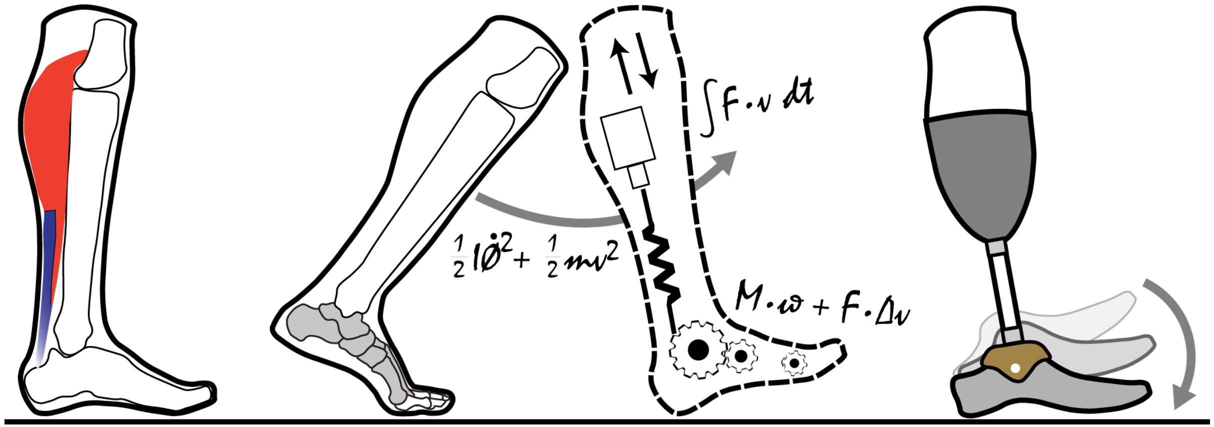
CENTER FOR
REHABILITATION ENGINEERING
+ ASSISTIVE TECHNOLOGY



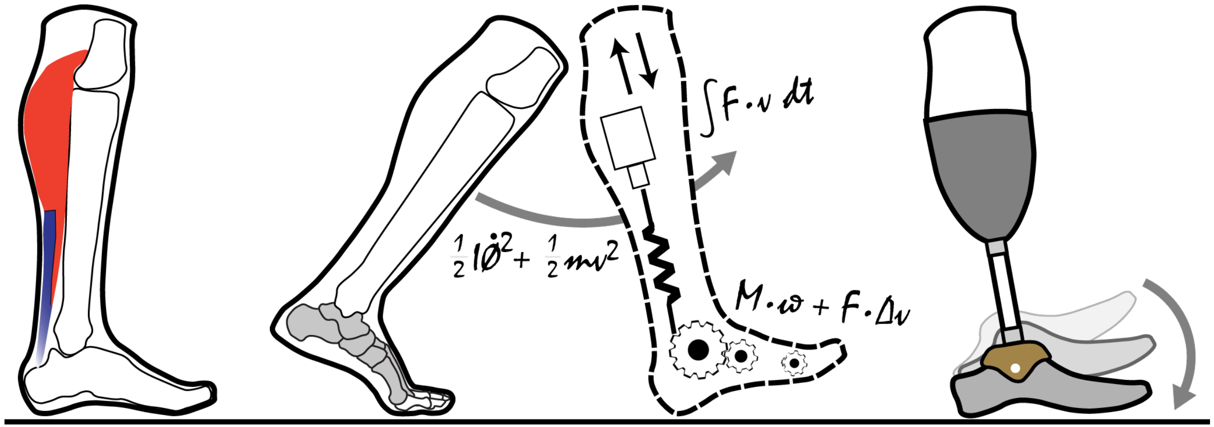
Biomechanics to bionics:

how scientific insights can unleash our imagination & inspire new design solutions for assistive tech

Prof. Karl Zelik

VANDERBILT®
SCHOOL OF ENGINEERING

CREATE CENTER FOR REHABILITATION ENGINEERING + ASSISTIVE TECHNOLOGY



Biomechanics to bionics:

how scientific insights can unleash our imagination & inspire new design solutions for assistive tech

Prof. Karl Zelik

VANDERBILT® SCHOOL OF ENGINEERING

You’re not that smart

You’re not that smart*

*neither am I

You're not that smart*

relative to complexity of movement

*neither am I

Mechanisms underlying movement are often unexpected & non-intuitive

Takeaway 3

Non-intuitive mechanisms are key to innovative new assistive tech & broadening societal impact

