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

VANDERBILT

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Background

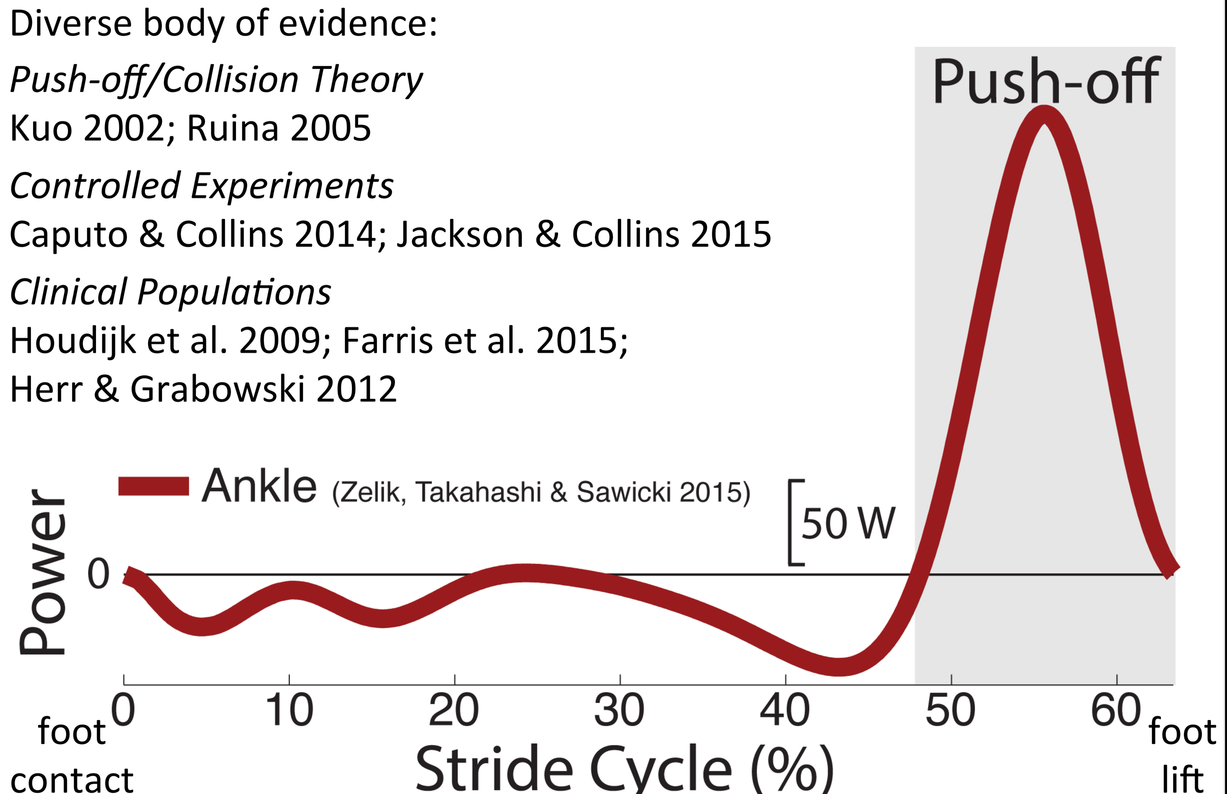
Ankle Push-off is Beneficial for Economical Human Walking

Diverse body of evidence:

Push-off/Collision Theory
Kuo 2002; Ruina 2005

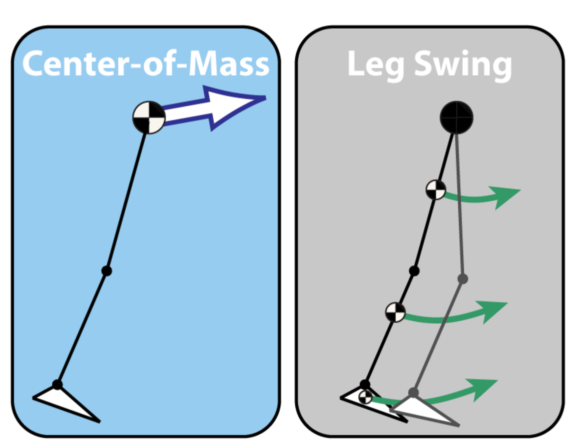
Controlled Experiments
Caputo & Collins 2014; Jackson & Collins 2015

