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The role of series ankle elasticity in bipedal walking

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HIGHLIGHTS

- Ankle elasticity can aid walking economy by redirecting COM, reducing collisions.
- Theoretically, zero active muscle work is required to walk with an elastic ankle.
- Economy of walking depends on the ratio between ankle stiffness and foot length.
- Proper ratio yields the optimal timing and magnitude of elastic energy storage/return.
- Ankle and hip powering strategies can both benefit from series ankle elasticity.

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ABSTRACT

The elastic stretch-shortening cycle of the Achilles tendon during walking can reduce the active work demands on the plantarflexor muscles in series. However, this does not explain why or when this ankle work, whether by muscle or tendon, needs to be performed during gait. We therefore employ a simple bipedal walking model to investigate how ankle work and series elasticity impact economical locomotion. Our model shows that ankle elasticity can use passive dynamics to aid push-off late in single support, redirecting the body's center-of-mass (COM) motion upward. An appropriately timed, elastic push-off helps to reduce dissipative collision losses at contralateral heelstrike, and therefore the positive work needed to offset those losses and power steady walking. Thus, the model demonstrates how elastic ankle work can reduce the total energetic demands of walking, including work required from more proximal knee and hip muscles. We found that the key requirement for using ankle elasticity to achieve economical gait is the proper ratio of ankle stiffness to foot length. Optimal combination of these parameters ensures proper timing of elastic energy release prior to contralateral heelstrike, and sufficient energy storage to redirect the COM velocity. In fact, there exist parameter combinations that theoretically yield collision-free walking, thus requiring zero active work, albeit with relatively high ankle torques. Ankle elasticity also allows the hip to power economical walking by contributing indirectly to push-off. Whether walking is powered by the ankle or hip, ankle elasticity may aid walking economy by reducing collision losses.

1. Introduction

Elastic energy storage and return is thought to improve economy of human locomotion by reducing the mechanical and metabolic energy demands on muscles (Hof et al., 1983; Alexander, 1991). In walking, the Achilles tendon acts elastically during stance, stretching during ankle dorsiflexion and then shortening during plantarflexion (Ishikawa et al., 2005; Fukunaga et al., 2002). The calf (triceps surae) muscles simultaneously produce force in series with the tendon, and may additionally perform active shortening work during plantarflexion (Ishikawa et al., 2005; Fukunaga et al., 2002). Thus, elasticity appears to reduce active work compared to the same overall action performed by a muscle without a tendon (Lichtwark and Wilson, 2007, 2008). But that presumes a need for the stretch-shortening cycle itself. Without that cycle, the muscles might potentially be activated later in the stride to perform shortening

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Nomenclature

α	half angle between legs (when both feet are flat on the ground)
δ	angle between toe-to-COM line and vertical line
θ	leg angle (measured past vertical)
θ_{HO}	leg angle (measured past vertical) at heel-off
C	collision
COM	center-of-mass
g	gravitational acceleration
k_{ank}	torsional ankle spring stiffness
k_p	torsional pelvic spring stiffness
L	leg length
l_f	foot length
M	concentrated pelvic mass
m	infinitesimal mass of foot
mCOT	mechanical cost of transport
P	push-off
R_{toe}	ground reaction force at toe
s	step length
T_{ank}	ankle torque
v	walking velocity
v^-	velocity immediately before stance leg heel-off
v_r^-	velocity after ankle reversal
v_0	velocity immediately before contralateral heelstrike
v^+	velocity immediately after contralateral heelstrike
w^-	negative work
w^+	positive work

work alone, and perhaps achieve better economy with no tendon at all. This might seem a highly unlikely possibility, but there lacks a clear explanation for the presumed advantages of the normal stretch-shortening cycle. We therefore employ a simple bipedal walking model to investigate how series elasticity at the ankle impacts economical locomotion.