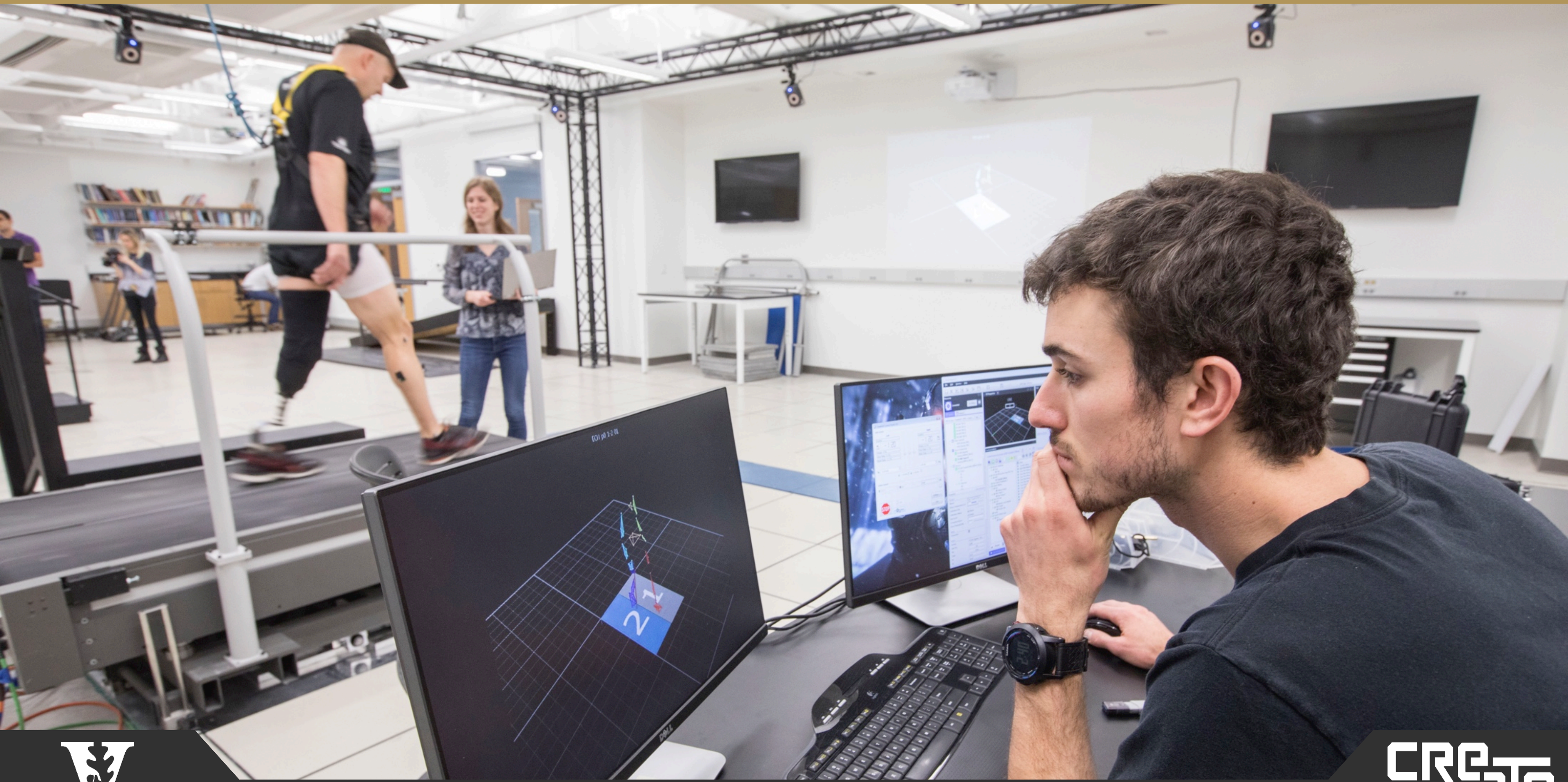
Rehabilitation Engineering

restore mobility, independence &
health to individuals with disabilities
(& prevent future injuries/disabilities)

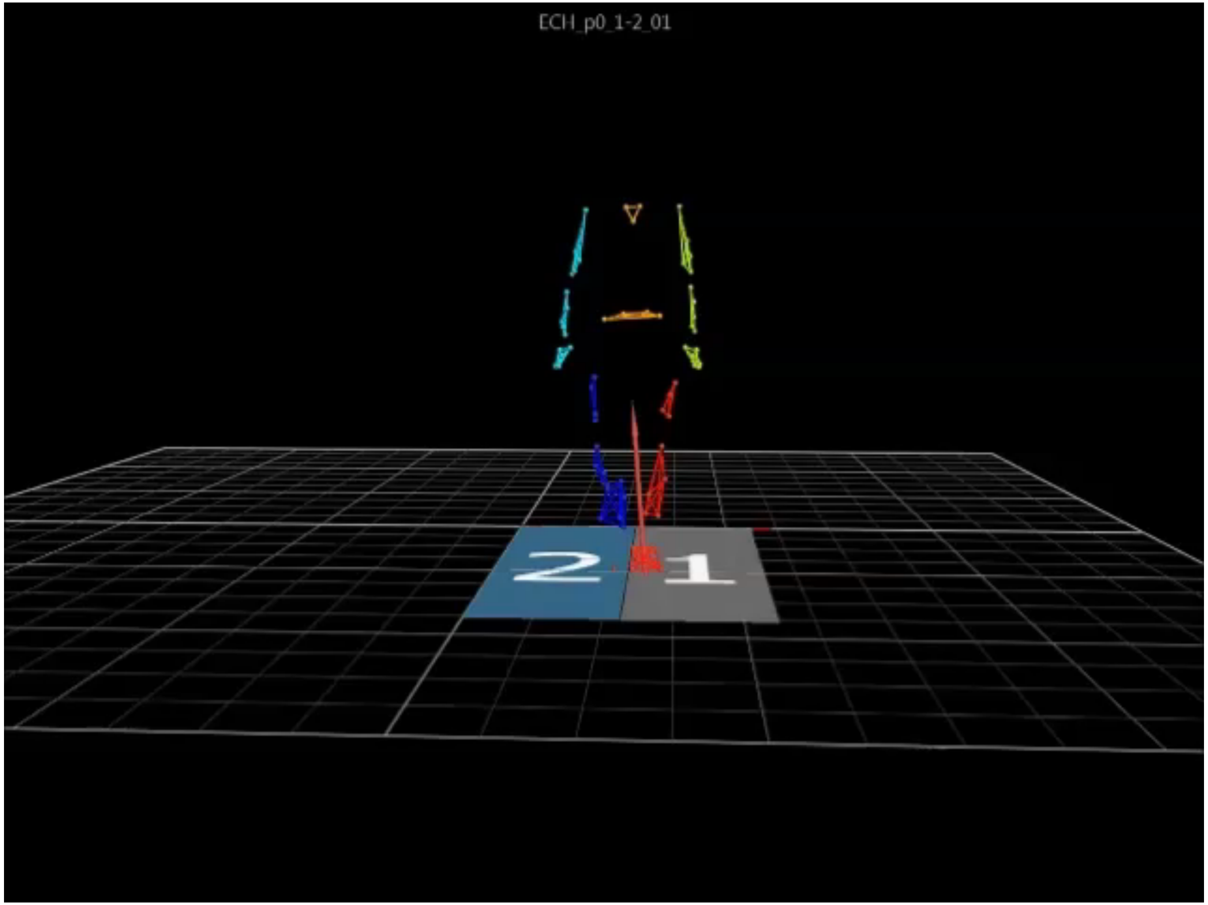
1. Study the science of human movement (biomechanics)

1. Study the science of human movement (biomechanics)

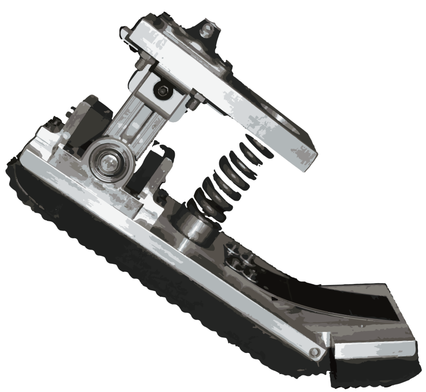
1. Study the science of human movement (biomechanics)



