Power to the Foot! Understanding and Applying Distal Power Calculations in Biomechanics

Eric Honert & Kota Takahashi

Our Slack link: https://tinyurl.com/ISBfootpower

ISB·JSB
FUKUOKA 2023
50 years of the International Society of Biomechanics

Workshop #2

Power to the Foot! Understanding and Applying Distal Power Calculations in Biomechanics

Dr. Kota Takahashi
(University Utah, USA)

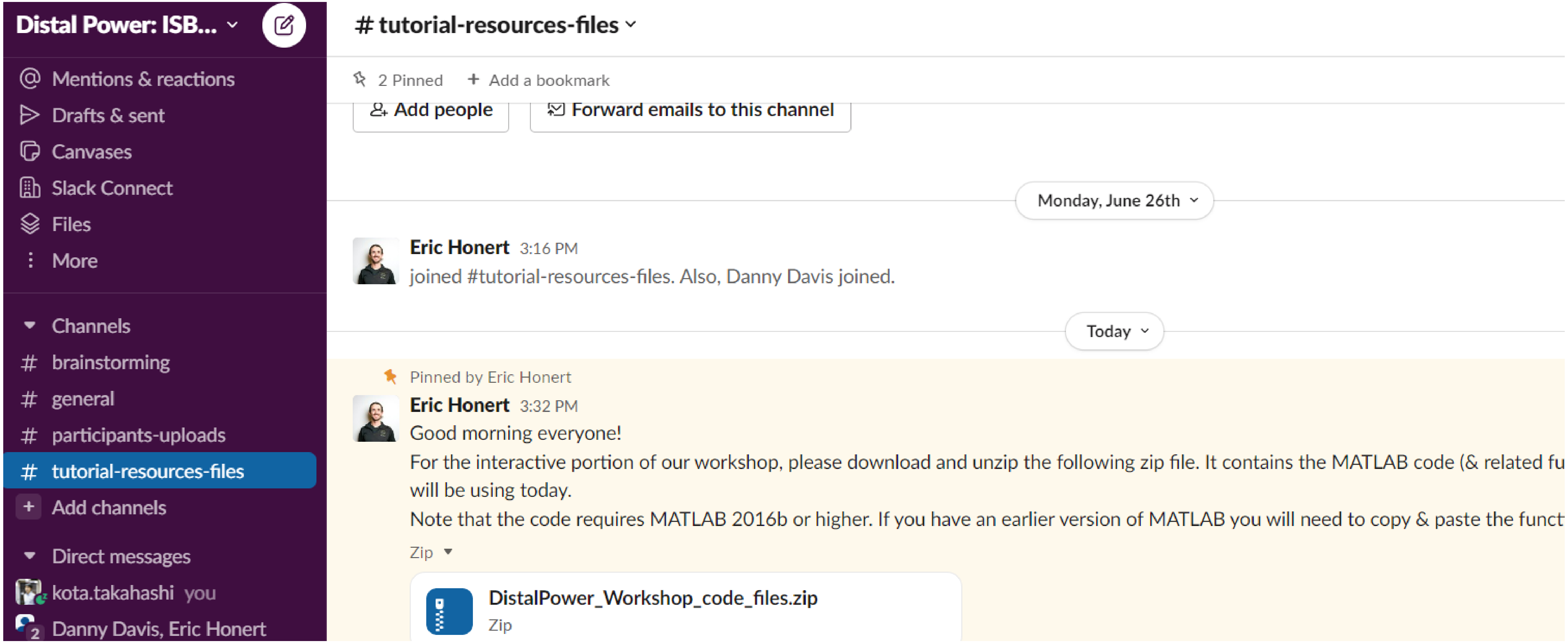
Dr. Eric C. Honert
(BOA Technology Inc., USA)

30 July | 10 AM
@
Fukuoka International Congress Centre

Join our Slack workspace

https://tinyurl.com/ISBfootpower

Tutorial Resources – via Slack



Eric Honert 3:16 PM

joined #tutorial-resources-files. Also, Danny Davis joined.

Eric Honert 3:32 PM

Good morning everyone!

For the interactive portion of our workshop, please download and unzip the following zip file. It contains the MATLAB code (& related fu

will be using today.

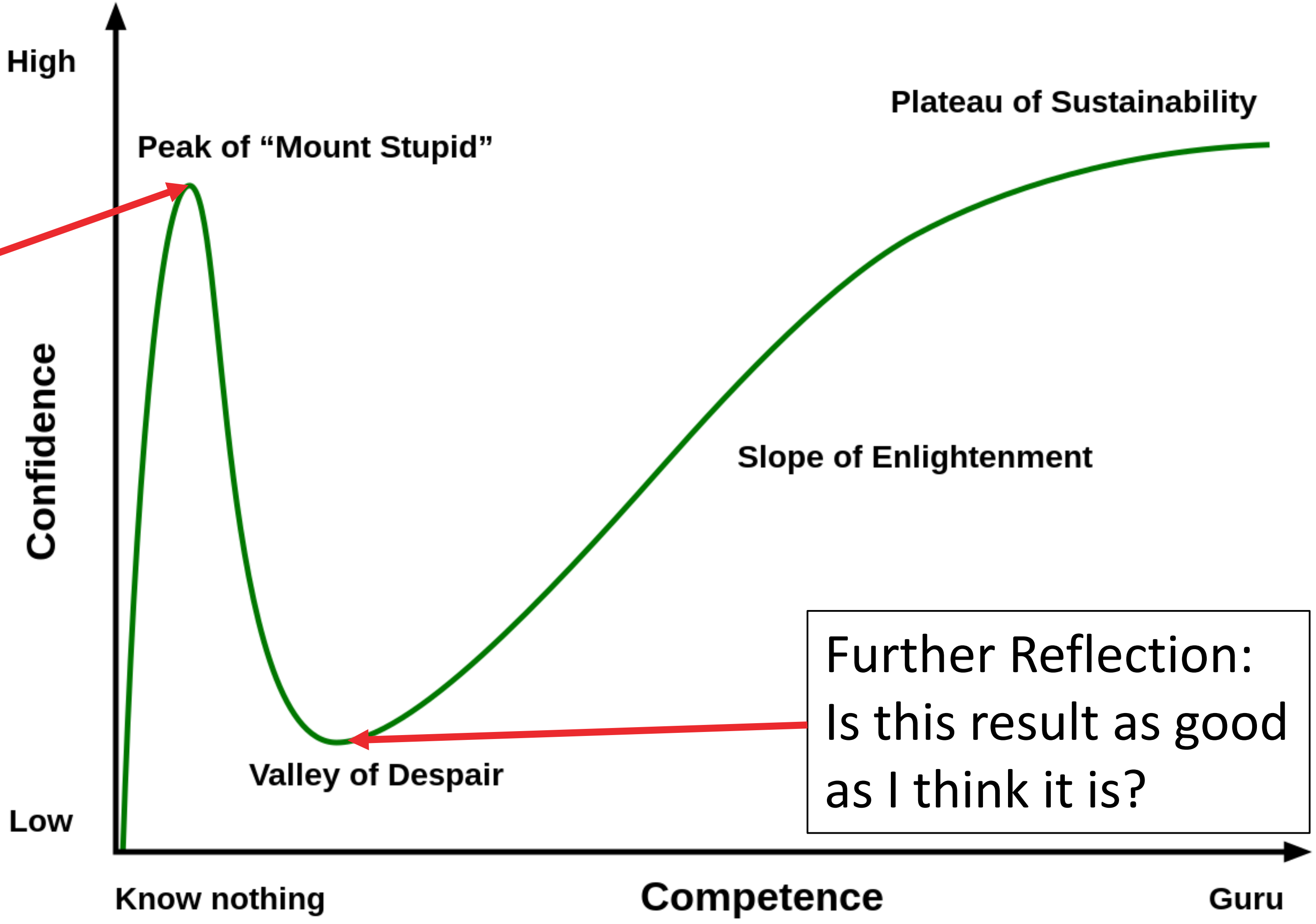
Note that the code requires MATLAB 2016b or higher. If you have an earlier version of MATLAB you will need to copy & paste the funct

Zip

DistalPower_Workshop_code_files.zip

Zip

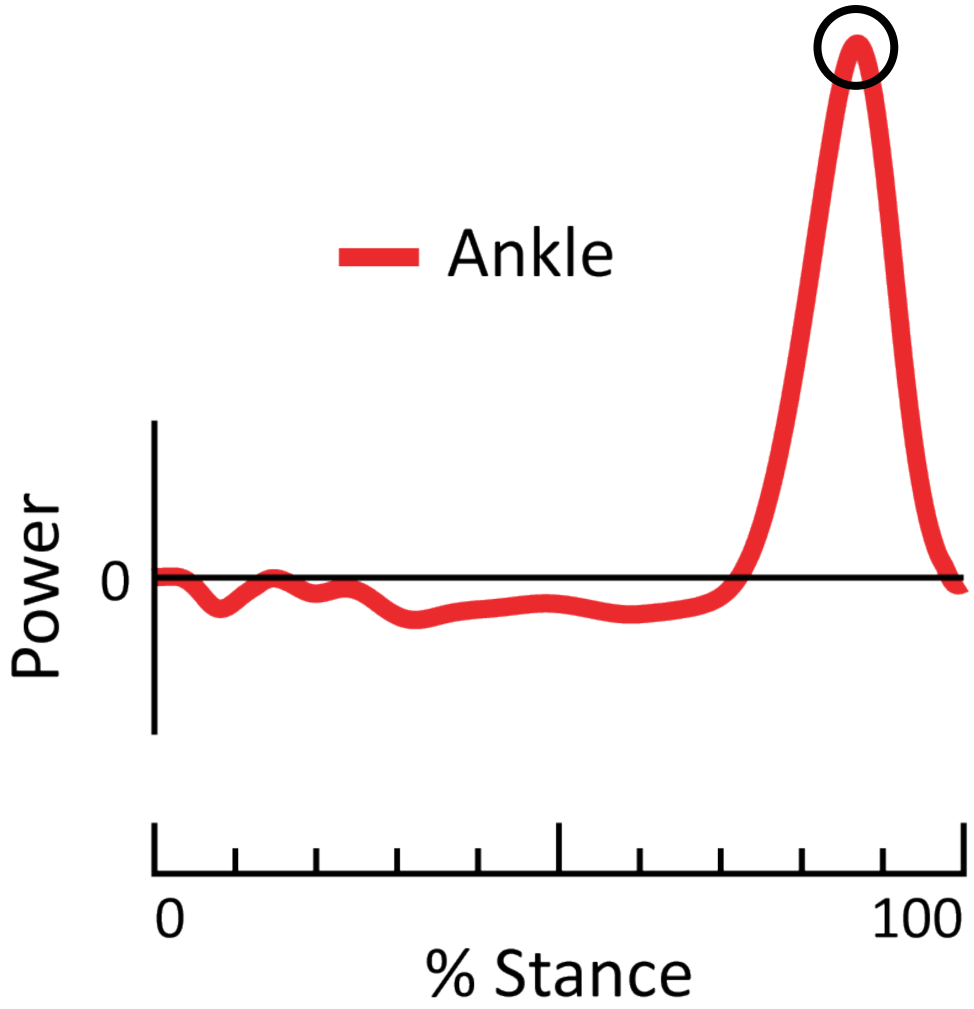
Dunning-Kruger of Methodologies



Initial Reaction:
Apply a cool new technique with impressive results

Further Reflection:
Is this result as good as I think it is?

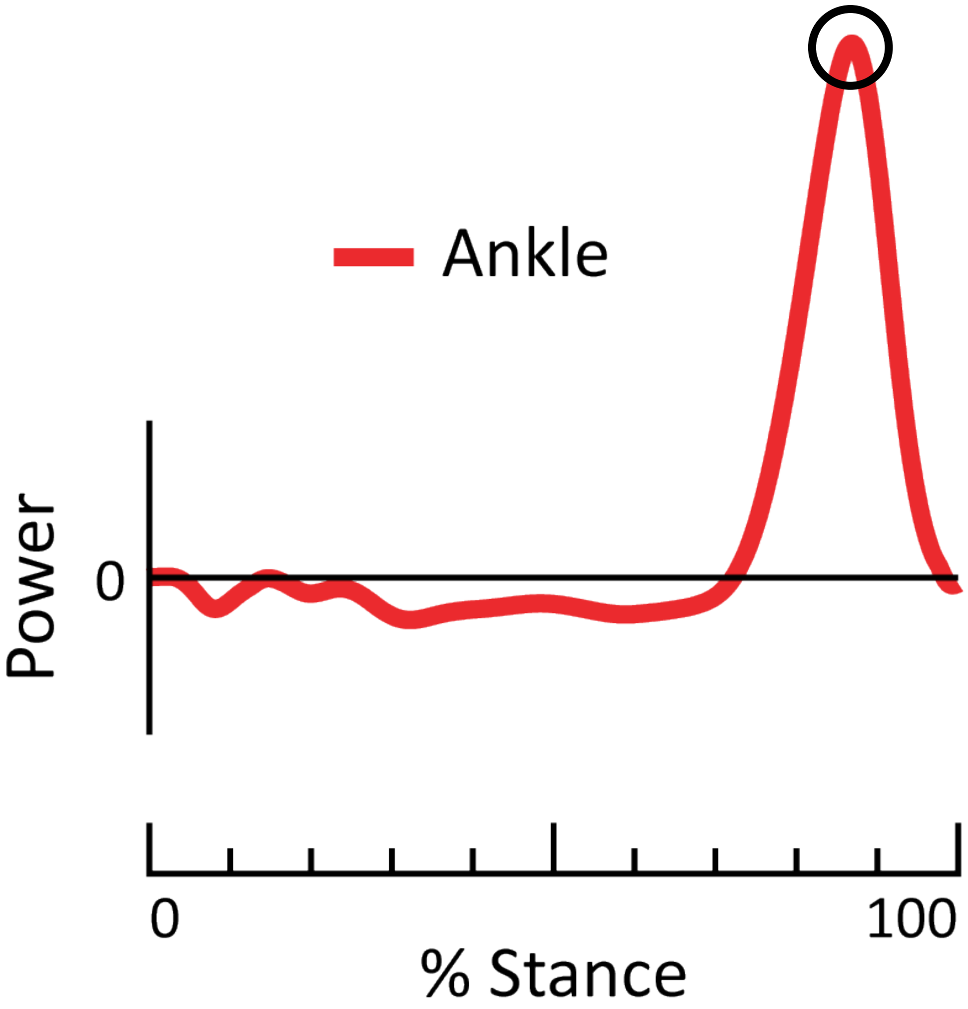
Beneficial Ankle Push-off



Zelik & Honert 2018

N=1

Beneficial Ankle Push-off

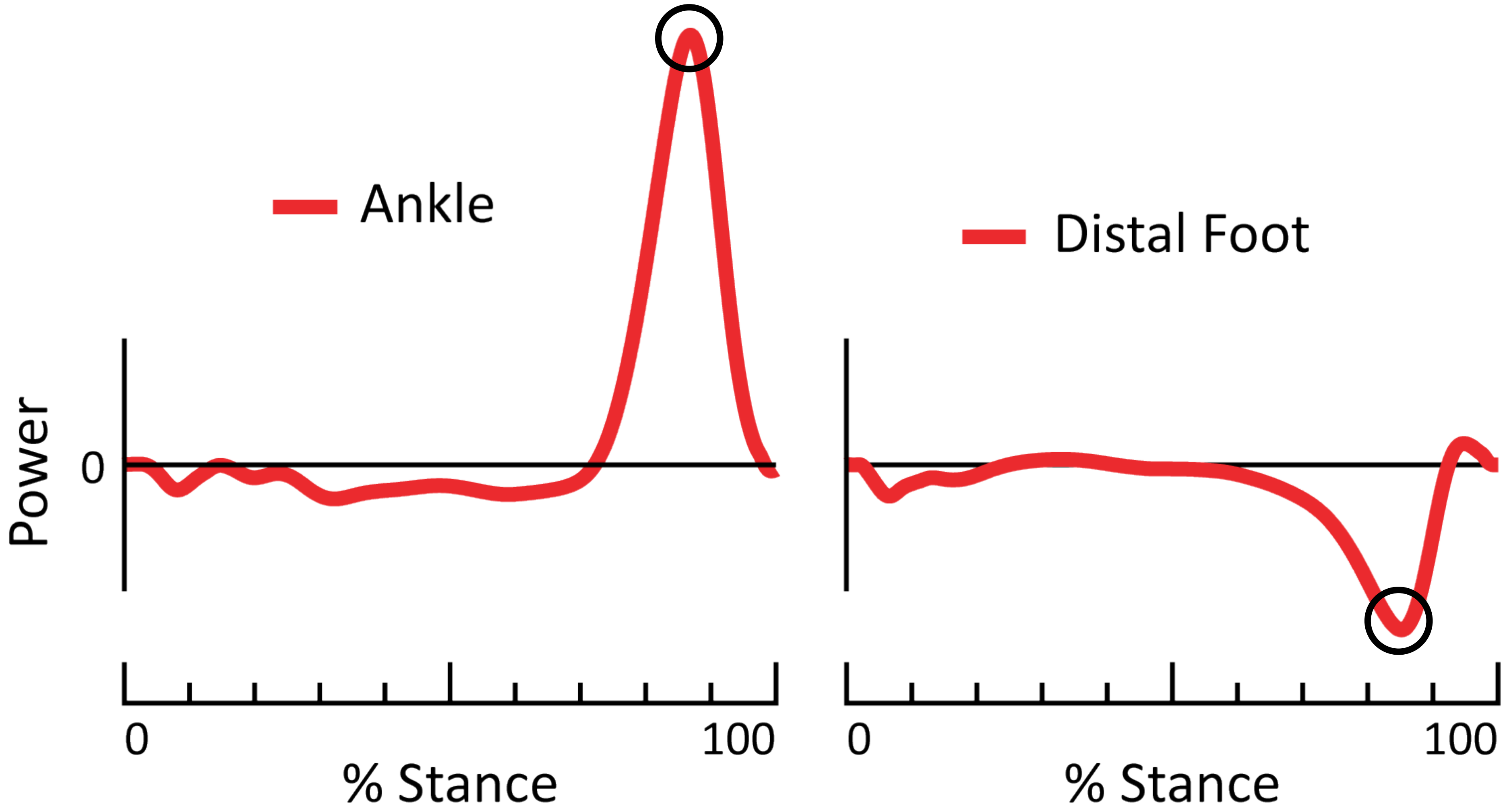


Initial Reaction:
Apply a cool new technique with impressive results

Zelik & Honert 2018

N=1

Ankle Push-off with Foot Absorption?

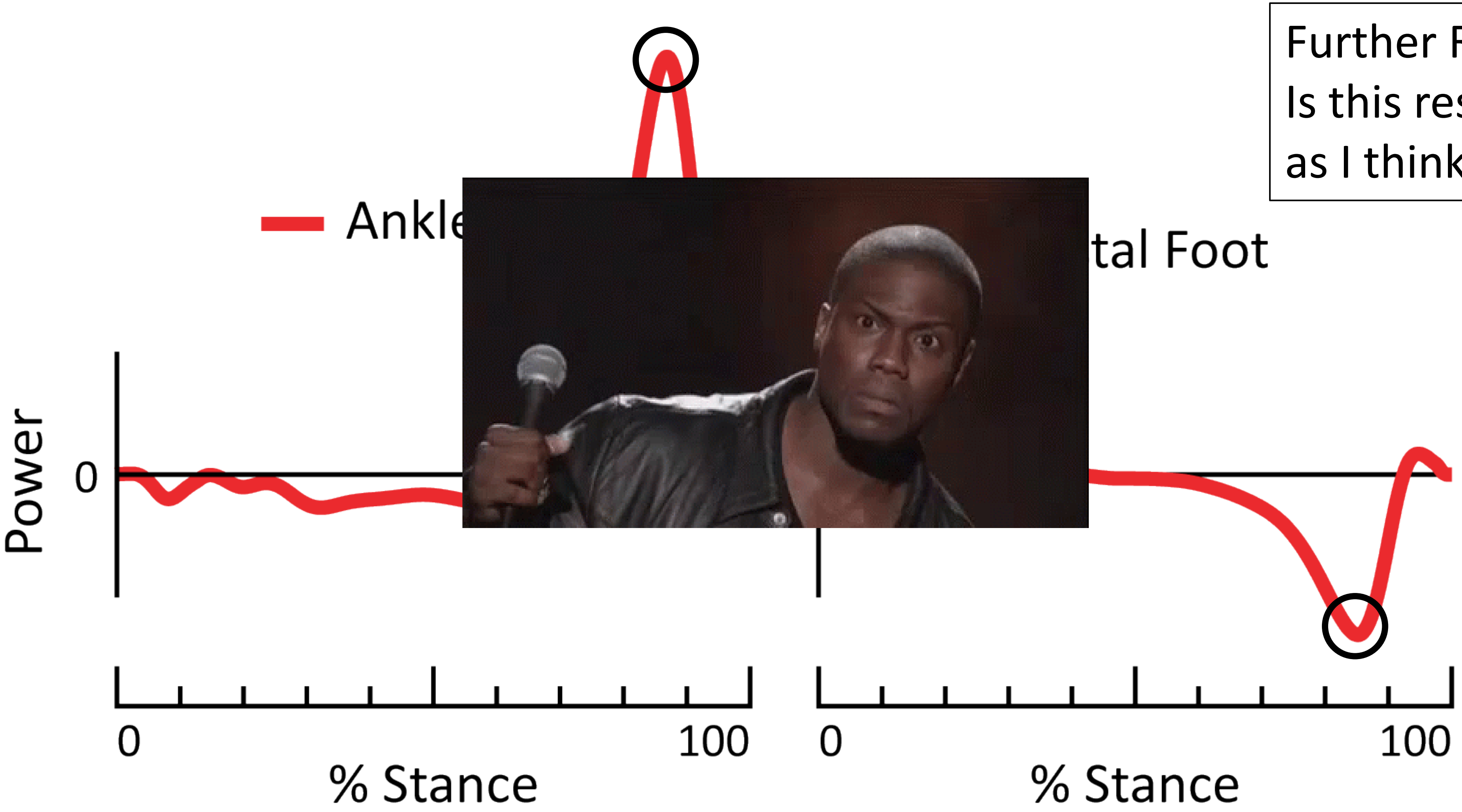


Zelik & Honert 2018

N=1

Ankle Push-off with Foot Absorption?

Further Reflection:
Is this result as good as I think it is?

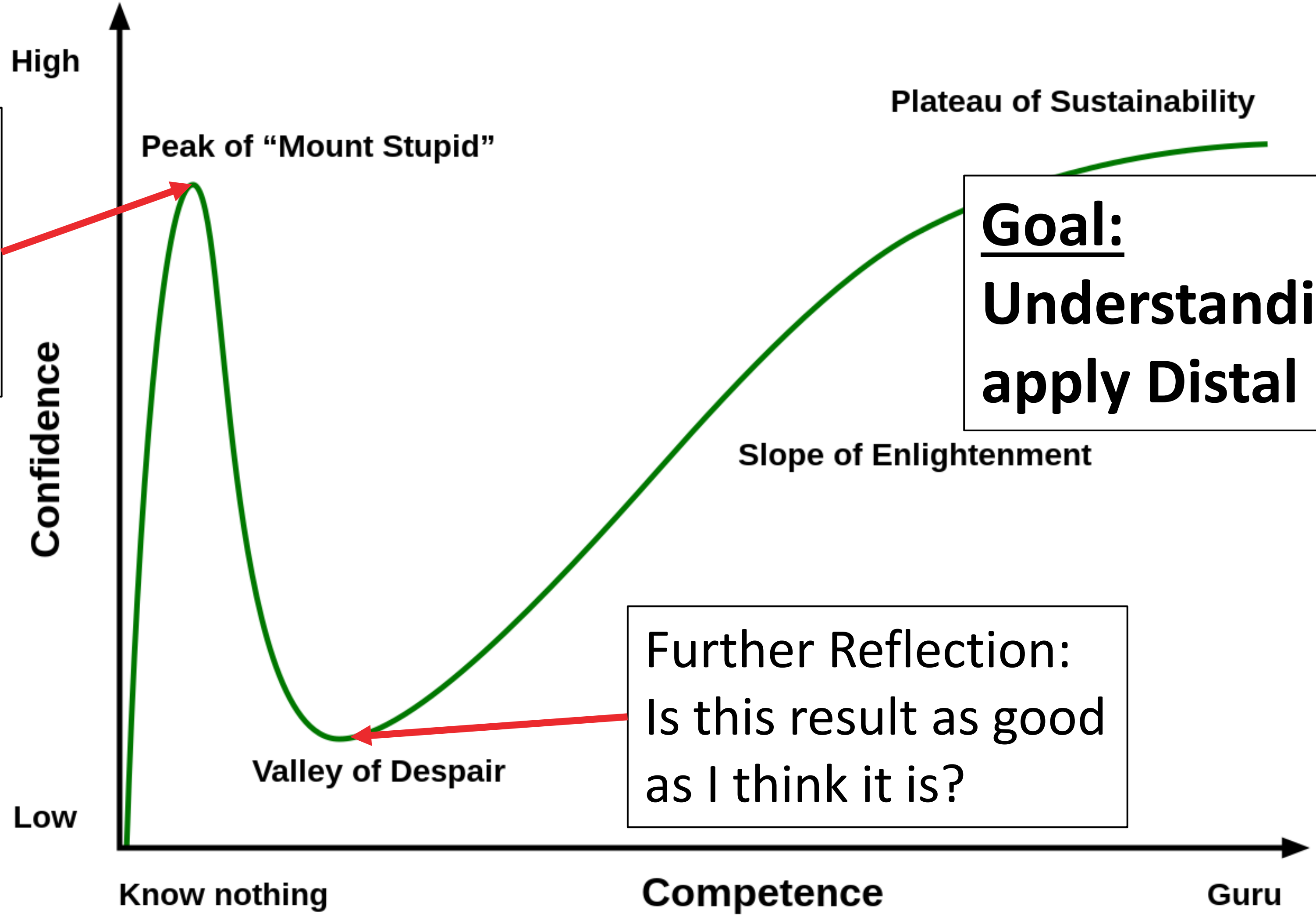


Zelik & Honert 2018

N=1

Workshop Goal: Slope of Enlightenment

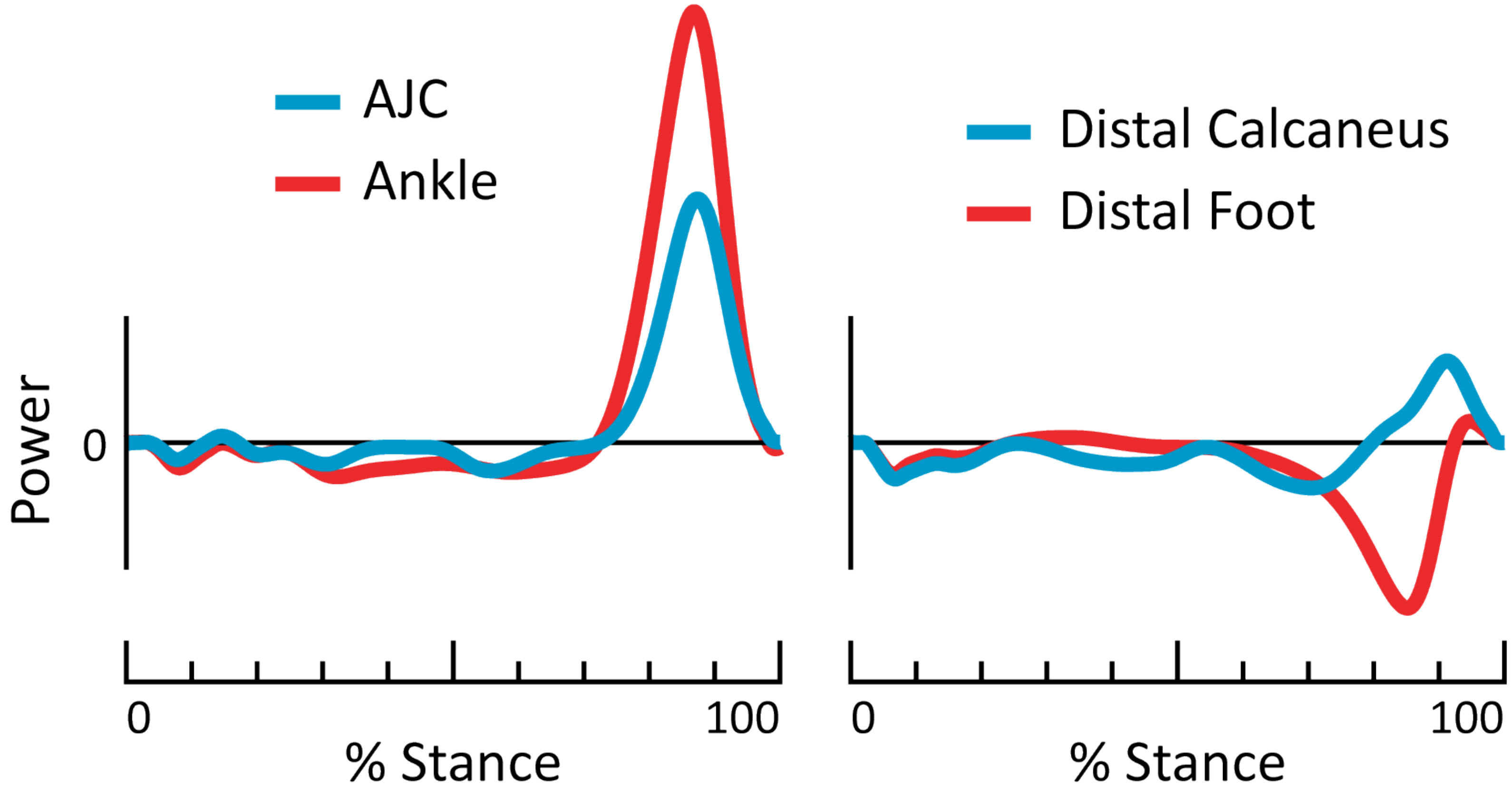
Initial Reaction:
Apply a cool new technique with impressive results



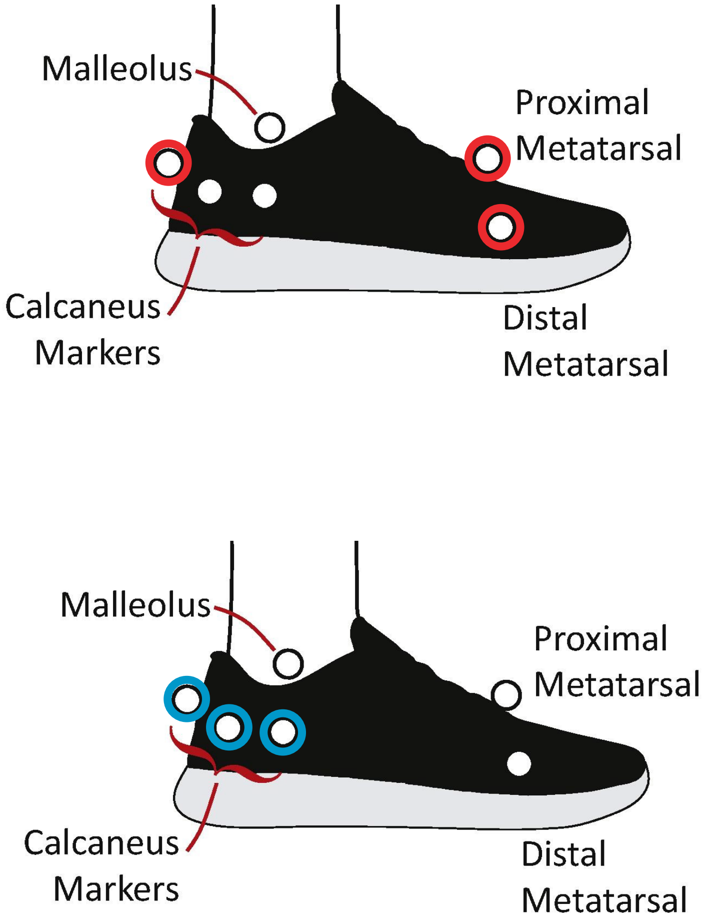
Goal:
Understanding & ability to apply Distal Power analysis

Further Reflection:
Is this result as good as I think it is?

