

# Improved empirical estimates of work production in human walking motivate updated theory of step-to-step transition

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## 1 Summary

Measuring biomechanical work performed by the body is critical for understanding muscle-tendon function, joint-specific contributions and energy-saving mechanisms during gait. Yet, we found that when we sum empirical joint- and segment-level measures of work that they fail to capture substantial *positive* work performed by the body. For example, 25% of the total positive work that we know is performed by the human body during walking is missed by the most commonly-used estimates of work (at the hip, knee, ankle and foot). However, we discovered that this unmeasured work could be explained by extending conventional 3 degree-of-freedom (3DOF) inverse dynamics to full 6DOF joint work analysis. This 6DOF analysis, in turn, revealed that hip work may contribute more to walking than previously thought, including more positive work during mid and late stance phases of gait.

We next considered this additional hip work in the context of dynamic walking principles. Classical Push-off-Collision theory suggests that optimal step-to-step transition occurs when active Push-off magnitude of the trailing limb is equivalent to Collision of the leading limb (Kuo 2005), in which case there is no need for additional active work during other portions of the gait cycle (i.e., the stance limb can simply act as a passive inverted pendulum). During human walking (~1.4-1.8 m/s) empirical measurements indicate that center-of-mass (COM) Push-off work is indeed roughly equal to Collision (Zelik and Kuo 2010); however, the updated 6DOF estimates indicate substantial positive work performed by the hip during mid-stance. Since this additional work is not predicted by the conventional step-to-step transition theory, it begs the question: why do humans perform this extra hip work at all? We resolve this question by extending the *active* Push-off-Collision model to include *passive* ankle elasticity (i.e., modeling the function of the Achilles tendon).

Using this dynamic walking model we demonstrate that elastic Push-off contributions alter the theoretical conditions for optimal (economical) transitions, and that the new model predictions can better explain the experimentally-observed hip work performed during human gait.

**Preferred Presentation: Oral**

## 2 Experimental Methods

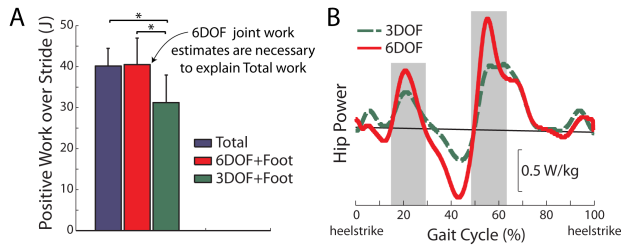
We integrated various empirical measures to investigate how biomechanical work and power were distributed amongst different body joints and segments during level-ground walking. We analyzed shod walking data for 10 healthy subjects (7 males, 3 females,  $24 \pm 2.5$  years old,  $73.5 \pm 15$  kg,  $1.76 \pm 0.11$  m) walking at 1.4 m/s. We computed five complementary estimates of mechanical power, all for a single limb. Two measures summarized whole-body mechanics: COM and Peripheral powers, due to the motion of the COM and to the motion of lower-limb segments relative to the body's COM, respectively. The sum of COM and Peripheral powers reflects an estimate of Total Mechanical power of the body. Two additional power estimates were computed for the lower-limb joints, based on 3DOF and 6DOF inverse dynamics, the latter of which includes both rotational and translational joint power terms (Buczek et al. 1994). A final power estimate was computed for the foot segment, based on a deformable body model (Takahashi et al. 2012). We then integrated the power estimates over the stride, and over specific phases of gait, to compute the work performed.

3DOF joint work (about ankle, knee and hip) and work performed by the foot segment represent the contemporary standards (i.e., most commonly used and accepted methods) for measuring contributions from joint- and segment-level sources within the body. Therefore, we compared the 3DOF+Foot work estimate to the summed whole-body measure (Total Mechanical work) to assess its ability to explain the overall work performed by the body. Similarly, we then compared the 6DOF+Foot work estimates to Total Mechanical work.

## 3 Experimental Results & Discussion

We found that 3DOF+Foot work estimates failed to capture about 25% of the Total positive work ( $31.2 \pm 6.7$  vs.  $40.1 \pm 4.3$  J,  $P = 0.002$ ), whereas 6DOF+Foot work measures ( $40.5 \pm 6.5$  J) fully accounted for the Total positive work performed during gait (Fig. 1A). Furthermore, 6DOF analysis revealed that much work missed by 3DOF estimates may be performed by the hip, with substantial increases in positive work during mid and late stance (Fig.

1B; Rebound and Push-off phases of gait are shaded). These experimental findings improve our biomechanical understanding of gait, but also motivate us to reconsider our current theoretical models of walking.