1. Study the science of human movement (biomechanics)

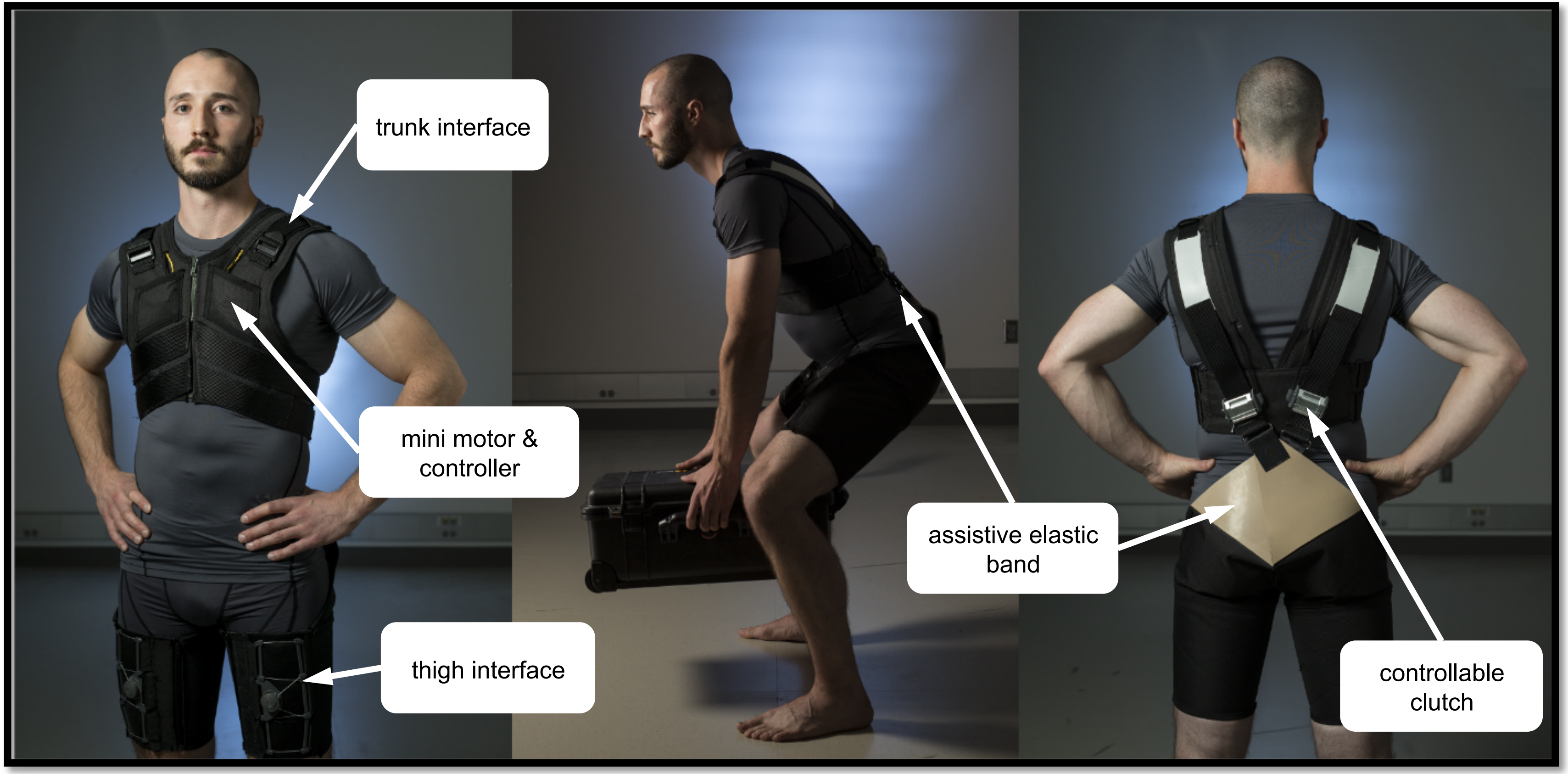


2. Develop assistive technology (prostheses)



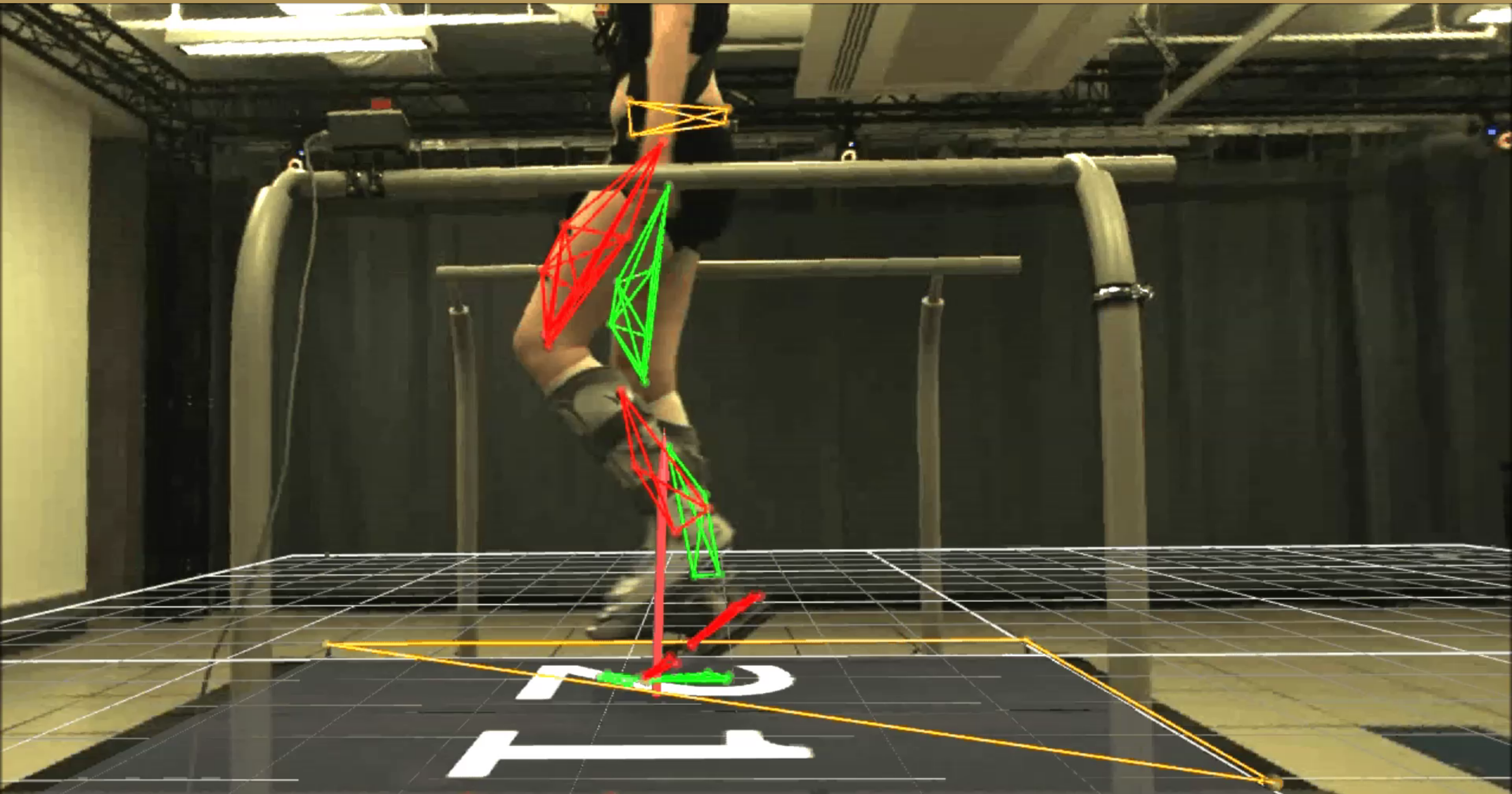
2. Develop assistive technology (exoskeletons)