Understanding the Ankle & Foot



Foot Tracking Markers



Zelik & Honert 2018

N=1

Workshop Outline

- Current Distal power Applications
- Two Perspectives on the Methodology
- Applying the Distal power
- Future Applications

Application: Understanding Footwear

Brooks Hyperion Elite 2

Nike VaporFly

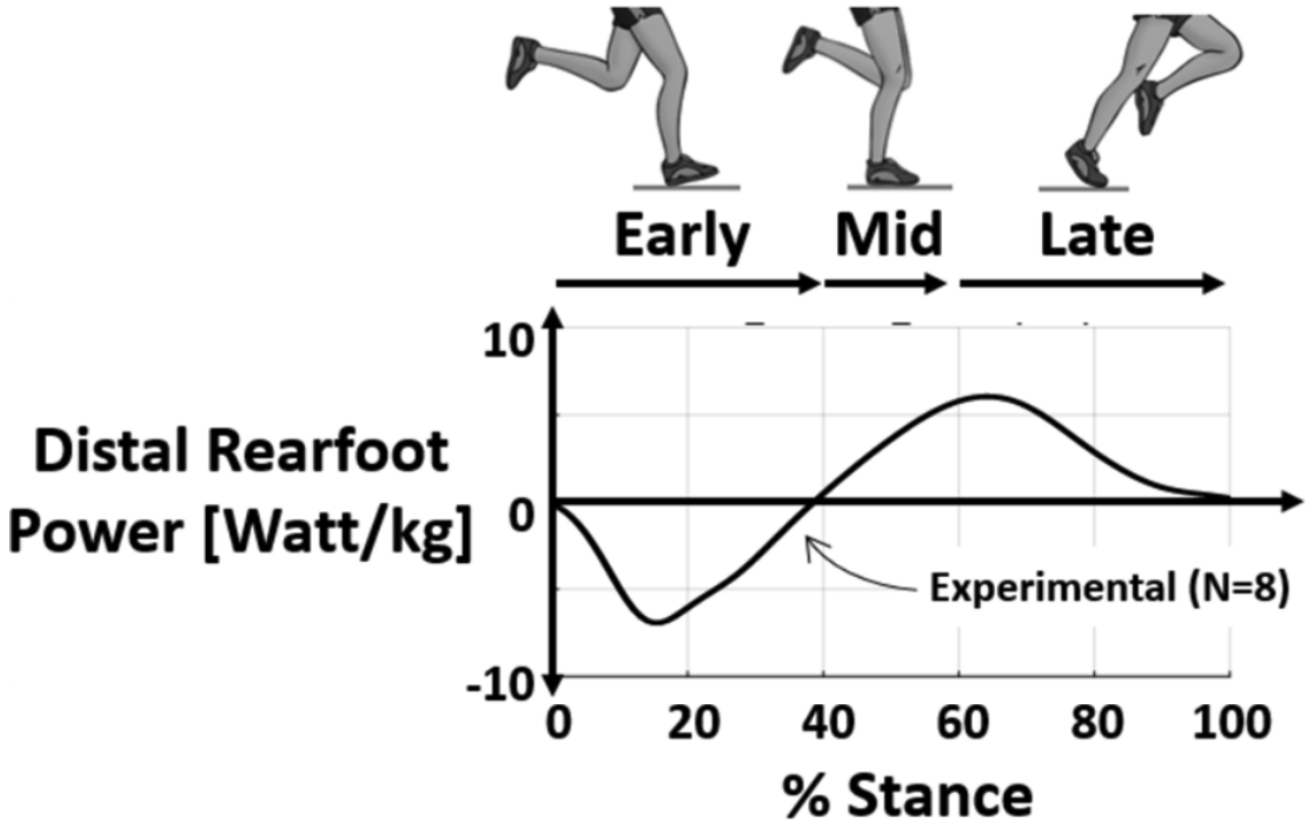
HOKA ONE ONE Carbon X 2

Adidas Adizero Adios Pro

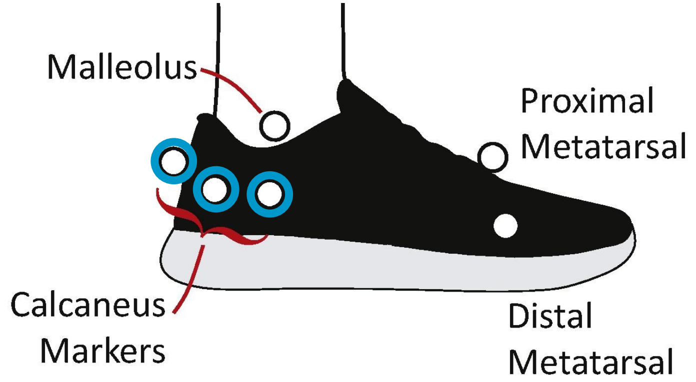
Nike AlphaFly

Saucony Endorphin Pro

Understanding Advanced Footwear

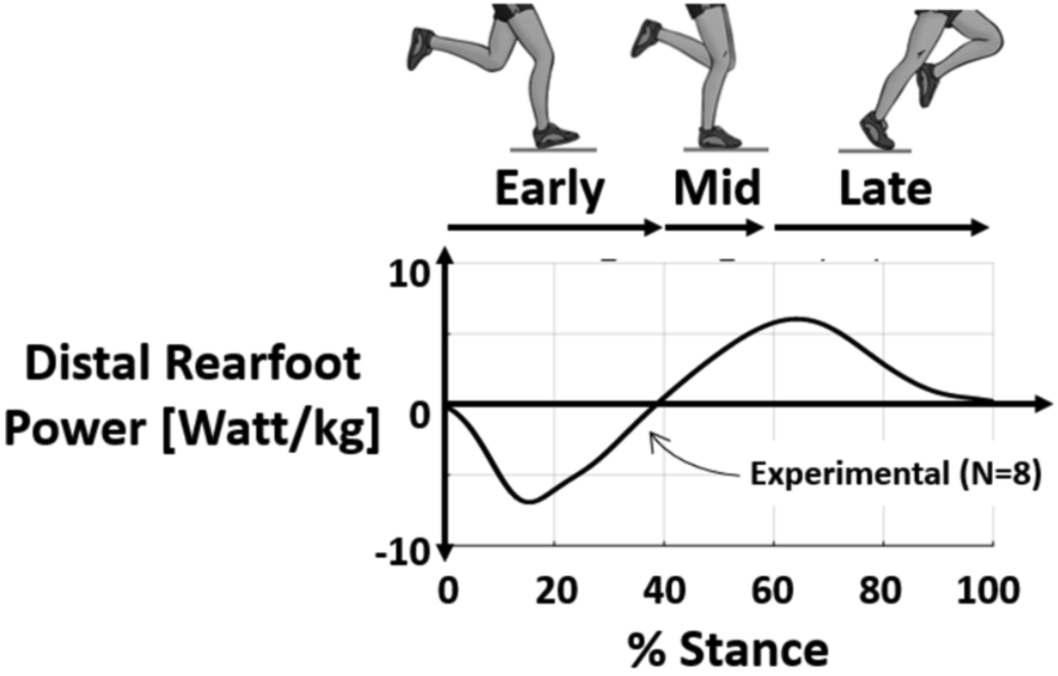


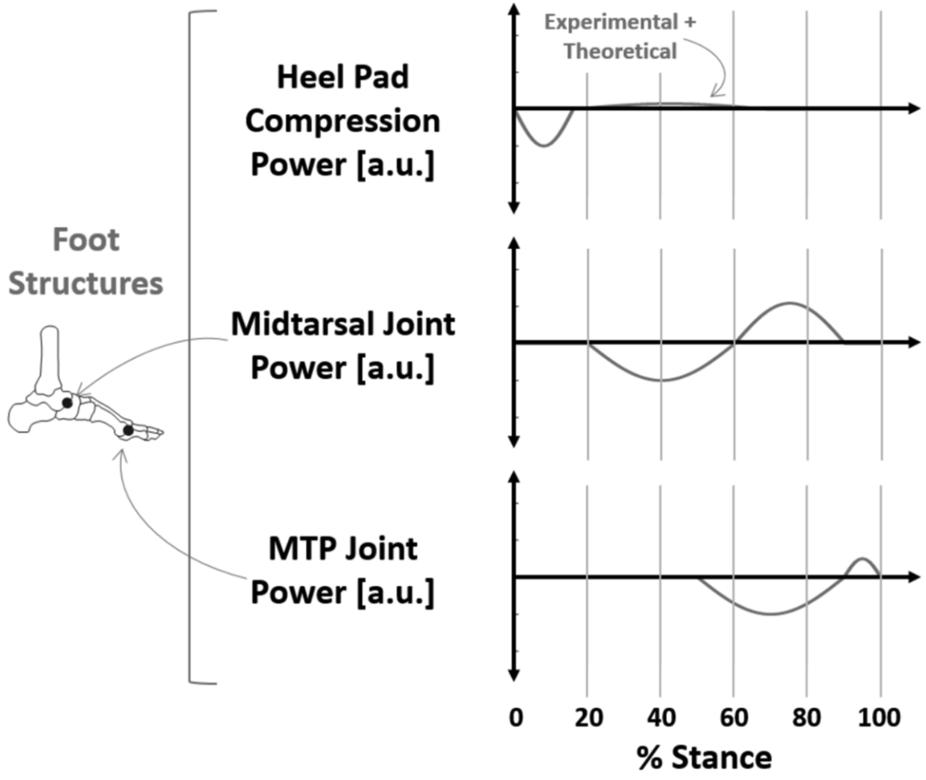
Foot Tracking Markers



Matijevich et al. 2022

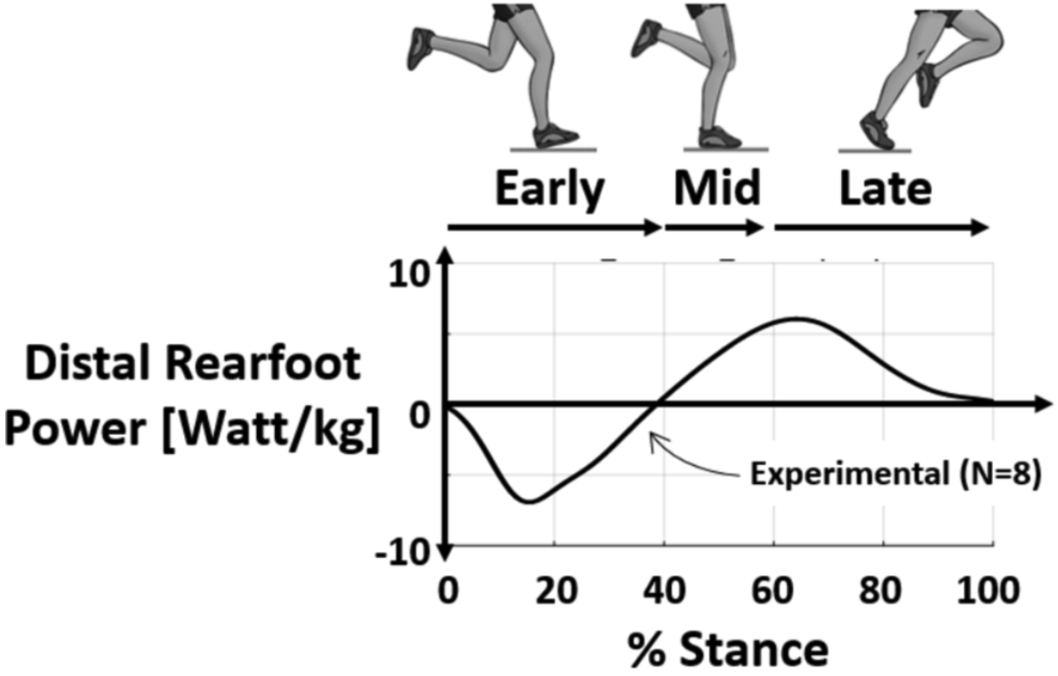
Understanding Advanced Footwear

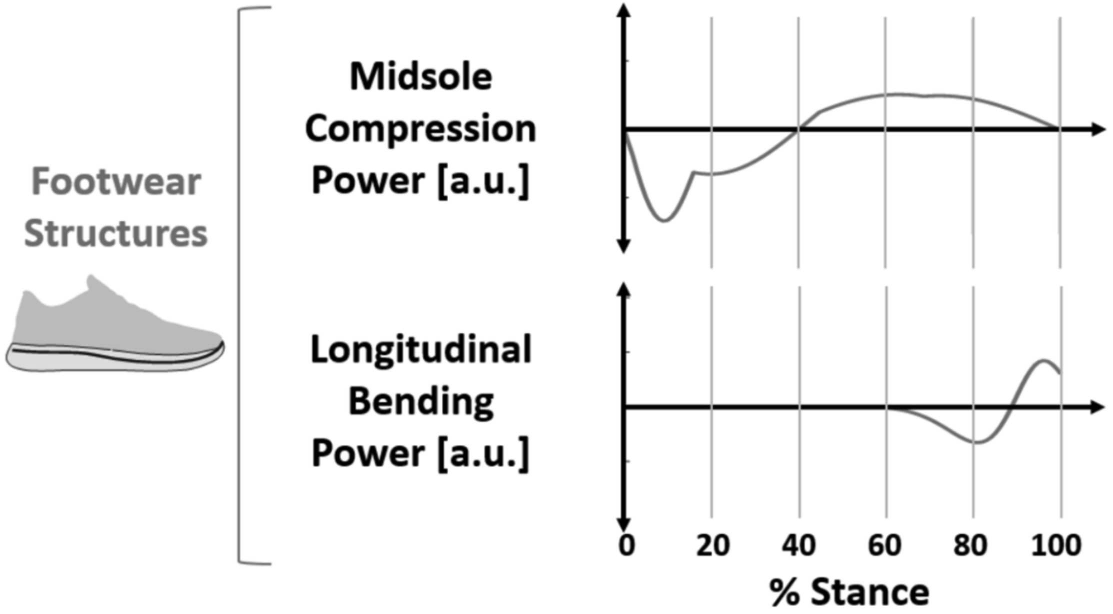




Matijevich et al. 2022

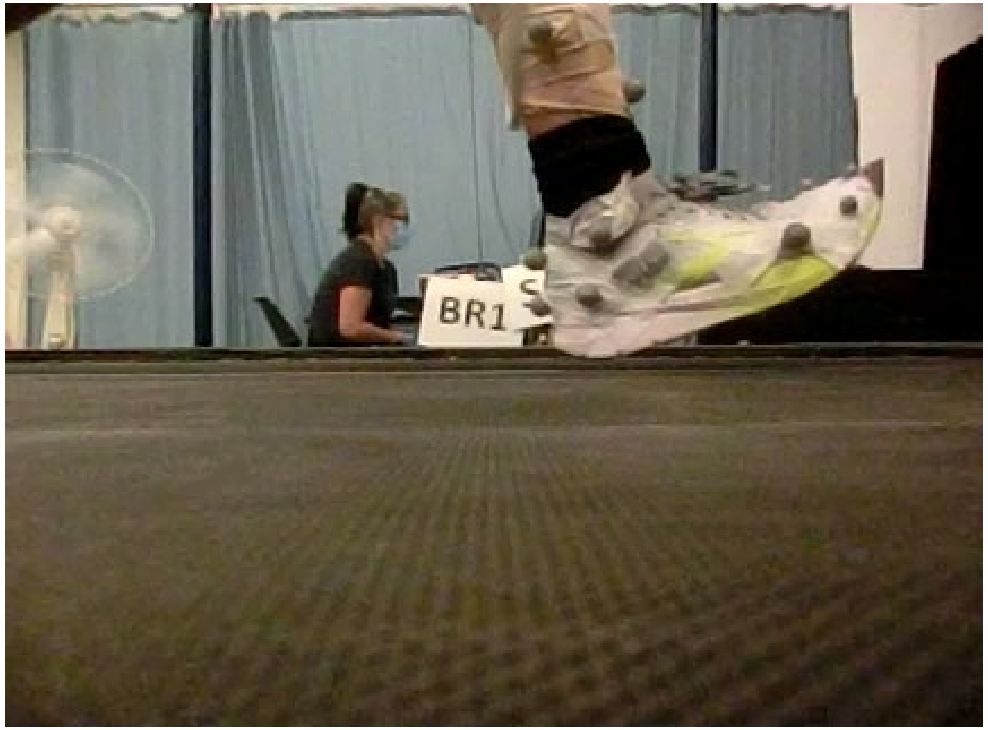
Understanding Advanced Footwear

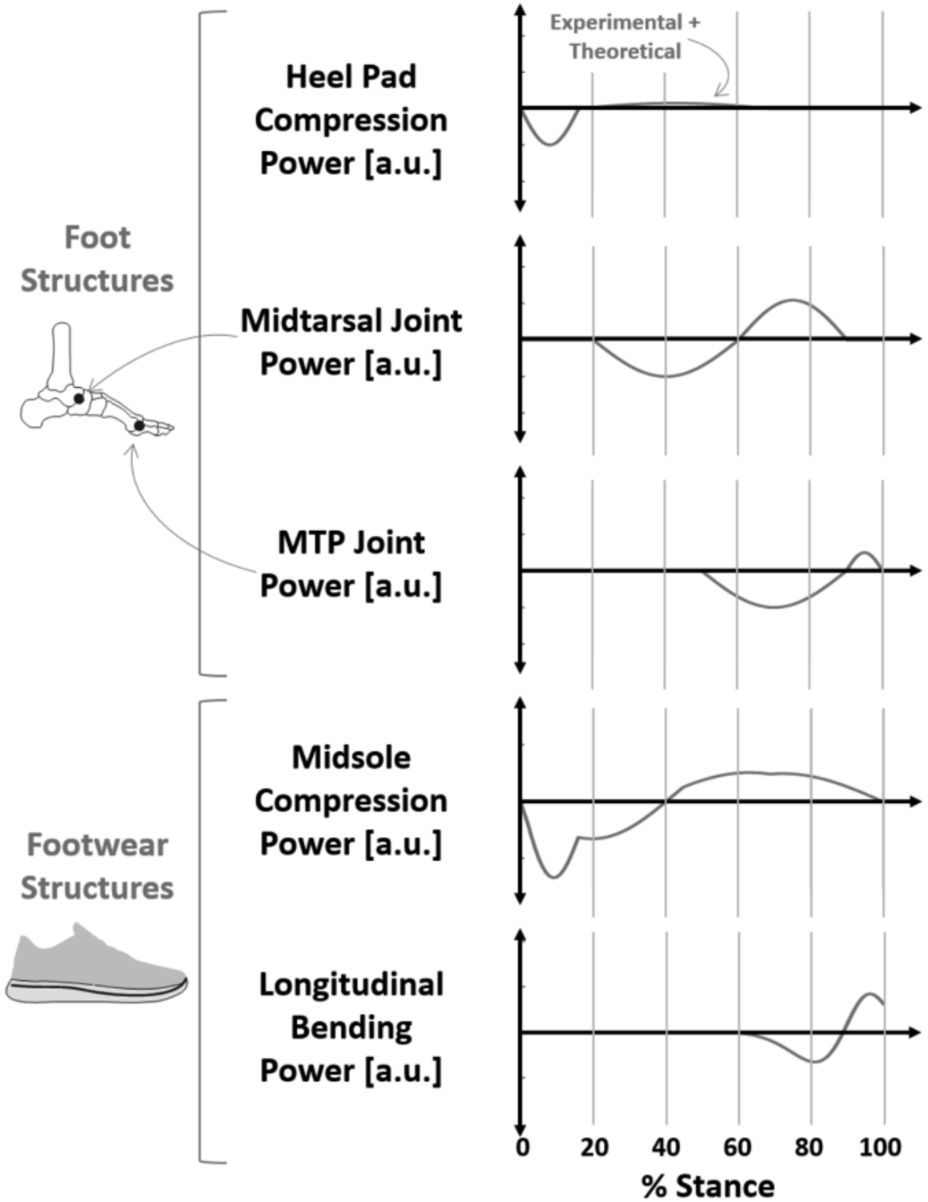




Matijevich et al. 2022

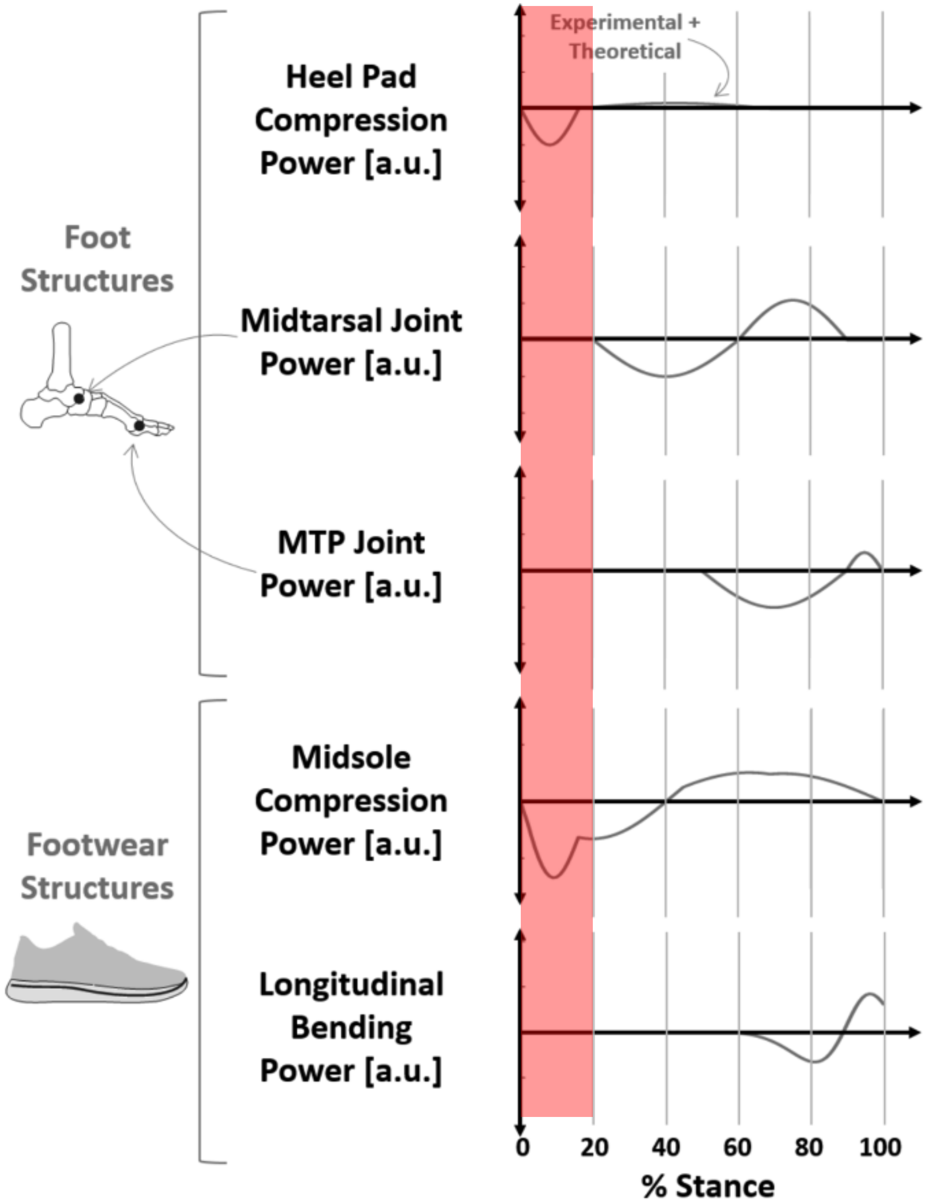
Understanding Advanced Footwear





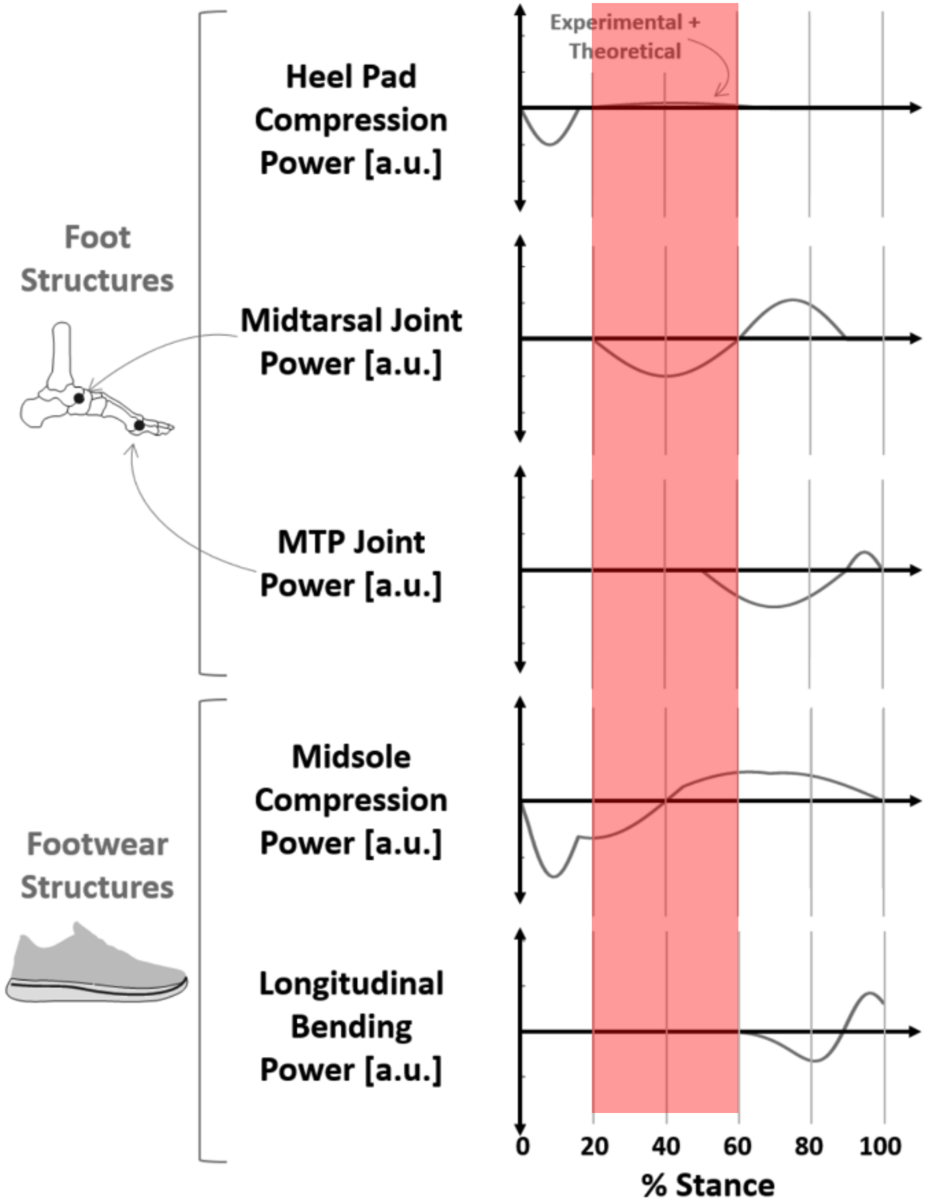
Matijevich et al. 2022

Understanding Advanced Footwear



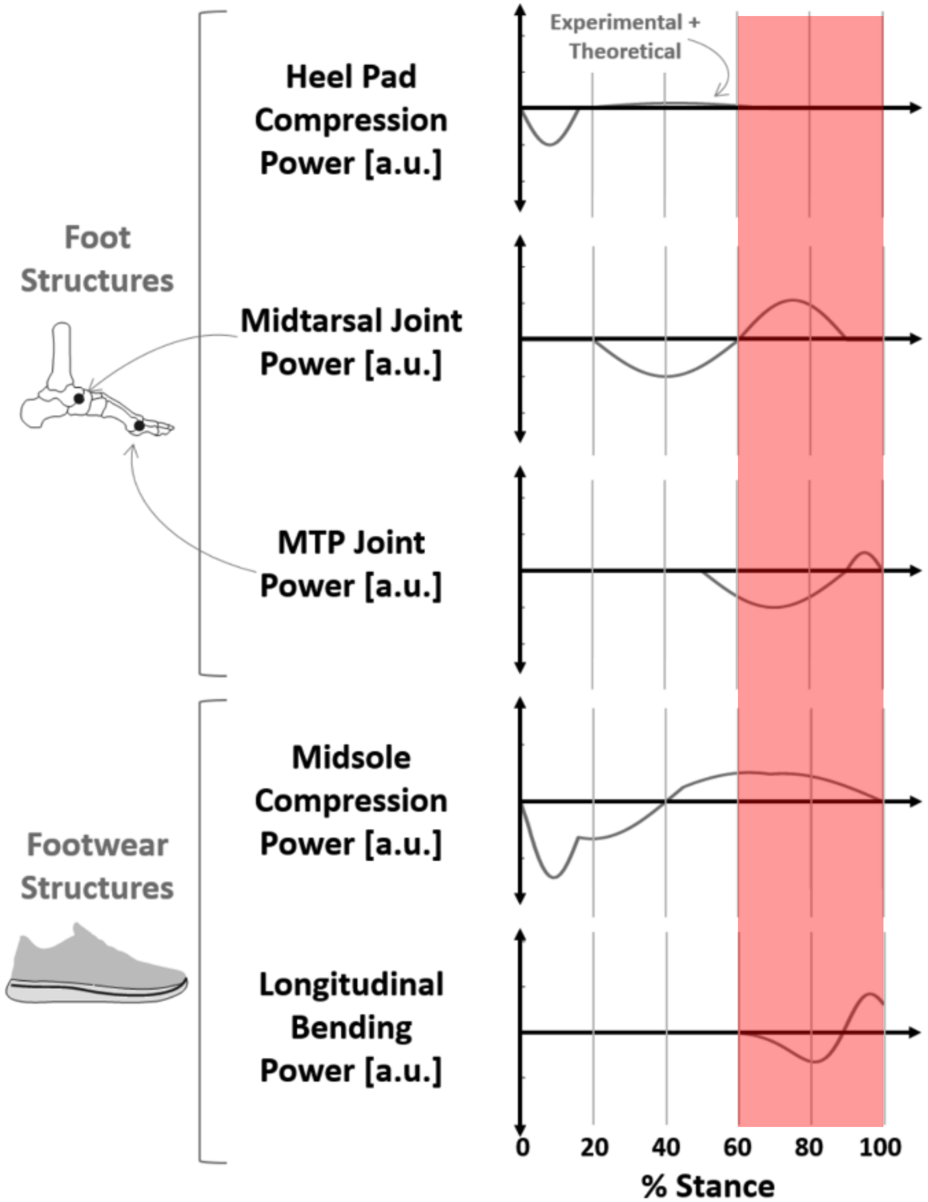
Matijevich et al. 2022

Understanding Advanced Footwear



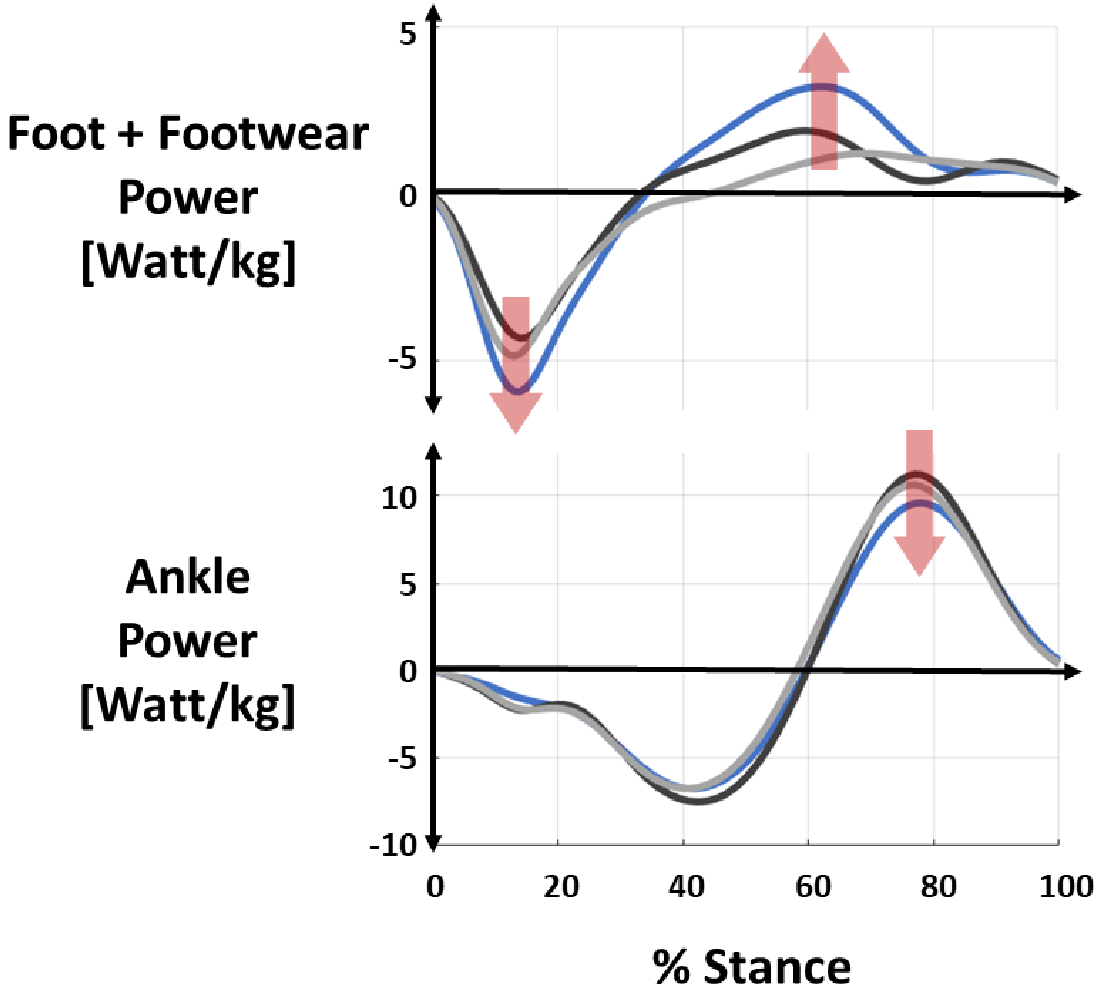
Matijevich et al. 2022

Understanding Advanced Footwear



Matijevich et al. 2022

Advanced Footwear: Offset Ankle Work

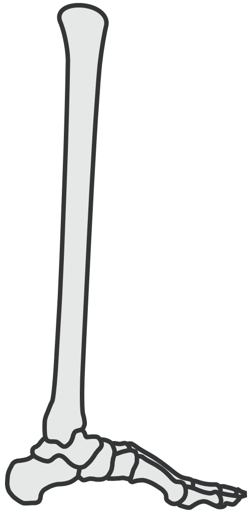


Matijevich et al. 2023, *In Review*

N=15

Methodology Applied to Different Segments

Combined Foot Power
(Distal Rearfoot)



