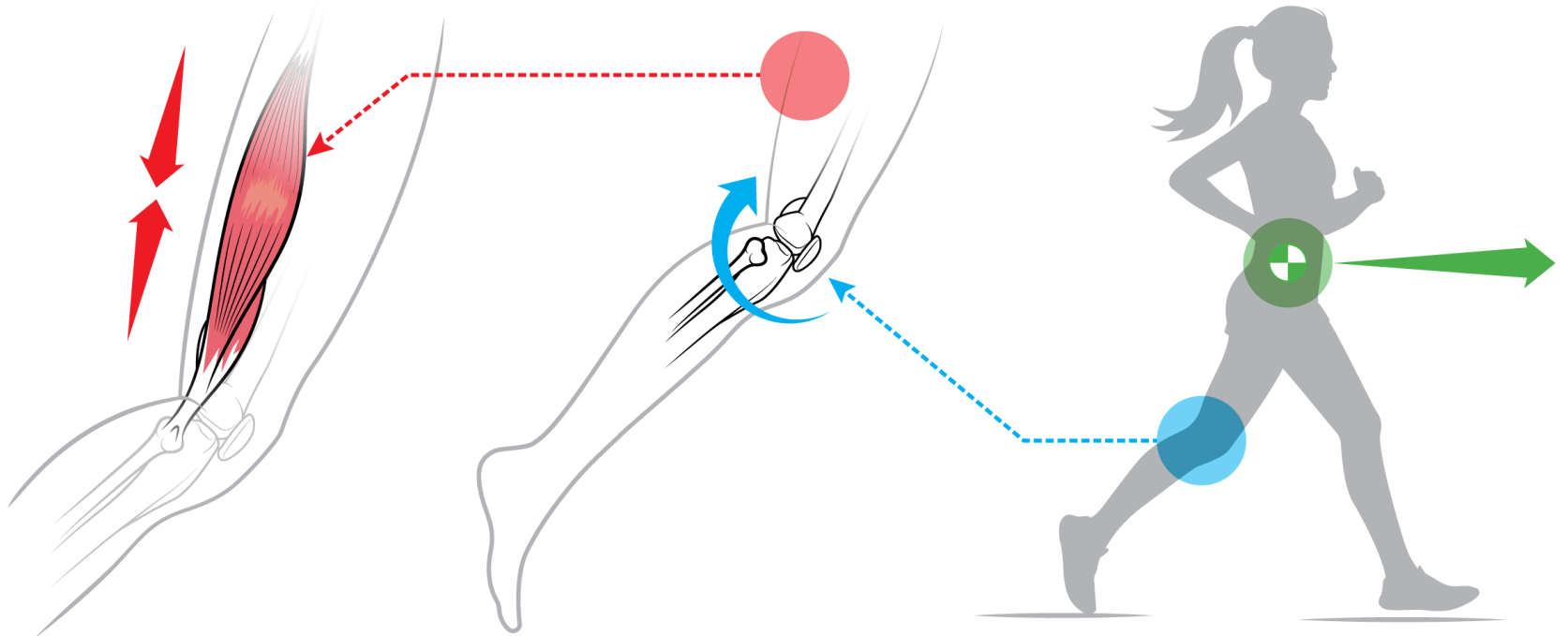
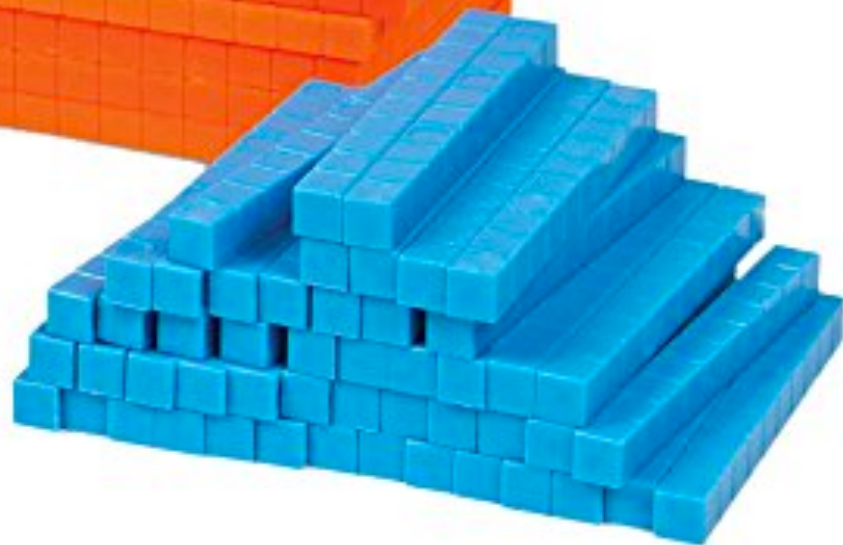
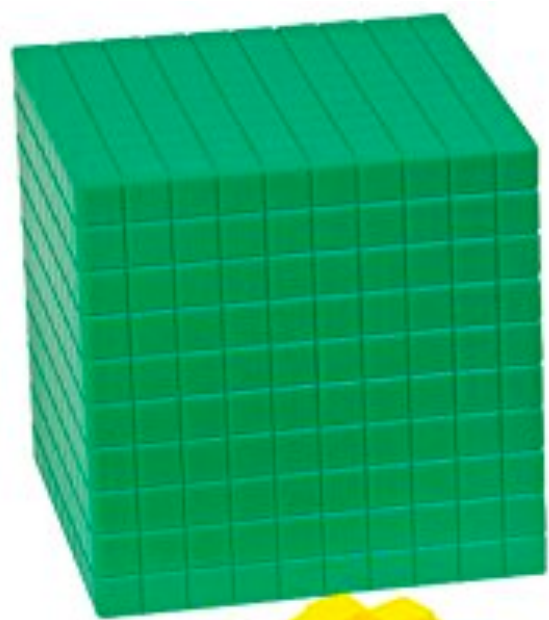


# Towards a Unified Multi-Scale Understanding of Human Biomechanics

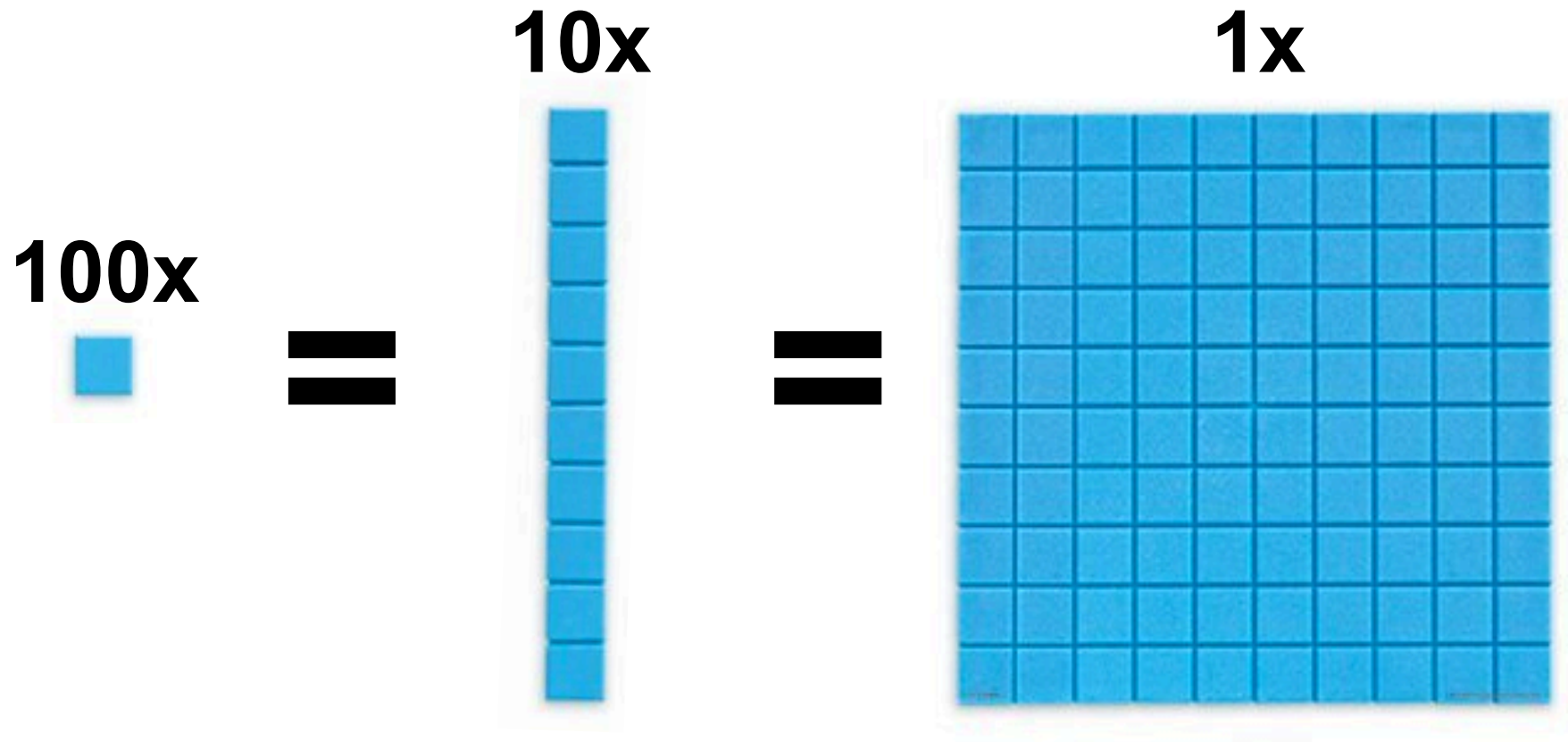
## From Muscle-Tendon Work to Whole-Body Energy



Karl E. Zelik  
Biomechanics & Assistive Technology Lab  
Vanderbilt University, Nashville, TN, USA



# Mathematics (Base 10 Blocks)



# Currency

100x



10x



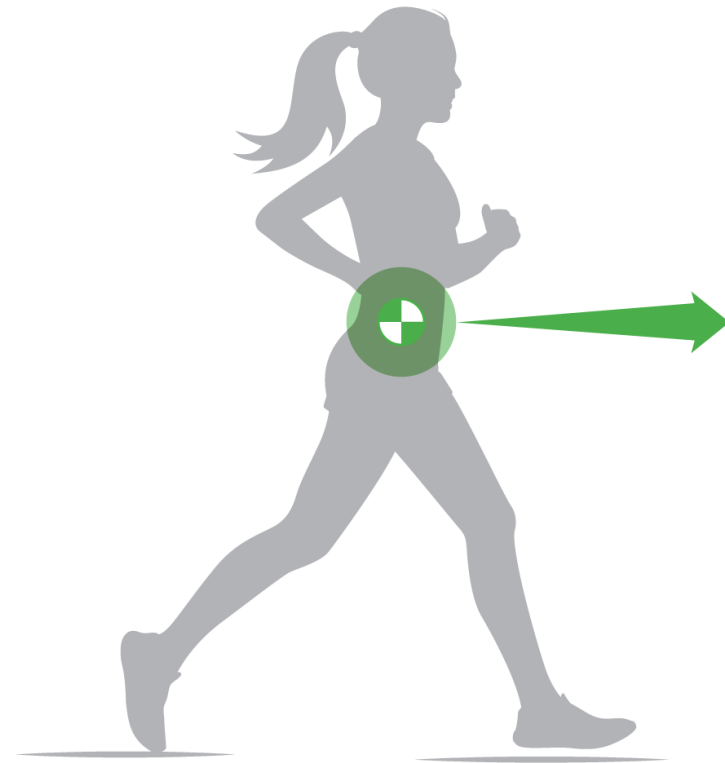
1x





# Experimental Biomechanics - Grand Challenge

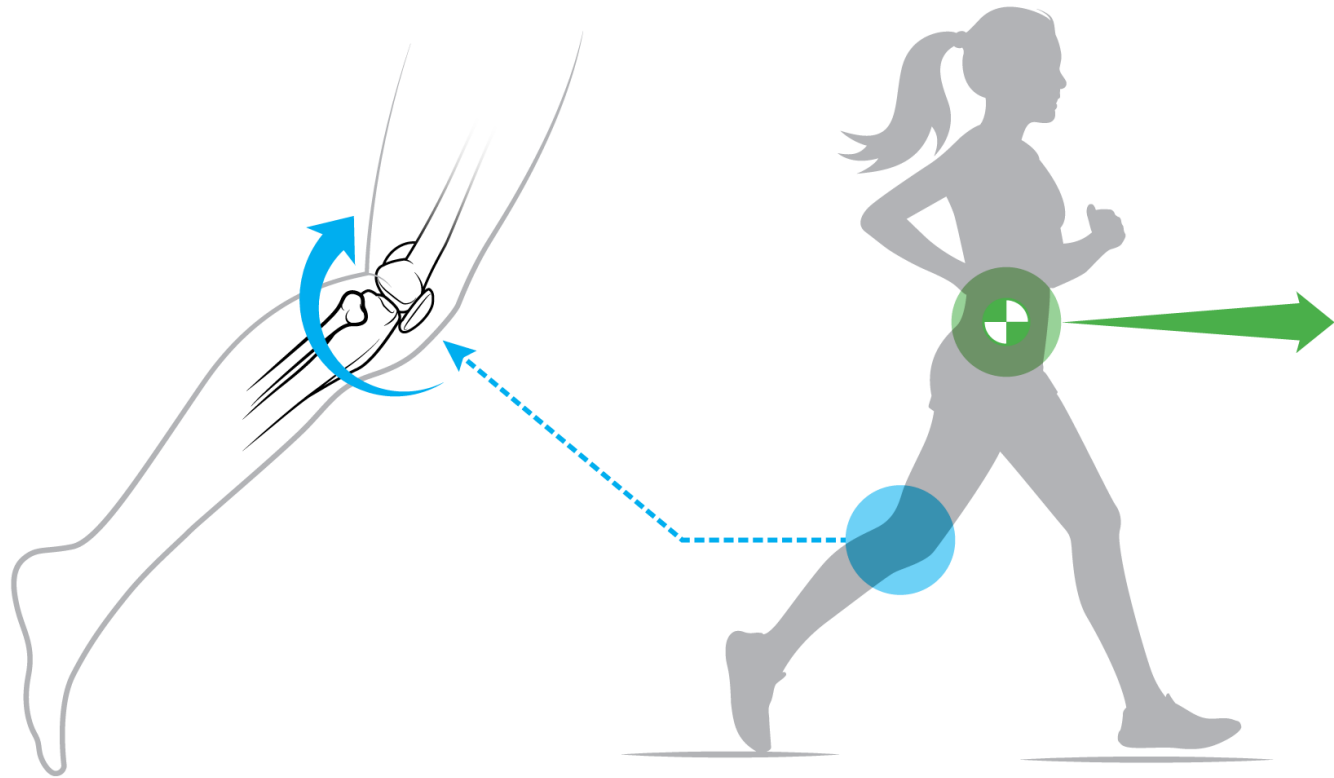
**WHOLE-BODY**



# Experimental Biomechanics - Grand Challenge

**JOINT-SEGMENT**

**WHOLE-BODY**

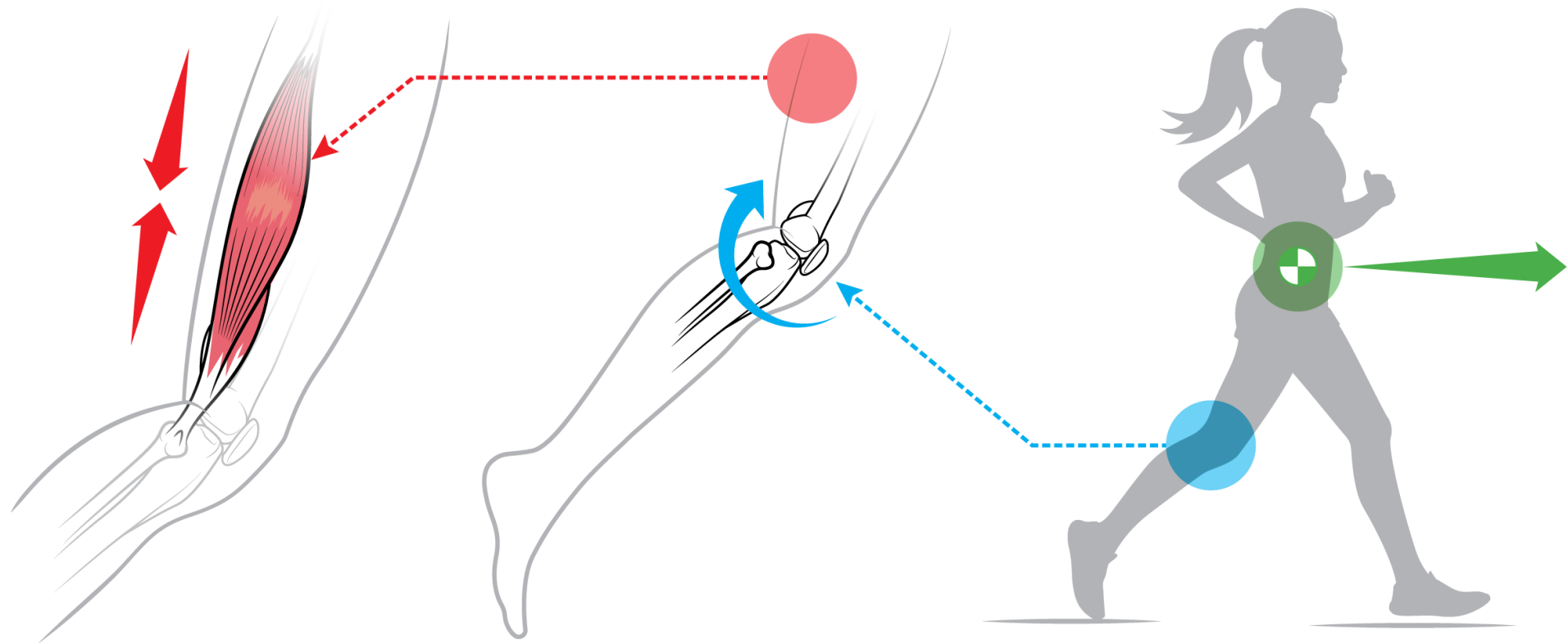


# Experimental Biomechanics - Grand Challenge

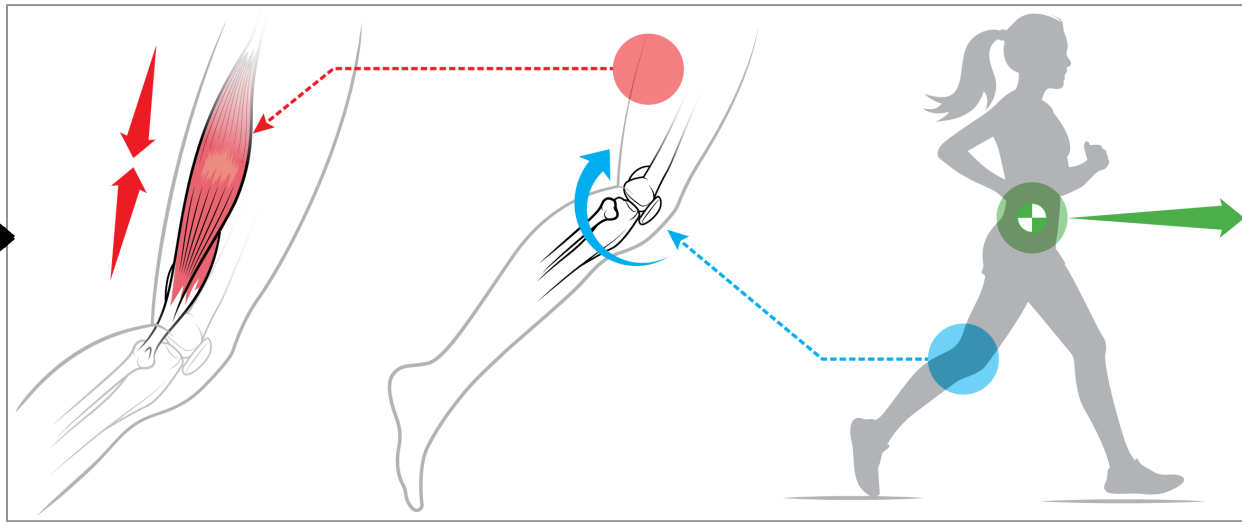
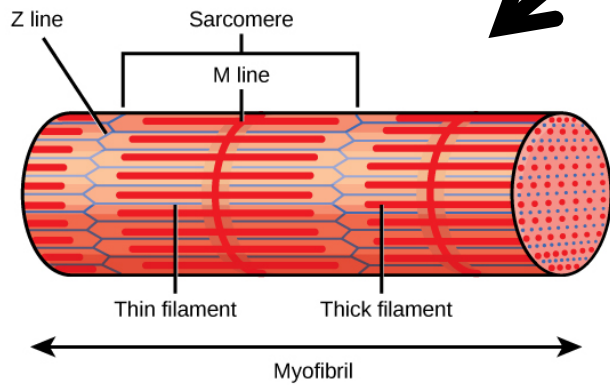
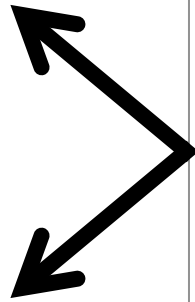
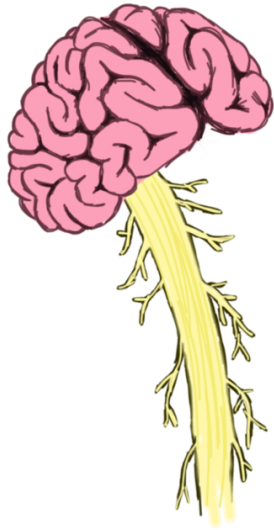
**MUSCLE-TENDON**

