Foot Dissipation during Ankle Push-off: Human Walking Insights from a Multiarticular EMG-Driven Musculoskeletal Model

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Does neglecting multiarticular muscles affect our biomechanical understanding of ankle and foot kinetics? A key assumption in inverse dynamics and other segment-based kinetics estimates (e.g., Takahashi et al. 2013) is that joint moments and powers originate from monoarticular sources (e.g., muscle-tendon units). **Hypothesis: Not accounting for multiarticular muscles that cross the ankle and the toe joints causes conventional approaches to overestimate positive ankle and negative foot powers during the push-off phase of gait.** We developed a data-driven model of ankle-foot muscles to test this hypothesis.

Methods

Six subjects (3 male, 3 female, Age 22±2, Weight 69.9±10.6 kg, Height 1.74±0.07 m) participated in a gait analysis study performed at four different speeds (0.75, 1.00, 1.25, 1.50 m/s). Prior to walking, EMG sensors (Delsys Trigno) were placed on the triceps surae (soleus, medial and lateral gastrocnemius) and the peroneus longus. Two additional muscles, the flexor digitorum and hallucis longus (FDHL, measured together due to limitations in surface EMG), were recorded via a Delsys Trigno Mini Sensor.

Muscle activity was used to estimate ankle power, based on an EMG-driven musculoskeletal model (Figure 1), which shared some similarities with previously published models (e.g., Buchanan et al. 2004, Farris et al. 2012). We examined ankle plantarflexor muscles that contribute to push-off, the main phase of positive power generation during walking. The model allowed us to estimate contributions from individual muscle-tendon units and to estimate the effects of multiarticular musculature that cross the ankle and metatarsophalangeal (toe) joints.