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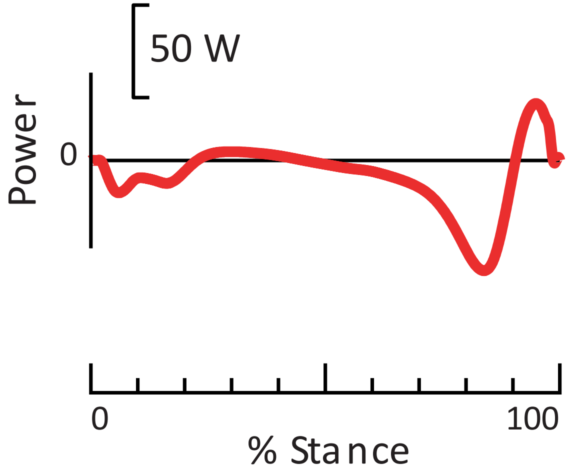

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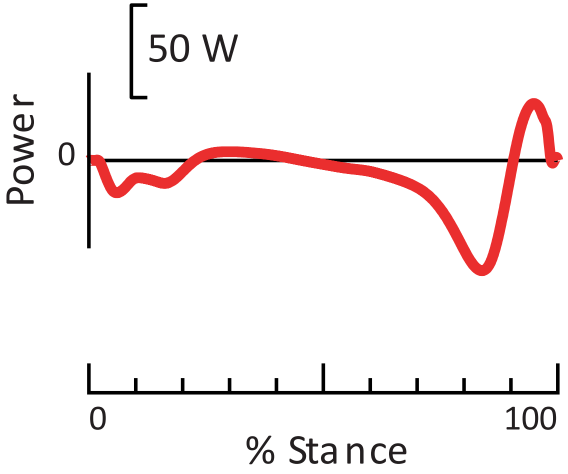
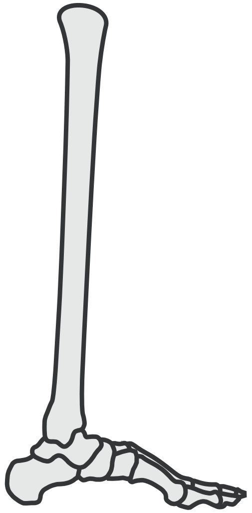


Ankle+Foot Power
(Distal Shank)



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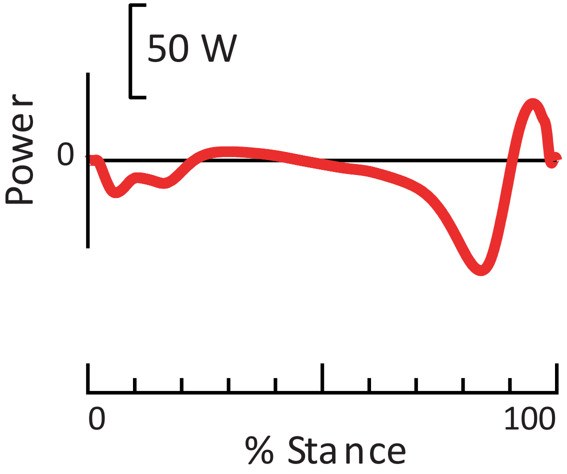

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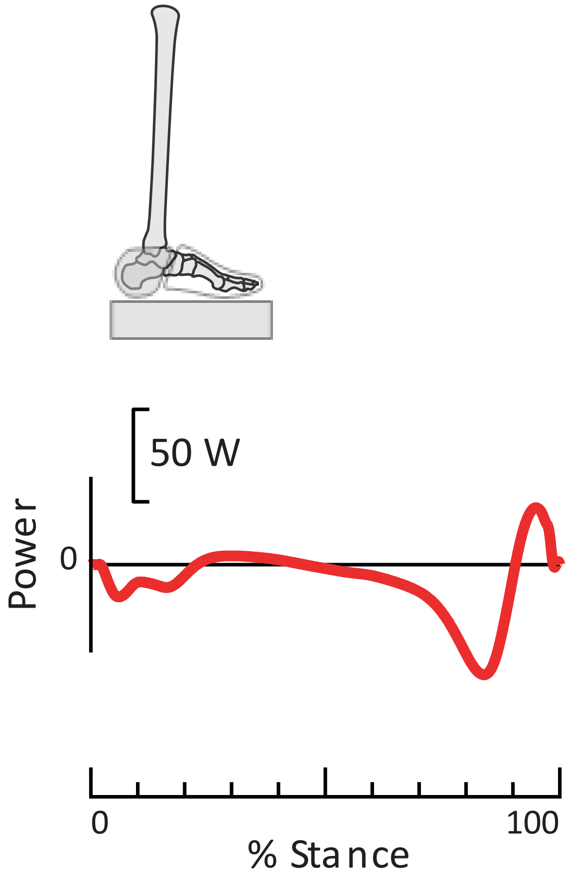

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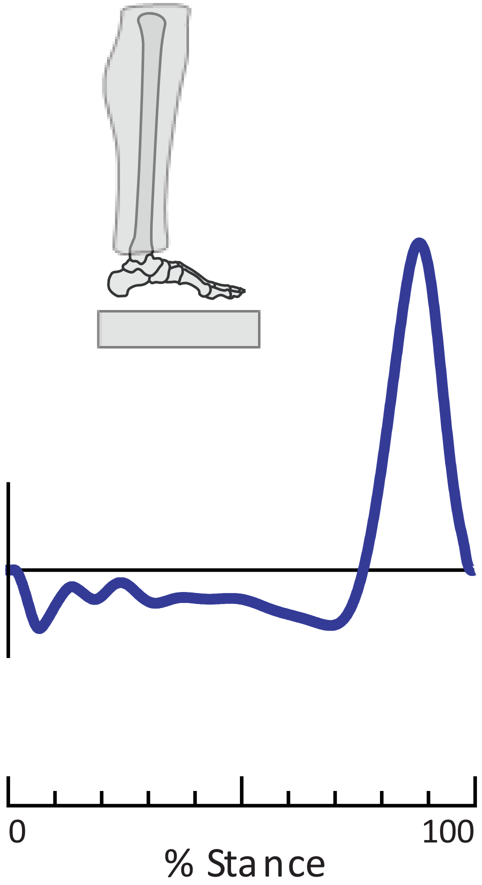
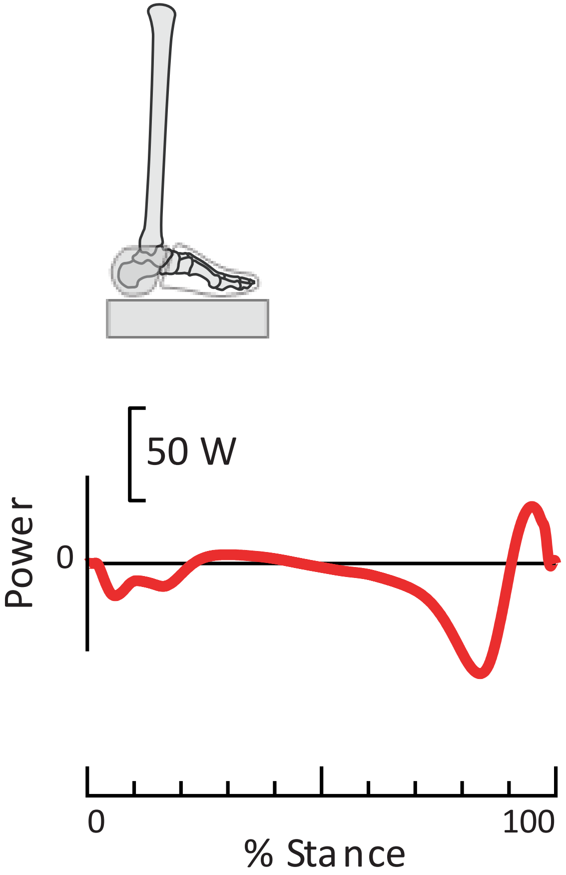


Same Methods: Prosthesis Contributions

Combined Foot Power
(Distal Rearfoot)



Ankle+Foot Power
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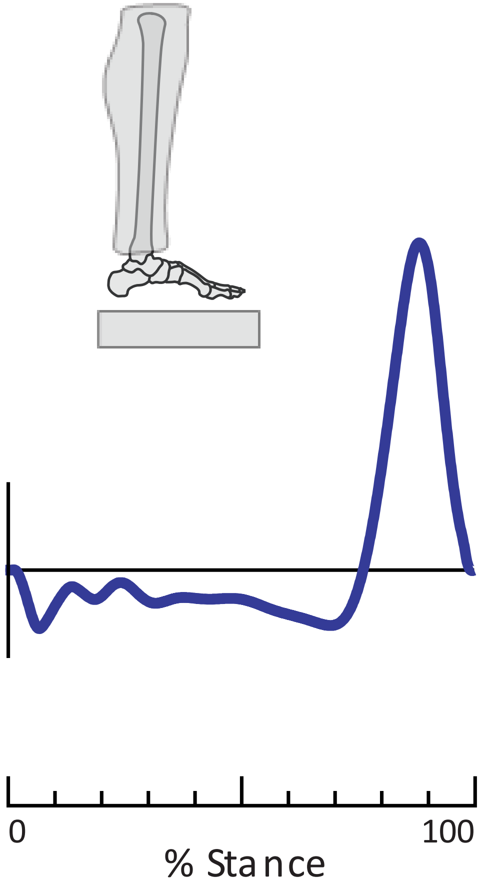
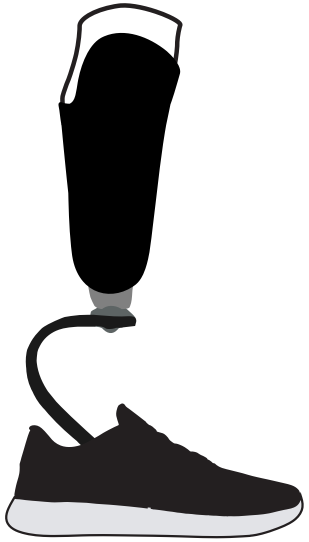


Prosthesis Power
(Distal Shank)



Same Methods: Prosthesis Contributions

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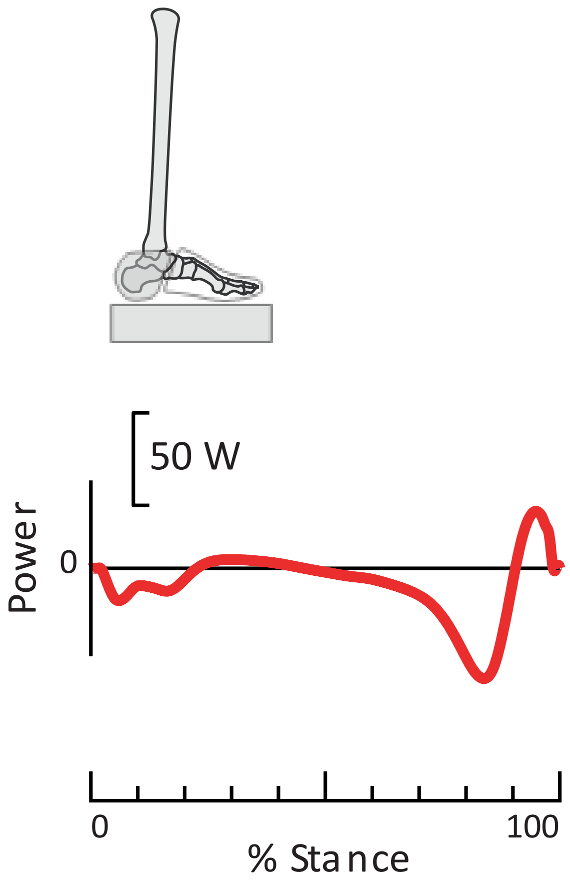

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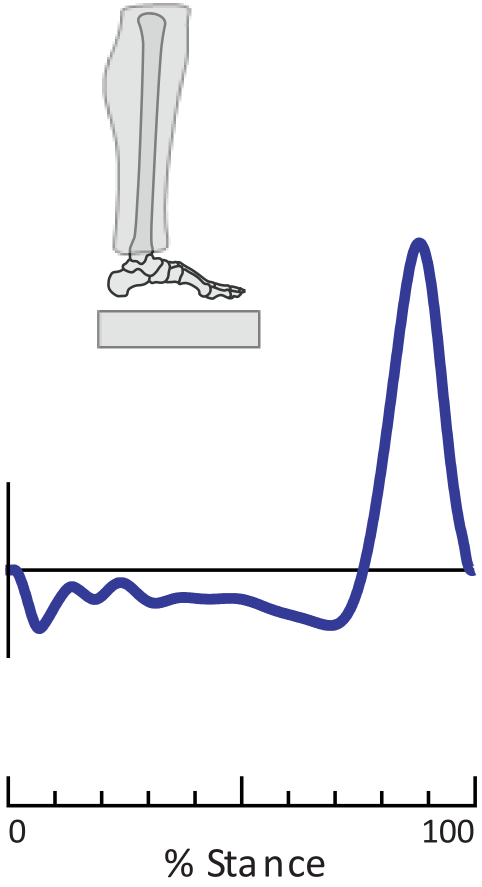

Prosthesis Power
(Distal Shank)

Same Methods: Prosthesis Contributions

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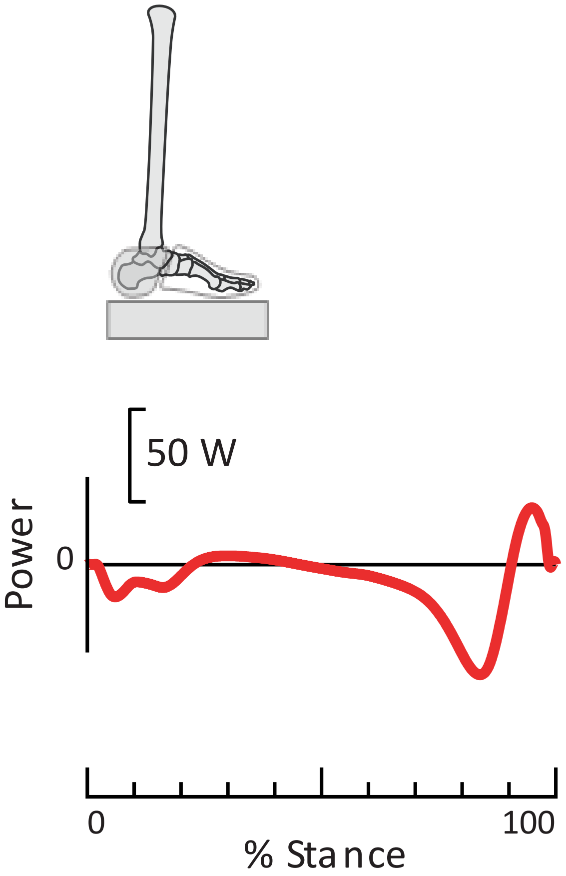

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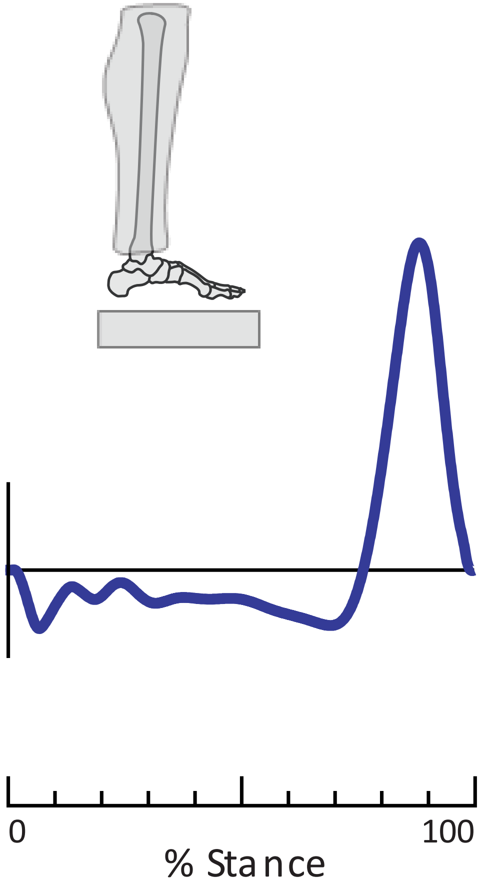

Prosthesis Power
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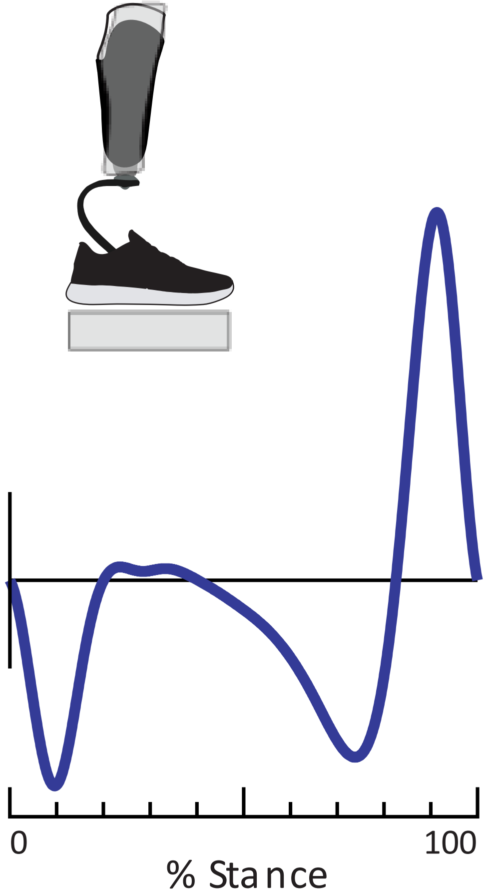
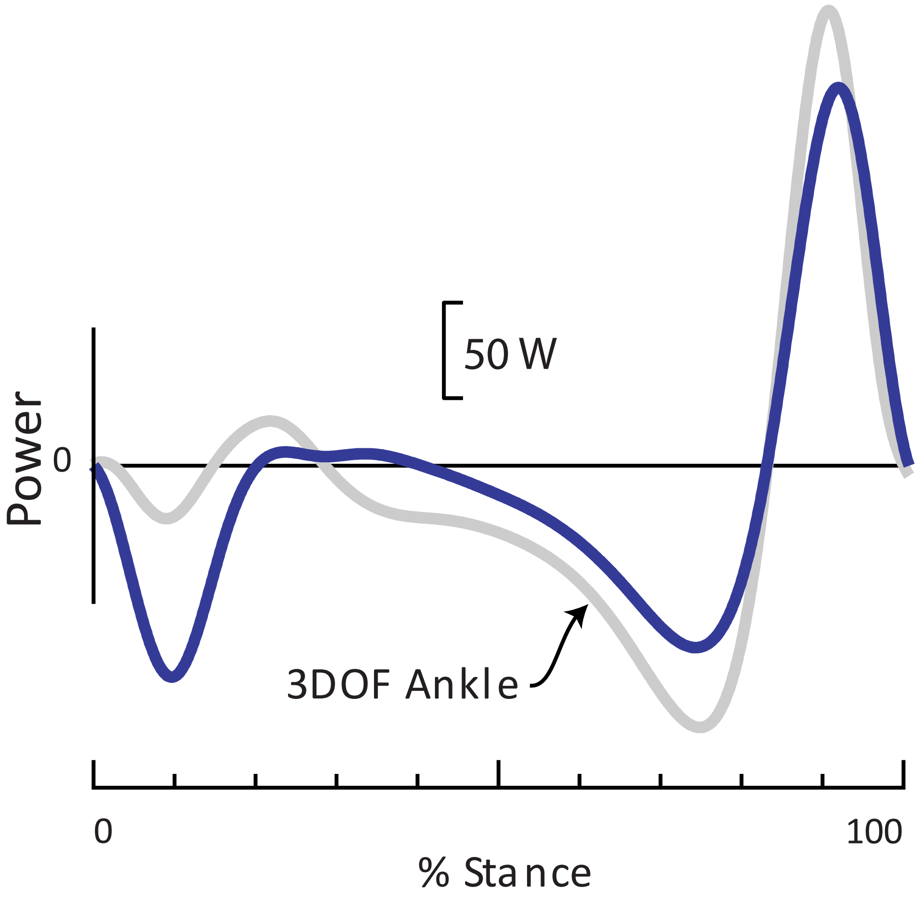
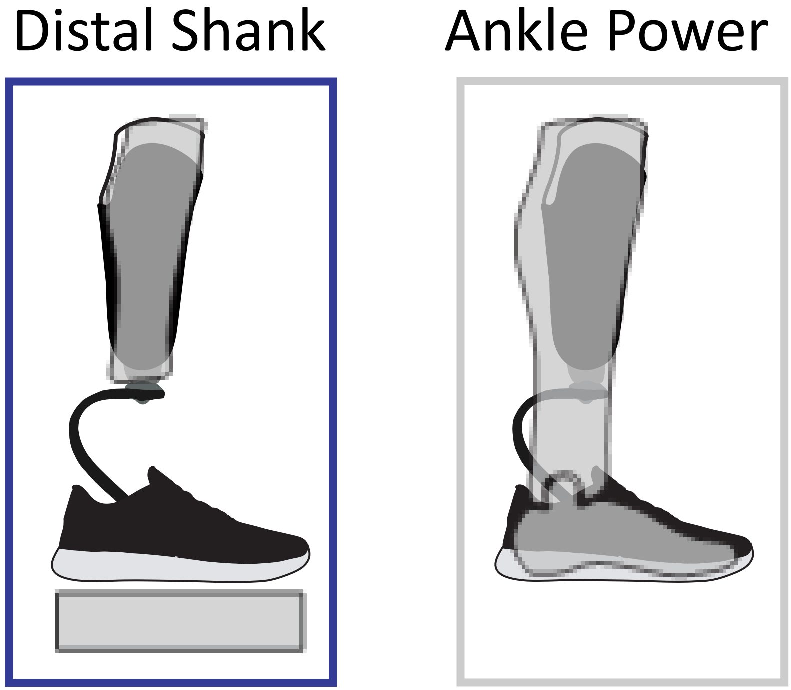