**JOINT-SEGMENT**

**WHOLE-BODY**



# Neuromechanics - Even Grander Challenge



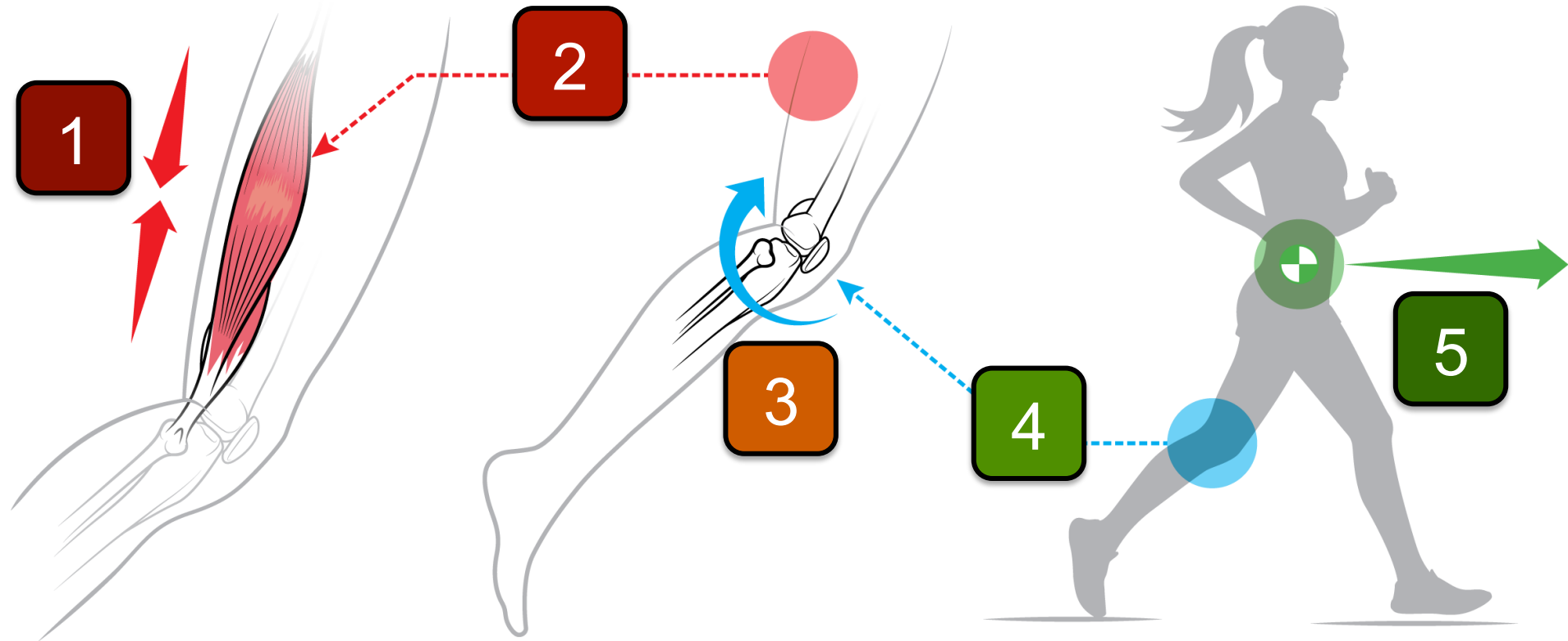


# 5 Gaps & Challenges

**MUSCLE-TENDON**

**JOINT-SEGMENT**

**WHOLE-BODY**

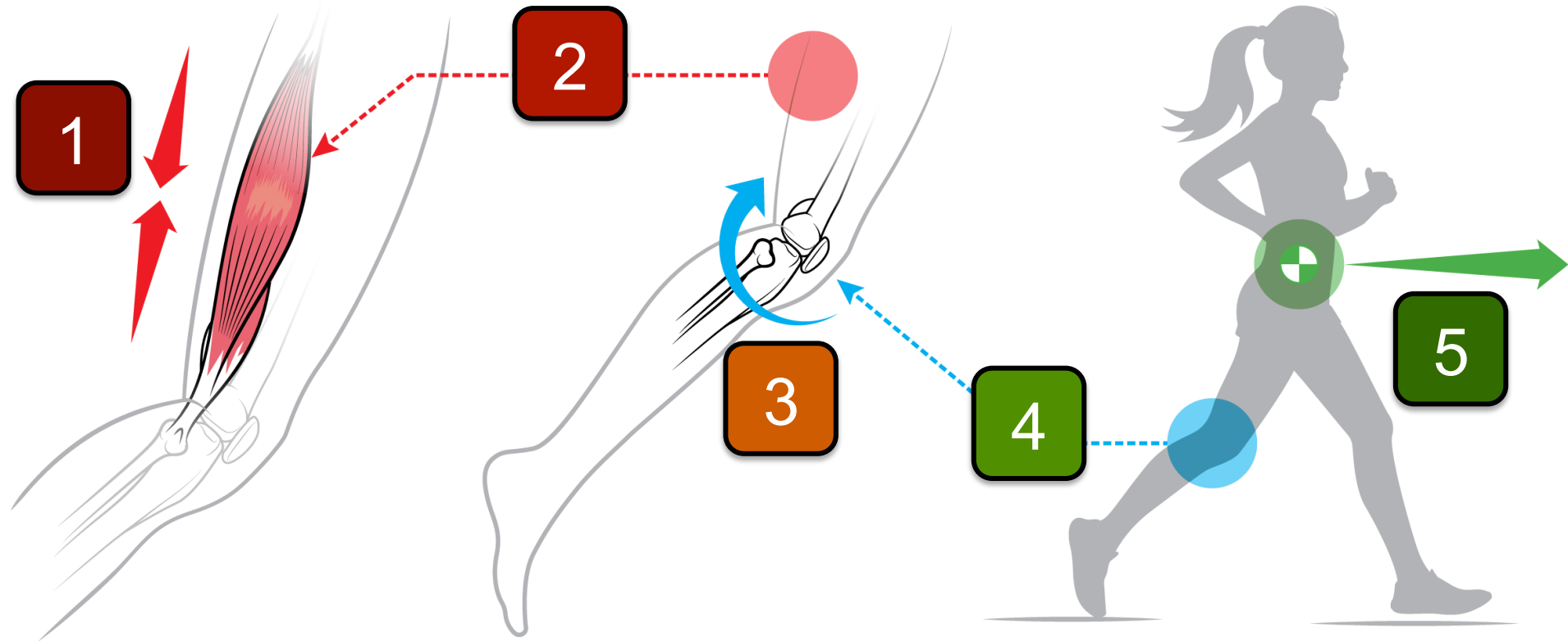


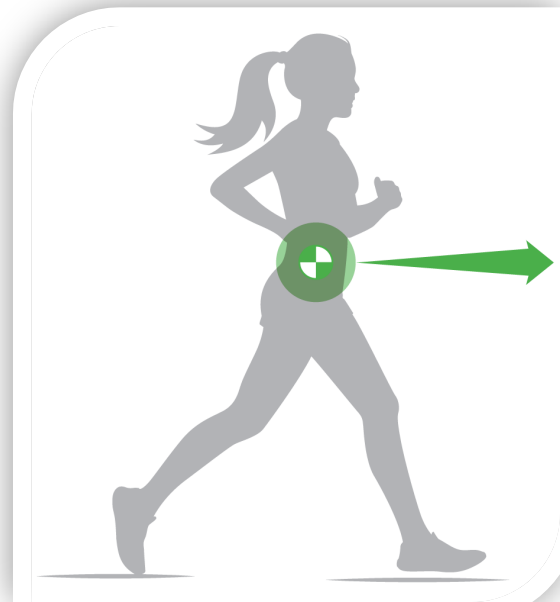
# Hodgepodge of Thoughts on Multi-Scale Biomechanics

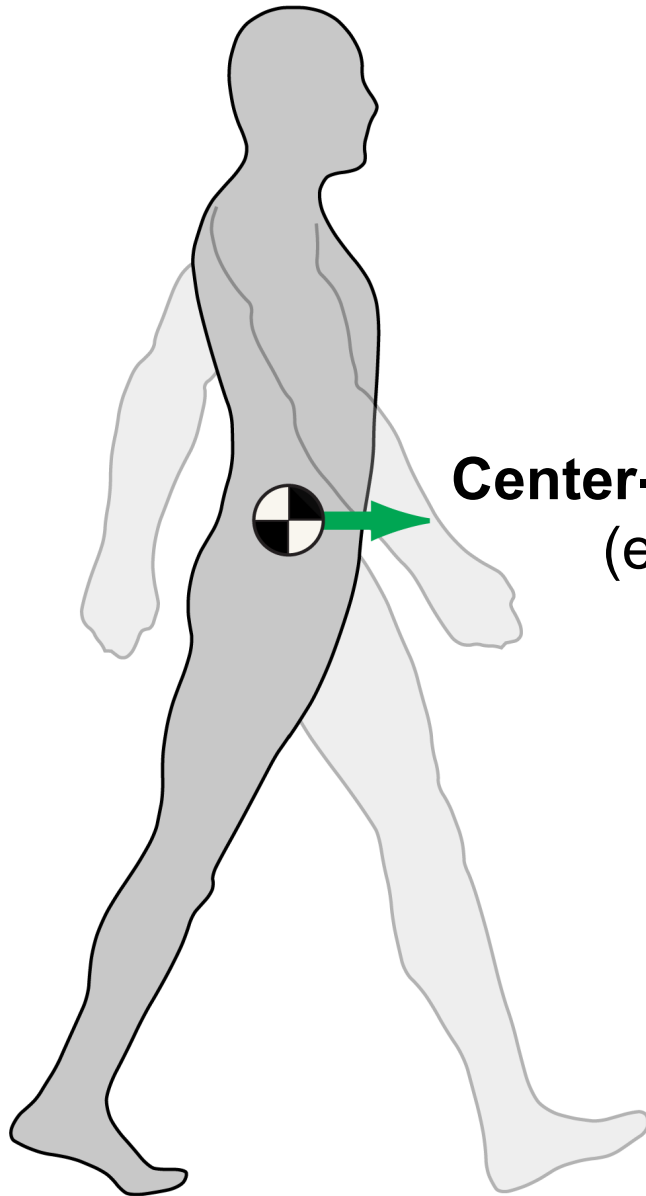
**MUSCLE-TENDON**

**JOINT-SEGMENT**

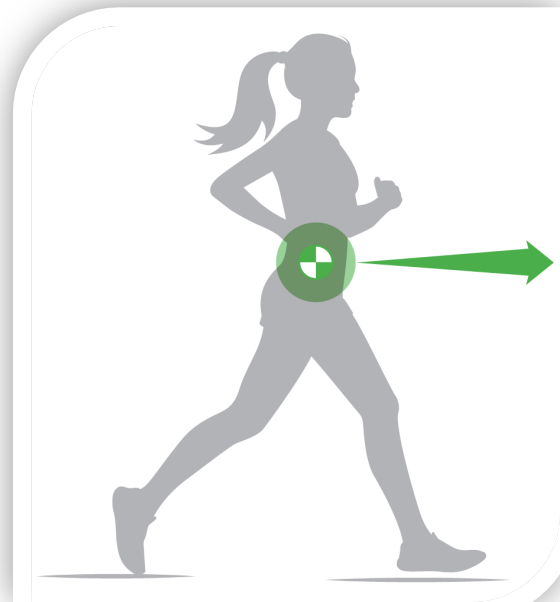
**WHOLE-BODY**



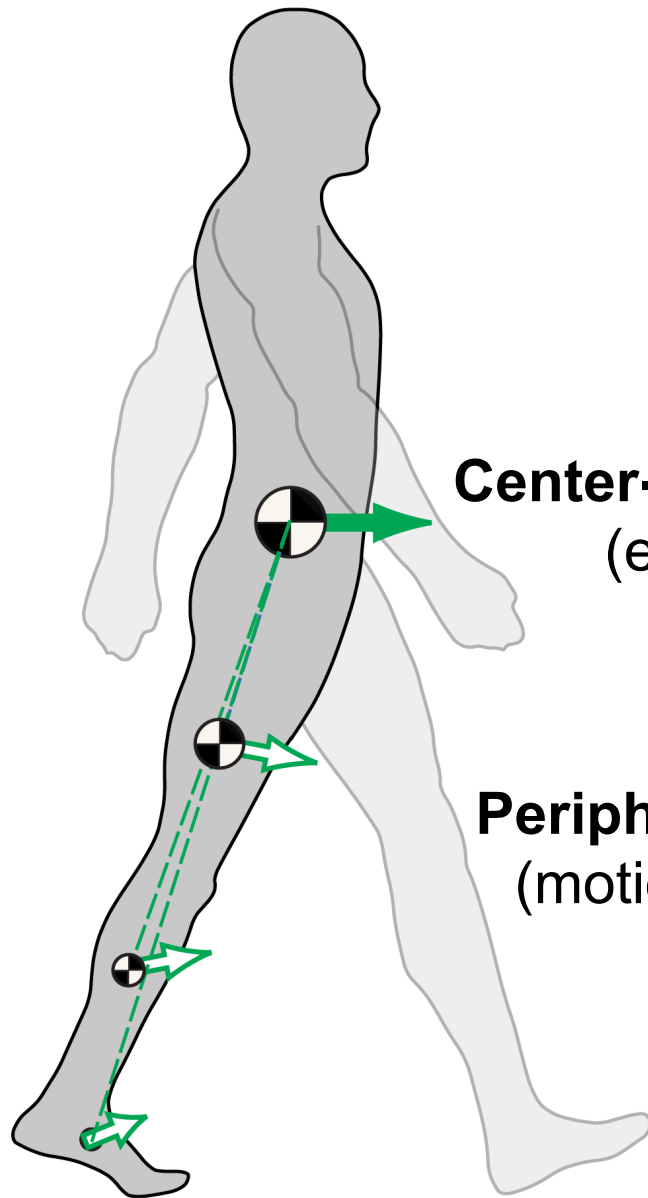




**Center-of-Mass (COM) energy change**  
(estimated from force plates)



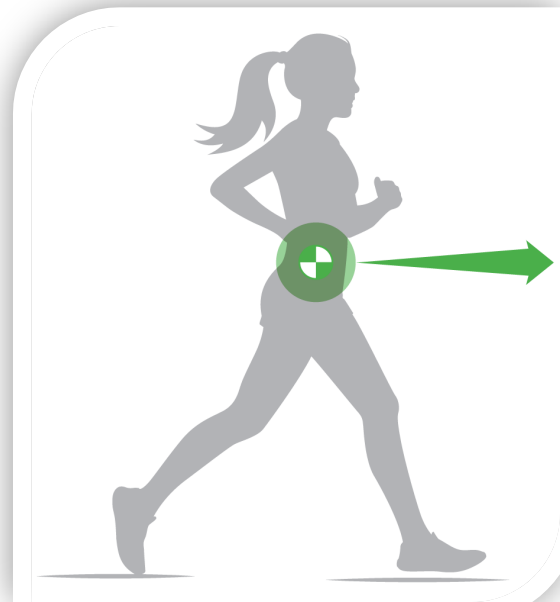




**Center-of-Mass (COM) energy change**  
(estimated from force plates)

+

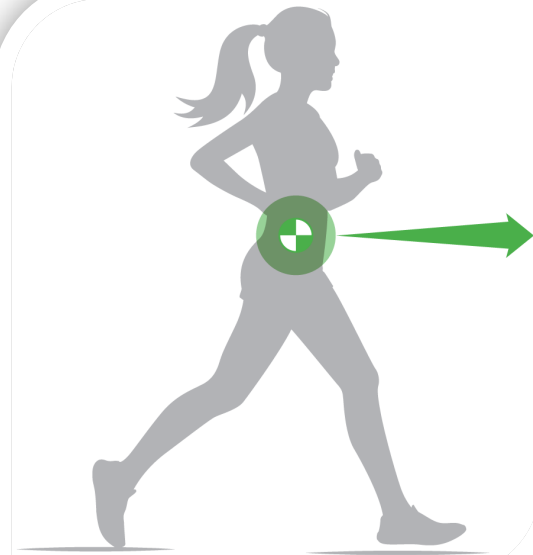
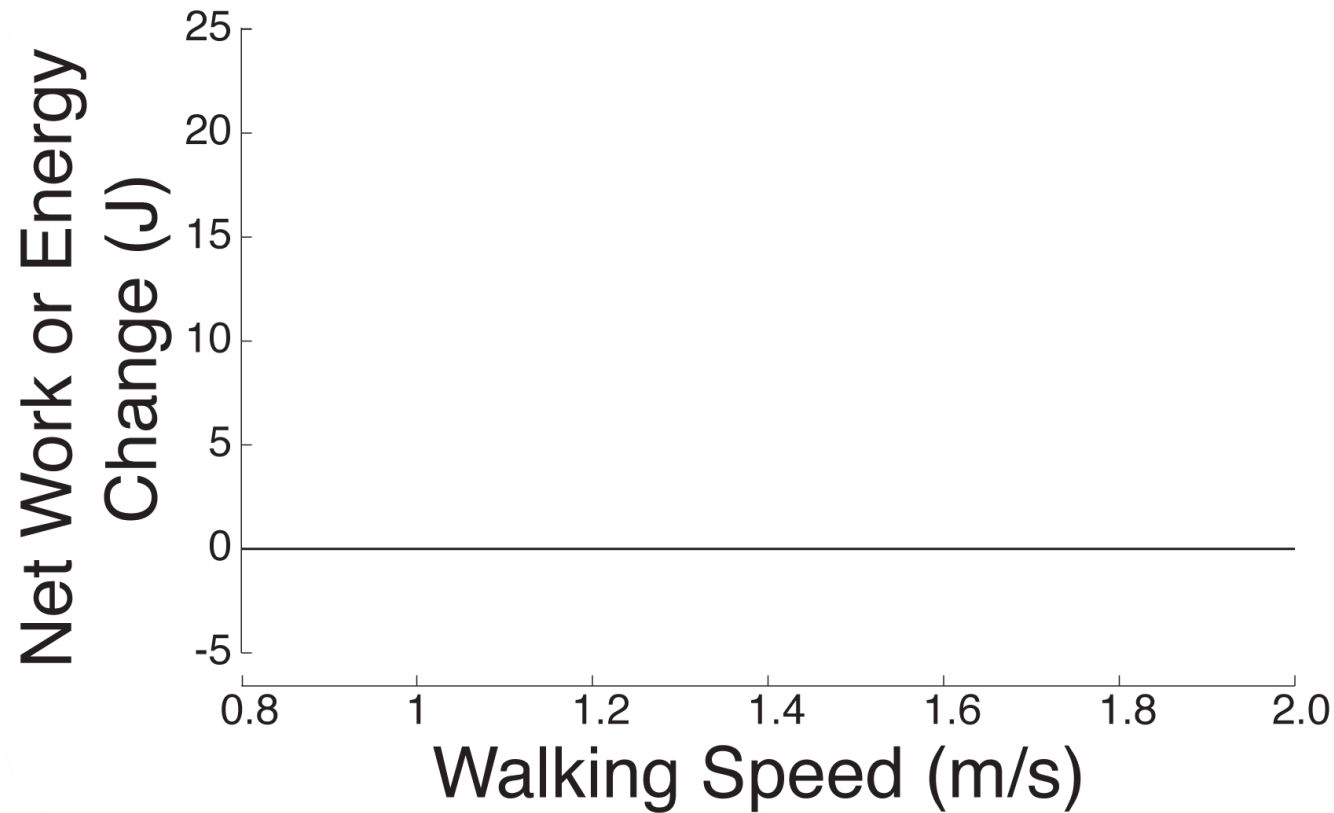
**Peripheral energy change**  
(motion relative to COM)



