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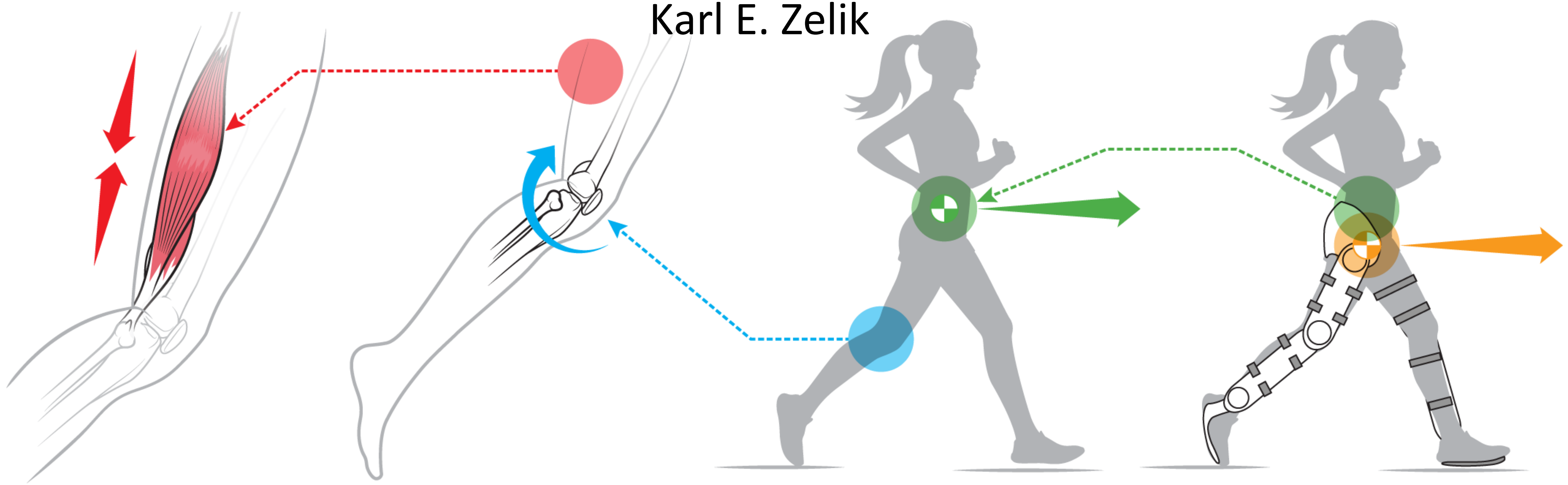
Towards a Cohesive, Multi-Scale Understanding of Biomechanics

Karl E. Zelik



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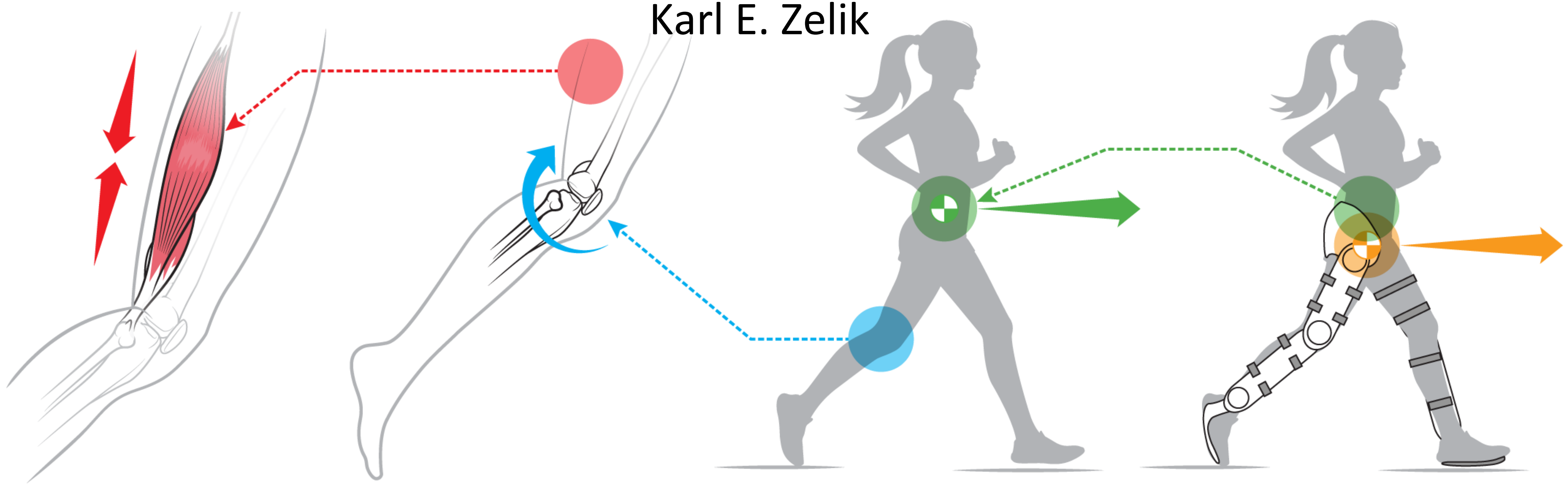

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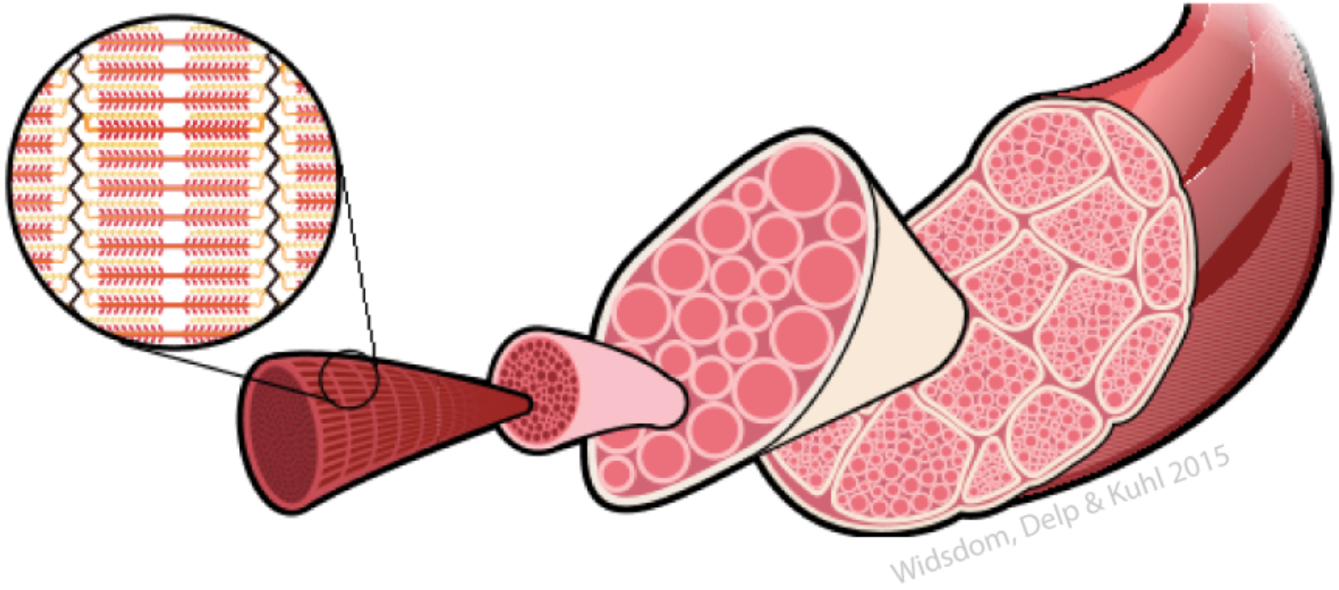
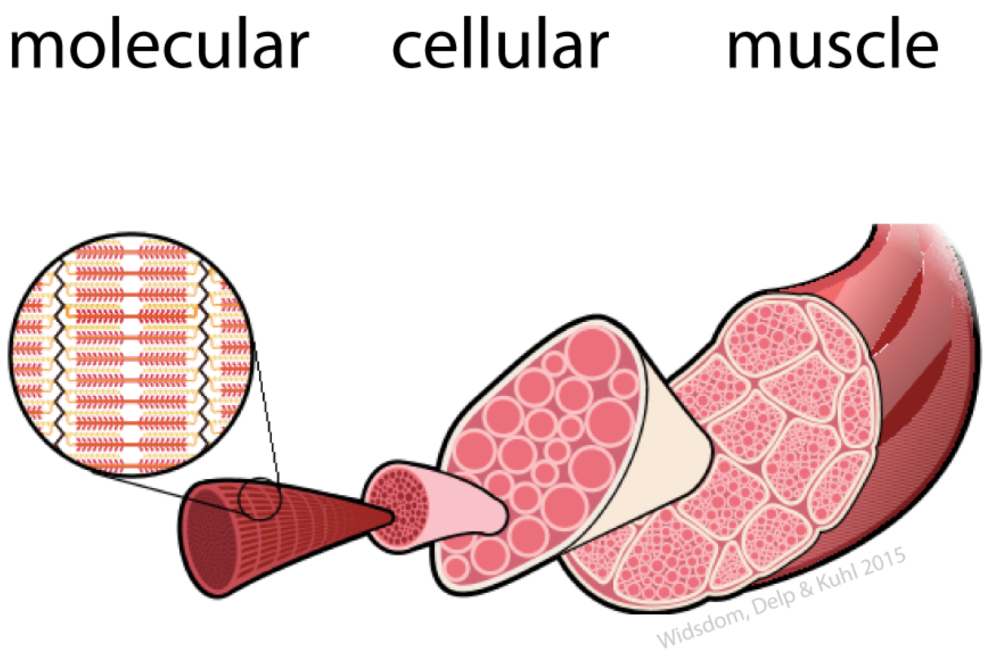
Tutorial: modeling multi-scale biomechanics

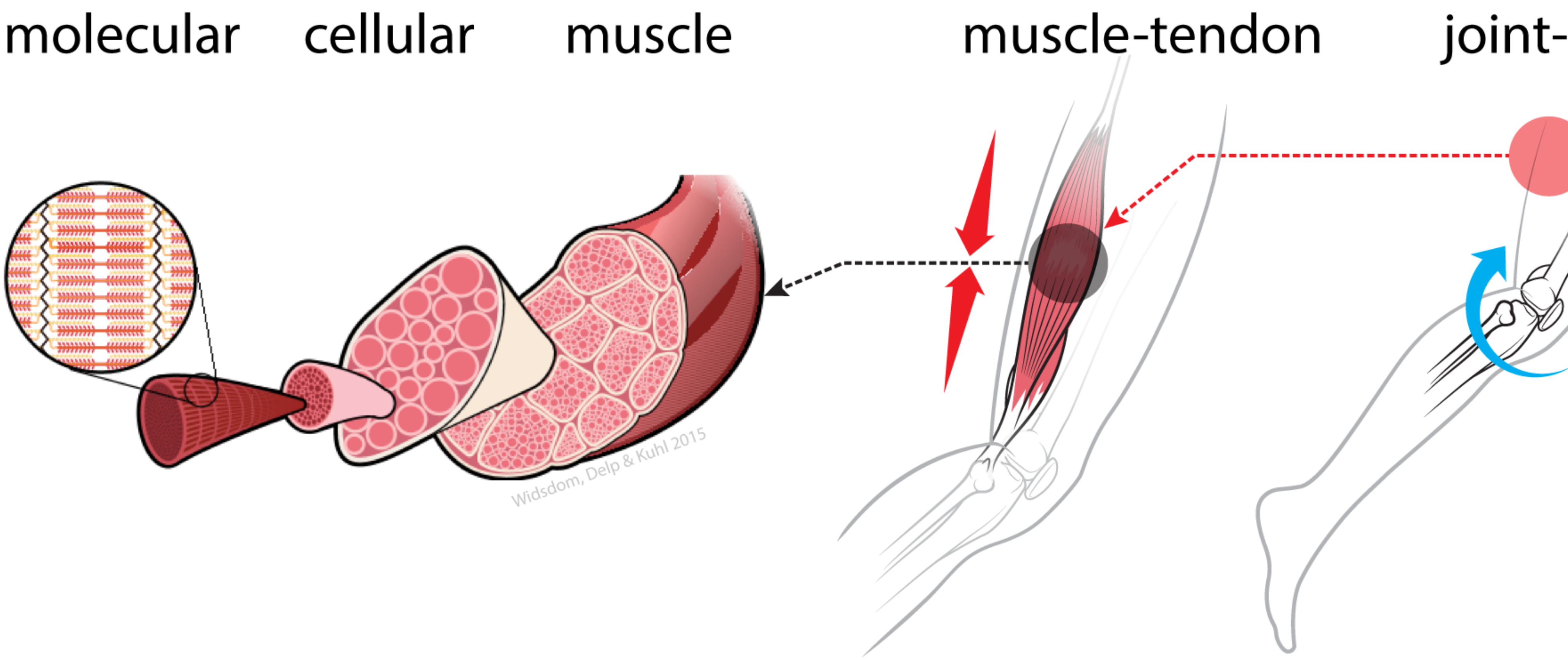
molecular cellular muscle



Developing a cohesive, multi-scale understanding



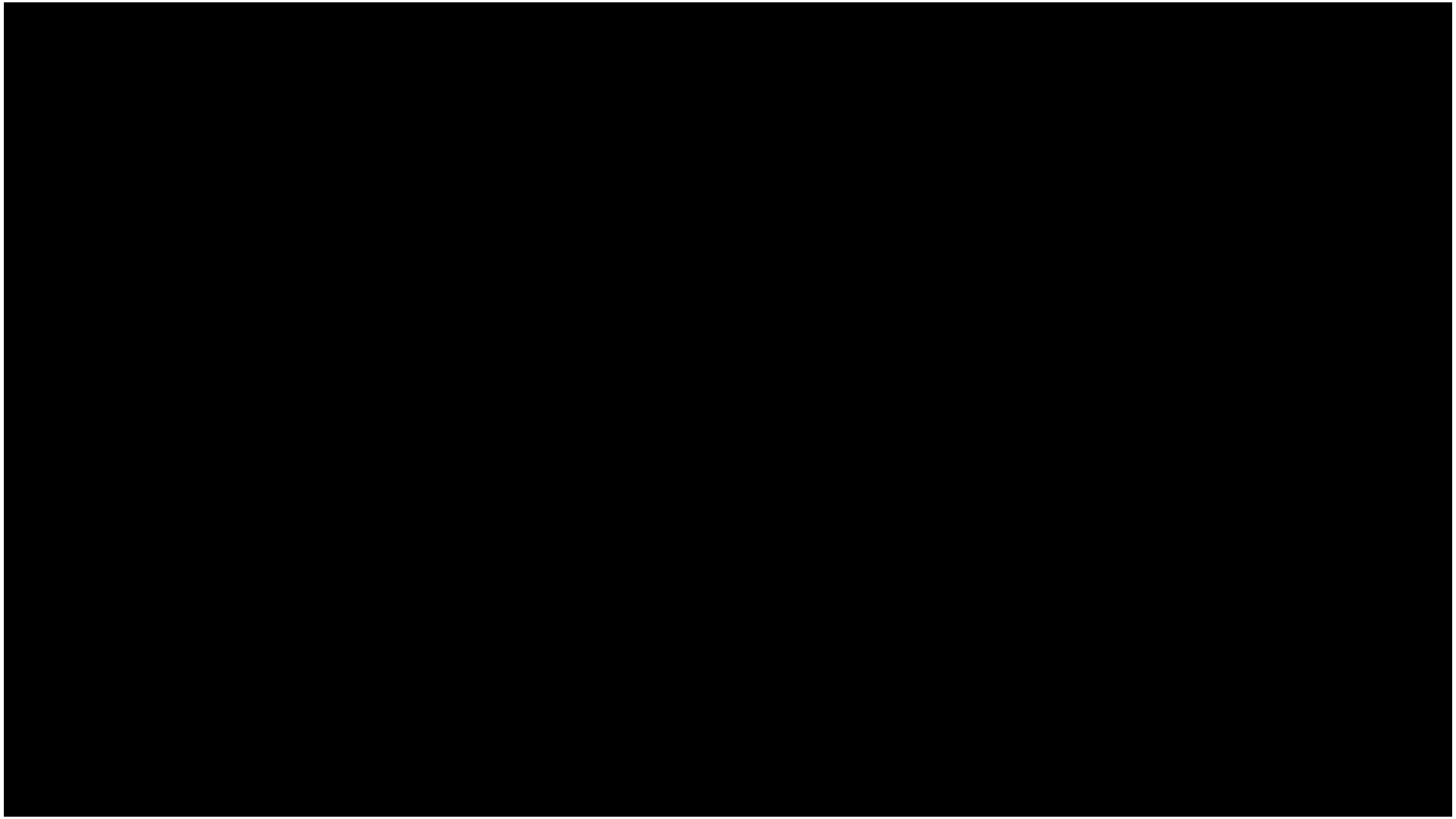
Developing a cohesive, multi-scale understanding



IKEA

Furniture warehouse

~~Furniture warehouse.~~ Warehouse of potential furniture

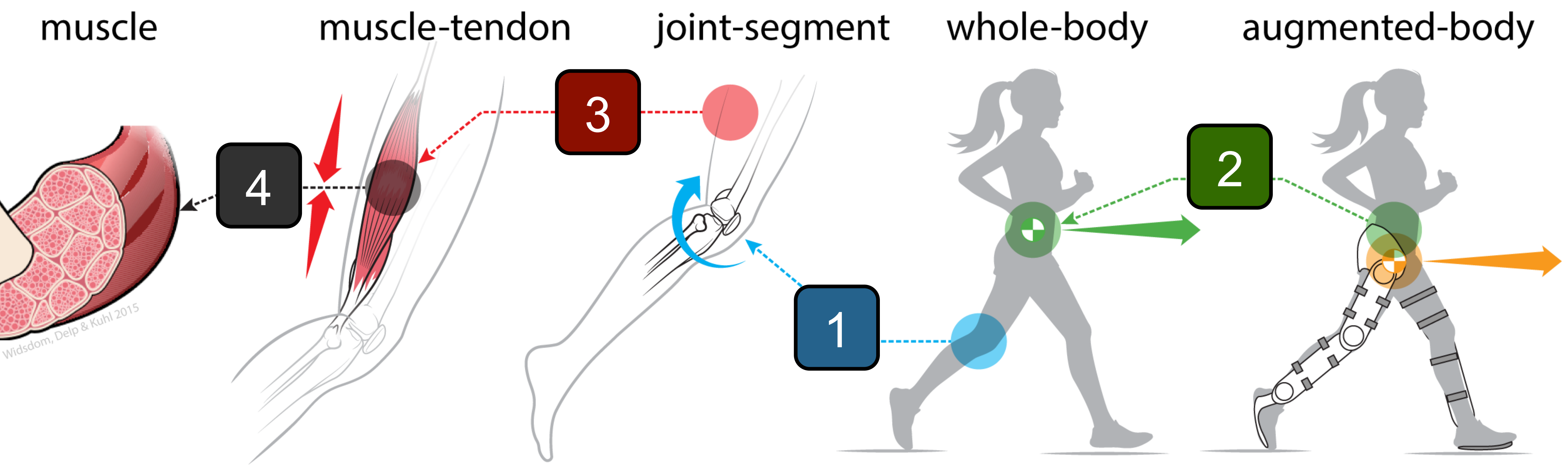


Multi-scale biomechanics is like IKEA furniture

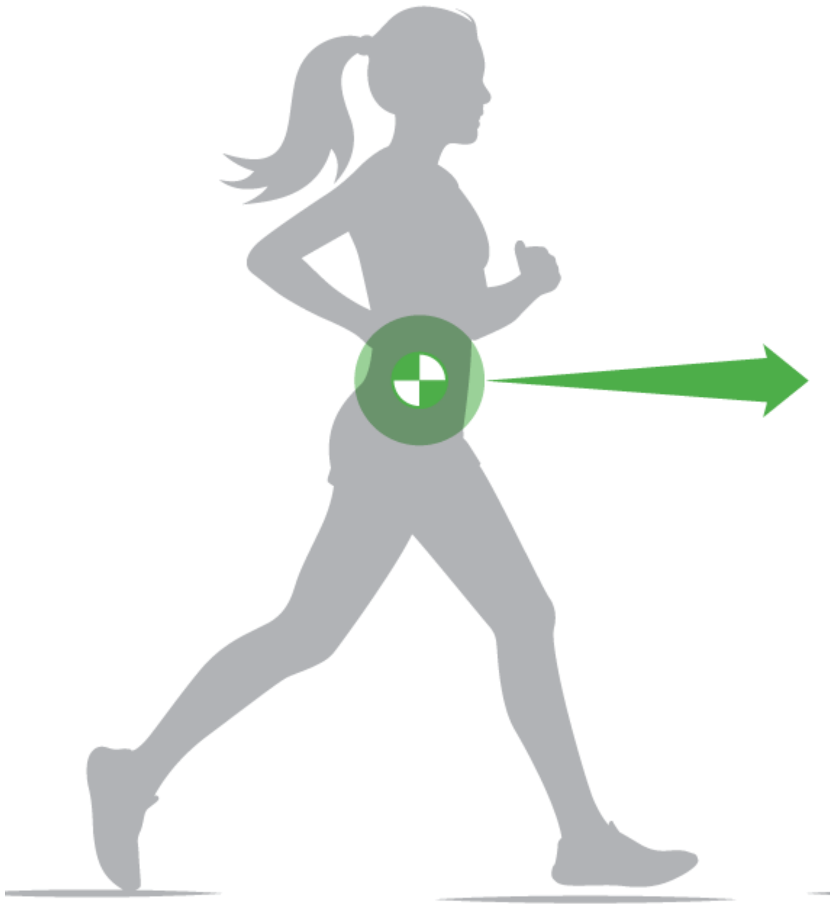
1. It’s complicated
2. Sometimes there are leftover parts
3. Sometimes parts seem to be missing

Discrepancies provide important insight!

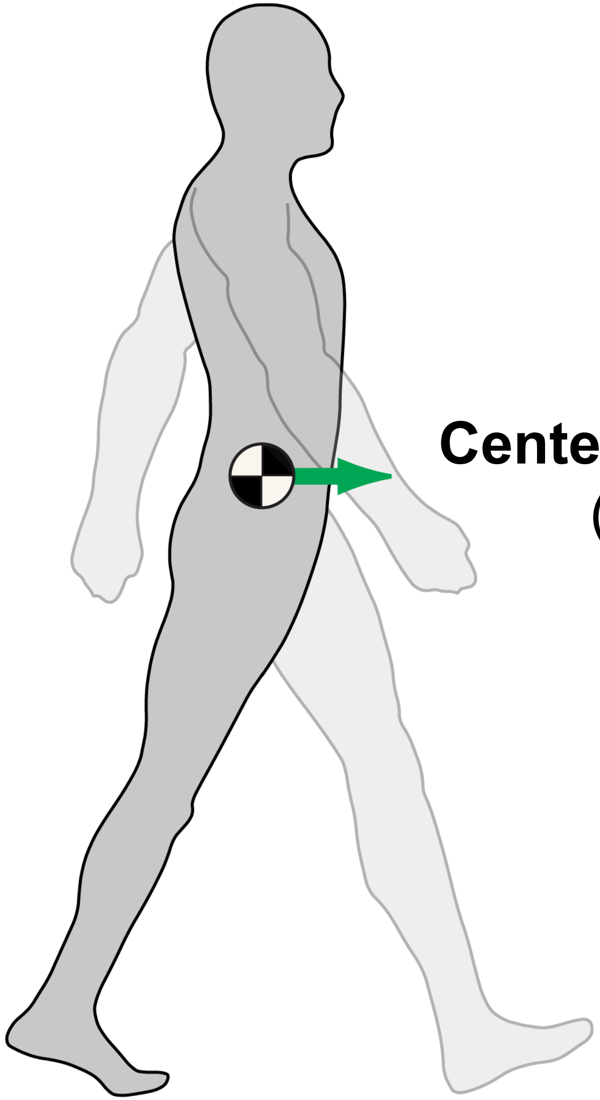
Estimates at one scale should be consistent with others



Whole-Body



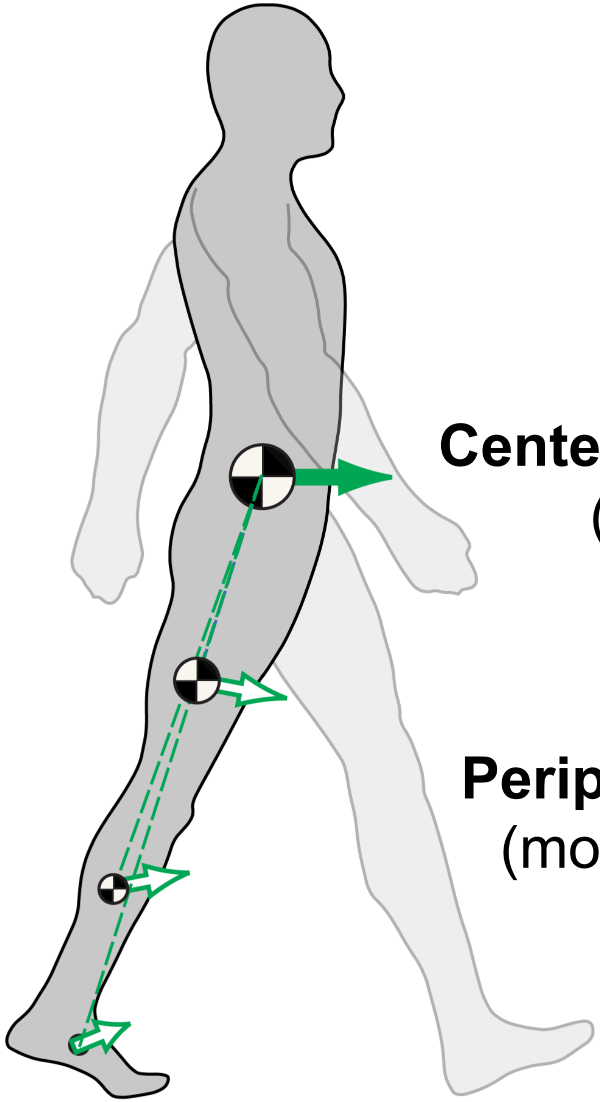
Estimate energy changes on/about body's center-of-mass



Center-of-Mass (COM) energy change
(estimated from force plates)

$$\int F_{grf} \cdot v_{COM} \, dt$$

Estimate energy changes on/about body's center-of-mass



Center-of-Mass (COM) energy change
(estimated from force plates)

$$\int F_{grf} \cdot v_{COM} \, dt$$

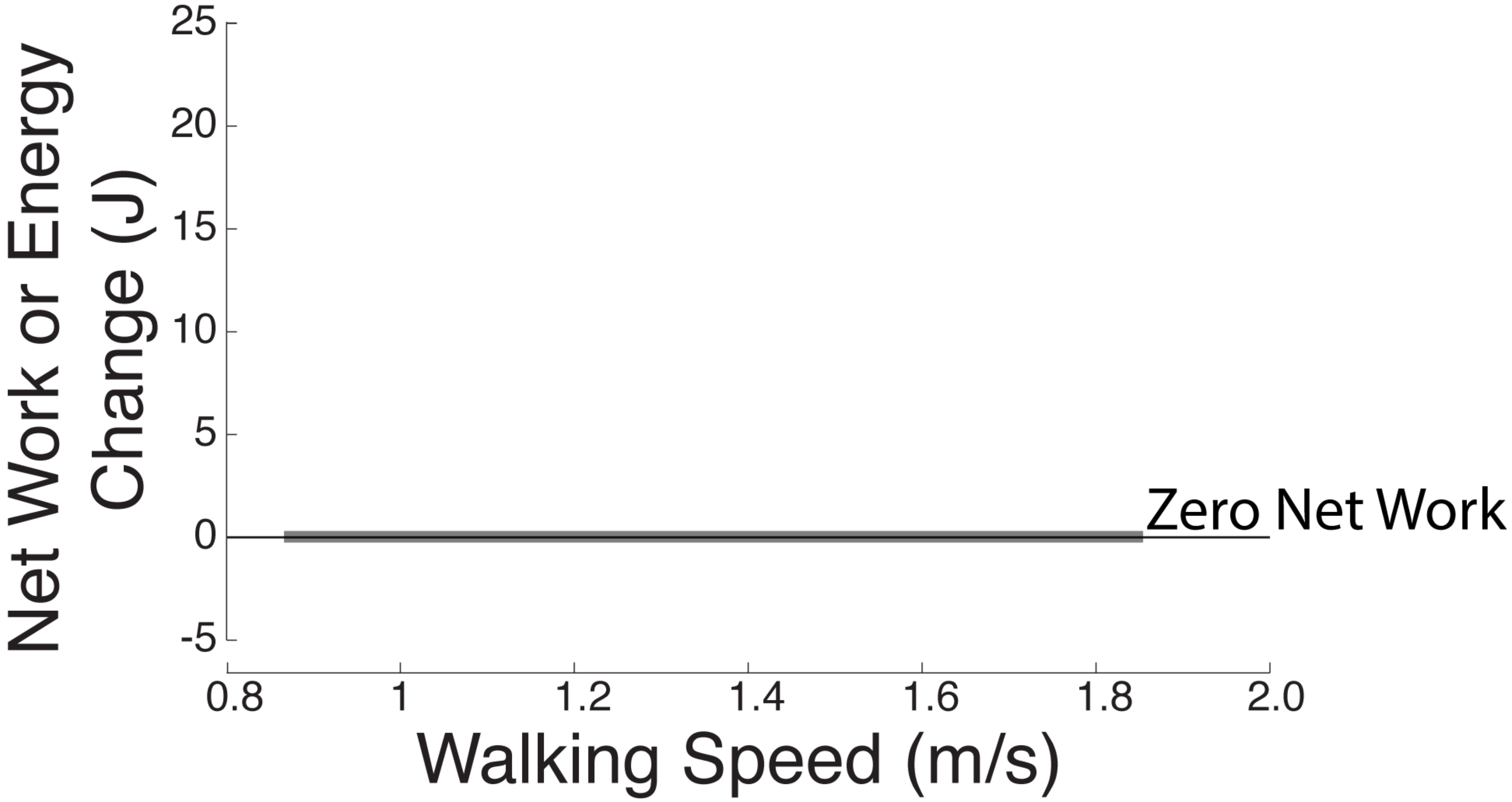
+

Peripheral energy change
(motion relative to COM)

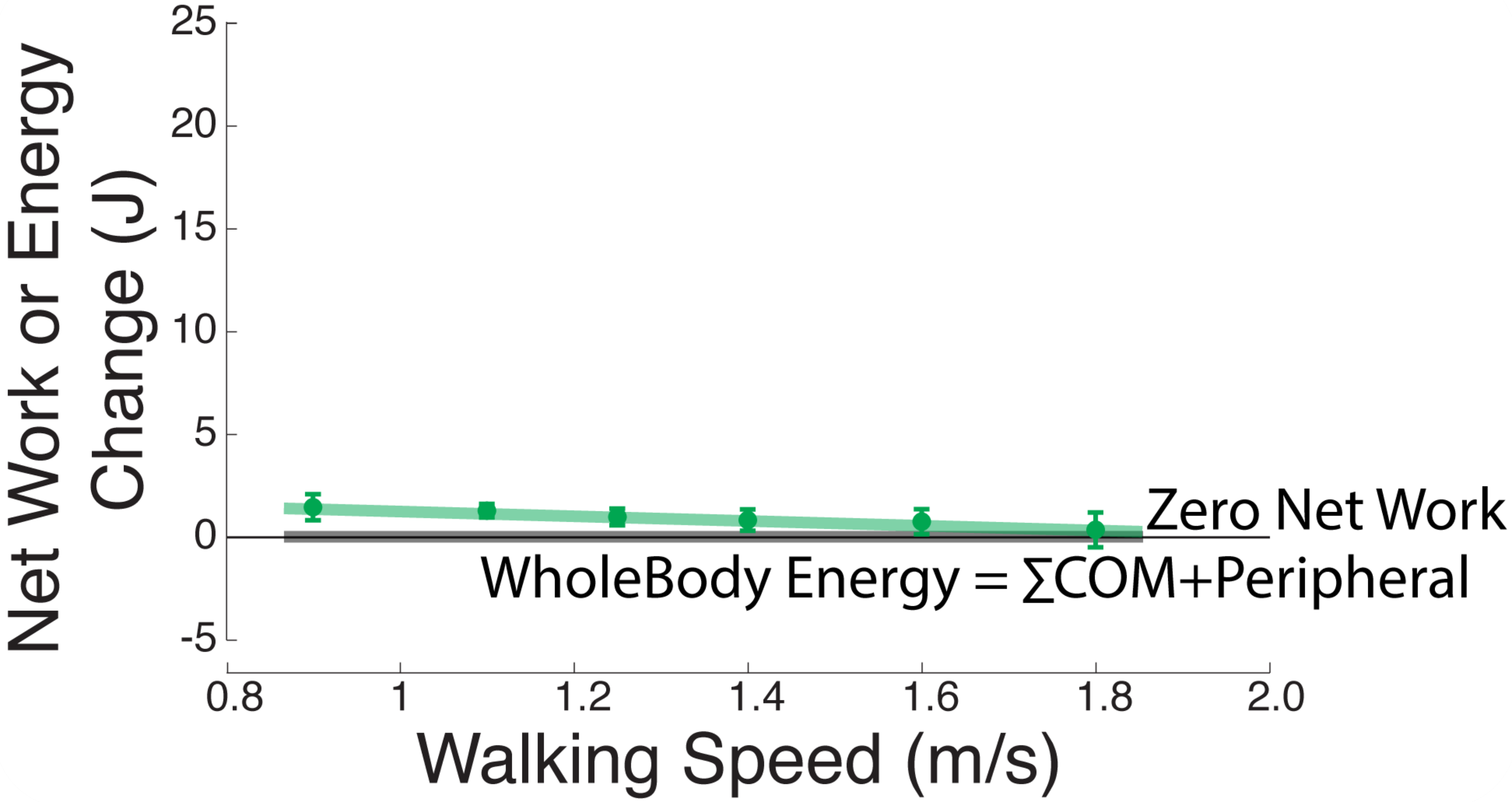
$$\sum_{\text{segments}} \frac{1}{2} m_s (v_s - v_{COM})^2 + \frac{1}{2} I_s \cdot \omega_s^2$$