Comparison to "Traditional" Estimates

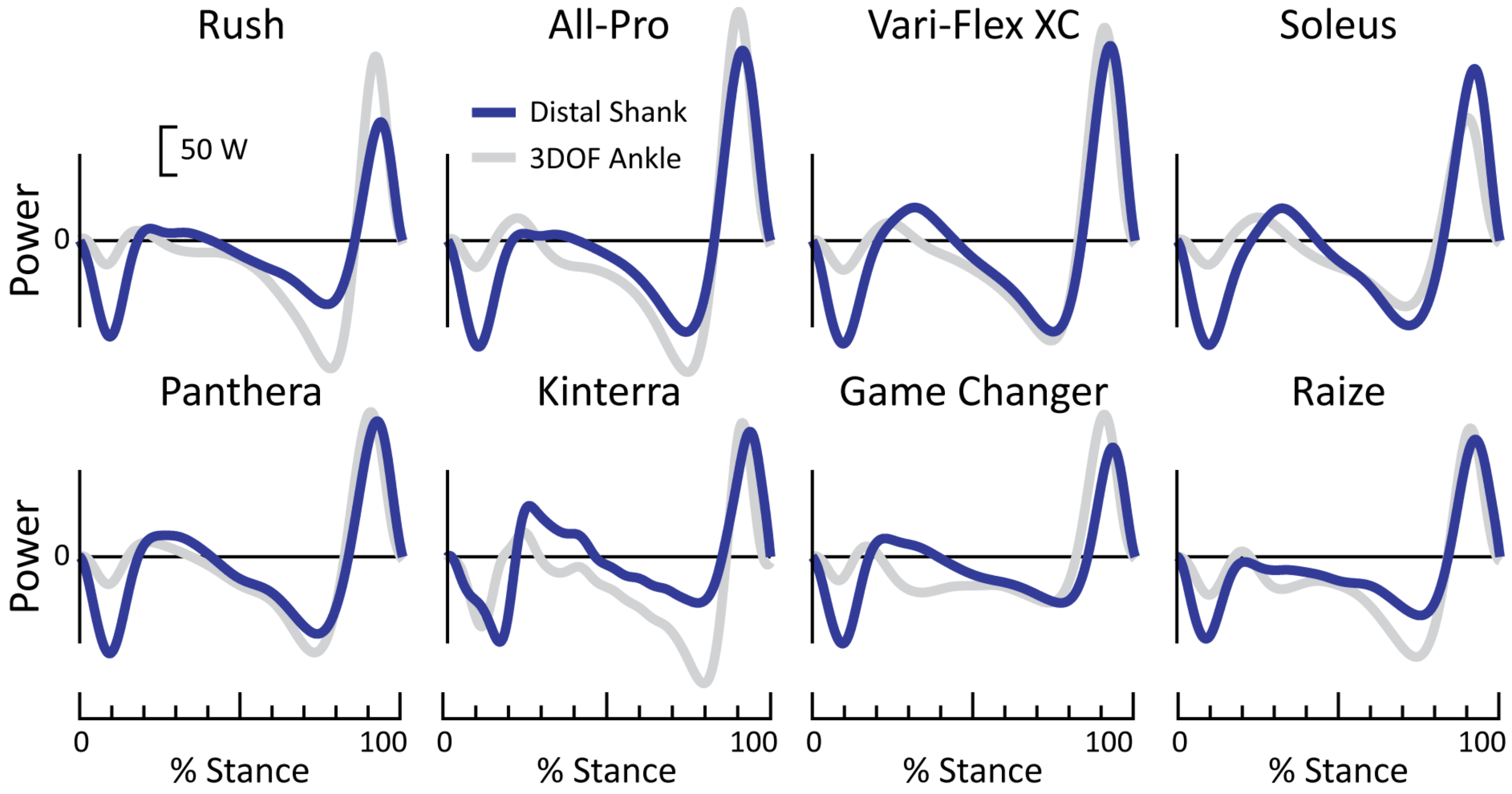




Zelik & Honert 2018

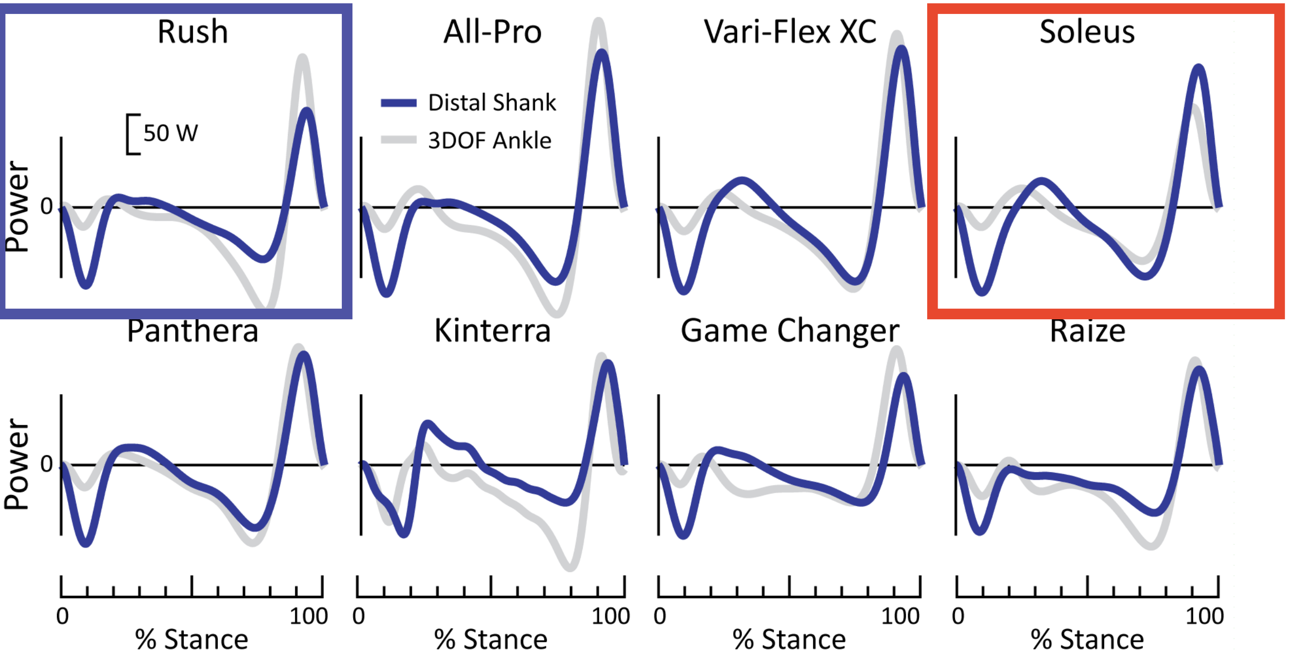
N=1

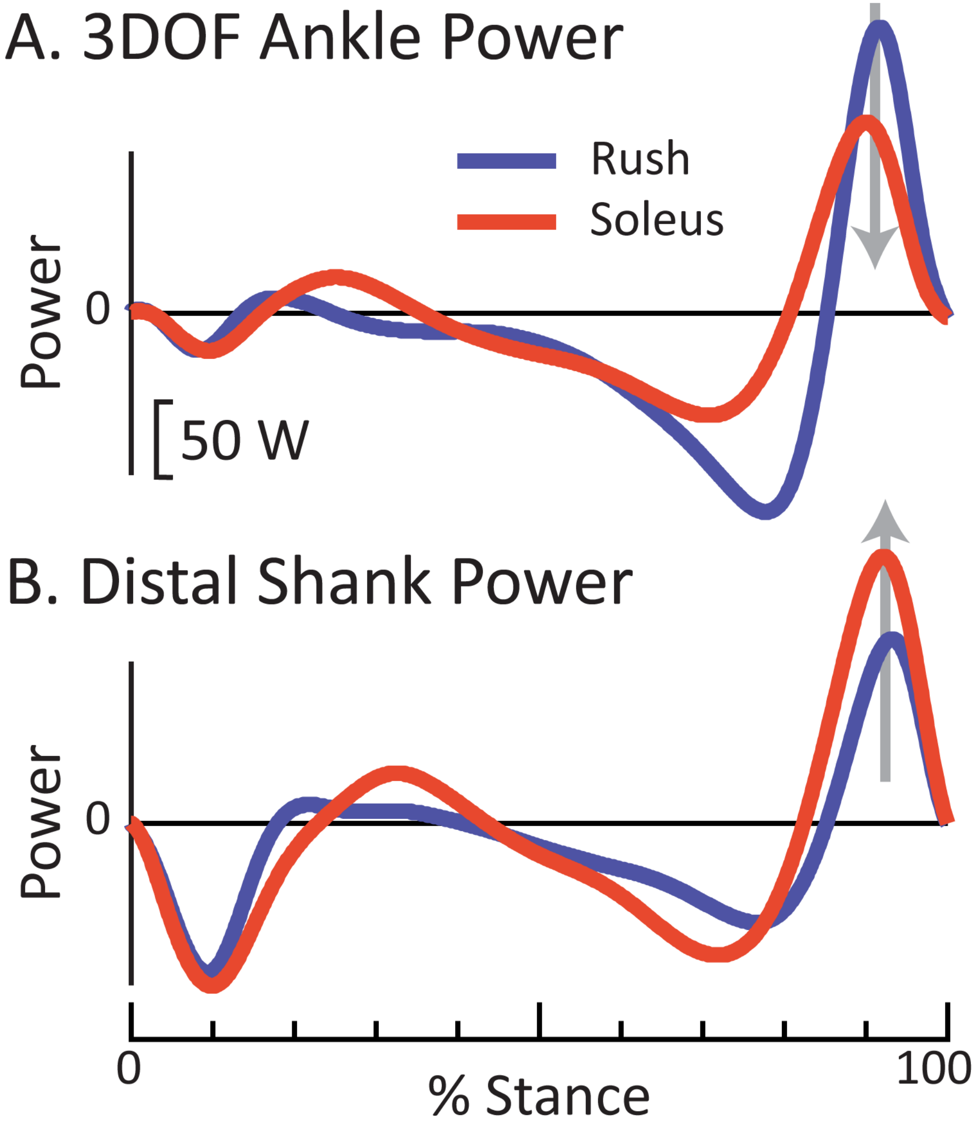
"Traditional" Methods can Mis-Estimate Prosthesis Contributions



Zelik & Honert 2018

…which may skew interpretations



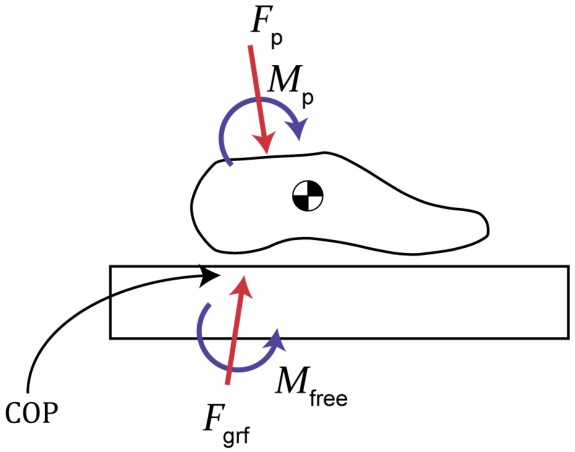

A. 3DOF Ankle Power

B. Distal Shank Power

Zelik & Honert 2018

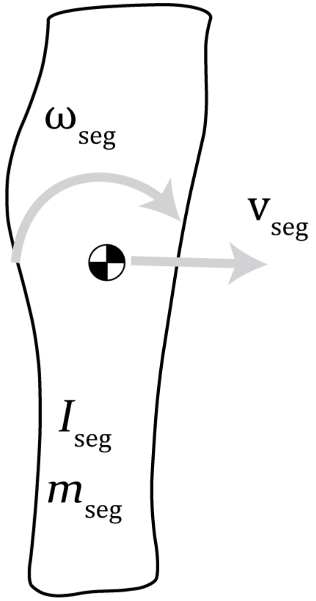
'Distal power' as an extension of segment power

(and a brief history of ‘power imbalance’ in biomechanics)



Segment power can be quantified in two ways:

1) Kinematic method:



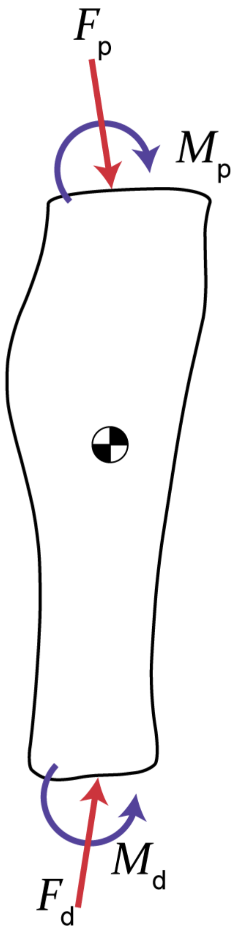
$$E_{seg} = \underbrace{\frac{1}{2}m\vec{v}^2 + \frac{1}{2}I\vec{\omega}^2}_{\text{Kinetic Energy}} + \underbrace{mgh}_{\text{Potential Energy}}$$

$$\dot{E}_{seg} = P_{seg}$$

(Rate of Energy Change = Segment Power)

Segment power can be quantified in two ways:

2) Kinetic method:



$$P_{seg} = \underbrace{\vec{M}_p \cdot \vec{\omega}_p + \vec{F}_p \cdot \vec{v}_p}_{\text{Proximal Seg. Terms}} + \underbrace{\vec{M}_d \cdot \vec{\omega}_d + \vec{F}_d \cdot \vec{v}_d}_{\text{Distal Seg. Terms}}$$

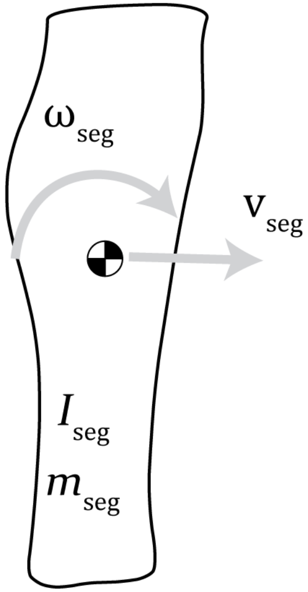
$\vec{M}$ & $\vec{F}$: (from inverse dynamics)

$\vec{v}$ & $\vec{\omega}$: (from MoCap)

In theory, these two methods should match…

(i.e., power balance)

Kinematics method



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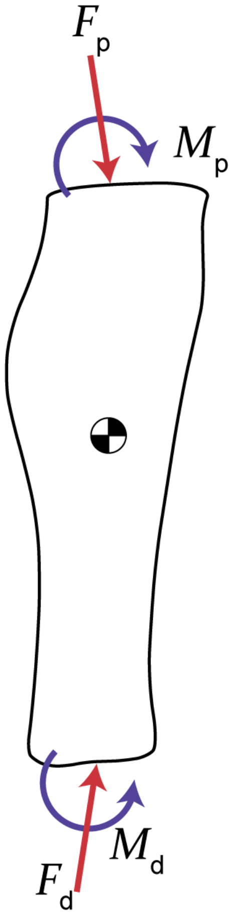
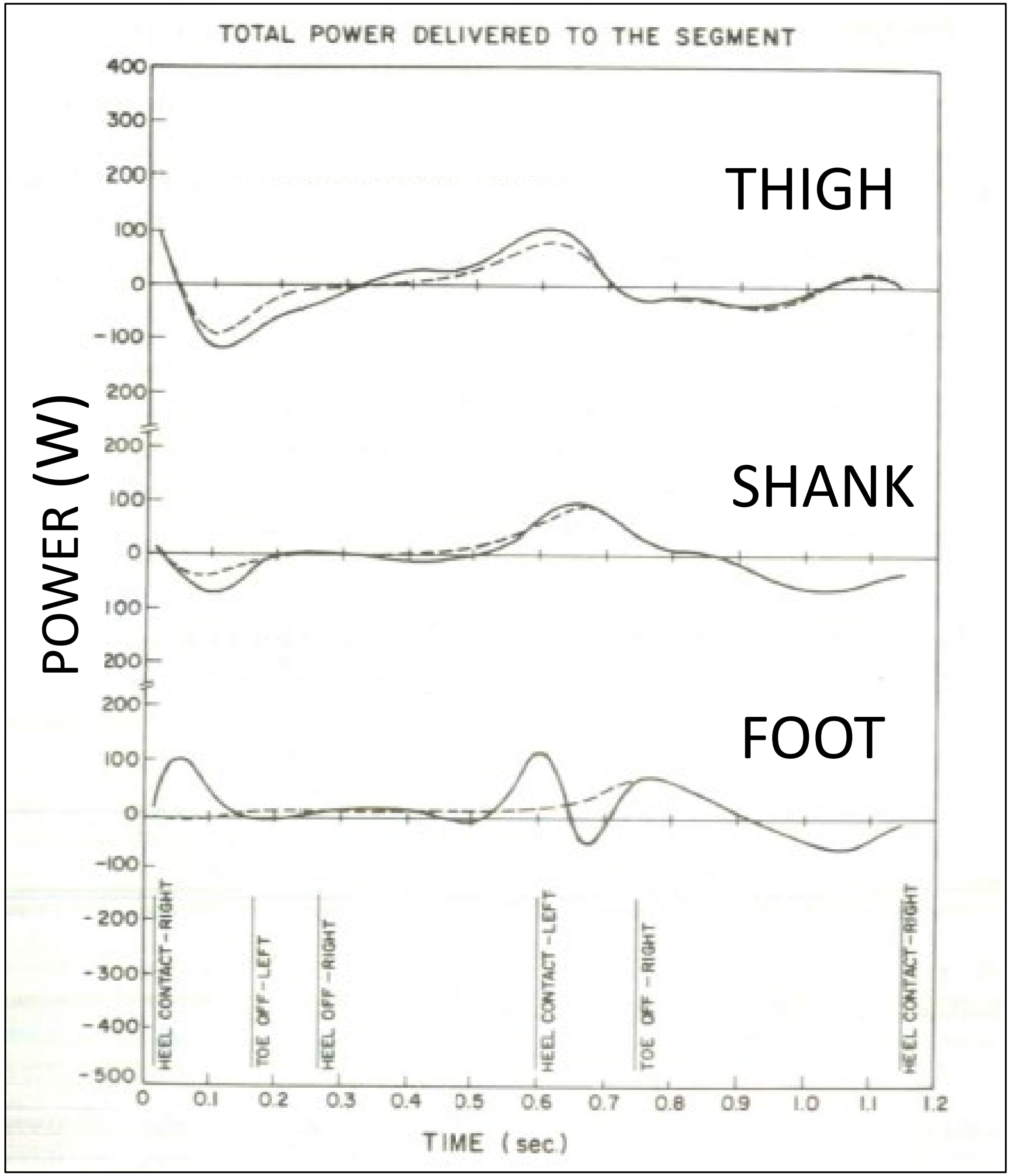
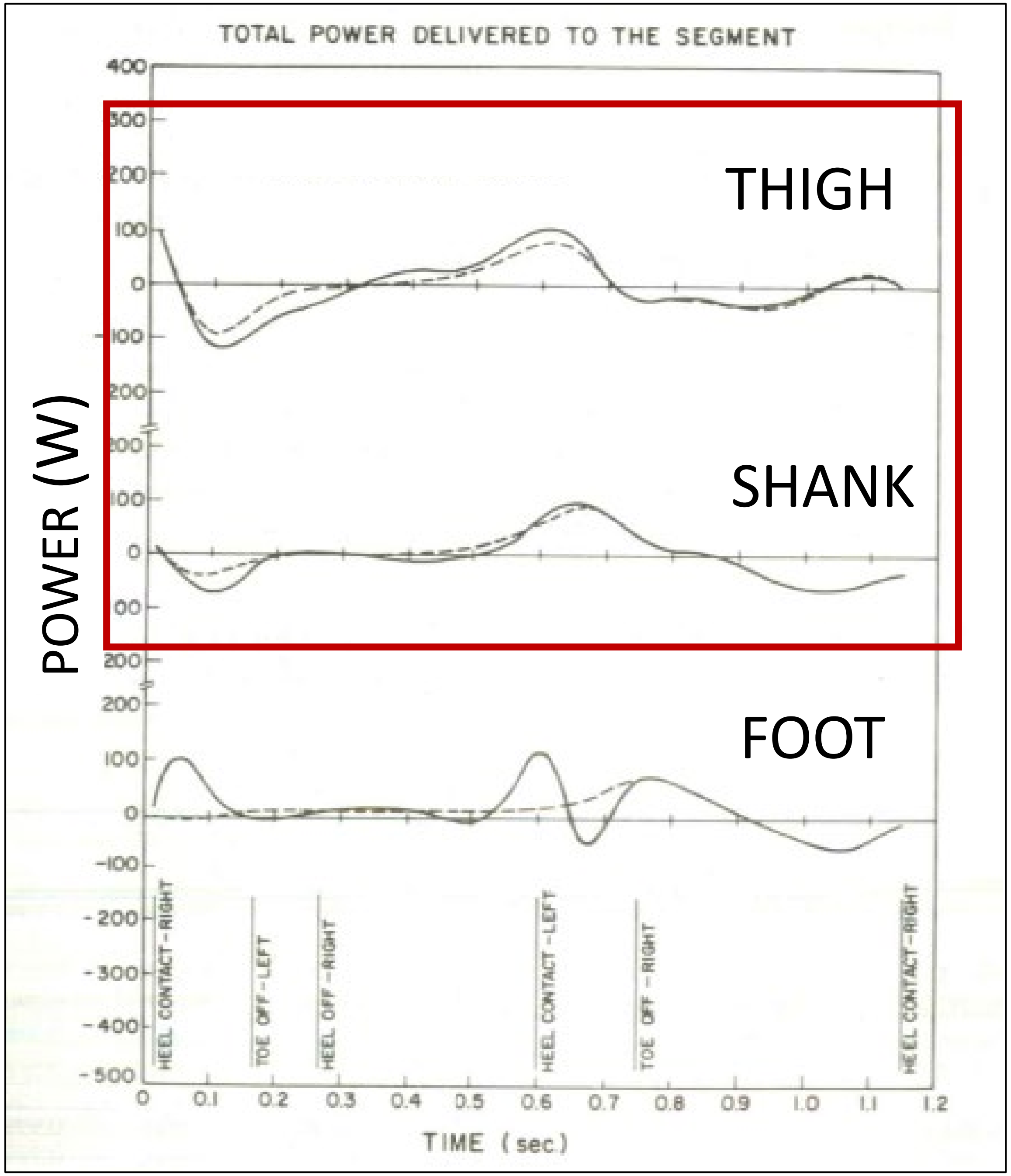


Kinetics method

$$\dot{E}_{seg} = P_{seg}$$



Robertson DG and Winter DA, 1980
Journal of Biomechanics

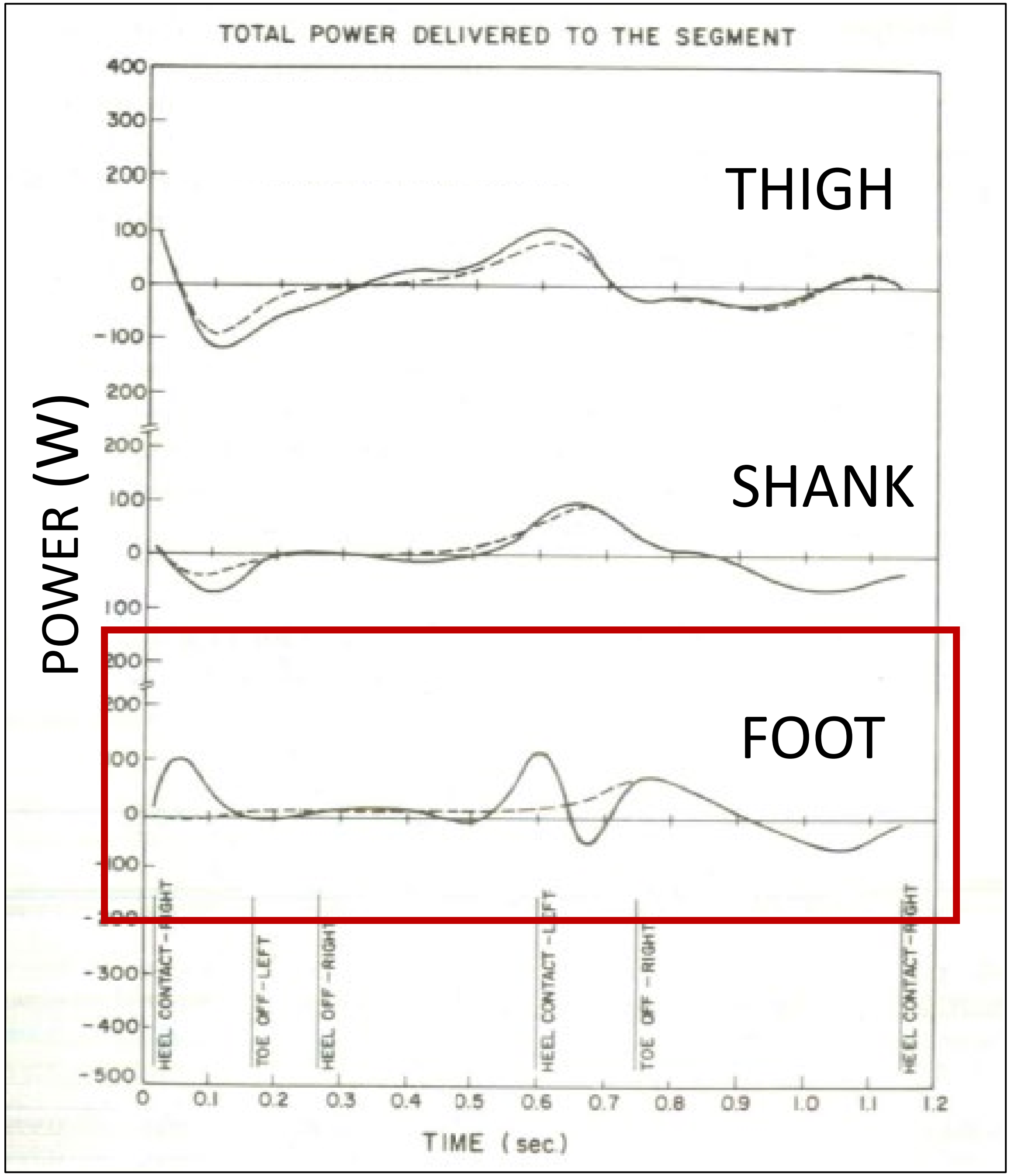


- - - - Kinematic method

—— Kinetic method

Good agreement at the thigh and shank

Robertson DG and Winter DA, 1980
Journal of Biomechanics



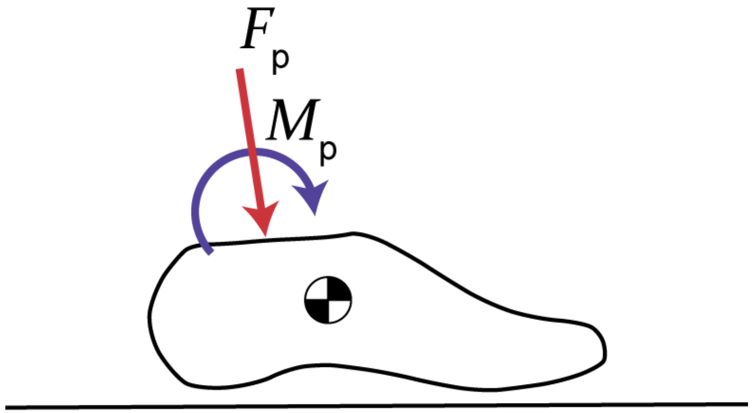
- - - Kinematic method

—— Kinetic method

‘Power imbalance’ at the foot!

Robertson DG and Winter DA, 1980
Journal of Biomechanics

Imbalance due to lack of ‘distal power’ terms at the foot



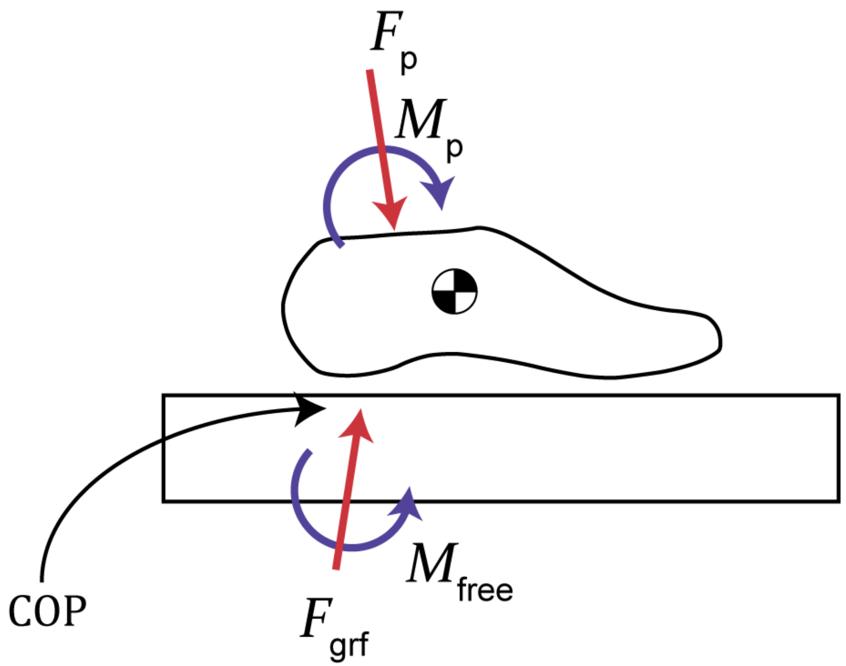
Assumptions:

The foot is rigid & foot did not slip….

- Distal velocity ($\vec{v}_d$)= 0
- Distal power = 0

Siegel KL et al, 1996
Journal of Biomechanics

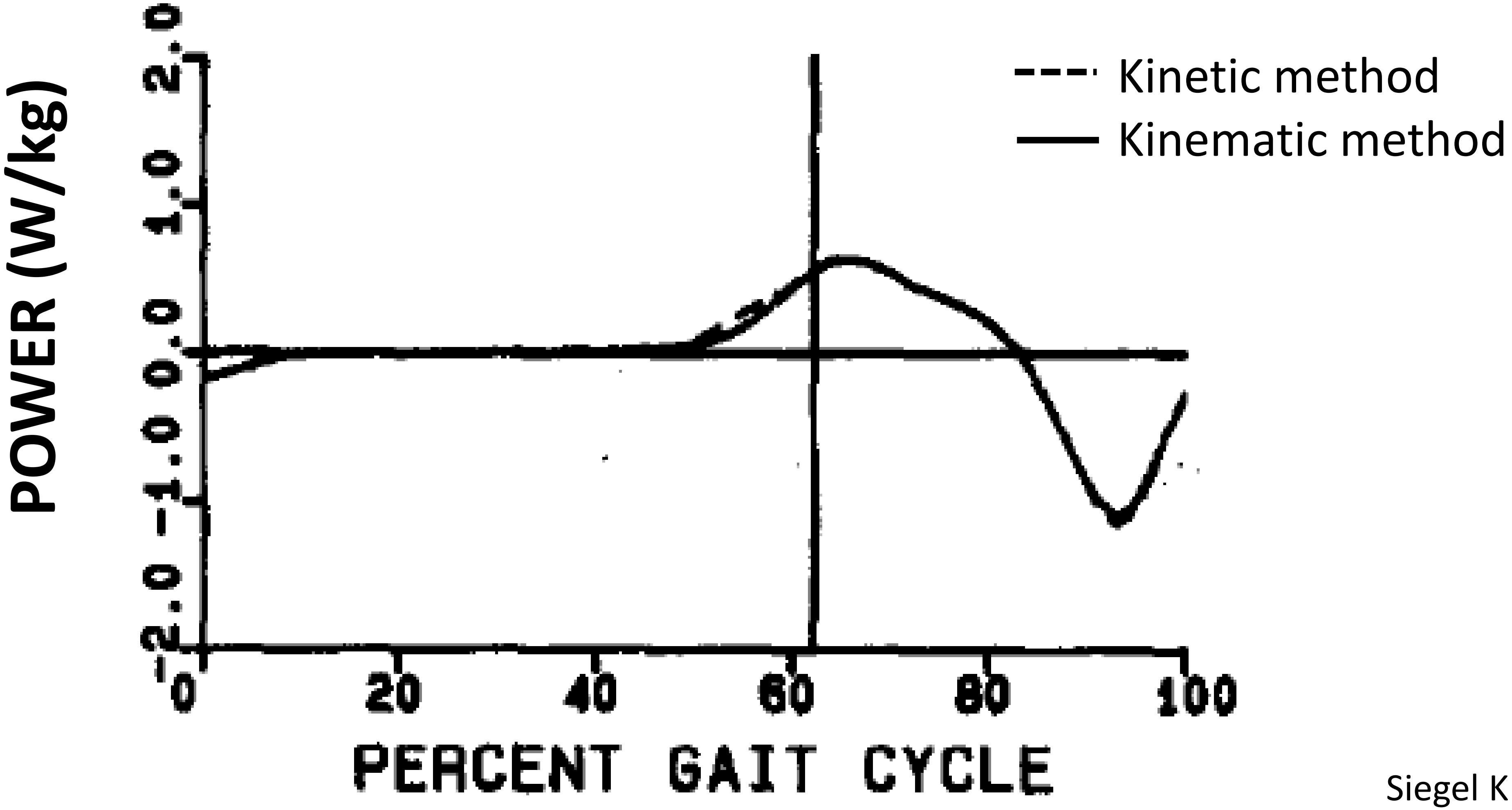
Adding 'distal' terms achieves power balance at the foot



$$\underbrace{\vec{F}_d = \vec{F}_{grf} \qquad \vec{M}_d = \vec{M}_{free}}_{\text{from Force Plates}}$$

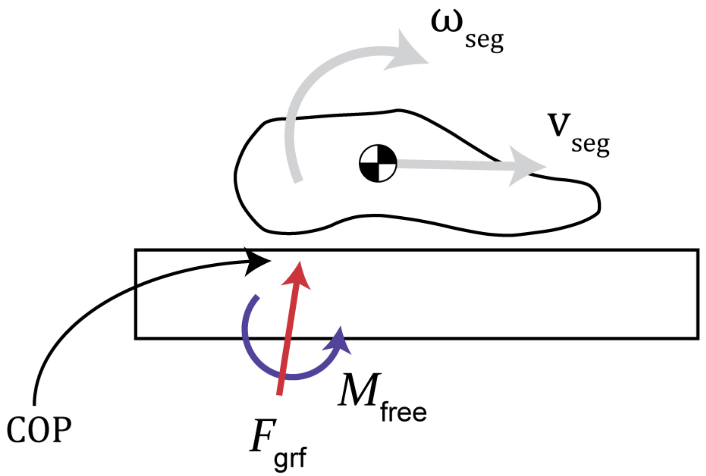
Siegel KL et al, 1996
Journal of Biomechanics

Adding ‘distal’ terms achieves power balance at the foot



Siegel KL et al, 1996
Journal of Biomechanics

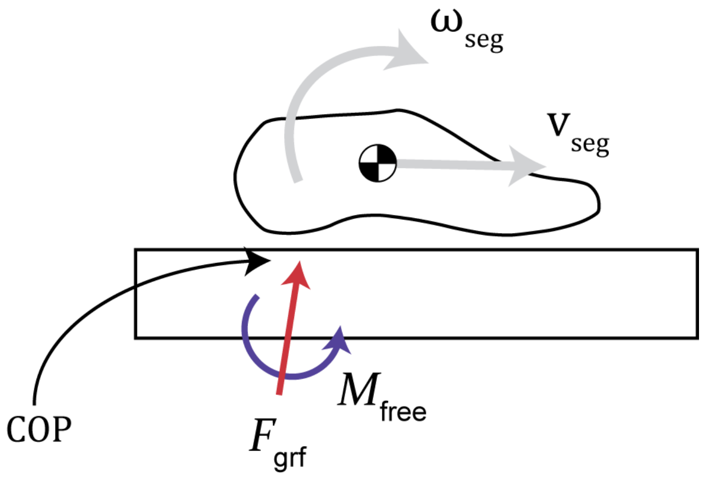
So, what exactly is this 'distal power' ($\boldsymbol{P_{dist}}$)?



$$\boldsymbol{P_{dist}} = \underbrace{\overrightarrow{\boldsymbol{F}}_{\boldsymbol{grf}} \cdot \overrightarrow{\boldsymbol{v}}_{\boldsymbol{dist}}}_{} + \underbrace{\overrightarrow{\boldsymbol{M}}_{\boldsymbol{free}} \cdot \overrightarrow{\boldsymbol{\omega}}_{\boldsymbol{seg}}}_{\text{This term is so small… we can ignore for now}}$$

This term is so small…
we can ignore for now

So, what exactly is this 'distal power’ ($\boldsymbol{P_{dist}}$)?