5

WHOLE-BODY → MOSTLY RESOLVED

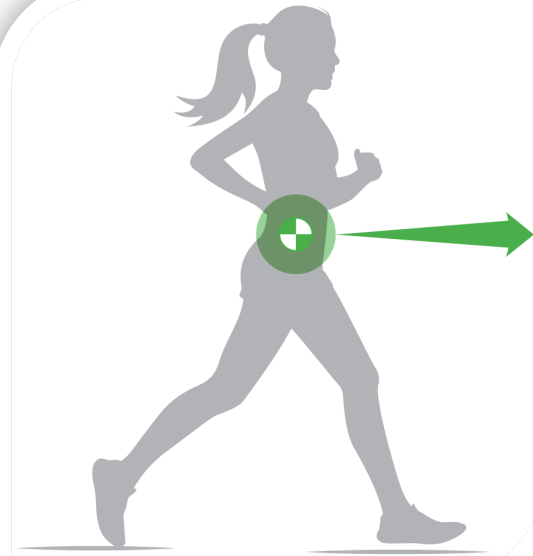
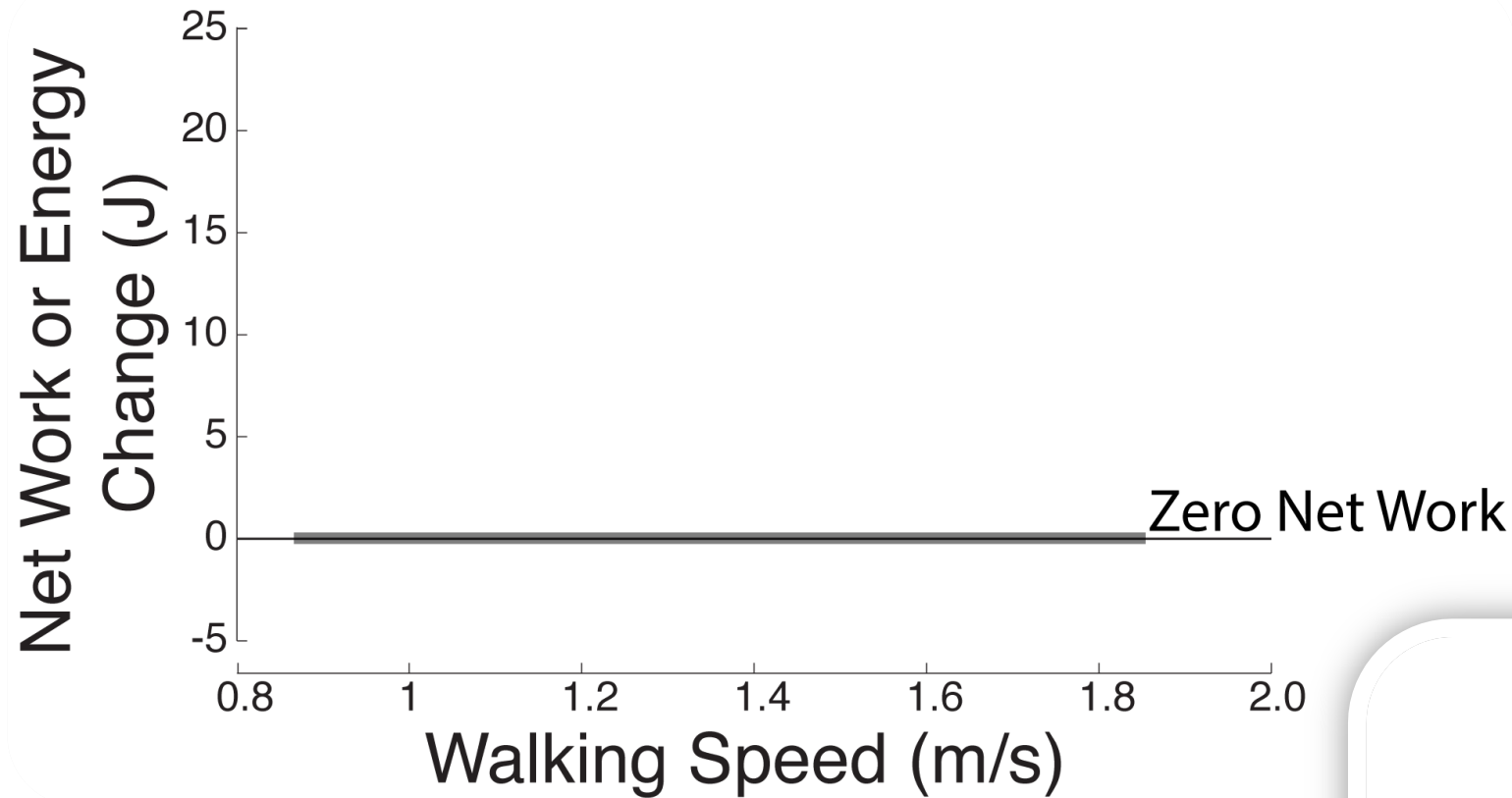
Trust whole-body mechanics b/c they add up properly



5

WHOLE-BODY → MOSTLY RESOLVED

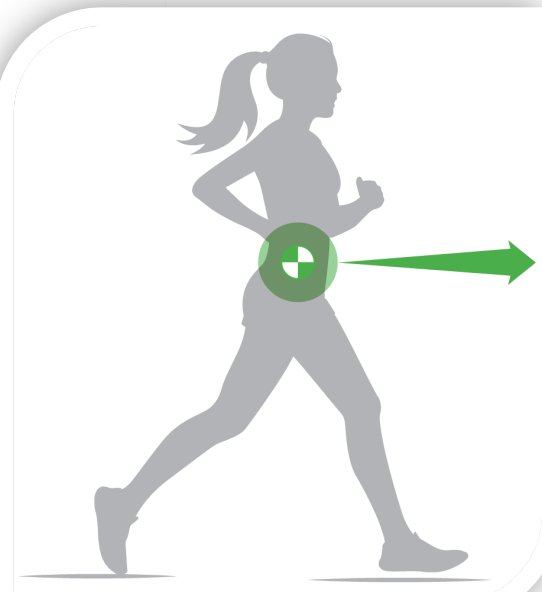
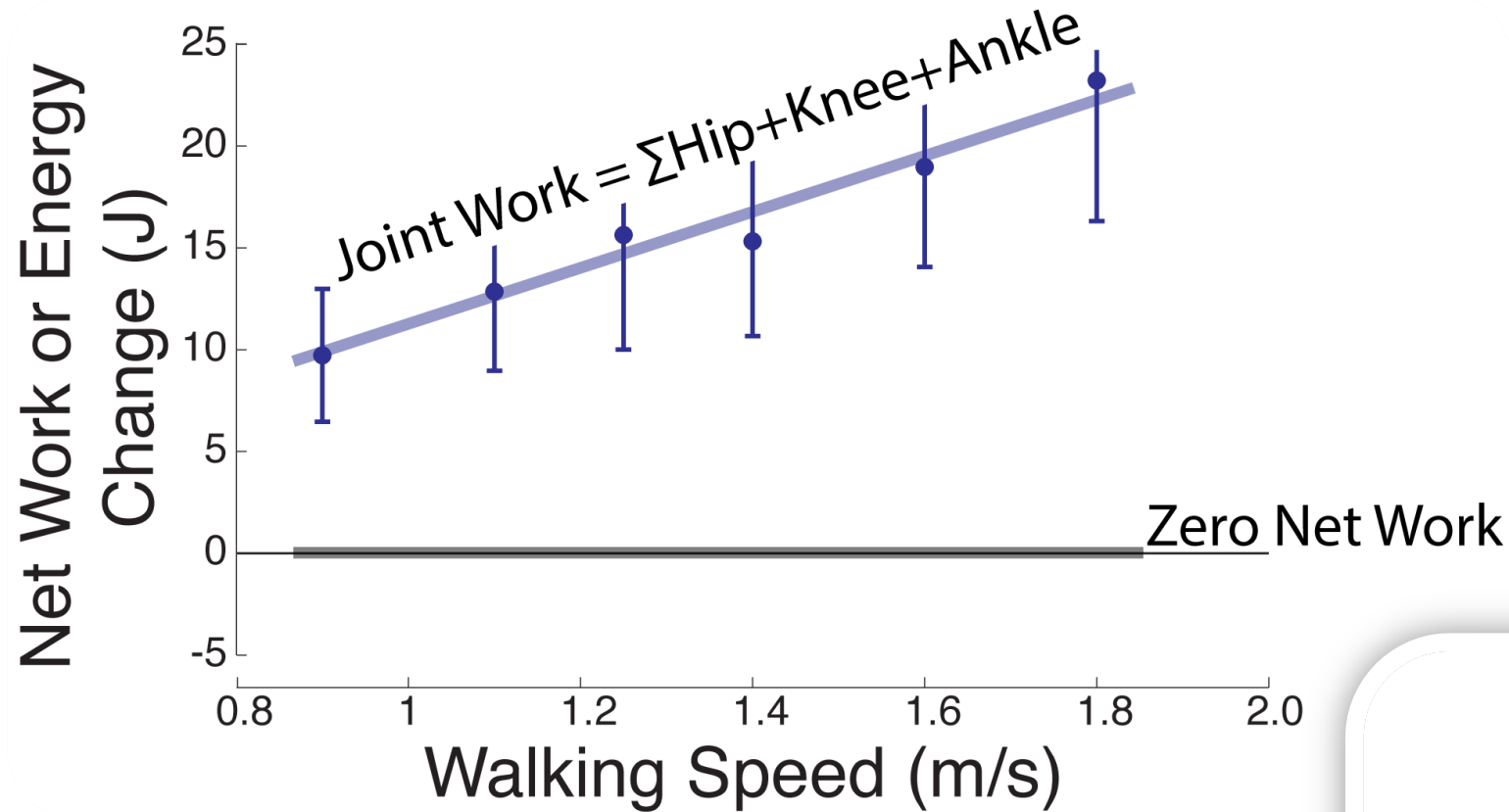
Trust whole-body mechanics b/c they add up properly



5

WHOLE-BODY → MOSTLY RESOLVED

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

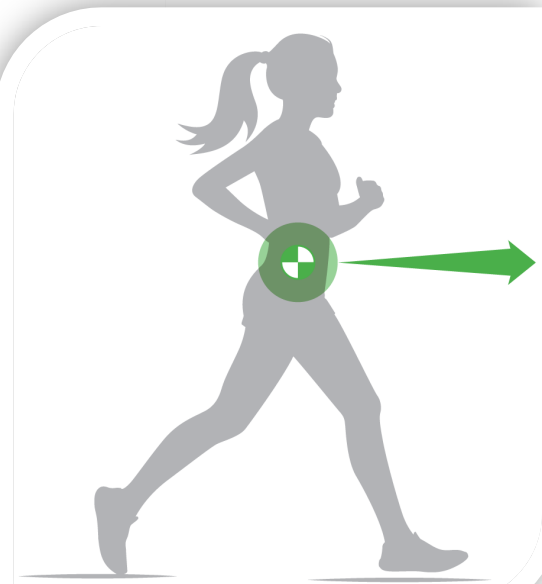
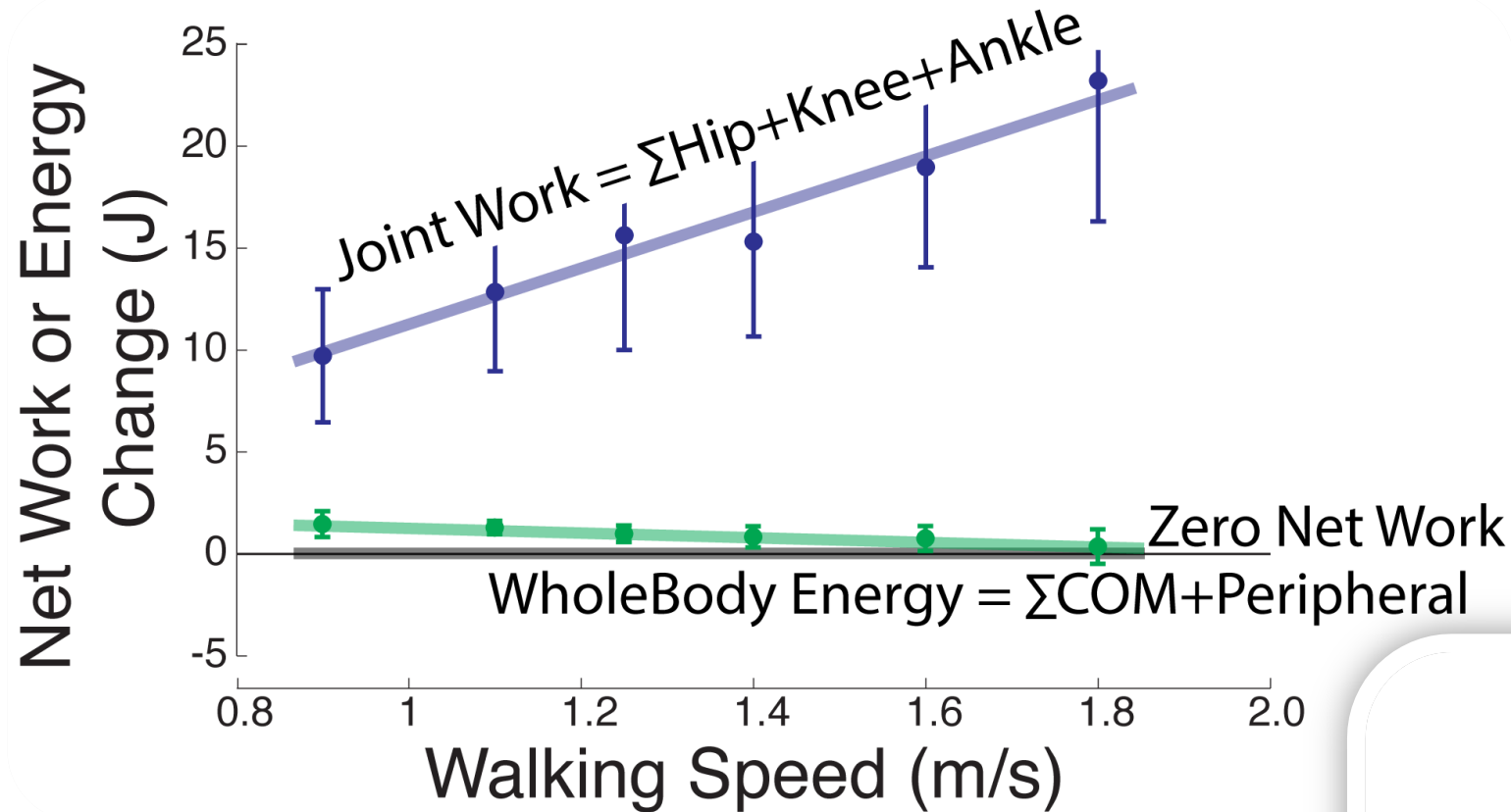


