factor (A_f) were adjusted based on spaceflight data for the post-flight cases:
 - F_{max} was decreased proportionately to muscle volume (V) [1-2]
 - V_{max} and A_f were changed based upon measurements made from gastrocnemius and soleus biopsy fibers [3]

Muscle	Preflight F_{max}	Post-flight F_{max}	Preflight V_{max}	Post-flight V_{max}	Preflight A_f	Post-flight A_f
Flexor Digitorum Longus	310	279	10	9.56	0.3	0.329
Flexor Hallucis Longus	322	290	10	9.56	0.3	0.329
Lateral Gastrocnemius	683	615	10	9.56	0.3	0.329
Medial Gastrocnemius	1558	1402	10	9.56	0.3	0.329
Peroneus Brevis	435	392	10	9.56	0.3	0.329
Peroneus Longus	943	849	10	9.56	0.3	0.329
Soleus	3549	3017	10	11.8	0.3	0.387
Tibialis Posterior	1588	1429	10	9.56	0.3	0.329
Extensor Digitorum Longus	512	458	10	9.56	0.3	0.329
Extensor Hallucis Longus	162	145	10	9.56	0.3	0.329
Peroneus Tertius	180	161	10	9.56	0.3	0.329
Tibialis Anterior	905	810	10	9.56	0.3	0.329

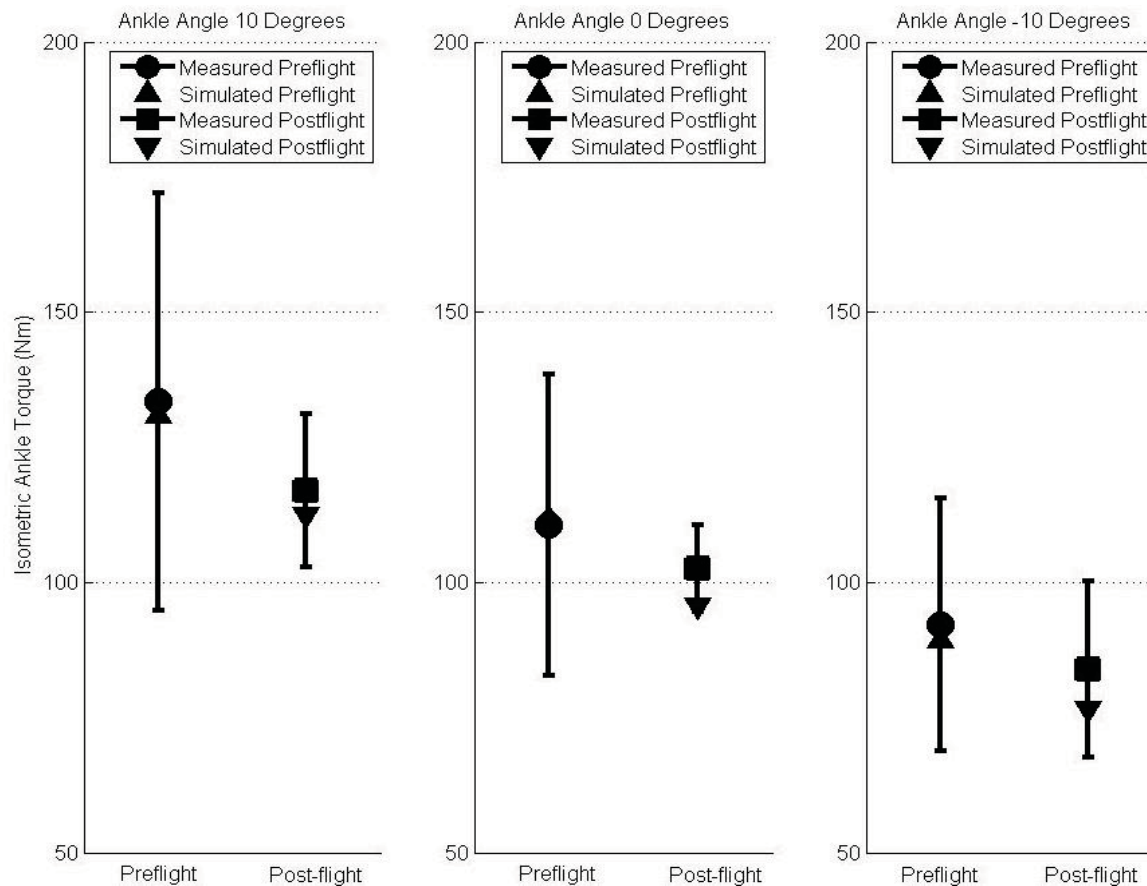
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Isometric Validation Analysis Results

