MUSCLE PHYSIOLOGY REDUCES THE ENDPOINT WRENCH 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 set (EWS). To achieve any endpoint wrench during motor tasks, neural commands must define actions producing muscle forces, which in turn produce joint torques [2]. The EWS 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 EWS contributes to our understanding of neural control.

In this study, we used OpenSim [3] modeling and simulation to examine the EWS for the human lower-limb joints during normal gait and determine how sensitive the EWS is to different models of muscle physiology, including l^m and v^m. We hypothesized that simulations accounting for l^m would reduce the EWS compared to those assuming maximum isometric muscle forces (F_0^m); in addition, simulations accounting for both l^m and v^m would reduce the EWS 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 EWS for 3 cases of varying muscle physiology inclusion. For no muscle physiology (case 1), muscle forces were simply 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 (R^m) and used to compute the joint torques:

$$\tau^m = R^m F^m$$

where F^m denotes the force of the muscle obtained by:

$$F^m = F^{case} a^m$$

where a^m is the muscle activation obtained from the neural command space and F^{case} is the muscle force in each case.

The Jacobian of the limb, denoted by $\boldsymbol{J} \in \boldsymbol{R}^{3\times N}$ where 3 signifies the degrees of freedom of the end point and N signifies the kinematic degrees of freedom and where each column of the limb Jacobian is the instantaneous endpoint velocity vector produced by one unit of the corresponding joint angular velocity [2].

The EWS is then obtained by:

$$w = J^{-T} R^m F^m$$

which by substitution,

$$w = J^{-T} R^m F^0 a^m$$

where J^{-T} denotes the Jacobian pseudoinverse transpose of the body segment and, in this case, it is the left calcaneus.

Because the center of pressure for the foot moves along the foot during gait, it is important to consider this for calculating the location for the application of endpoint forces. To produce a truly robust model of how the EWS changes during gait, we must consider the location of this endpoint. The center of pressure (CoP) is the relative point location of the ground reaction forces and was obtained from data of the same model.

The EWS was determined by the Minkowski sum of all possible linear combinations of each muscle's contribution to the end point forces on the left calcaneus, producing a 2D (sagittal plane) convex polygon, or zonotope. EWS zonotope areas 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 EWS's during gait were affected (represented by smaller zonotope areas) by including muscle physiology model components (Figure 1). The EWS was largest overall with no muscle physiology considerations (case 1). The EWS was reduced (p < 0.01) by 23%, on average, when including l^m effects (case 2) and reduced (p < 0.01) by 31%, on average, when including l^m and v^m effects (case 3). Relative area changes with l^m and v^m effects were 7.8% larger over the entire gait cycle than those with lm effects alone during both stance (6.4% larger) and swing (7.8% larger). Wrench space zonotopes coincided with local maxima and minima for the ground reaction forces (Figure 2).

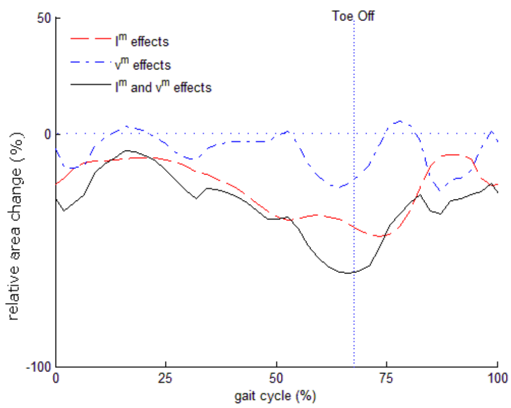

Figure 1: Muscle fiber length, l^m, (red) and fiber velocity, v^m, (black) effects on the endpoint wrench space for the forces on the left calcaneus (EWS) during gait, represented by zonotope area changes relative to the EWS using maximum isometric muscle forces without muscle physiology considerations. Muscle fiber length and velocity effects (blue) reduce the EWS areas below the non-physiological case during gait.

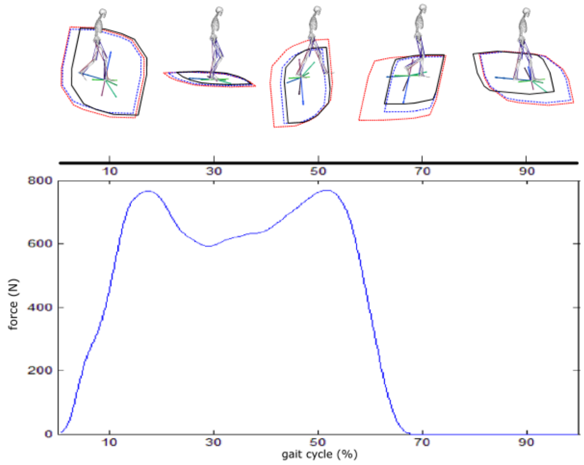

Figure 2: EWS for the lower limb is related to the ground reaction force during stance. Note: Zonotope areas for the end point wrench are smallest during midstance and largest during the weight acceptance. [4] No muscle physiology considerations produced the largest zonotope (red).

CONCLUSIONS

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

ACKNOWLEDGEMENTS

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