**Figure 1:** Positive work & hip power during human gait.

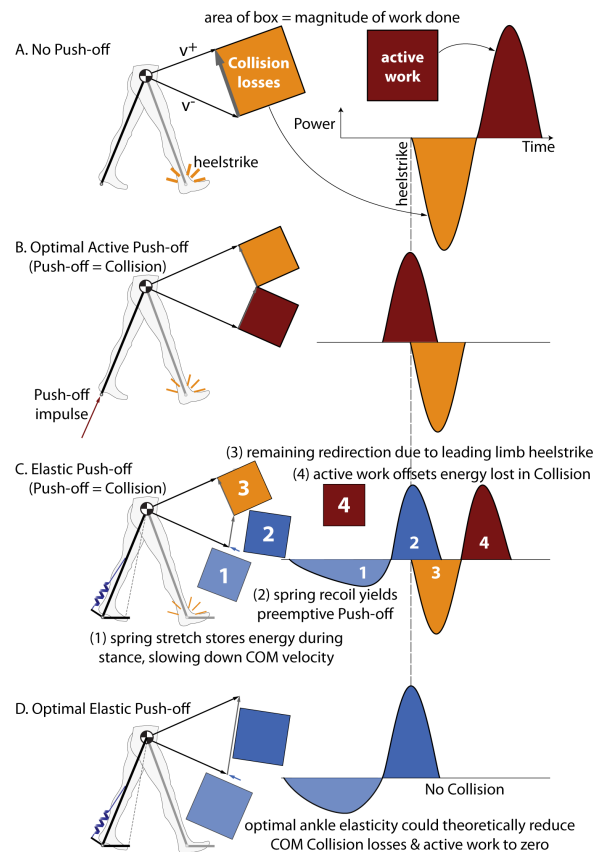
#### 4 Dynamic Walking Model

We consider a recently developed dynamic walking model with series elasticity at the ankle (Zelik et al. 2014). The model extended the simplest walking model by including feet and torsional springs at the ankles (depicted as extension springs in Fig. 2C and D for convenience). Thus, it is a planar model with a point mass at the pelvis, springs about the ankle and hip, two legs that swing about the hip, and massless, forward-facing feet, which can perform spring-like energy storage and release at the ankle (qualitatively similar to that performed by the Achilles tendon in human gait). The model could be powered by hip and/or ankle actuation, and as with previous dynamic walking simulations, heelstrike with the ground was modeled as an instantaneous and inelastic Collision. We used predictions made by this model to glean insight into passive vs. active Push-off strategies.

#### 5 Dynamic Walking Model Results & Discussion

The traditional dynamic walking view is that during the step-to-step transition the COM velocity must be redirected from forward and downward ( $v^-$  in Fig. 2A) to forward and upward ( $v^+$ ). If no Push-off work is performed by the trailing limb, then redirection of the COM velocity is entirely due to the Collision of the leading leg with the ground (Fig. 2A). However, to continue walking at steady speed the mechanical energy losses due to Collision (yellow box) must then be offset by active positive work done by muscles (red box). The plot to the right (power vs. time) shows a cartoon of how energy might be dissipated in Collision and then compensated by muscle work, although the precise power profile is not important (only the work magnitude, represented by the shaded areas under the curves). These Collision losses could be reduced by an *active* preemptive Push-off, which occurs optimally when Push-off magnitude is equal to Collision magnitude (Fig. 2B; Kuo et al. 2005). Although this Push-off = Collision condition is observed during human walking at moderate speed (Zelik & Kuo 2010), it remains unclear why humans also perform additional positive hip work during stance (which is energetically costly, and is not predicted by the current step-to-step transition model).

However, the elastic ankle walker model demonstrated that Collision can also be reduced by a *passive* elastic Push-off, when energy stored in a spring (light blue box in Fig. 2C) slows down the body's COM and then spring energy return (dark blue box) redirects COM velocity upward. This parallels empirical observations of human gait, which indicate that much of Push-off work is due to recoil of the (passive, elastic) Achilles tendon (Ishikawa et al. 2005); although we note that human walking transitions are perhaps best explained by a combination of Figs. 2B and C (since active muscle work also contributes to Push-off). Nevertheless, the simplified elastic ankle model is useful for explaining the fundamental mechanism: if Push-off is performed passively (by an ankle spring), then having equal amounts of Push-off and Collision work is no longer optimal (Fig. 2C), because the walker still requires additional active work to offset Collision losses. Experimental evidence suggests that much of this active work is performed by the hip. Meanwhile, the model predicts that the optimal elastic Push-off would yield zero COM Collision losses (whether or not the ankle spring is in series with a muscle/actuator), suggesting that the active work required to walk could theoretically be reduced (to zero) if ankle stiffness and foot length were optimally tuned (Fig. 2D; Zelik et al. 2014).



**Figure 2:** Step-to-step transition models.

In summary, by considering the role of passive ankle elasticity during walking we propose an updated theoretical model of the step-to-step transition that better explains experimentally-measured work performed by the body and presents a new perspective on optimal gait economy.