- The percent error between the simulated and measured [1] isometric ankle torque was:
 - 1.0 – 3.2% for the preflight case, similar to the calculation error
 - 3.9 – 8.7% for the post-flight case, includes both calculation and prediction error



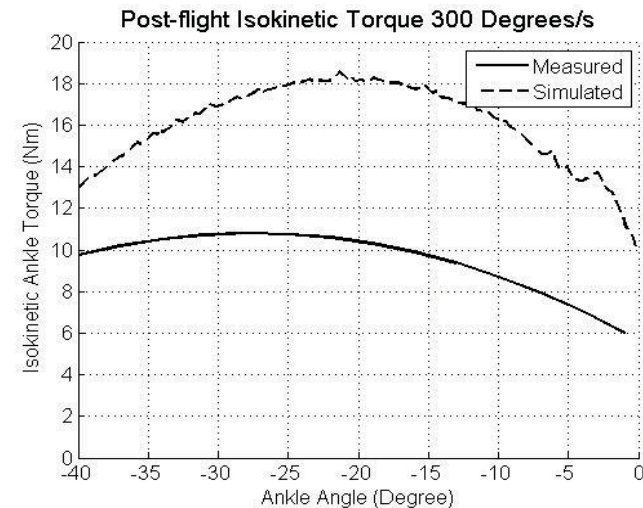
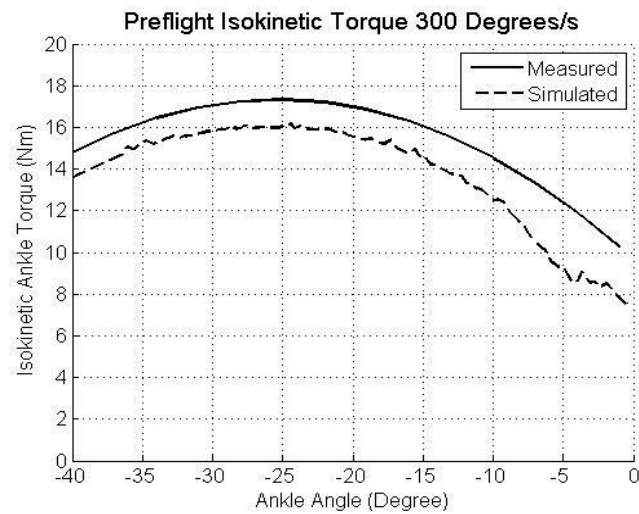
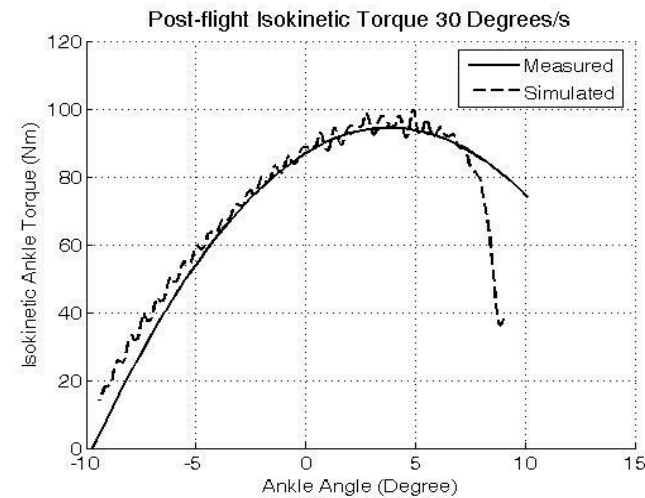
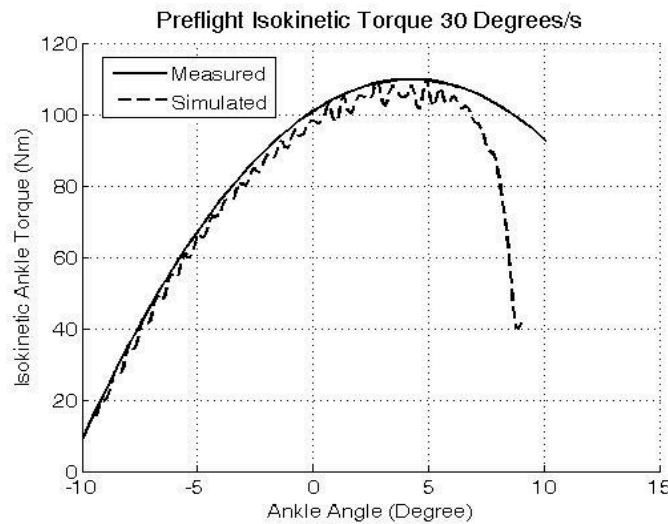
[1] Trappe et al. (2009) *J Appl Physiol*, 106(4) 1159-68



