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

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**Background**

Ankle Push-off is Beneficial for Economical Human Walking

- Diverse body of evidence: Push-off/Collision Theory  
  - Xiu 2002; Ruina 2005  
- Controlled Experiments  
  - Caputo & Collins 2014; Jackson & Collins 2015  
- Clinical Populations  
  - Houdijk et al. 2009; Farris et al. 2015; Herr & Grabowski 2012

Ankle Push-off Primarily Contributes to Both COM Kinetics & Leg Swing Initiation*

*Not mutually exclusive. Both are equally valid descriptions of Push-off contributions.

Dissipating Ankle Push-off is Detrimental To Gait Economy (e.g., Walking on Sand)

**Empirical Estimates**

Empirical Estimates Suggest that Foot may Dissipate 25-35% of Ankle Push-off Work during Walking

- Siegel, Kepple & Caldwell 1996  
- Takahashi & Stanhope 2013  
- Zelik, Takahashi & Sawicki 2015

**Results & Methods**

**Rigid-Body Inverse Dynamics**

\[ P_{\text{abd}} = M_{\text{abd}} \dot{\omega}_{\text{abd}} \]

Takahashi, Kepple & Stanhope 2012

**Multi-Segment Foot Model + Inverse Dynamics**

\[ P_{\text{abd}} = M_{\text{abd}} \dot{\omega}_{\text{abd}} + F_{\text{abd}} \dot{\gamma}_{\text{abd}} + F_{\text{ext}} \]

Prince & Winter 1994

**Deformable Foot Model (two estimates)**

- \( P_{\text{abd}} = M_{\text{abd}} \dot{\omega}_{\text{abd}} \)
- \( P_{\text{abd}} = M_{\text{abd}} \dot{\omega}_{\text{abd}} + F_{\text{abd}} \dot{\gamma}_{\text{abd}} + F_{\text{ext}} \)

Takahashi, Kepple & Stanhope 2012  
Prince & Winter 1994

**Discussion**

**Possibility 1**

Foot is Working Against Ankle

Feet are complex, evolved to perform various functions. Foot dissipation may be detrimental to gait economy, but perhaps beneficial for other reasons (e.g., adaptability, Song & Geyer 2011).

**Possibility 2**

Foot is Working With Ankle (Indirectly)

Dissipation may be detrimental, but foot's behavior might still be beneficial, for instance by enabling the calf muscles to operate at a more favorable length or velocity (e.g., Carrier et al. 1994).

**Possibility 3**

Incorrect Empirical Ankle-Foot Estimates

Current biomechanical estimates may fail to accurately capture ankle-foot dynamics (e.g., due to neglecting multarticular muscles, Zelik et al. 2015; Zelik, Takahashi & Sawicki 2015)

**Why does this matter? One reason is because of the implications for prosthetic foot design...**

**Implication 1: Avoid Biomimicry.** Fatigue & increased metabolic demands are common problems for amputees. If goal is to improve amputee gait economy, then don’t mimic wasteful foot behavior.

**Implication 2: Actuation Not Required.** Ankle+foot work (over stride) is not net positive (Takahashi & Stanhope 2013). Prosthetic actuator not needed to emulate ankle+foot kinetics for level gait.

**Implication 3: Avoid Mimicking Current Estimates.** If current estimates are incomplete or inaccurate, then we need to improve empirical measures before trying to mimic biological function.

**Implication 2: Reassess Actuation Needs.** Understanding the role of multarticular muscles may inform the design/control of powered prostheses, which typically do not contain multarticular actuation.