2. Develop assistive technology (smart clothing)

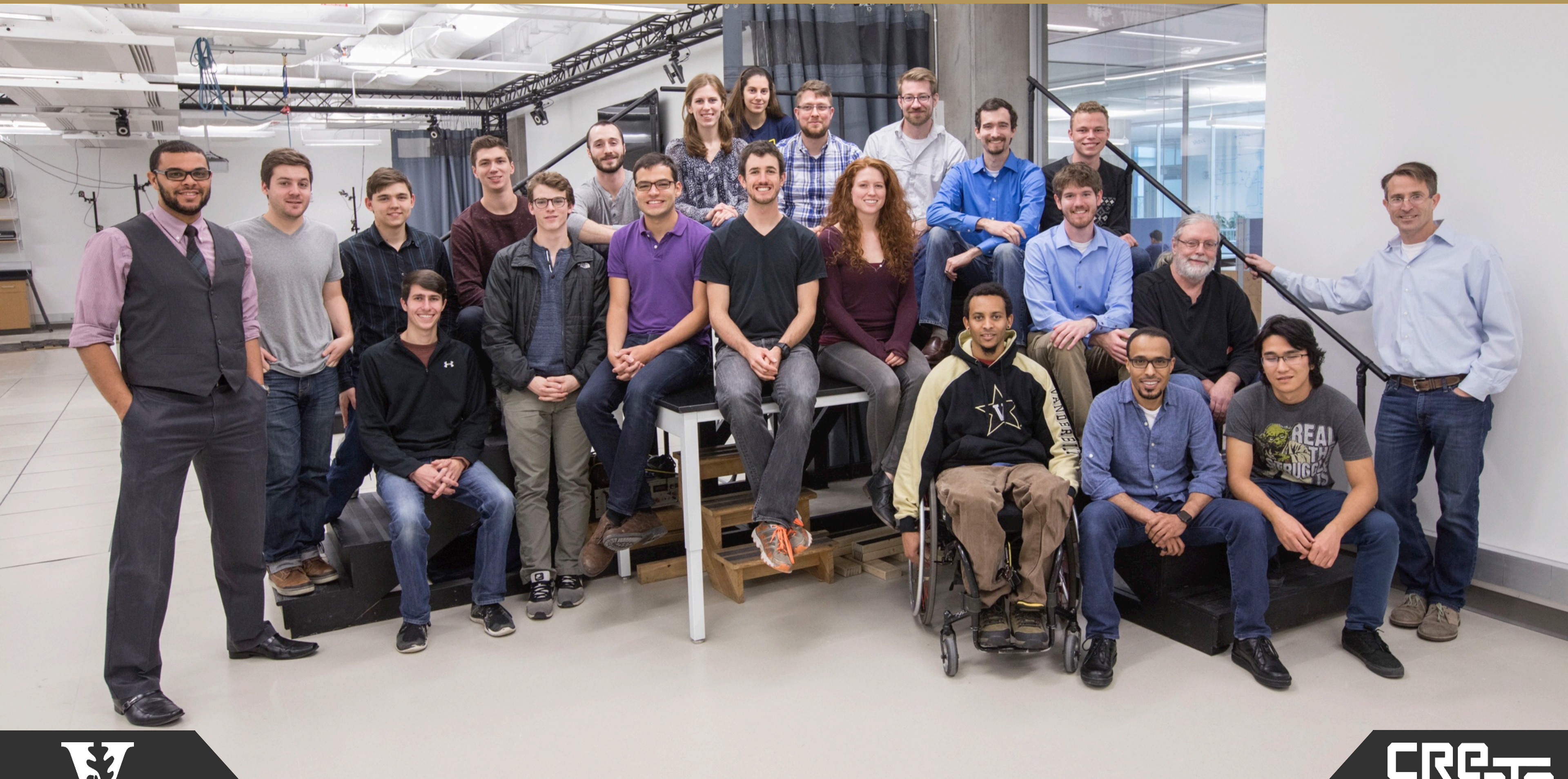


3. Perform experiments to measure benefits & refine devices

3. Perform experiments to measure benefits & refine devices



4. Train next generation of engineers, scientists & innovators

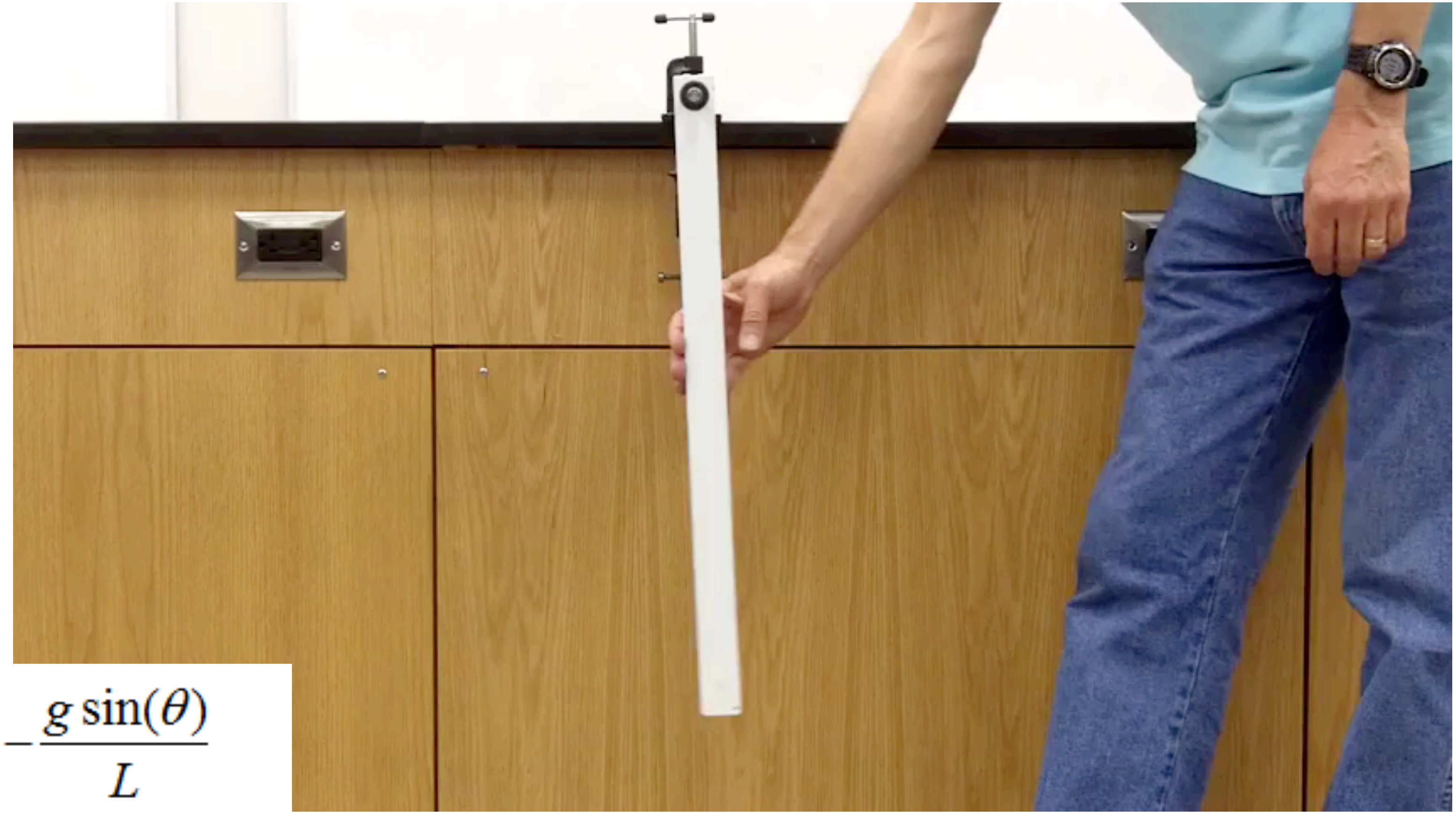


Takeaway 1

You & I are not that smart

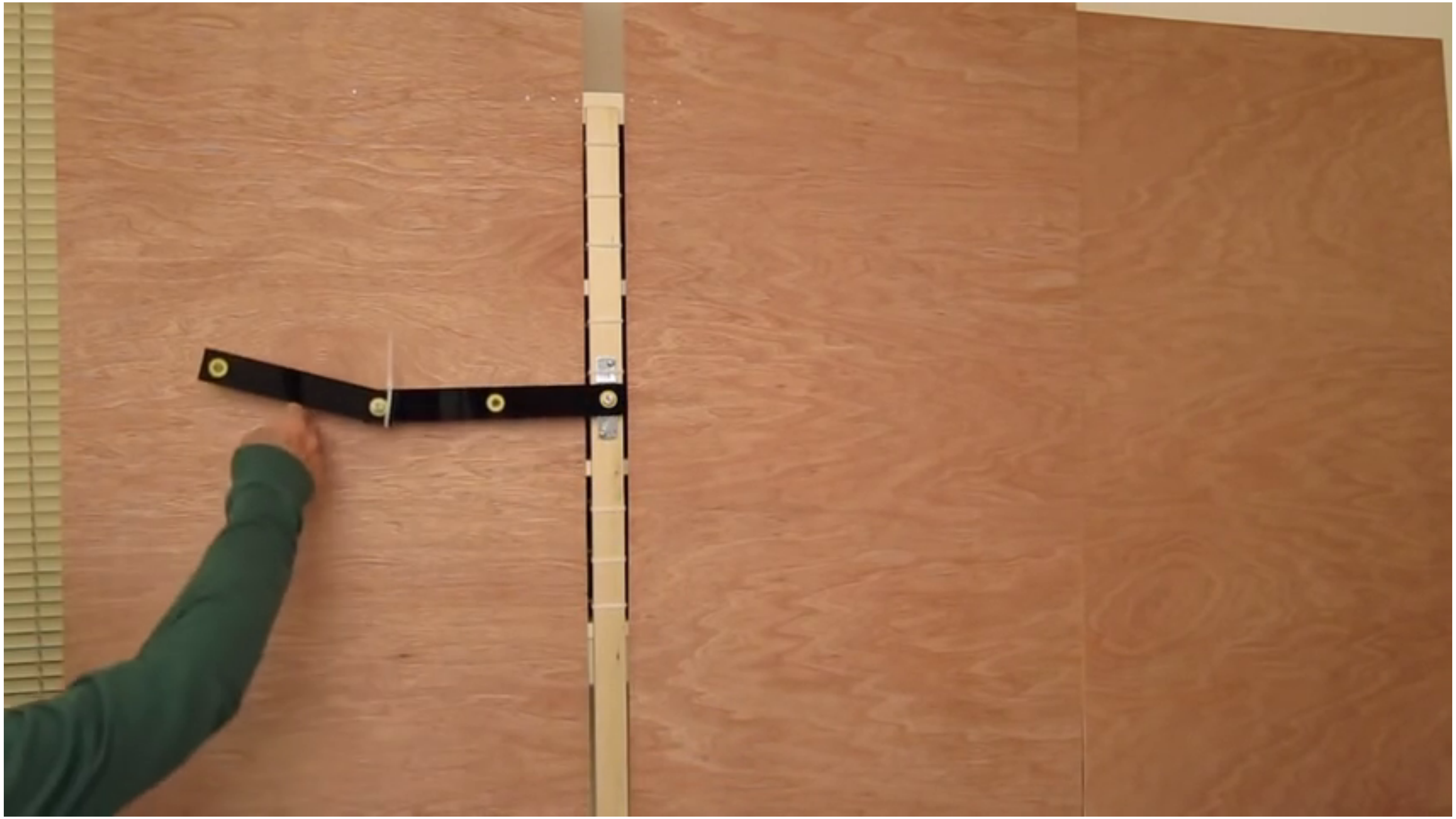
relative to complexity of movement

1 segment (single pendulum) → we've got this one!