**rigid-body assumptions*

Trust whole-body biomechanics b/c they add up properly

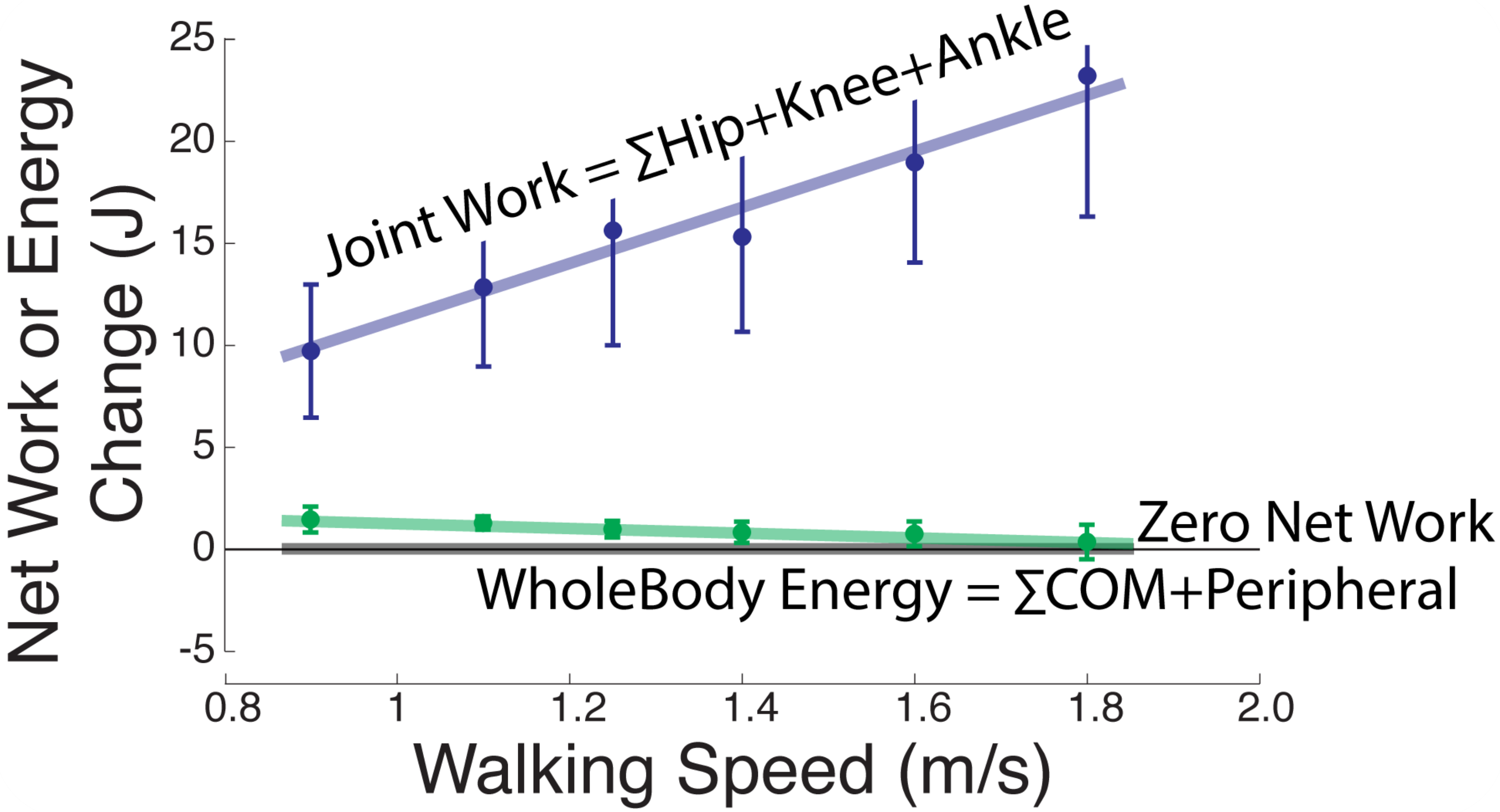


Trust whole-body biomechanics b/c they add up properly



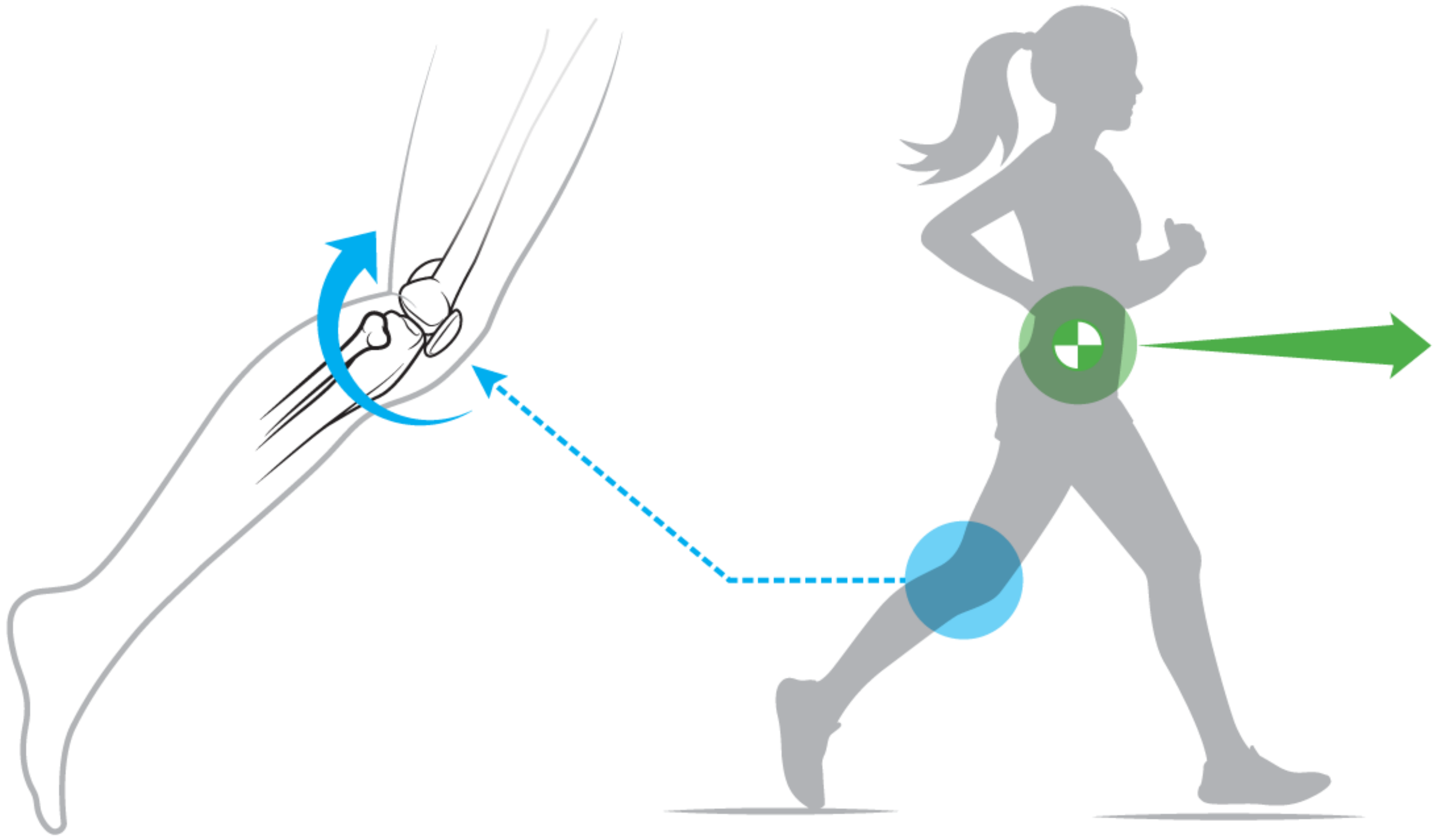
Zelik & Kuo 2010

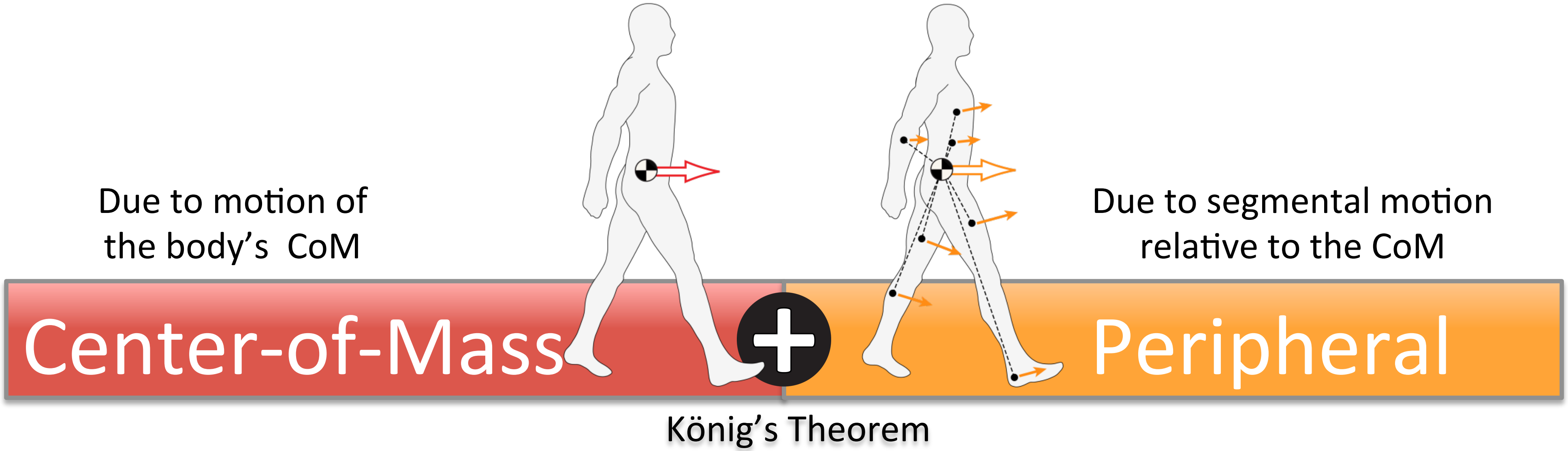
Trust whole-body biomechanics b/c they add up properly



Zelik & Kuo 2010

Joint-Segment ←→ Whole-Body

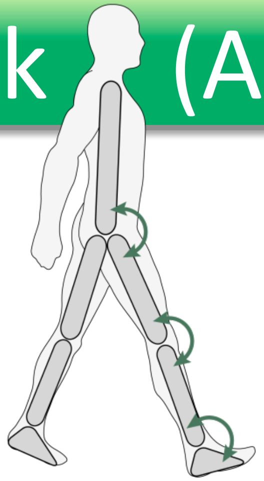




Zelik & Kuo 2010 & 2012

Whole-Body Energy Change

ideal scenario

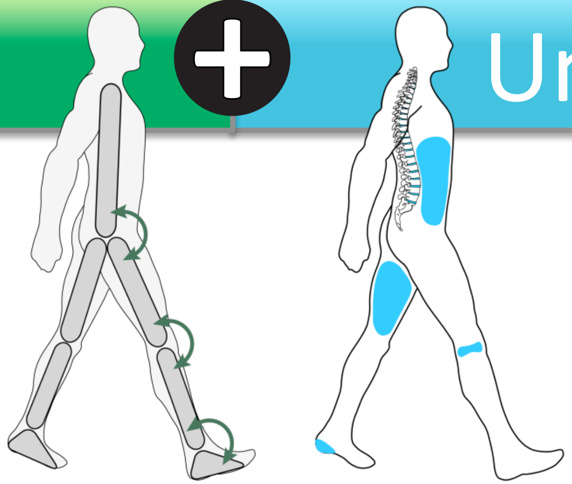
Joint Work  (Ankle + Knee + Hip + ...)

Due to muscles, tendons and ligaments about each joint

Zelik & Kuo 2010 & 2012

Whole-Body Energy Change

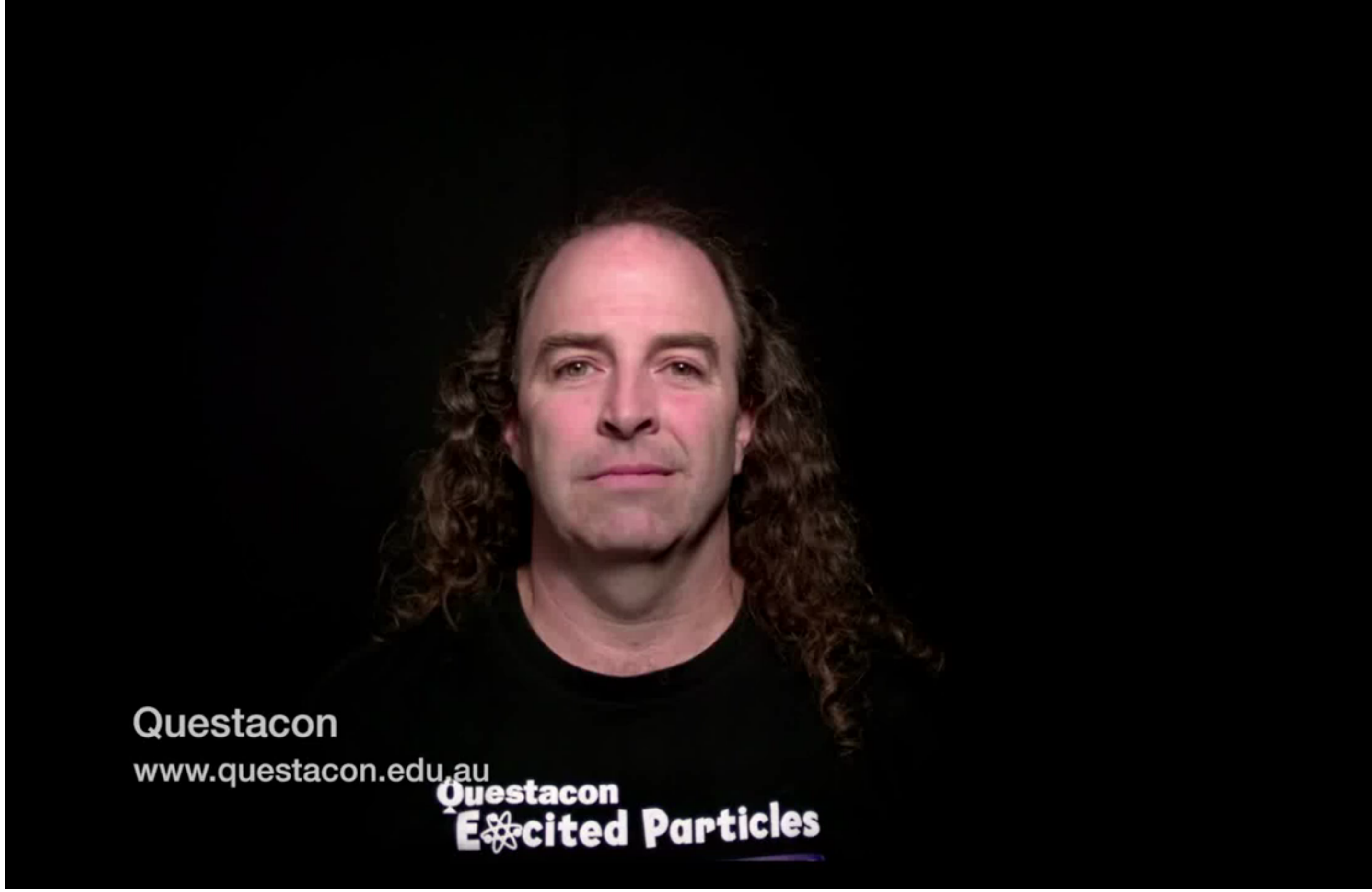
Joint + **Unmeasured**



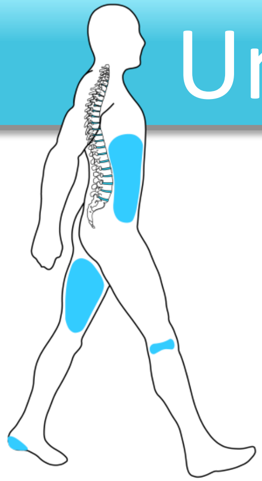
Due to muscles, tendons and ligaments about each joint

Everything else, notably work due to deformations of soft tissues

Zelik & Kuo 2010 & 2012



Unmeasured



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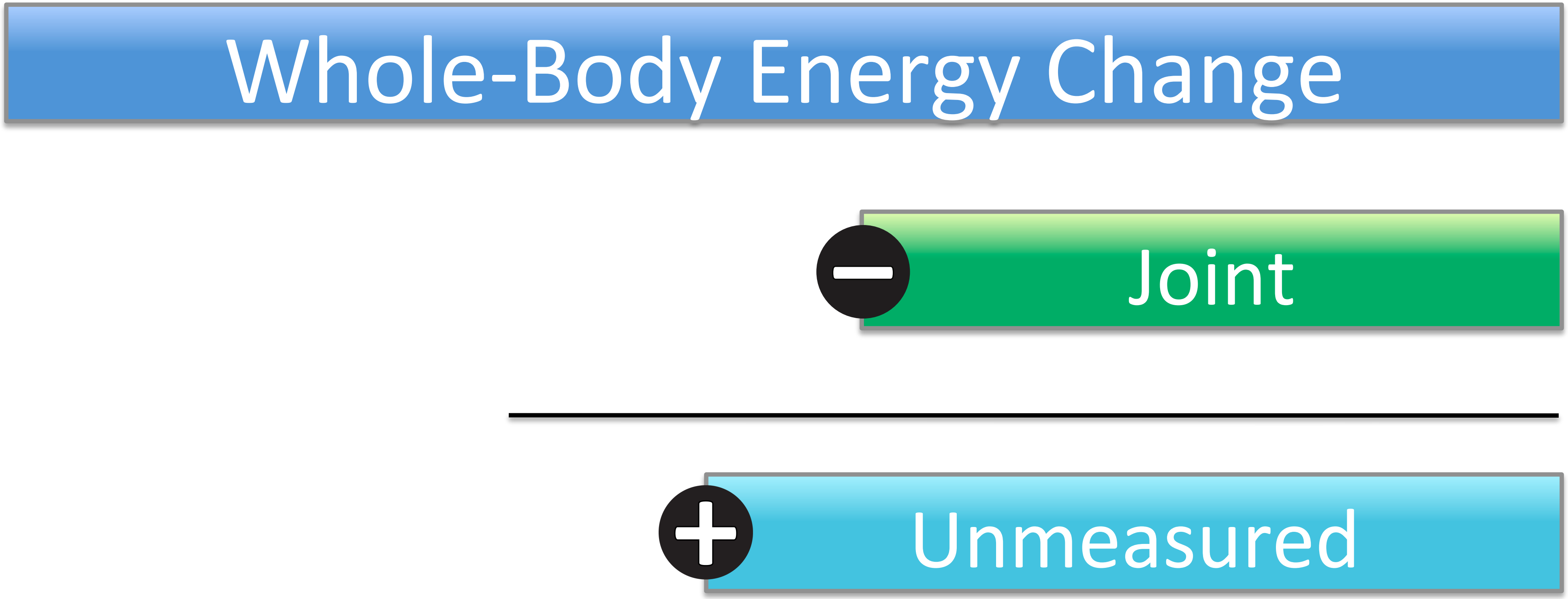
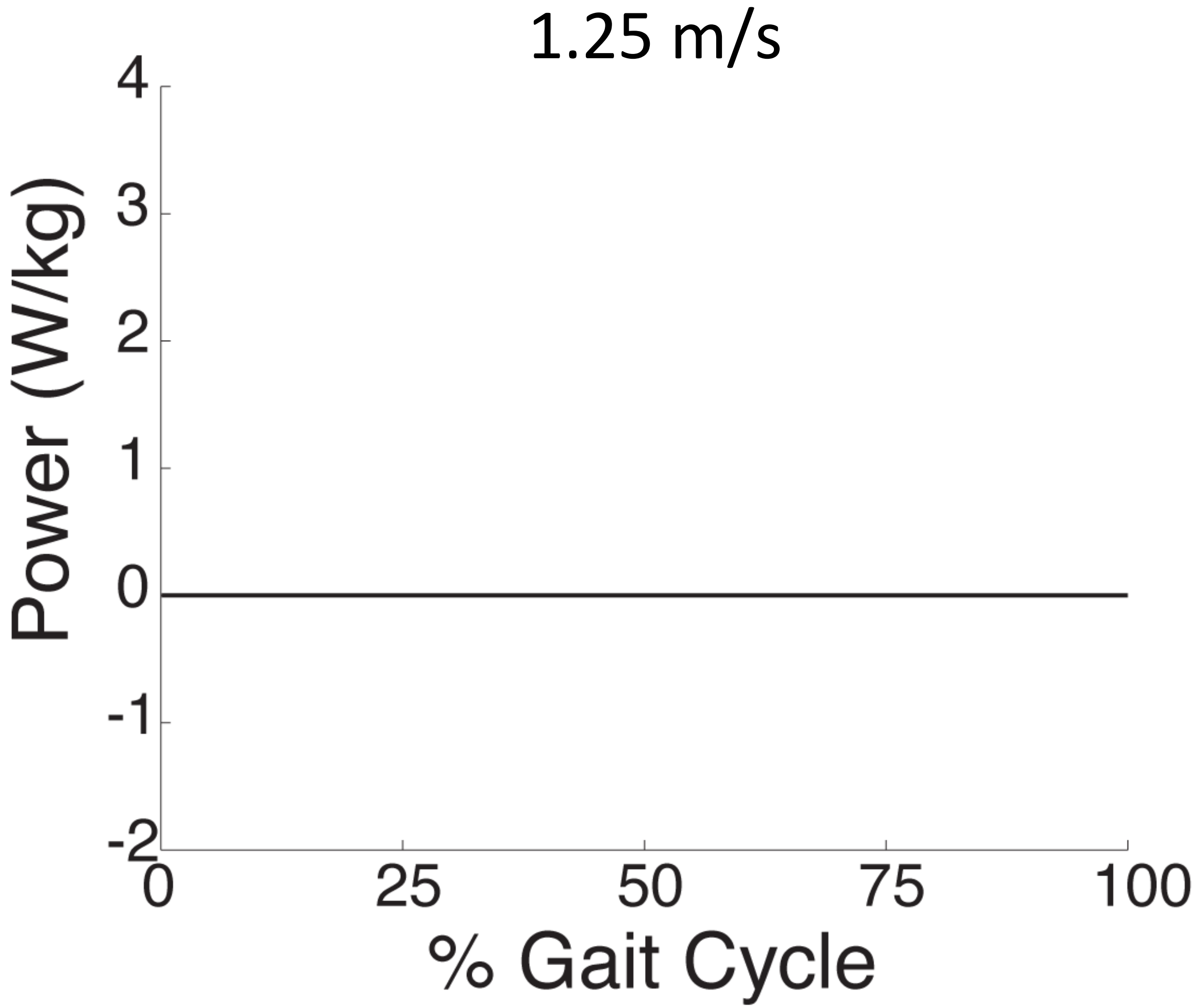


Zelik & Kuo 2010 & 2012

Center-of-Mass

Peripheral



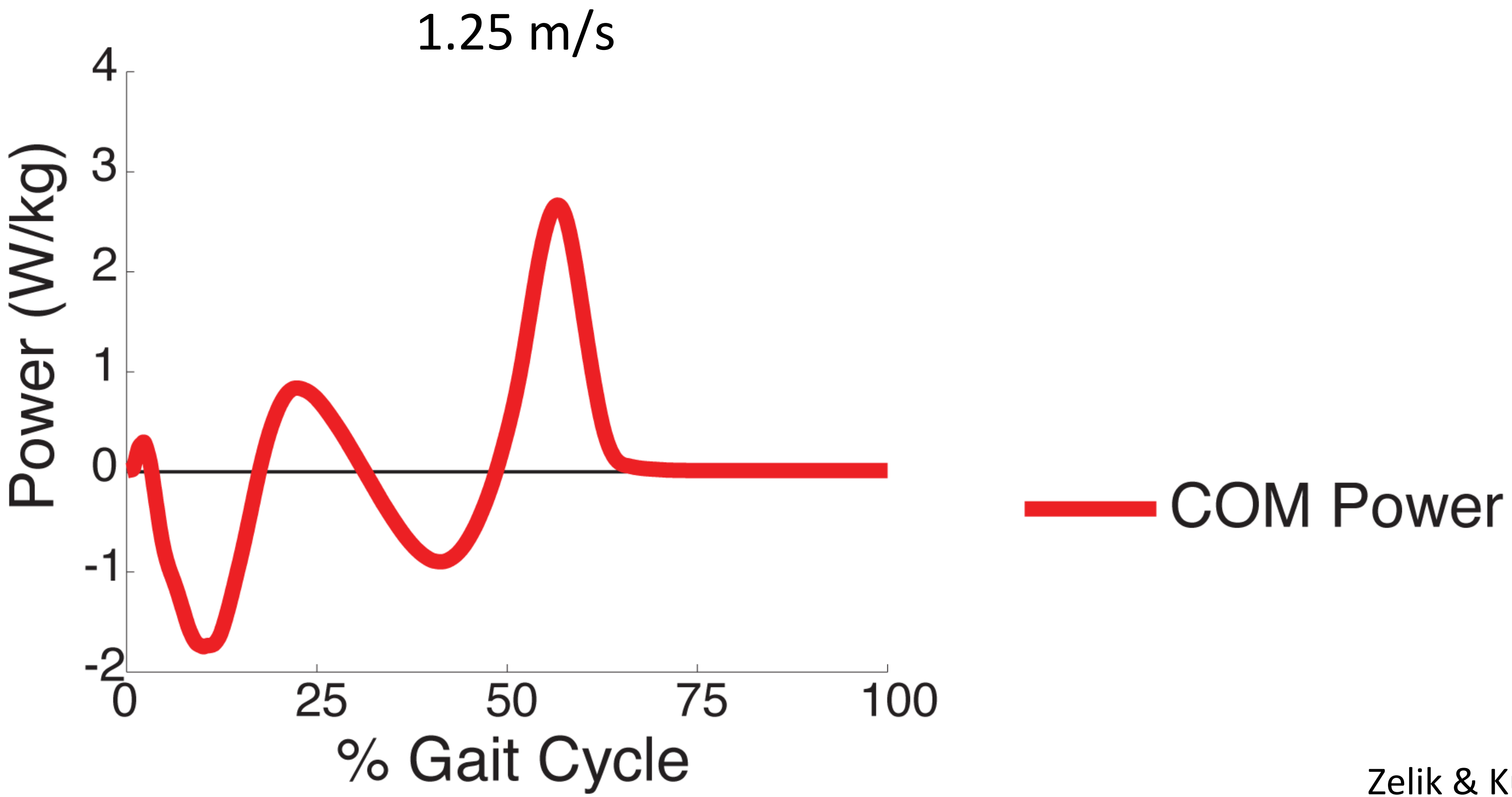
Joint

Unmeasured

Center-of-Mass

Peripheral

$F_{grf} \cdot v_{COM}$



Zelik & Kuo 2010

Joint

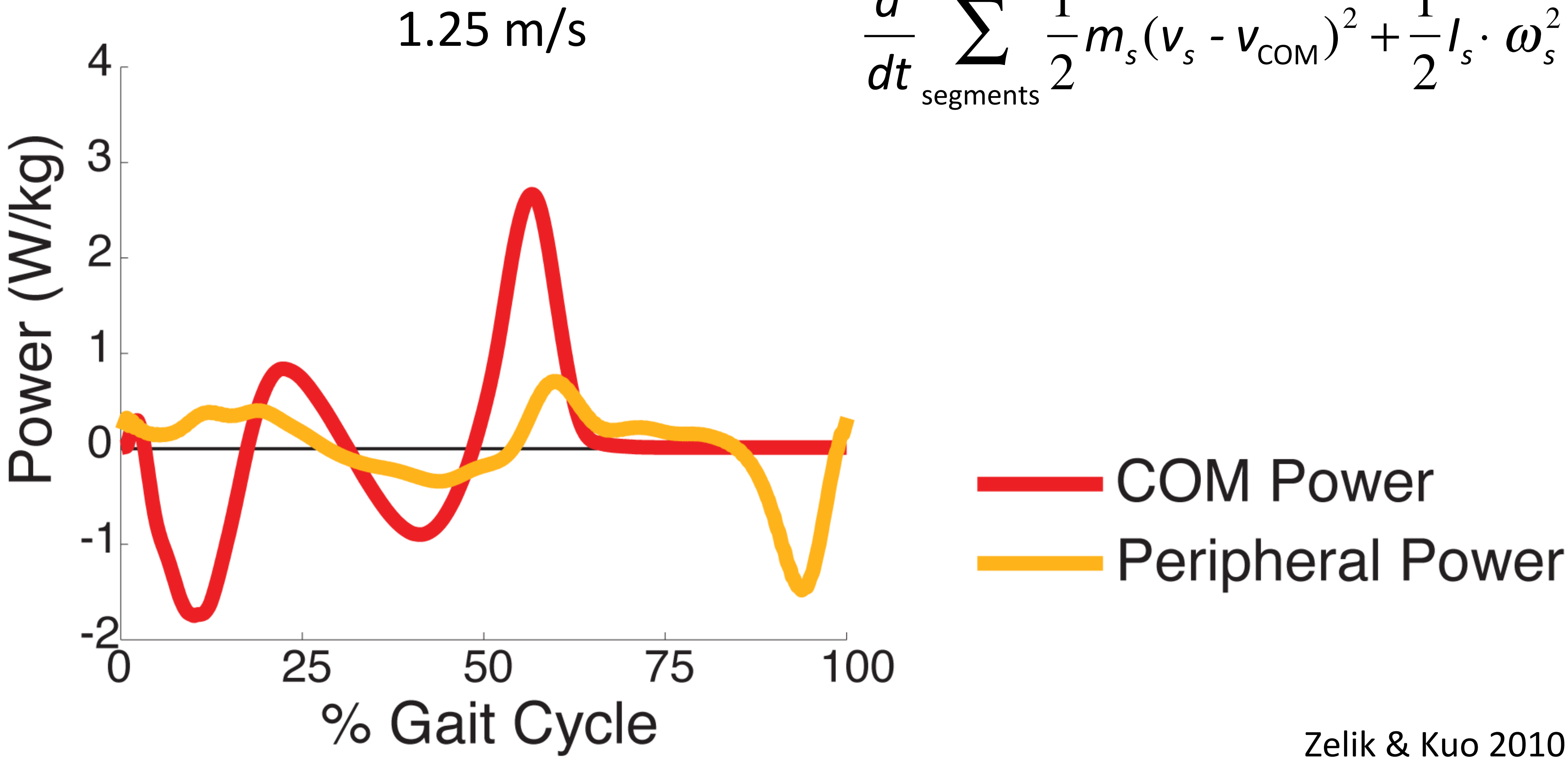
Unmeasured

Center-of-Mass

Peripheral

$F_{grf} \cdot v_{COM}$

$$\frac{d}{dt}\sum_{\text{segments}} \frac{1}{2} m_s (v_s - v_{COM})^2 + \frac{1}{2} I_s \cdot \omega_s^2$$

