DYNAMIC SIMULATION OF ELASTIC ANKLE EXOSKELETON EFFECTS ON PLANTARFLEXOR MUSCLE-TENDON NEUROMECHANICS DURING WALKING

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INTRODUCTION

Recent breakthroughs in assistive walking exoskeletons (exos) using a spring-clutch mechanism in parallel with the ankle plantarflexors have been shown to reduce the net metabolic cost of walking by up to 7% [1]. Joint level analysis revealed that this decrease in metabolic cost occurred in a "sweet spot" of stiffness, where walking economy increased and muscle activity decreased. Simple modeling results suggest that plantarflexor muscle mechanics are negatively impacted when working in parallel with an elastic "exo-tendon" [2]. However, the impact of altered ankle kinematics and individual muscle contributions on plantarflexor mechanics and energetics during exo-assisted gait remains unknown. In order to address this knowledge gap, we employed multi-joint models to drive forward simulations with experimental data and investigated the muscle-level impact of exo-assisted walking in the "sweet spot." We hypothesized that the "sweet spot" occurs when the costs of detuning underlying muscle dynamics to less favorable mechanical conditions and the benefits of reduced muscle force requirements are effectively balanced, resulting in reduced muscle-level metabolic cost.

METHODS

A subset of data collected from a previous study [1] including four healthy adults (2 F, 2 M; 21.8 ± 2.5 yrs.) walking (1.25 $m \cdot s^{-1}$) at three conditions (no exo, exo with no spring, exo with spring stiffness of 180 $N \cdot m \cdot rad^{-1}$) was analyzed. Kinematic data were collected using a motion capture system (Vicon), ground reaction forces from an instrumented treadmill (Bertec) and muscle activity from a wired electromyography (EMG) system (Biometrics Ltd).

All data were processed using OpenSim and Matlab (MathWorks). A lower limb model [3] was modified by removing all muscles except the medial and lateral gastrocnemii (MG and LG), soleus (SOL), and tibialis anterior (TA) and adding a metabolic probe [4, 5]. This base model was then scaled to each subject's anthropometry using marker data from static trials. These individualized models were used to create forward dynamic simulations driven by the measured EMG of the muscles crossing the ankle with simultaneously constrained kinematics and ground reaction forces; this method has been previously described for simulating hopping with an exo [6]. Raw EMG data were processed for input to the simulations using custom Matlab scripts that rectified, filtered (4th order band pass filter, 20-300 Hz), and enveloped (rolling root mean square, 100 ms window) the signal. Because EMG from maximum voluntary contraction was unavailable, a subject-specific scale factor was applied to the EMG activation envelope; the value was selected such that the muscle-generated ankle moment during no exo walking minimized errors when compared to the net ankle moment from inverse dynamics [6]. Verification of the models and analyses was done by comparing inverse kinematics, moments and powers from the same subjects previously reported [1]. From these simulations, we analyzed the muscle states including fiber force, activation, fiber length and metabolic power.

RESULTS AND DISCUSSION

Joint level analyses of kinematics and moments predicted by our simulations are consistent with previously published values [1], and the simulated muscle-generated ankle moments demonstrated similar moment profiles when walking without an exo and with an exo without a spring. The difference between the biological moment production in the exo no spring and spring conditions was congruent with spring force provided by the exo during stance (0-60% stride); limited differences among all conditions were seen during swing, as expected (Fig. 1).

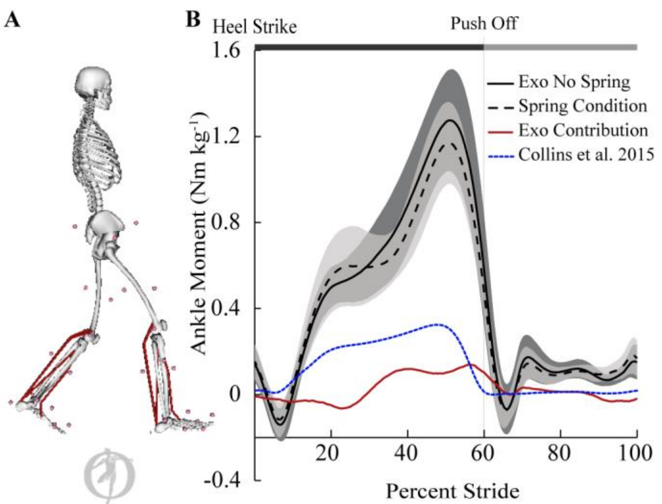

Figure 1: **A:** Simulated model **B:** Average summed muscle moment across subjects for exo no spring (solid) and spring (dashed) conditions. Difference in exo no spring and spring conditions yields exo contribution (red), previous findings in blue (dotted).

Muscle-level mechanics of the plantarflexors are dominated by the uniarticular SOL, which accounts for approximately 60% of the summed physiological cross-sectional area. Decreases in the net ankle moment were reflected by a decrease in SOL fiber forces (10.5%) and reduced activations (7.8%) during stance (Fig. 2A,B). SOL force generation ability during stance was not found to be substantially reduced (0.8%) (Fig. 2C). However, in support of our hypothesis, there was an increase in SOL fiber lengths (Fig. 2D). Metabolic power for the SOL was found to decrease (6.1%) in the spring condition compared to no spring (Fig. 2E).

CONCLUSIONS

Our simulations show reduced biological force production during stance resulting from passive exo assistance. The SOL force-generating ability remained unchanged despite a shift in muscle dynamics. The metabolic cost reduction found in the SOL demonstrates that at the "sweet spot" the trade-off between reduced force requirements and detuned muscle dynamics is managed. Future work will include *in vivo* ultrasound measurements to confirm and expound upon current knowledge of plantarflexor dynamics during assisted walking.

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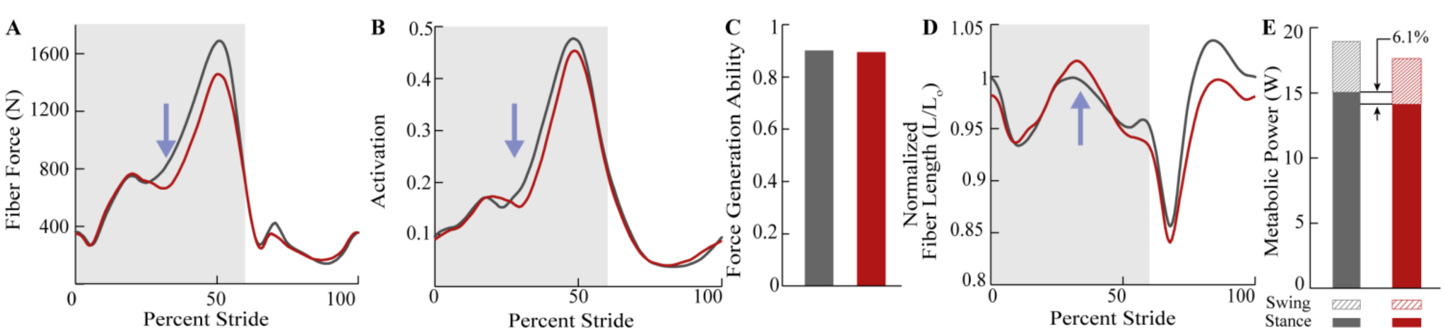

Figure 2: Exo no spring (Grey) vs Spring (Red) for SOL **A:** Fiber Force **B:** Activation **C:** Average Force Generation Ability during stance (force per unit activation) **D:** Fiber Length **E:** Average Metabolic Power