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

Karl E. Zelik
Vanderbilt University
Mechanical Engineering
Physical Medicine & Rehabilitation
Is the Beach Working With or Against the Ankle During Human Walking?
Sand dissipates energy during walking

60-150% more biomechanical work, 110-150% higher metabolic cost

Lejeune, Willems & Heglund 1998
Sand dissipates ankle Push-off

- **Sand** (Lejeune, Willems & Heglund 1998)
- **Ankle** (Zelik, Takahashi & Sawicki 2015)

![Graph showing power versus stride cycle percentage with labels for 'Sand' and 'Ankle' with corresponding references.](image-url)
Consensus: Push-off facilitates economical gait

*Push-off/Collision Theory:* Kuo 2002; Ruina 2005; etc.
*Controlled Experiments:* Caputo & Collins 2014; Jackson & Collins 2015; etc.
*Clinical Populations:* Houdijk et al. 2009; Farris et al. 2015; etc.

![Diagram showing power output over stride cycle phase with a peak at push-off phase, labeled "Ankle (Zeli, Takahashi & Sawicki 2015)".](Diagram.png)
No consensus: primary function of ankle Push-off

Center-of-Mass

Leg Swing
Good news: these are not mutually exclusive

Both are equally valid descriptions
Push-off primarily contributes to leg swing & COM kinetics

Ankle Push-off primarily affects COM kinetics by localized acceleration of the trailing leg.

Center-of-Mass

Leg Swing

[Graph showing rate of energy change over stance phase with segments and COM contributions]
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![Graph showing power output vs. stride cycle with emphasis on ankle power during push-off]
Consensus: Push-off is good

Corollary: dissipating Push-off is bad (for gait economy)
Is the Foot Working With or Against the Ankle (Push-off) During Human Walking?
Feet are complex, contain 25% of bones in the body.
Foot kinetics estimated using deformable body model
Foot kinetics estimated using deformable body model

Prince & Winter 1994
Siegel, Kepple & Caldwell 1996
Zelik et al. 2011
Takahashi, Kepple & Stanhope 2012
Zelik, Takahashi & Sawicki 2015
Foot* absorbs energy during push-off, returns little

*everything distal to the ankle joint

\[ P_{foot} = F_{grf} v_{distal\_foot} + M_{free} \omega_{foot} \]
Foot* absorbs energy during push-off, returns little

*everything distal to the ankle joint

\[ P_{foot} = M_{\text{ankle}} \omega_{\text{shank}} + F_{\text{ankle}} v_{\text{ankle}} - P_{\text{ankle}} \]
Foot absorption partly due to negative toe joint work

*everything distal to the ankle joint

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**Power**

- **Ankle** (Zelik, Takahashi & Sawicki 2015)
- **Foot** (Method: Takahashi, Kepple & Stanhope 2012)
- **Foot** (Method: Prince & Winter 1994)
- **Toes** (MacWilliams, Cowley & Nicholson 2003)

**Stride Cycle (%)**
EMGs provide supplemental perspective
Negative toe work during active muscle contractions

foot absorption not simply the result of passive deformation

flexor hallucis & digitorum longi EMG

flexor digitorum brevis EMG

Zelik et al. 2015 EJAP

Power

Toes (MacWilliams, Cowley & Nicholson 2003)

50 W

Stride Cycle (%)

0 10 20 30 40 50 60 70
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![Graph showing power output over stride cycle (%)](image)
What is going on with the foot?

3 Possibilities...

Why does it matter?

Example: implications for prosthetic foot design
Possibility 1: Foot is working against the ankle

Foot absorption detrimental to gait economy, perhaps beneficial for other reasons (e.g., adaptability)?

Song & Geyer 2011, Song, Collins & Geyer 2013

![Diagram showing power output over stride cycle with labels for Ankle, Foot, and Toes]
Possibility 1: Foot is working against the ankle

Foot absorption detrimental to gait economy, perhaps beneficial for other reasons (e.g., adaptability)?

Song & Geyer 2011; Song, Collins & Geyer 2013

Prosthetic Foot Implication 1: Avoid Biomimicry
If goal is to improve amputee walking economy, then don’t mimic wasteful foot behavior.

*Fatigue & increased metabolic demands are common problems for amputees.*
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*Fatigue & increased metabolic demands are common problems for amputees.*

Prosthetic Foot Implication 2: Actuation Not Required
Ankle+foot work is not net positive. Powered prostheses may not be needed to emulate ankle+foot function during gait.
Takahashi & Stanhope 2013; Zelik, Takahashi & Sawicki 2015
Possibility 2: Foot is working with the ankle

Foot absorption itself is bad, but may enable calf muscles to operate at more favorable length or velocity (e.g., Carrier et al. 1994) or extend time duration of Push-off (e.g., clapskates, Houdijk et al. 2000), etc.
Possibility 2: Foot is working with the ankle

Foot absorption itself is bad, but may enable calf muscles to operate at more favorable length or velocity (e.g., Carrier et al. 1994) or extend time duration of Push-off (e.g., clapskates, Houdijk et al. 2000), etc.

Prosthetic Foot Implication 1: Avoid Biomimicry (probably)
If foot behavior enables calf muscles to operate more effectively, then not applicable to amputees/prosthetics.

Prosthetic Foot Implication 2: Actuation Not Required
Ankle+foot work is not net positive. Powered prostheses may not be needed to emulate ankle+foot function during gait.
Takahashi & Stanhope 2013; Zelik, Takahashi & Sawicki 2015

Relevant (upcoming) talks
- Shreyas Mandre – foot stiffness
- Keonyoung Oh – toe joint function
- Matt Yandell – shod vs. barefoot gait
Possibility 3: Foot is working with the ankle, BUT…

our conventional biomechanical estimates fail to measure it (e.g., due to neglecting multiarticular muscles)

Zelik et al. 2015 EJAP; Zelik, Takahashi & Sawicki 2015 JEB
Thought expt: multiarticular muscle acting isometrically
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Push-off → ankles and toes extend together
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Push-off $\rightarrow$ ankles and toes extend together
Push-off $\rightarrow$ multiarticular muscle moments

$M_{\text{ank}}$, $\omega_{\text{ank}}$, $M_{\text{mtp}}$, $\omega_{\text{mtp}}$
Inverse dynamics $\rightarrow$ apparent negative foot work

\[ P_{\text{joint}} = M_{\text{joint}} \omega_{\text{joint}} \]
\[ W_{\text{joint}} = \int P_{\text{joint}} \, dt \]
Inverse dynamics $\rightarrow$ apparent positive ankle work

$$P_{\text{joint}} = M_{\text{joint}} \omega_{\text{joint}}$$

$$W_{\text{joint}} = \int P_{\text{joint}} \, dt$$
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Prosthetic Foot Implication: Avoid Mimicking Current Estimates

We need better empirical estimates to understand & restore normal ankle-foot function.

Relevant talks & posters

• Eric Honert (poster 54) – accounting for multiarticular ankle-foot muscles
• Ryan Riddick – modeling & estimating foot kinetics
Concluding Remarks

1. Thank you DW committee (for session on feet)

2. Encourage everyone to think more about feet
   - not to a creepy fetish level, but to a level reflective of foot’s importance
   - ignoring foot is akin to ignoring knee during gait

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Zelik, Takahashi & Sawicki 2015
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1. Thank you DW committee (for session on feet)

2. Encourage everyone to think more about feet
   - not to a creepy fetish level, but to a level reflective of foot’s importance
   - ignoring foot is akin to ignoring knee during gait (Zelik, Takahashi & Sawicki 2015)

3. Request feedback, thoughts, new perspectives...
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