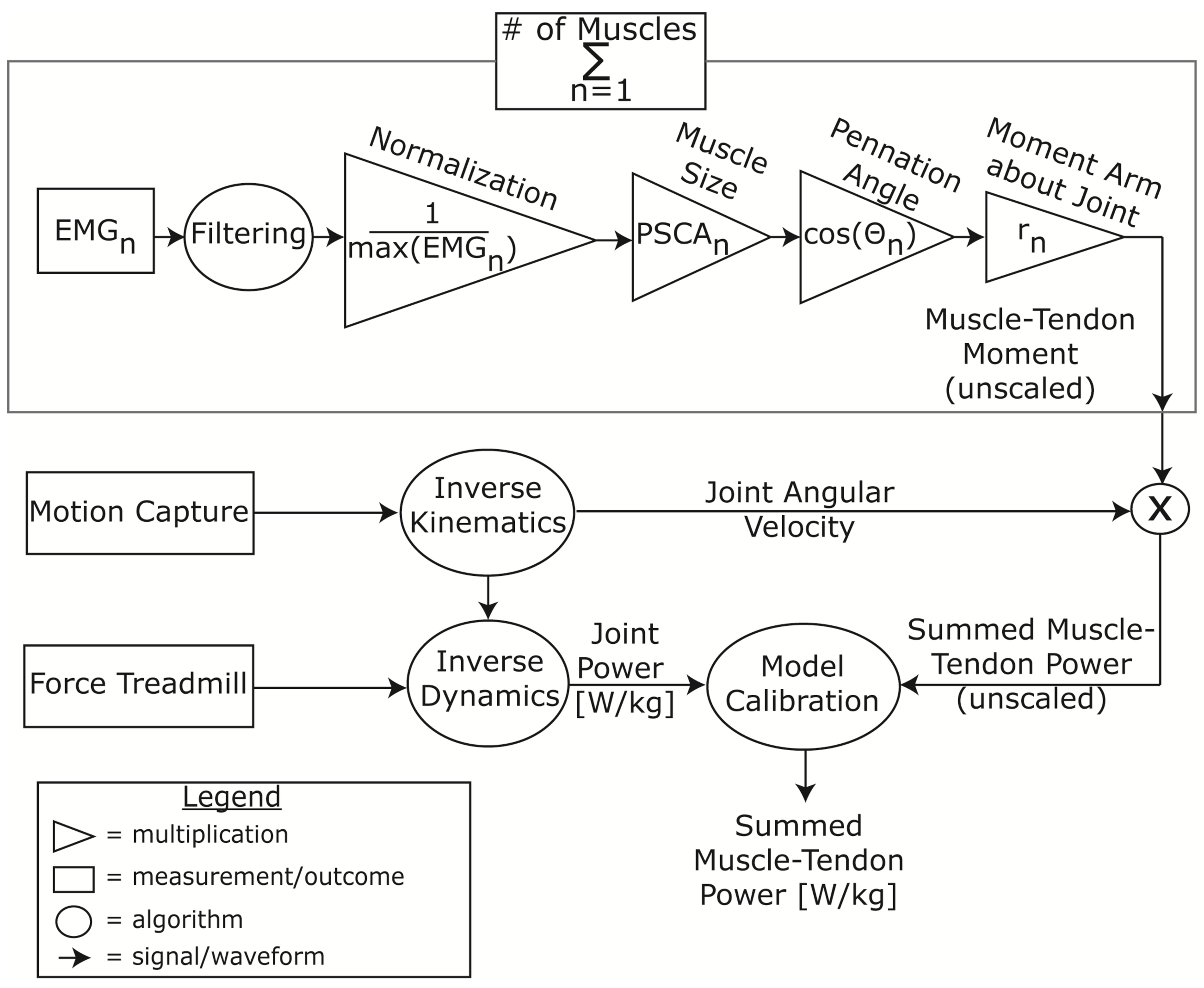

Figure 1: Summary of EMG-driven model.

We estimated the maximum potential errors in conventional ankle and foot power calculations. We assumed the multiarticular FDHL muscle-tendon units performed no mechanical work (isometric contractions), and computed how much the FDHL contributed to the conventional ankle and foot power calculations. Subtracting these multiarticular power contributions from the conventional ankle and foot estimates yielded updated estimates for ankle and foot power.