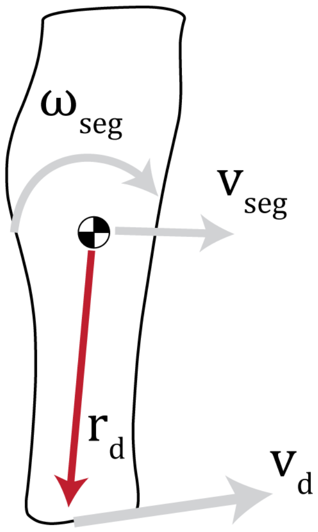


$$P_{dist} = \vec{F}_{grf} \cdot \vec{v}_{dist} + \xcancel{\vec{M}_{free} \cdot \vec{\omega}_{seg}}$$

$$\vec{v}_{dist} = \vec{v}_{seg} + \left(\vec{\omega}_{seg} \times \vec{r}_{dist}\right)$$

Consider a <u>rigid body segment</u> translating and rotating in space…

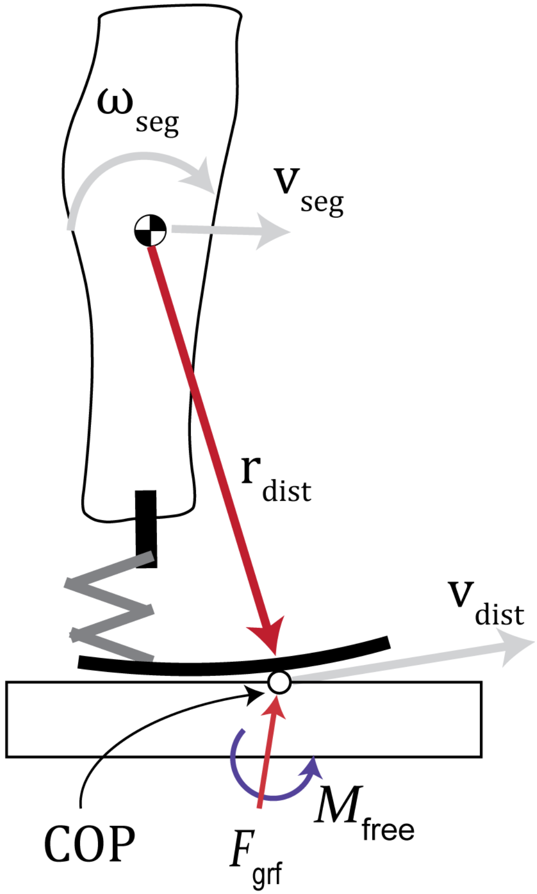
Segment endpoint velocity ($\vec{v}_d$):



$$\vec{v}_d = \vec{v}_{seg} + \left(\vec{\omega}_{seg} \times \vec{r}_d\right)$$

* $\vec{r}_d$ will be a constant for a rigid body

Now, a rigid body segment with a deforming distal component…



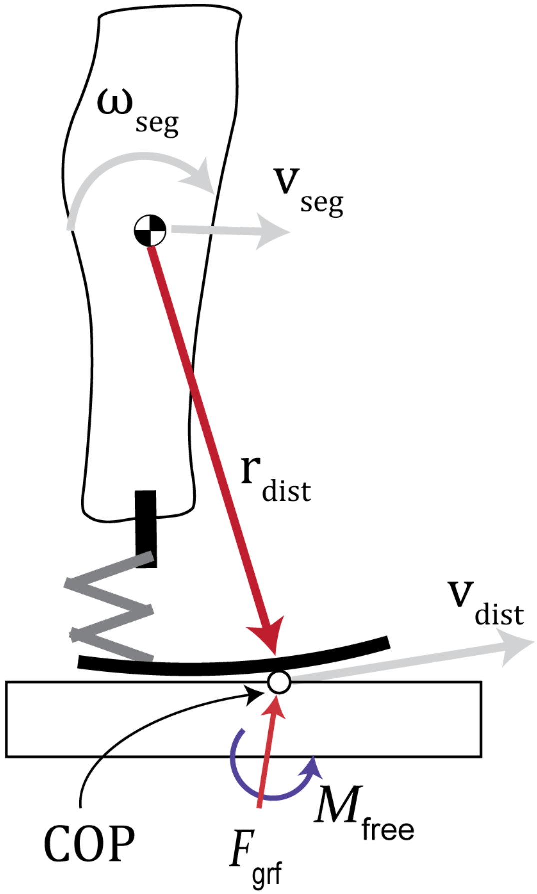
‘Distal’ velocity ($\vec{v}_{dist}$):

$$\vec{v}_{dist} = \vec{v}_{seg} + (\vec{\omega}_{seg} \times \vec{r}_{dist})$$

($\vec{r}_{dist}$ - displacement of COP relative to COM)

* $\vec{r}_{dist}$ is a non-constant value

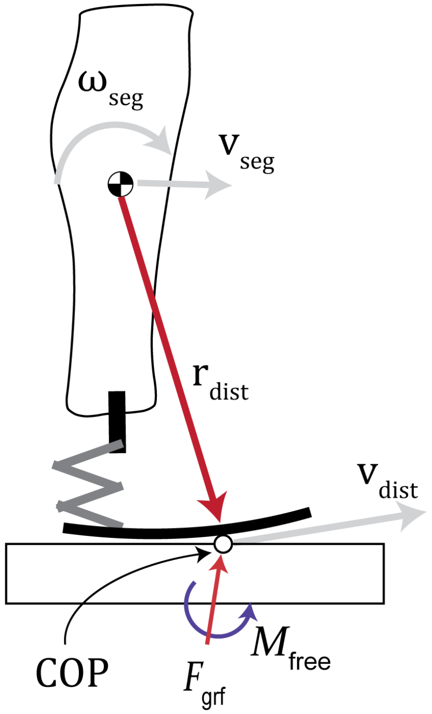
Now, a rigid body segment with a deforming distal component…



$$\vec{v}_{dist} = \vec{v}_{seg} + (\vec{\omega}_{seg} \times \vec{r}_{dist})$$

$$P_{dist} = \underbrace{\vec{F}_{grf} \cdot \vec{v}_{dist}} + \cancel{\vec{M}_{free} \cdot \vec{\omega}_{seg}}$$

Force and 'distal velocity'
(or 'net deformation')

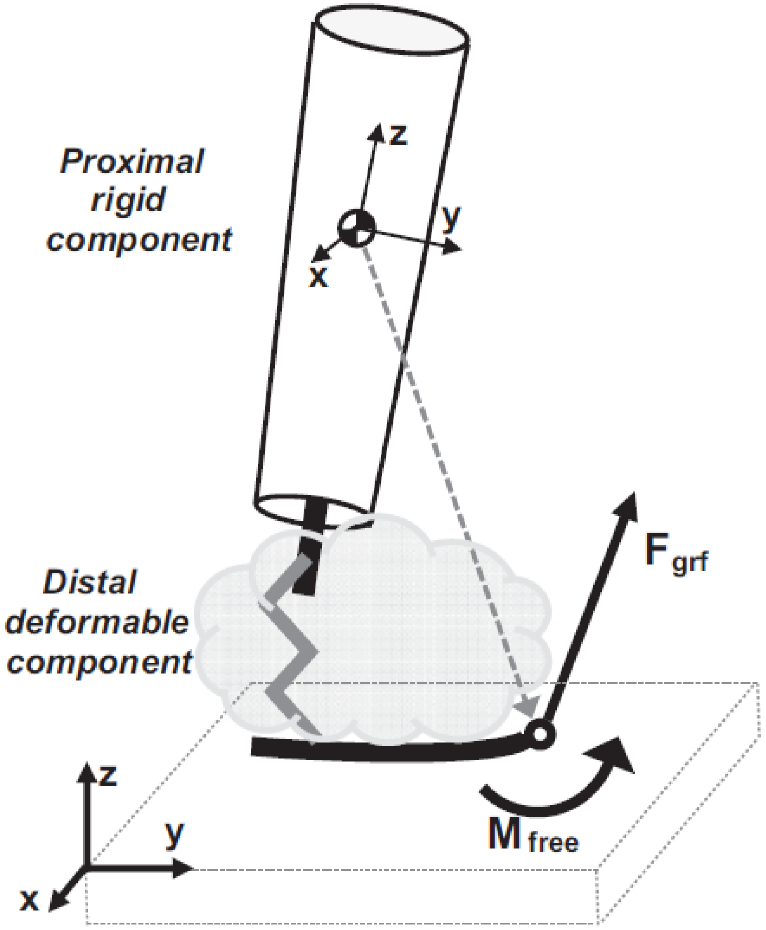


$$P_{dist} = \underbrace{\vec{F}_{grf} \cdot \vec{v}_{dist}}_{\substack{\textit{Force and 'distal velocity'} \\ \textit{(or 'net deformation')}}} + \xcancel{\vec{M}_{free} \cdot \vec{\omega}_{seg}}$$

Generalized equation that can be applied to different segments

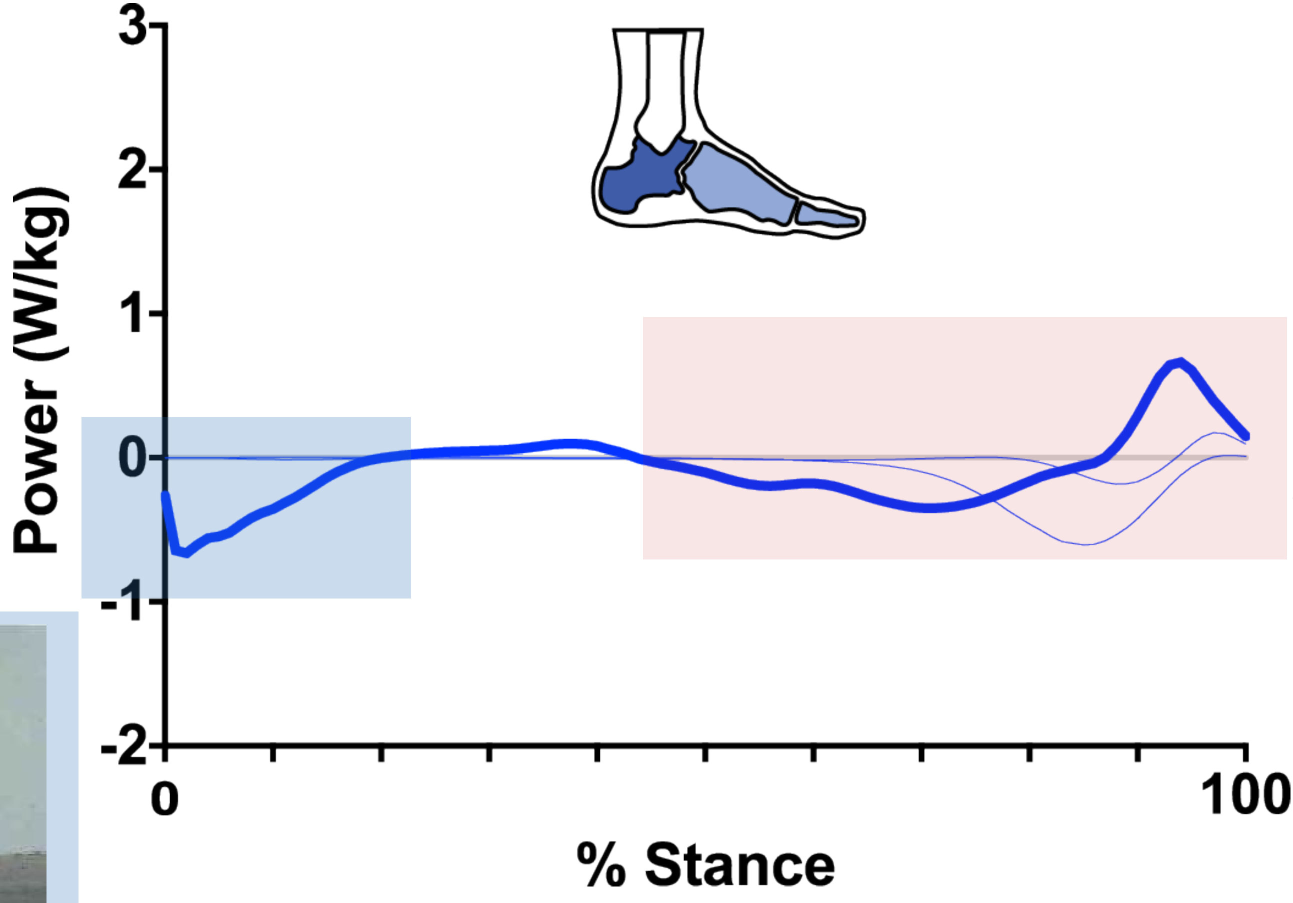
- Summed effects of all structures distal to a chosen segment
- No need to define ‘joint’ centers
- Inertial parameters not needed

Unified Deformable (UD) Segment Power



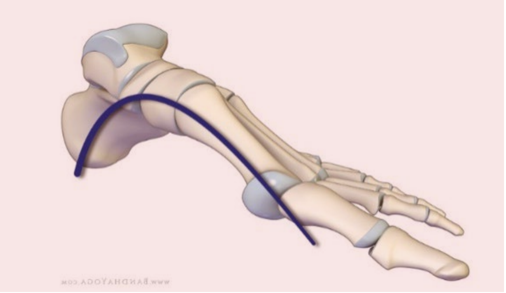
Takahashi, Kepple, Stanhope, 2012 Journal of Biomechanics

Hindfoot (i.e., entire foot)

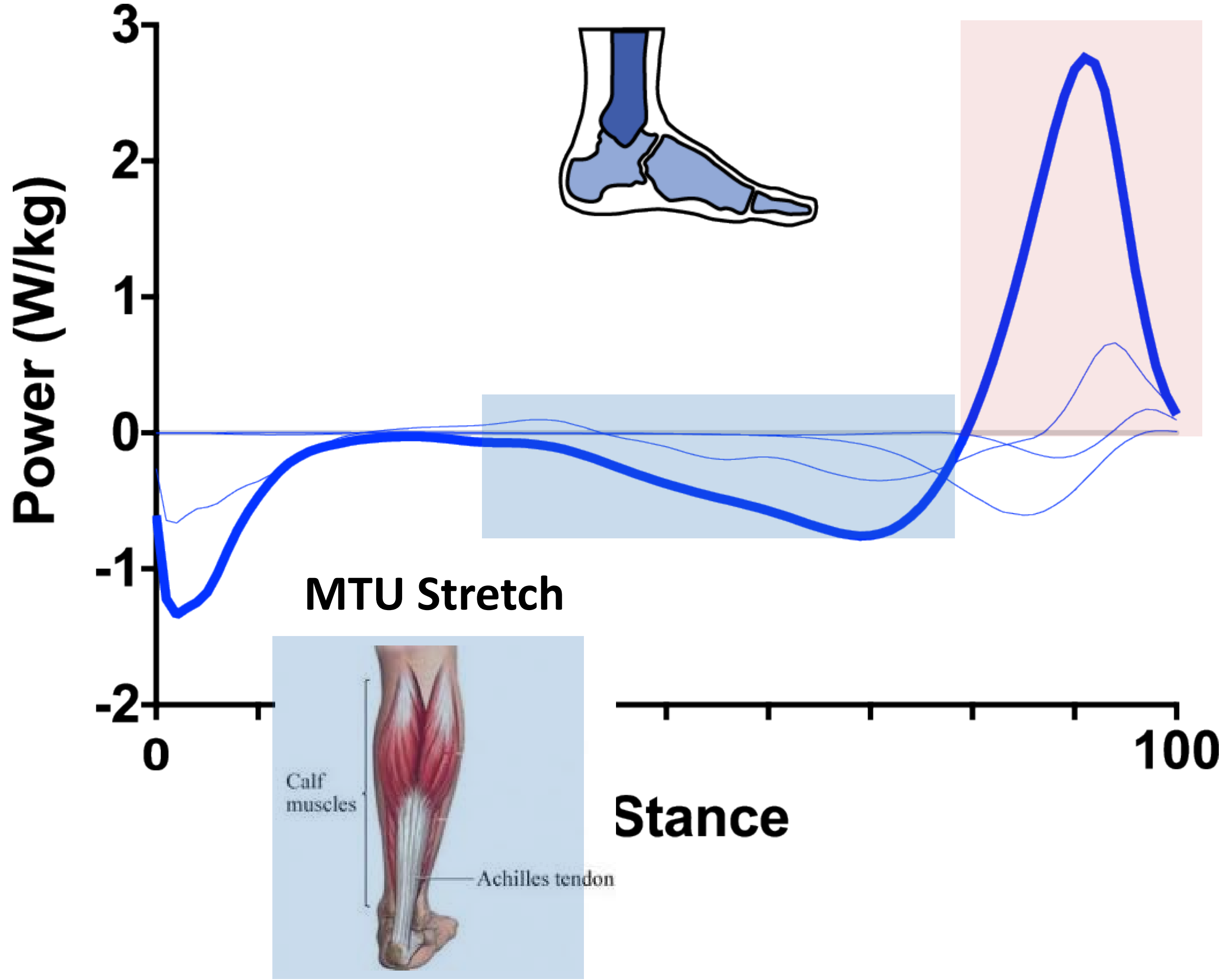


Heel Pad

Arch Energy Storage & Return
and/or Active Muscles

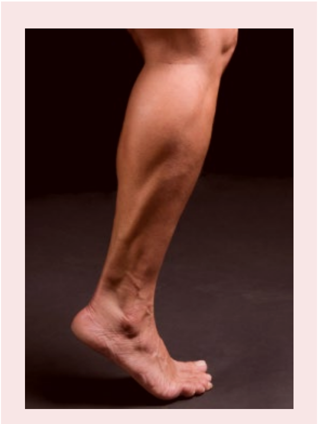


Shank (i.e., ankle+foot)

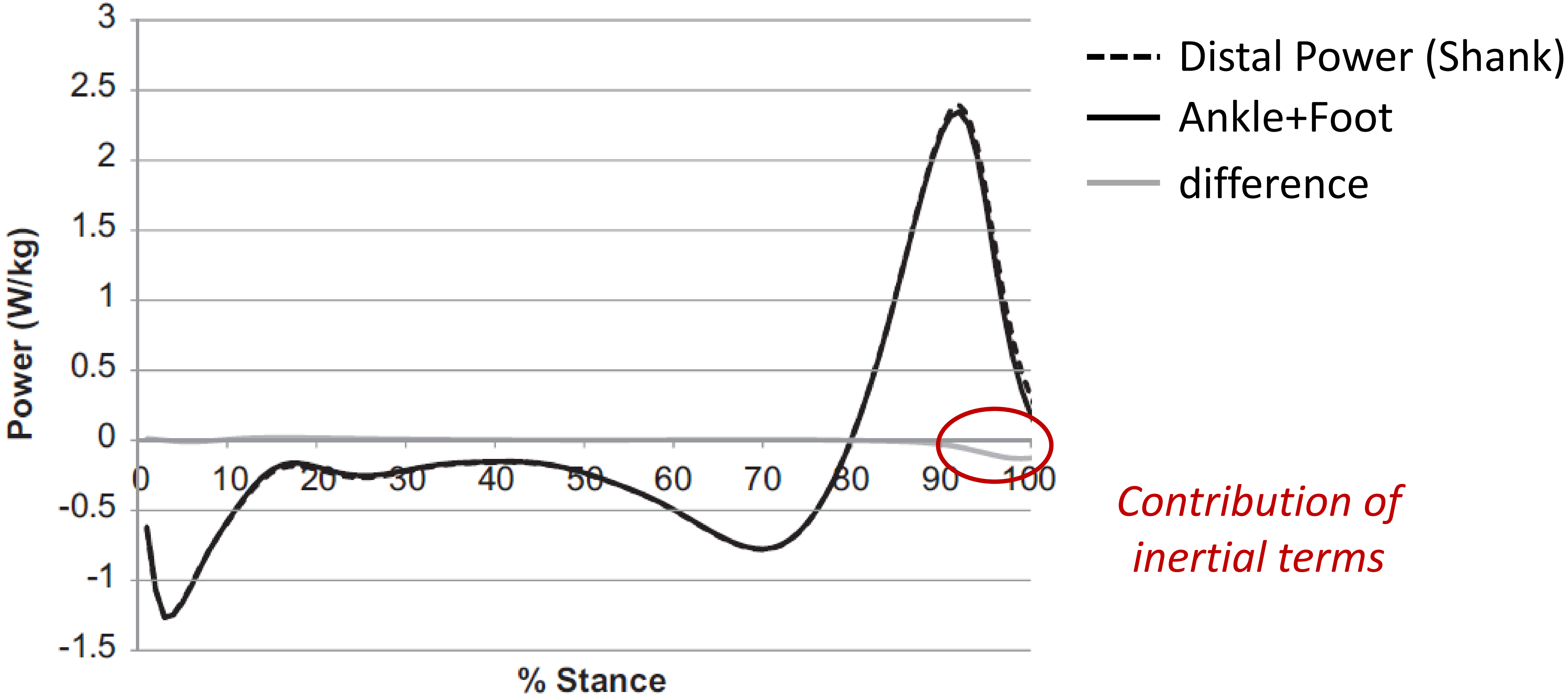


MTU Stretch

Ankle Plantar Flexion



Distal power (at shank) is nearly equal to ‘ankle+foot’ power



Contribution of inertial terms

Takahashi KZ, Kepple TM, Stanhope SJ 2012, Journal of Biomechanics

Limitations of ‘distal power’ method

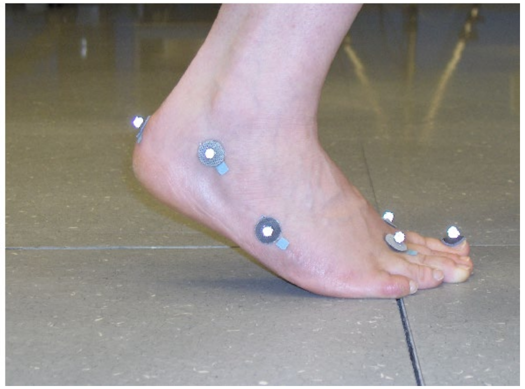
Misses inertial contributions

- Swing phase = 0
- Errors propagate when applying to proximal segments

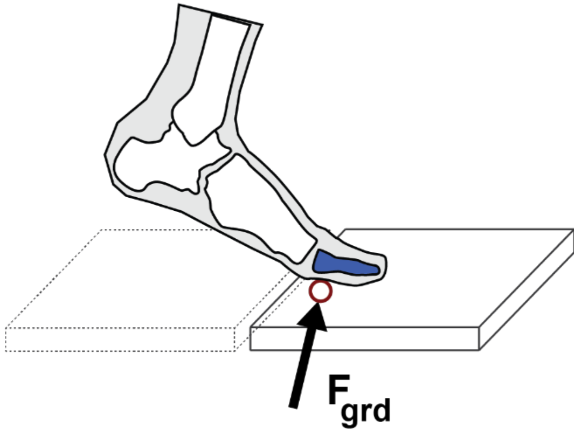
Sums the effects of all distal structures

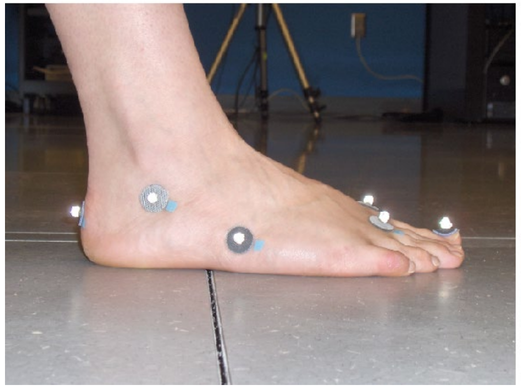
- Cannot partition contributions of isolated structures (without additional techniques)

Partitioning power from isolated regions

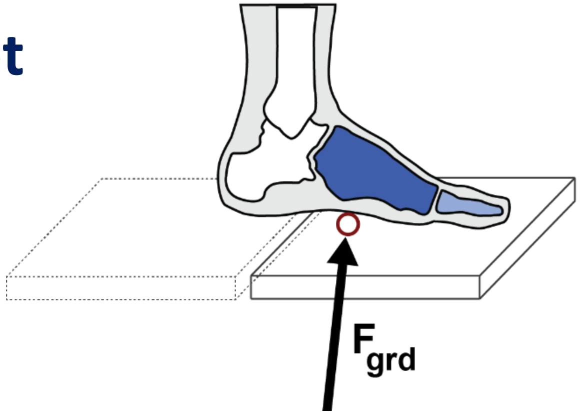


Isolate Hallux





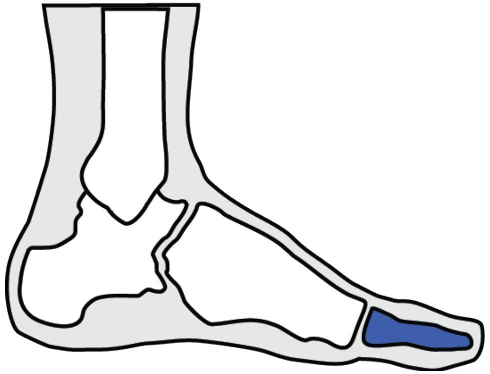
Isolate Forefoot



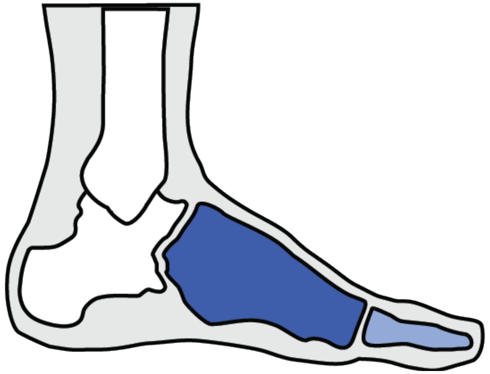
[Takahashi KZ, Worster K, Bruening DA 2017 Scientific Reports; Bruening DA and Takahashi KZ 2018 Gait & Posture]

Partitioning power from isolated regions

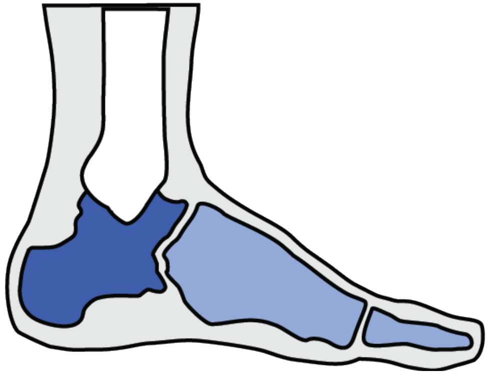
distal → *proximal*



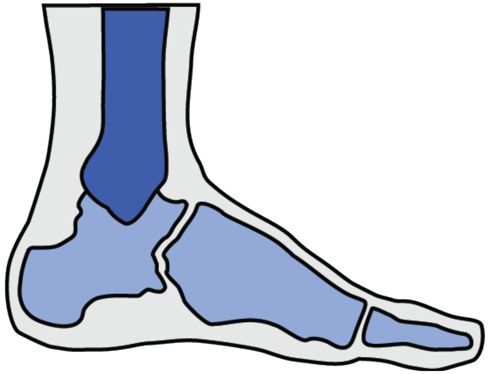
Hallux



Forefoot
(+ distal structures)

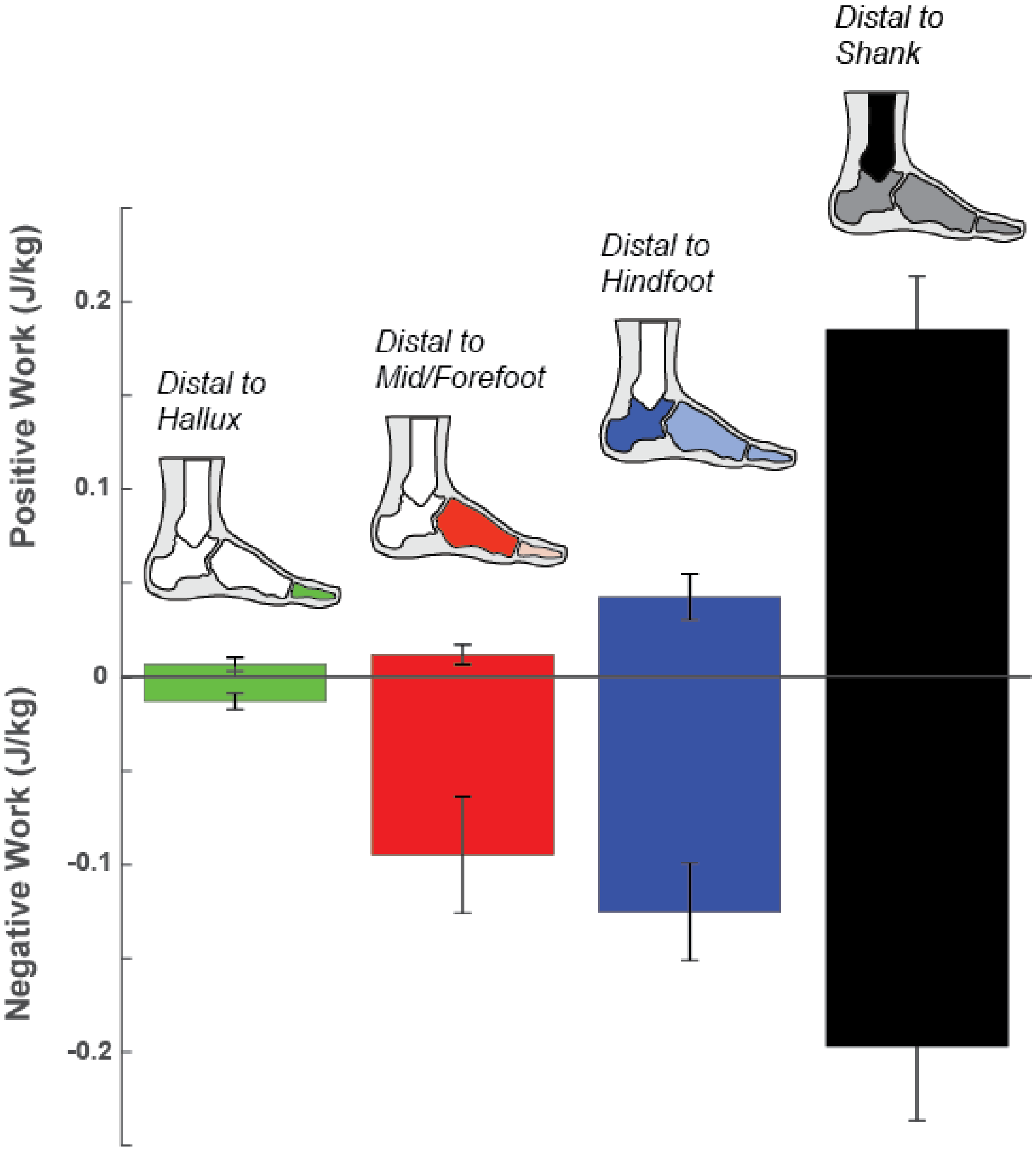


Hindfoot
(+ distal structures)