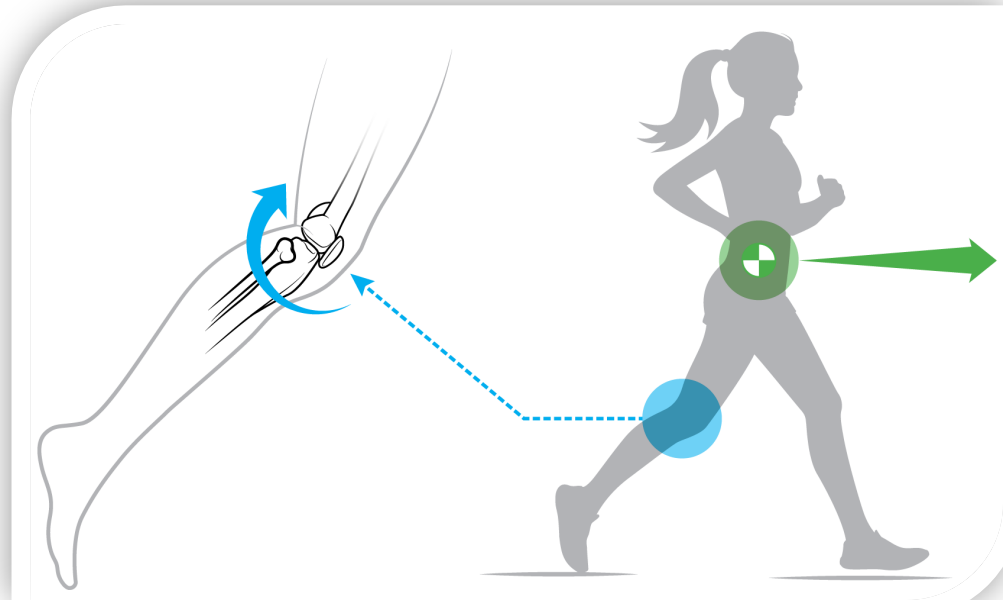


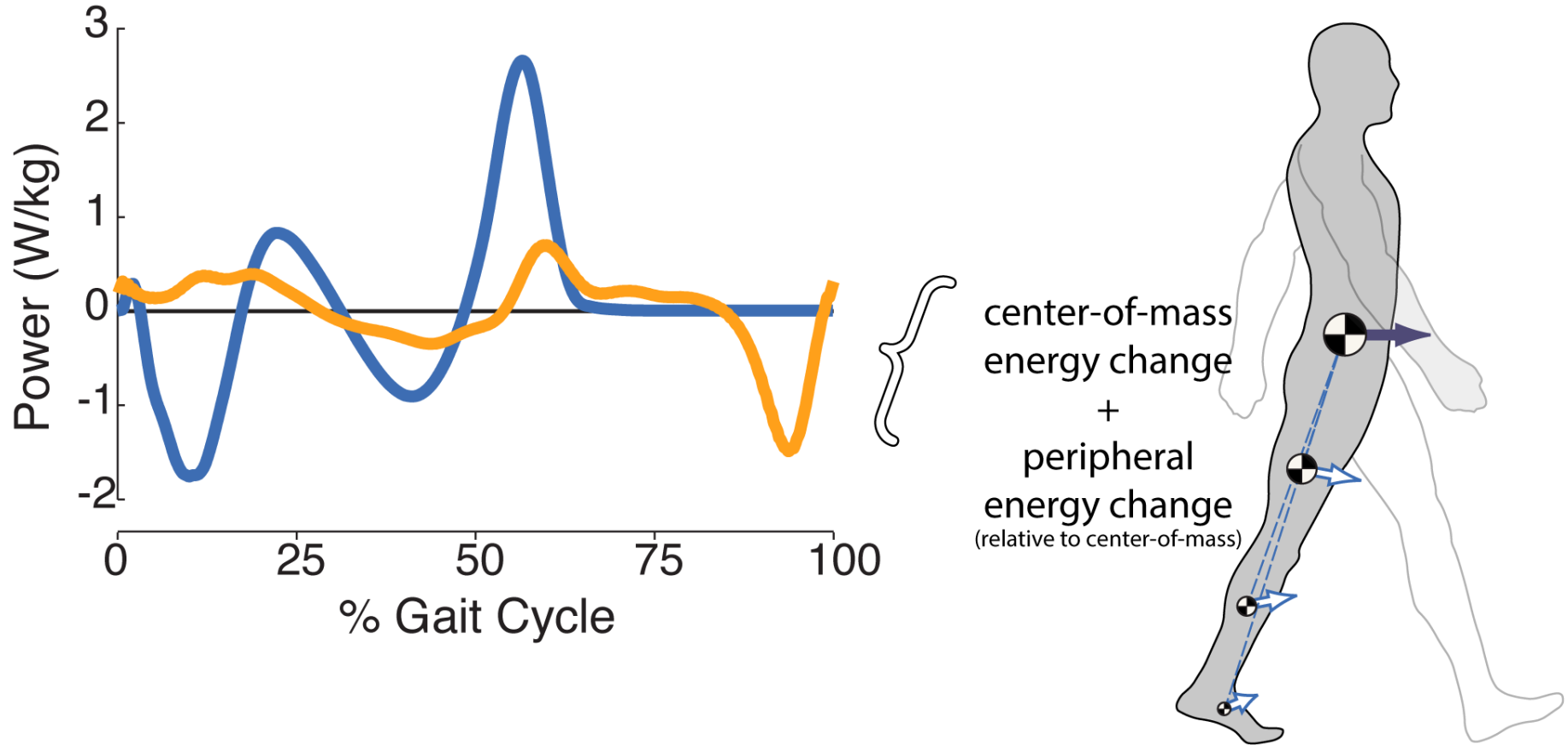
5

WHOLE-BODY → MOSTLY RESOLVED

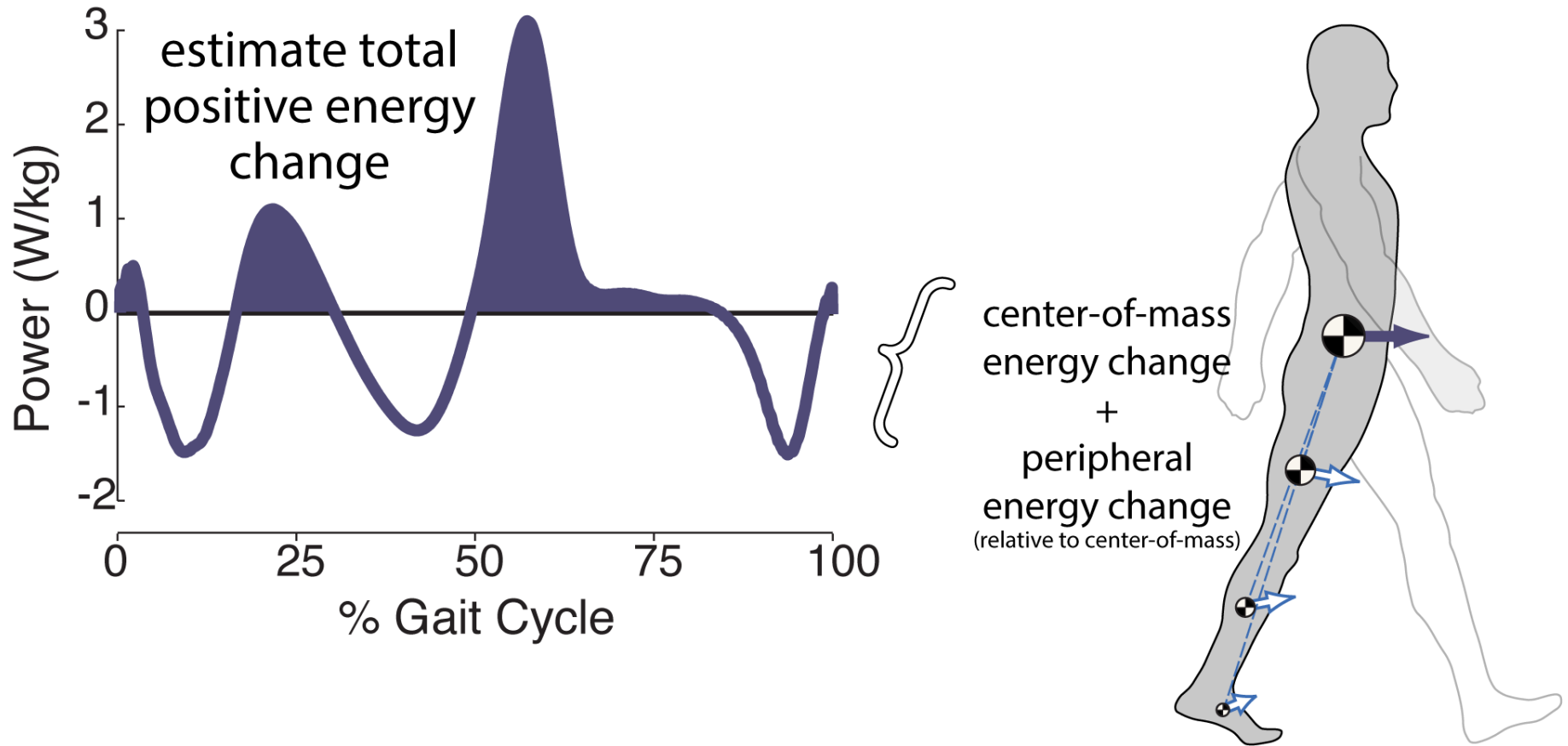
Trust whole-body mechanics b/c they add up properly







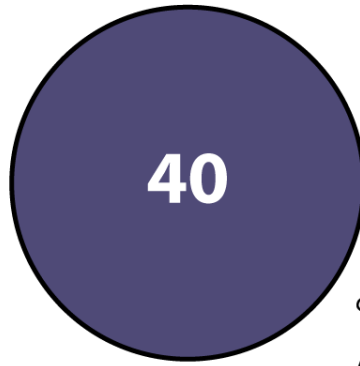
## Whole-Body Energy Change



**Whole-Body Energy Change**



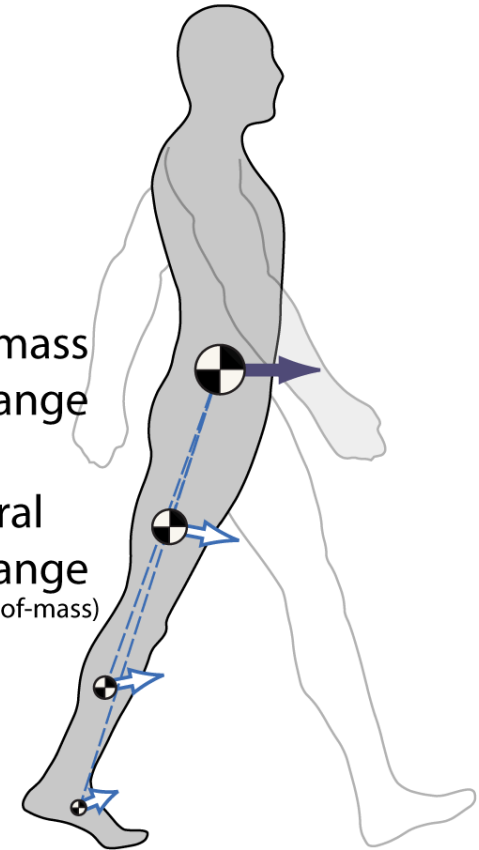
positive energy change (J)



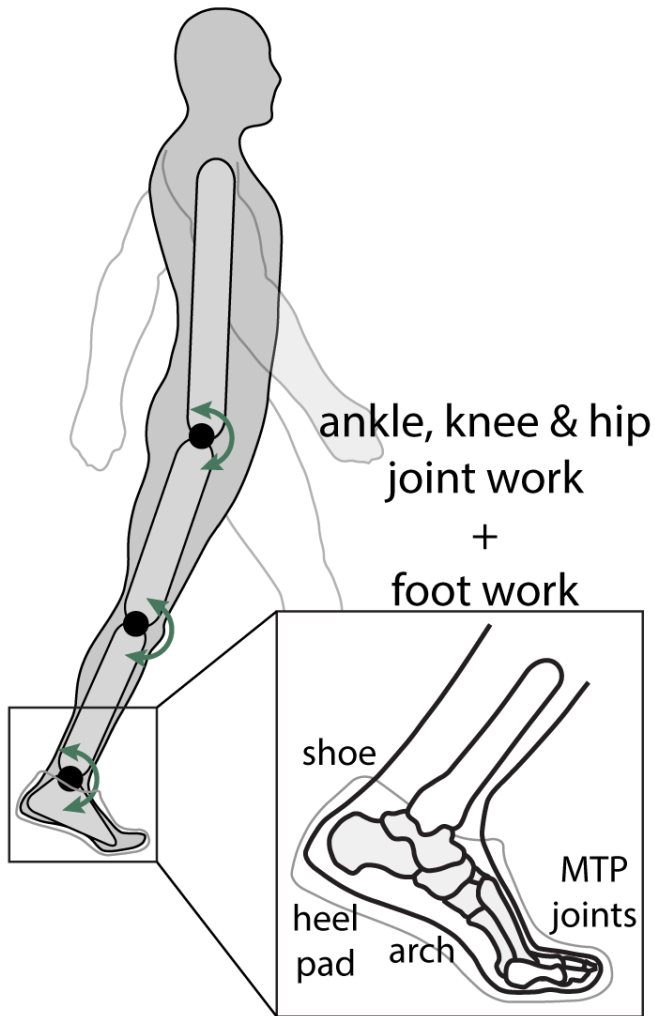
center-of-mass  
energy change

+

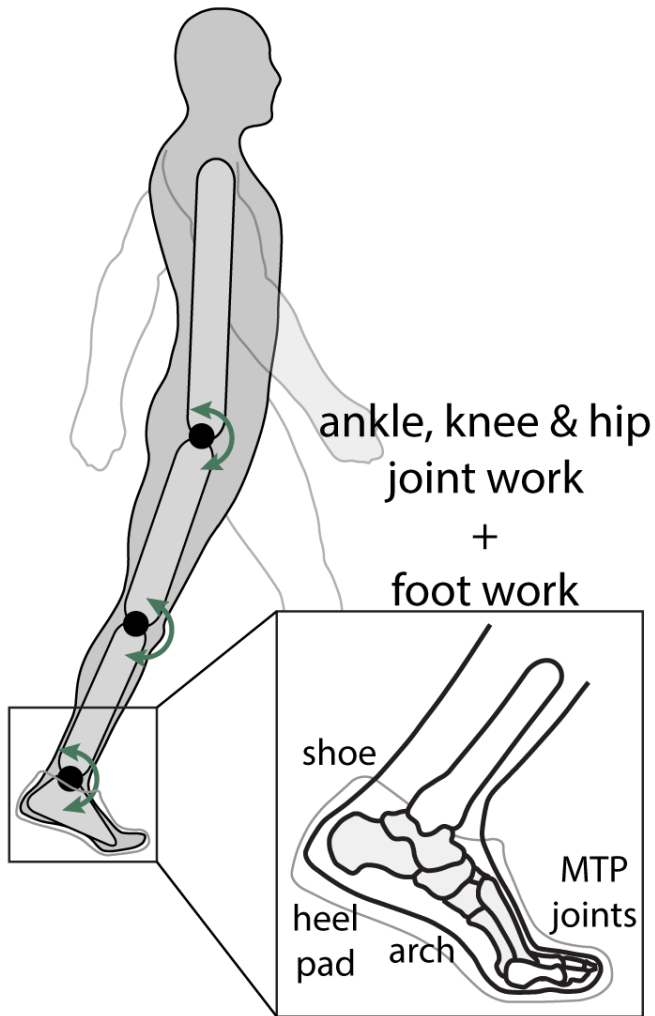
peripheral  
energy change  
(relative to center-of-mass)



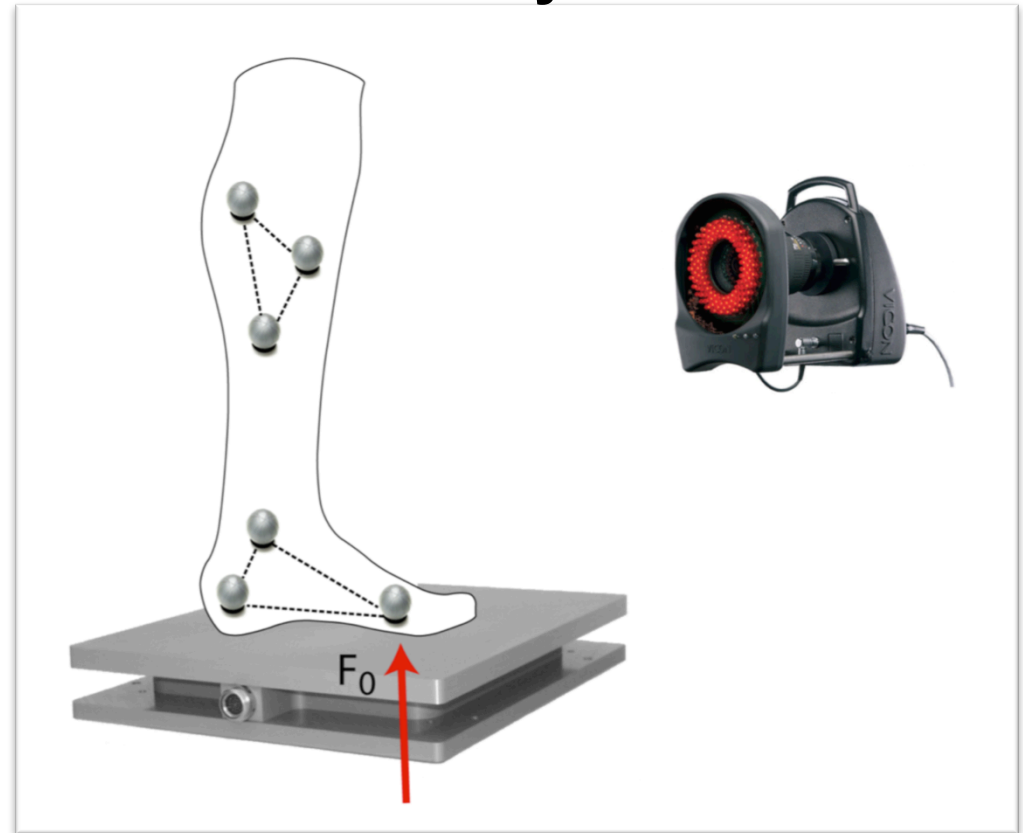
walking at 1.4 m/s



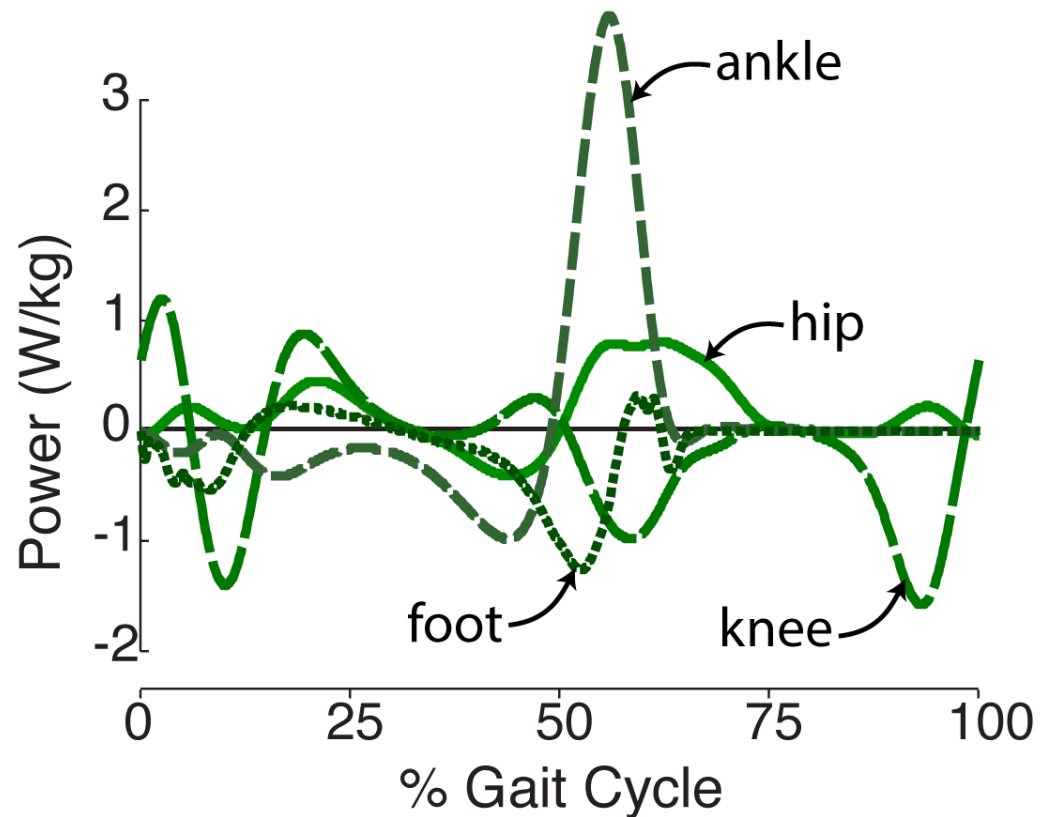
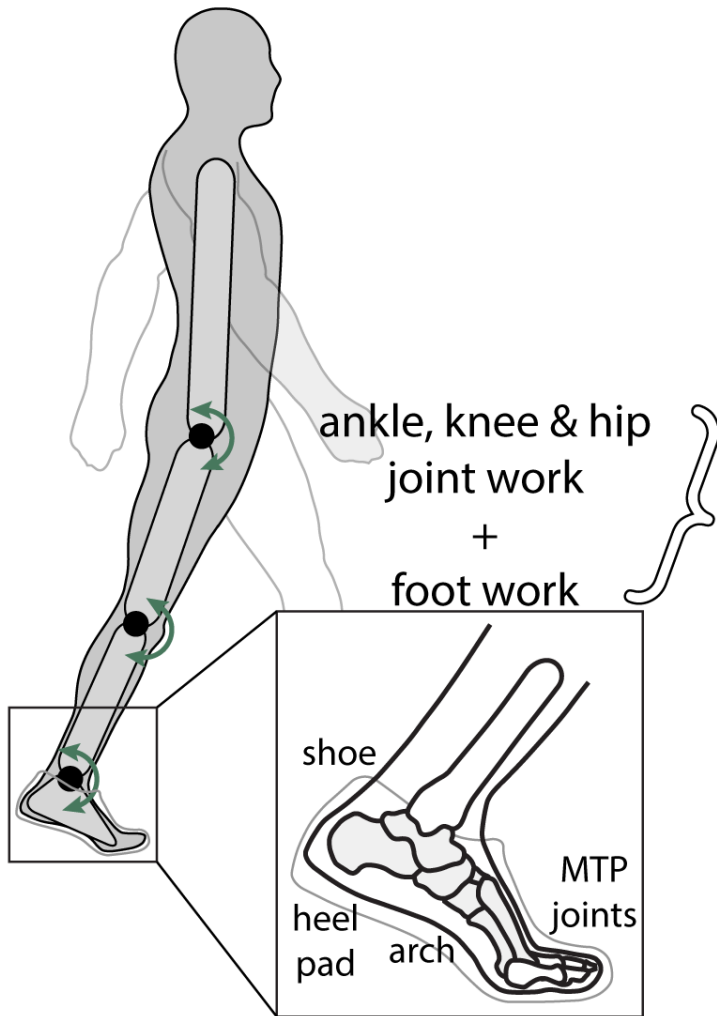
**Joint-Segment Work**



