Is the Foot Working With or Against the Ankle During Human Walking?

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1 Introduction

The muscles and tendons acting about the ankle joint perform a critical Push-off function that facilitates economical gait. This ankle Push-off, due in part to elastic recoil of the Achilles tendon, is primarily transmitted upward along the leg to the rest of the body, and helps to redirect the body's center-of-mass during step-to-step transitions in walking. However, biomechanical estimates indicate that the foot dissipates substantial energy during this Push-off phase of gait. This foot energy absorption detracts from the positive ankle Push-off work, and may therefore undermine the power transferred to the rest of the body and the energetic benefits of the Achilles tendon, potentially degrading gait economy. From a basic science perspective the foot's behavior is perplexing. From a translational science perspective, it is unclear if prosthetic feet should be designed to mimic this dissipative foot behavior, or if non-biomimetic prostheses might instead improve gait beyond natural capabilities. These unresolved questions motivated our recent investigations into biological foot function. The purpose of this research abstract is threefold:

1. To summarize our recent work on the coordination and contributions of individual foot muscles to gait
2. To review our recent findings on foot kinetics within the context of prior experimental/theoretical research
3. To discuss various plausible explanations for the seemingly wasteful foot behavior, and its interplay with the ankle during walking

2 Methods

We performed two studies of healthy human walking. The first investigated the coordination of intrinsic and extrinsic foot muscles [1], and the second quantified foot and lower-limb joint kinetics during gait [2].

<u>Experiment 1</u>
We analyzed surface electromyographic (EMG) recordings of 11 foot muscles in healthy individuals during level treadmill walking at 1.1 m/s (3 males, 4 females, 25.9 ± 2.7, years old, 1.76 ± 0.11 m, 74 ± 16 kg). We computed stride-averaged EMG envelopes and used the timing of peak muscle activity to assess coordination.

<u>Experiment 2</u>
We analyzed 6 degree-of-freedom (6DOF) foot kinetics, in conjunction with 6DOF ankle, knee and hip kinetics during human gait (7 males, 3 females, 24 ± 2.5 years old, 1.76 ± 0.11 m, 73.5 ± 15 kg). We computed power due to compression and rotation of the foot, using a deformable body model [3] to account for the foot's many internal degrees of freedom (e.g., metatarsophalangeal (MTP) joints, heel pad, arches). This foot power estimate encompasses contributions from all structures distal to the ankle, including the shoe.

3 Results

We found that groups of intrinsic and extrinsic foot muscles exhibited peak activations in a consistent progression during forward walking. The period around Push-off could be roughly characterized by sequential peak muscle activity from the ankle plantarflexors, MTP flexors, then MTP extensors and finally ankle dorsiflexors (Fig. 1). Functionally, this muscle activation sequence represents torque contributions to ankle plantarflexion Push-off, followed by an MTP flexion moment near terminal stance phase. MTP flexor activity has been suggested to support/stabilize the foot arch, but these muscle-tendon units may also perform negative work against the extending toe joint, contributing to energy absorption in the foot.