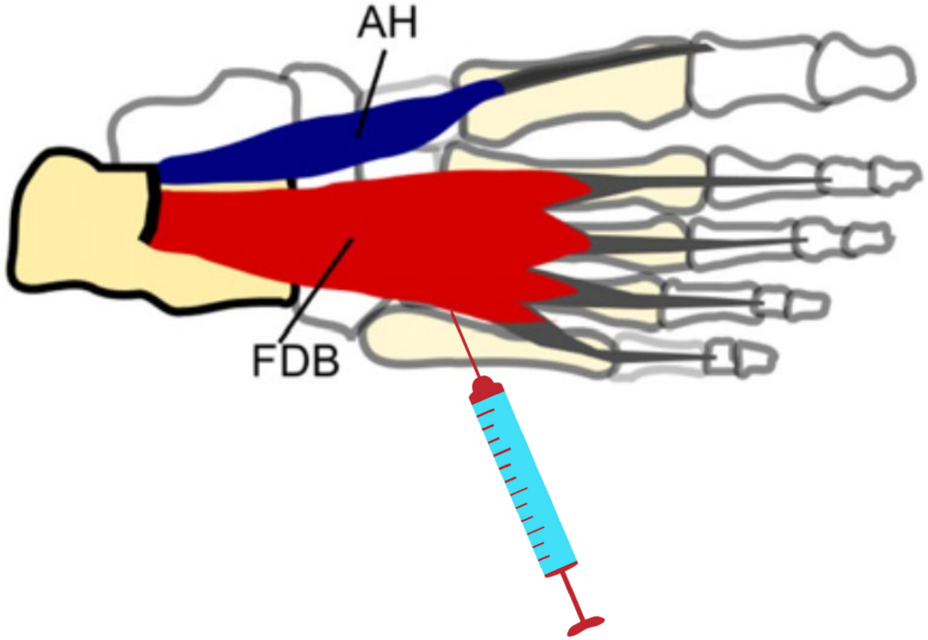


Shank
(+ distal structures)

Takahashi KZ, Worster K, Bruening DA, Scientific Reports, 2017


Distal to Hallux
Distal to Mid/Forefoot
Distal to Hindfoot
Distal to Shank
Positive Work (J/kg)
Negative Work (J/kg)
0.2
0.1
0
-0.1
-0.2

Isolating role of intrinsic foot muscles

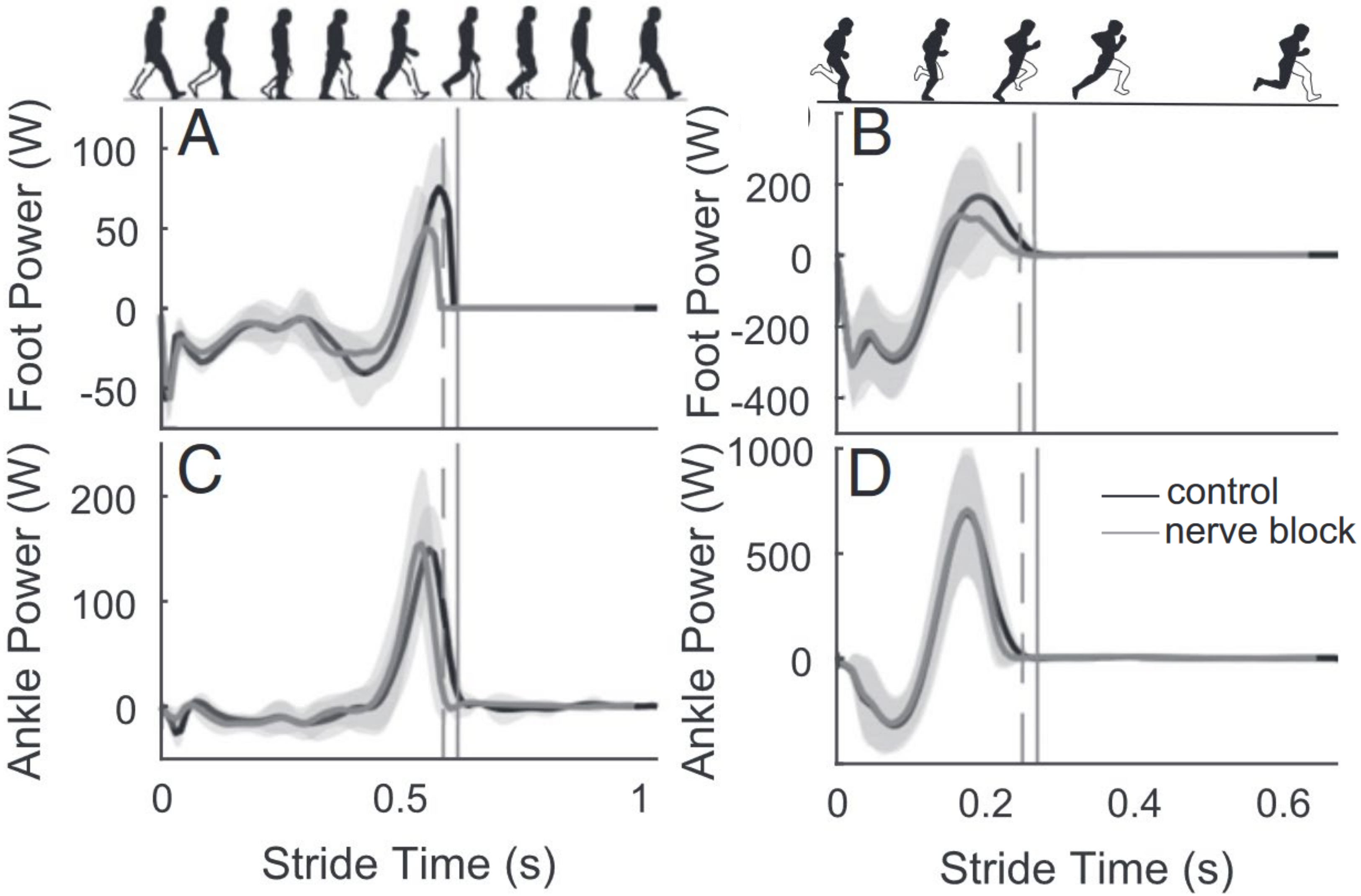


Nerve Block

Farris et al., 2019

N=12

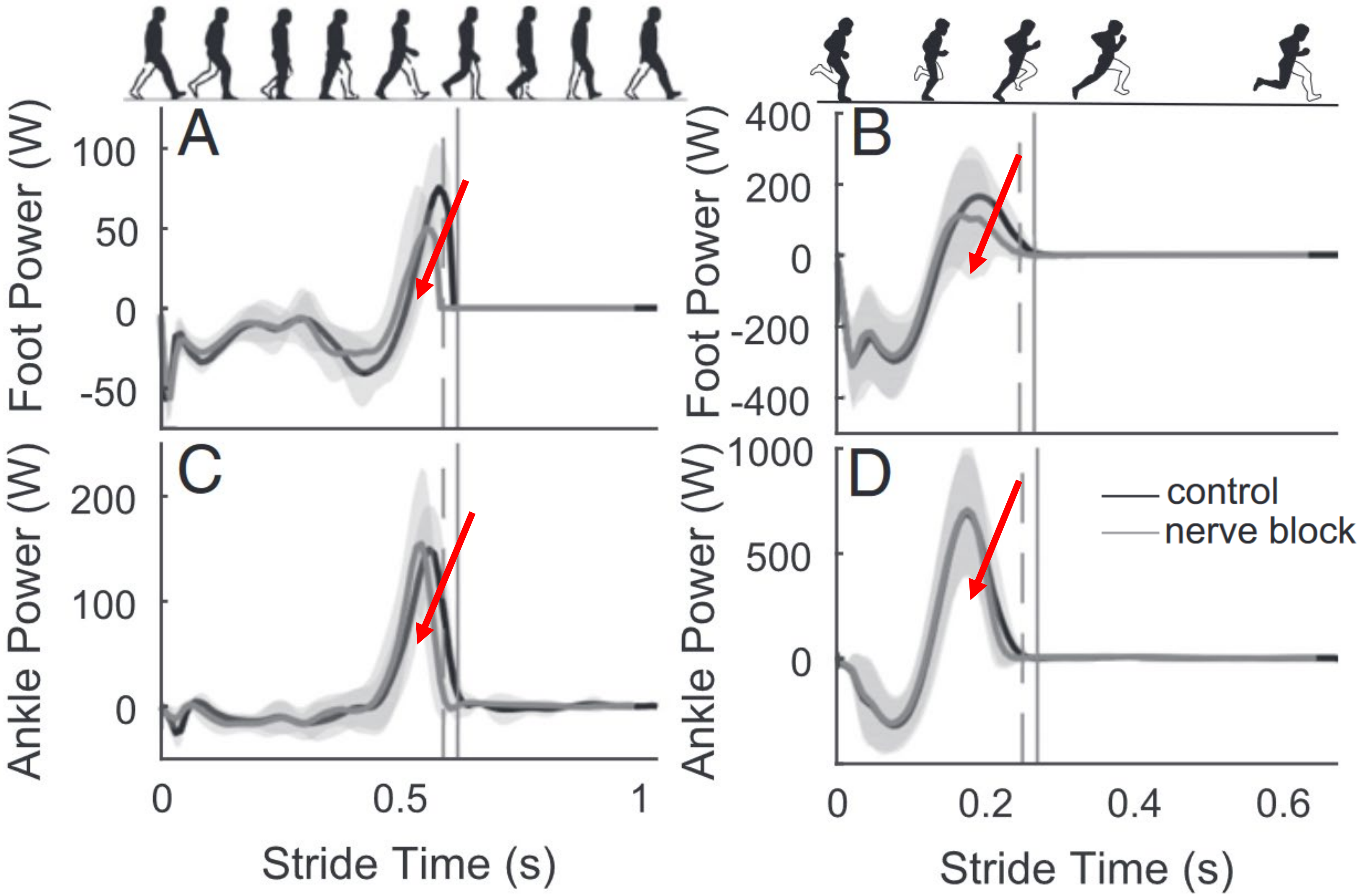
Isolating role of intrinsic foot muscles



Farris et al., 2019

N=12

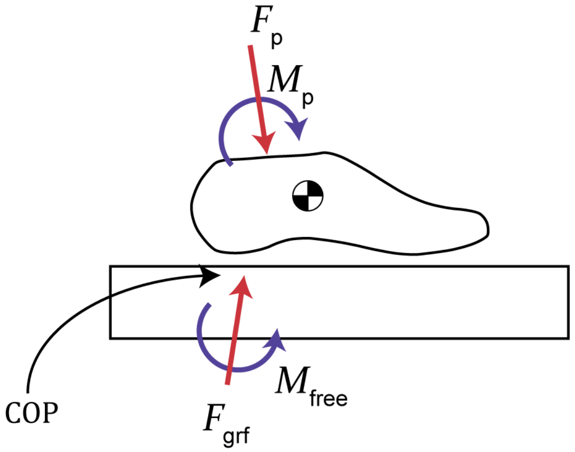
No foot muscles: Reduced Foot & Ankle Power

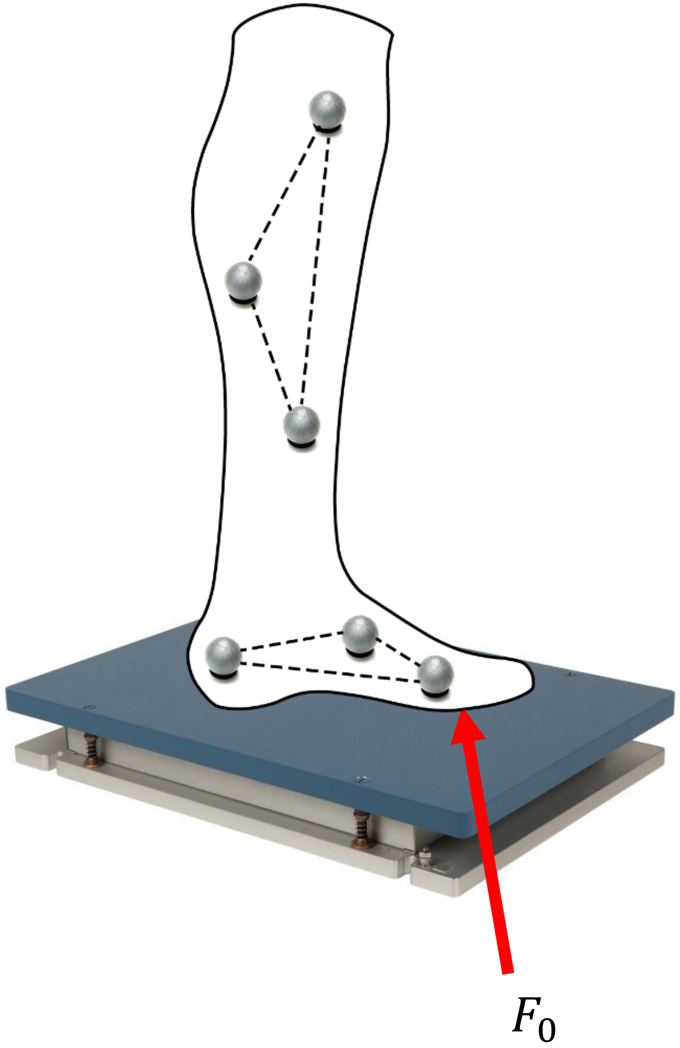


Farris et al., 2019

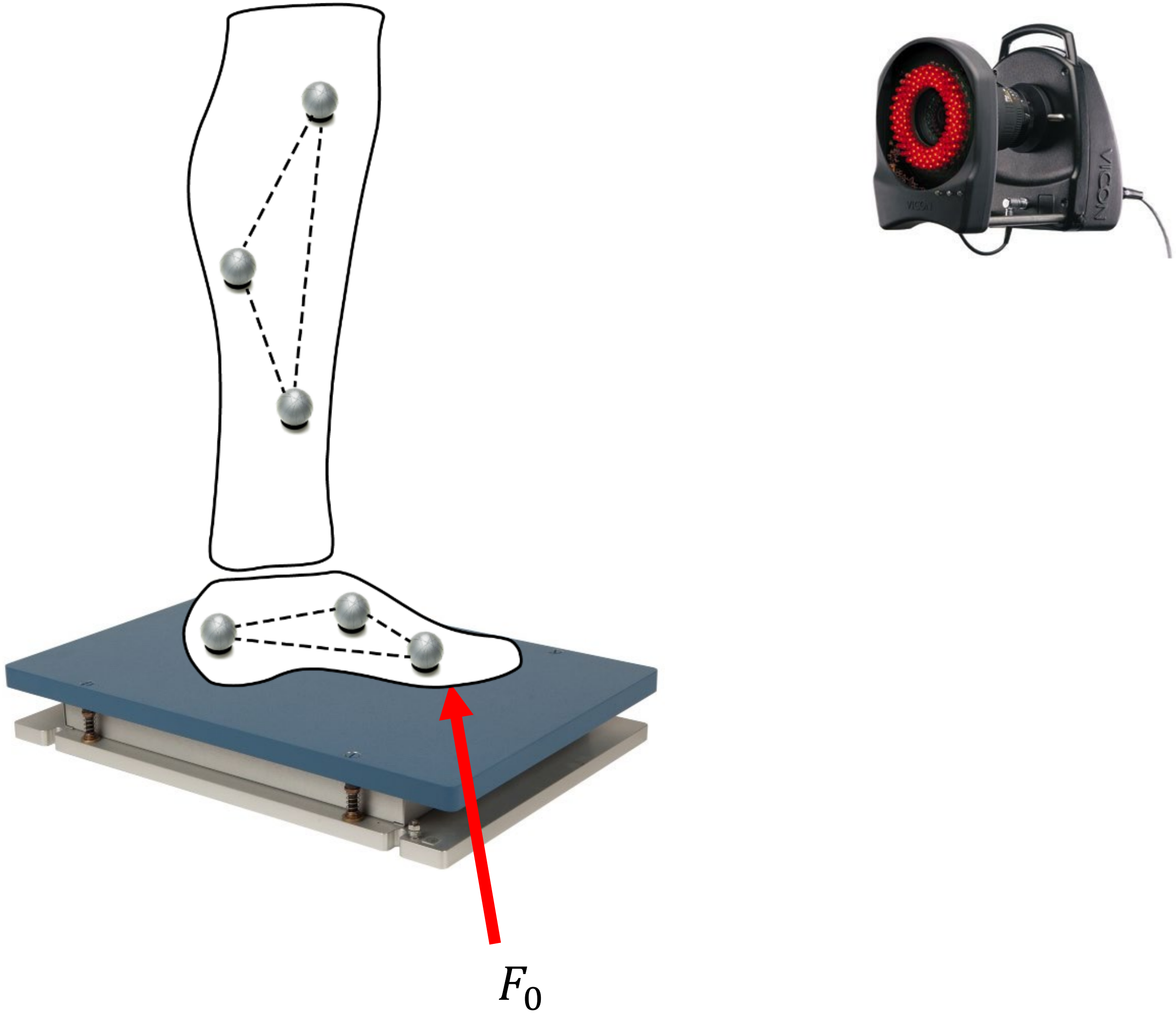
N=12

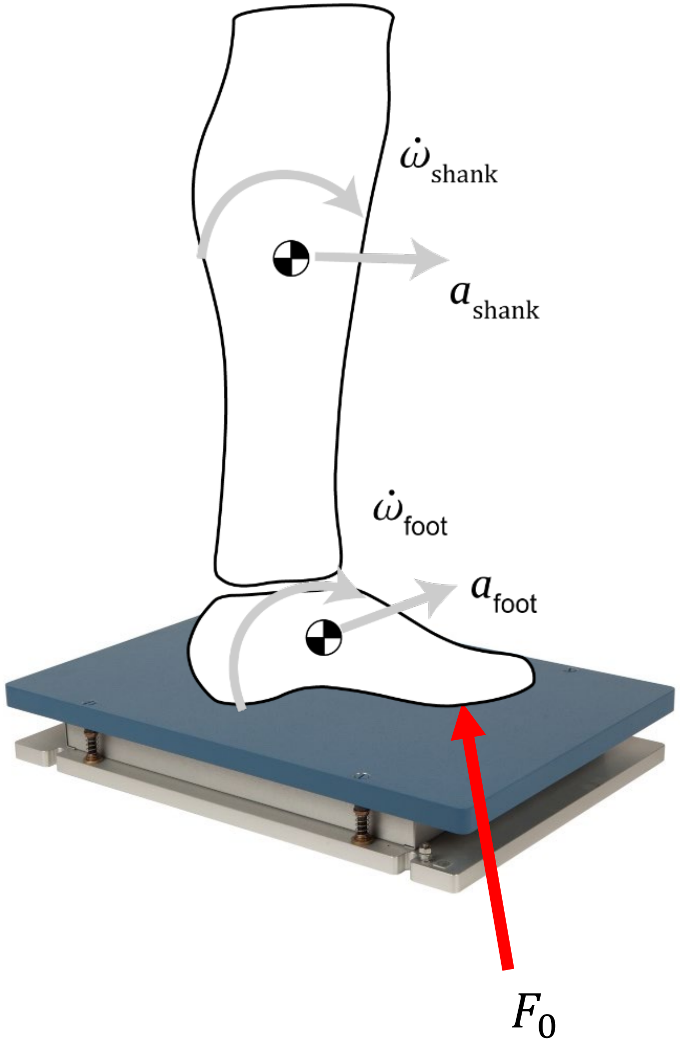
'Distal power' as an extension of joint power



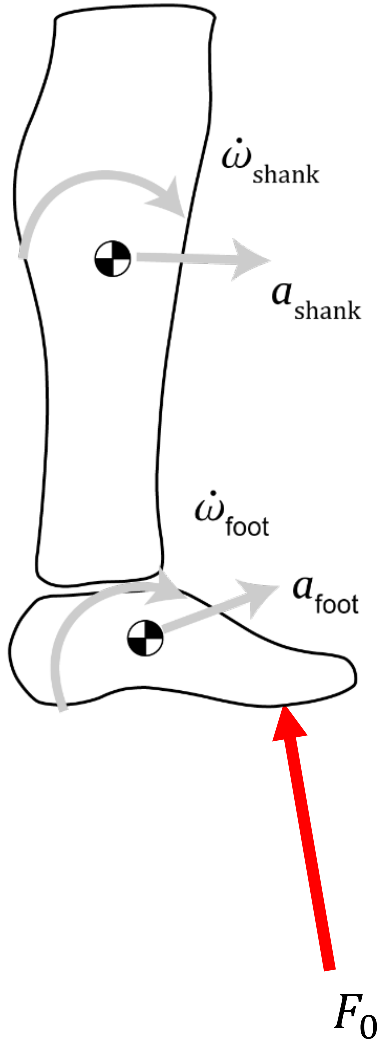

F_0


VICON


F_0


$\dot{\omega}_{\text{shank}}$
a_{shank}
$\dot{\omega}_{\text{foot}}$
a_{foot}
F_0


VICON

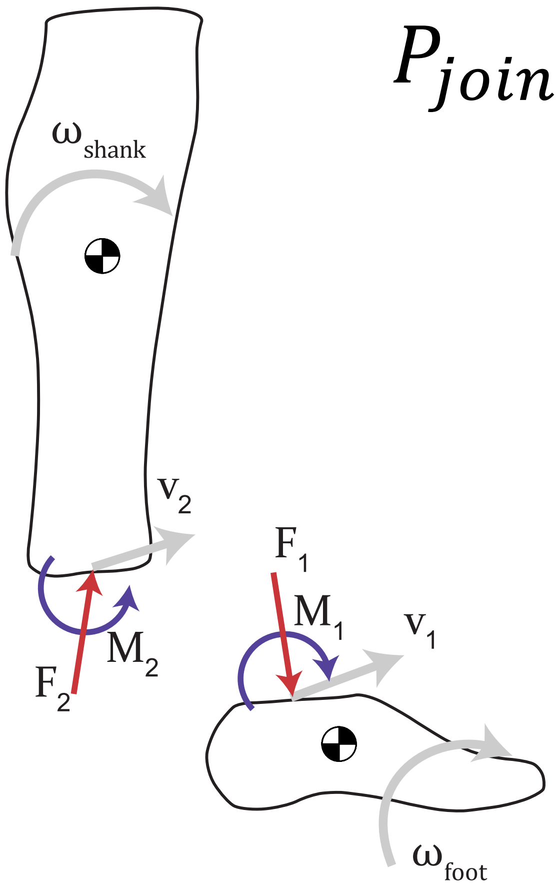


$$\sum \vec{F} = m \cdot \vec{a}$$

$$\sum \vec{M} = I \cdot \vec{\dot{\omega}}$$

6 DOF Joint Power

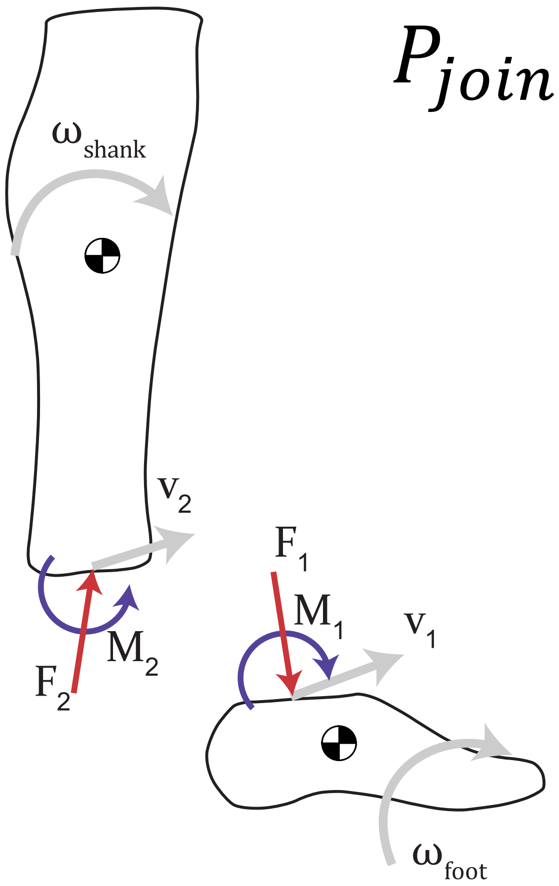
$$P_{joint,6DOF} = \underbrace{\vec{M}_d \cdot \vec{\omega}_d + \vec{M}_p \cdot \vec{\omega}_p}_{\text{Rotational Power}} + \underbrace{\vec{F}_d \cdot \vec{v}_d + \vec{F}_p \cdot \vec{v}_p}_{\text{Translational Power}}$$



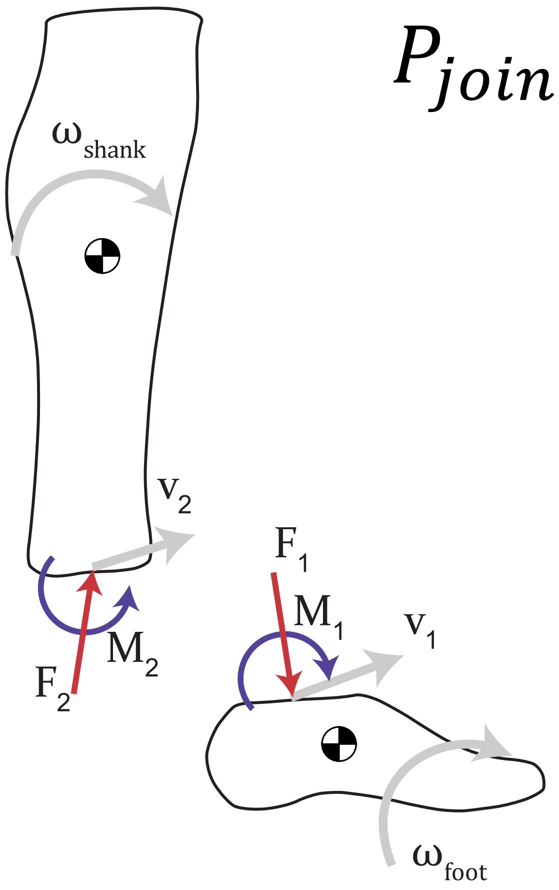
Buczek et al., 1994

6 DOF Joint Power

$$P_{joint,6DOF} = \underbrace{\vec{M}_d \cdot \vec{\omega}_d + \vec{M}_p \cdot \vec{\omega}_p}_{\text{Rotational Power}} + \underbrace{\vec{F}_d \cdot \vec{v}_d + \vec{F}_p \cdot \vec{v}_p}_{\text{Translational Power}}$$



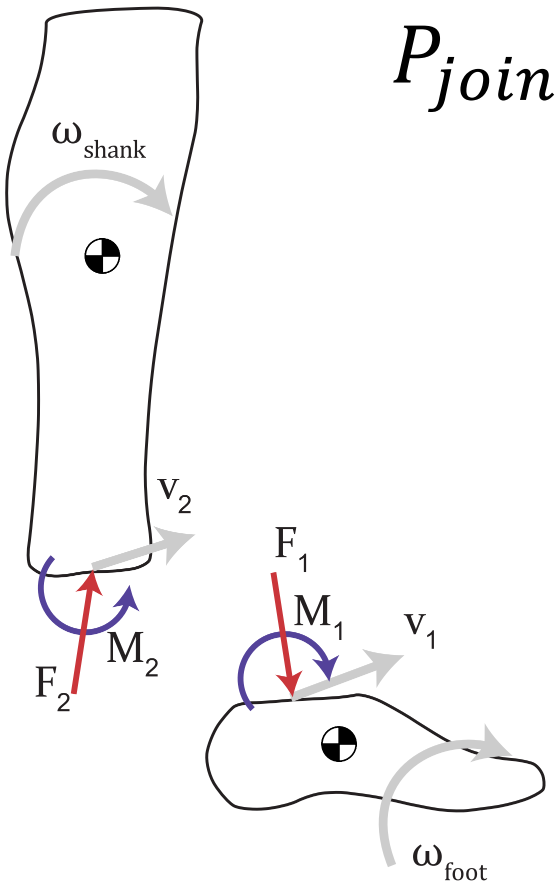
6 DOF Joint Power



$$P_{joint,6DOF} = \underbrace{\vec{M}_d \cdot \vec{\omega}_d + \vec{M}_p \cdot \vec{\omega}_p}_{\text{Rotational Power}} + \underbrace{\vec{F}_d \cdot \vec{v}_d + \vec{F}_p \cdot \vec{v}_p}_{\text{Translational Power}}$$

$$P_{joint,rot} = \vec{M}_1 \cdot \vec{\omega}_{foot} + \vec{M}_2 \cdot \vec{\omega}_{shank}$$

6 DOF Joint Power



$$P_{joint,6DOF} = \underbrace{\vec{M}_d \cdot \vec{\omega}_d + \vec{M}_p \cdot \vec{\omega}_p}_{\text{Rotational Power}} + \underbrace{\vec{F}_d \cdot \vec{v}_d + \vec{F}_p \cdot \vec{v}_p}_{\text{Translational Power}}$$

$$P_{joint,rot} = \vec{M}_1 \cdot \vec{\omega}_{foot} + \vec{M}_2 \cdot \vec{\omega}_{shank}$$

Traditional Assumption: Pin Joint

$$\vec{M}_1 = -\vec{M}_2$$

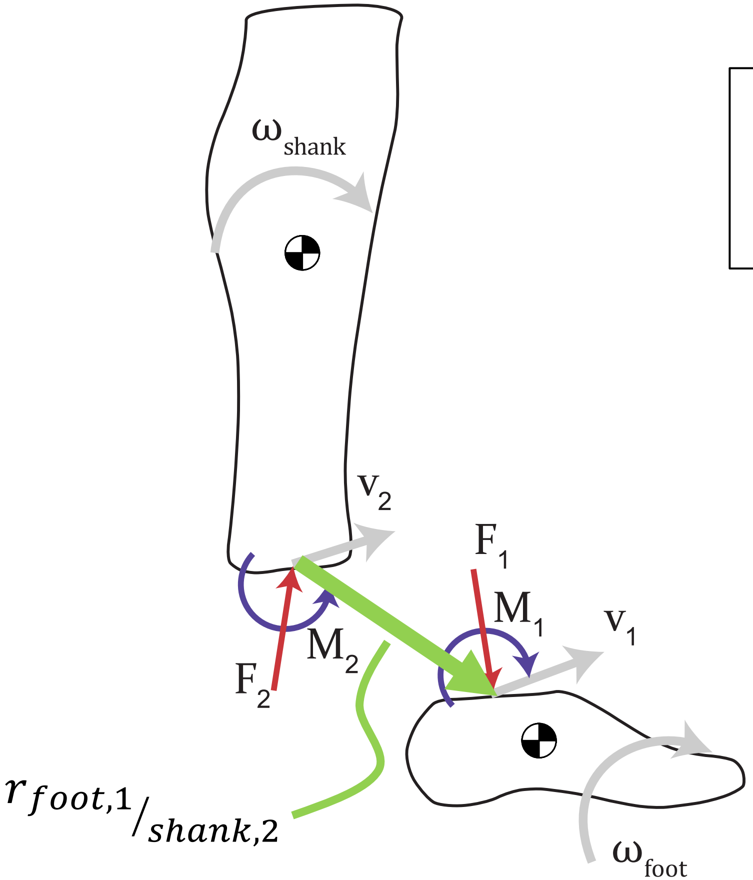
$$P_{joint,rot} = \vec{M}_1 \cdot (\vec{\omega}_{foot} - \vec{\omega}_{shank})$$