Elastic energy return at the ankle contributes to a large burst of positive work at the end of stance phase in human walking (Hof et al., 1983; Ishikawa et al., 2005; Fukunaga et al., 2002; Sawicki et al., 2009). Elastic energy is first stored earlier in stance phase, when the soleus and gastrocnemius muscle fascicles produce force but undergo relatively little displacement, particularly at slower walking speeds (Ishikawa et al., 2005; Fukunaga et al., 2002; Lichtwark and Wilson, 2007, 2008). Without series elasticity, the same ankle moment and displacement would presumably require more active negative and positive work from the muscle fascicles, and thus greater metabolic cost (Katz, 1939; Abbott et al., 1952; Margaria, 1968). But with varying amounts of elasticity, it is also quite possible that a different ankle action might be preferable. To examine that possibility, it is helpful to consider when and how work must be performed.

The net work requirement for steady state walking is zero. To maintain periodic body motion over level ground, any mechanical energy dissipation within a gait cycle requires an equal amount of positive work, not necessarily at the same time or location. Dissipation can occur actively in muscles or passively by other soft tissues in the body (Zelik and Kuo, 2010), with a major loss occurring during heelstrike collisions in the transition between pendulum-like steps (McGeer, 1990; Donelan et al., 2002; Kuo et al., 2005). In humans, energy is mainly restored by positive muscle work about the ankle and hip (e.g., Eng and Winter, 1995). However, less positive work would be required if the energy losses could be reduced.

Simple models of walking suggest collision losses may be reduced by pushing off with the trailing leg just before the collision (Kuo et al., 2005; Ruina et al., 2005). Indeed, humans perform ankle push-off with timing and work that largely offset the collision losses (Kuo et al., 2005; Soo and Donelan, 2010). Those losses could theoretically be reduced further with an ankle spring that resists the collision by producing a passive dorsiflexion moment and then assists push-off with a passive plantarflexion moment, as demonstrated by a dynamic walking model powered by the hips (Hobbelen and Wisse, 2008). A separate model of walking with an elastic ankle orthosis shows that a passive plantarflexion push-off can indeed reduce collisions and improve walking economy (Bregman et al., 2011), for a gait powered by the hips. What remains unanswered is to what degree collisions can be reduced, and how active work by the ankles should supplement an elastic stretch-shortening cycle for best economy.

In this study, we use a dynamical model to systematically investigate the biomechanical benefits of series ankle elasticity on walking economy, along with possible strategies for actively powering gait. Rather than using a detailed model of the muscle-tendon unit (Ishikawa et al., 2005; Fukunaga et al., 2002; Lichtwark and Wilson, 2007, 2008), we model the tendon as an elastic spring, with an actuator that can produce an active work loop similar to the human ankle. The model may also be powered by the hips, making it possible to consider a variety of powering strategies. We use this model to determine how active powering and passive elastic energy storage and return at the ankle should best be configured for economy of gait.

2. Model

We developed a dynamic walking model with series elasticity at the ankle, and used it to investigate how elasticity can affect the energetics and mechanics of locomotion (Fig. 1). This is a minimal model that yields a dynamic gait with single- and double-support phases, a passively swinging leg, and spring-like energy storage and release at the ankle (Fig. 1A). A key feature is the timing of elastic ankle push-off, which begins with stance heel lift-off—referred to as *heel-off*. If model parameters are selected to cause heel-off to occur pre-emptively relative to opposite leg heelstrike, it can potentially reduce the collisional energy losses from that event (Kuo, 2002). The model will demonstrate the conditions for proper push-off timing, the amount of energy that is optimally stored and released by the ankle, and the options for powering walking by the ankle and the hip.

We added ankle elasticity to the previous “simplest walking model” (Garcia et al., 1998; Kuo, 2001, 2002). This is a planar model with a point mass M for the pelvis and two legs that swing about the hip, each with length L and an infinitesimal foot mass m at its end. To this was added a massless, forward-facing foot of length l_f freely rotating about that point. Brief scuffing of the swing foot on the ground during mid-swing was ignored. As with previous dynamic walking models, heelstrike with ground was modeled as an instantaneous and perfectly inelastic collision (McGeer, 1990; Garcia et al., 1998; Kuo, 2001). We tested this model for walking gaits, meaning limit cycle behaviors without an aerial phase. We considered only long-period gaits (McGeer, 1990; Kuo, 1999; Kwan and Hubbard, 2007), referring to gaits where the swing leg reverses motion prior to heelstrike (i.e., the swing hip reaches a peak flexion angle and then begins extending before foot contact). We therefore ignore short-period gaits where the heelstrike occurs while the swing hip is still flexing.