Simple Model of Foot Deformation in Human Locomotion

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1 Introduction

When humans walk or run, the foot deforms under load to store, release, and dissipate energy. The heel pad, plantar fascia, and other elements of the foot cushion the body and provide elastic energy return (Ker et al., 1988**.** Most traditional analysis of locomotion is performed at the level of the ankle, knee, and hip, without taking such deformation into account. The net effect of the joints of the body is to perform negative work during collision and positive work during push-off. However, it has been proposed that the foot dissipates significant energy during the push-off phase, in the metatarsophalangeal joints during running (Stefanyshyn and Nigg, 1997), and overall foot during walking (Takahashi and Stanhope, 2013). This behavior seemingly opposes the positive work of push-off. We propose instead that the energy apparently dissipated in the foot could actually be redirected to the Achilles tendon, a feature not easily measured in conventional experiments.

Due to limitations of motion capture, power in the foot is often measured indirectly. In human walking, a measure of foot deformation power termed “distal foot power” (Takahashi and Stanhope, 2013), is calculated as the dot product of the ground reaction force and the rigid-body velocity estimate for the foot’s point of contact with ground. During push-off, this measure appears to show that the foot dissipates significant energy, proportional to walking speed. But push-off also compresses the foot, whose bending may cause the rigid-body model to introduce artifacts into estimates of distal foot velocity.

We present a simple model that demonstrates how energy could be transferred from the foot to the Achilles tendon, and how that may cause parts of the foot to apparently perform negative work when using conventional measurements. Deformation of the foot late in stance is not necessarily dissipative, and could even be beneficial to economy for locomotion.

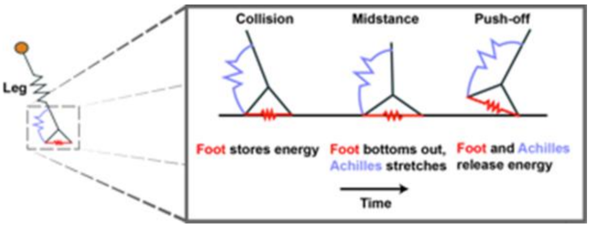

Figure 1: A deformable foot model with a point mass pelvis and elastic springs modeling the leg, foot, and Achilles tendon. Vertical compression of foot and stretching of Achilles allow energy storage during early stance, and release at push-off.

2 Deformable Foot Model

We modeled deformation of the foot as modeled with two foot segments and two springs (Fig. 1). The two foot segments represent separate heel and forefoot segments, both rotating about a mediolateral axis near the ankle, and configured in an upside-down “V” upon the ground. The foot can thus flatten, resisted by a linear “foot spring” representing the plantar fascia. The other spring represents the Achilles tendon, modeled as a rotational spring producing plantarflexion torque between shank and foot. The load of the body was modeled as a mass-spring system, or spring-loaded inverted pendulum (McMahon and Cheng, 1990).

The mechanical power of the foot and Achilles springs are easily calculated by multiplying the force exerted by the springs by the velocity between the two end points.

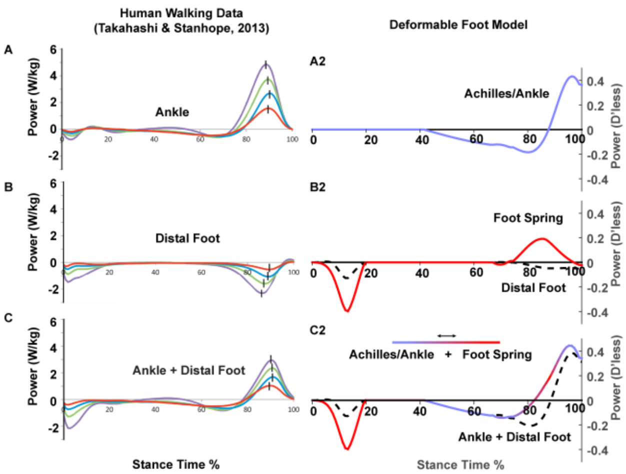

Figure 2: Comparison of human walking data (left column) to deformable foot model (right column). **(A)** Ankle performs negative work prior to positive work at push-off (multiple speeds shown). **(B)** Distal foot power apparently shows negative work at collision and push off. In model, the foot spring actually performs positive work at push-off **(C)** The sum of ankle + distal foot power measures is similar between human and model, but the latter shows how foot deformation energy can actually be returned.

This calculation was compared against an inverse dynamics estimate of distal foot power (Takahashi and Stanhope, 2013) used in human experiment, but computed on the deformable foot model as if the foot was a rigid body.

3 Results

The results show that the model qualitatively reproduces the inverse dynamics calculated distal foot power negative peaks at collision and toe off (Figs 2A and 2B). The distal foot power does capture the energetics of the foot during collision, but does not during push off. The foot is performing positive work during push off (Fig. 2C), while distal power estimates it to be negative (Fig. 2B). The net work performed by the foot is negative, the difference from zero being approximately equal to the energy supplied to the Achilles tendon. The Achilles is loaded during stance and provides a burst of positive work at push off (Fig. 2C).

4 Discussion

The results show that the choice of model for the deformation of the foot can impact the measured energetics. Motion of the foot is difficult to capture during locomotion, and inverse dynamics methods typically cannot account for energy transfer through tendon. While distal foot power and other measures may capture deformation energetics during collision, it is possible that the dissipation late in push-off is misattributed. One major source of error is that a rigid body model is used to estimate the distal velocity of the foot at push-off, at a time when the foot behaves least like a rigid body. By fitting a rigid foot model whose parameters are computed during an uncompressed state, an artifactual velocity is added to the distal end of the foot. This artifact in velocity is roughly antiparallel with the ground reaction force because of the direction of the angular velocity of the foot. As a result, the foot appears to perform negative work at push-off. These results suggest that more refined models and measurements of the foot are required to explain an apparently uneconomical behavior of the foot during locomotion.

References

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