Rotational Component Joint Power

$$P_{joint,rot} = \vec{M}_1 \cdot \vec{\omega}_{foot} + \vec{M}_2 \cdot \vec{\omega}_{shank}$$

6DOF Assumption:

Foot & Shank Joint Centers may not be Coincident

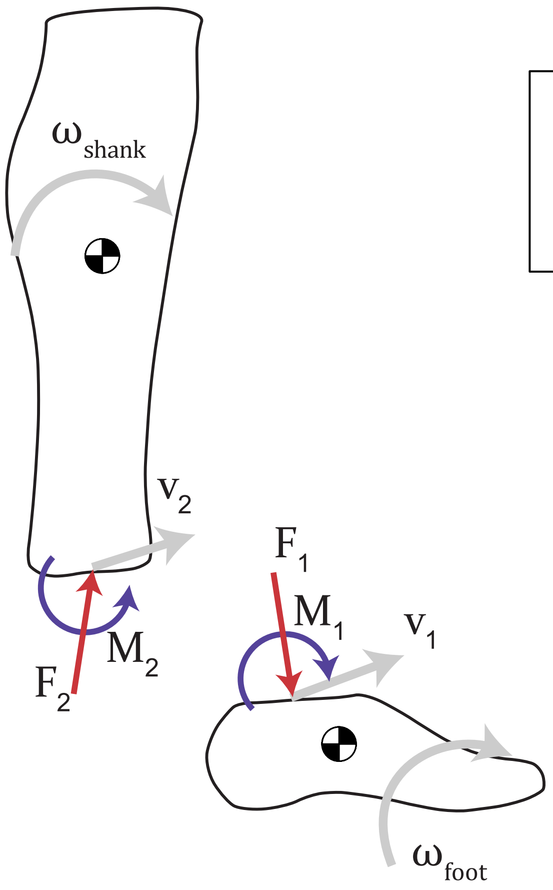


$$\sum \vec{M} = I \cdot \dot{\vec{\omega}}$$

$$\vec{M}_2 + \vec{M}_1 + \vec{r}_{foot,1}/_{shank,2} \times \vec{F}_1 = 0$$

Rotational Component Joint Power

$$P_{joint,rot} = \vec{M}_1 \cdot \vec{\omega}_{foot} + \vec{M}_2 \cdot \vec{\omega}_{shank}$$



6DOF Assumption:

Foot & Shank Joint Centers may not be Coincident

$$\sum \vec{M} = I \cdot \dot{\vec{\omega}}$$

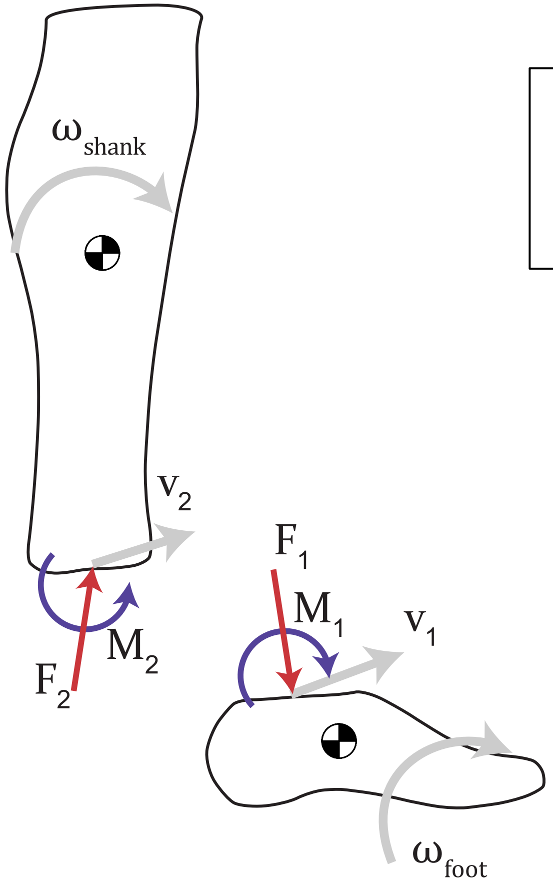
$$\vec{M}_2 + \vec{M}_1 + \vec{r}_{foot,1/_{shank,2}} \times \vec{F}_1 = 0$$

$$\vec{M}_2 = -\vec{M}_1 + \vec{r}_{shank,2/_{foot,1}} \times \vec{F}_1$$

$$P_{joint,rot} = \vec{M}_1 \cdot \vec{\omega}_{foot} + (-\vec{M}_1 + \vec{r}_{shank,2/_{foot,1}} \times \vec{F}_1) \cdot \vec{\omega}_{shank}$$

Rotational Component Joint Power

$$P_{joint,rot} = \vec{M}_1 \cdot \vec{\omega}_{foot} + \vec{M}_2 \cdot \vec{\omega}_{shank}$$



6DOF Assumption:
Foot & Shank Joint Centers may not be Coincident

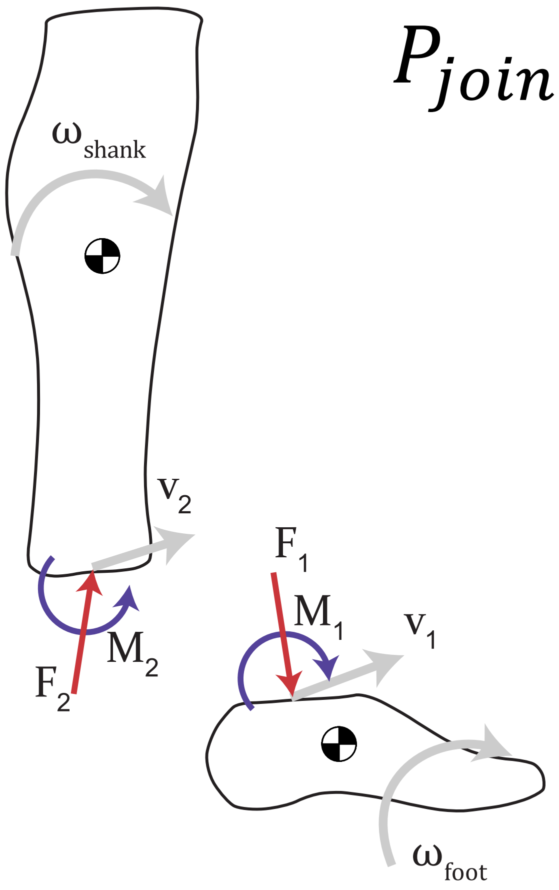
$$\sum \vec{M} = I \cdot \dot{\vec{\omega}}$$

$$\vec{M}_2 + \vec{M}_1 + \vec{r}_{foot,1/shank,2} \times \vec{F}_1 = 0$$

$$\vec{M}_2 = -\vec{M}_1 + \vec{r}_{shank,2/foot,1} \times \vec{F}_1$$

$$P_{joint,rot} = \vec{M}_1 \cdot (\vec{\omega}_{foot} - \vec{\omega}_{shank}) + \vec{F}_1 \cdot (\vec{\omega}_{shank} \times \vec{r}_{shank,2/foot,1})$$

6 DOF Joint Power



$$P_{joint,6DOF} = \underbrace{\vec{M}_d \cdot \vec{\omega}_d + \vec{M}_p \cdot \vec{\omega}_p}_{\text{Rotational Power}} + \underbrace{\vec{F}_d \cdot \vec{v}_d + \vec{F}_p \cdot \vec{v}_p}_{\text{Translational Power}}$$

$$P_{joint,trans} = \vec{F}_1 \cdot \vec{v}_1 + \vec{F}_2 \cdot \vec{v}_2$$

$$\sum \vec{F} = m \cdot \vec{a}$$

$$\vec{F}_1 = -\vec{F}_2$$

$$P_{joint,trans} = \vec{F}_1 \cdot (\vec{v}_1 - \vec{v}_2)$$

6 DOF Joint Power

$$P_{joint,6DOF} = P_{joint,rot} + P_{joint,trans}$$

$$= \overrightarrow{M}_1 \cdot (\vec{\omega}_{foot} - \vec{\omega}_{shank}) + \vec{F}_1 \cdot (\vec{v}_1 - \vec{v}_2 + \vec{\omega}_{shank} \times \vec{r}_{shank,2}{}_{/_{foot,1}})$$

6 DOF Joint Power

$$P_{joint,6DOF} = P_{joint,rot} + P_{joint,trans}$$

$$= \vec{M}_1 \cdot (\vec{\omega}_{foot} - \vec{\omega}_{shank}) + \vec{F}_1 \cdot (\vec{v}_1 - \vec{v}_2 + \vec{\omega}_{shank} \times \vec{r}_{{shank,2}/_{foot,1}})$$

Side Note 1:
Why moments and forces on the foot (distal body)?

These parameters are innately provided by V3D

6 DOF Joint Power

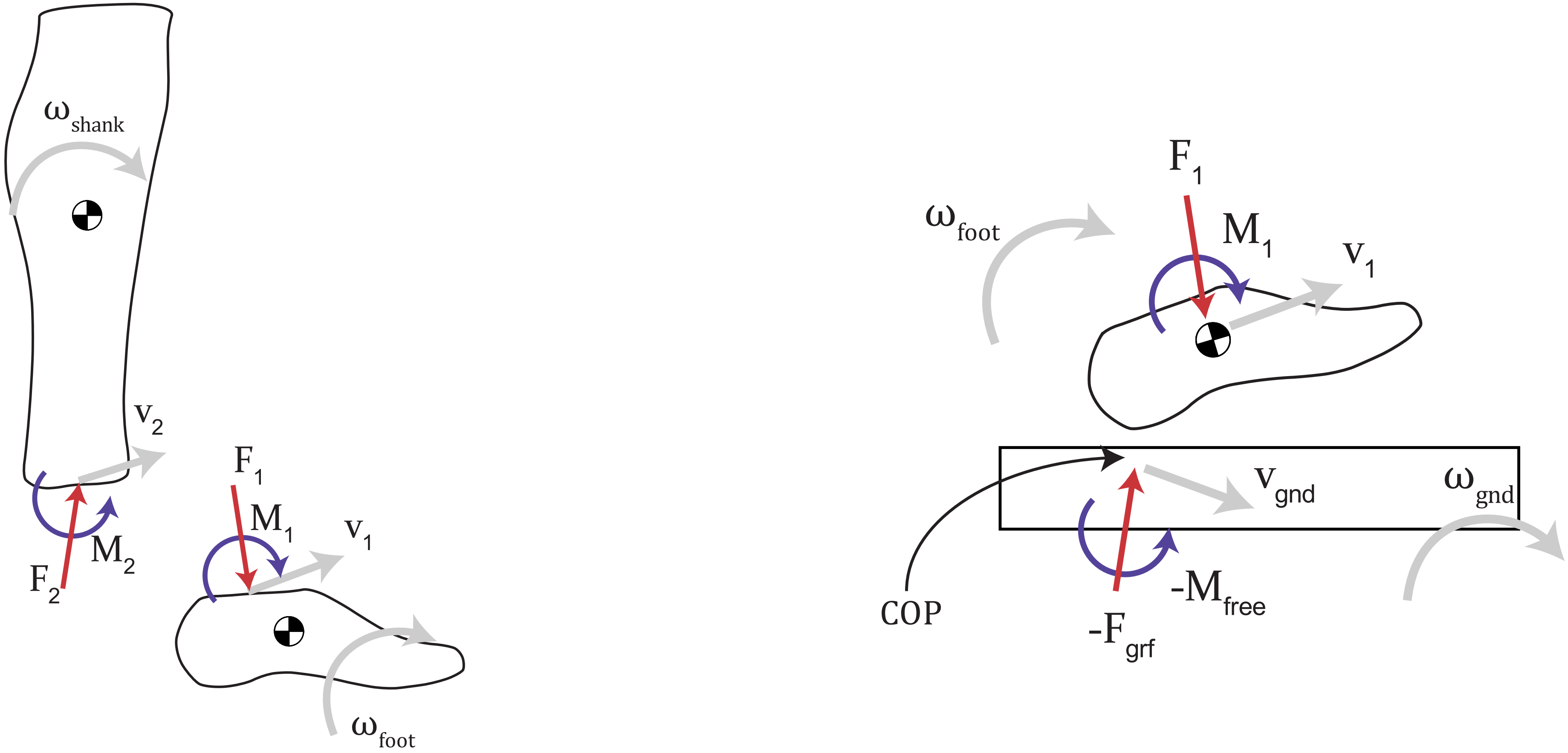
$$P_{joint,6DOF} = P_{joint,rot} + P_{joint,trans}$$

$$= \vec{M}_1 \cdot (\vec{\omega}_{foot} - \vec{\omega}_{shank}) + \vec{F}_1 \cdot (\vec{v}_1 - \vec{v}_2 + \vec{\omega}_{shank} \times \vec{r}_{shank,2/foot,1})$$

Side Note 2:
Is this a velocity term?

This looks like a rigid body velocity term… however, it is a consequence of rearranging our equations.

Applying 6 DOF Joint Power to the Foot & Ground

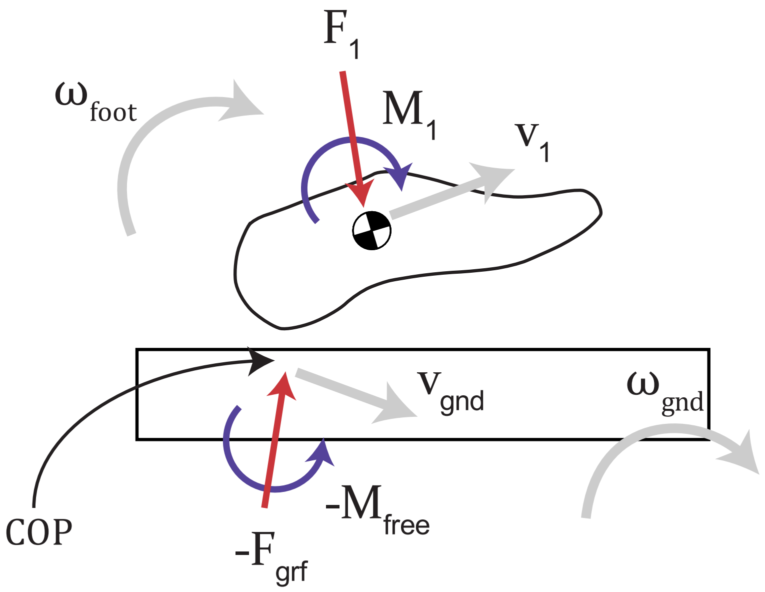


Applying 6 DOF Joint Power to the Foot & Ground

$$P_{joint,6DOF} = P_{joint,rot} + P_{joint,trans}$$

$$= \vec{M}_d \cdot \left(\vec{\omega}_d - \vec{\omega}_p\right) + \vec{F}_d \cdot \left(\vec{v}_d - \vec{v}_p + \vec{\omega}_p \times \vec{r}{p}_{/_{d}}\right)$$

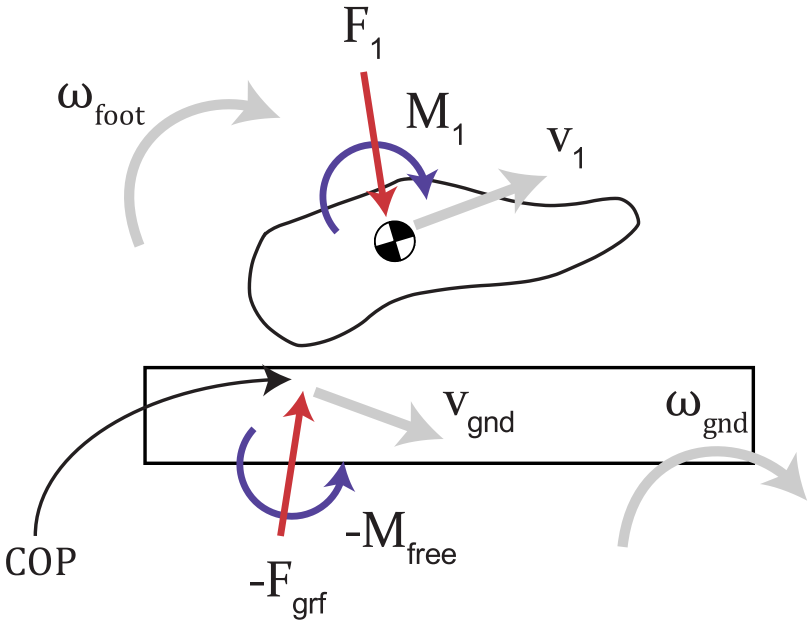
$$= -\vec{M}_{free} \cdot \left(\vec{\omega}_{gnd} - \vec{\omega}_{foot}\right) - \vec{F}_{grf} \cdot \left(\vec{v}_{gnd} - \vec{v}_{foot} + \vec{\omega}_{foot} \times \vec{r}_{foot_{/_{COP}}}\right)$$



Applying 6 DOF Joint Power to the Foot & Ground

$$P_{joint,6DOF} = P_{joint,rot} + P_{joint,trans}$$

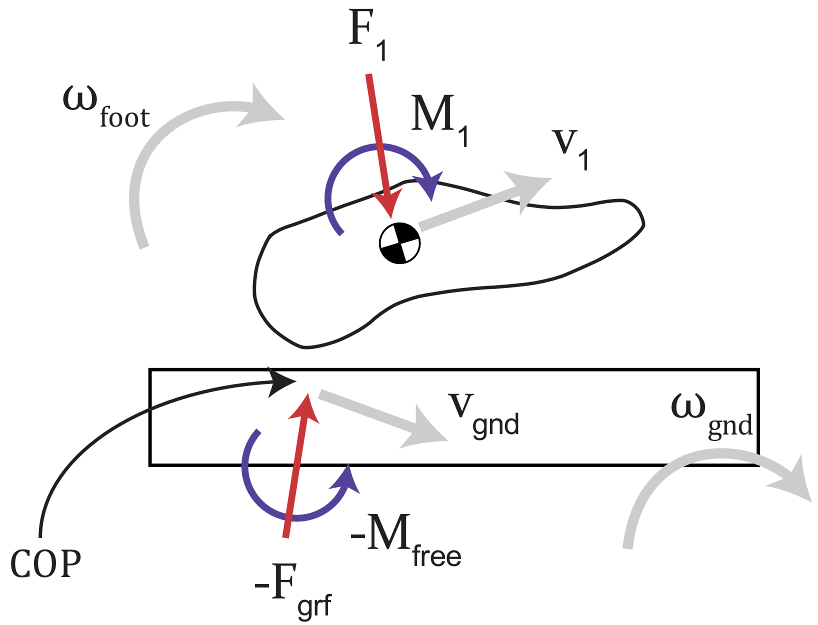
$$= -\vec{M}_{free} \cdot \left(\cancelto{0}{\vec{\omega}_{gnd}} - \vec{\omega}_{foot}\right) - \vec{F}_{grf} \cdot \left(\cancelto{0}{\vec{v}_{gnd}} - \vec{v}_{foot} + \vec{\omega}_{foot} \times \vec{r}_{foot/_{COP}}\right)$$



Applying 6 DOF Joint Power to the Foot & Ground

$$P_{joint,6DOF} = P_{joint,rot} + P_{joint,trans}$$

$$P_{DistalFoot} = \vec{F}_{grf} \cdot (\vec{v}_{foot} + \vec{\omega}_{foot} \times \vec{r}_{COP/_{foot}}) + \vec{M}_{free} \cdot \vec{\omega}_{foot}$$

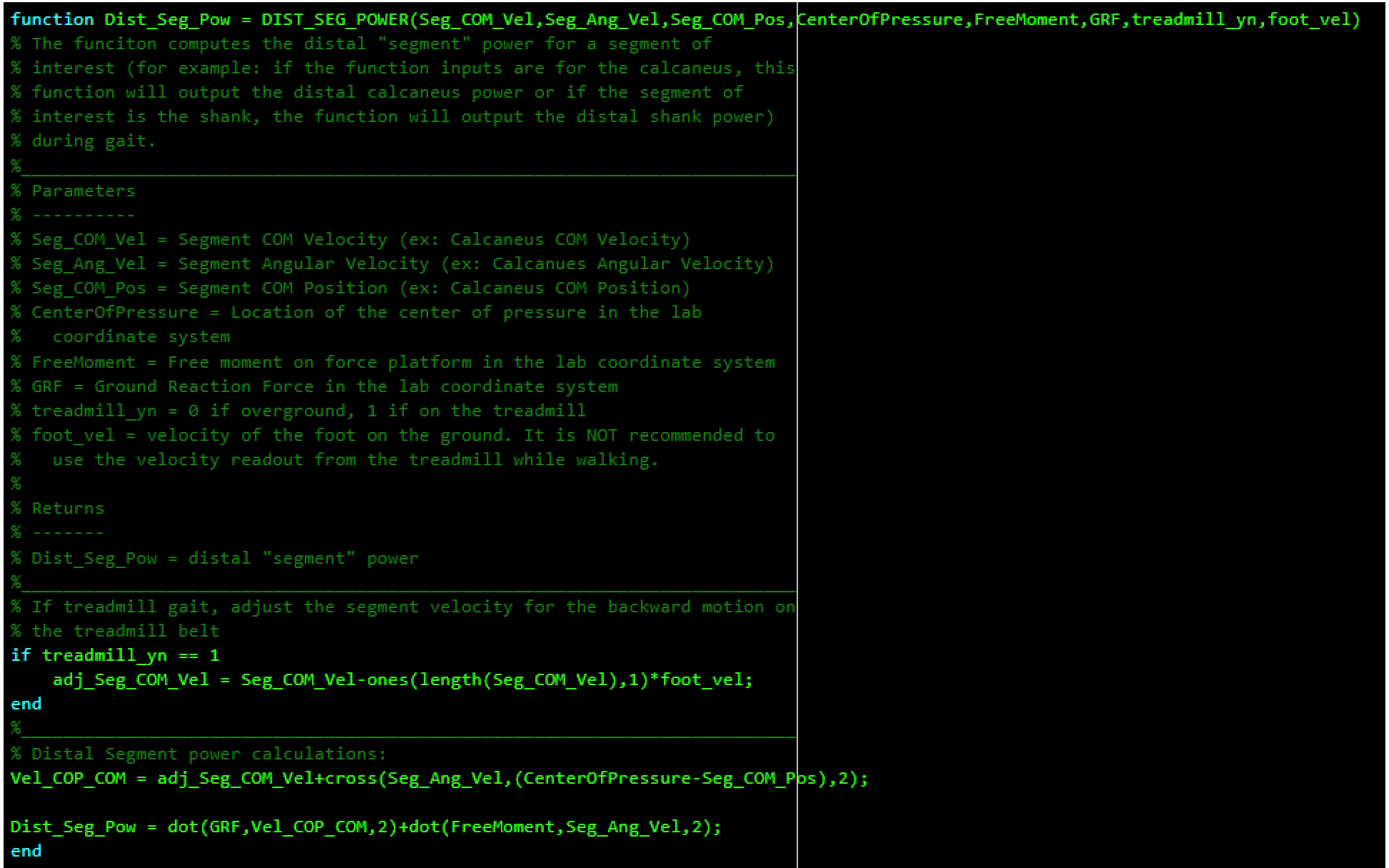


Hands-on Session

Hands-on Session

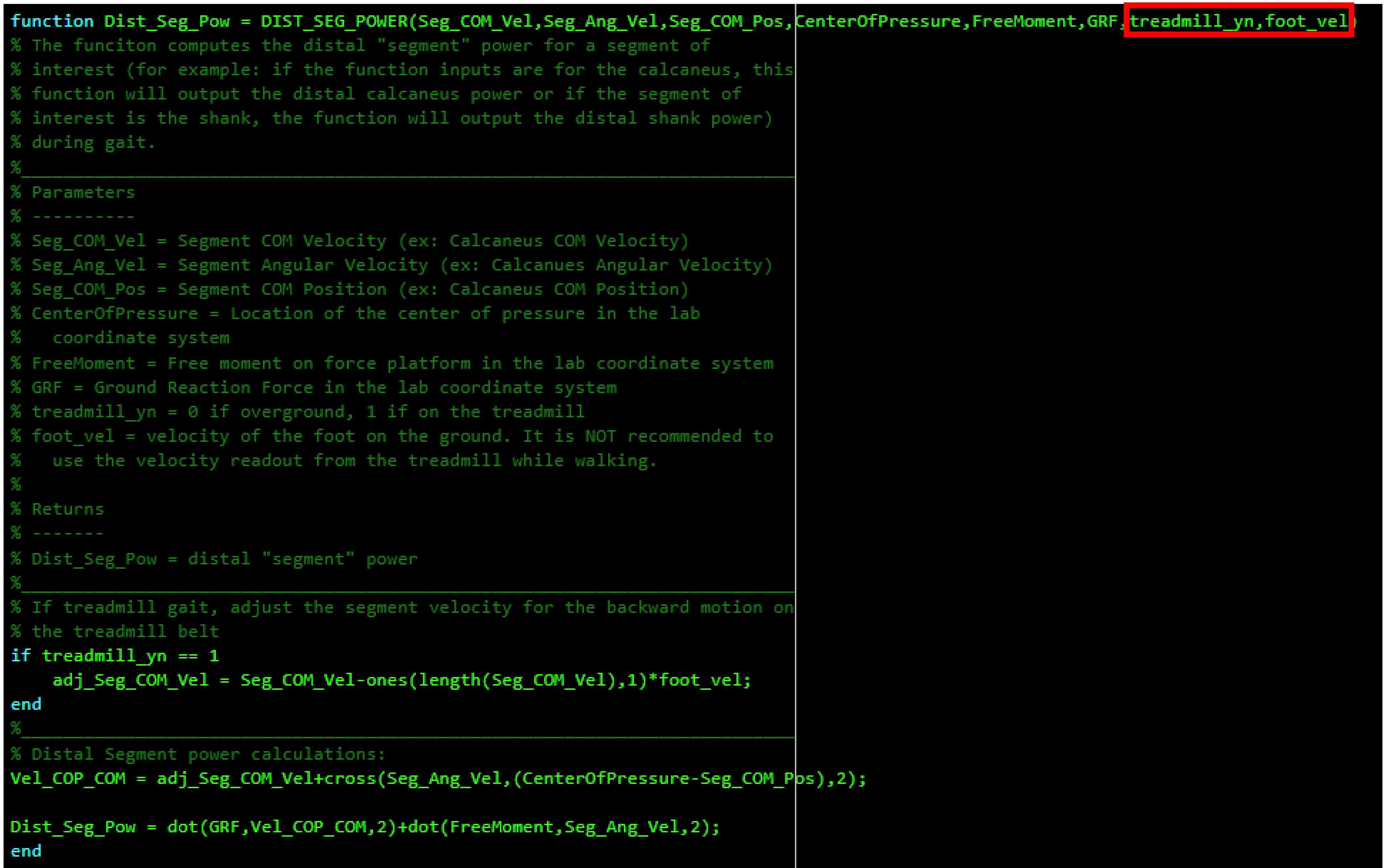
- Slack:
  - Channel: #tutorial-resources-files
  - Download & extract: DistalPower_Workshop_code_files.zip
- Open “WorkshopCode_fillin.m” in MATLAB

Code: Computing Distal Segment Power



```
function Dist_Seg_Pow = DIST_SEG_POWER(Seg_COM_Vel,Seg_Ang_Vel,Seg_COM_Pos,CenterOfPressure,FreeMoment,GRF,treadmill_yn,foot_vel)
% The funciton computes the distal "segment" power for a segment of
% interest (for example: if the function inputs are for the calcaneus, this
% function will output the distal calcaneus power or if the segment of
% interest is the shank, the function will output the distal shank power)
% during gait.
%__________________________________________________________________________
% Parameters
% ----------
% Seg_COM_Vel = Segment COM Velocity (ex: Calcaneus COM Velocity)
% Seg_Ang_Vel = Segment Angular Velocity (ex: Calcanues Angular Velocity)
% Seg_COM_Pos = Segment COM Position (ex: Calcaneus COM Position)
% CenterOfPressure = Location of the center of pressure in the lab
%   coordinate system
% FreeMoment = Free moment on force platform in the lab coordinate system
% GRF = Ground Reaction Force in the lab coordinate system
% treadmill_yn = 0 if overground, 1 if on the treadmill
% foot_vel = velocity of the foot on the ground. It is NOT recommended to
%   use the velocity readout from the treadmill while walking.
%
% Returns
% -------
% Dist_Seg_Pow = distal "segment" power
%__________________________________________________________________________
% If treadmill gait, adjust the segment velocity for the backward motion on
% the treadmill belt
if treadmill_yn == 1
    adj_Seg_COM_Vel = Seg_COM_Vel-ones(length(Seg_COM_Vel),1)*foot_vel;
end
%__________________________________________________________________________
% Distal Segment power calculations:
Vel_COP_COM = adj_Seg_COM_Vel+cross(Seg_Ang_Vel,(CenterOfPressure-Seg_COM_Pos),2);

Dist_Seg_Pow = dot(GRF,Vel_COP_COM,2)+dot(FreeMoment,Seg_Ang_Vel,2);
end
```