Clinical Populations
Houdijk et al. 2009; Farris et al. 2015; Herr & Grabowski 2012

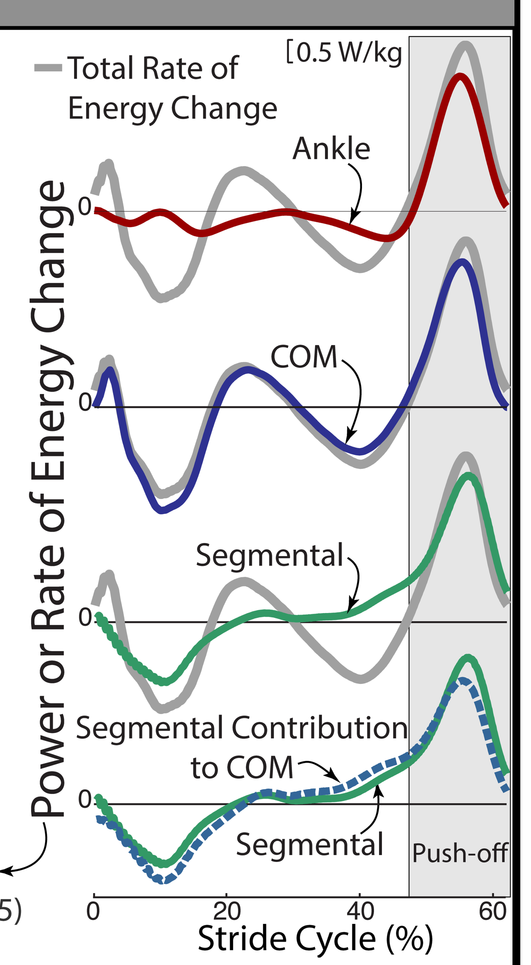


Ankle Push-off Primarily Contributes to Both COM Kinetics & Leg Swing Initiation*