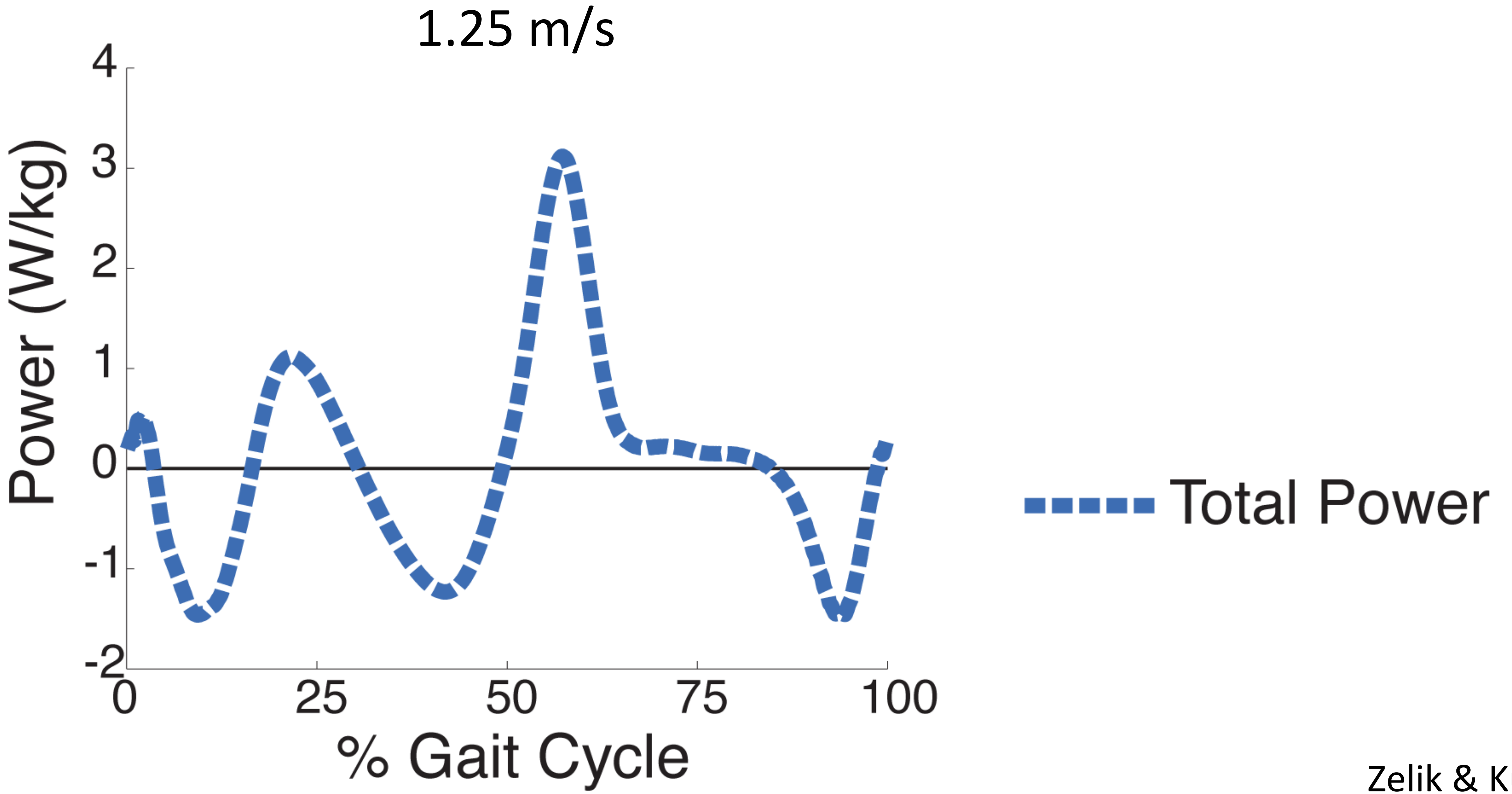


Zelik & Kuo 2010

Joint

Unmeasured

Whole-Body

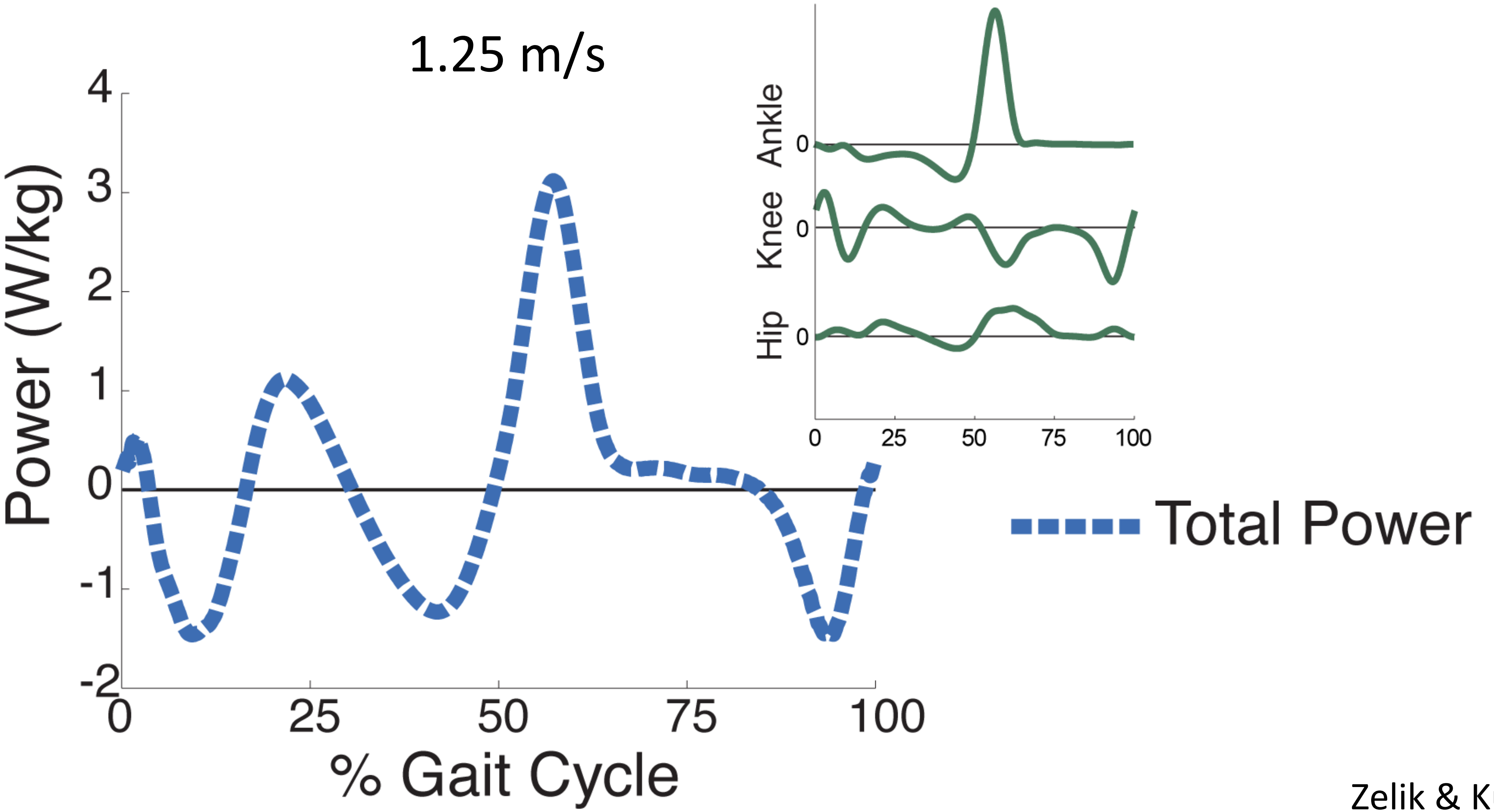


Zelik & Kuo 2010

Joint

Unmeasured

Whole-Body



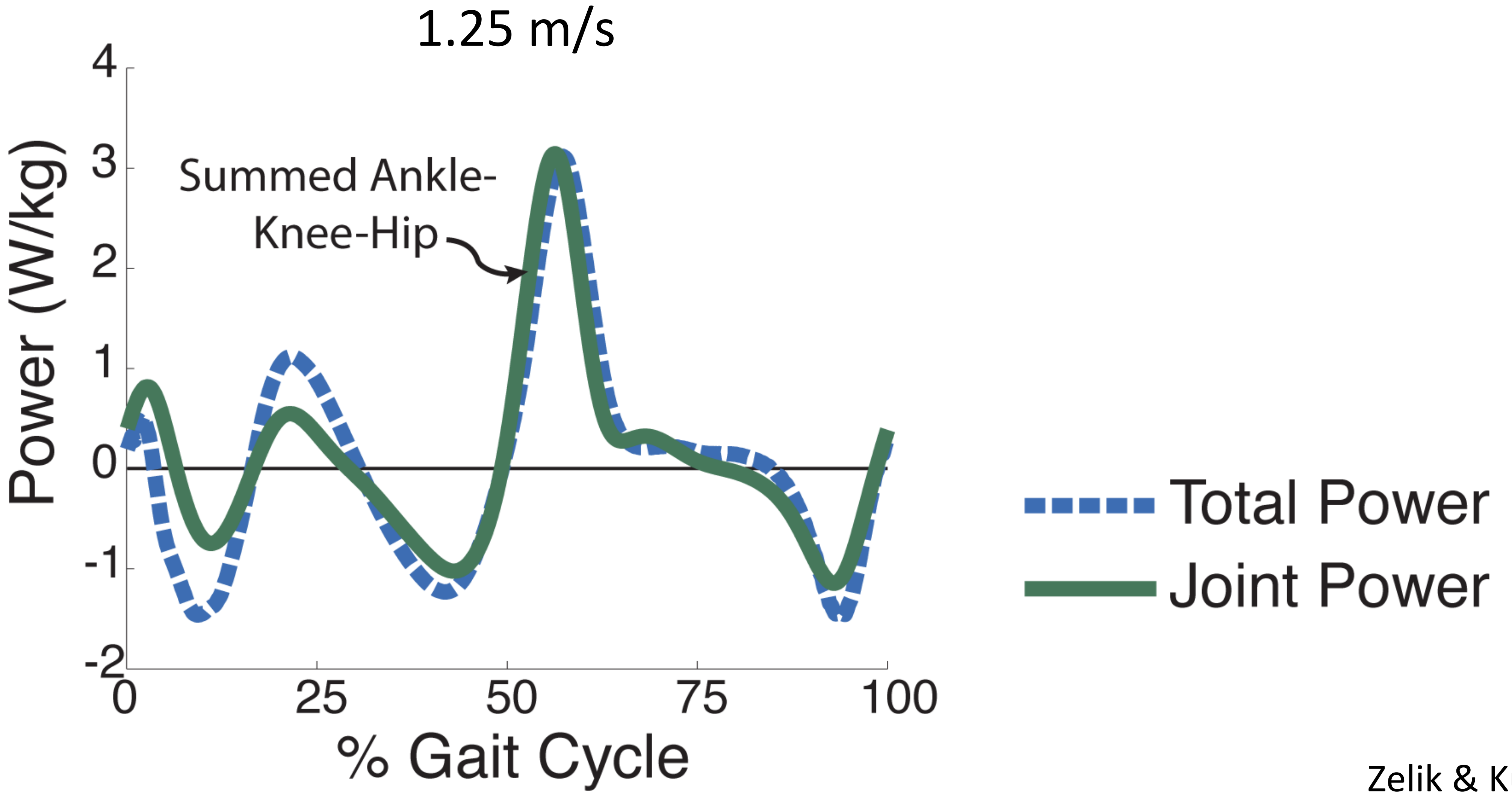
$$\sum_{joints} M_j \cdot \omega_j$$

Zelik & Kuo 2010

Joint

Unmeasured

Whole-Body



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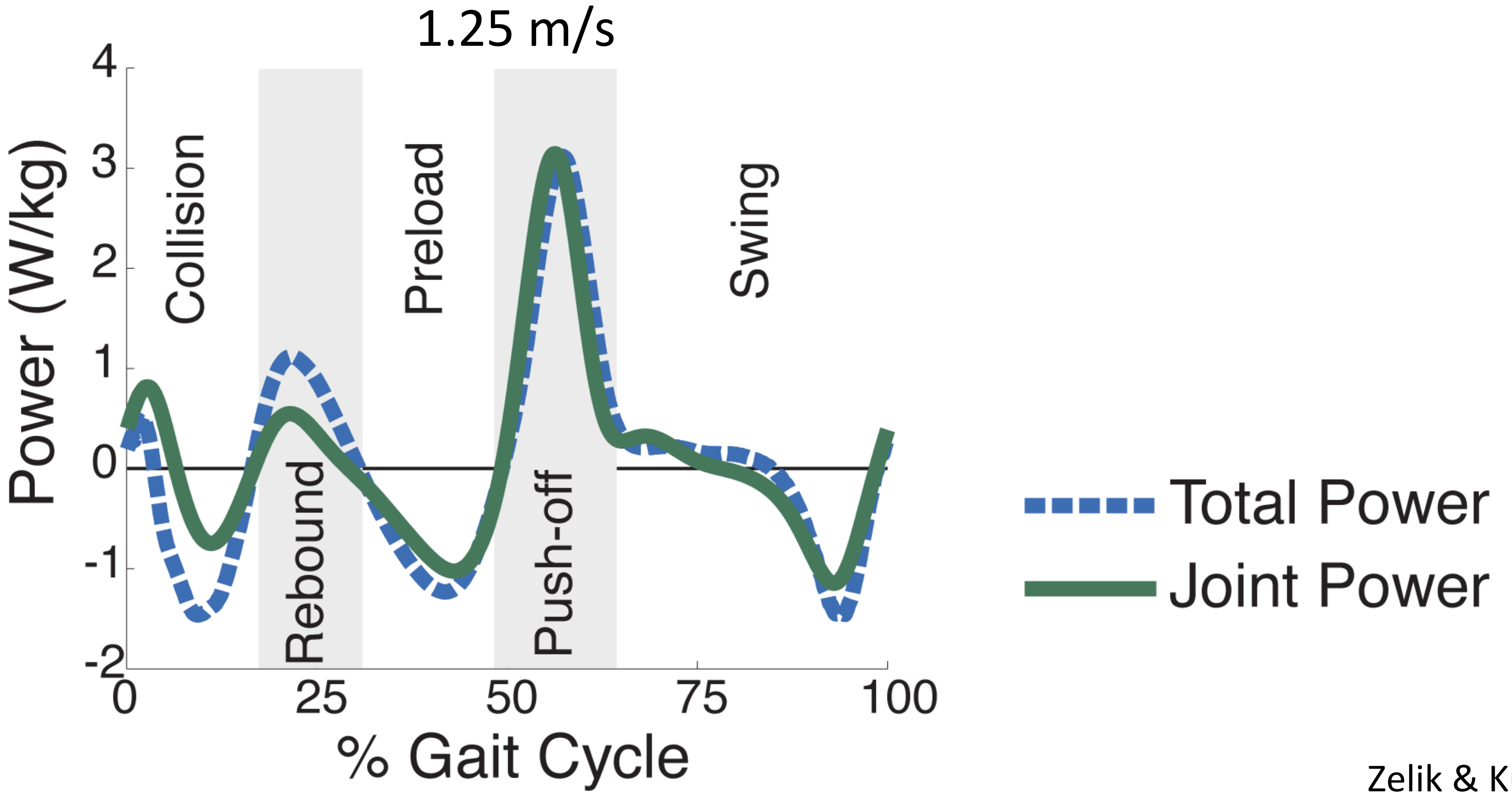
Zelik & Kuo 2010

Joint

Unmeasured

Whole-Body



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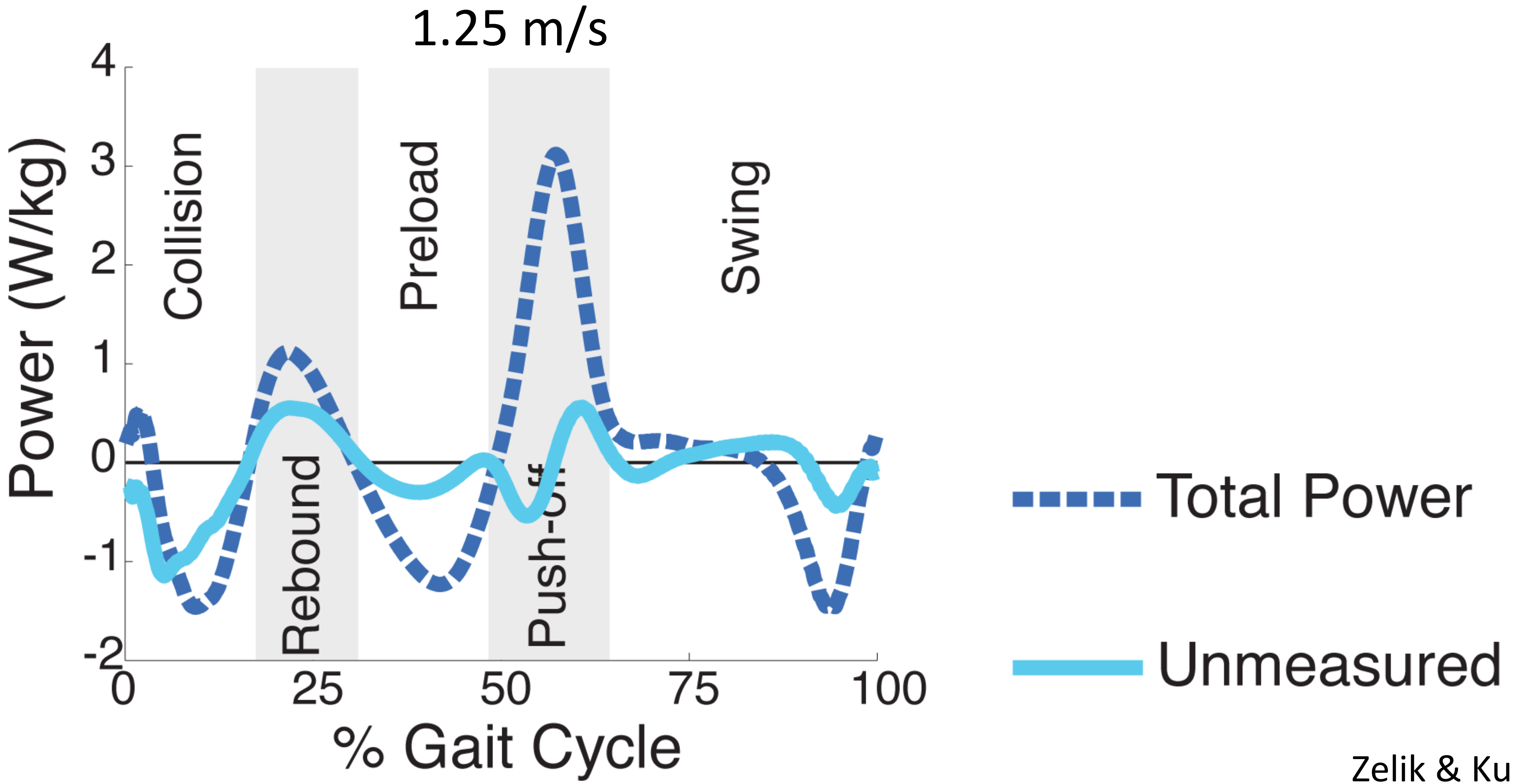
Zelik & Kuo 2010

Joint

Unmeasured

Whole-Body



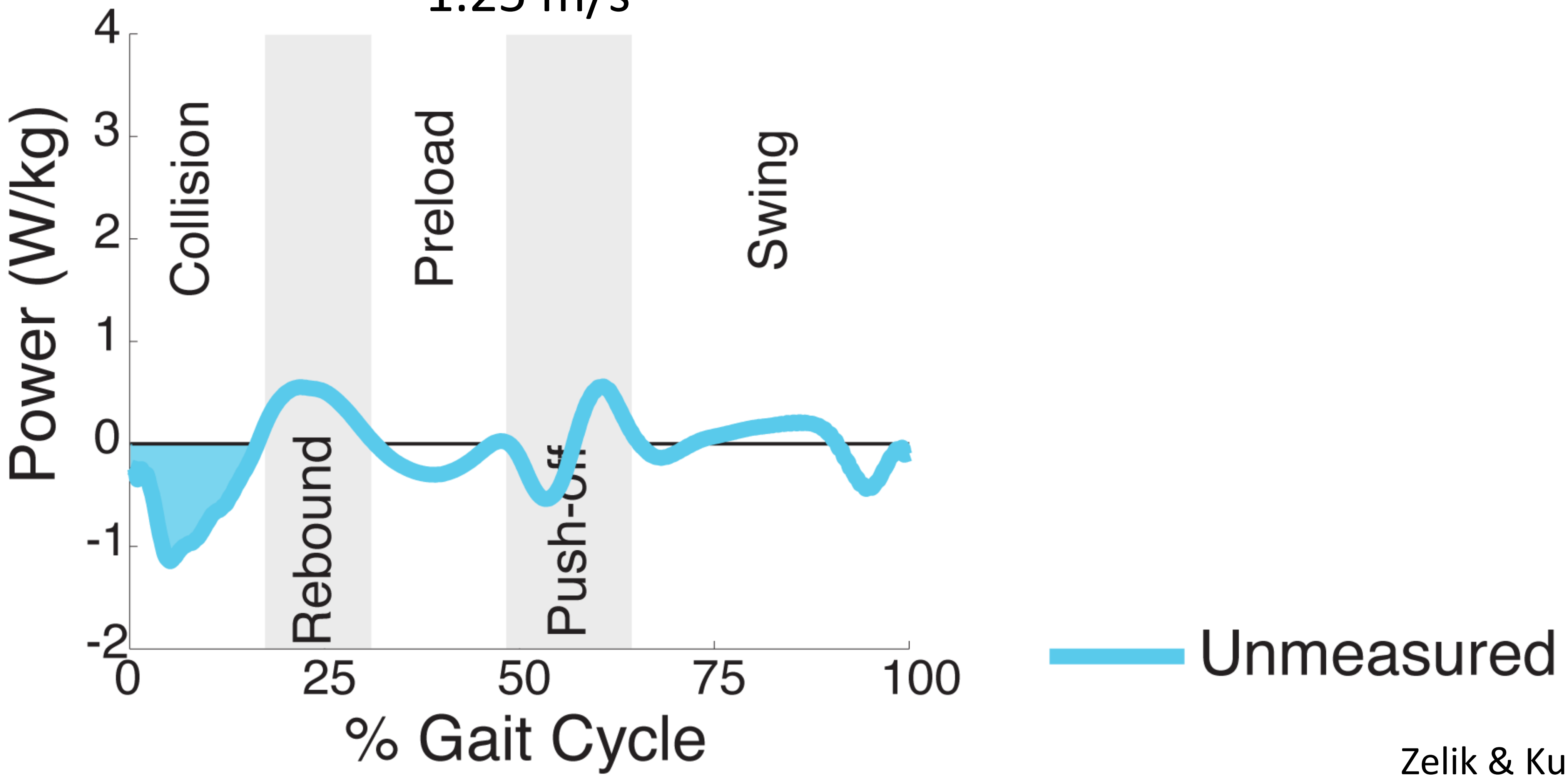
Zelik & Kuo 2010

Joint

Unmeasured

Whole-Body

1.25 m/s

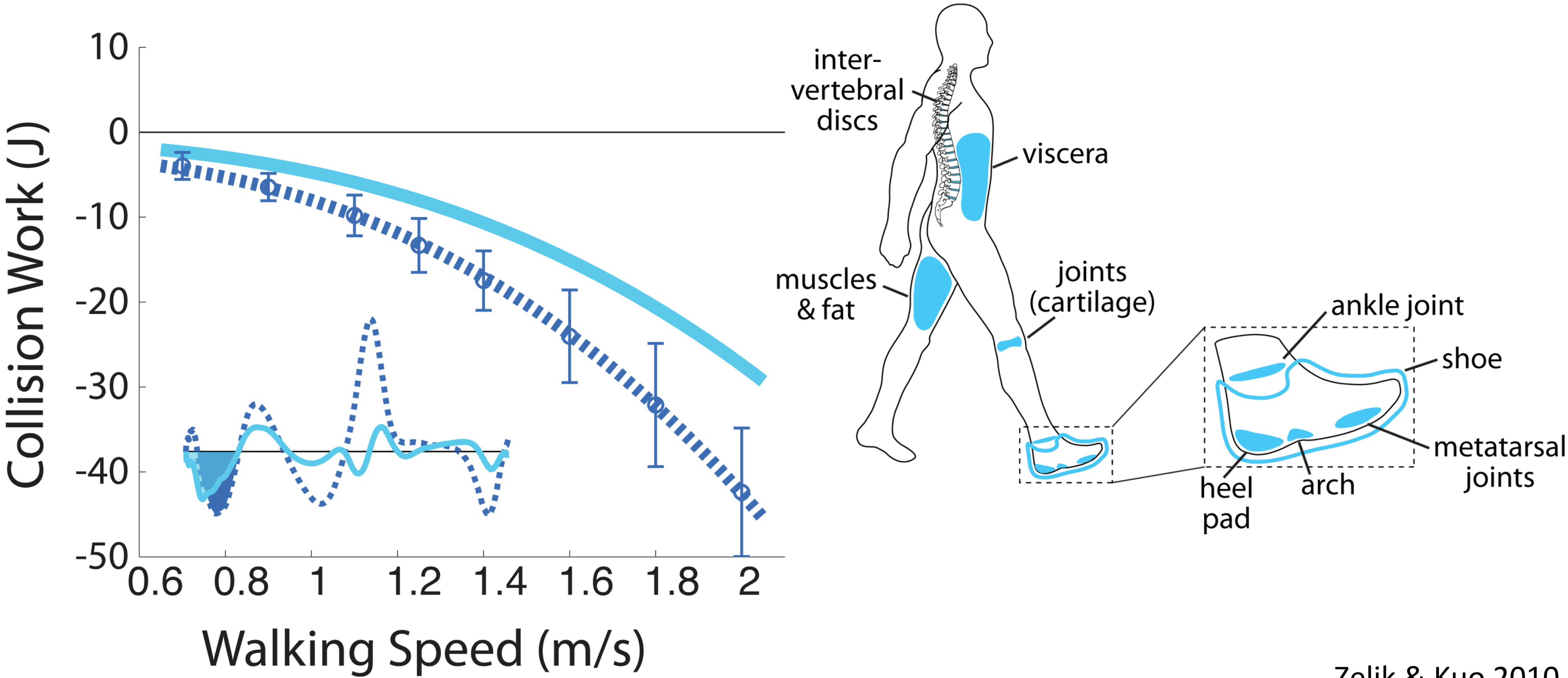


Zelik & Kuo 2010

Joint

Unmeasured

Whole-Body



Zelik & Kuo 2010

Joint

Unmeasured

More evidence soft tissues absorb energy during collision

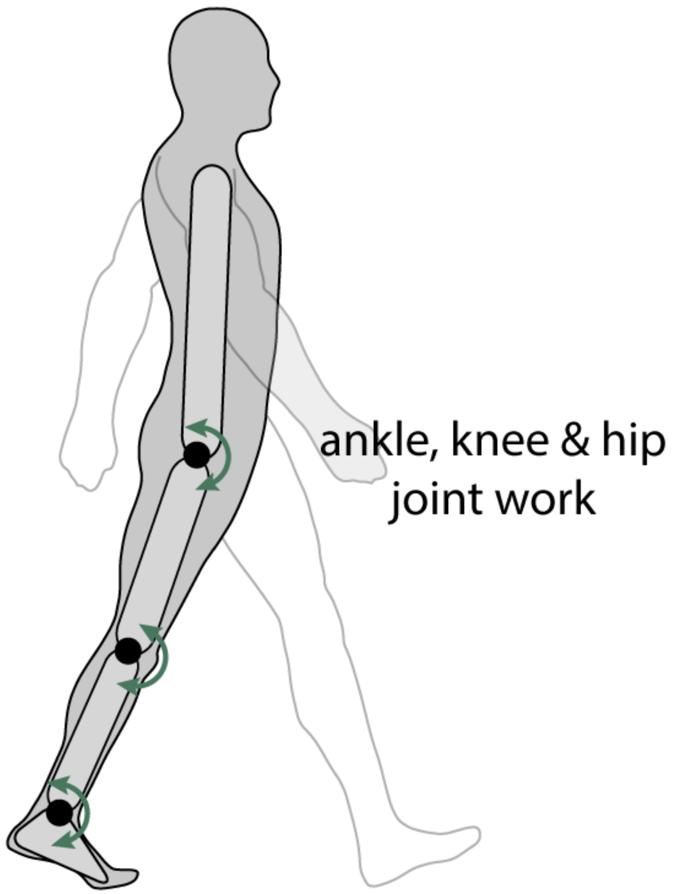
Based on similar energy accounting methods

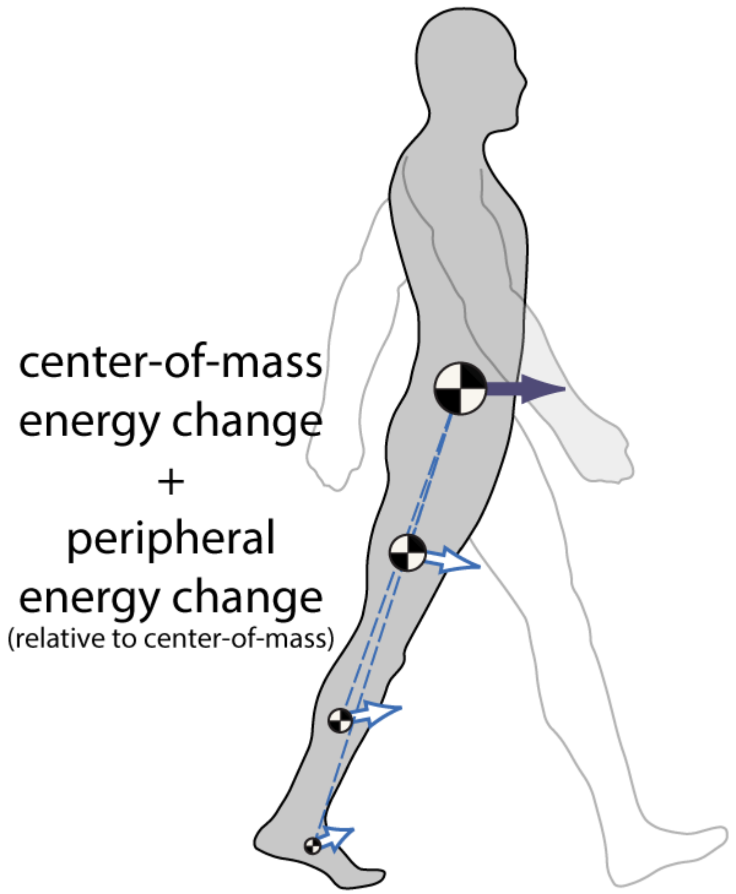
- Jump/drop landings (Zelik & Kuo 2012, Masters & Challis 2016)
- **Obese vs. non-obese gait (Fu et al. 2015)**
- Running (Riddick & Kuo 2016)
- Step-to-step transition (Soo & Donelan 2010)

Based on different methods

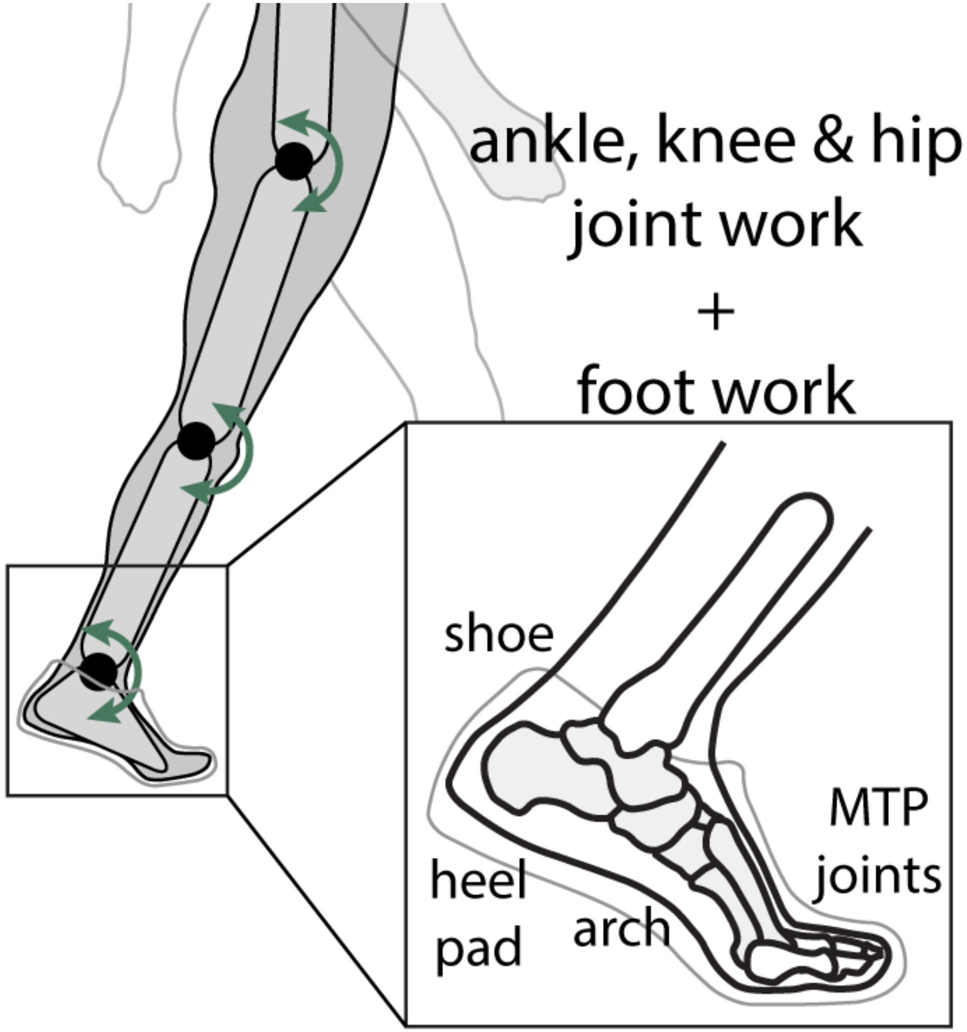
- Wobbling mass kinematics (Pain & Challis 2002, Gruber at al. 1998)
- Visceral pistoning (Cazzola 2010, Daley & Usherwood 2010)
- Incline/decline gait (DeVita et al. 2007)

