MUSCLE PHYSIOLOGY REDUCES THE FEASIBLE TORQUE SET DURING HUMAN GAIT

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INTRODUCTION

All neuromusculoskeletal systems can be mathematically described as linear mappings from a neural command space to an eventual mechanical wrench space [1]. In nature, the set of feasible neural command inputs is larger than the set of feasible mechanical outputs [2] and different sets of neural commands can achieve the same motion. The culmination of mechanical actions that a joint system produces can be described as the endpoint wrench space. To achieve any particular endpoint wrench set during motor tasks, neural commands must define actions producing muscle forces, which in turn produce joint torques. The hypothetical set of all possible joint torques is referred to as the Feasible Torque Set (FTS) [2]. The FTS sensitivity to physiological parameters of muscle fiber length (l^m) and fiber velocity (v^m) is not well understood. Identifying relationships between force-length-velocity properties and FTS contributes to our understanding of neural control.

In this study, we used OpenSim [3] modeling and simulation to examine the FTS for the human lower-limb joints during normal gait and determine how sensitive the FTS is to different models of muscle physiology, including l^m and v^m. We hypothesized that simulations accounting for l^m would reduce the FTS compared to those assuming maximum isometric muscle forces ($\boldsymbol{F}_0^m$); in addition, simulations accounting for both l^m and v^m would reduce the FTS further.

METHODS

For proof-of-concept, simplicity, and reduced computational costs, we used a two-dimensional gait model with 10 degrees of freedom and 18 muscles available in OpenSim. The model was scaled to the anthropometry of the subject (75 kg, 1.8 m). Inverse kinematics determined model kinematics matching experimental marker data of the subject walking at 1.2 m/s on a treadmill. A residual reduction algorithm adjusted model kinematics and inertial properties to minimize dynamic inconsistencies between the model dynamics and experimental ground reaction forces. Computed muscle control determined muscle excitations and resulting model states for a forward dynamic simulation.

The gait simulation's model and states were used to investigate the effects of l^m and v^m on the FTS for 3 cases of varying muscle physiology inclusion. For no muscle physiology (case 1), muscle forces were simply $\boldsymbol{F}_0^m$. For l^m effects (case 2), muscle forces with activations of 1 were computed along an inextensible tendon when model velocity states were set to 0 and joints locked at each time frame of position data. For both l^m and v^m effects (case 3), muscle forces were computed as in case 2, but model velocity states were from gait and joints unlocked. To isolate v^m effects alone, muscle forces were found by subtracting case 2 from 3. In all cases, the matrix of muscle moment arms about each joint was computed ($\boldsymbol{R}^m$) and used to compute the joint torques ($\boldsymbol{\tau}^m = \boldsymbol{R}^m \cdot \boldsymbol{F}^m$). The FTS was determined by the Minkowski sum of all possible joint torques of the hip, knee, and ankle producing a 3D convex polyhedron, or zonohedron. Zonohedra volumes for the varying muscle physiology cases were compared and we evaluated our hypotheses by conducting one-tailed *t*-tests at the 0.01 significance level.

RESULTS AND DISCUSSION

The FTS's during gait were affected (represented by smaller zonohedra volumes) by including muscle physiology model components (Figure 1). The FTS was largest overall with no muscle physiology considerations (case 1). The FTS was reduced ($p < 0.01$) by 34%, on average, when including l^m effects (case 2) and reduced ($p < 0.01$) by 46%, on average, when including l^m and v^m effects (case 3). Relative volume changes with l^m and v^m effects were 11.5% larger over the entire gait cycle than those with l^m effects alone during both stance (13% larger) and swing (9.5% larger).

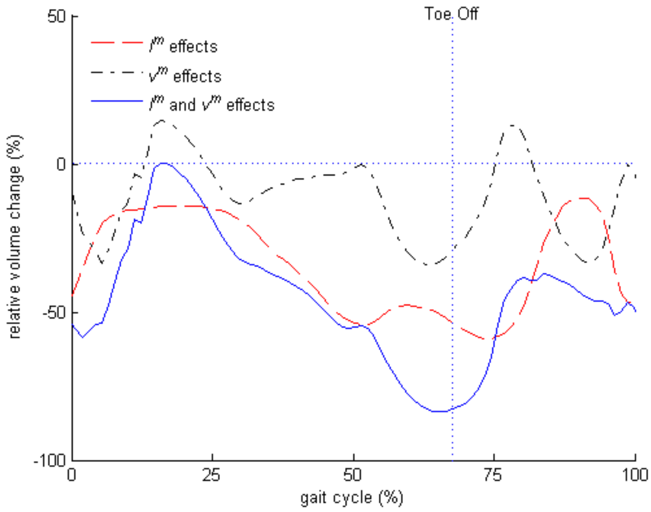

Figure 1: Muscle fiber length, l^m, (*red*) and fiber velocity, v^m, (*black*) effects on hip, knee, and ankle feasible torque sets (FTS) during gait, represented by zonohedron volume changes relative to the FTS using maximum isometric muscle forces without muscle physiology considerations. Muscle fiber length and velocity effects (*blue)* reduce the FTS volumes below the non-physiological case during gait.

CONCLUSIONS

Muscle physiology substantially reduces the lower-limb FTS during gait, and l^m effects are more significant than v^m. To obtain a better understanding of FTS behavior during dynamic movements, it will be necessary to consider additional modeled parameters, such as tendon compliance. Future work to investigate mappings from neural command space to endpoint wrench space should consider tendon compliance as well as the muscle fiber length and velocity. Identifying the function of FTS during movement provides insights to improve our understanding of complex neural control for behavioral tasks.

REFERENCES

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