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

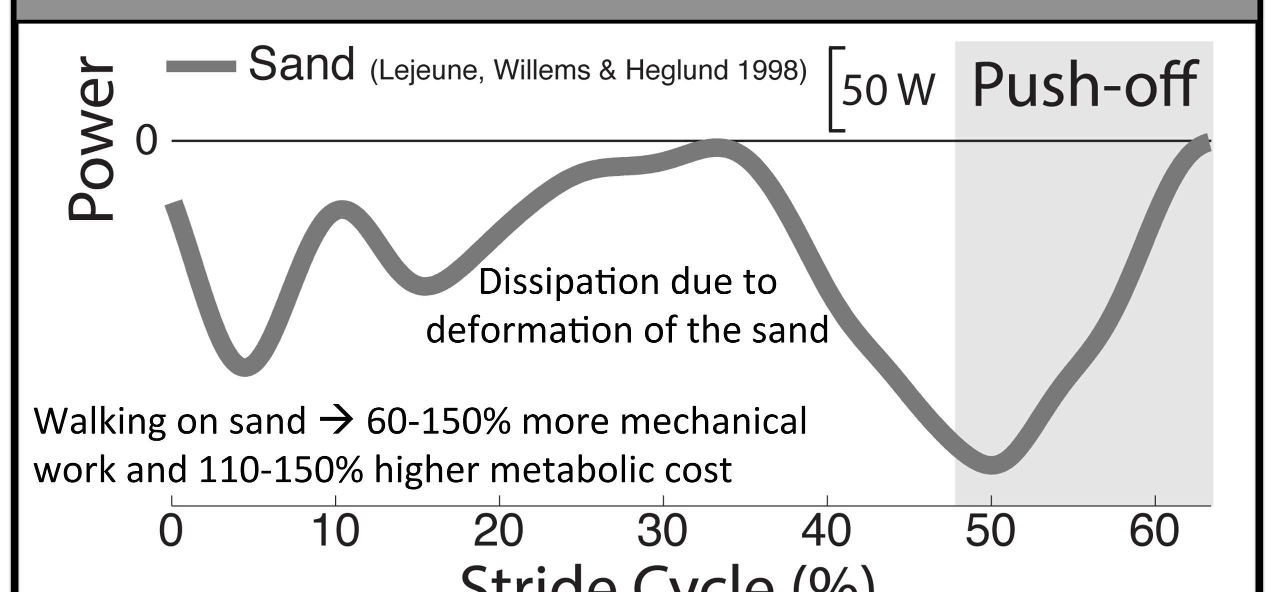


Ankle Push-off primarily affects center-of-mass (COM) kinetics by a localized acceleration of the trailing leg.

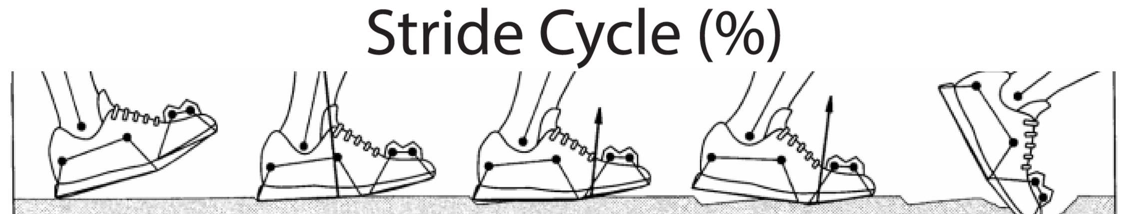