Good news: agreement between scales, except for collisions





Bad news: feet deform & absorb energy



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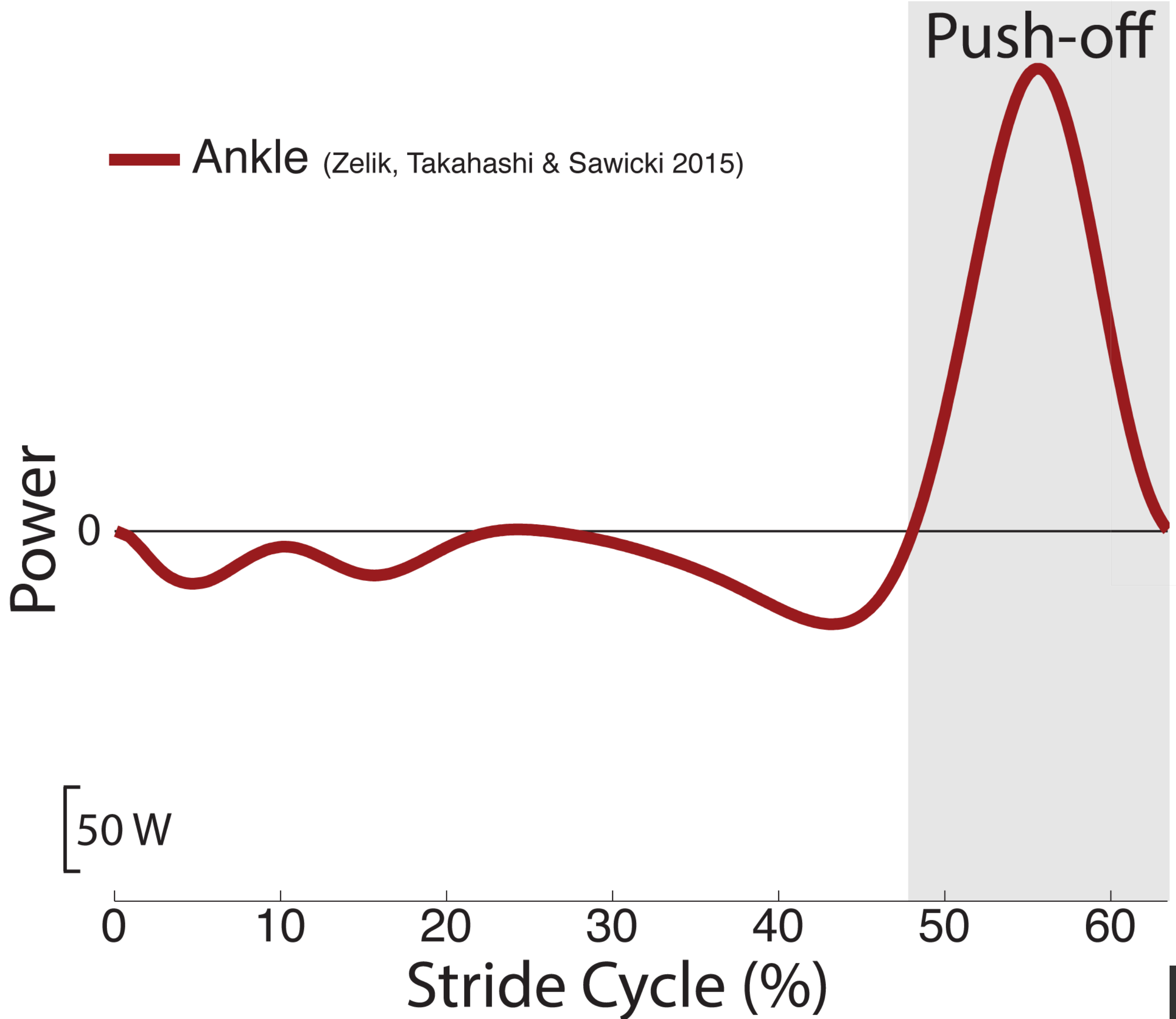
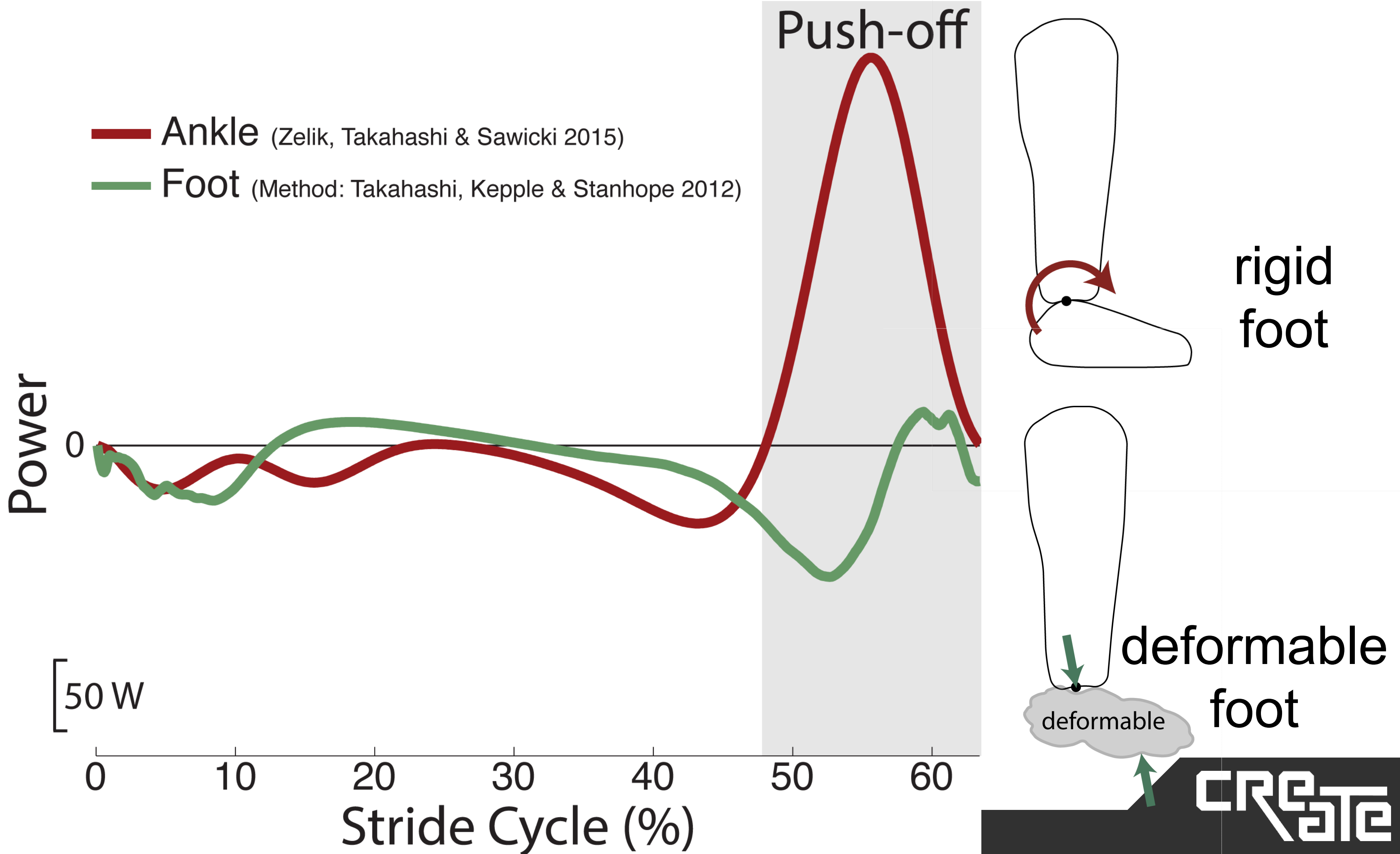


rigid
foot

Bad news: feet deform & absorb energy



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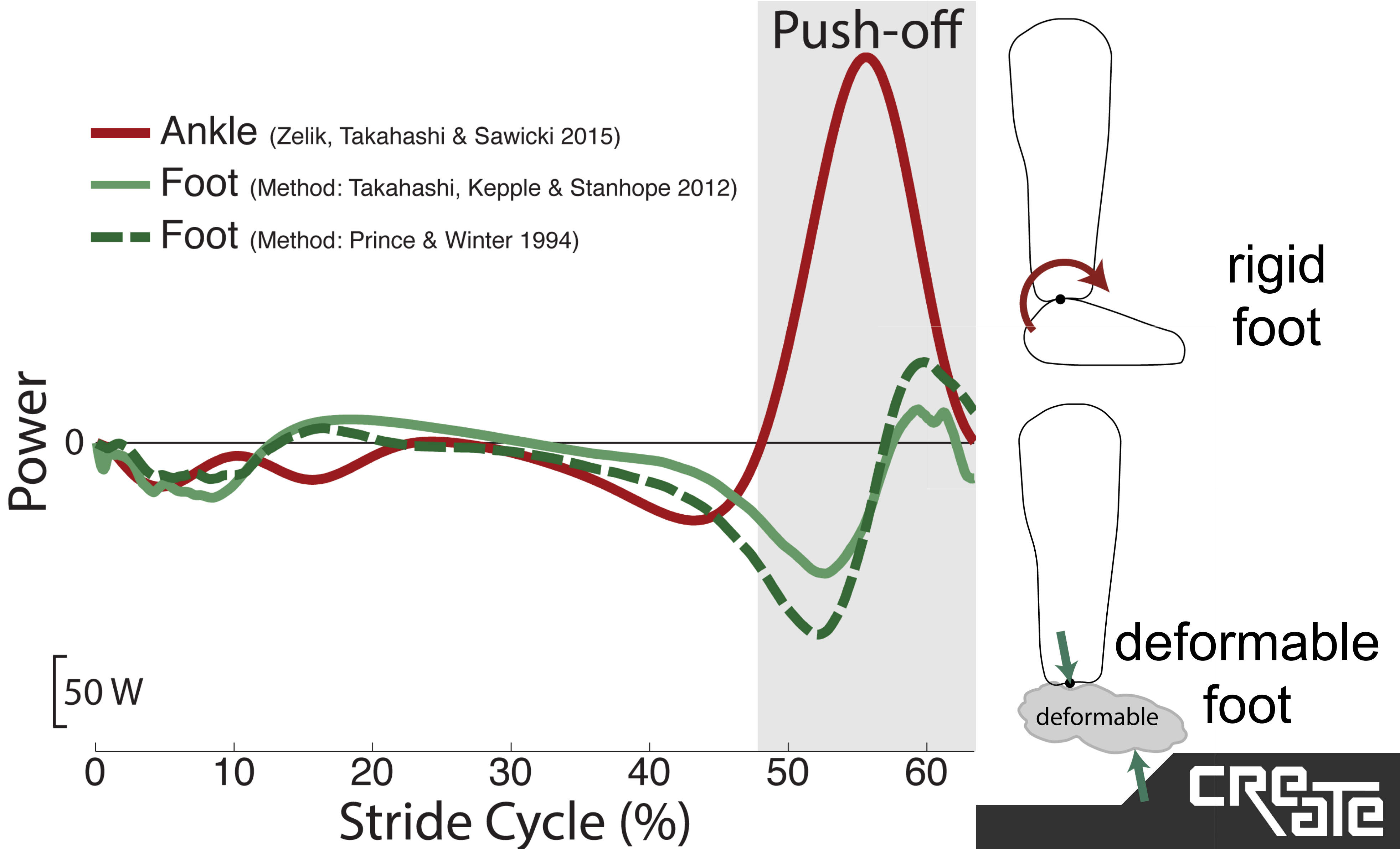

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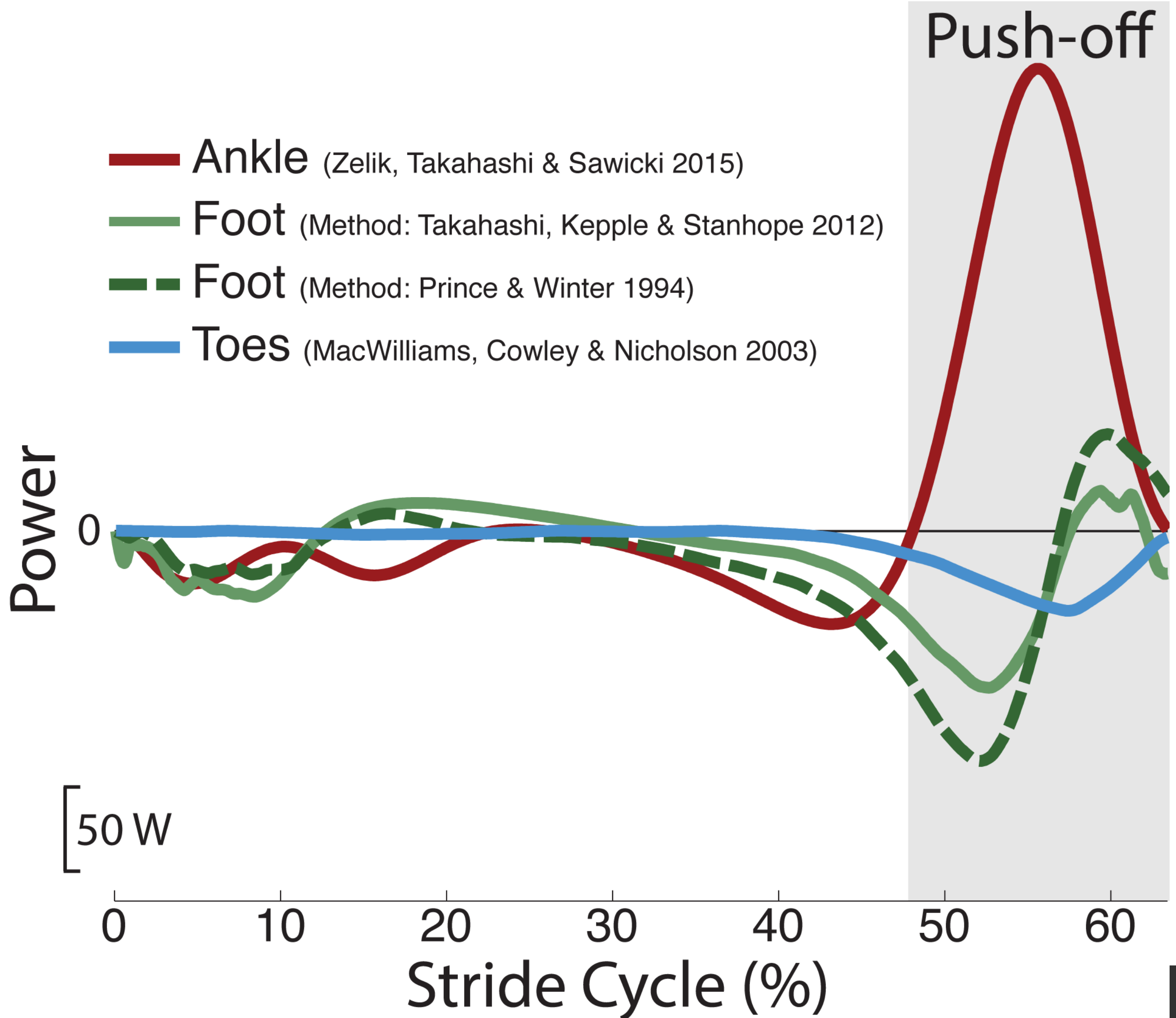
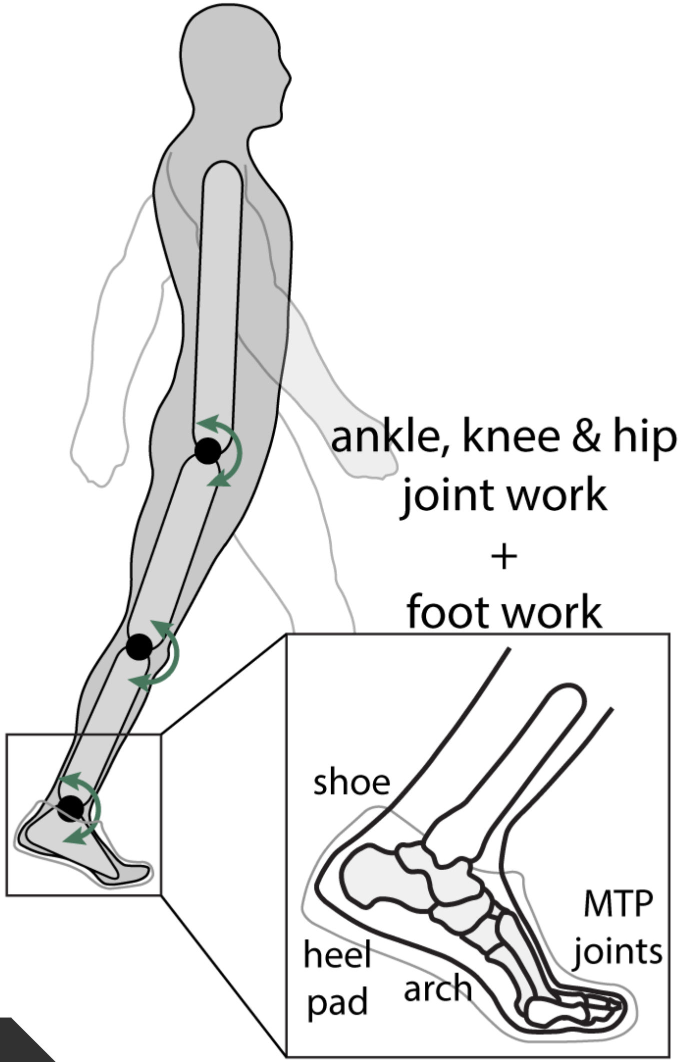
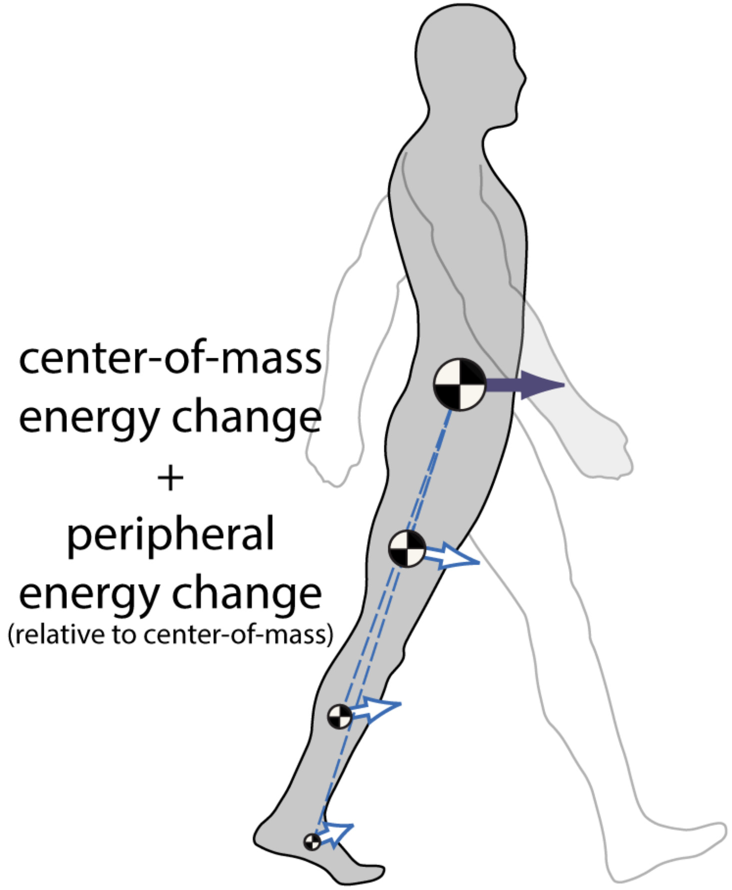


Problem: Work sources no longer explain energy change





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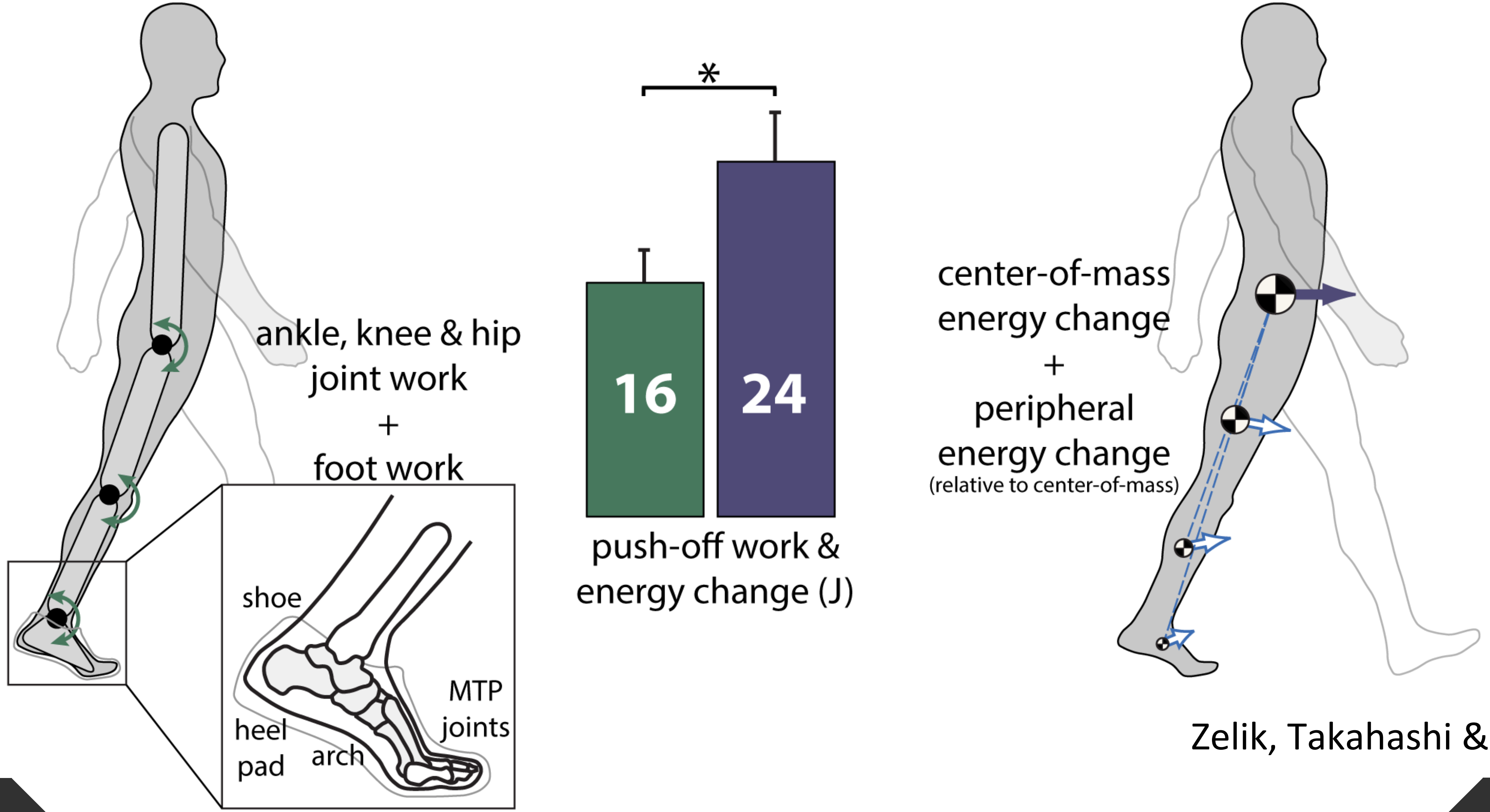
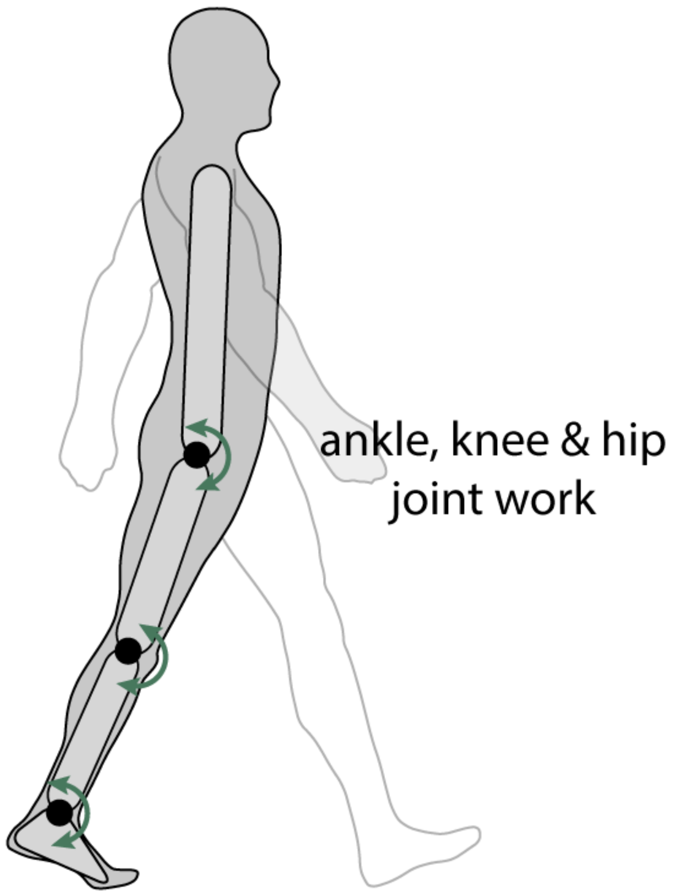


Zelik, Takahashi & Sawicki 2015

Non-obvious culprit: conventional 3DOF inverse dynamics

DOF = degrees of freedom



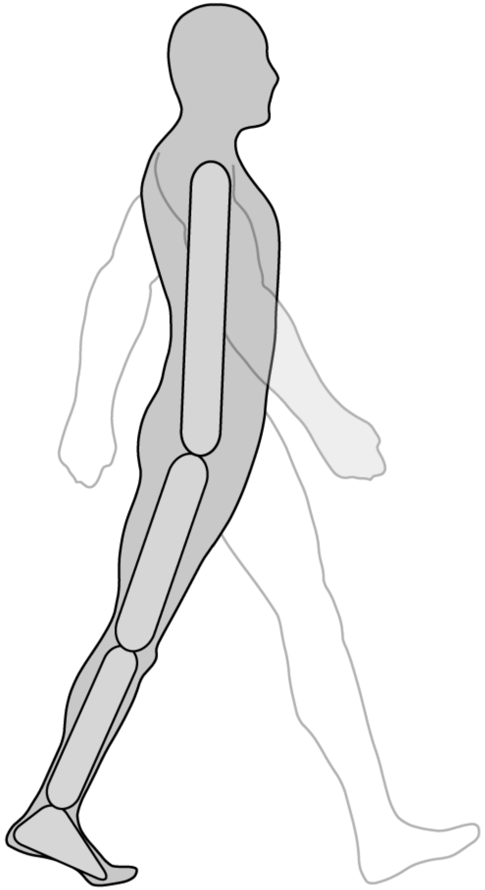
3DOF inverse dynamics

How much work to **rotate** body segments?

$$W_{joint} = \int \left(M_{joint} \omega_{joint} \right) dt$$

Non-obvious solution: 6DOF analysis of hip+knee+ankle+foot

DOF = degrees of freedom



6DOF inverse dynamics

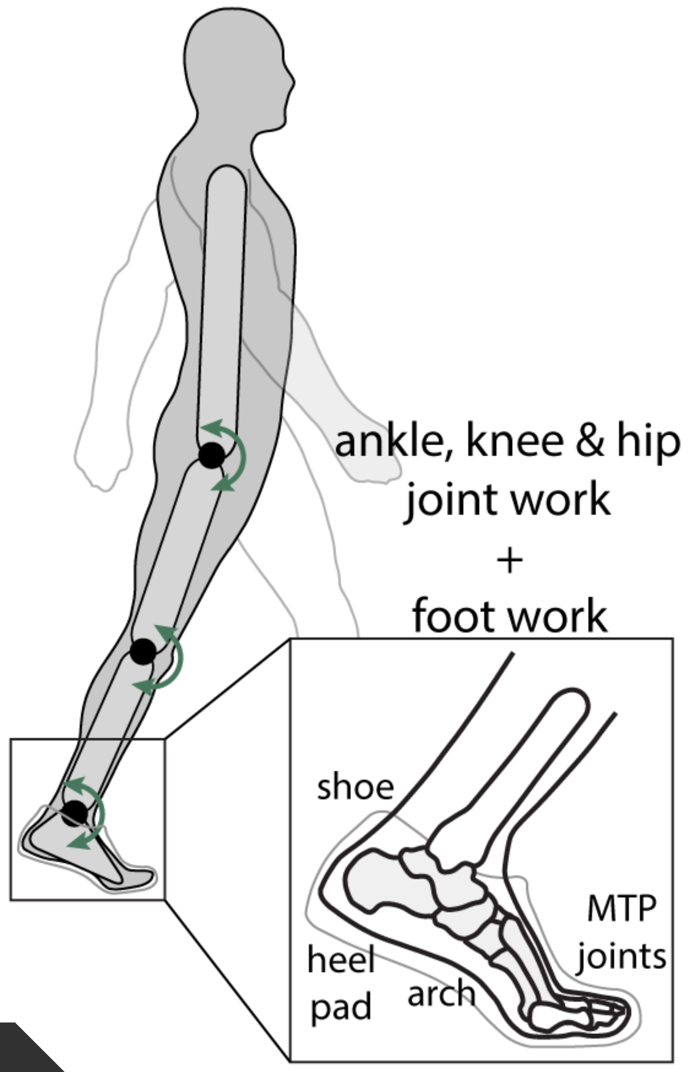
How much work to **<u>move</u>** body segments?