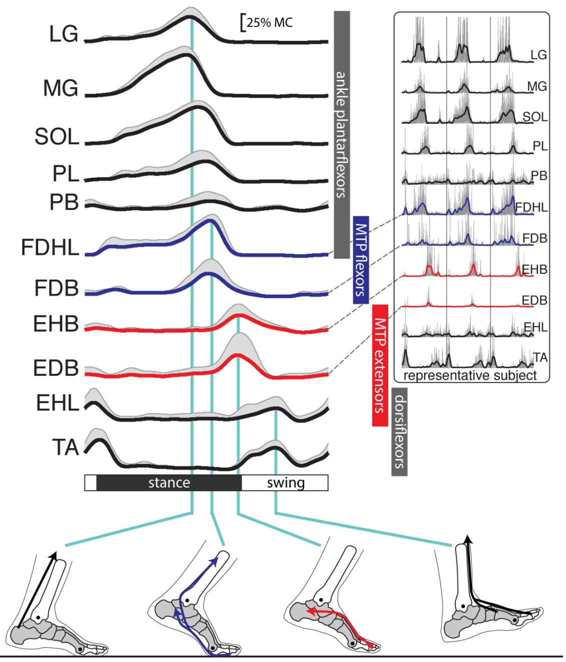

Figure 1: Foot muscle EMGs during walking [1]. Lateral (LG) & medial (MG) gastroc., soleus (SOL), peroneus longus (PL) & brevis (PB), flexor dig./hal. longus (FDHL), flexor dig. brevis (FDB), extensor hal. (EHB) & dig. brevis (EDB), extensor hal. longus (EHL), tibialis anterior (TA). EMG magnitude is depicted as a percentage of muscle maximum contraction (MC).

Using 6DOF inverse dynamics we estimated ankle Push-off work to be approximately 23 J at 1.4 m/s (Fig. 2). However, we also found about -6 J of simultaneous work done by the foot, similar to previous studies (e.g., [4]). The magnitude of foot work during Push-off was comparable to the simultaneous work performed about the knee joint, indicating that foot contributions should not be neglected in understanding whole-body gait dynamics. Additional studies are needed to determine how this work is distributed between the various muscles, tendons and other biological tissues in the foot, and materials in the shoe.

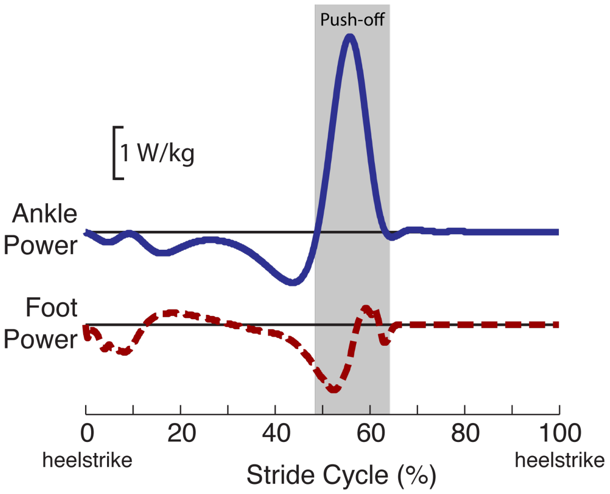

Figure 2: Ankle Push-off power may be undermined by energy dissipation in the foot during walking [2].

4 Discussion

We observed evidence that the foot dissipates substantial energy during the Push-off phase of walking, which may be due in part to negative muscle-tendon work as the toes extend in late stance. This foot behavior may subvert the energy-saving benefits of Achilles tendon recoil and ankle Push-off during walking. Several plausible explanations exist for this observed phenomenon:

I. The foot is working *against* the ankle…
One possibility is that the foot absorbs substantial energy through deformation and rotation of structures within the foot/shoe, and that this dissipation is indeed detrimental to level-ground walking economy [5]. However, perhaps this foot behavior is useful for other reasons (e.g., balance, adaptability, conforming to non-level terrains), and it would be valuable to further explore functional trade-offs.

II. The foot is working *with* the ankle, indirectly…
Another possibility is that the foot absorption is beneficial to locomotor economy, albeit indirectly; for example, by serving as a gearing mechanism that facilitates economical force production of the calf muscles [6], or contributing to arch support during gait.

III. The foot is working *with* the ankle, but our conventional biomechanical estimates fail to capture it…
Yet another possibility, and one that has received little attention, is that the foot may not absorb as much energy as it presently appears. Methodological limitations might result in over-estimating the magnitude of negative foot work, and failing to capture positive work performed by structures within the foot and shoe. For instance, apparent foot dissipation may be due to limitations in conventional biomechanical estimates, which fail to account for multi-articular muscle contributions.

5 Summary

In summary, we present recent findings on foot muscle coordination and kinetics, and propose several potential explanations for the seemingly sub-optimal foot behavior during gait. Additional experimental and computational studies are needed to discern these various explanations of foot function during gait, which has implications for prosthetic foot design, walking simulations and our fundamental understanding of bipedal locomotion.

References

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