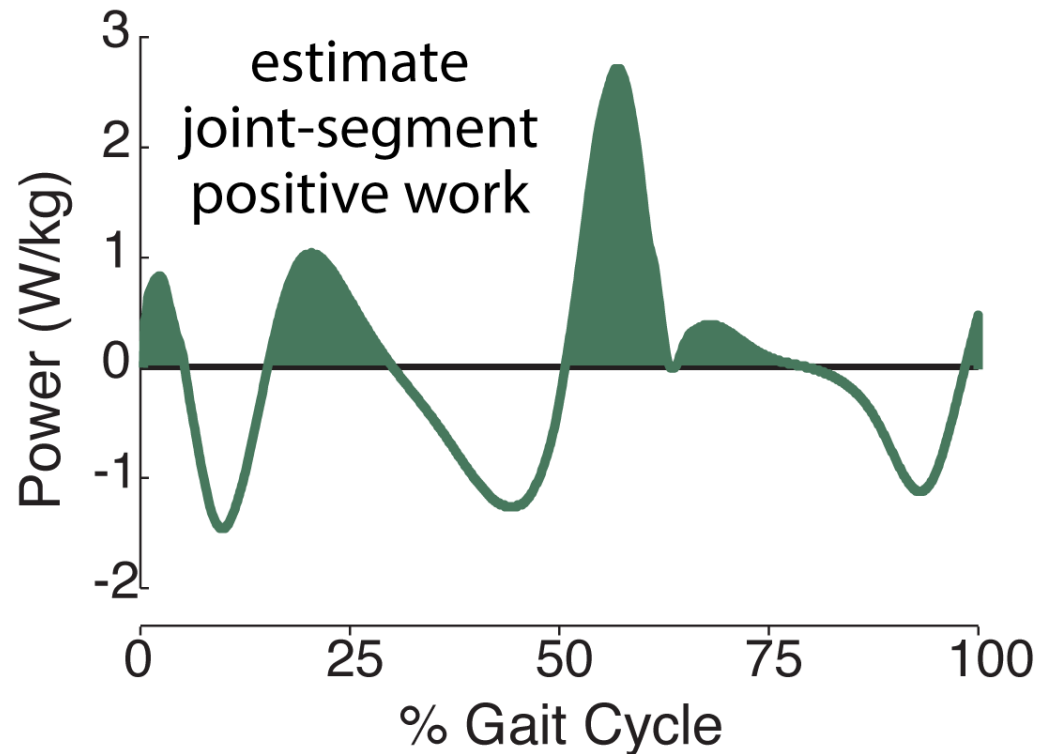
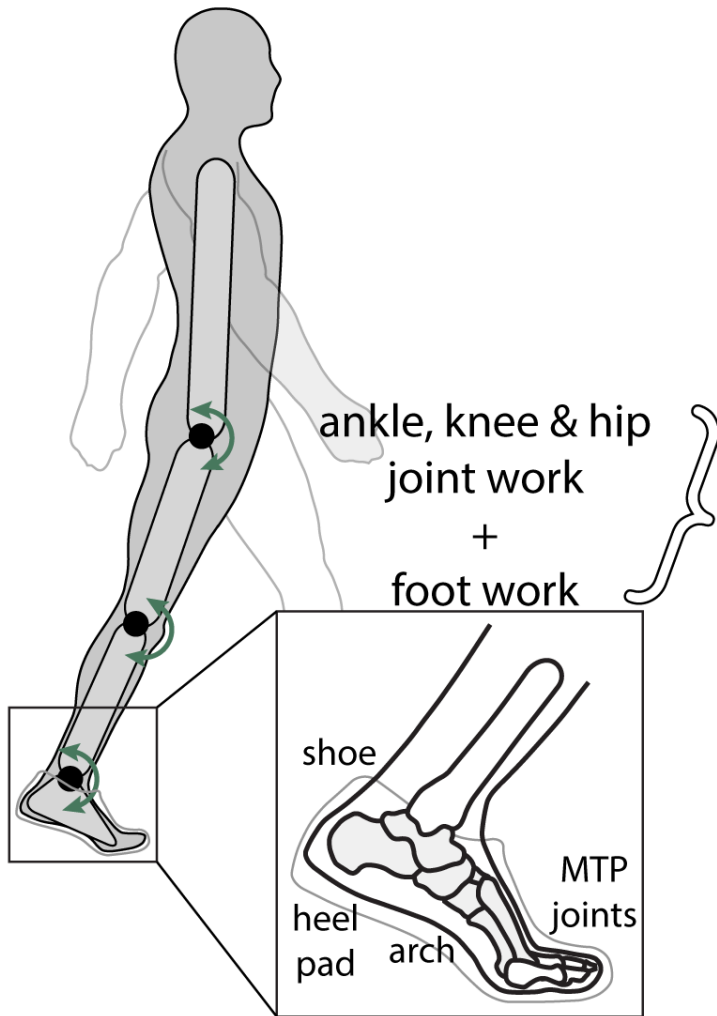
## Inverse Dynamics



**Joint-Segment Work**

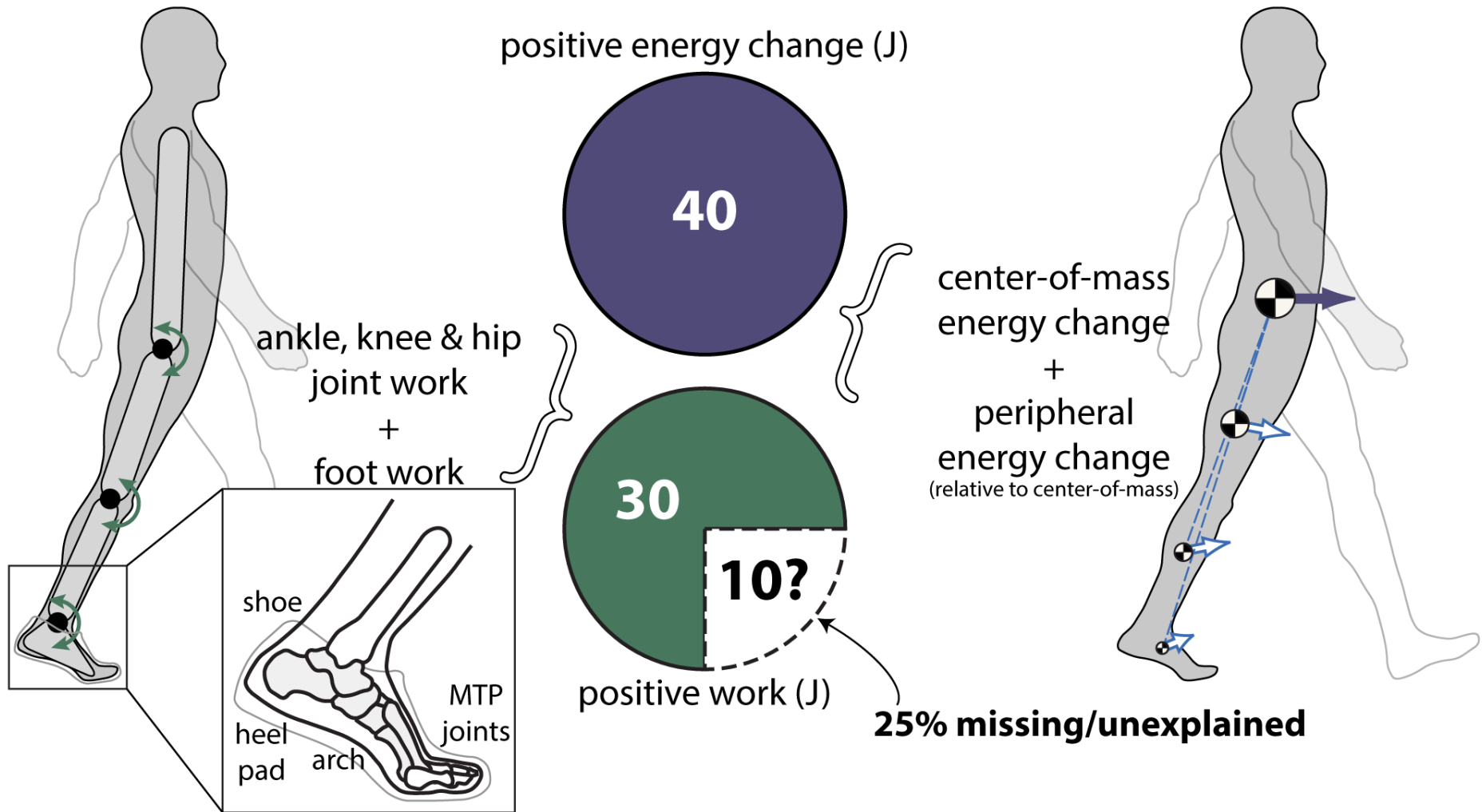


**Joint-Segment Work**



**Joint-Segment Work**

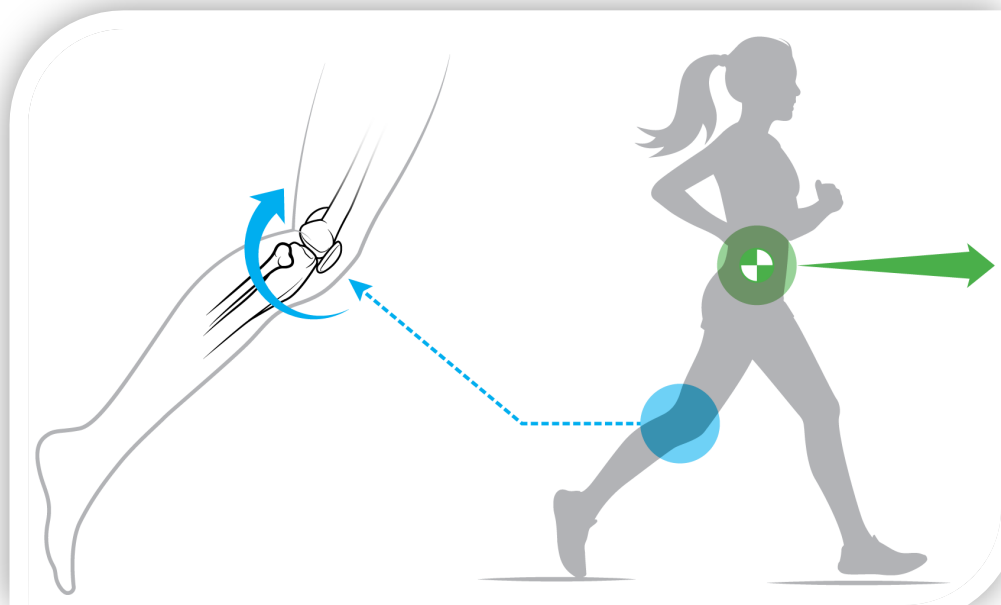
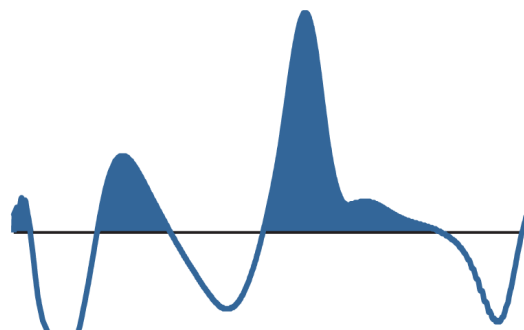
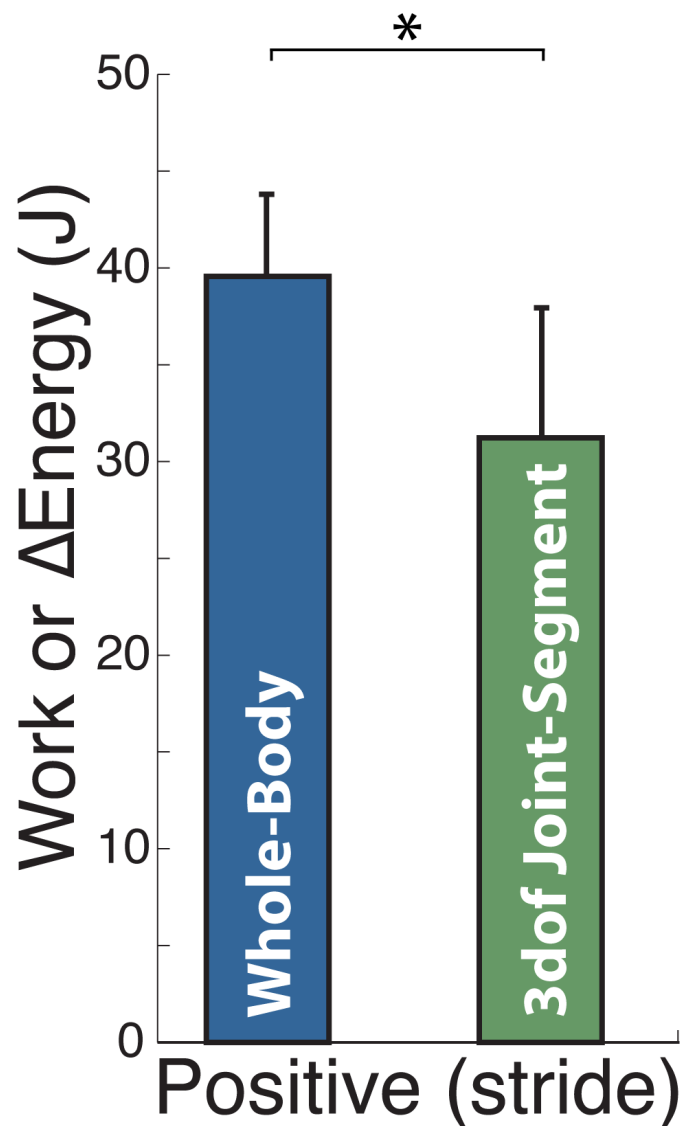
# JOINT-SEGMENT VS. WHOLE-BODY



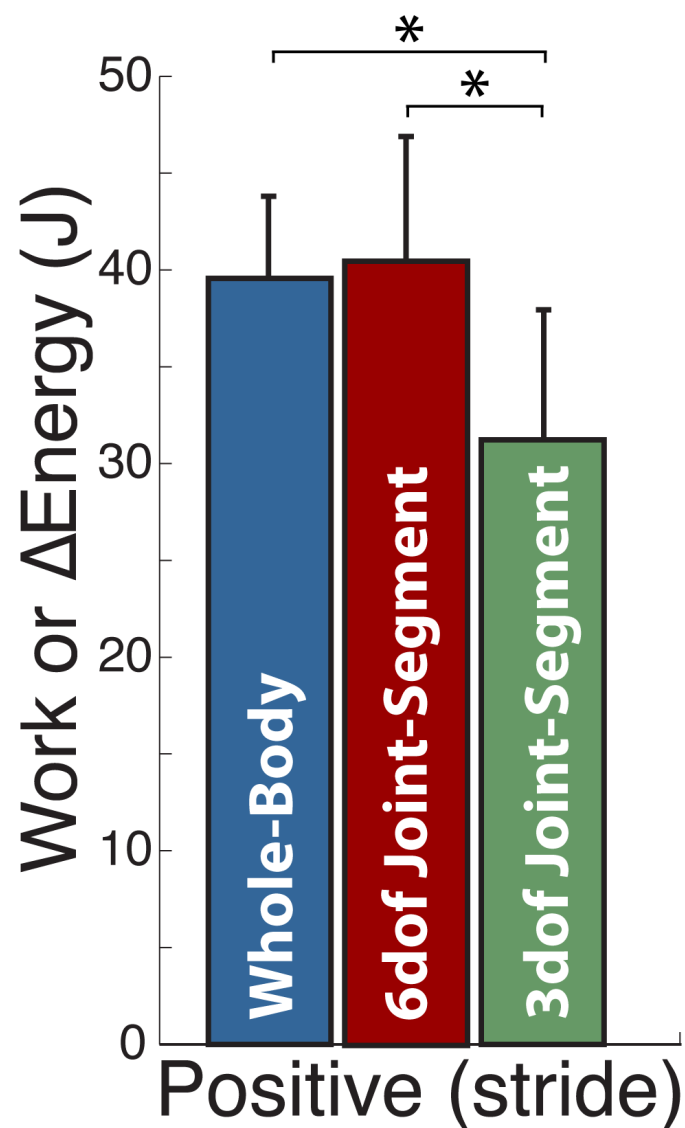
4

## JOINT-SEGMENT VS. WHOLE-BODY → PARTLY RESOLVED

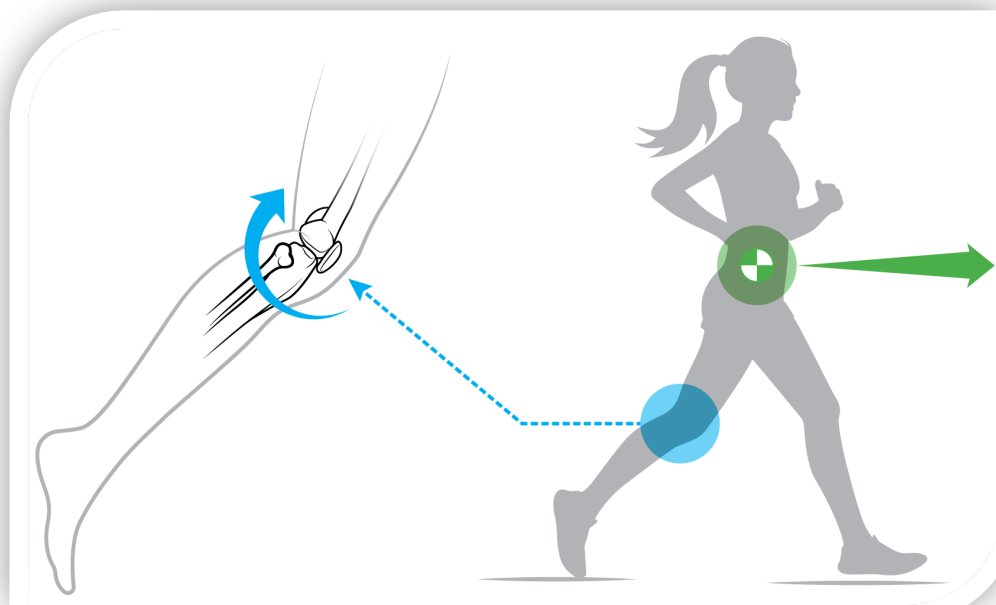
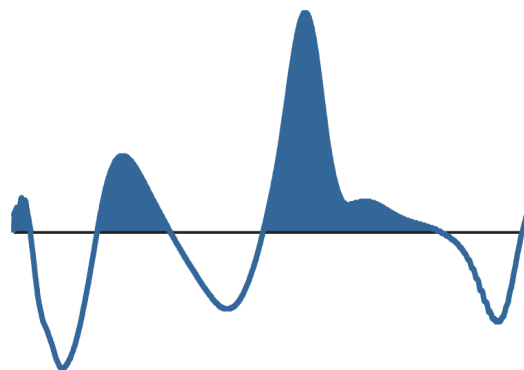
3DOF joint-segment work fails to explain whole-body energy