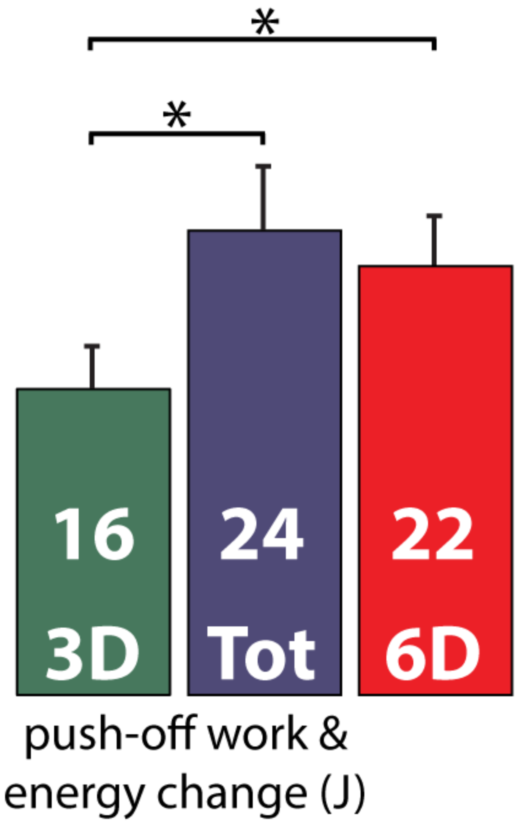
$$W_{joint} = \int \left(M_{joint}\omega_{joint} + F_{joint}\Delta v_{joint} \right) dt$$

rotational work + translational work

Buczek 1994, Duncan 1997

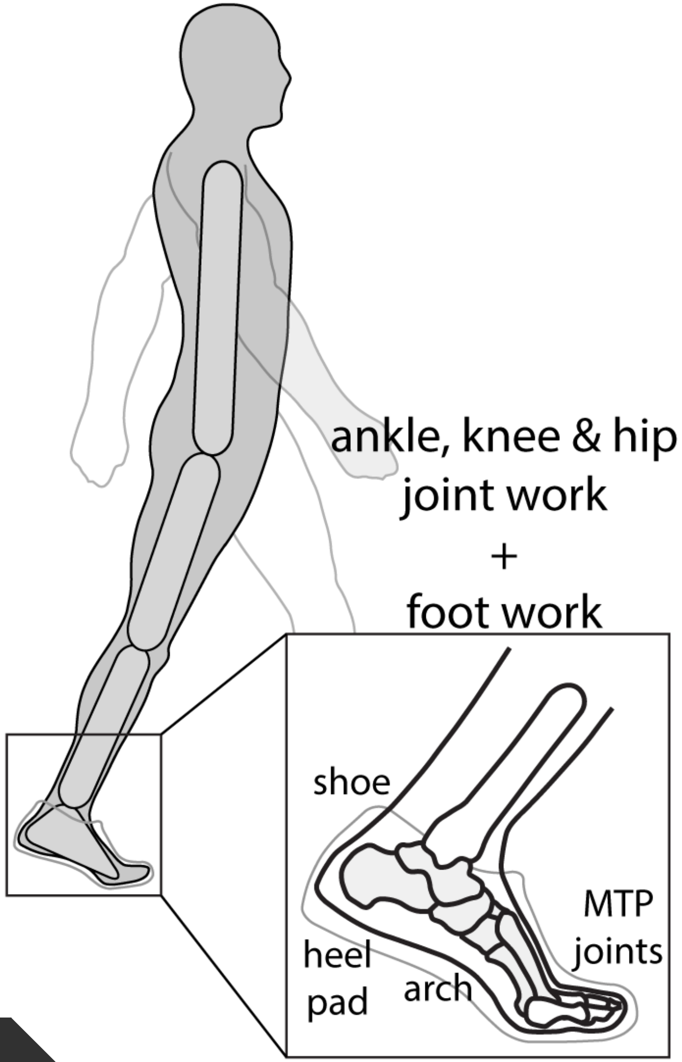
Non-obvious solution: 6DOF analysis of hip+knee+ankle+foot

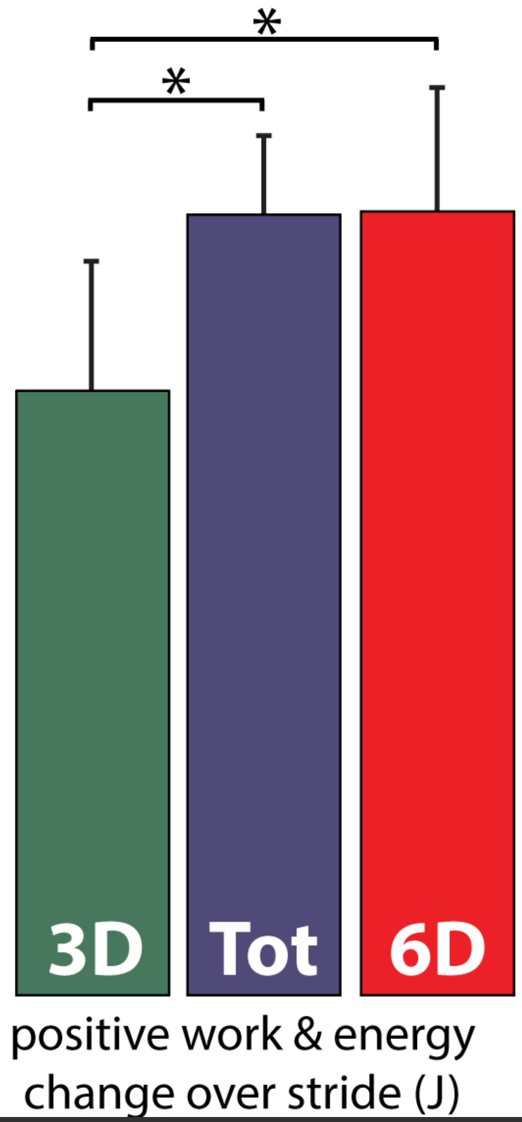




Zelik, Takahashi & Sawicki 2015

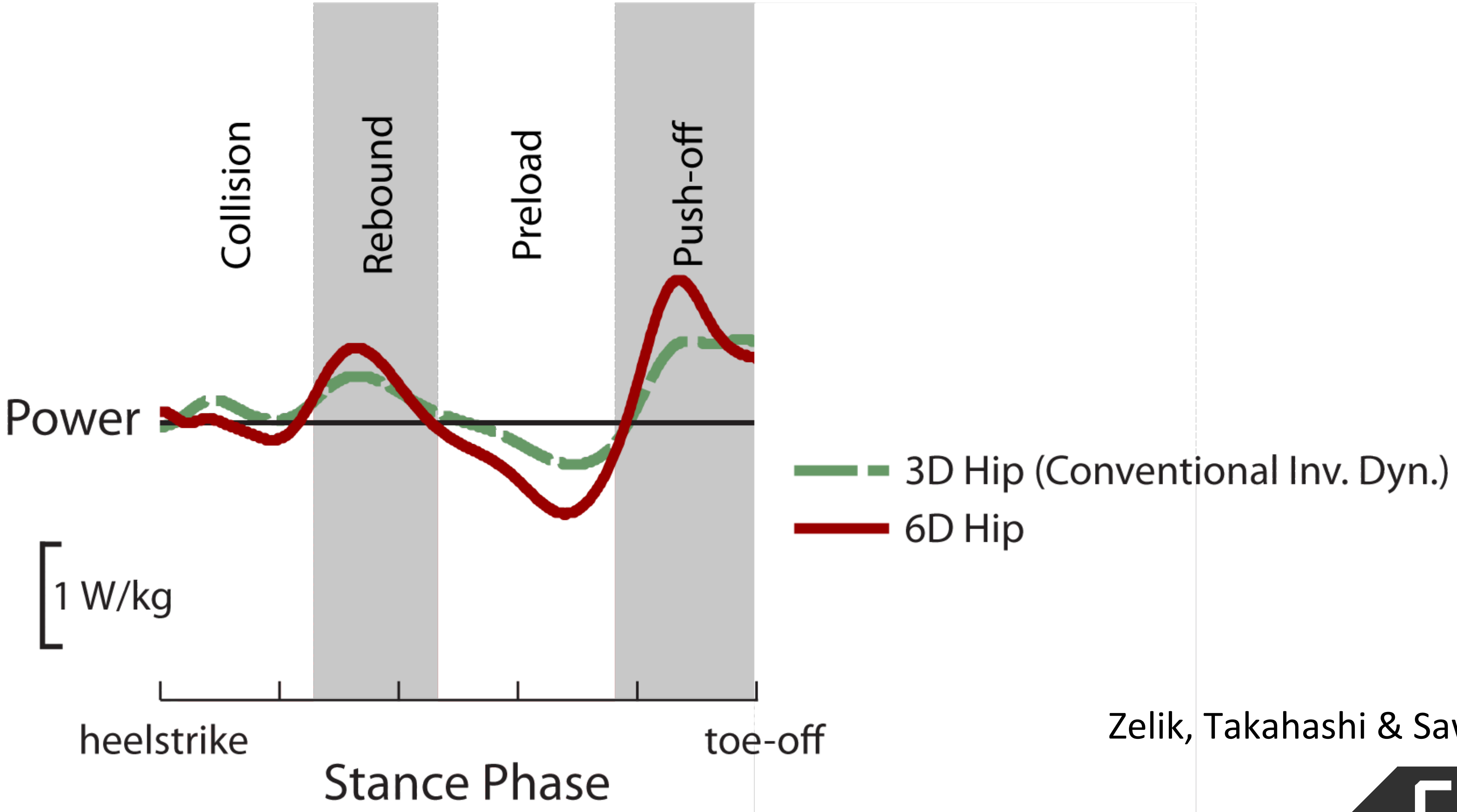
Non-obvious solution: 6DOF analysis of hip+knee+ankle+foot





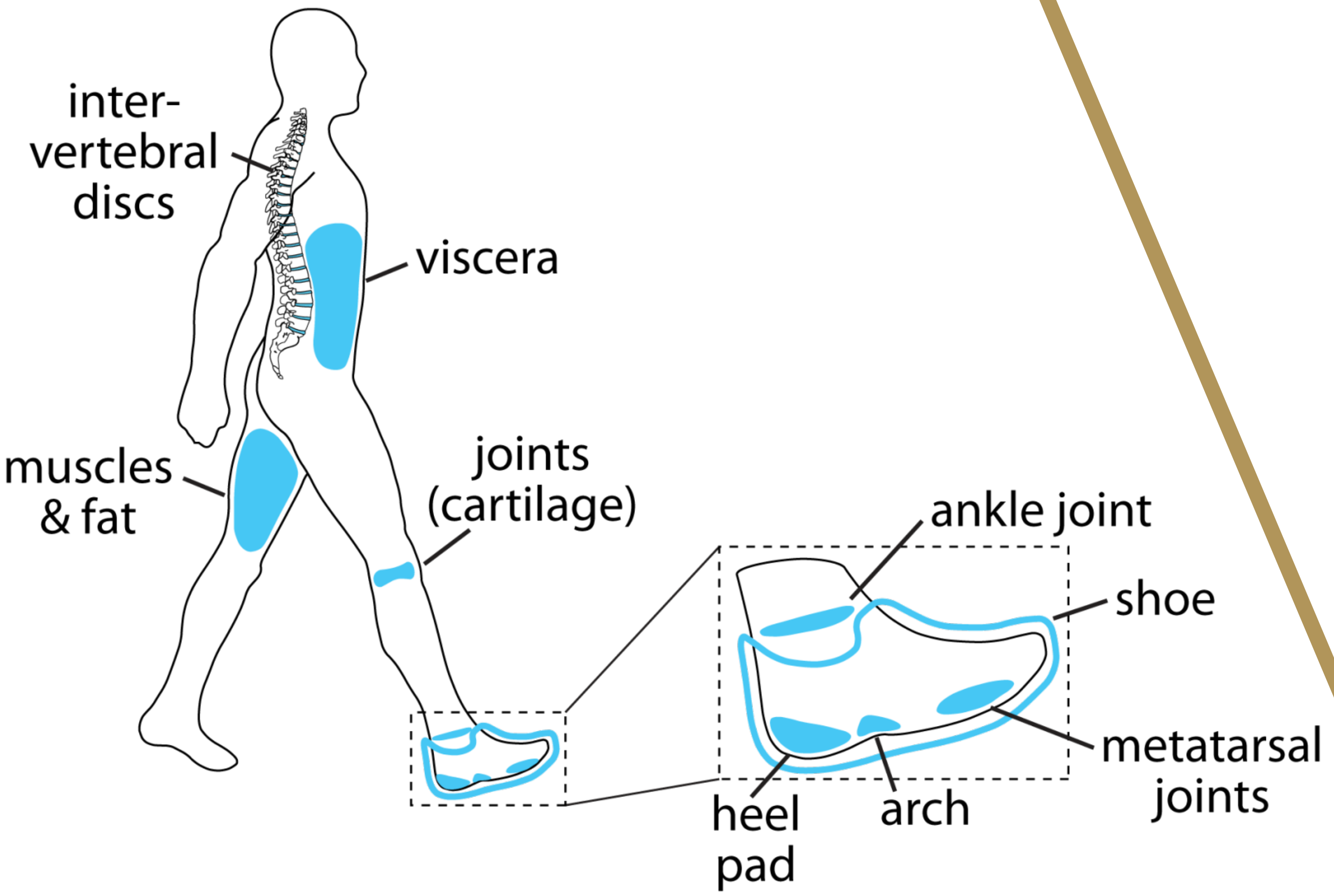
Zelik, Takahashi & Sawicki 2015

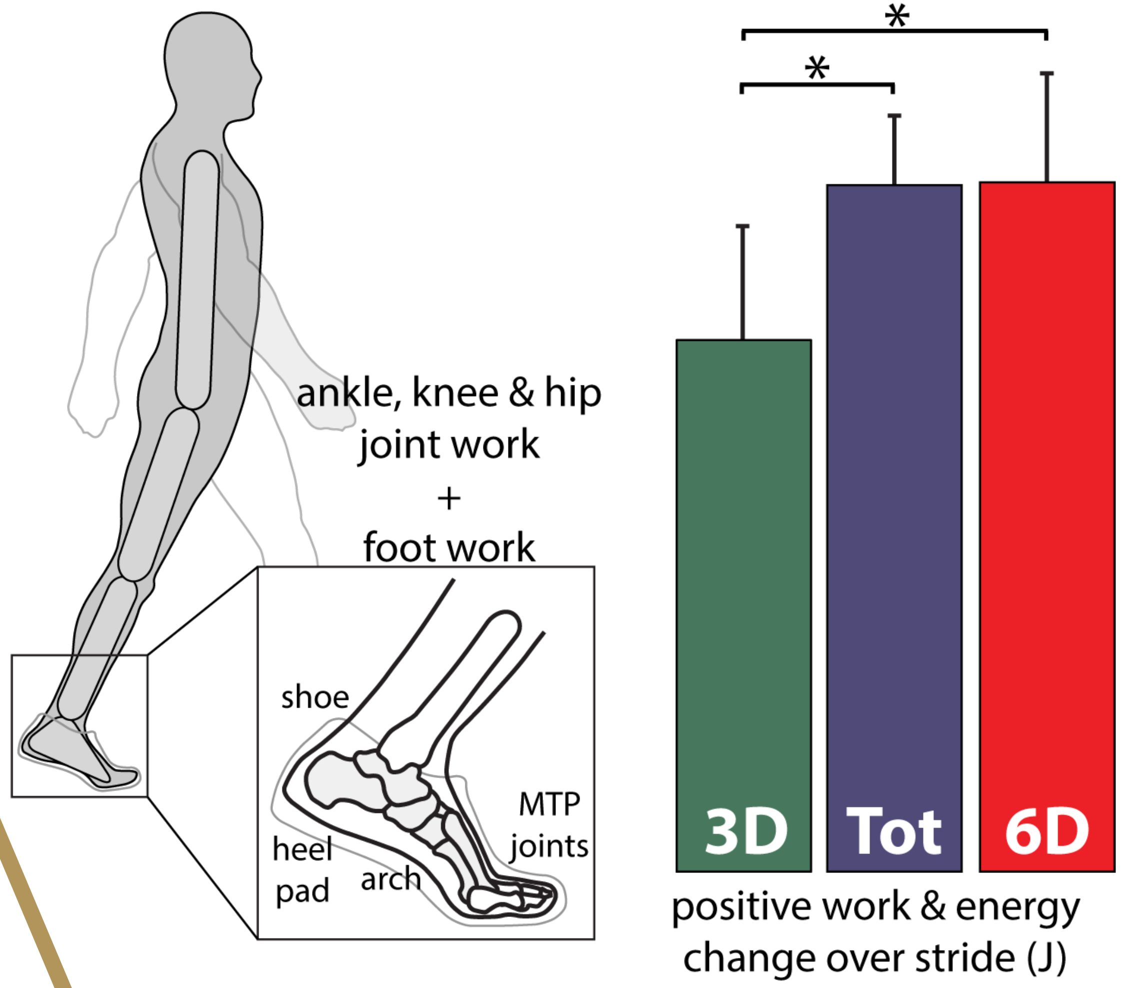
Why 6DOF vs. 3DOF matters: 50% more hip Push-off work



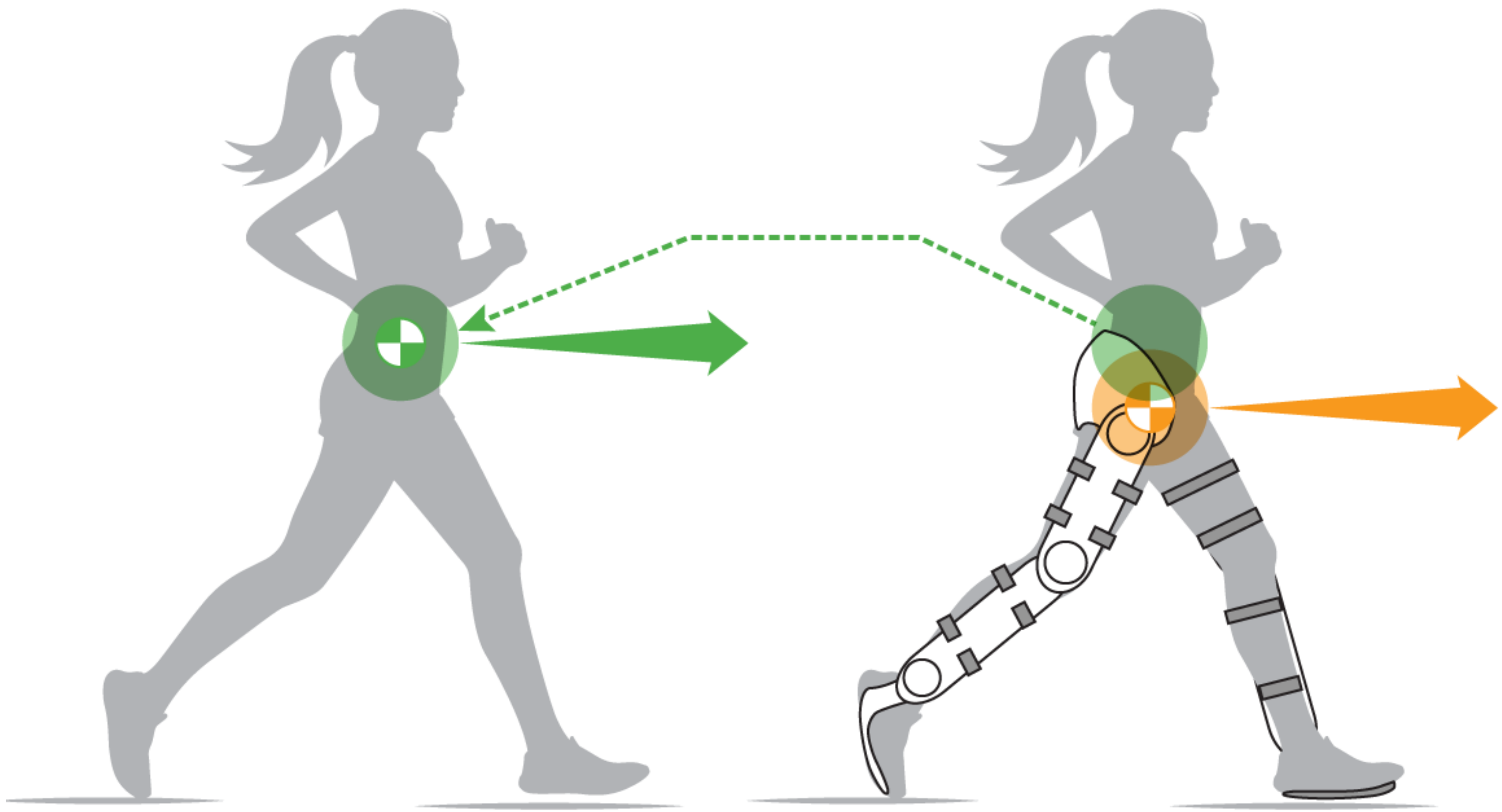
Zelik, Takahashi & Sawicki 2015

Discrepancies → soft tissues; completeness of work estimates

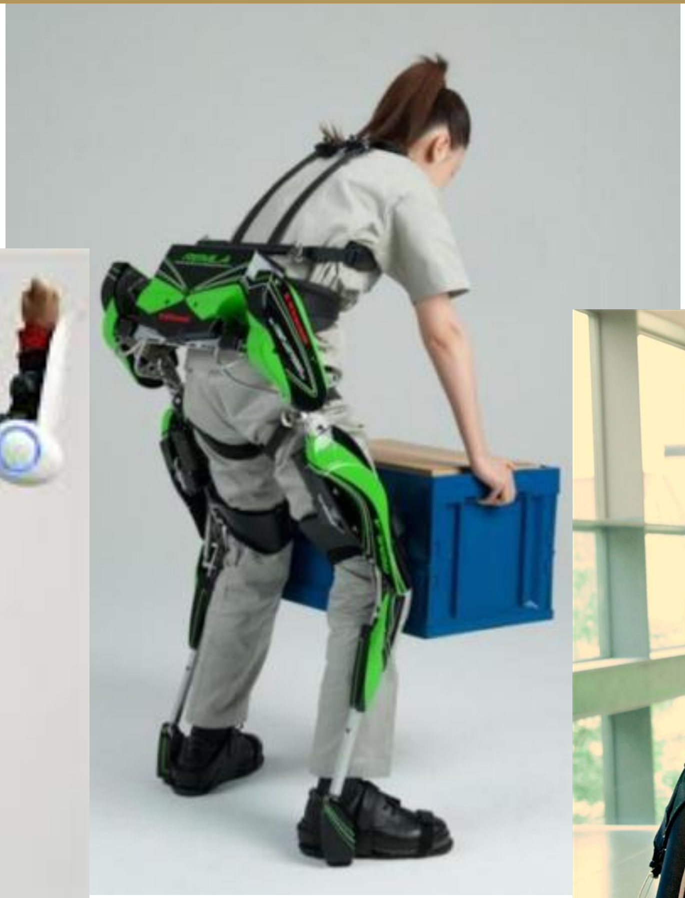


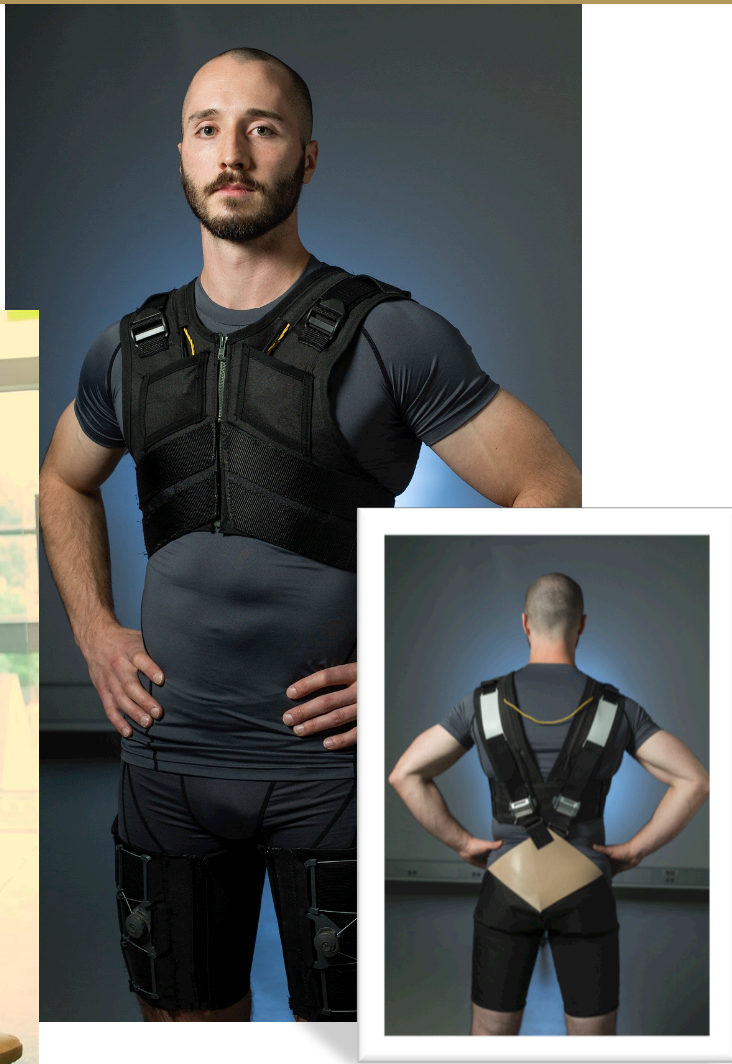


Whole-Body ←→ Augmented-Body

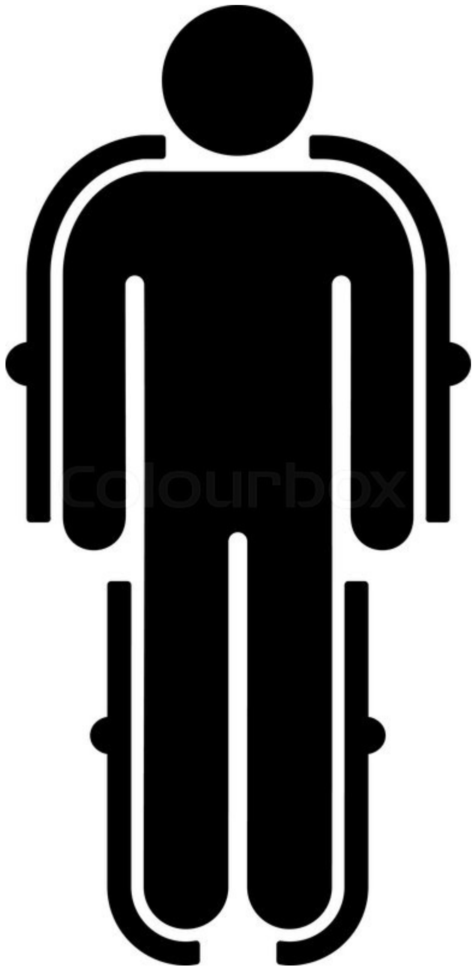


Rise of wearable exoskeletons, exosuits & smart clothing





Exoskeletons: $70 million worth sold in 2014



x 40% CAGR

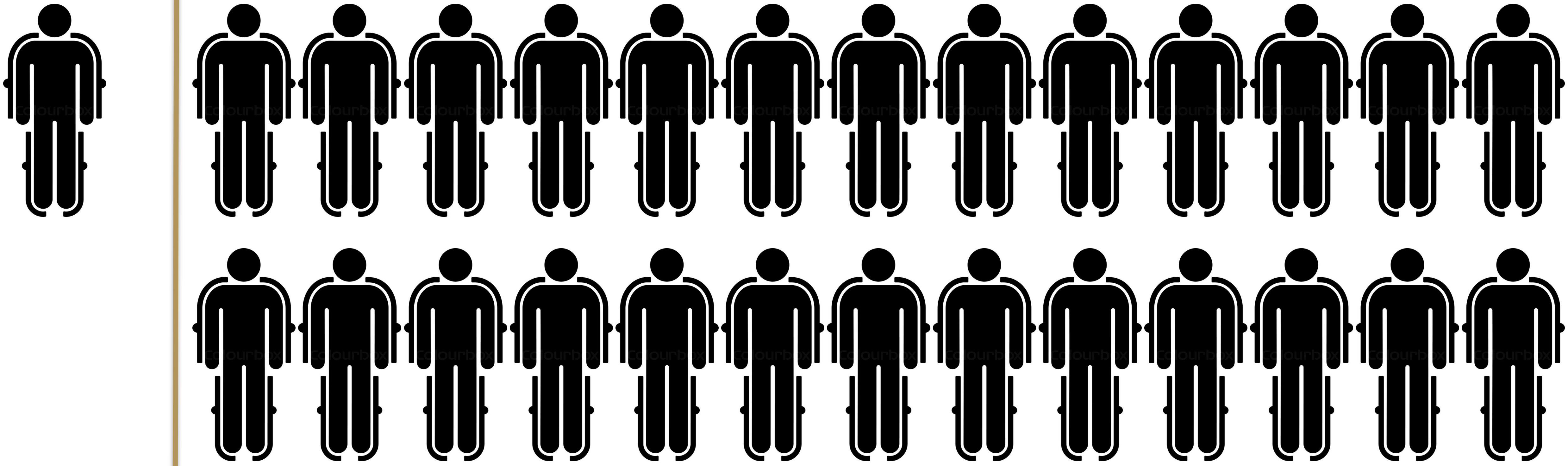
(compounded annual growth rate)

ABI Research Report 2015

Exoskeletons: $2 billion projected for 2025

2014

2025



ABI Research Report 2015

What does this mean for biomechanics community?

2014

2025

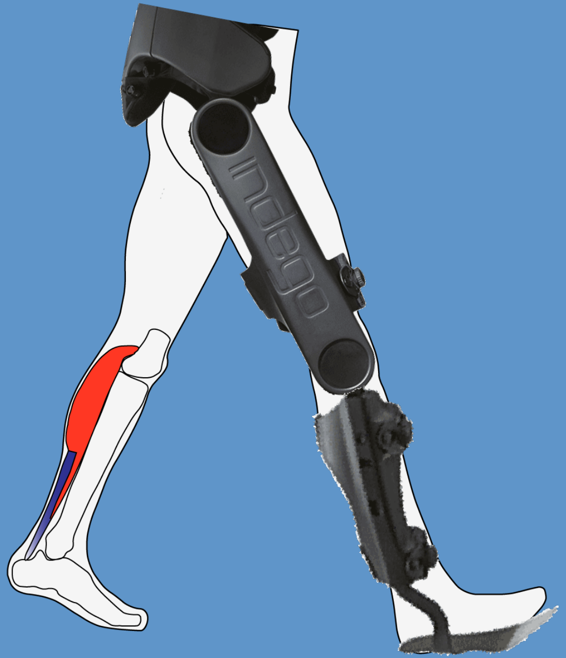
Quantifying human augmentation from wearable devices

Device Performance

Quantifying human augmentation from wearable devices

Device Performance

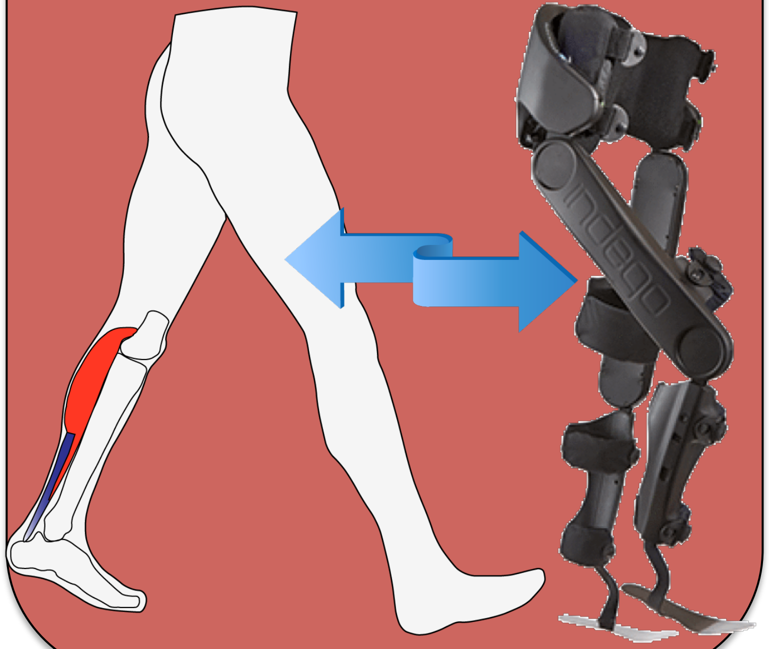
Human-Device Performance



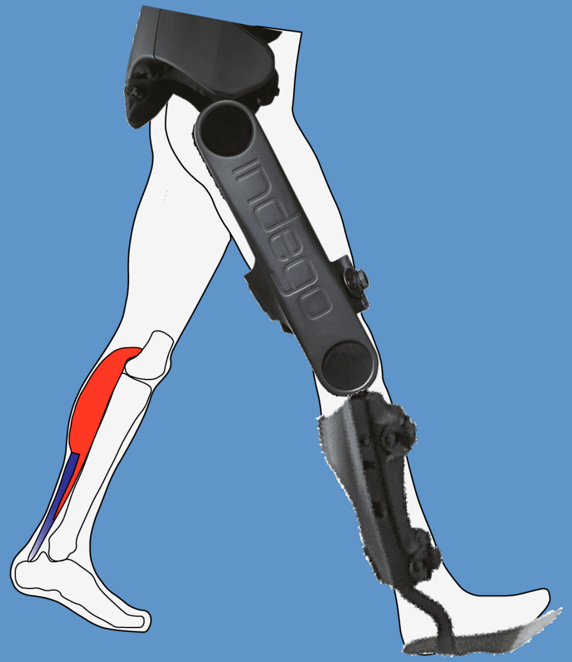
Quantifying human augmentation from wearable devices

Device Performance

Human-Device Interaction

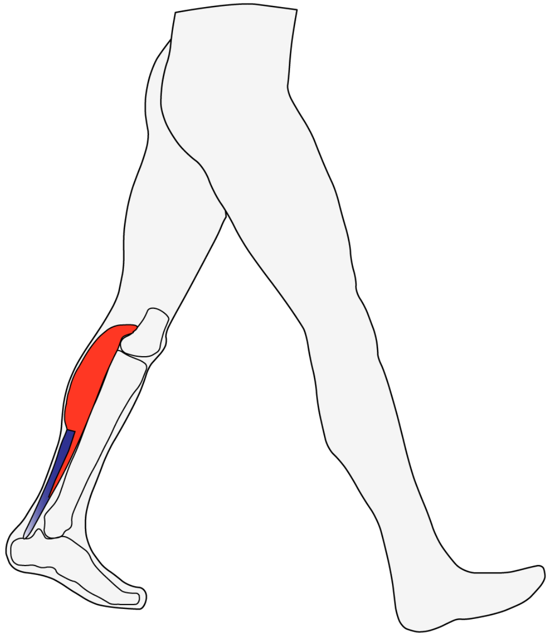


Human-Device Performance



Common way to partition human vs. device dynamics

Biological



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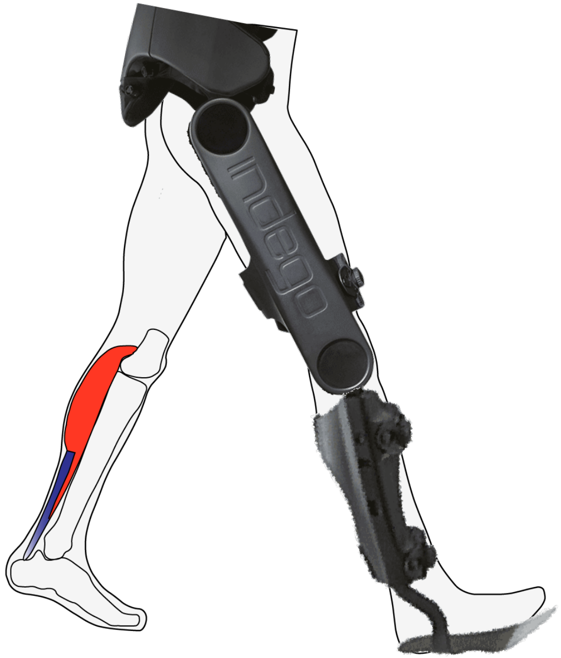
Augmented-Body