EMG-Driven Model Able to Reproduce Inverse Dynamics Ankle Power

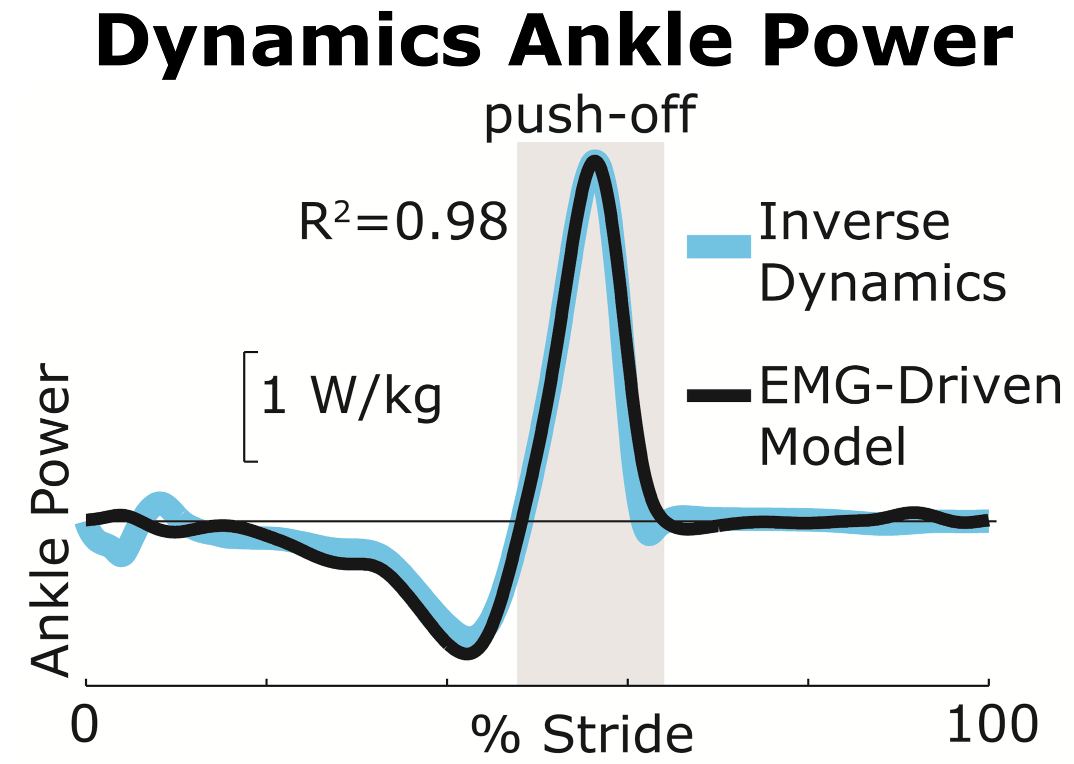

Figure 2: EMG-driven musculoskeletal model power reproduced the sagittal plane inverse dynamics estimate (representative subject at 1.25 m/s).

Validation:

- Model able to reproduce sagittal plane ankle power at all 4 speeds (R^2= 0.98±0.02)
- EMG to force scaling coefficient from model calibration at 1.25 m/s able to reproduce ankle power at other speeds (R^2= 0.98±0.02)

Proposed Model is Simpler yet Consistent with Hill-Type Model Estimates

Table 1: Percent contributions of plantarflexors muscles at peak push-off power based on two different muscle models

	EMG-Driven Model	Hill-Type Model (Bogey et al. 2005)
% Flexor Digitorum & Hallucis Longus	7%	6%
% Peroneus Longus	5%	2%
% Triceps Surae	88%	92%

Conclusions

1) EMG-driven model was able to reproduce inverse dynamics estimates using fewer parameters (less complexity) than a Hill-type model.
2) Inverse dynamics may be overestimating negative foot power by 10%, and overestimating ankle push-off by 7%.
3) A similar modeling approach could be used to examine multiarticular muscle contributions at other joints such as the knee or hip.

Inverse Dynamics may Overestimate Ankle Muscle-Tendon Power during Push-off by ~7%