## 6DOF joint-segment work explains whole-body energy



but commonly-used 3DOF analysis does not





## 6DOF joint-segment work explains whole-body energy

but commonly-used 3DOF analysis does not

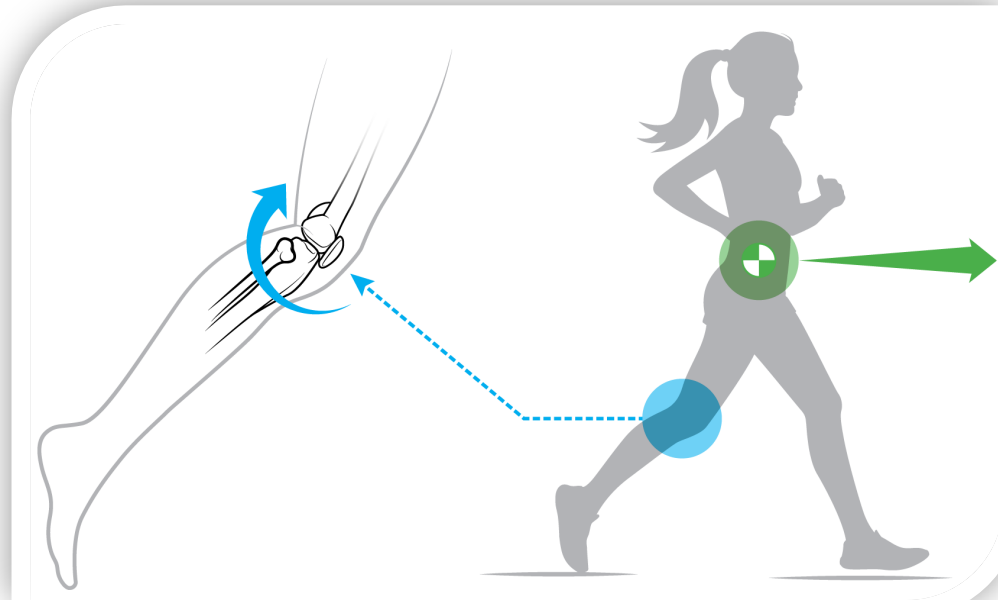
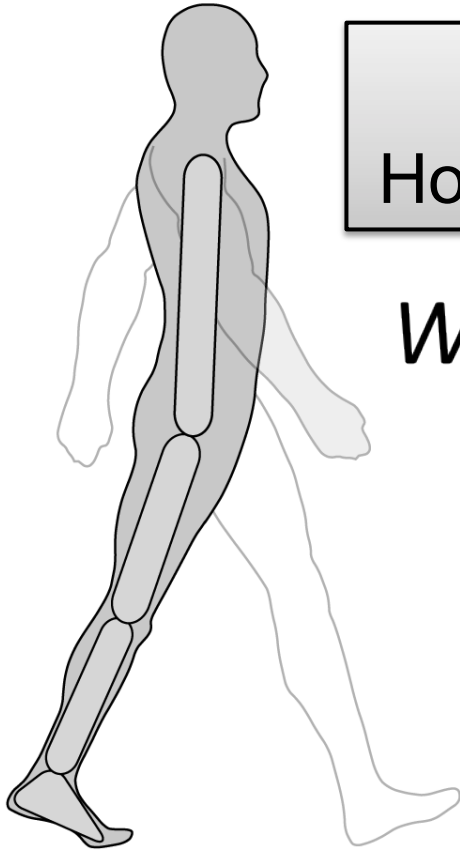
## 6DOF inverse dynamics

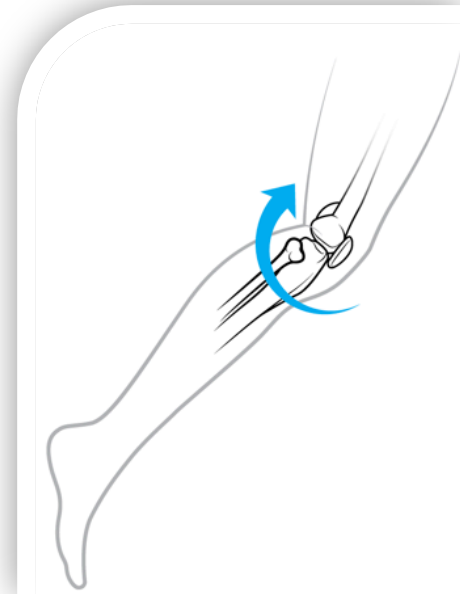
How much work to **move** body segments?

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

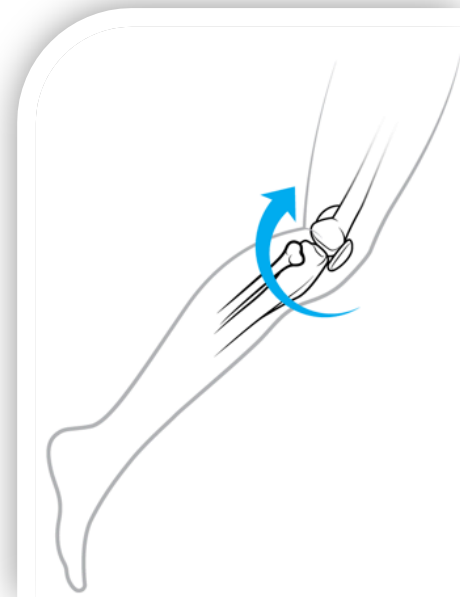
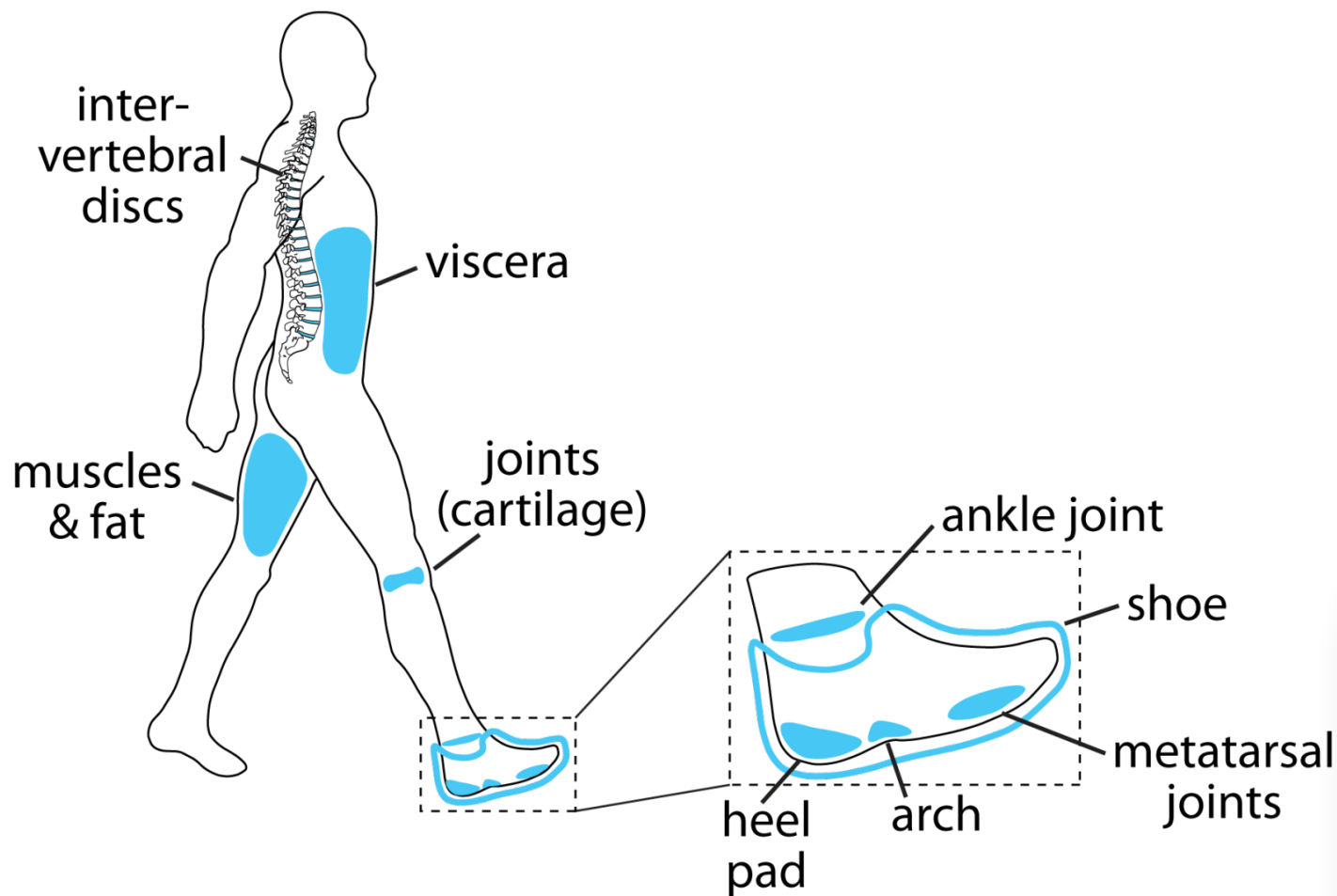
rotational work + translational work

Buczek 1994, Duncan 1997





estimates still miss negative soft tissue work



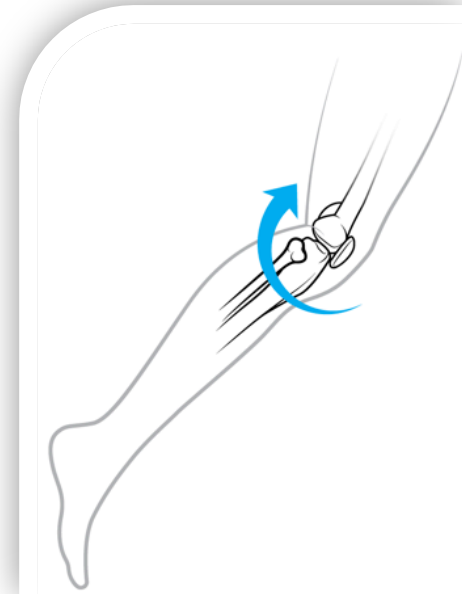
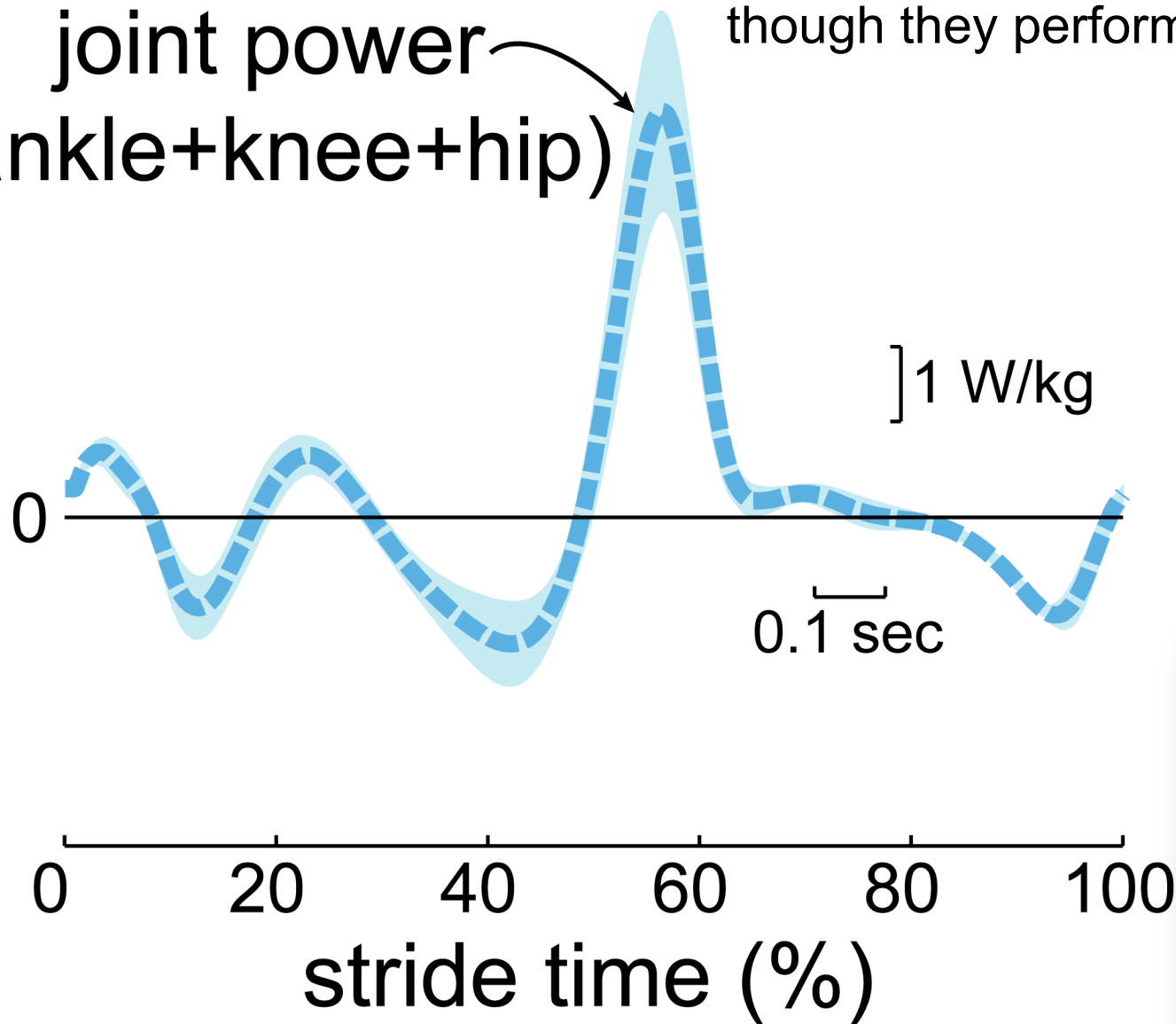
3

**JOINT-SEGMENT → PARTLY RESOLVED, BUT CONCERNING**

Reasonable estimates, but soft tissues & feet usually neglected

joint power  
(ankle+knee+hip)

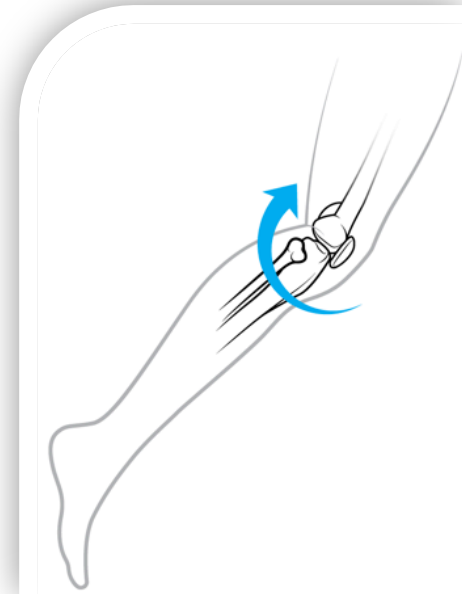
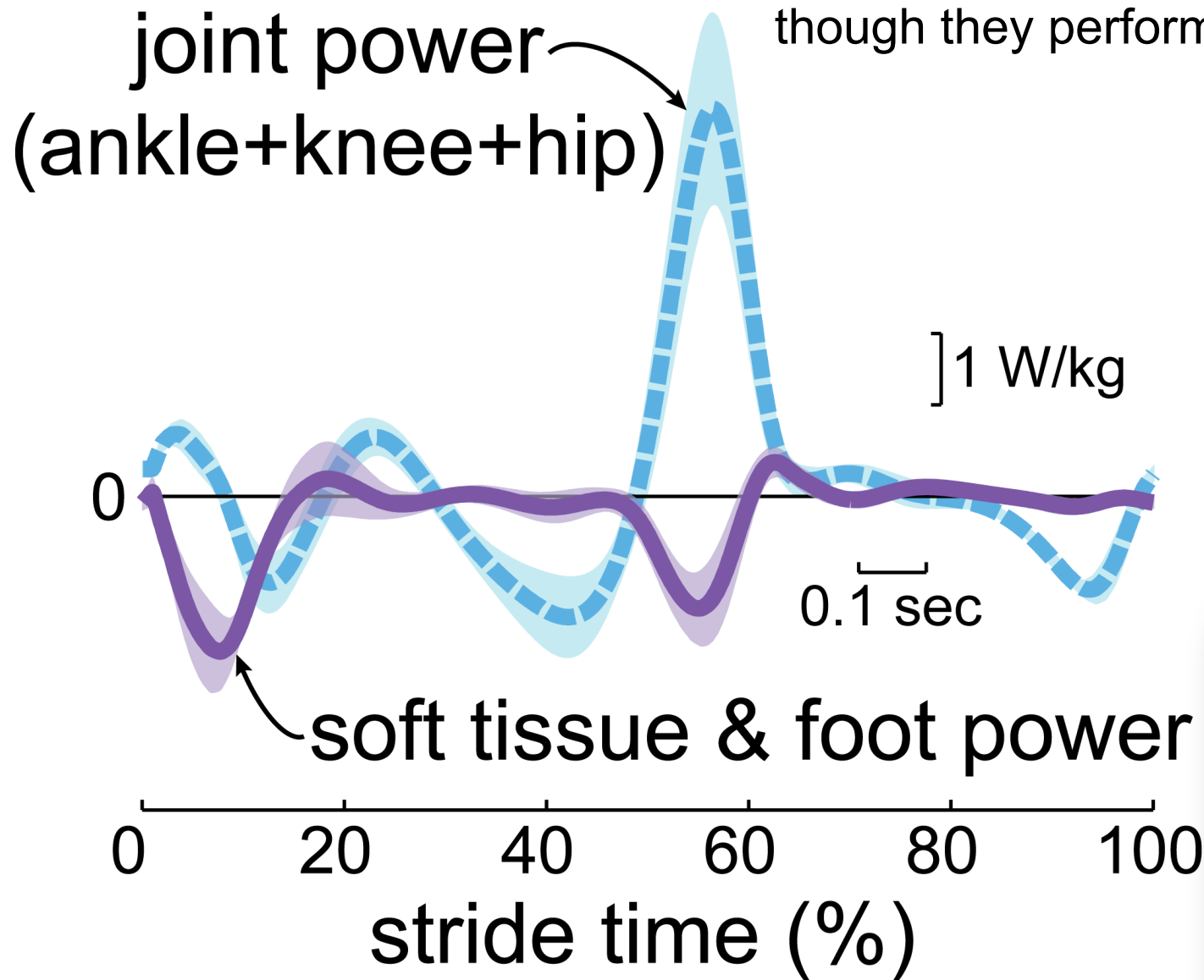
though they perform substantial work