Code: Computing Distal Segment Power

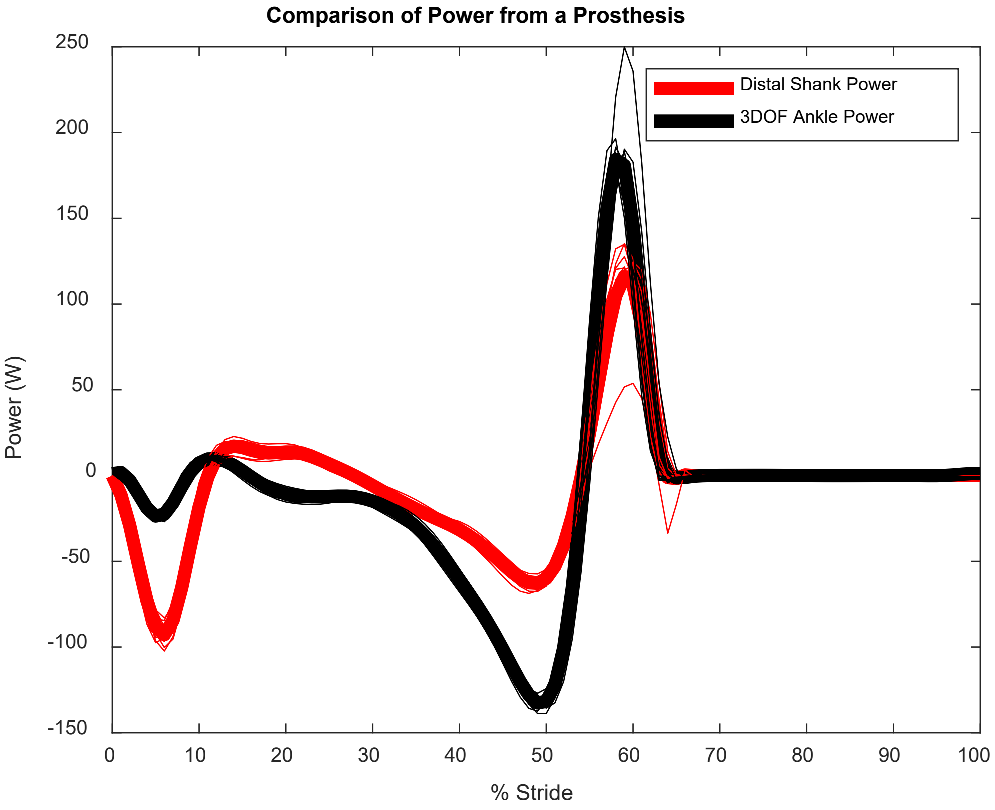


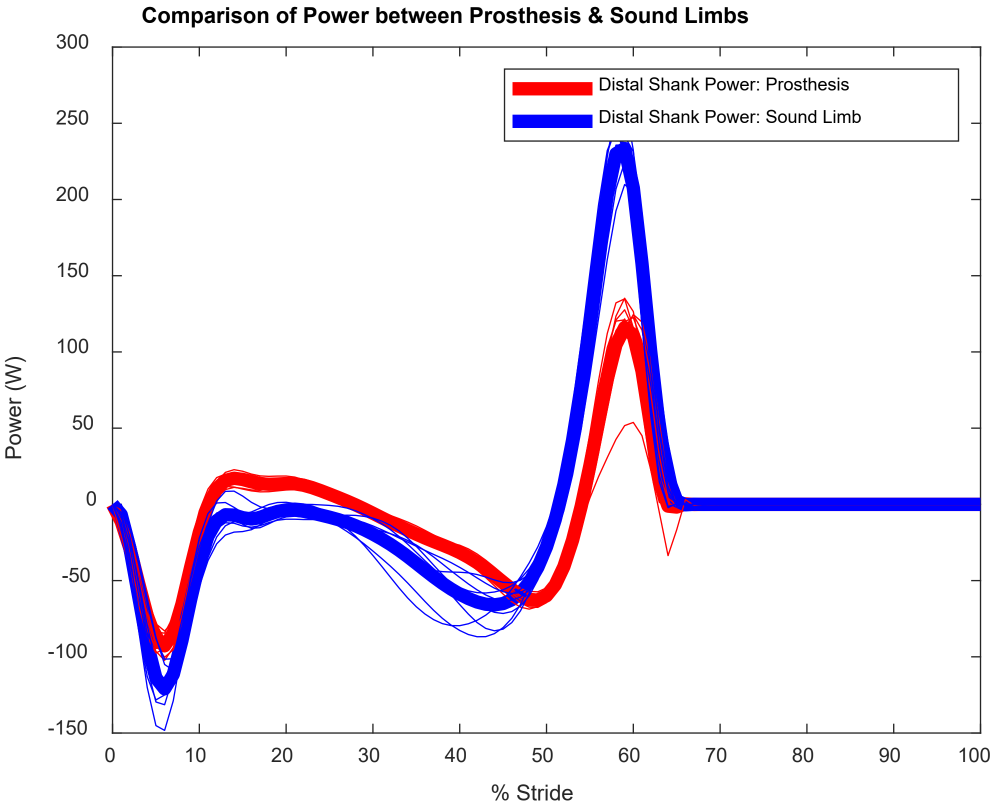
```
function Dist_Seg_Pow = DIST_SEG_POWER(Seg_COM_Vel,Seg_Ang_Vel,Seg_COM_Pos,CenterOfPressure,FreeMoment,GRF,treadmill_yn,foot_vel)
% The funciton computes the distal "segment" power for a segment of
% interest (for example: if the function inputs are for the calcaneus, this
% function will output the distal calcaneus power or if the segment of
% interest is the shank, the function will output the distal shank power)
% during gait.
%__________________________________________________________________________
% Parameters
% ----------
% Seg_COM_Vel = Segment COM Velocity (ex: Calcaneus COM Velocity)
% Seg_Ang_Vel = Segment Angular Velocity (ex: Calcanues Angular Velocity)
% Seg_COM_Pos = Segment COM Position (ex: Calcaneus COM Position)
% CenterOfPressure = Location of the center of pressure in the lab
%   coordinate system
% FreeMoment = Free moment on force platform in the lab coordinate system
% GRF = Ground Reaction Force in the lab coordinate system
% treadmill_yn = 0 if overground, 1 if on the treadmill
% foot_vel = velocity of the foot on the ground. It is NOT recommended to
%   use the velocity readout from the treadmill while walking.
%
% Returns
% -------
% Dist_Seg_Pow = distal "segment" power
%__________________________________________________________________________
% If treadmill gait, adjust the segment velocity for the backward motion on
% the treadmill belt
if treadmill_yn == 1
    adj_Seg_COM_Vel = Seg_COM_Vel-ones(length(Seg_COM_Vel),1)*foot_vel;
end
%__________________________________________________________________________
% Distal Segment power calculations:
Vel_COP_COM = adj_Seg_COM_Vel+cross(Seg_Ang_Vel,(CenterOfPressure-Seg_COM_Pos),2);

Dist_Seg_Pow = dot(GRF,Vel_COP_COM,2)+dot(FreeMoment,Seg_Ang_Vel,2);
end
```

Treadmill speed?

```matlab
function foot_vel = foot_vel_treadmill(HS,Speed,Foot_Vel)
% This function is used to compute the velocity of the foot on the ground.
% When computing distal "segement" power during walking, it is encouraged
% to compute the treadmill velocity based on foot segment kinematics (or
% foot markers). The treadmill velocity is computed from "foot flat" which
% is approximately 20% to 40% of stride. This period of "foot flat" was
% determined from observing a cohort of 10 subjects walking on various
% speeds and slopes (Honert & Zelik 2019).
%
% Parameters
% ----------
% HS = Heel Strike (or foot contact events)
%   Array of heel strikes indicies can be either left or right
% Foot_Vel = velocity of the foot center-of-mass in the lab coordinate
%   system. This is to adjust the velocity of the foot on a treadmill.
% Speed = speed entered into the treadmill (e.g., 1.0)
%   (This variable is for debugging purposes)
%
% Returns
% -------
% foot_vel = average velocity of the foot moving backwards on the treadmill
%
% Debugging:
debug = 0;  % 1 to compare treadmill velocity and foot velocity
%
% When using a treadmill when computing distal segment power it is
% necessary to adjust the speed of the treadmill based otherwise there will
% be an artificial power term within the computation. In order to do this,
% it is approximated by the foot_flat variable when the foot is on the
% treadmill and moving at the pace of the treadmill backwards.
%
% Estimation when foot flat is to adjust for velocity in terms of stride.
% Examining 20% to 40% of stride has been successful in the past.
foot_flat = [.2,.4];
%
% Index through the heel strikes
for ii = 1:(length(HS)-1)
    strideframe = HS(ii+1)-HS(ii);
    vel_foot_flat = (HS(ii)+round(foot_flat(1)*strideframe)):(HS(ii)+round(foot_flat(2)*strideframe));
    stride_foot_velocity(ii,:) = mean(Foot_Vel(vel_foot_flat,:));
end
% Debug mode: Show estimated velocity vs. treadmill velocity
if debug == 1
    figure(1010)
    plot(1:length(stride_foot_velocity(:,1)),Speed*ones(1,length(stride_foot_velocity(:,1))),1:length(stride_foot_velocity(:,1)),rssq(stride_foot_velocity,2),'r')
end
foot_vel = mean(stride_foot_velocity,1);
end
```

Evaluating prosthesis energy storage & return



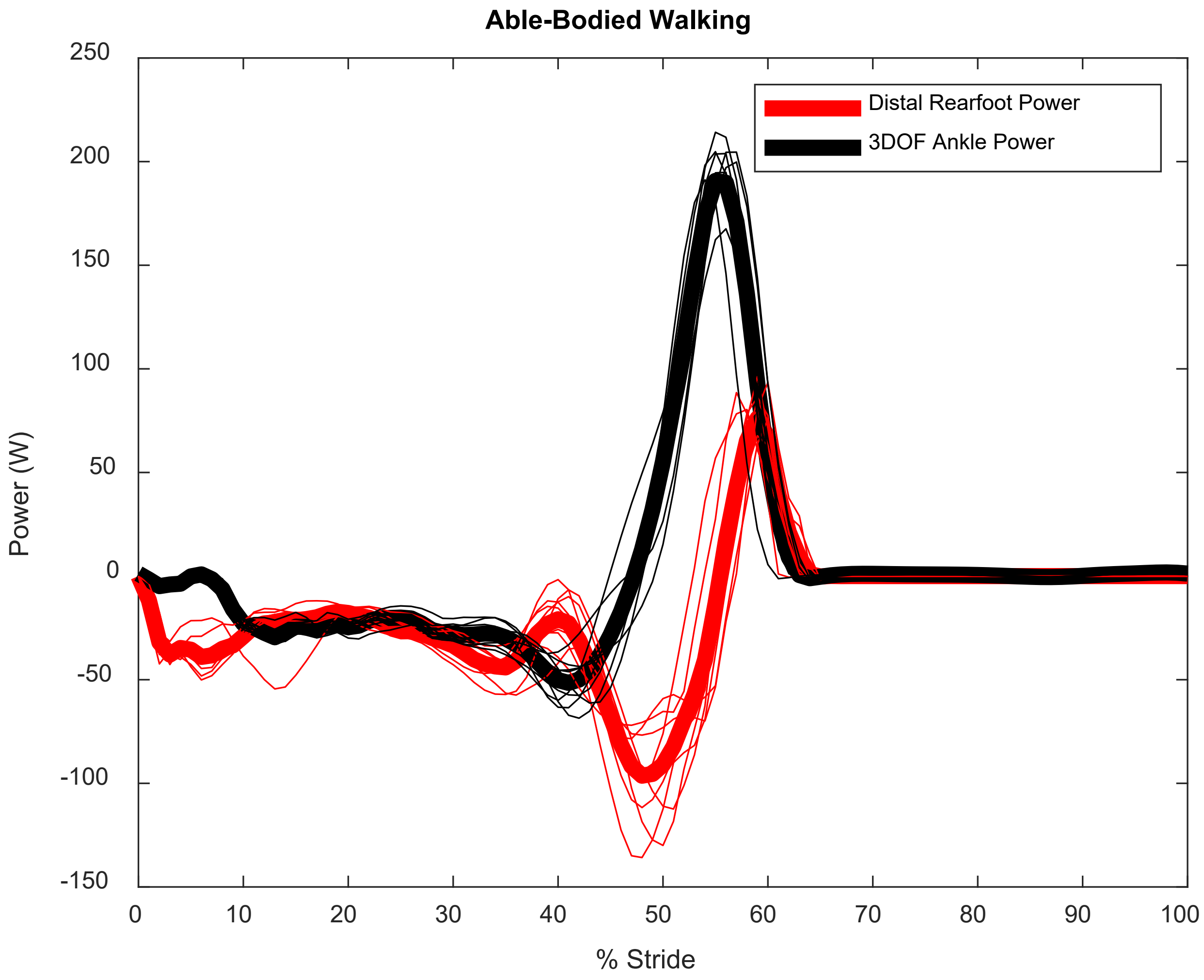


Your turn! Able-Bodied Data or your Data

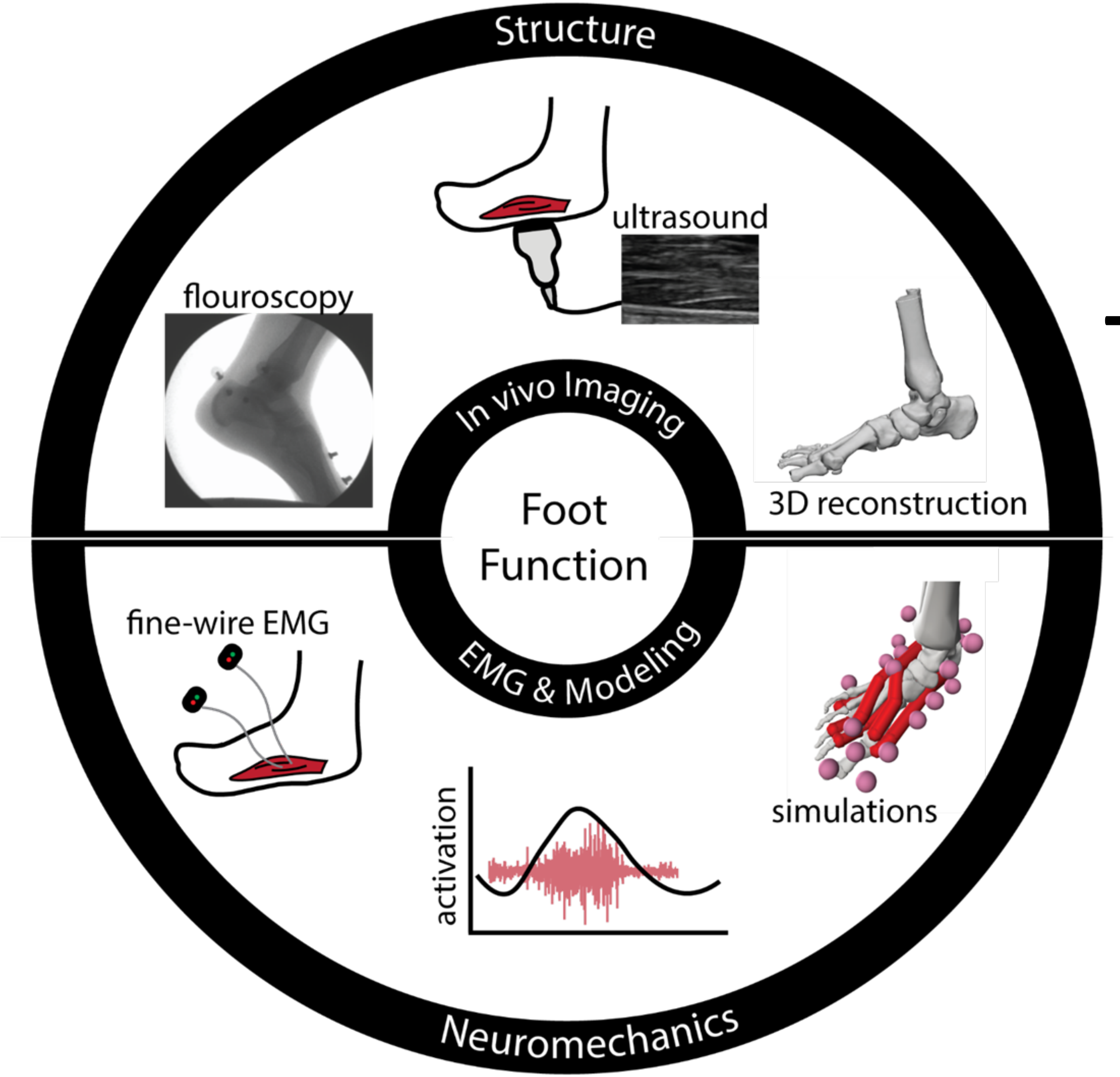
Goal:

- Create a comparison plot between distal rearfoot (hindfoot) and 3DOF ankle power
- Submit a screenshot of your plots to slack under #participant-uploads

Able-Bodied Walking: Distal Rearfoot Power



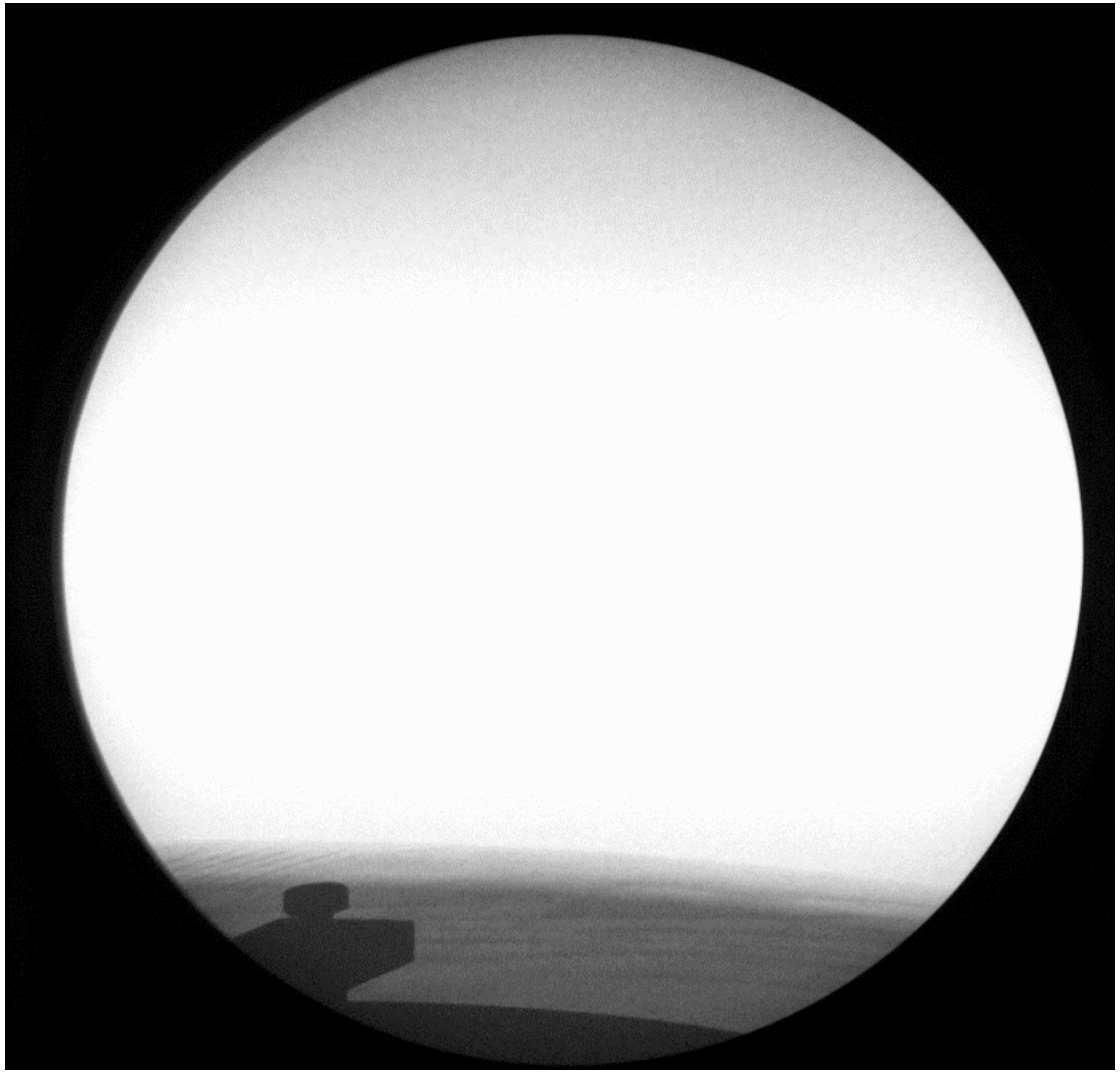
Future Directions



Towards tissue-level understanding

Takahashi KZ et al. 2022

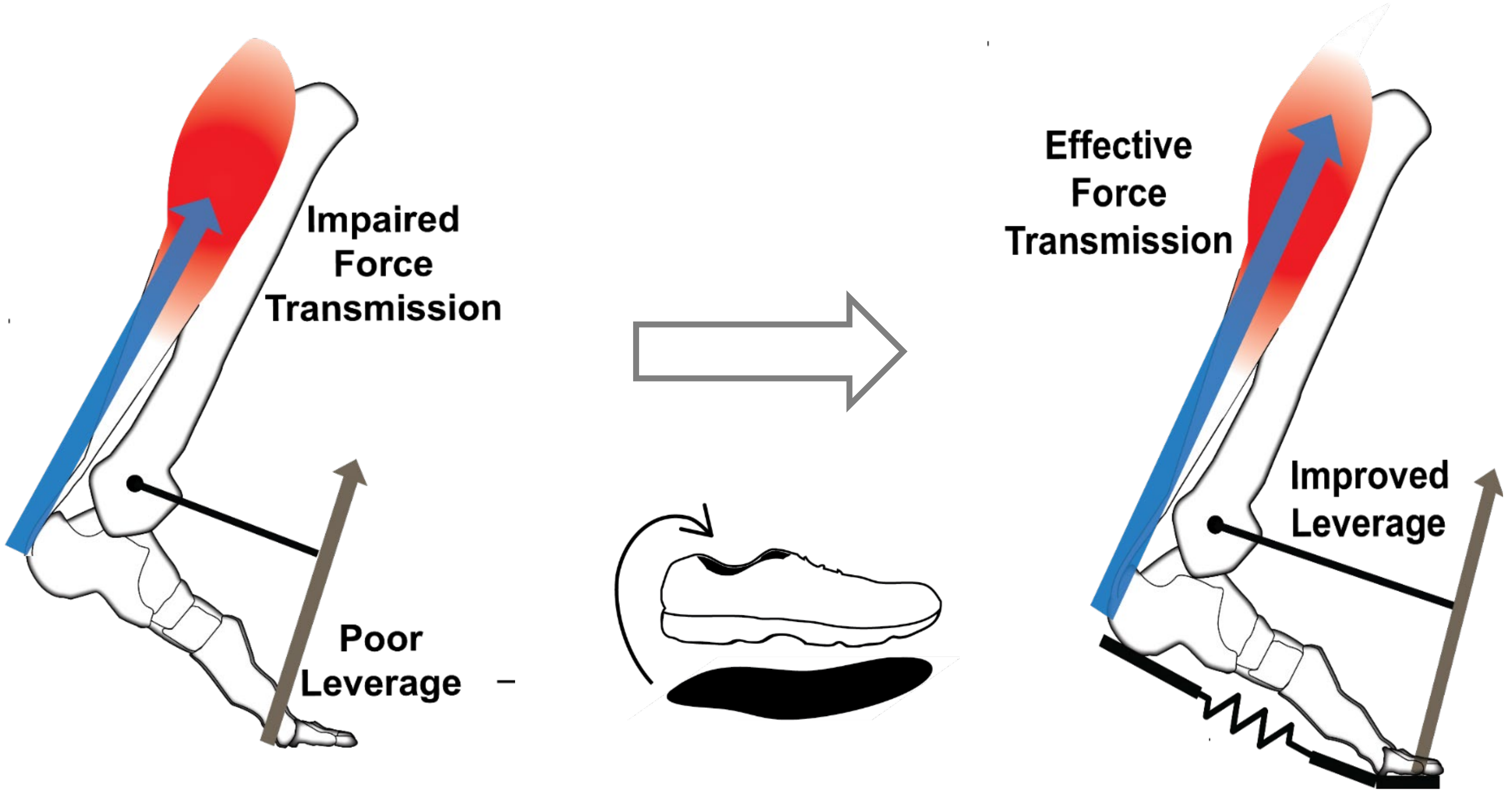
Imaging feet inside shoes and insoles



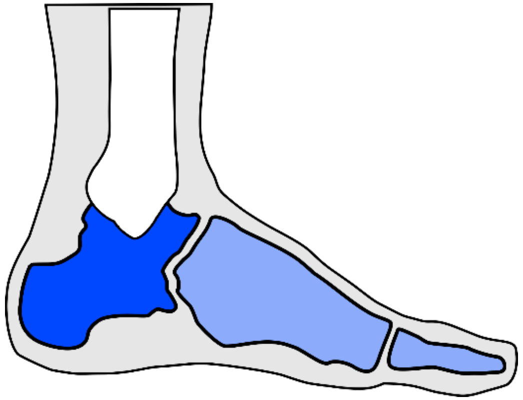
Biplane fluoroscopy
from Dr. Amy Lenz lab
(University of Utah)

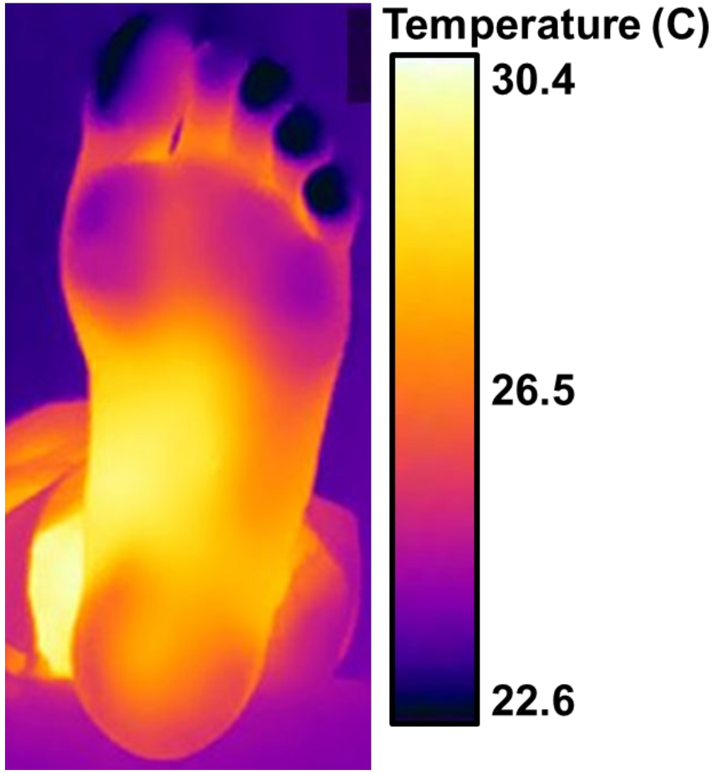
Enhancing Foot Function and Mobility

Shoes + Insoles to reduce foot energy loss in older adults



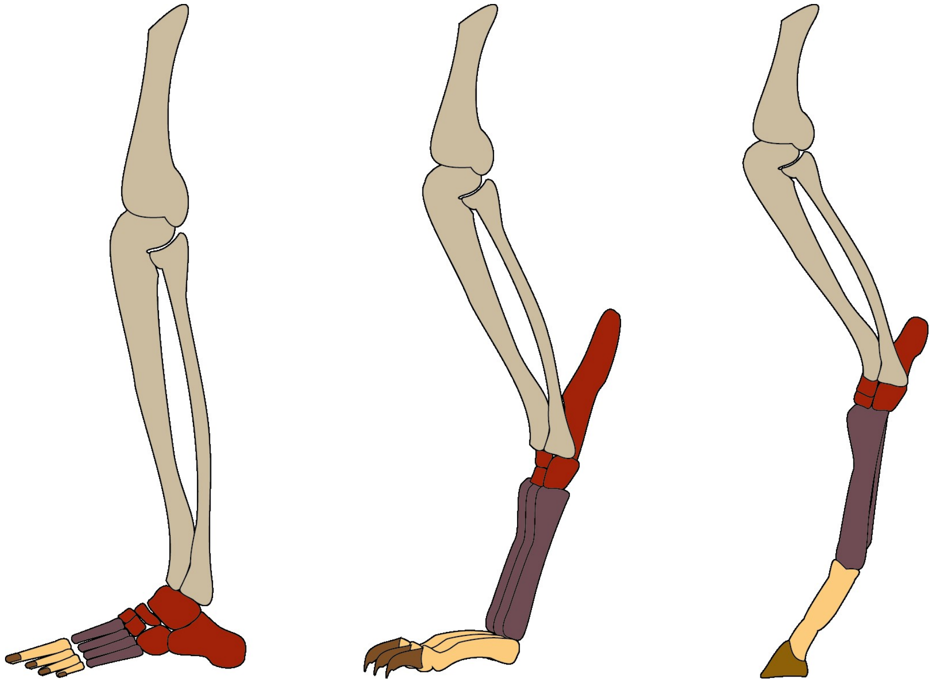
Foot energy loss -> heat dissipation?



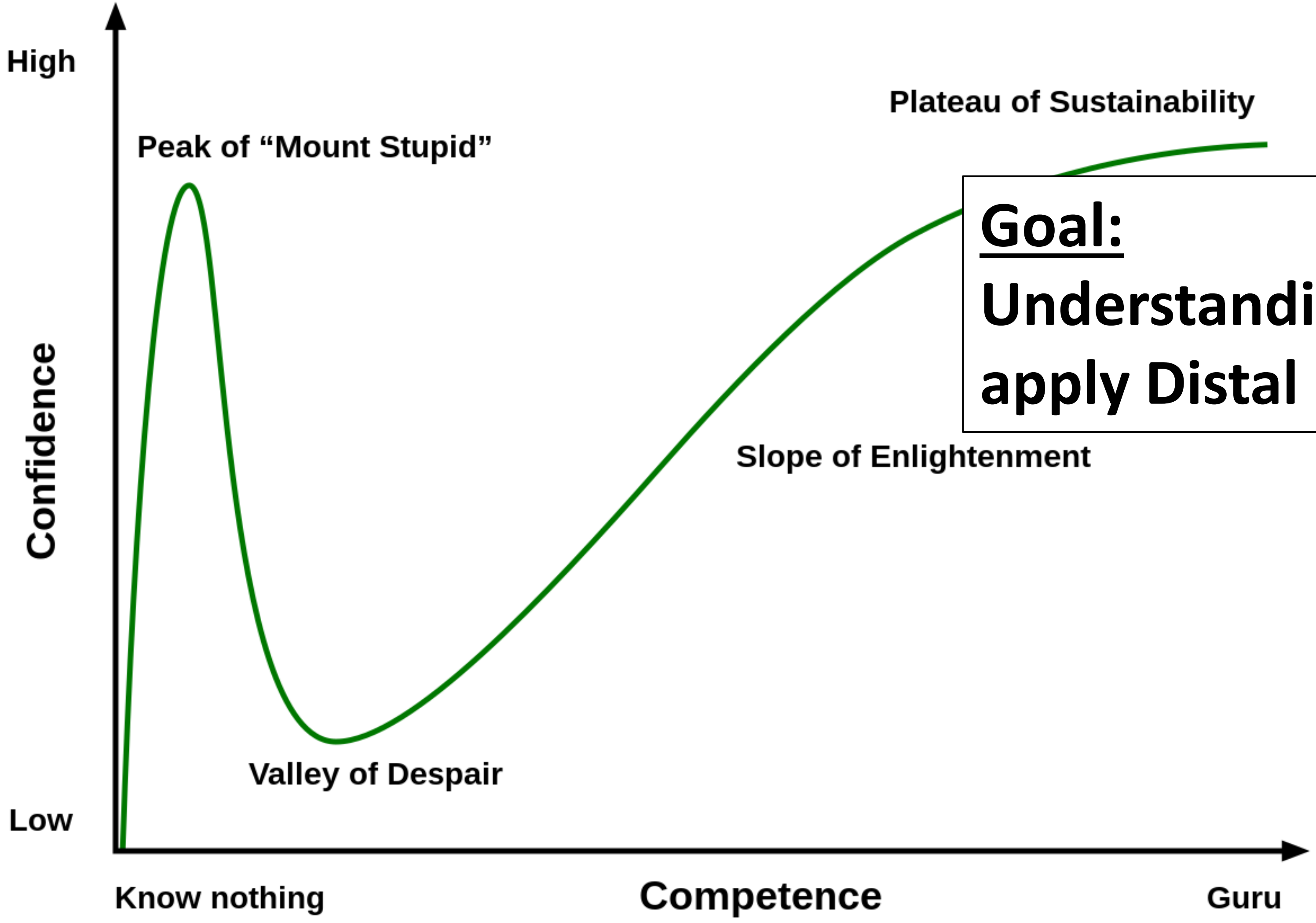


Diabetic Ulcers

Comparing structures across species and artificial limbs



Workshop Goal: Slope of Enlightenment



<u>Goal:</u>
Understanding & ability to apply Distal Power analysis

Acknowledgements

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