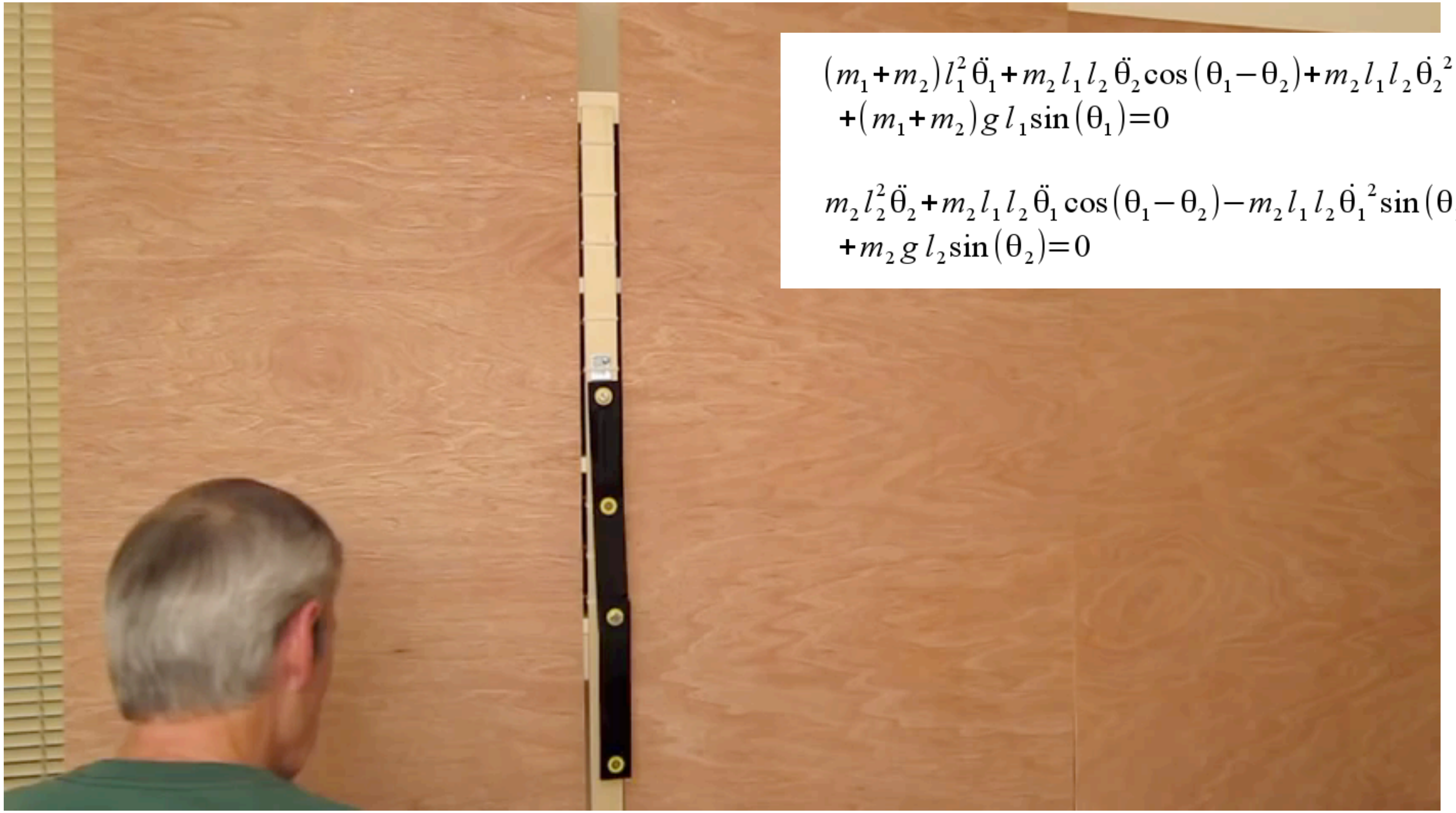


$$\frac{d^2\theta}{dt^2} = -\frac{g\sin(\theta)}{L}$$

2 linked segments (double pendulum) → maybe we get it



2 linked segments (double pendulum) → maybe we don't



$$(m_1+m_2)l_1^2\ddot{\theta}_1+m_2 l_1 l_2 \ddot{\theta}_2\cos(\theta_1-\theta_2)+m_2 l_1 l_2 \dot{\theta}_2^{\,2}\sin(\theta_1-\theta_2)$$
$$+(m_1+m_2)g\,l_1\sin(\theta_1)=0$$

$$m_2 l_2^2\ddot{\theta}_2+m_2 l_1 l_2 \ddot{\theta}_1\cos(\theta_1-\theta_2)-m_2 l_1 l_2 \dot{\theta}_1^{\,2}\sin(\theta_1-\theta_2)$$
$$+m_2 g\,l_2\sin(\theta_2)=0$$

2 linked segments (double inverted pendulum) → hmmm…

Passive Dynamic Walking

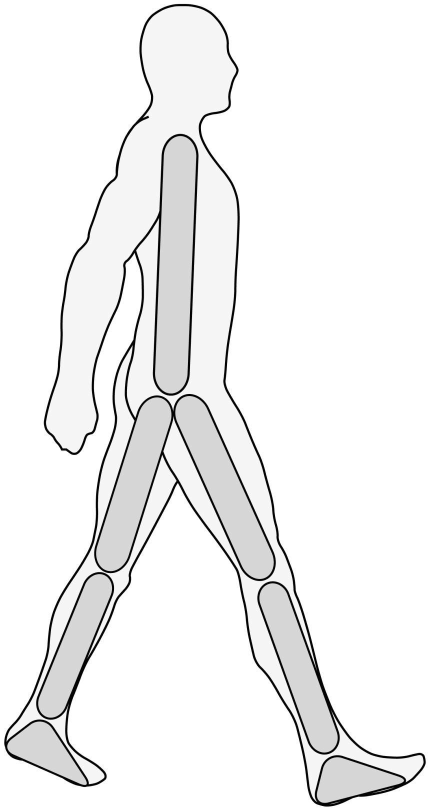
3 linked segments (triple pendulum) → well #%$&

3 linked segments (triple pendulum) → well #%$&

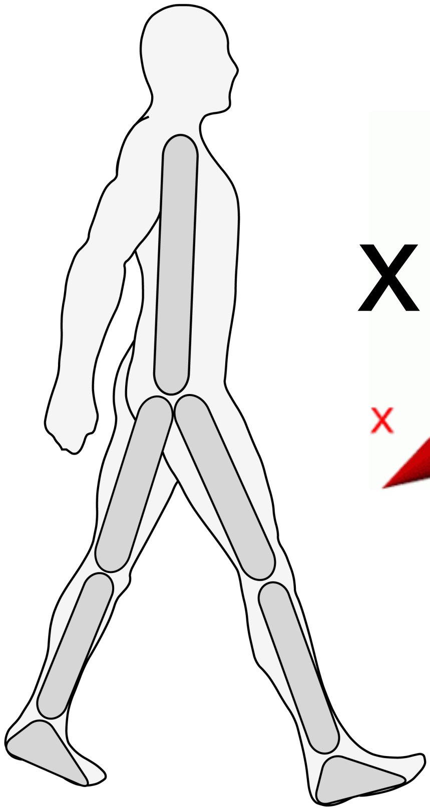
Just one of the three equations of motion:

$$
\begin{aligned}
\ddot{\theta}_1 = {} & -(2((l_3^2 m_3^2 \sin(2\theta_1 - 2\theta_3)(4I_2 - l_2^2 m_2) + l_2^2 \sin(2\theta_1 - 2\theta_2)(m_2 + 2m_3)(m_2 m_3 l_3^2 + 4I_3(m_2 + \\
& 2m_3)))l_1^2 \dot{\theta}_1^2 + (l_2(\sin(\theta_1 - \theta_2)((m_2 m_3(m_2 + 3m_3)l_3^2 + 4I_3(m_2^2 + 6m_2 m_3 + 8m_3^2))l_2^2 + 4I_2(m_3(m_2 + \\
& m_3)l_3^2 + 4I_3(m_2 + 2m_3))) + l_3^2 m_3^2 \sin(\theta_1 + \theta_2 - 2\theta_3)(4I_2 - l_2^2 m_2))\dot{\theta}_2^2 - 4k_2 l_2(cos(\theta_1 - \theta_2)(m_3(m_2 + \\
& m_3)l_3^2 + 4I_3(m_2 + 2m_3)) - l_3^2 m_3^2 cos(\theta_1 + \theta_2 - 2\theta_3))\dot{\theta}_2 + l_3 m_3(\sin(\theta_1 - \theta_3)(8I_3 m_3 l_2^2 + 4I_2 m_3 l_3^2 + 16I_2 I_3) + \\