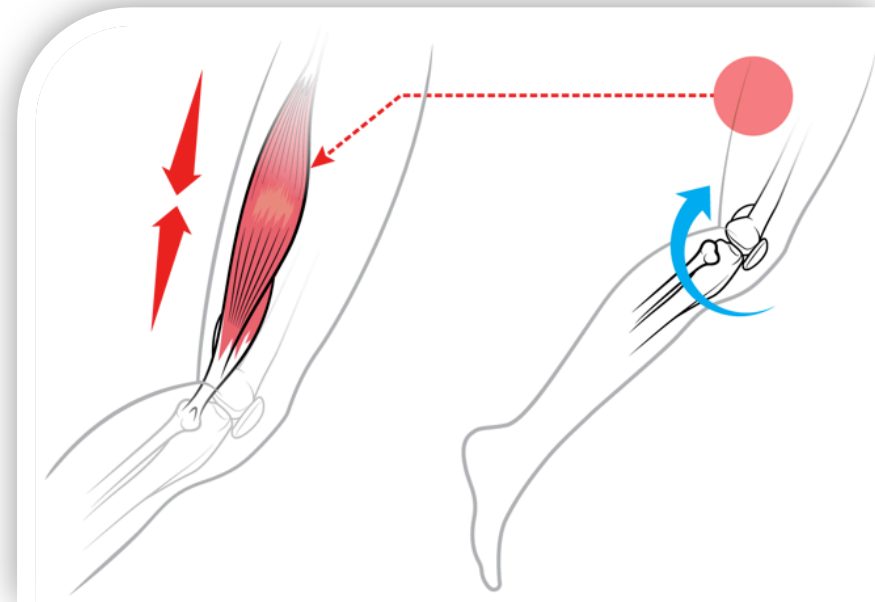


3

**JOINT-SEGMENT → PARTLY RESOLVED, BUT CONCERNING**

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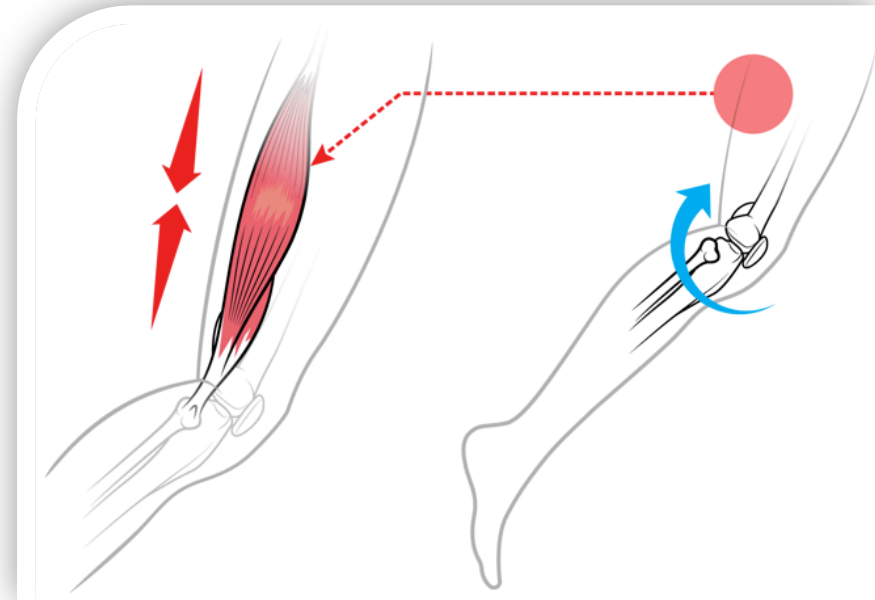




2

**MUSCLE-TENDON VS. JOINT-SEGMENT → UNKNOWN**

Consistency hard to assess

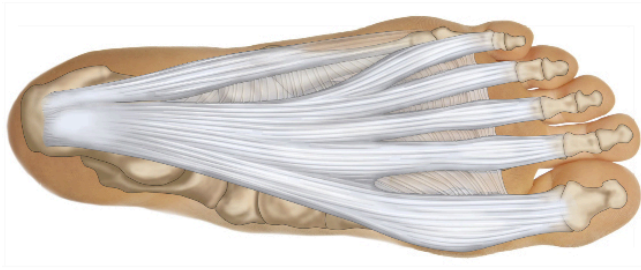


2

## MUSCLE-TENDON VS. JOINT-SEGMENT → UNKNOWN

Consistency hard to assess, but anecdotal evidence of problem

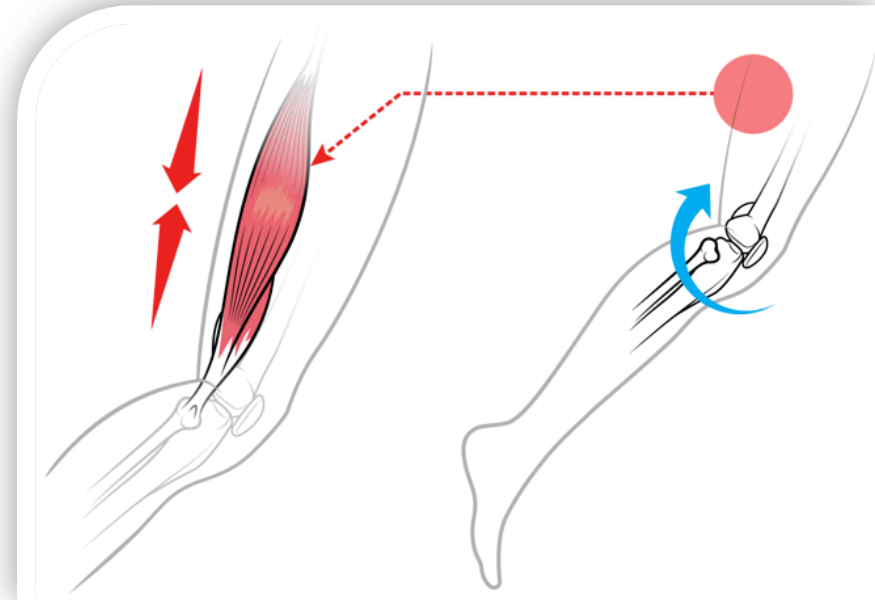
What is mechanical function of foot during push-off in walking or running?



Ker et al. 1987

Stearne et al. 2016

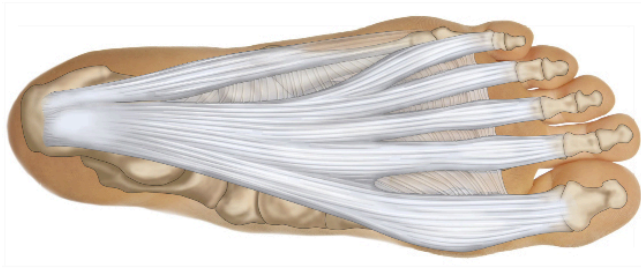
**Acts like a spring!**





Consistency hard to assess, but anecdotal evidence of problem

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



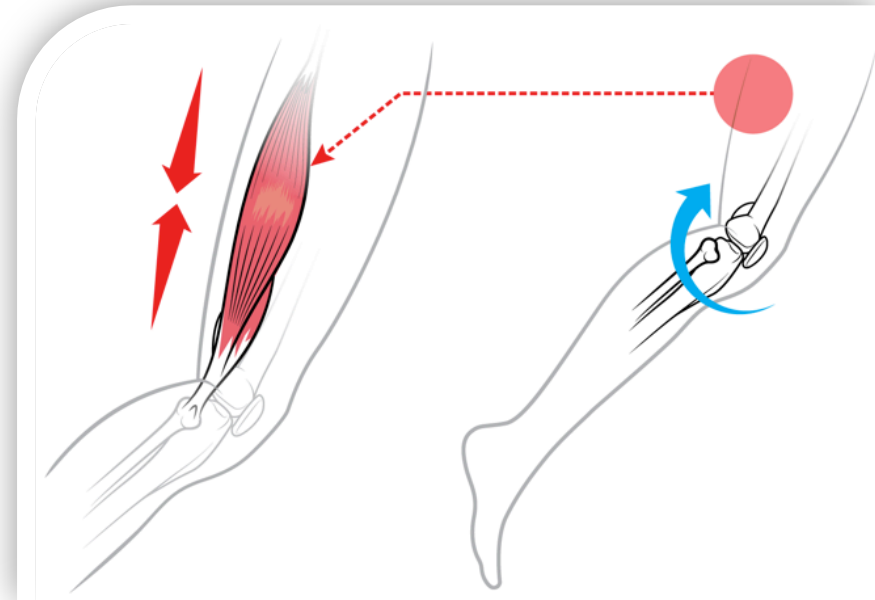
Ker et al. 1987  
Stearne et al. 2016

**Acts like a spring!**



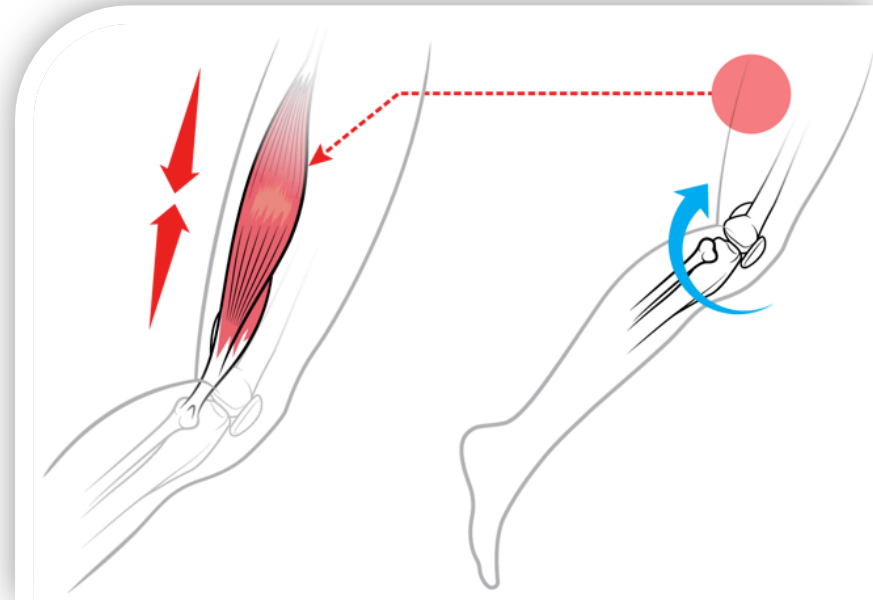
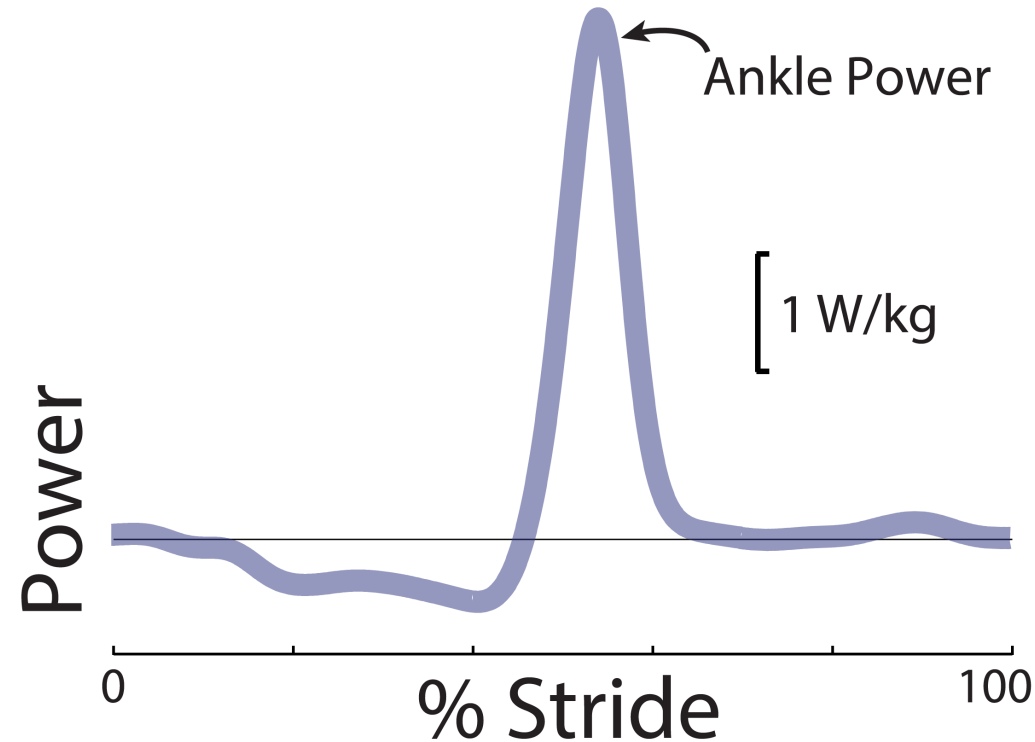
Stefanyshyn & Nigg 1997  
Takahashi & Stanhope 2013

**Acts like a damper!**



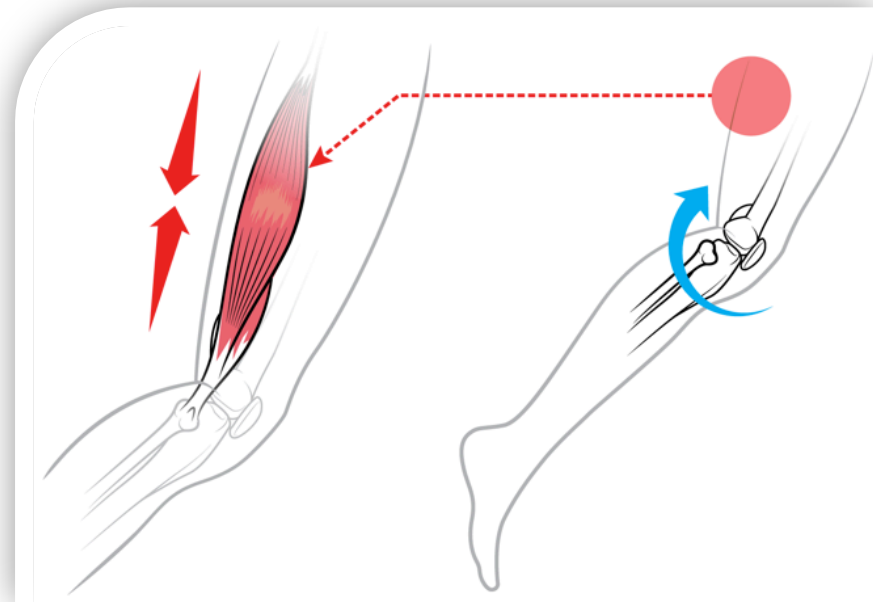
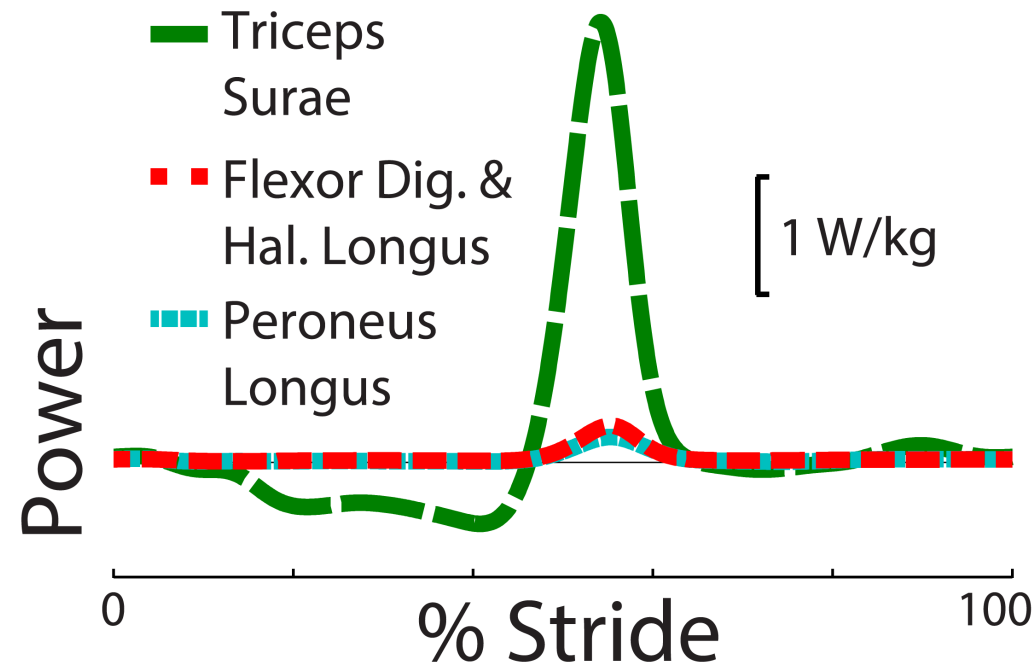
Consistency hard to assess, but anecdotal evidence of problem

Potential approach: data-driven musculoskeletal modeling



Consistency hard to assess, but anecdotal evidence of problem

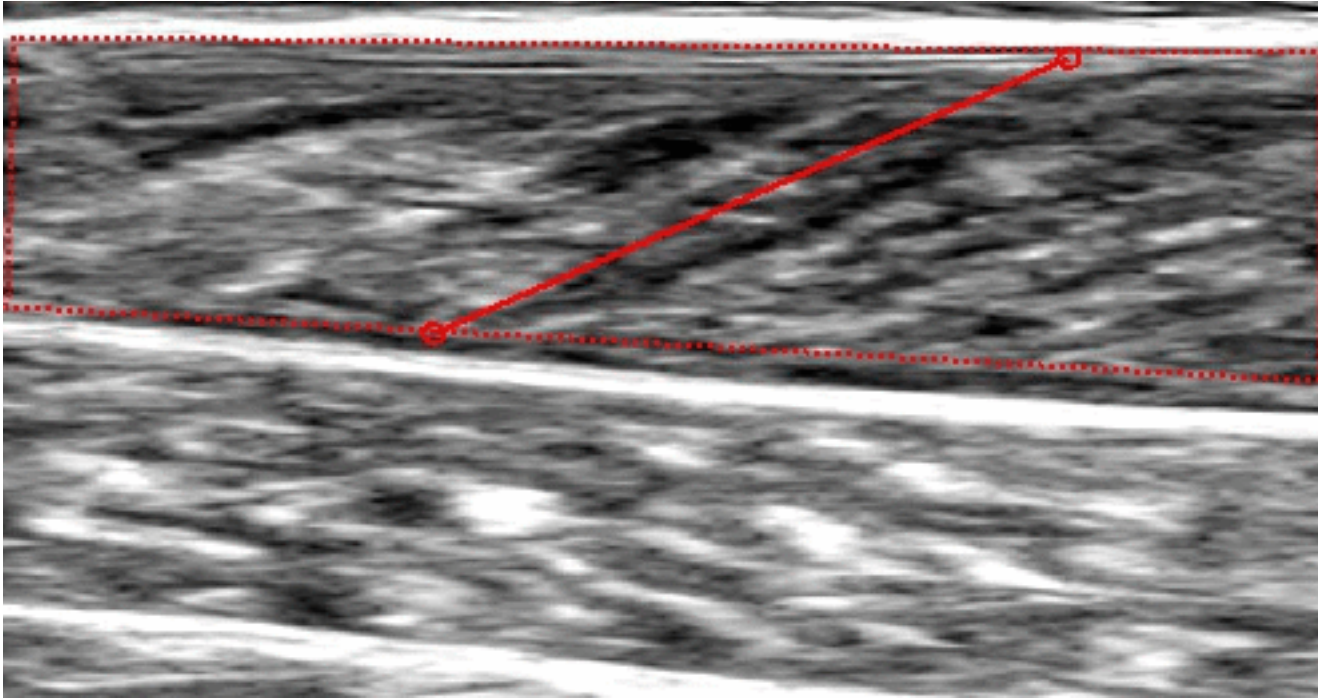
Potential approach: data-driven musculoskeletal modeling