Estimates based on Energy Accounting Analysis of healthy human gait (Zelik, Takahashi & Sawicki 2015)

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



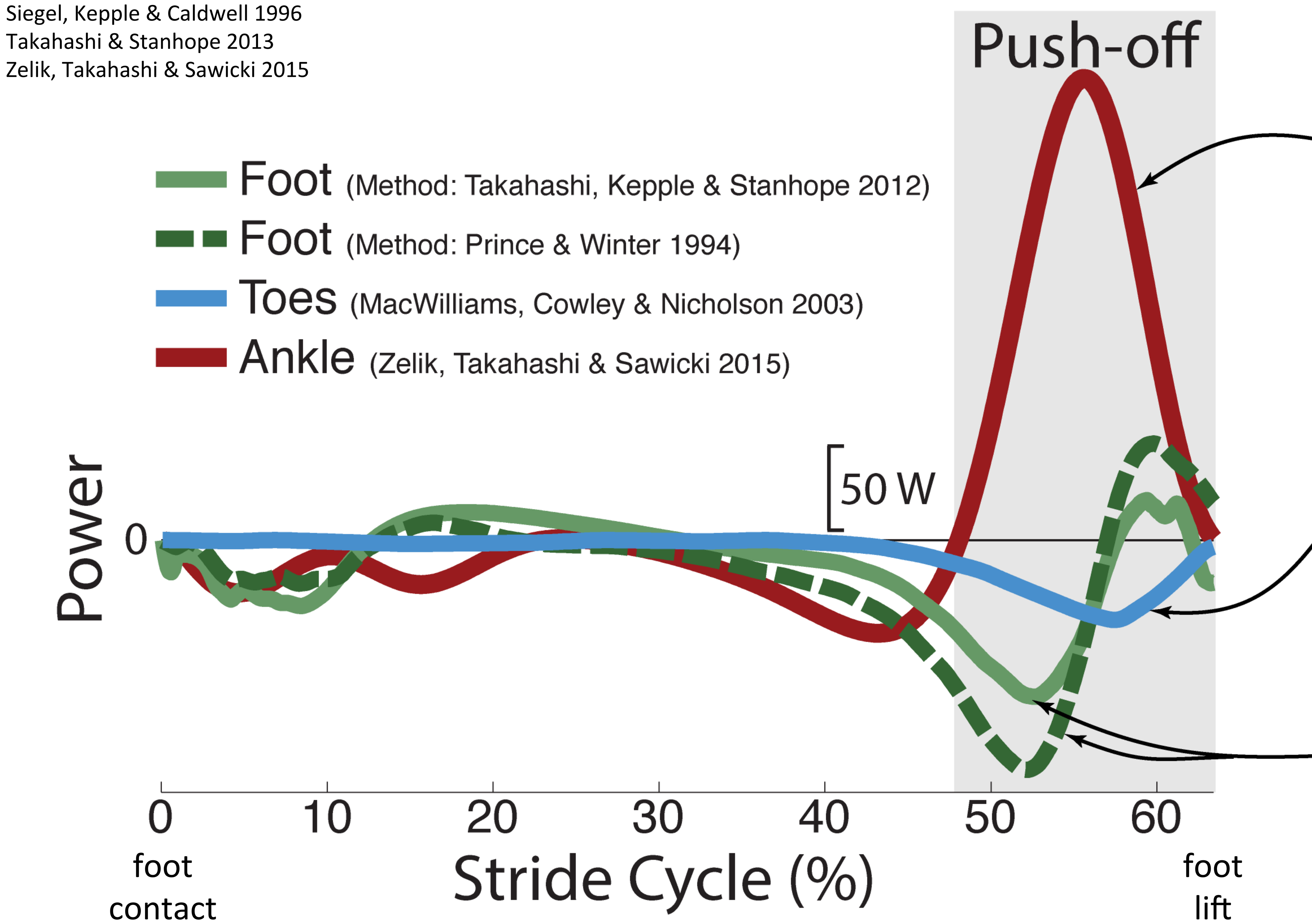
Walking on sand → 60-150% more mechanical work and 110-150% higher metabolic cost