& l_2^2 \sin(\theta_1 - 2\theta_2 + \theta_3)(m_2 m_3 l_3^2 + 4I_3(m_2 + 2m_3)))\dot{\theta}_3^2 - 4k_3 l_3 m_3(cos(\theta_1 - \theta_3)(2m_3 l_2^2 + 4I_2) - l_2^2 cos(\theta_1 - \\
& 2\theta_2 + \theta_3)(m_2 + 2m_3))\dot{\theta}_3 - g(\sin(\theta_1)((m_3(m_1 m_2 + 2m_1 m_3 + 3m_2 m_3 + m_2^2)l_3^2 + 4I_3(m_2^2 + 6m_2 m_3 + \\
& m_1 m_2 + 4m_3^2 + 4m_1 m_3))l_2^2 + 4I_2(m_3(m_1 + 2m_2 + m_3)l_3^2 + 4I_3(m_1 + 2m_2 + 2m_3))) + l_3^2 m_3^2(\sin(\theta_1 - \\
& 2\theta_3)(4I_2 - l_2^2 m_2) - 2l_2^2 cos(2\theta_2 - 2\theta_3)\sin(\theta_1)(m_1 + m_2)) + l_2^2 \sin(\theta_1 - 2\theta_2)(m_2 + 2m_3)(m_2 m_3 l_3^2 + \\
& 4I_3(m_2 + 2m_3))))l_1 + 2k_1(4I_2(m_3 l_3^2 + 4I_3) + l_2^2(m_3(m_2 + 2m_3)l_3^2 + 4I_3(m_2 + 4m_3)) - 2l_2^2 l_3^2 m_3^2 cos(2\theta_2 - \\
& 2\theta_3))\dot{\theta}_1))/(64I_1 I_2 I_3 + 8I_3 l_1^2 l_2^2 m_2^2 + 8I_1 l_2^2 l_3^2 m_3^2 + 8I_2 l_1^2 l_3^2 m_3^2 + 32I_3 l_1^2 l_2^2 m_3^2 + 16I_2 I_3 l_1^2 m_1 + 16I_1 I_3 l_2^2 m_2 + \\
& 64I_2 I_3 l_1^2 m_2 + 16I_1 I_2 l_3^2 m_3 + 64I_1 I_3 l_2^2 m_3 + 64I_2 I_3 l_1^2 m_3 + 4I_3 l_1^2 l_2^2 m_1 m_2 + 4I_2 l_1^2 l_3^2 m_1 m_3 + 16I_3 l_1^2 l_2^2 m_1 m_3 + \\
& 4I_1 l_2^2 l_3^2 m_2 m_3 + 16I_2 l_1^2 l_3^2 m_2 m_3 + 48I_3 l_1^2 l_2^2 m_2 m_3 - 8I_1 l_2^2 l_3^2 m_3^2 cos(2\theta_2 - 2\theta_3) - 2l_1^2 l_2^2 cos(2\theta_1 - 2\theta_2)(m_2 + \\
& 2m_3)(m_2 m_3 l_3^2 + 4I_3(m_2 + 2m_3)) - 2l_1^2 l_3^2 m_3^2 cos(2\theta_1 - 2\theta_3)(-m_2 l_2^2 + 4I_2) + 2l_1^2 l_2^2 l_3^2 m_1 m_3^2 + 6l_1^2 l_2^2 l_3^2 m_2 m_3^2 + \\
& 2l_1^2 l_2^2 l_3^2 m_2^2 m_3 + l_1^2 l_2^2 l_3^2 m_1 m_2 m_3 - 2l_1^2 l_2^2 l_3^2 m_1 m_3^2 cos(2\theta_2 - 2\theta_3) - 4l_1^2 l_2^2 l_3^2 m_2 m_3^2 cos(2\theta_2 - 2\theta_3))
\end{aligned}
$$

