FOOT DISSIPATION DURING ANKLE PUSH-OFF: HUMAN WALKING INSIGHTS FROM A MULTIARTICULAR EMG-DRIVEN MUSCULOSKELETAL MODEL

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INTRODUCTION

Humans perform a burst of push-off work with their trailing limb during the step-to-step transition in walking. This push-off helps redirect the body's center-of-mass, reducing collisional energy losses after heelstrike and enabling economical gait [1]. However, the foot performs negative work during this phase of gait [2], which counteracts a fraction of the positive push-off work of the ankle. These conflicting ankle and foot behaviors are difficult to reconcile with previous findings on energy-saving mechanisms used during gait, and dynamic walking principles emphasizing the importance of center-of-mass push-off [1].

This study sought to investigate one plausible explanation for the conflicting ankle and foot behaviors during push-off. We hypothesized that our current understanding of ankle and foot function is obscured by methodological limitations in commonly-used biomechanical estimates. A key assumption in inverse dynamics and other segment-based kinetics estimates [2] is that joint moments and powers originate from monoarticular sources (e.g., muscle-tendon units). These estimates do not account for multiarticular muscles, such as the flexor digitorum and hallucis longus (FDHL) muscles, which articulate across the ankle and toe joints.

The purpose of this study was two-fold. First, we sought to develop a data-driven musculoskeletal model of the ankle and foot that allowed us to approximate muscle-specific contributions to gait. Second, we aimed to estimate the magnitude of work and power errors that may be inherent in conventional biomechanical estimates which neglect multiarticular muscles, and determine if these errors might impact our current interpretation of ankle and foot function during push-off in walking.

METHODS

Three healthy male subjects (24±5 years, 88±14 kg, height: 1.8±0.1 m) participated in this gait analysis study. All subjects gave informed consent to the protocol. Subjects walked at 1.25 m/s on a split-belt instrumented treadmill (Bertec). Six degree-of-freedom kinematics and kinetics of the shank and foot were derived from a ten camera motion tracking system (Vicon) in conjunction with post-processing via C-Motion Visual3D. Prior to walking, four surface EMG sensors (Delsys) were placed on muscles that contribute to ankle plantarflexion: soleus, medial gastrocnemius, lateral gastrocnemius, and the FDHL (measured together due to limitations in surface EMG). Marker and force data was filtered at 10 Hz and 25 Hz, respectively. EMG data was demeaned, high-pass filtered at 150 Hz, rectified, and low-pass filtered at 10 Hz. All filters used were 3rd order, zero-lag Butterworth filters.

We developed a sagittal plane musculoskeletal model in order to estimate the individual ankle and foot muscle contributions to push-off during walking. To do so, we used a simple EMG to force mapping algorithm and integrated it with conventional gait analysis measurements, using techniques and simplifying assumptions similar to previously published musculoskeletal models [3, 4].

To estimate the potential errors in conventional ankle and foot power calculations due to neglecting multiarticular muscles, we assumed the FDHL muscle-tendon units performed no mechanical work. In other words, we assumed the multiarticular FDHL acted isometrically during push-off, effectively like a cable across the ankle and toe joints. Using our model we then computed how much the FDHL contributed to the conventional ankle and foot power calculations (i.e., the inaccuracy error inherent in these measures if the multiarticular muscle were acting isometrically). Subtracting these multiarticular power contributions from the conventional ankle and foot estimates yielded updated estimates for ankle and foot power, which may better reflect the underlying physiology.

RESULTS and DISCUSSION

We found that our EMG-driven musculoskeletal model was able to reproduce inverse dynamics based sagittal plane ankle power with high fidelity ($R^2 = 0.98 \pm 0.01$, Fig. 1A).