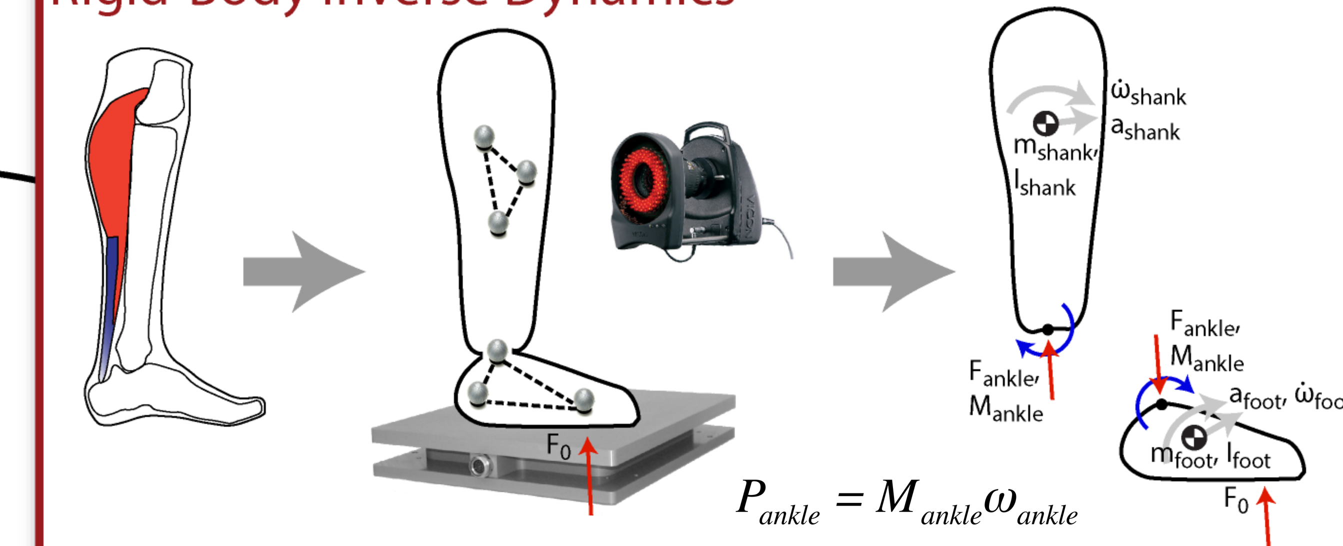
Results & Methods

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

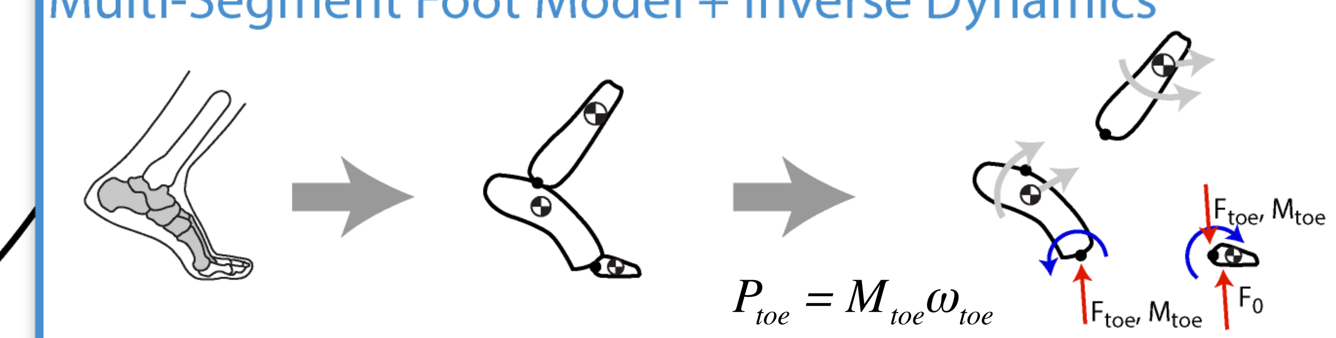


Rigid-Body Inverse Dynamics



$P_{ankle} = M_{ankle}\omega_{ankle}$

Multi-Segment Foot Model + Inverse Dynamics

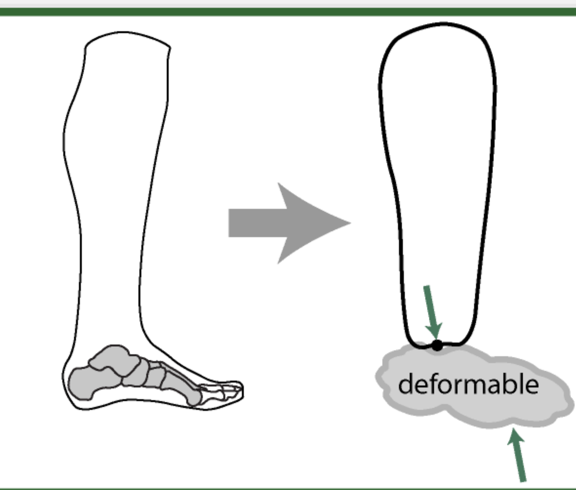


$P_{toe} = M_{toe}\omega_{toe}$

Deformable Foot Model (two estimates)

$P_{foot} = F_{grf}v_{distal\_foot} + M_{free}\omega_{foot}$
Takahashi, Kepple & Stanhope 2012

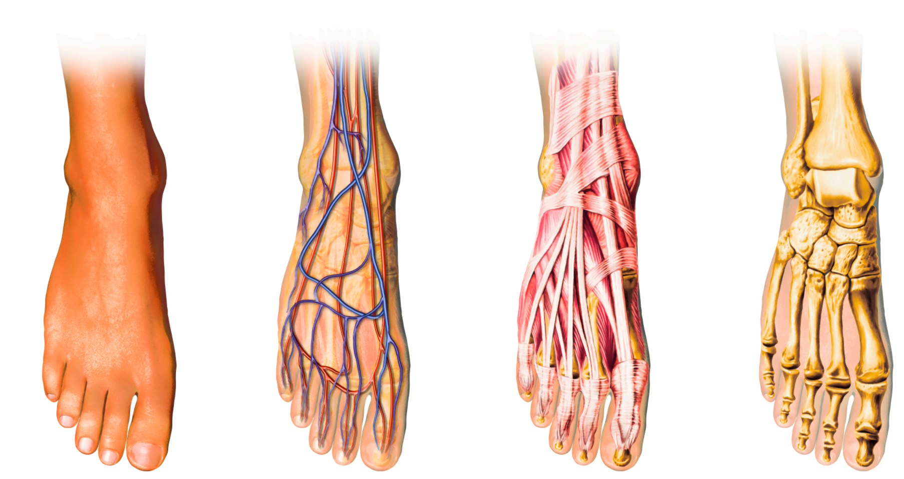
$P_{foot} = M_{ankle}\omega_{shank} + F_{ankle}v_{ankle} - P_{ankle}$
Prince & Winter 1994