Isokinetic Validation Analysis Results



- Percent error was reasonable for low velocities, unacceptably high for high velocities



Measured data from: Trappe et al. (2009) *J Appl Physiol*, 106(4) 1159-68



Future Work



- **Perform Uncertainty, Sensitivity and Validation Analyses using knee extension/flexion exercises and leg press exercises**
- **Continue development of the DAP muscle model, by creating models of the OpenSim muscle parameters as a function of time in space, based on spaceflight data**
 - Further investigate changes to maximum shortening velocity parameter
 - Investigate changes to muscle and tendon stiffness
 - Investigate optimization methods for determining muscle parameter models
- **Use the DAP Muscle Model:**
 - To develop input data for the DAP Bone Adaptation Model
 - To predict task performance during missions
 - To inform exercise countermeasure development



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- **Special thanks to:**
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 - DeVon Griffin and Marsha Nall for project management



- Parameter space for one-at-a-time sensitivity analysis

Muscle	Maximum Isometric Muscle Force (N)	Tendon Slack Length (m)	Optimal Fiber Length (m)	Maximum Shortening Velocity (m/s)	Pennation Angle (Rad)
Medial Gastrocnemius	1246 - 1870	0.312 - 0.468	0.048 - 0.072	8.0 - 12.0	0.237 - 0.356
Lateral Gastrocnemius	546 - 820	0.304 - 0.456	0.051 - 0.077	8.0 - 12.0	0.112 - 0.168
Soleus	2839 - 4259	0.2 - 0.3	0.04 - 0.06	8.0 - 12.0	0.349 - 0.524
Tibialis Posterior	1270 - 1906	0.248 - 0.372	0.025 - 0.037	8.0 - 12.0	0.168 - 0.251
Flexor Digitorum Longus	248 - 372	0.32 - 0.48	0.027 - 0.041	8.0 - 12.0	0.098 - 0.147
Flexor Hallucis Longus	258 - 386	0.304 - 0.456	0.034 - 0.052	8.0 - 12.0	0.14 - 0.21
Tibialis Anterior	724 - 1086	0.178 - 0.268	0.078 - 0.118	8.0 - 12.0	0.07 - 0.105
Peroneus Brevis	348 - 522	0.129 - 0.193	0.04 - 0.06	8.0 - 12.0	0.07 - 0.105
Peroneus Longus	754 - 1132	0.276 - 0.414	0.04 - 0.06	8.0 - 12.0	0.14 - 0.21
Peroneus Tertius	144 - 216	0.08 - 0.12	0.063 - 0.095	8.0 - 12.0	0.182 - 0.272
Extensor Digitorum Longus	410 - 614	0.276 - 0.414	0.082 - 0.122	8.0 - 12.0	0.112 - 0.168
Extensor Hallucis Longus	130 - 194	0.244 - 0.366	0.089 - 0.133	8.0 - 12.0	0.084 - 0.126