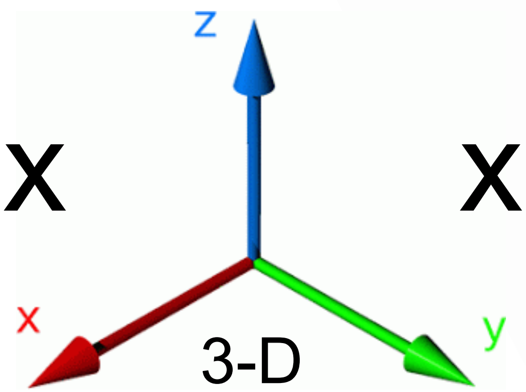
Human: multiple linked segments



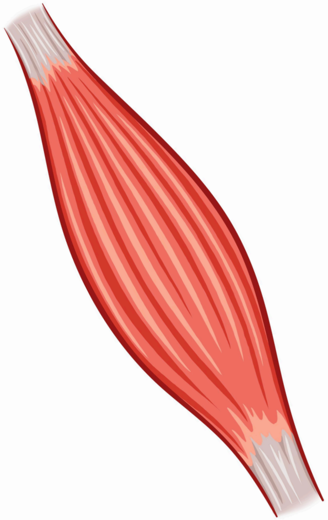
Human: multiple linked segments x 3-D x muscles x control