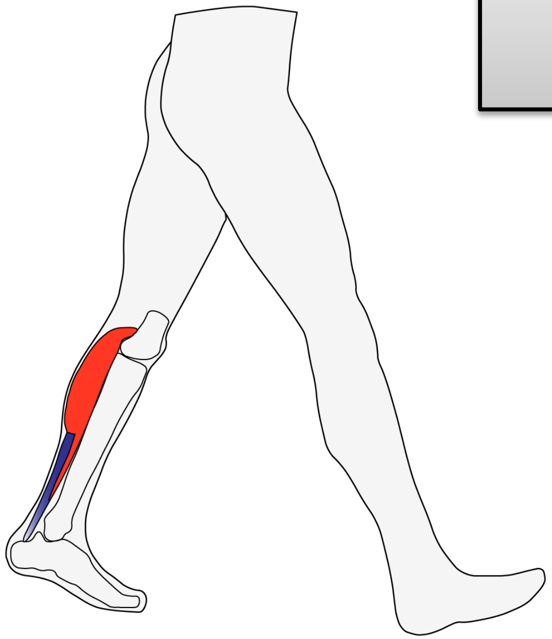


-

Device

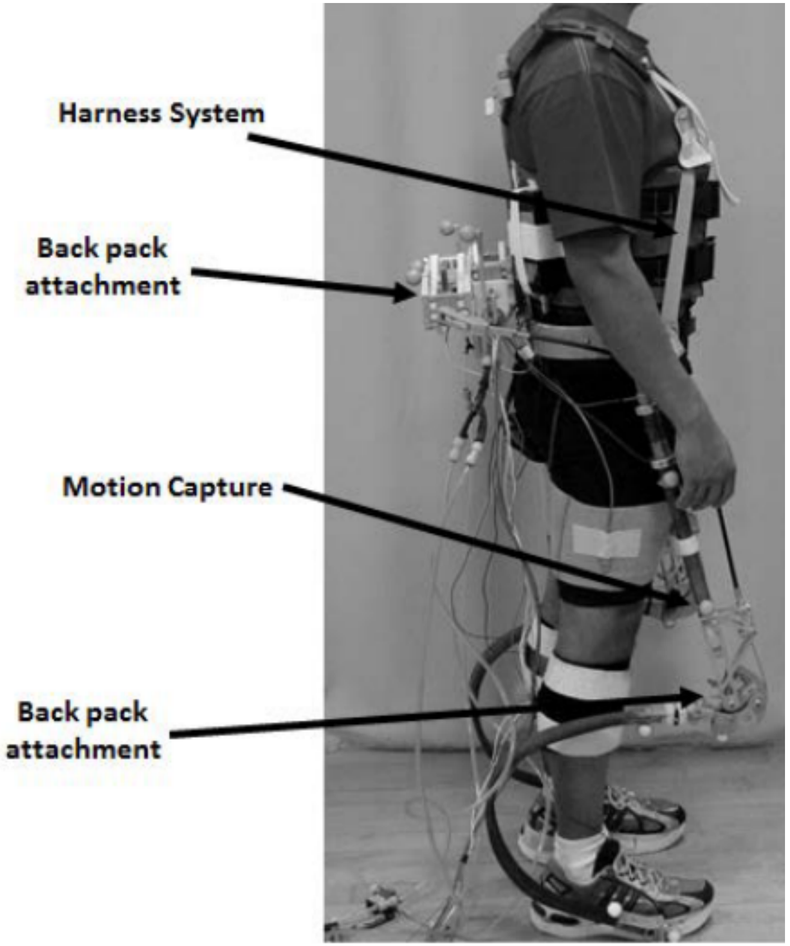
Common way to partition human vs. device dynamics

Biological

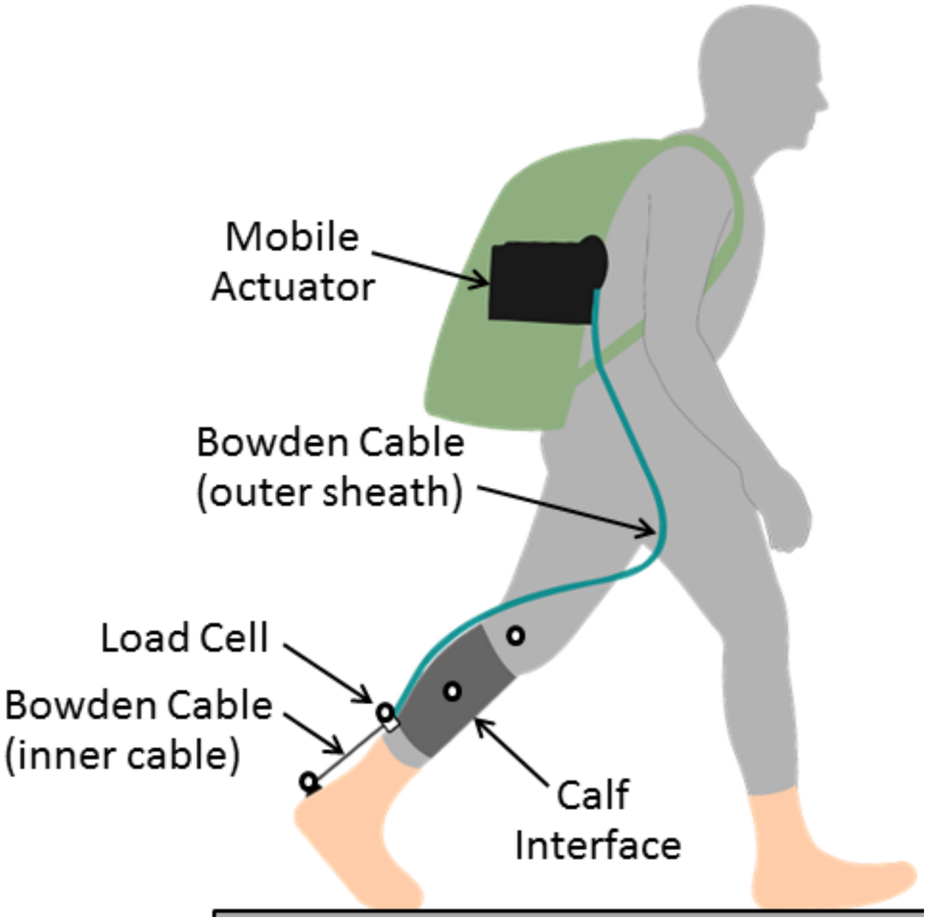


used to interpret how hard muscles are working

Problem: human-device interfaces neglected, but absorb energy



Running Exoskeleton
(Cherry et al. 2016)



Soft Robotic Exosuit
(Asbeck et al. 2014, Yandell et al. 2017)

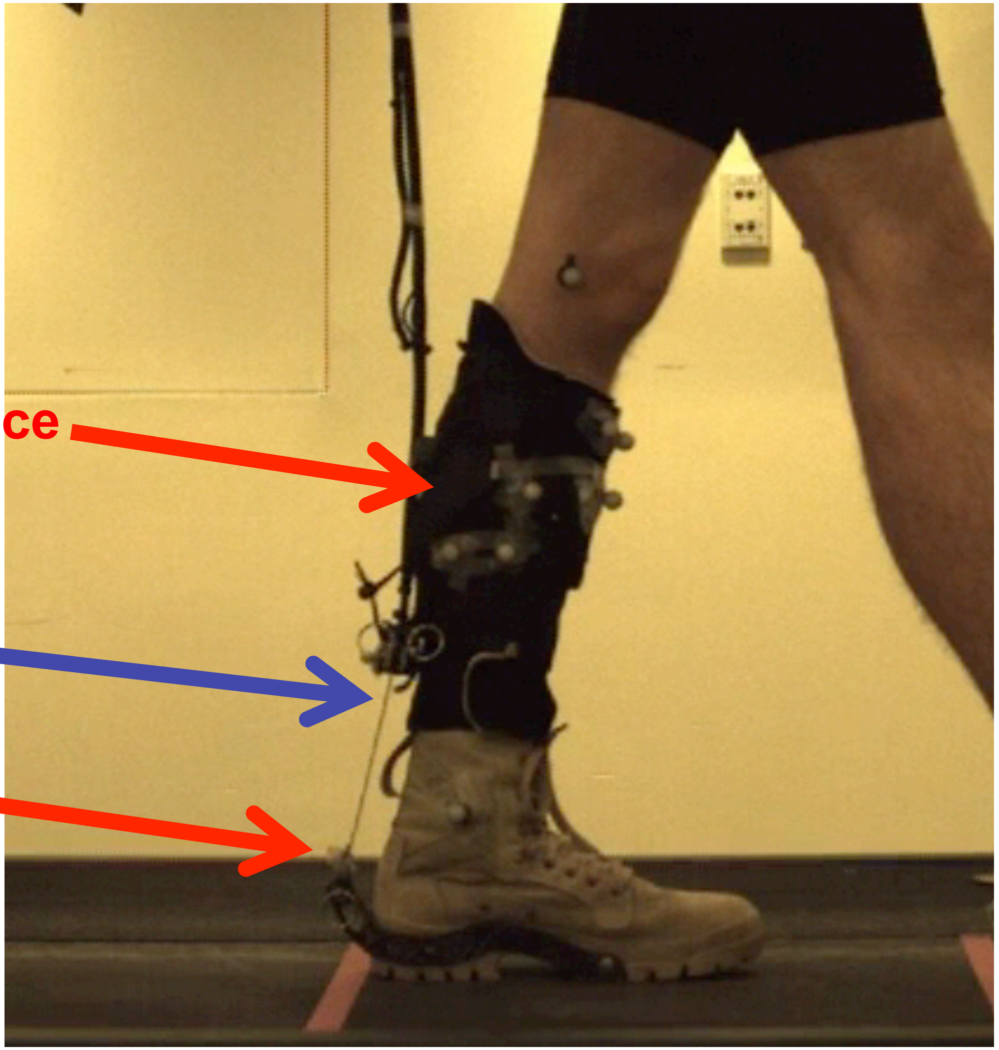
Problem: human-device interfaces neglected, but absorb energy

actuator (above, out of view)

proximal interface

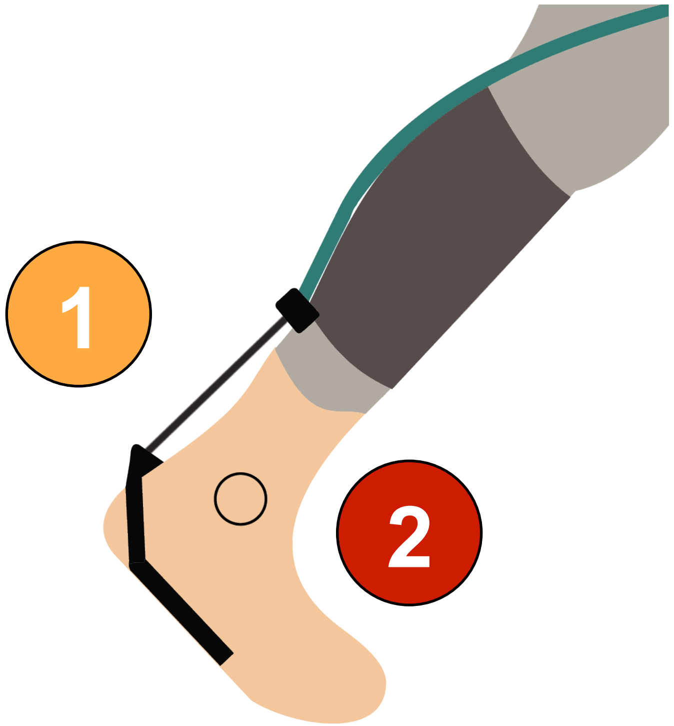
actuator cable

distal interface



Yandell et al. 2017 (JNER)

Device power can augment ankle or be absorbed by interfaces

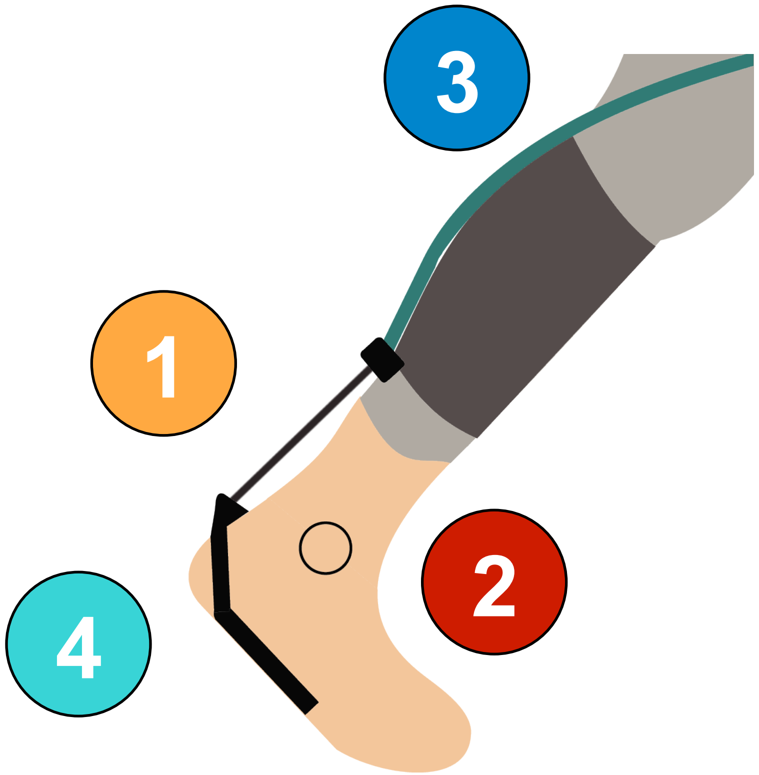


End-Effector Power =

Ankle Augmentation Power

Yandell et al. 2017 (JNER)

Device power can augment ankle or be absorbed by interfaces



End-Effector Power =

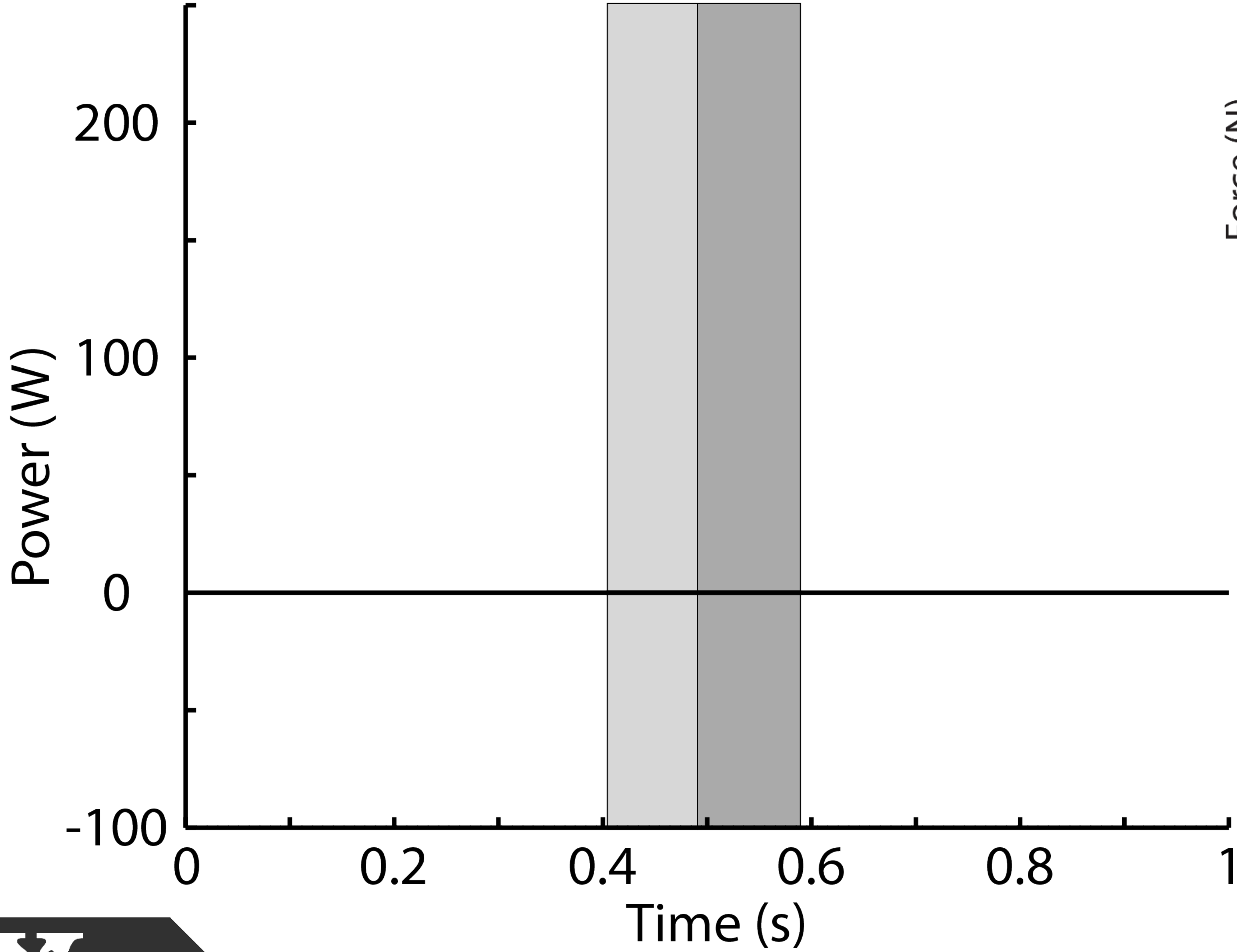
Ankle Augmentation Power

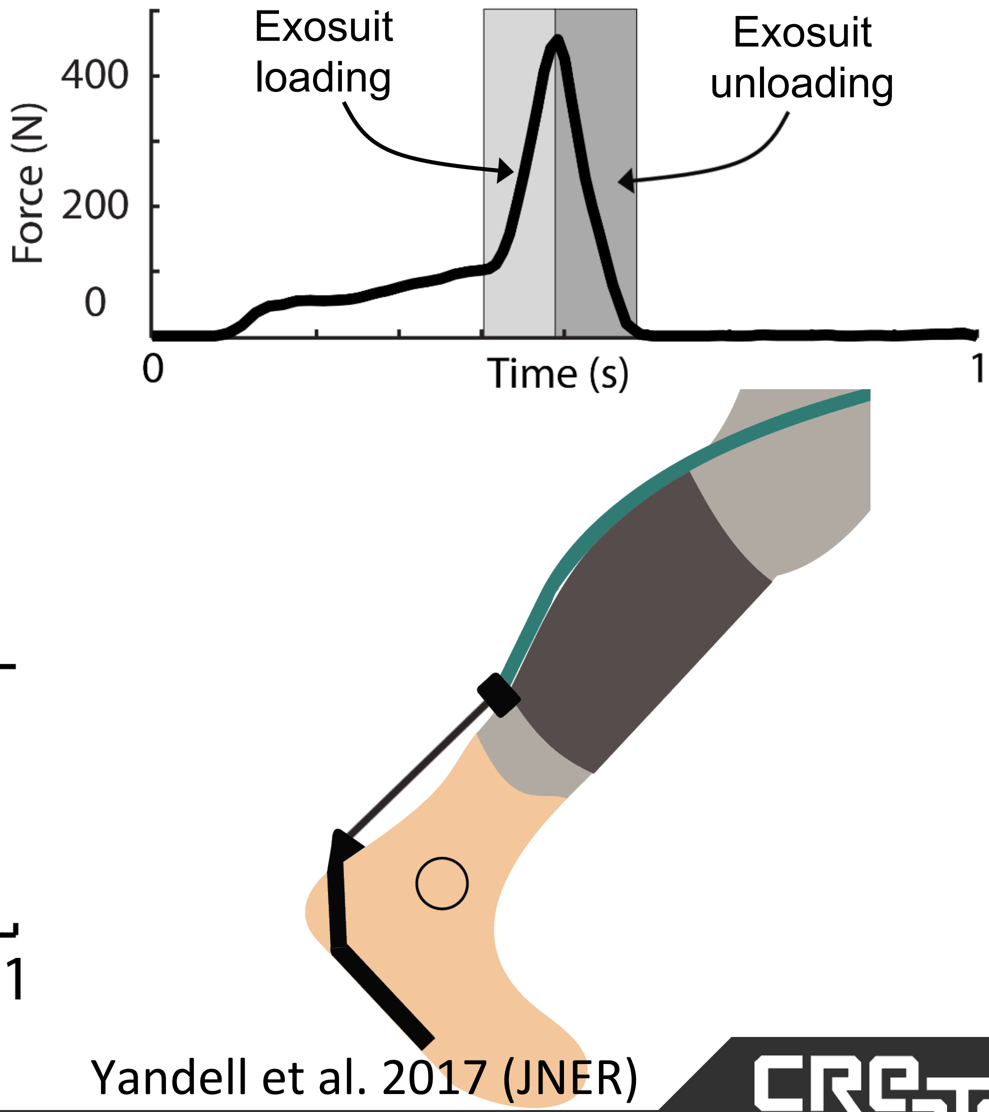
- Proximal Interface Power

- Distal Interface Power

Yandell et al. 2017 (JNER)

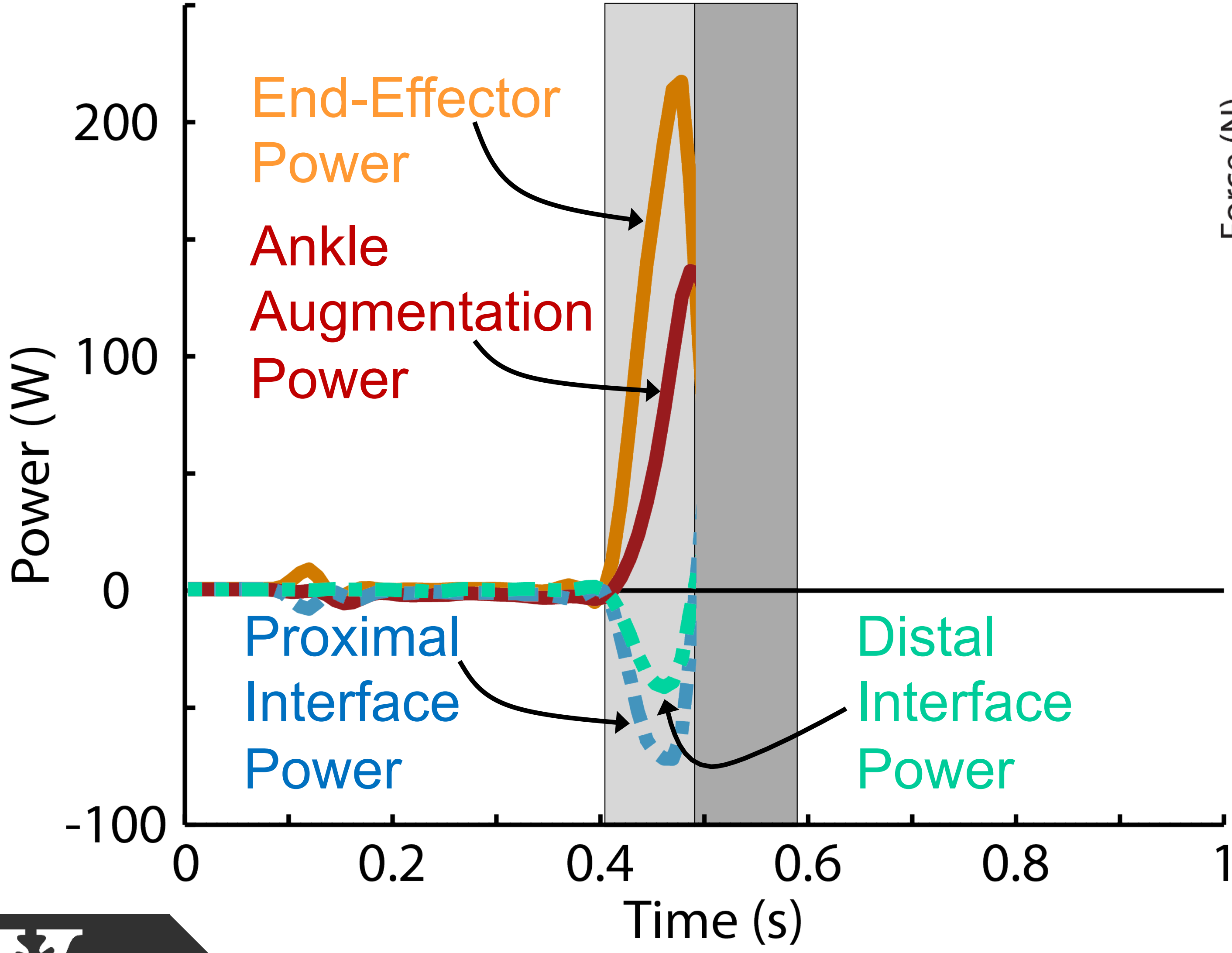
Robotic exosuit assisting ankle during walking

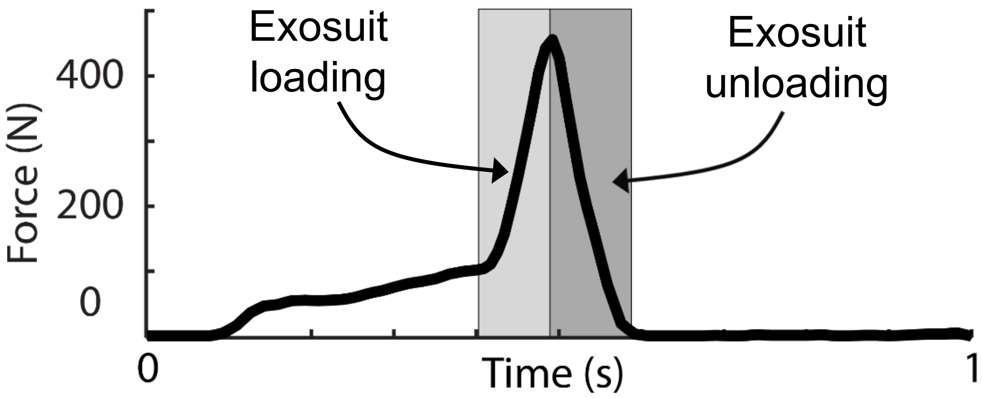




Yandell et al. 2017 (JNER)

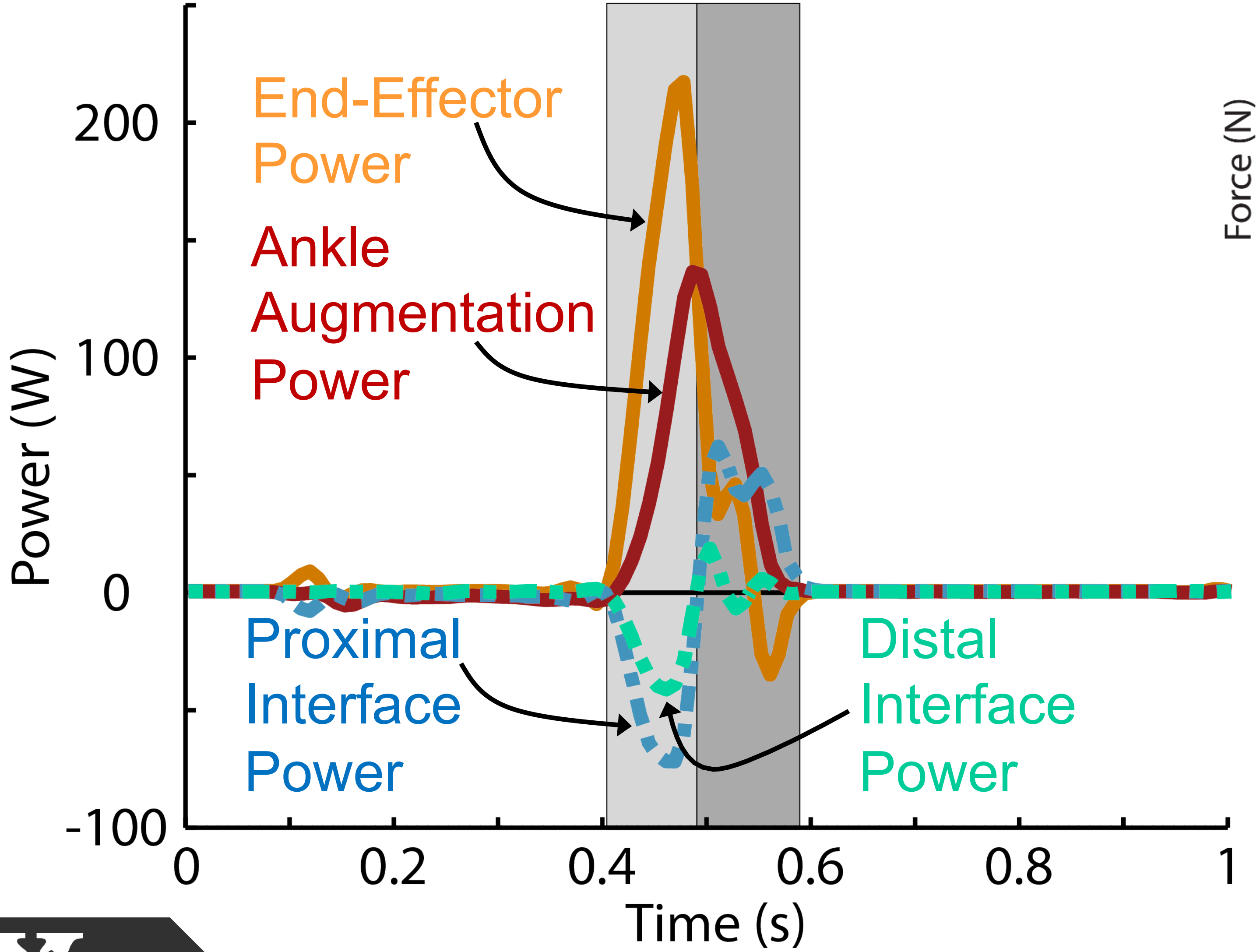
55% of device power was initially absorbed by interfaces

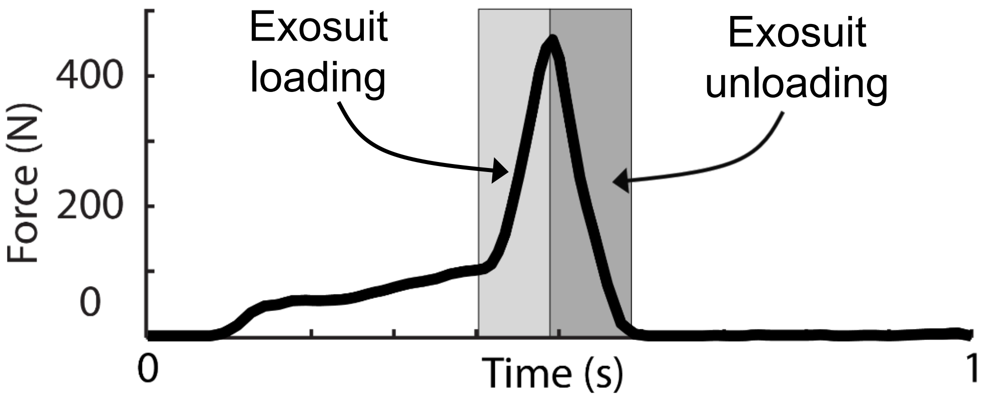




Yandell et al. 2017 (JNER)

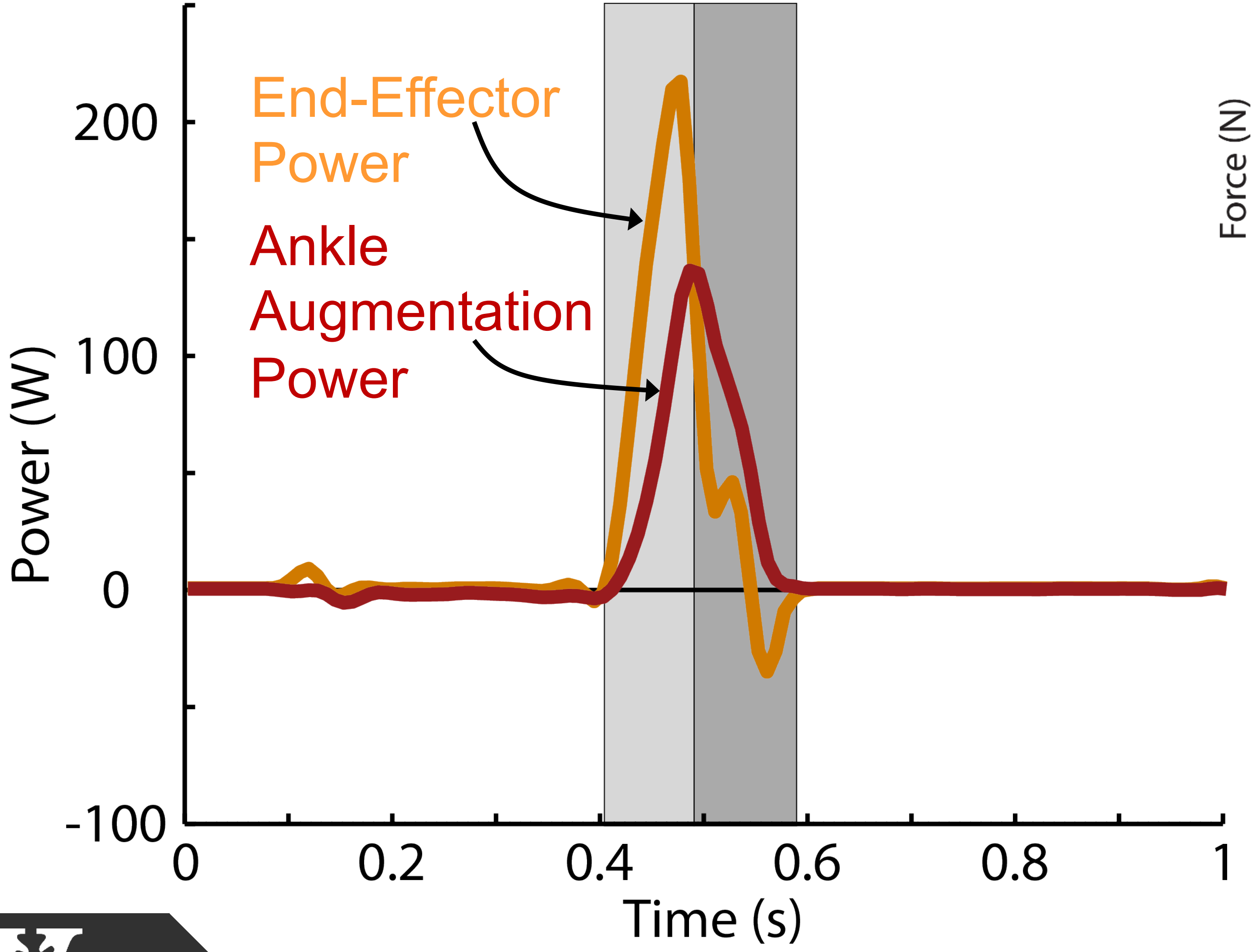
Most of interface power is then returned viscoelastically