# 1 MUSCLE-TENDON



# 1 MUSCLE-TENDON

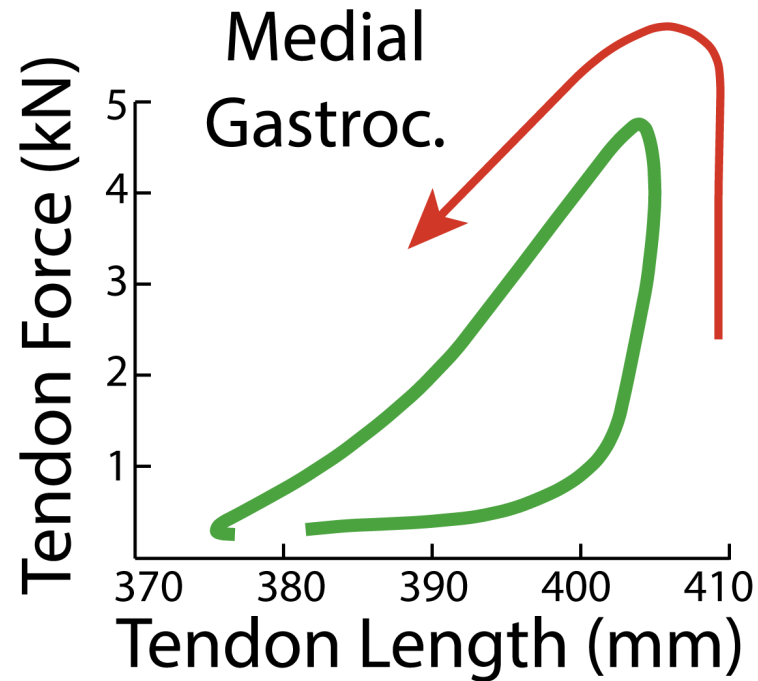


1

**MUSCLE-TENDON → TROUBLING**

# Net positive work by passive tendons indicates a problem

some current estimates indicate tendons act like motors



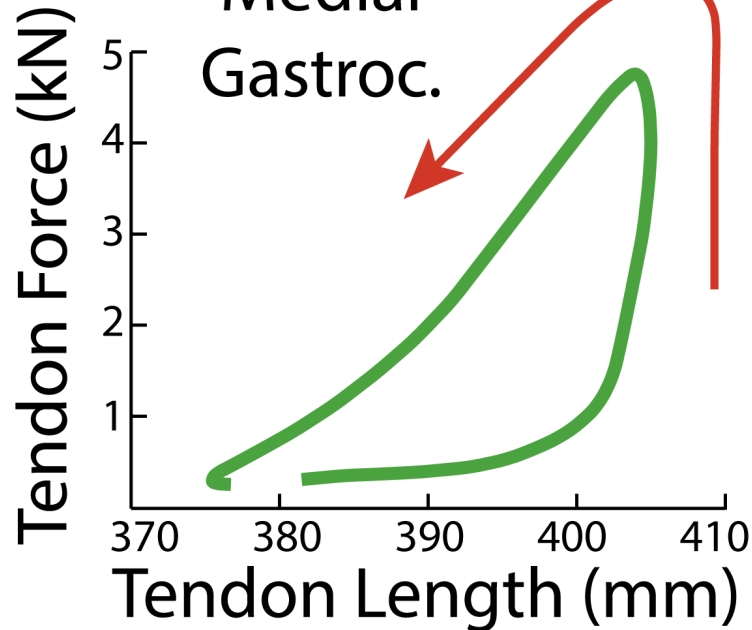
1

**MUSCLE-TENDON → TROUBLING**

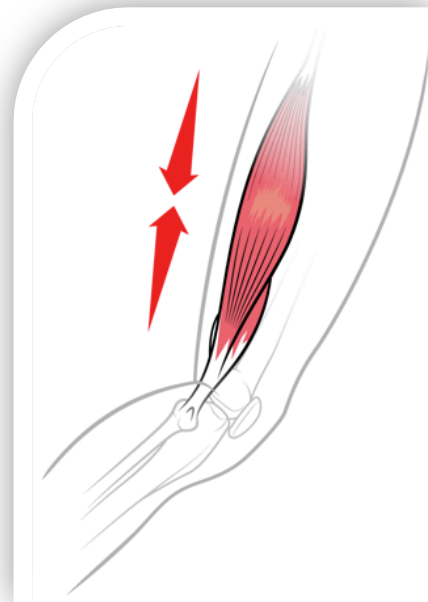
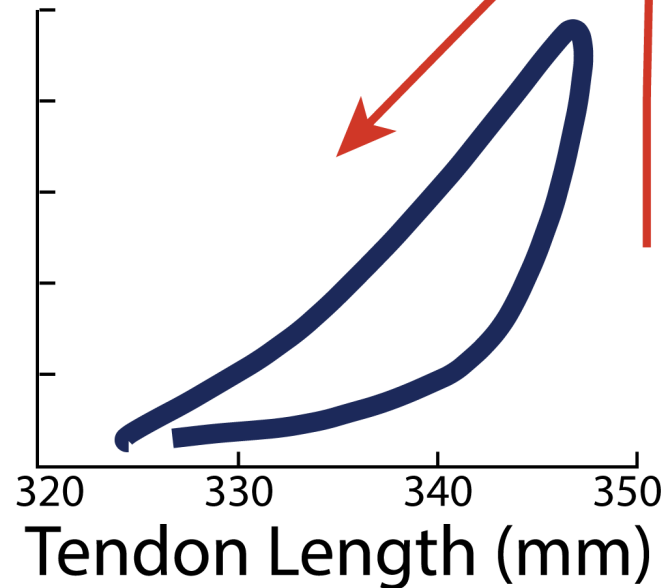
# Net positive work by passive tendons indicates a problem

some current estimates indicate tendons act like motors

Medial  
Gastroc.



Soleus

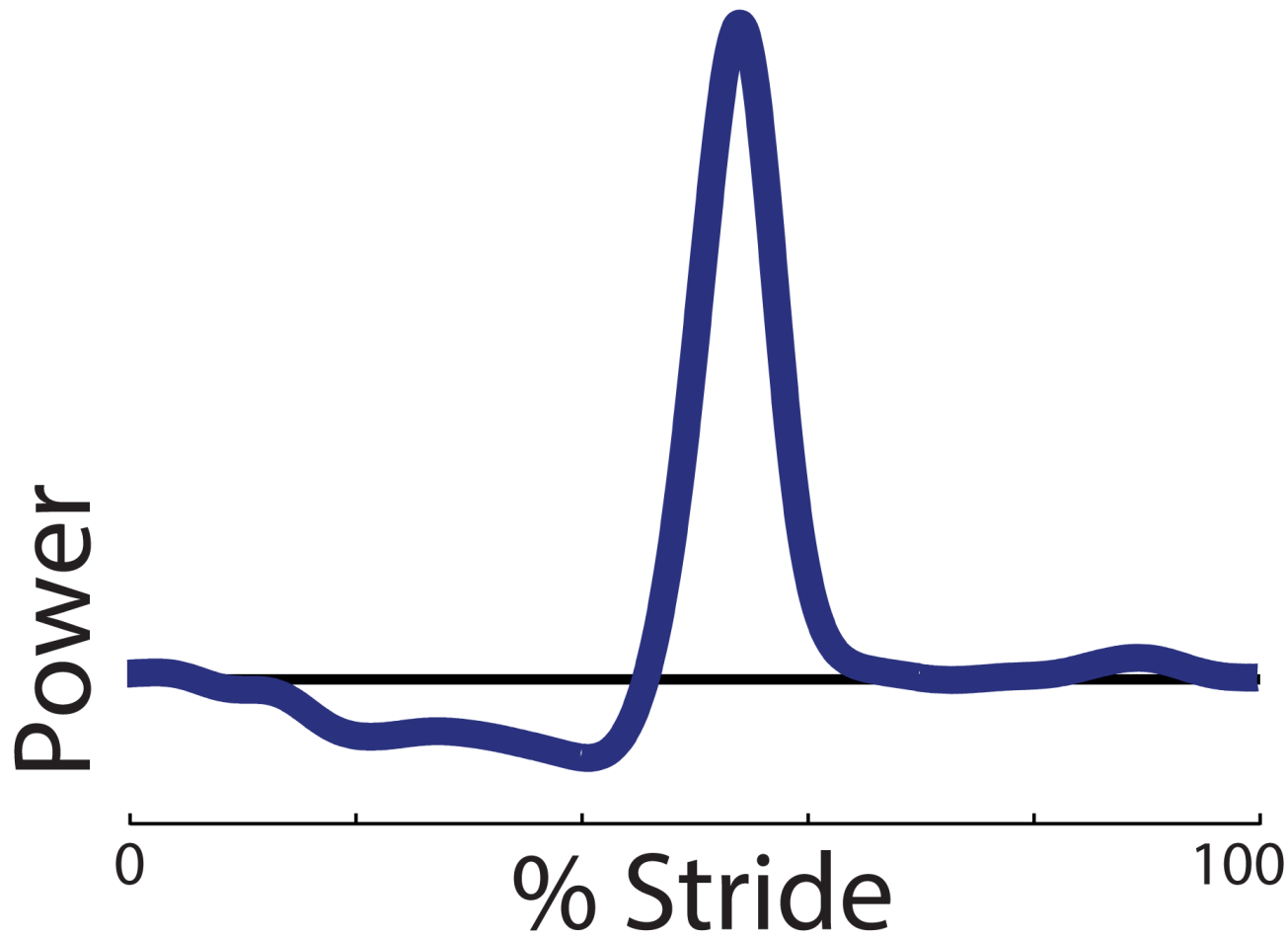


1

## MUSCLE-TENDON → TROUBLING

Net positive work by passive tendons indicates a problem

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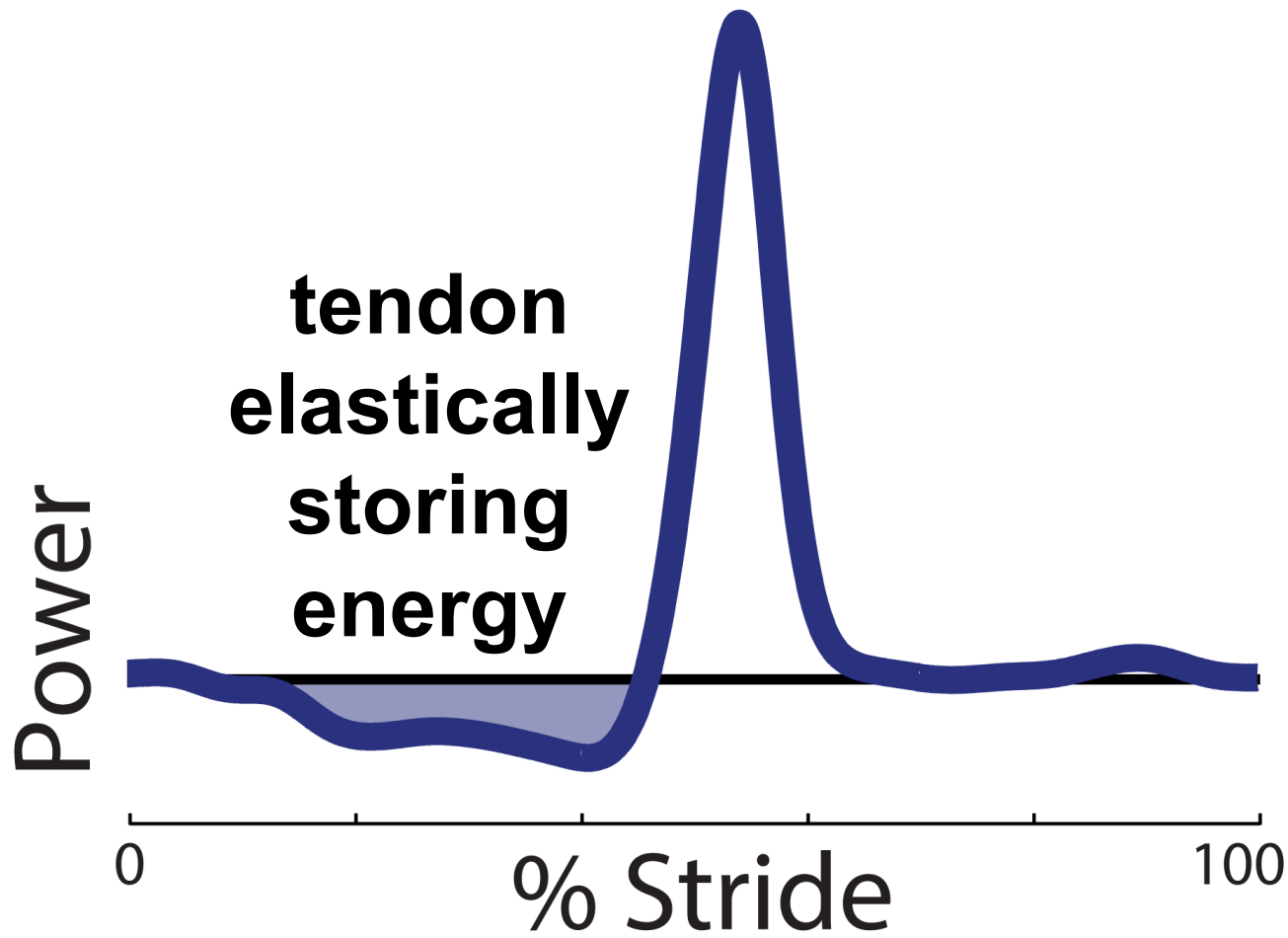


1

## MUSCLE-TENDON → TROUBLING

Net positive work by passive tendons indicates a problem

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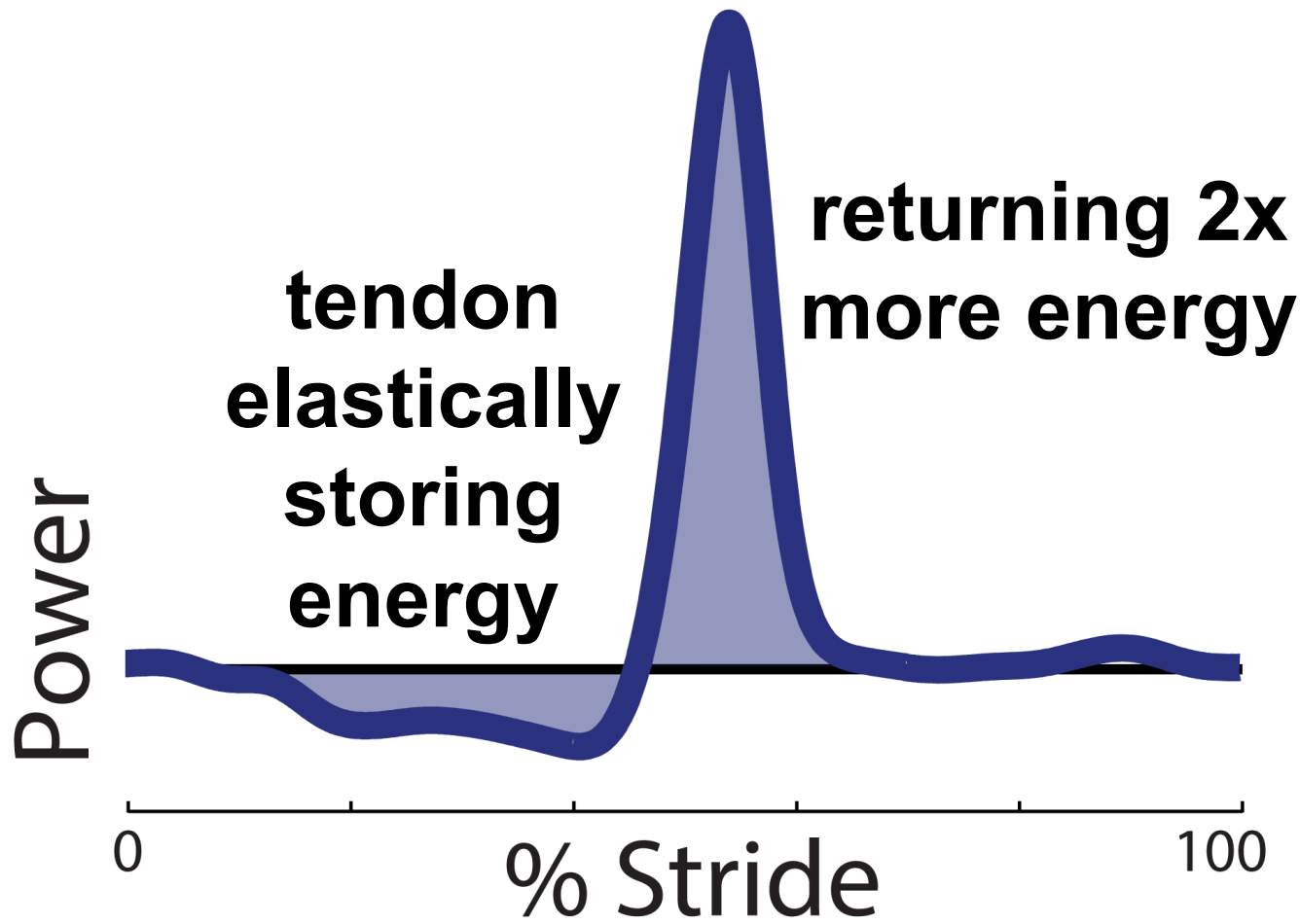


1

## MUSCLE-TENDON → TROUBLING

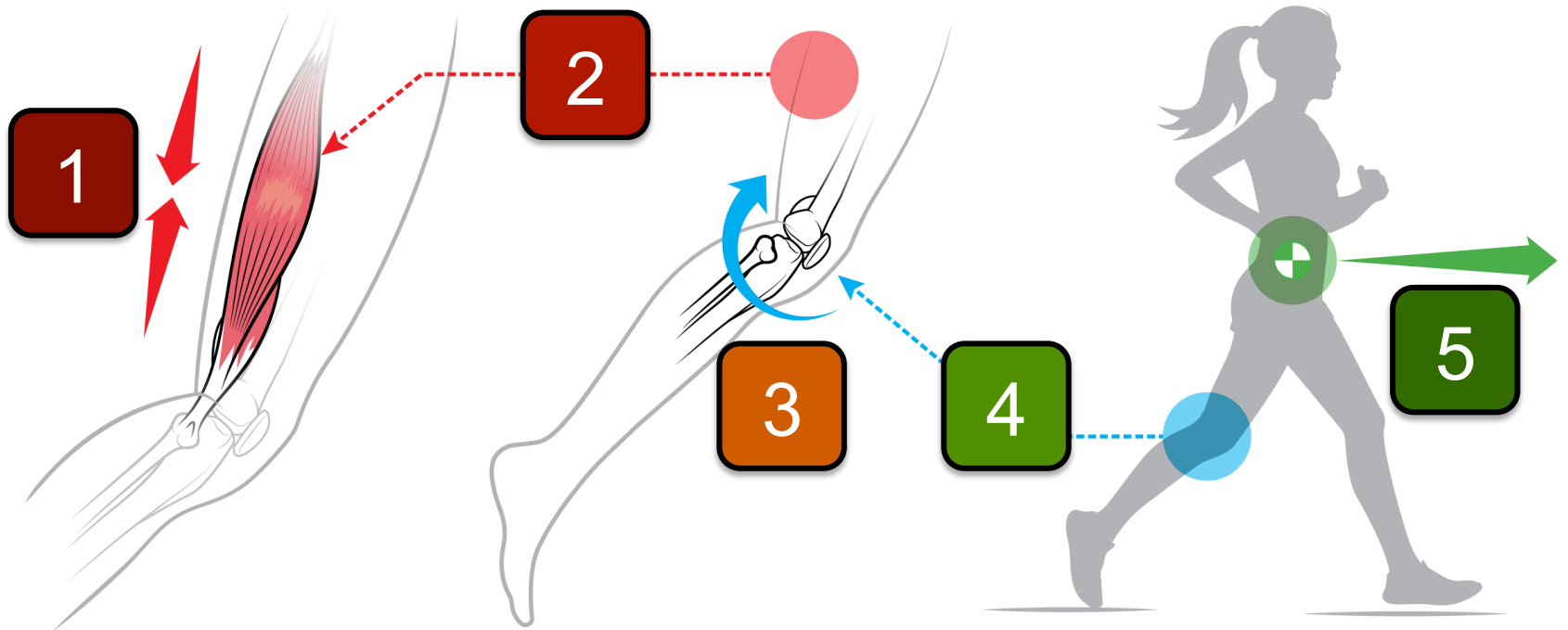
Net positive work by passive tendons indicates a problem

some current estimates indicate tendons act like motors



# Towards a Unified Multi-Scale Understanding of Human Biomechanics

## From Muscle-Tendon Work to Whole-Body Energy



Funding: NIH, NSF, Whitaker International

[my.vanderbilt.edu/batlab](http://my.vanderbilt.edu/batlab)