All spring, no fall: modeling trade-offs of ankle elasticity in walking

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Keywords: walking simulation, ankle spring, ankle powering, collision, cost of transport
Preferred format: Poster

BACKGROUND & MOTIVATION

Energy dissipated in heelstrike collisions must be replaced to maintain steady-state walking speed. **Large collision losses are energetically costly,** not simply because of the negative work itself, but because of the positive muscle work required to offset the lost energy (Zelik and Kuo, 2010). **Energy stored and returned by an ankle spring is one method of reducing these collision losses**. Although this concept has been studied for some specific applications (Bregman et al., 2011; Hobbelen and Wisse, 2008), the **fundamental relationships between spring stiffness, engagement timing, foot length, gait speed and step length have not been elucidated**. We sought a more mechanistic understanding of ankle elasticity and walking collisions, independent of application. We used walking simulations to systematically investigate the fundamental effects of and interplay between these different parameters. Beyond the role of passive elasticity, there also remain open questions regarding the selection of springs for use in series with actuators. Therefore, we studied ankle powering in series with ankle elasticity. This is highly relevant to biological and robotic applications. In the human body the gastrocnemius and soleus muscles act in series with the elastic Achilles tendon to plantarflex the foot about the ankle (Ishikawa et al., 2005), walking robots such as the IHMC's M2V2 use series elastic actuators to locomote (Pratt et al., 2008), and various powered prosthetic feet are being designed using series elastic principles to achieve ankle function (Herr and Grabowski, 2011; Sugar et al., 2011).

We **used walking simulations to systematically investigate ankle elasticity**. We extended the simplest two-dimensional walking model (Garcia et al.,1998; Kuo, 2001) to include flat-feet and torsional springs at each ankle and between the hips at the pelvis, with a concentrated point mass at the pelvis and feet of infinitesimally small mass. In the simulation, collisional energy losses are offset by positive work performed by gravity as the walker descends a gentle slope, whereas in humans the analogous dissipative loses are replaced by active muscle work. We defined the mechanical work per unit walking distance as the mechanical cost of transport (mCOT) of the walking model. A mCOT of zero indicates walking on level ground with no heelstrike collision losses and thus no need for any active or external powering.

RESULTS & DISCUSSION

The **optimal ankle stiffness** , the stiffness that minimizes mCOT, **depends on energy storage and timing of energy return**. Without an ankle spring, acceleration of the center of mass (COM) due to the falling inverted pendulum leads to a large collision (i.e., high mCOT). The addition of a soft spring allows some energy to be stored in the spring and thus removed from the kinetic energy of the COM, leading to a moderate collision. **An optimal spring stores and returns energy with appropriate timing to redirect the COM velocity before heelstrike and minimize collision,** and thus mCOT. However, if the spring is too stiff, the energy return occurs too soon, and the COM velocity begins falling again before collision occurs, leading again to a moderate collision magnitude.

We found that the **minimum mCOT decreases as foot length increases, with zero mCOT achievable** for foot length greater than about half of step length. But **long feet incur other non-work costs**, specifically higher hip spring stiffness and peak knee (extension) torques, which may reflect the need for increased effort from hip flexors to swing the legs and from knee flexors to prevent hyperextension during stance. In general, it is more economical for the ankle spring to engage early in stance because it allows more energy storage, but the **effect of spring engagement point on mCOT is small** compared to the effects of foot length and spring stiffness.

Optimal ankle stiffness increases with speed and decreases with step length (Fig. 1). Interestingly, the **optimal ankle stiffness is approximately constant when speed and step length increase along humans' preferred relationship** (step length = speed$^{0.42}$), across a wide range of speeds (approximately 0.6 to 1.9 m/s).

In general, **ankle powering is more economical than gravity powering** because it increases push-off work and makes push-off occur sooner (Fig. 2). However, for ankle springs stiffer than optimal, ankle powering can cause push-off to be too early (i.e., poorly timed), leading to larger collisions, and thus higher mCOT.