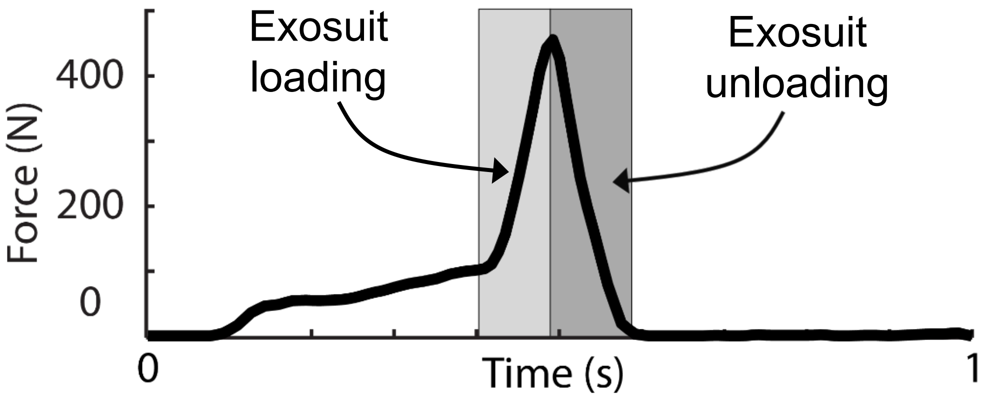




Yandell et al. 2017 (JNER)

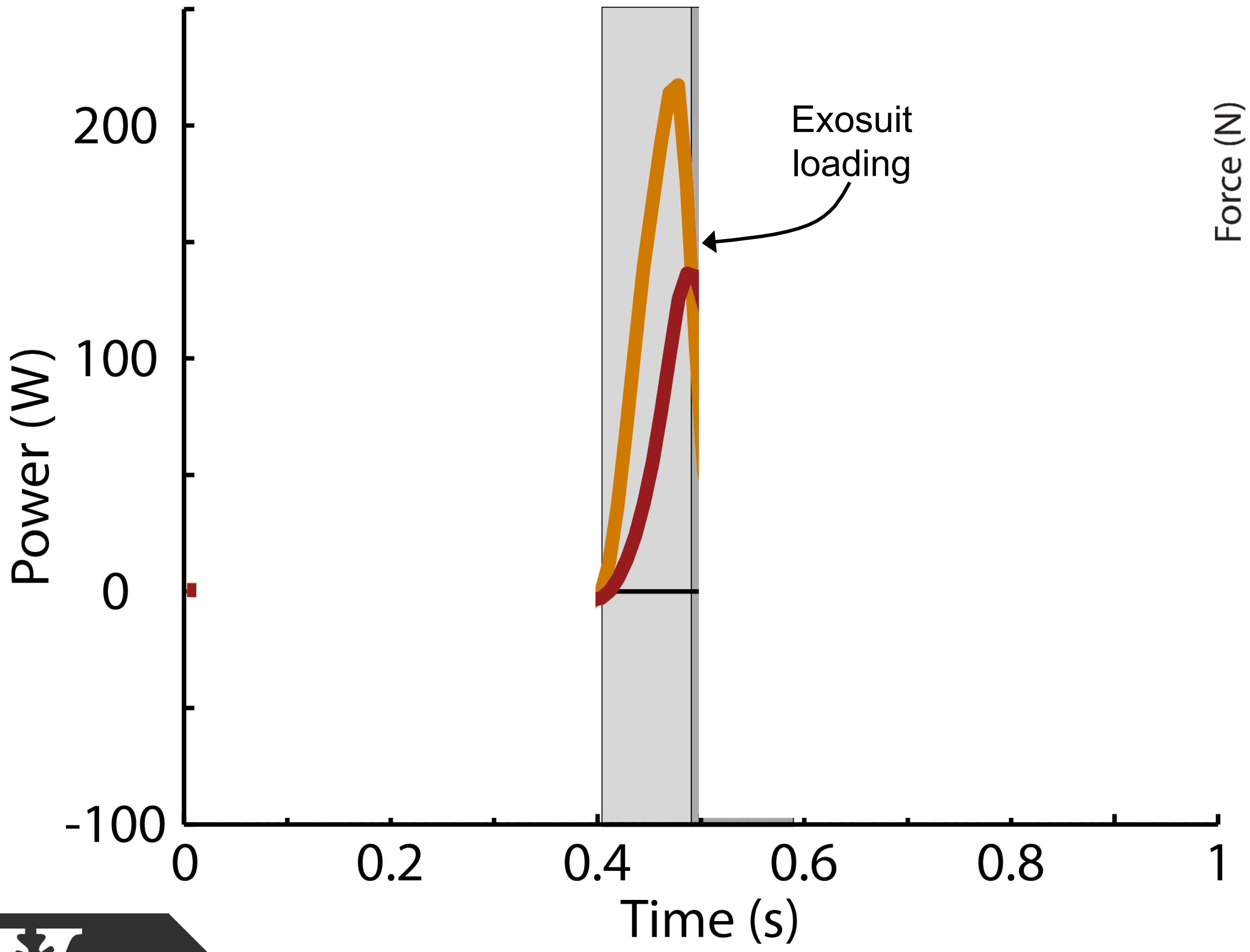
75% of device work assists ankle over stride, but timing delayed

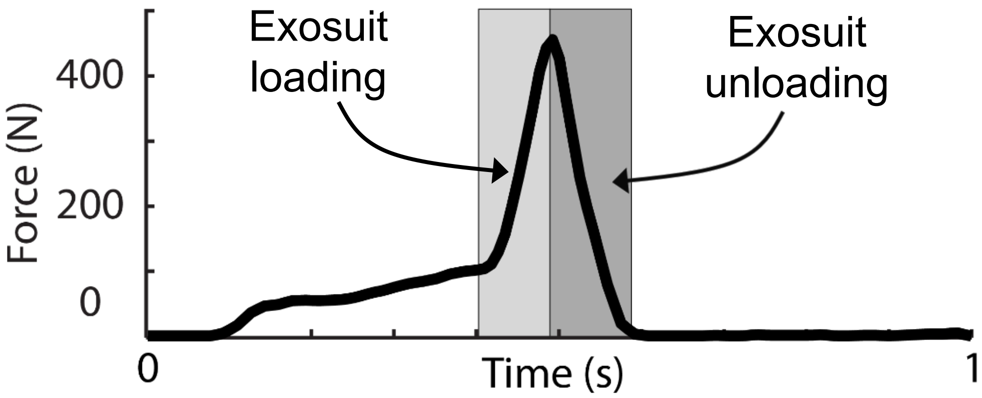




Yandell et al. 2017 (JNER)

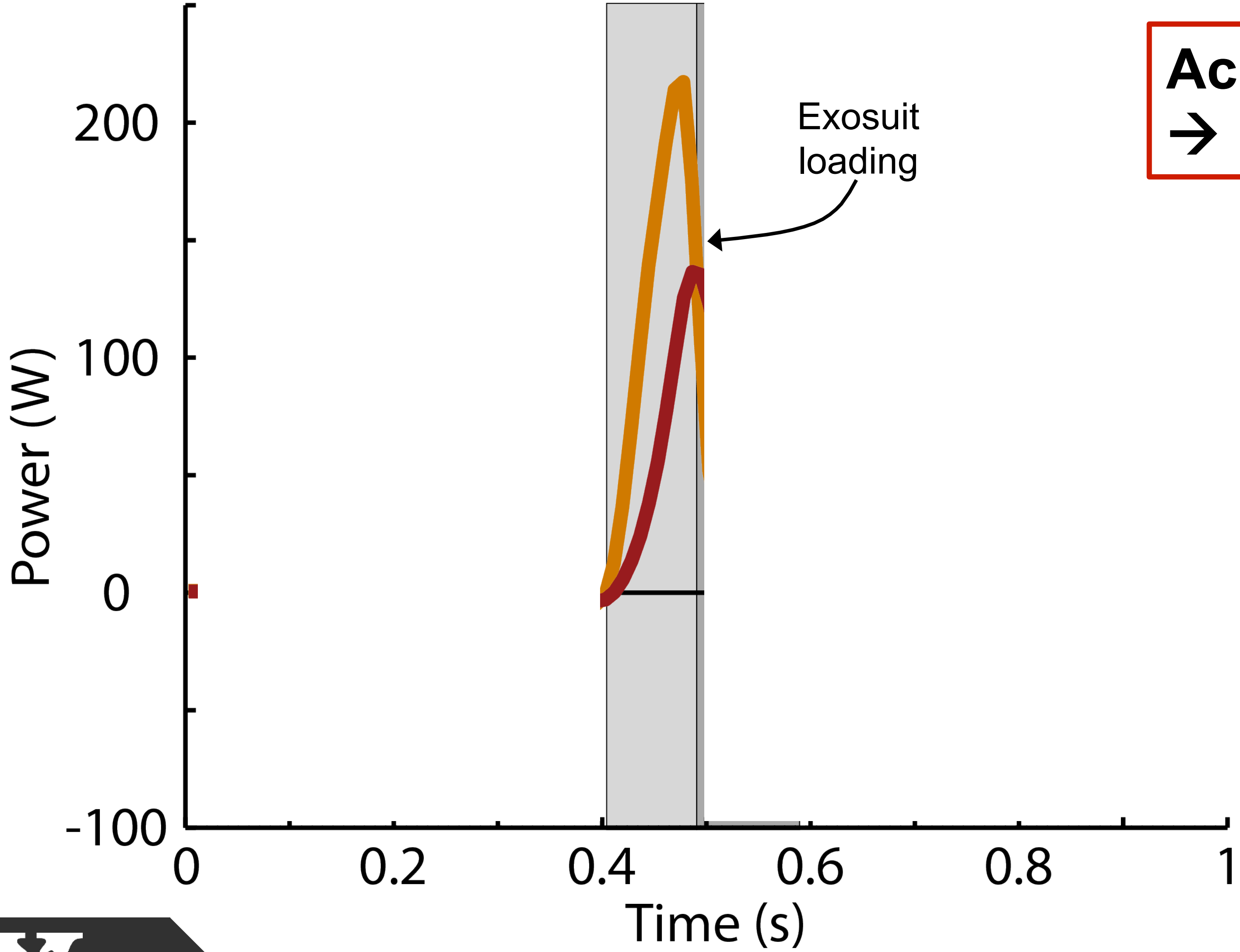
Neglecting interface dynamics affects scientific interpretation



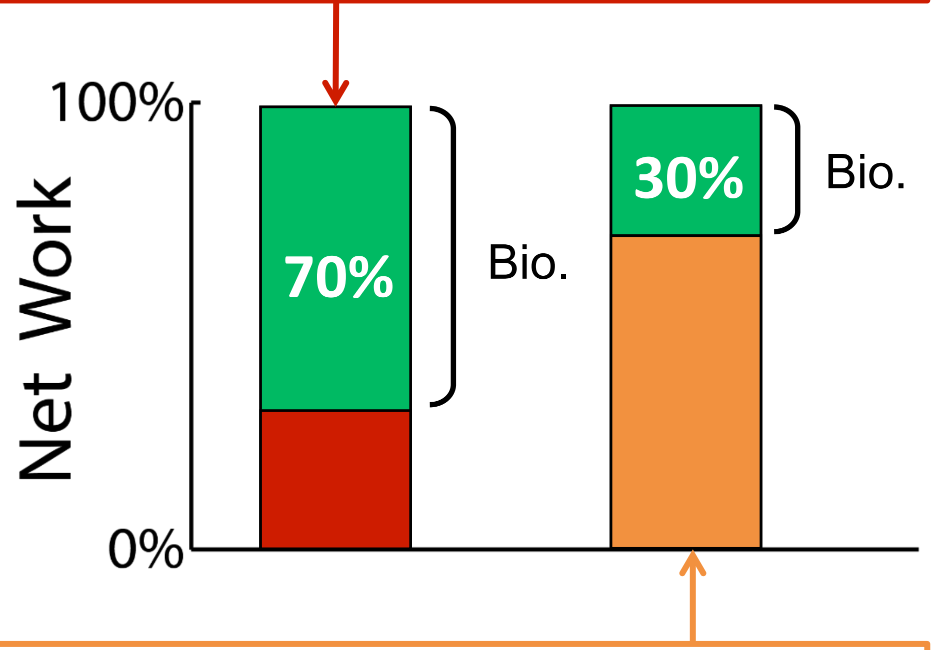


Yandell et al. 2017 (JNER)

Neglecting interface dynamics affects scientific interpretation



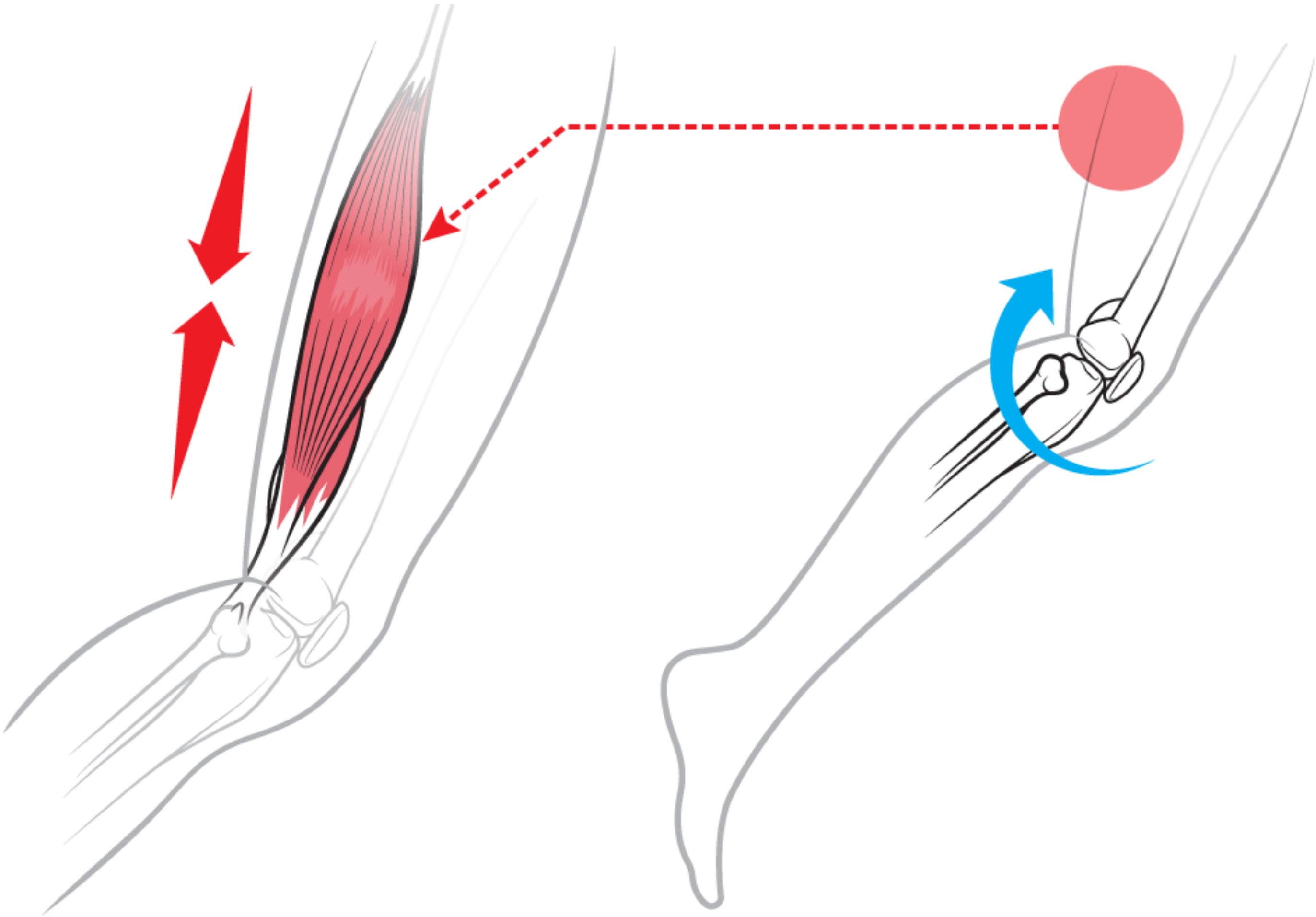
Accounting for interface dynamics → human dominates



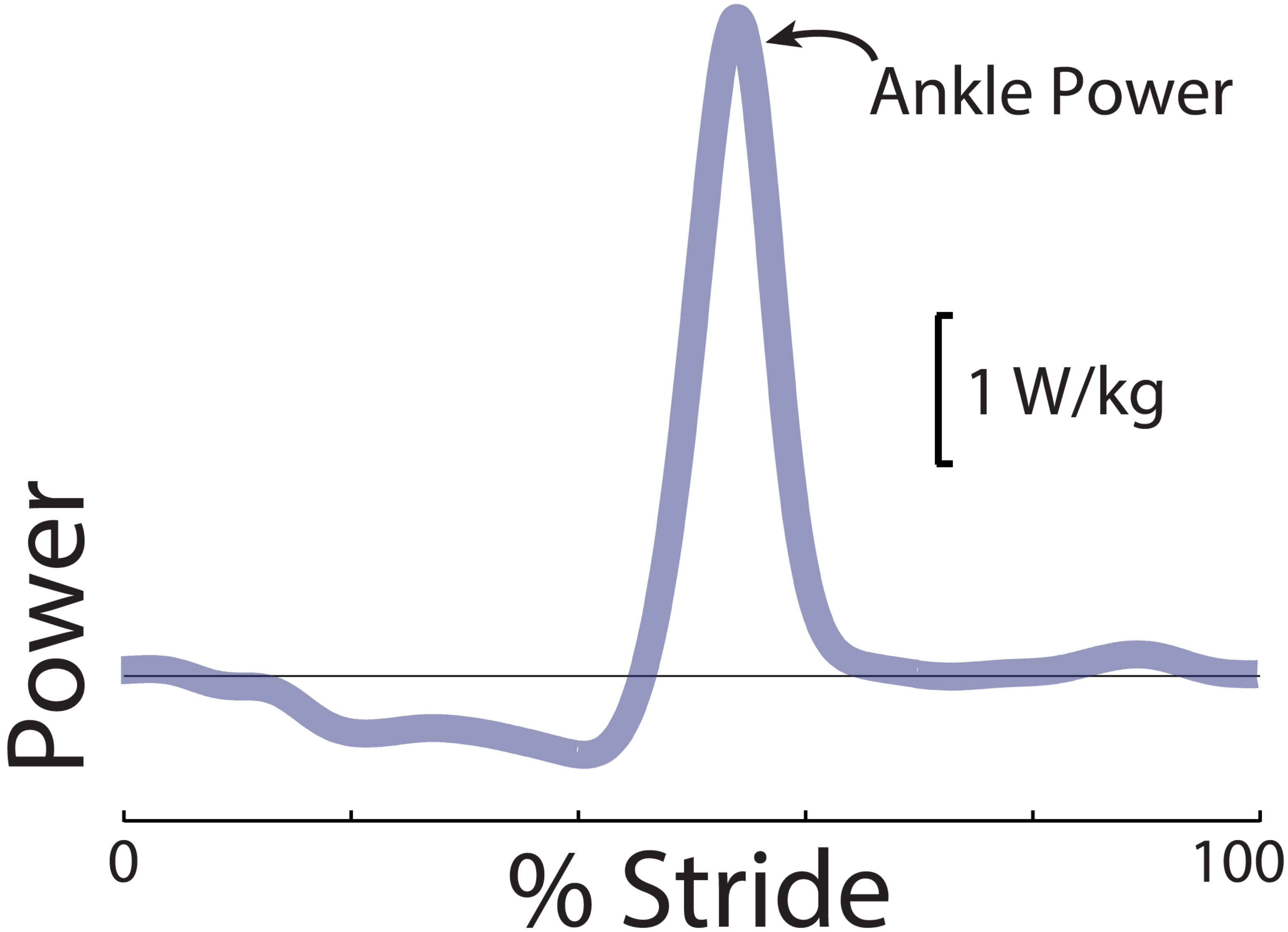
Ignoring interface dynamics → device dominates

Yandell et al. 2017 (JNER)

Muscle-Tendon ←→ Joint-Segment

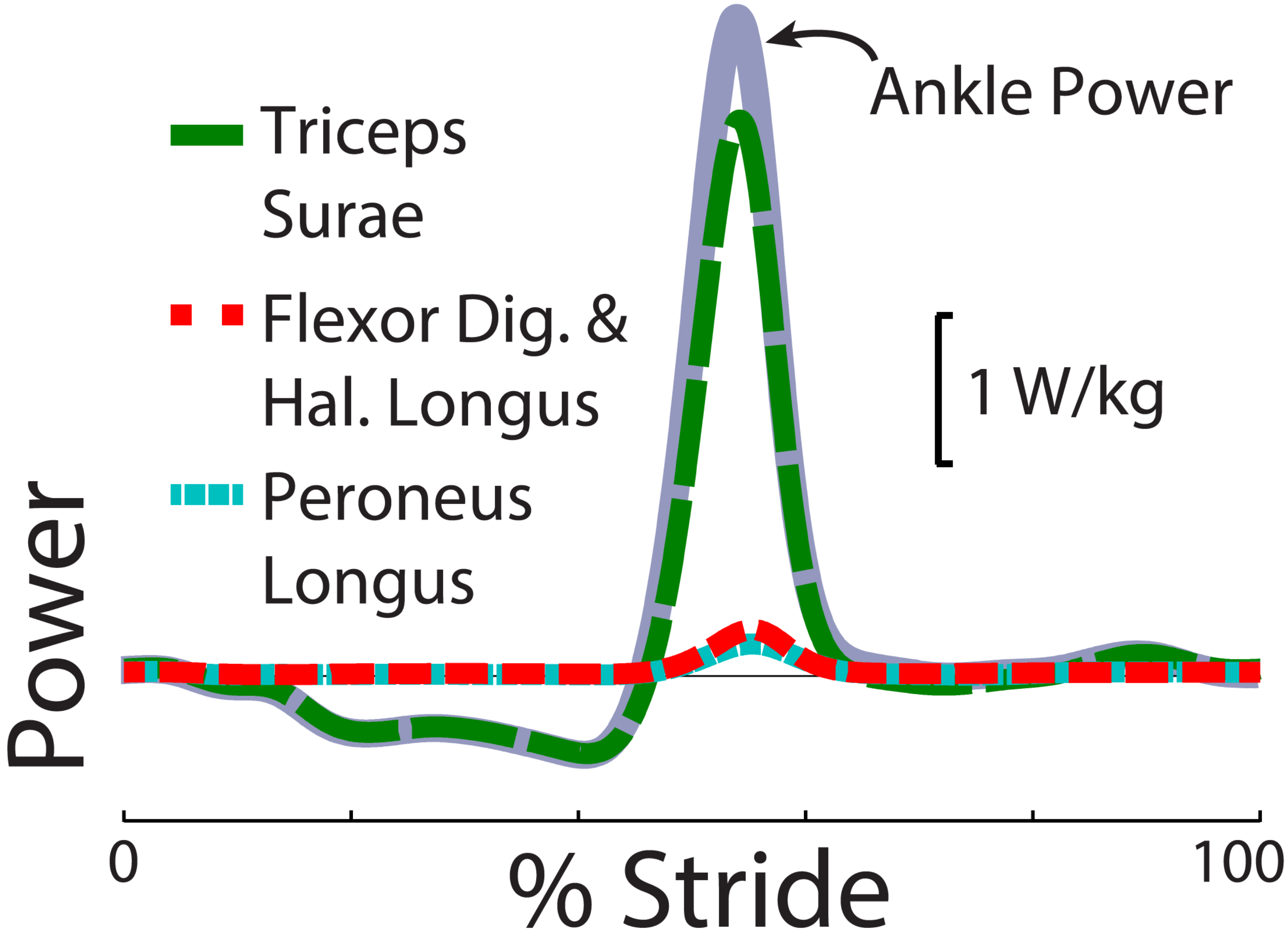


Hard to assess consistency



Honert & Zelik 2016

Hard to assess consistency



Honert & Zelik 2016

Hard to assess, but literature suggests discrepancy

What is mechanical function of foot during push-off in walking or running?

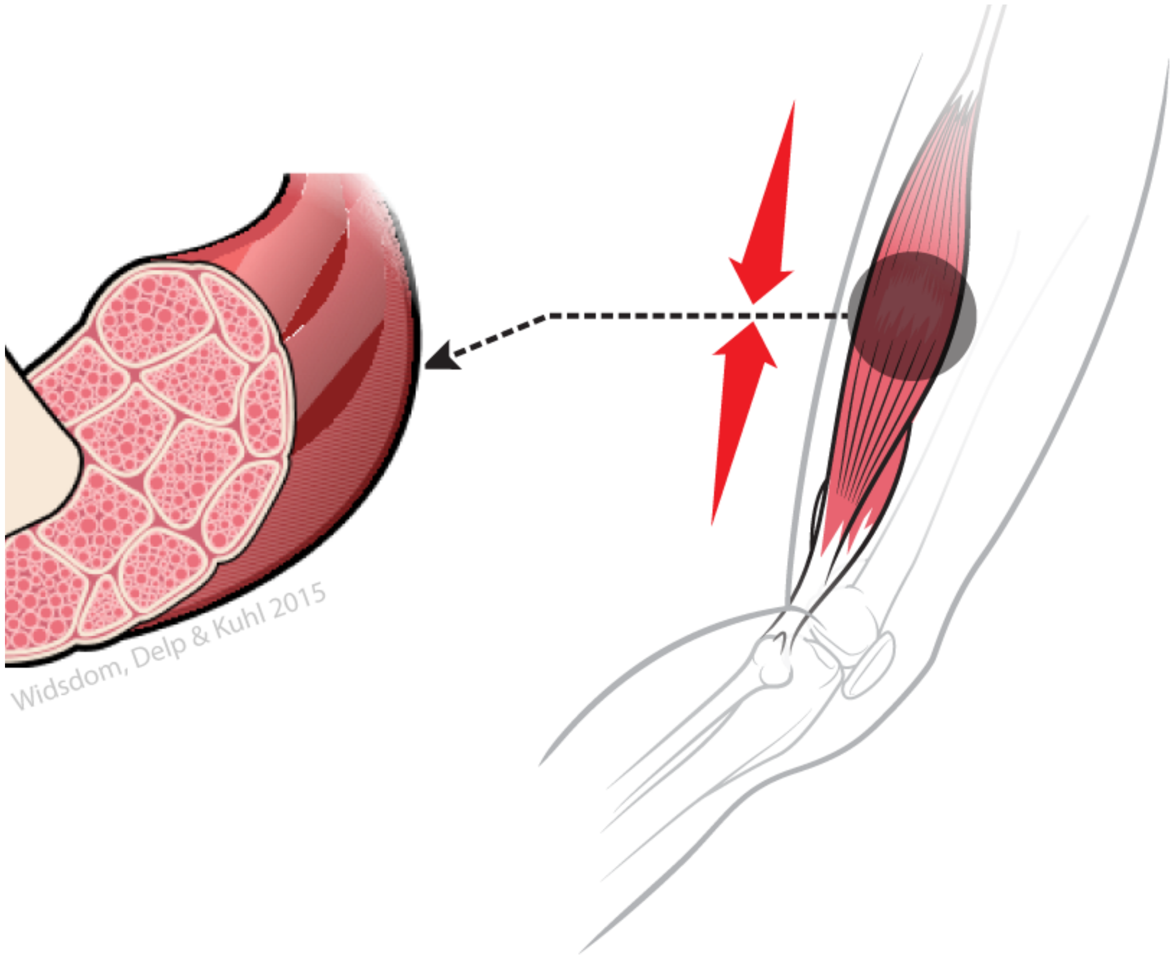
Ker et al. 1987
Stearne et al. 2016

Acts like a spring!

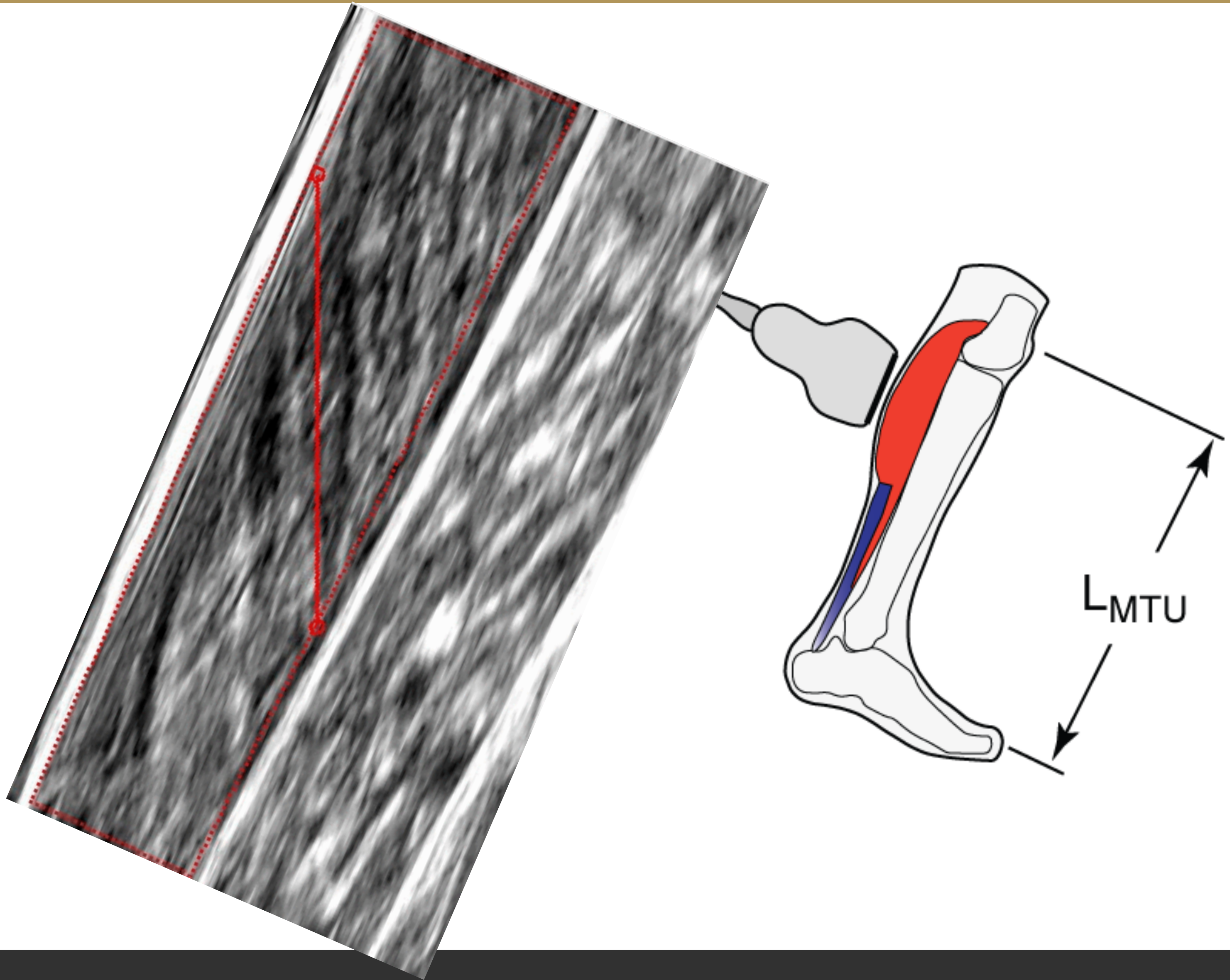
Stefanyshyn & Nigg 1997
Takahashi & Stanhope 2013

Acts like a damper!