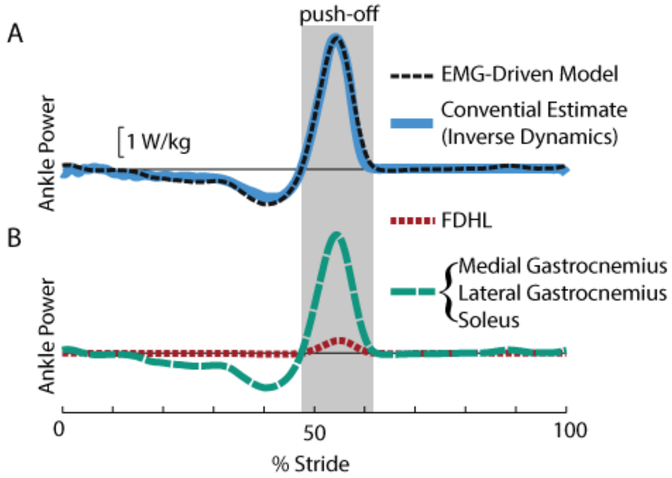

Figure 1: Ankle power at 1.25 m/s for one subject. (A) EMG-Driven Model power reproduced the sagittal plane inverse dynamics estimate. (B) Muscle group contributions to plantarflexion power based on EMG-Driven model. The FDHL are the multiarticular muscle tendon units acting about both the ankle and toe joints.

Next, we estimated the errors that might results from neglecting the multiarticular ankle-toe (FDHL) muscles in inverse dynamics. We found that inverse dynamics may over-estimate sagittal ankle push-off work by about 1.9 ± 0.9 J (Fig. 1B: area under FDHL muscle tendon unit power curve), or about 6% of ankle push-off work, at 1.25 m/s.

We also discovered that the foot may not dissipate as much energy as previously estimated (Fig. 2). On average, we found that there is -9.3 vs. -10.5 J (updated vs. conventional estimate) of negative foot work during push-off, and 2.2 vs. 1.5 J of positive foot work during push-off at 1.25 m/s.

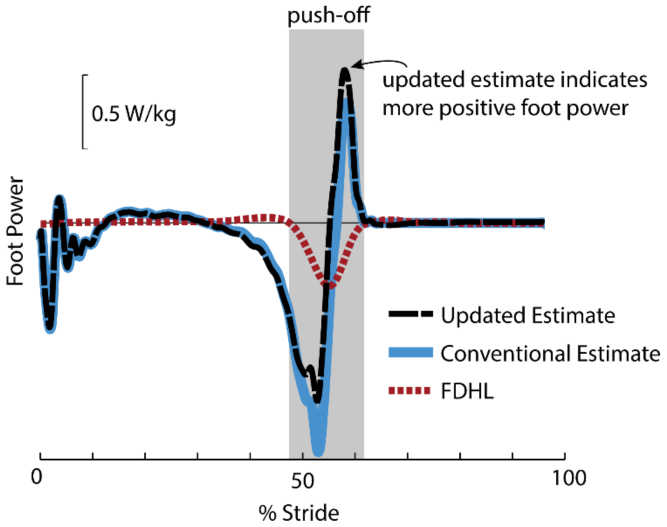

Figure 2: Updated Estimate of foot power was calculated by subtracting the multiarticular muscle tendon unit power (FDHL assuming isometric contractions) from the Conventional foot power estimate based on a deformable foot model [2].

The musculoskeletal model presented provides an estimate of muscle-specific power contributions to ankle plantarflexion push-off during walking, which can then be used to account for multiarticular muscle function. Preliminary findings suggest that the positive ankle work may be over-estimated, and positive foot power under-estimated, by about 1.9 J. Rather than purely dissipating energy during push-off, these findings suggest that the foot may also undergo a cycle of viscoelastic energy storage (~9 J) followed by energy return (~2 J), which may have implications for prosthetic foot design. However, the foot still appears to absorb more energy during push-off than it returns as positive work in terminal stance. This simple musculoskeletal modeling approach provides an updated estimate of muscle-specific contributions to gait, and could potentially be applied to other joints to improve our fundamental understanding of biological movement.

REFERENCES

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