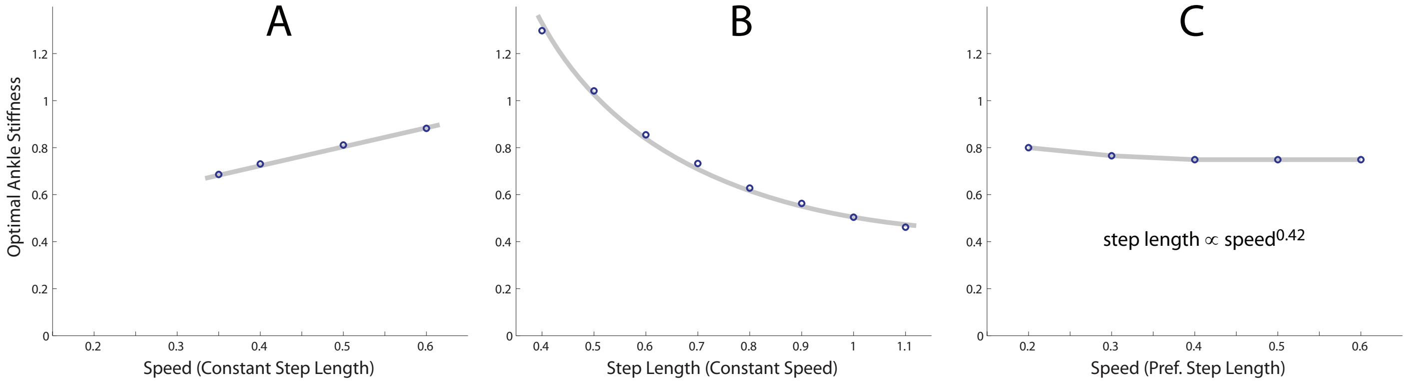

Figure 1: Optimal ankle stiffness as a function of speed and step length. Optimal ankle stiffness (A) increases with speed and (B) decreases with step length. When speed and step length increase together along humans' preferred relationship (step length $\propto$ speed$^{0.42}$), optimal ankle stiffness is approximately constant across a wide range of gaits. Speed and step length are reported as dimensionless. Dimensionless speeds of 0.2-0.6 correspond to approximately 0.6-1.9 m/s.

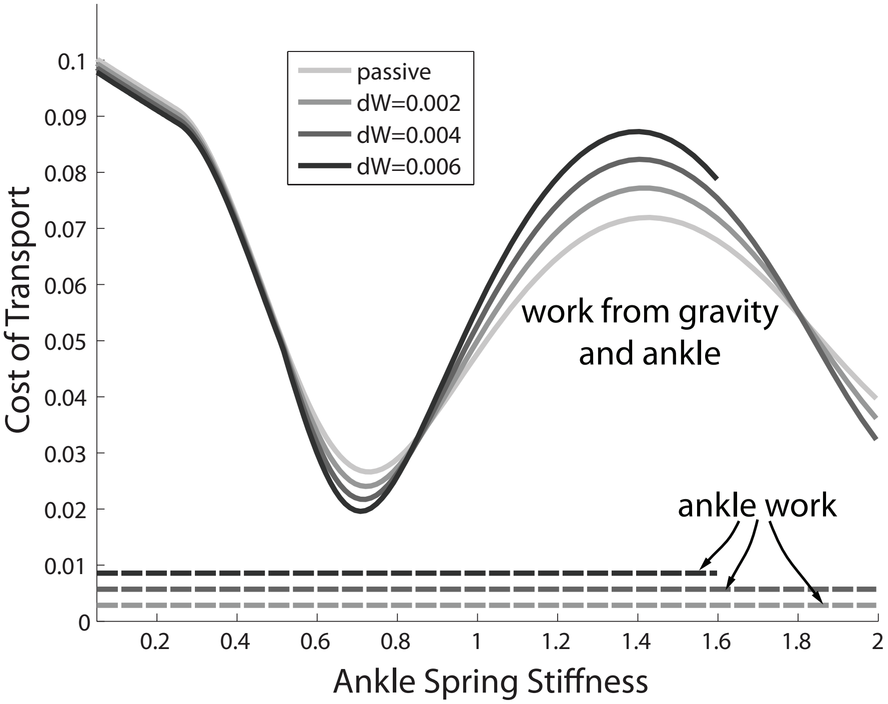

Figure 2: Effect of ankle work. Increasing ankle work (dW) reduces the minimum cost of transport (solid lines) substantially for spring stiffness near optimal, and reduces it slightly for softer springs. However, for ankle springs that are stiffer then optimal, ankle powering can actually cause higher cost of transport compared to the purely passive, gravity powered walker. Dashed lines show ankle work contributions to the total cost of transport. Both axes are expressed in dimensionless units.