Discussion

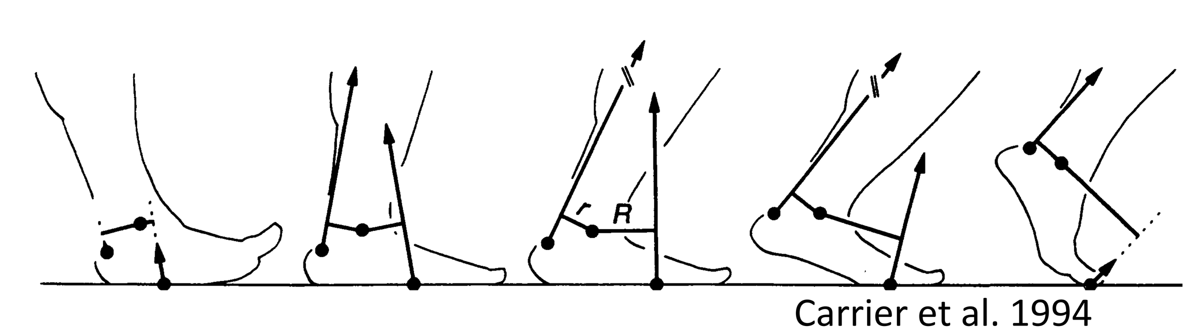
Possibility 1: Foot is Working Against Ankle

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)

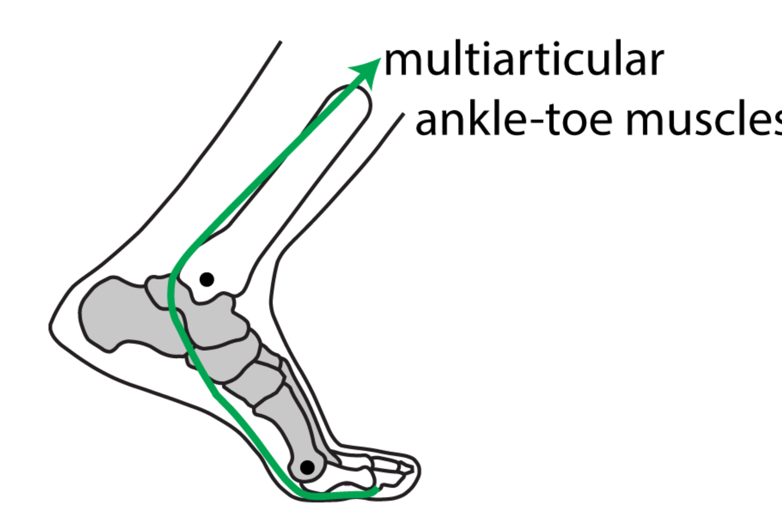
Dissipation may be detrimental, but foot's behavior might still be beneficial, for instance by enabling the calf muscles to operate at a more favorable length or velocity (e.g., Carrier et al. 1994).



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 multiarticular 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 1: Avoid Mimicking Impertinent Mechanisms. Although the foot may enable the calf muscles to operate more effectively, this is not applicable to amputees/prosthetics.

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 1: 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 multiarticular muscles may inform the design/control of powered prostheses, which typically do not contain multiarticular actuation.