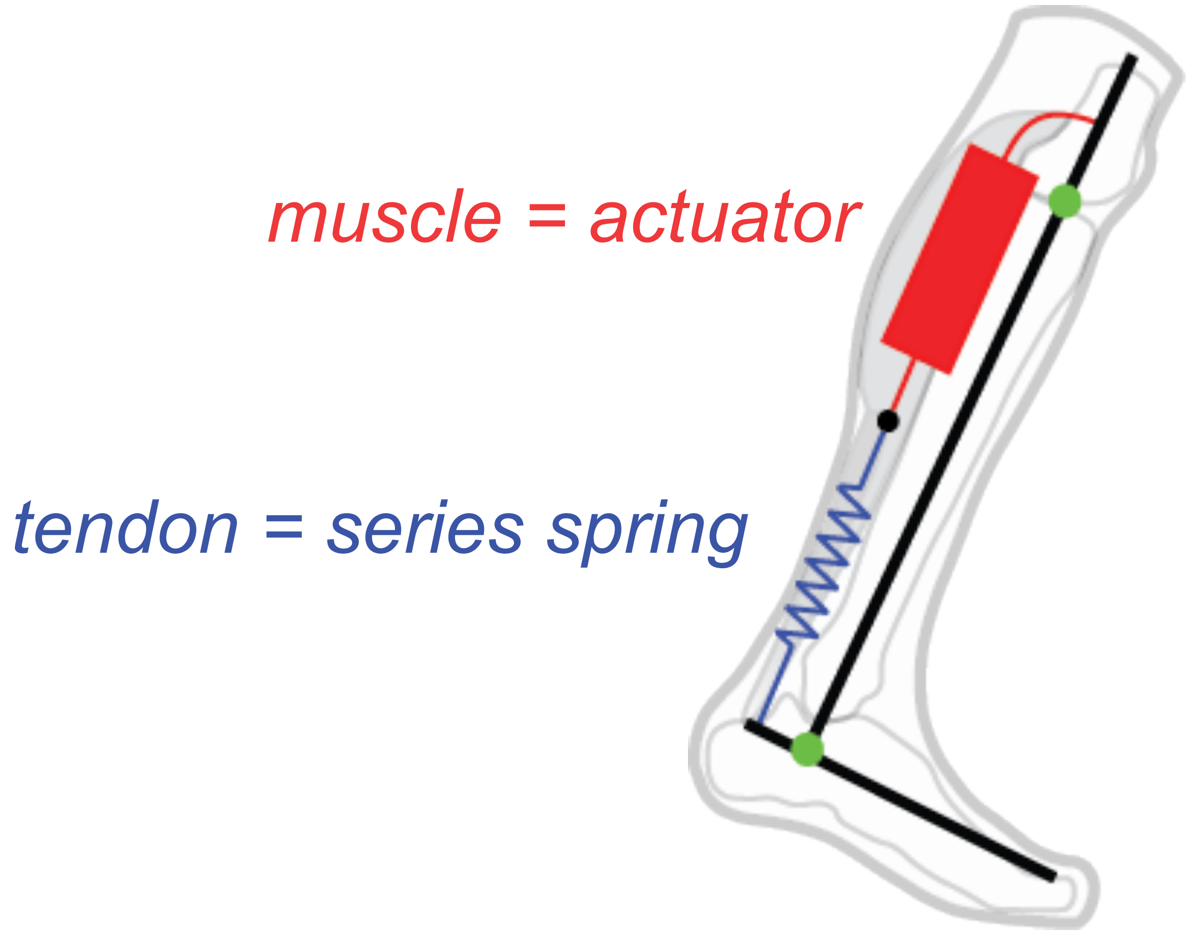
Muscle vs. Tendon ←→ Muscle-Tendon Unit (MTU)



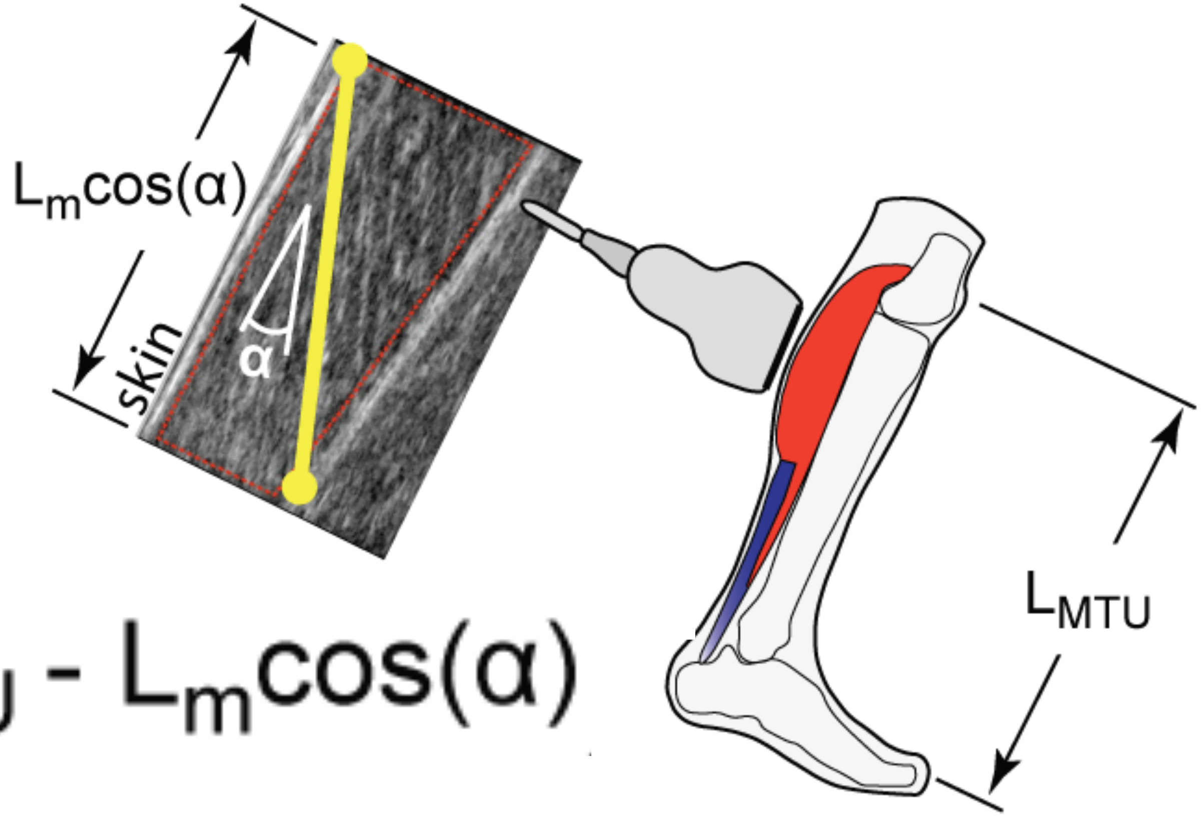
Ultrasound can track muscle fascicles, tendon or junction



Presumption: Tendon spring loaded in series with muscle

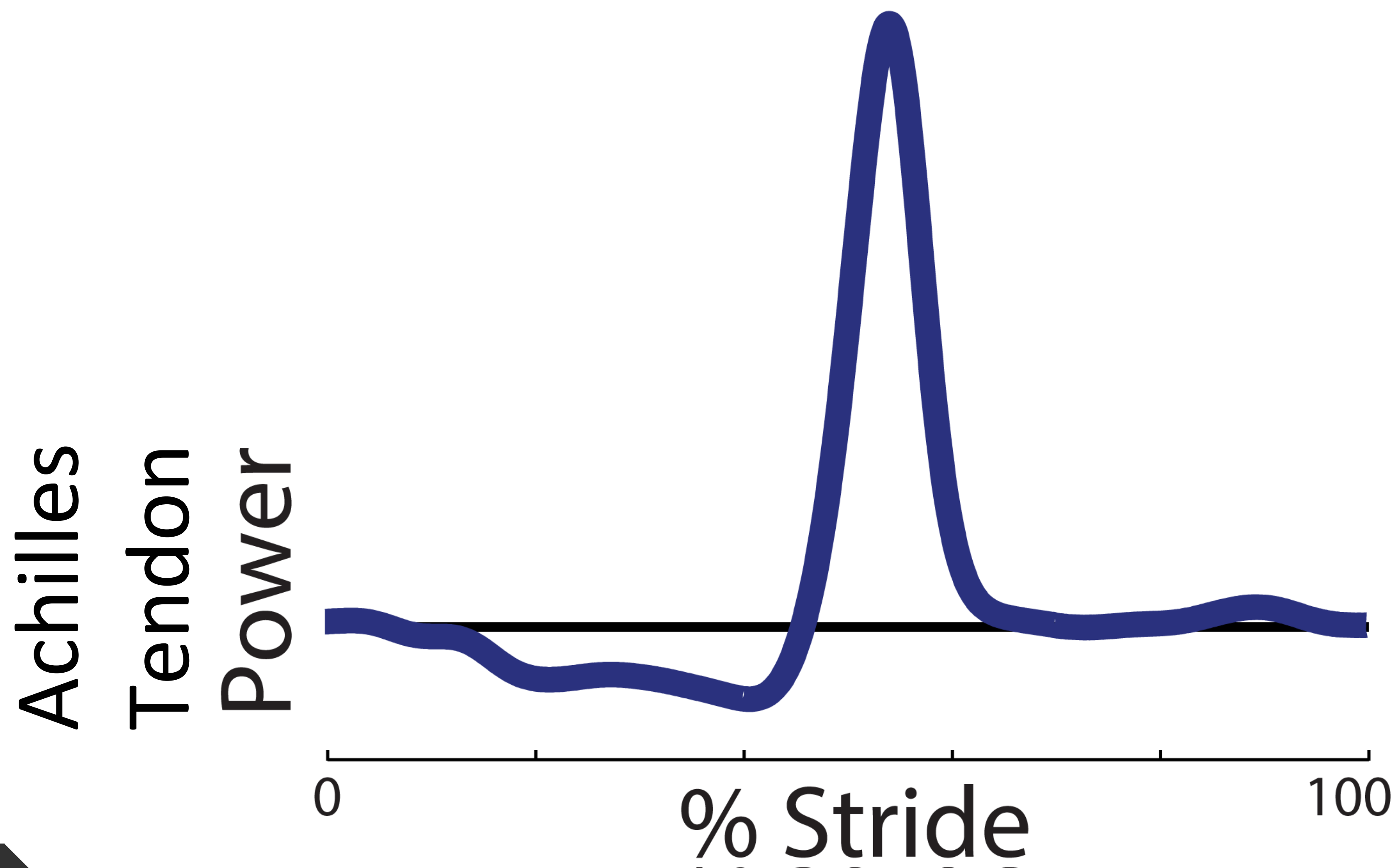


Presumption: Tendon (Passive) = MTU – Muscle (Active)

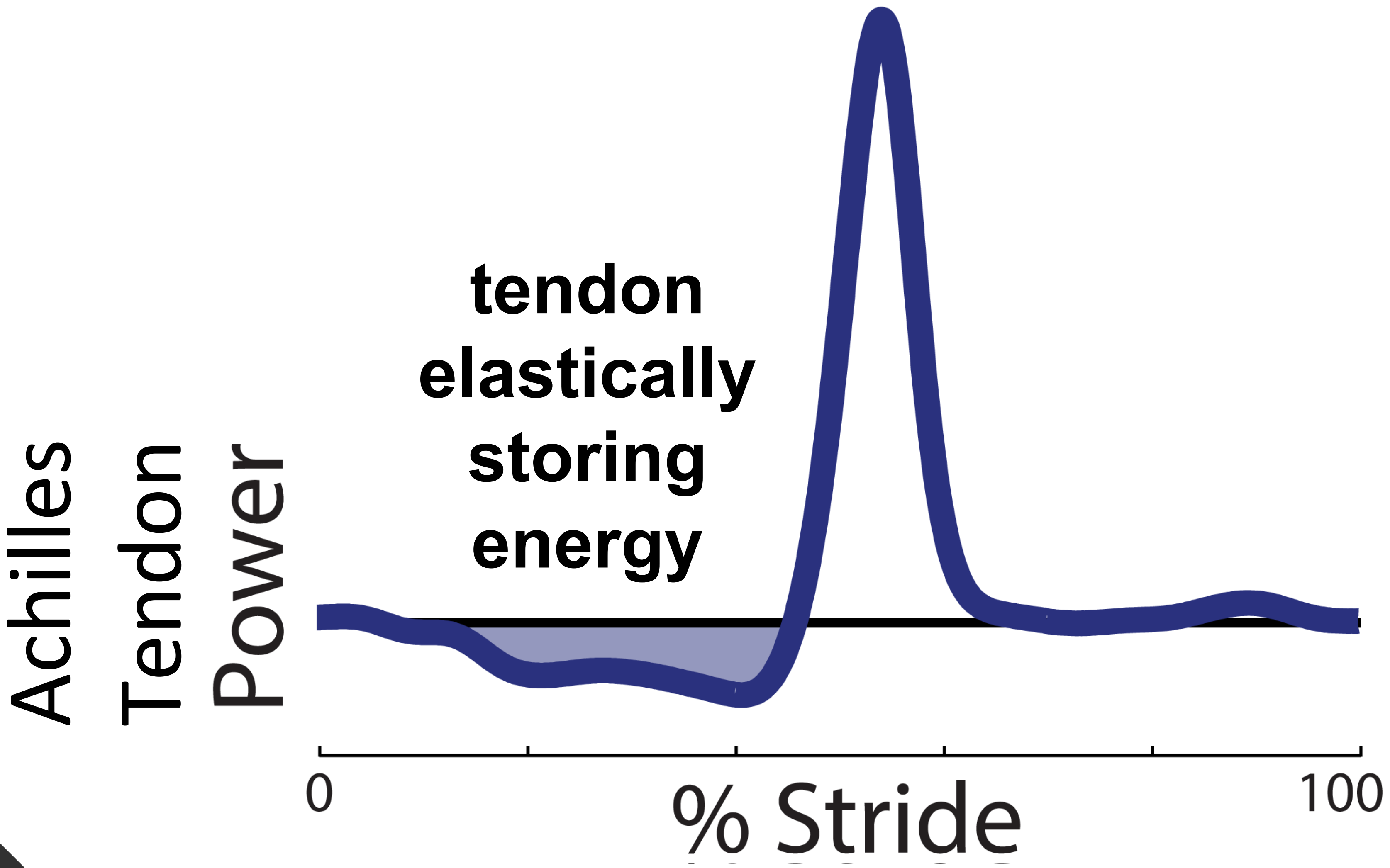


$$L_{Tendon} = L_{MTU} - L_m \cos(\alpha)$$

Problem: tendon estimated to return more energy than it stores

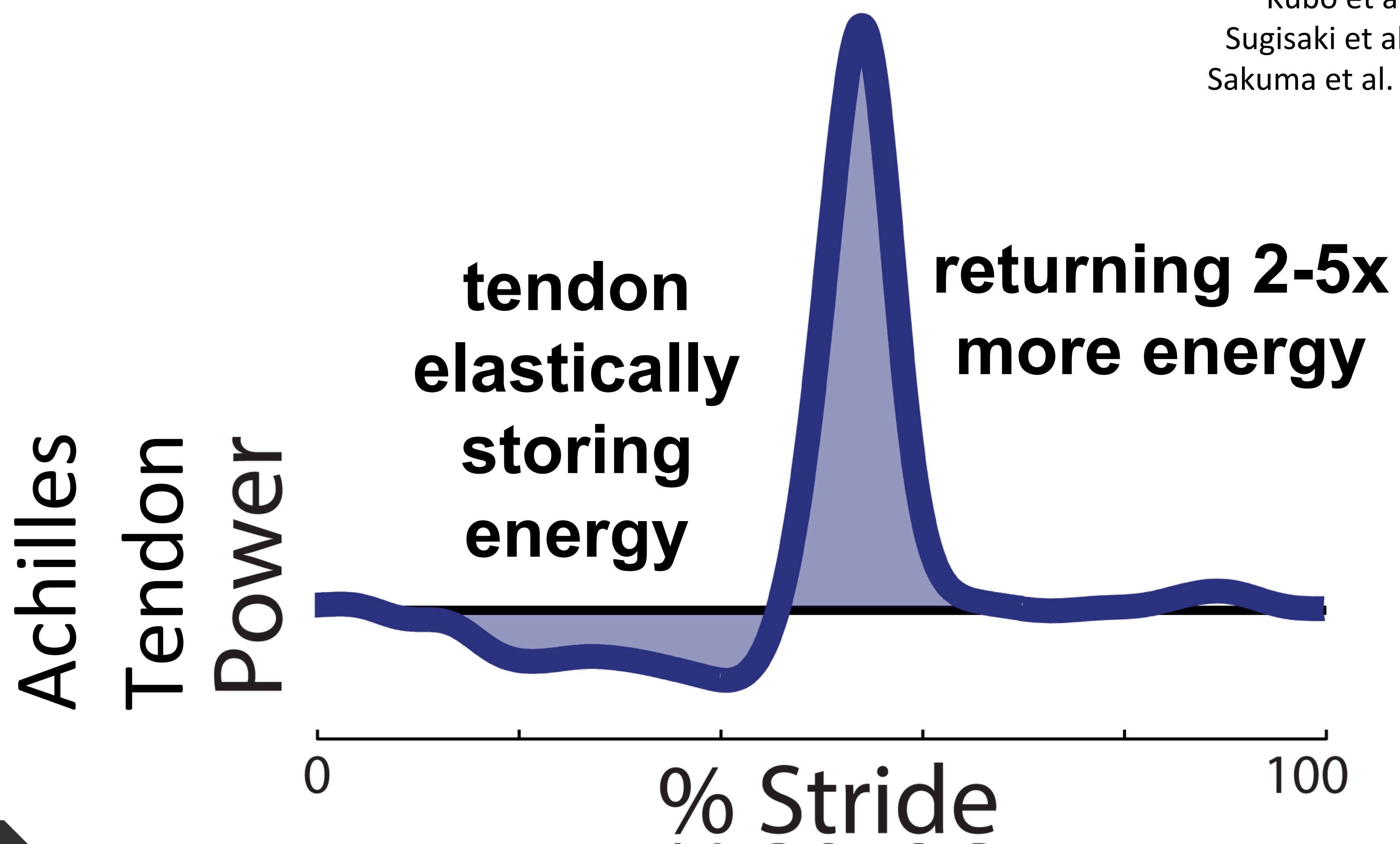


Problem: tendon estimated to return more energy than it stores



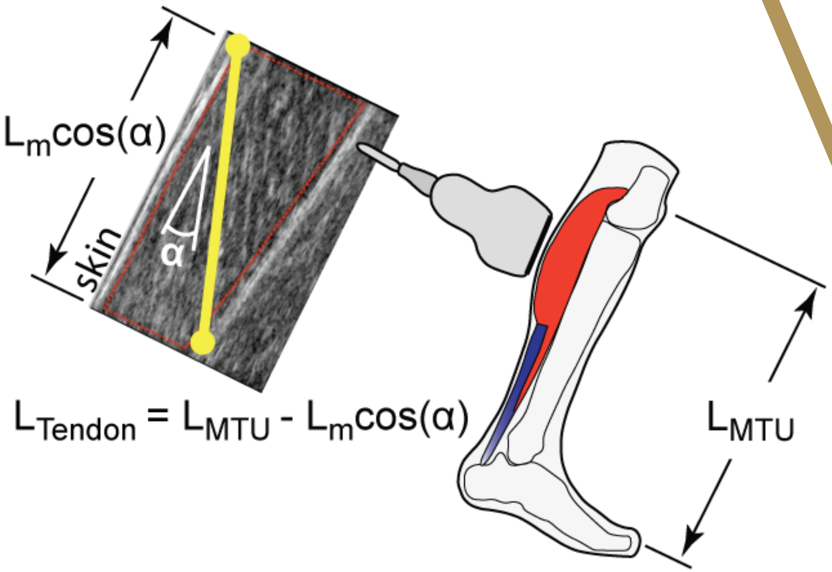
Problem: tendon estimated to return more energy than it stores

Kubo et al. 2000, Ishikawa et al. 2005, Sugisaki et al. 2005, Nigg & Herzog 2007, Sakuma et al. 2012, Farris & Sawicki 2012, Zelik & Franz 2017



Alternative methods → more plausible tendon energy return

Track Muscle Fascicle

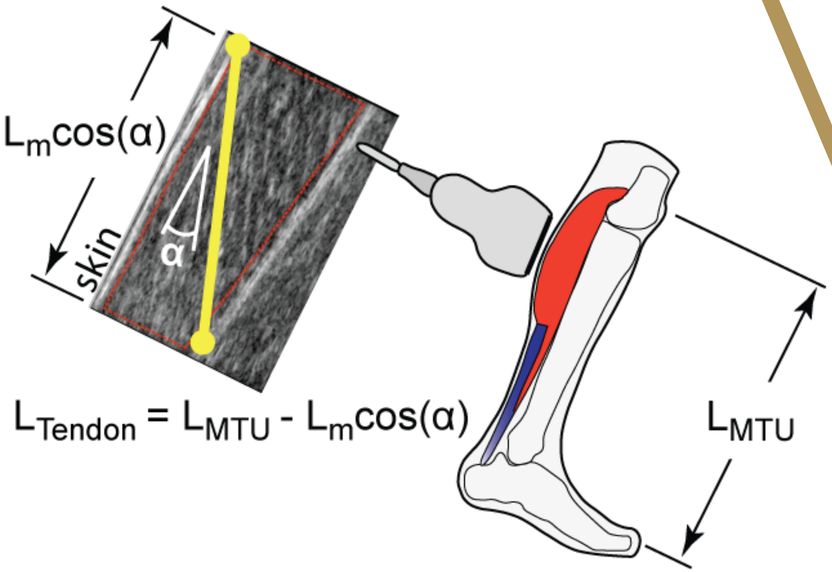


1 J stored, 2-5 J returned

Zelik & Franz 2017

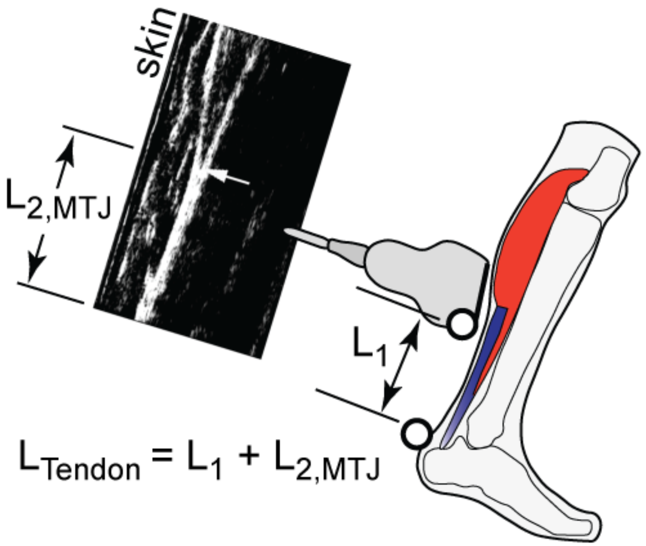
Alternative methods → more plausible tendon energy return

Track Muscle Fascicle



1 J stored,
2-5 J returned

Track Muscle-Tendon Junction



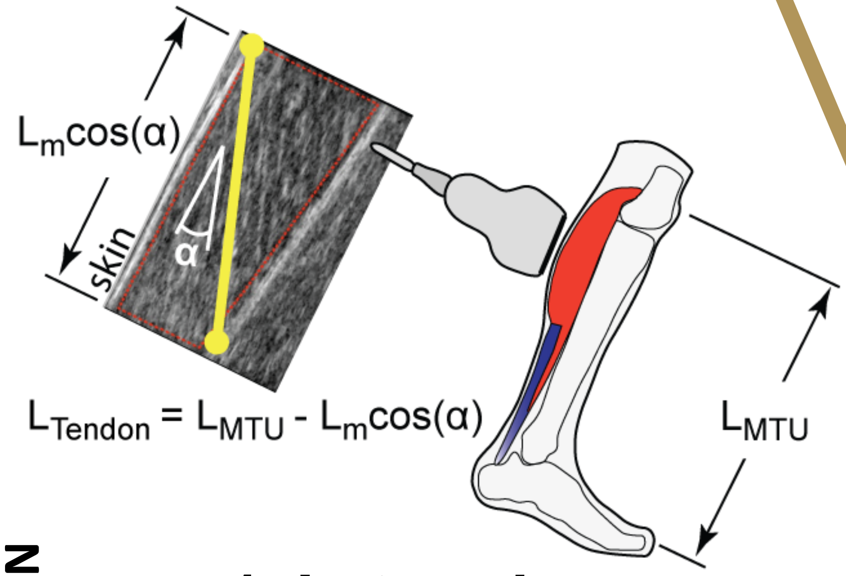
1 J stored,
0.5-0.9 J returned

Zelik & Franz 2017

Alternative methods → more plausible tendon energy return

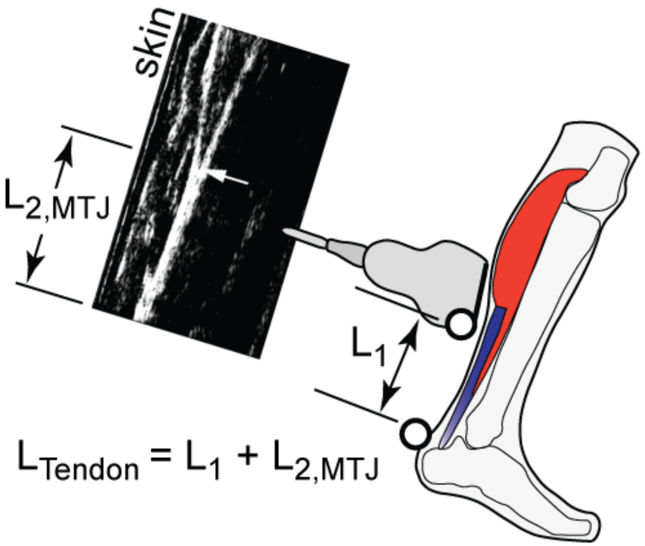
but exhibit unexpected trends with gait speed

Track Muscle Fascicle



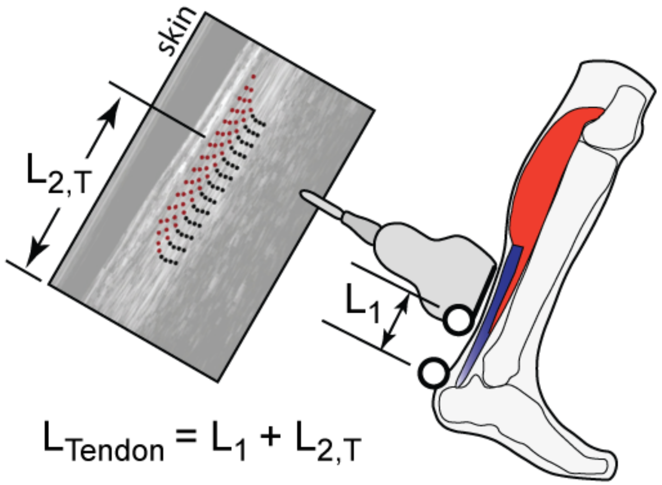
1 J stored,
2-5 J returned

Track Muscle-Tendon Junction



1 J stored,
0.5-0.9 J returned

Track Local Tendon Elongation

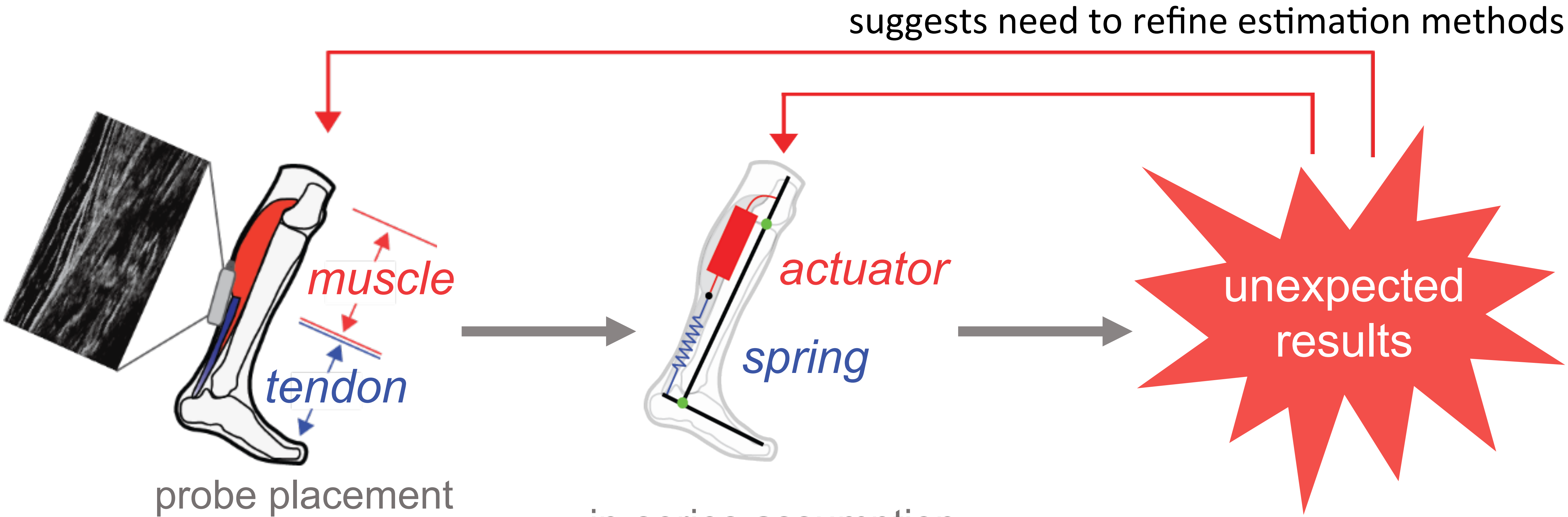


1 J stored,
0.7-1 J returned

TENDON

Zelik & Franz 2017

Discrepancy → Partitioning muscle vs. tendon is complicated

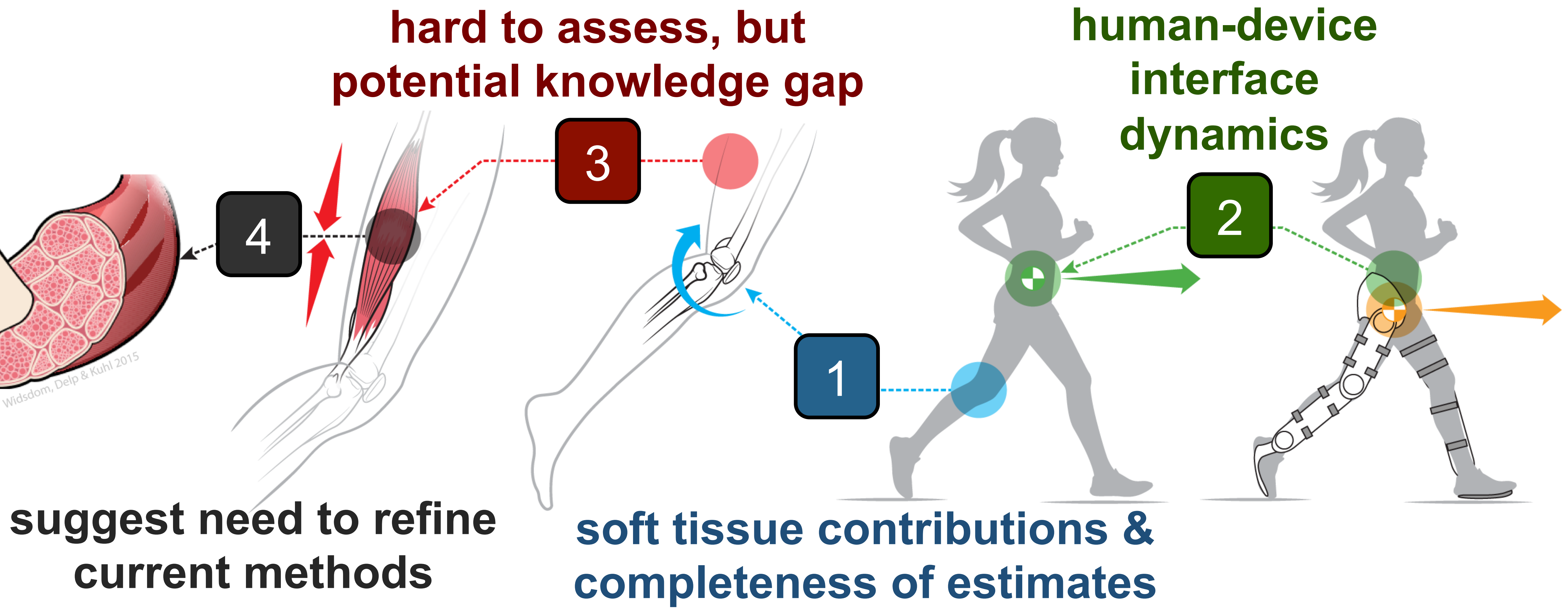


probe placement
3D architecture
tendon curvature
MTU regression

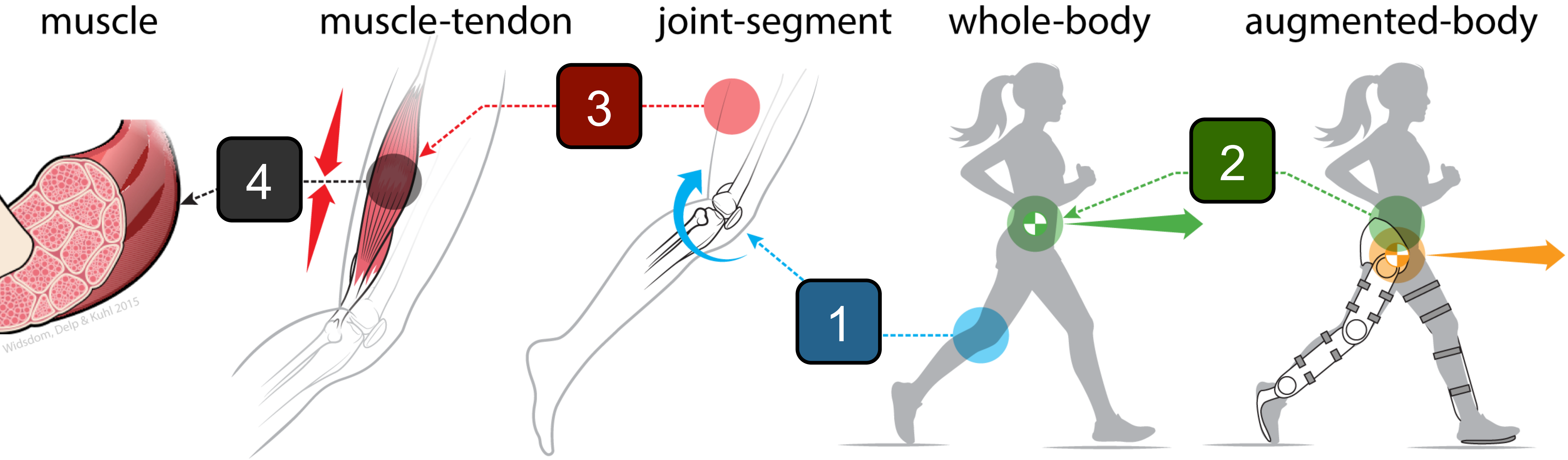
in-series assumption
transverse dynamics
adjacent MTUs

Matijevich, Branscombe & Zelik 2017 (ISB)

Discrepancies between scales provide important insights



Discrepancies between scales provide important insights



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Presentation Slides: Uploaded to my.vanderbilt.edu/batlab