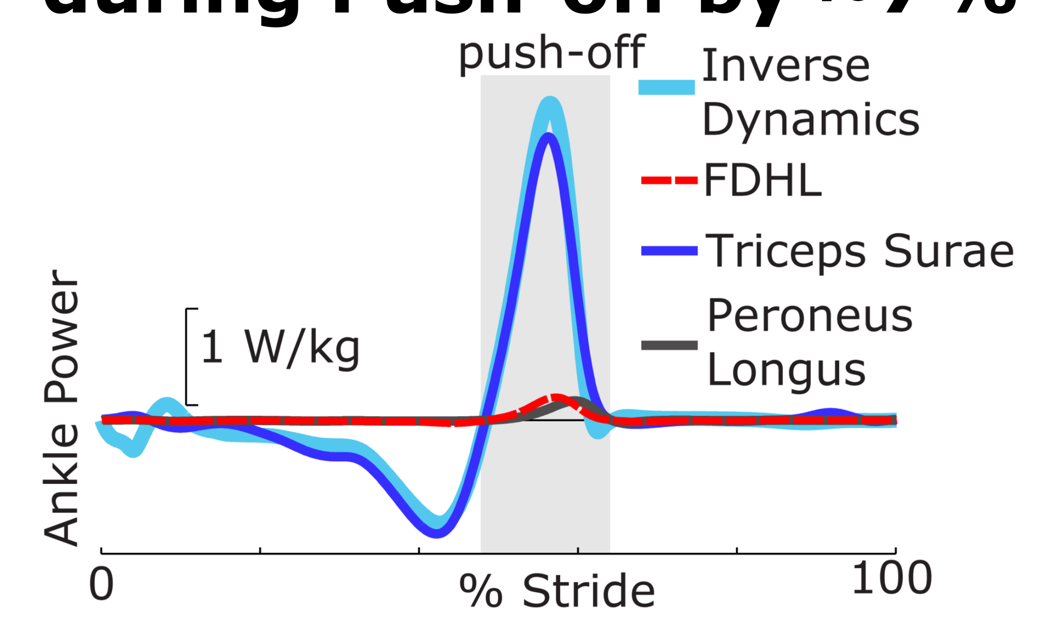

Figure 3: Muscle-tendon-specific contributions for a representative subject at 1.25 m/s. The FDHL multiarticular power signifies a potential overestimate by inverse dynamics.

Current Estimates may Overestimate Negative Foot Power by ~10%

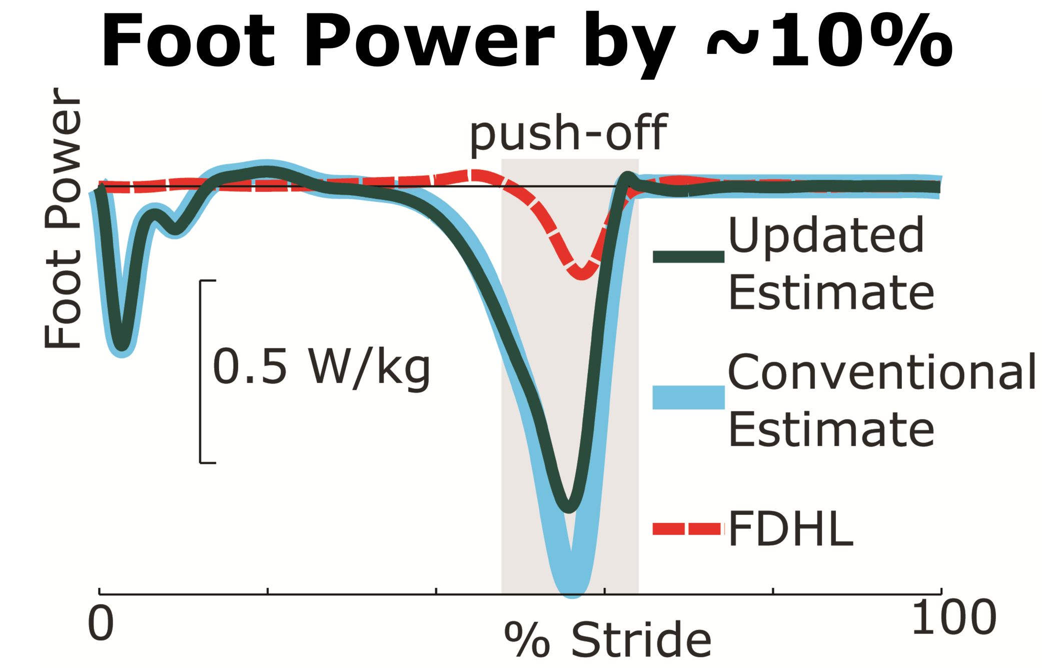

Figure 4: Updated estimate of foot power: the multiarticular muscle-tendon unit power subtracted from the power estimate based on a deformable foot model (Takahashi et al. 2013).

Key Model Limitations

1) EMG-driven model assumes linear EMG to Force mapping.
2) EMG-driven model has only been applied to walking, certain assumptions may break down for other tasks.

Future Work

1) Perform sensitivity analysis for the EMG-driven model.
2) Integrate ultrasound to separate muscle vs. tendon contributions.
3) Evaluate if model is robust for tasks such as calf raises or running that involve disparate muscle contractions.
4) Apply modeling approach to knee and hip joint musculature.

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