X

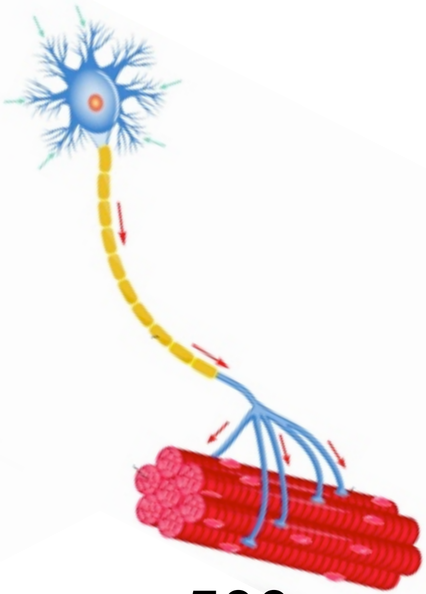


X



600
skeletal
muscles

X

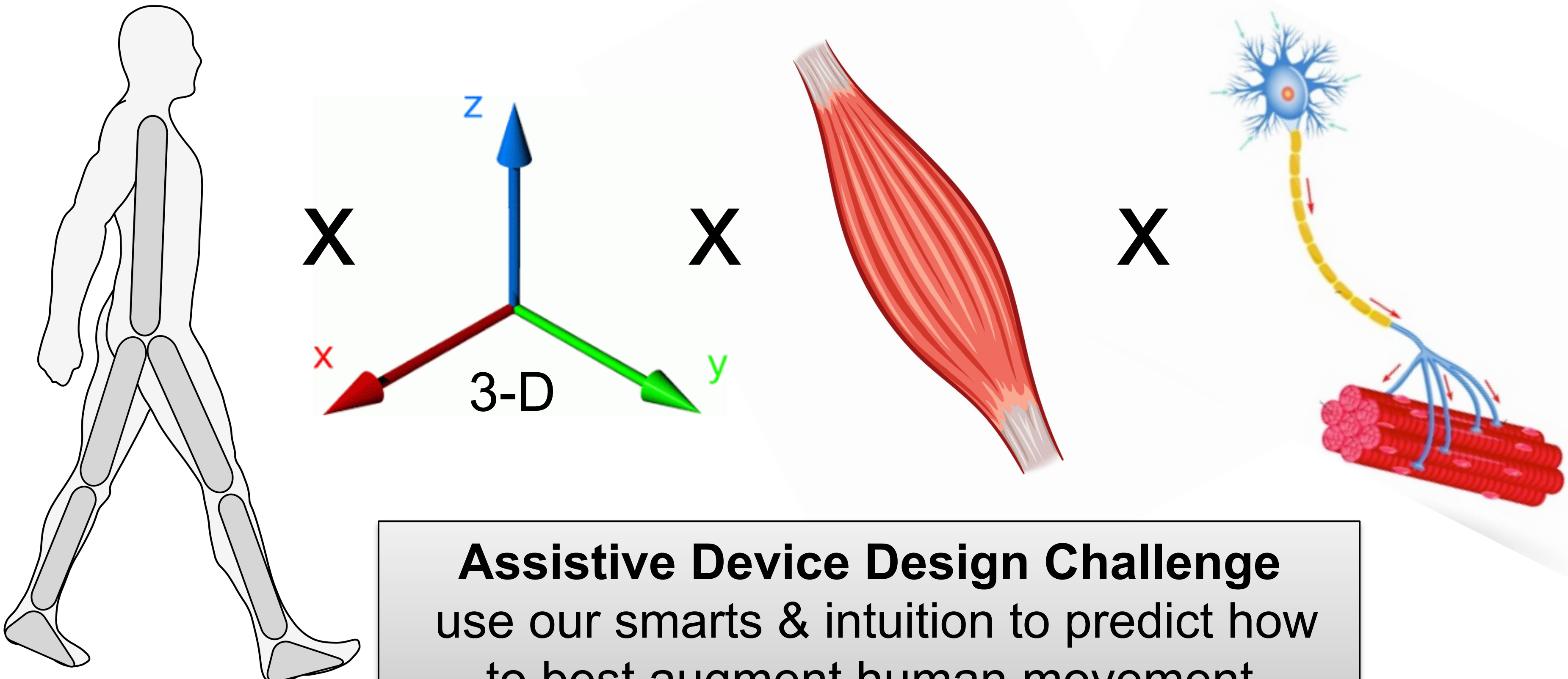


500
motoneuron/
muscle

smarts = ability to quickly reason, understand, intuit or predict

Human: multiple linked segments x 3-D x muscles x control

Human: multiple linked segments x 3-D x muscles x control

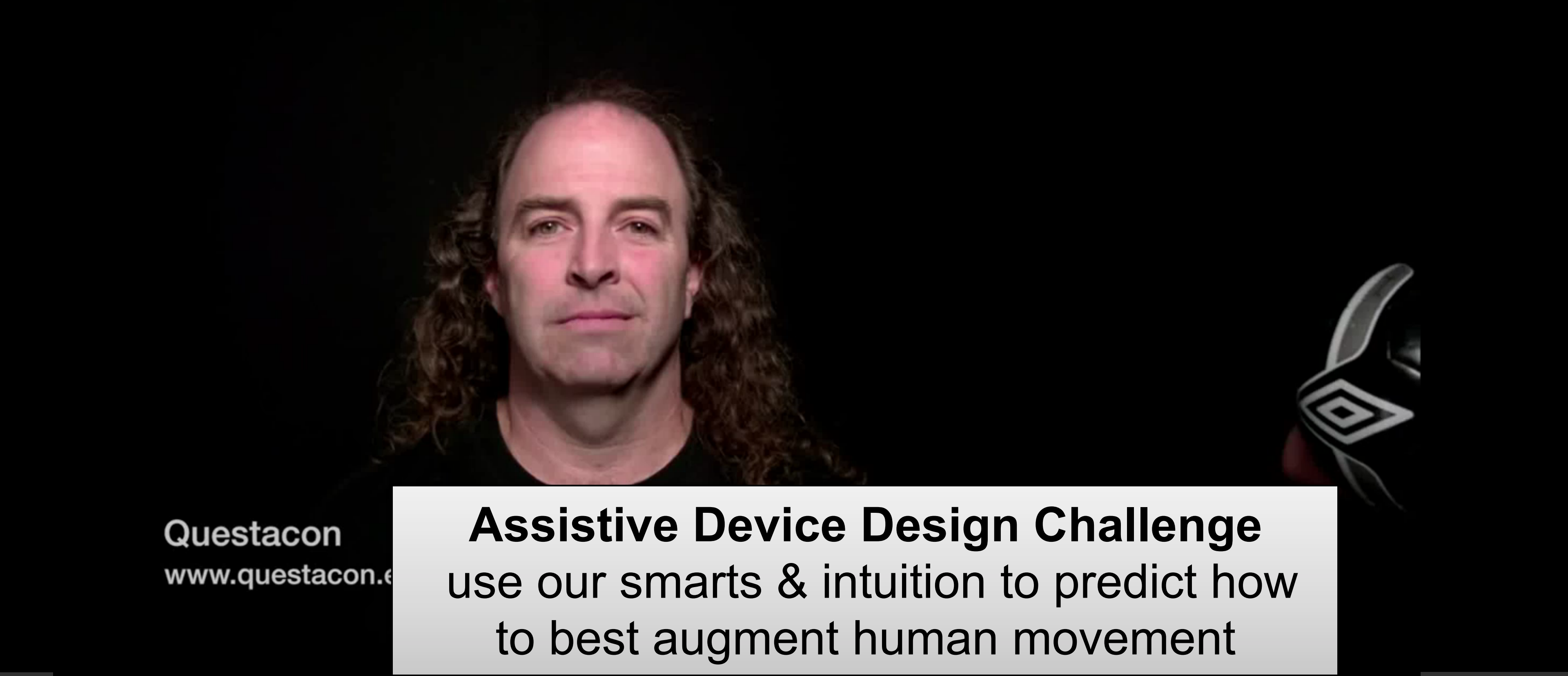


Assistive Device Design Challenge

use our smarts & intuition to predict how to best augment human movement

People are squishy when forces are applied to body

Yandell et al. 2017



Assistive Device Design Challenge
use our smarts & intuition to predict how to best augment human movement

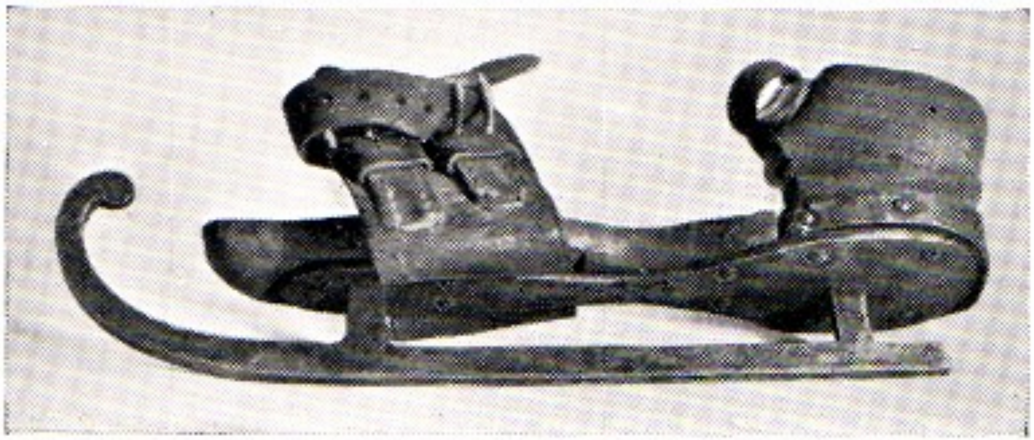
smarts = ability to quickly reason, understand, intuit or predict

Mechanisms underlying movement are often unexpected & non-intuitive

Non-intuitive mechanisms are key to innovative new assistive tech & broadening societal impact

Speed skating: Push-off power from ankle, knee & hip

Simple modification to traditional skate enhances speed



American skate about 1865

“a rigid blade fixed below a boot”

1700 — 1800 — 1900

Passive "toe" joint: seemingly small change has big impact!

1998 Olympics: Records broken in every single speed skating event (men's & women's)

1700

1800

1900

Relevance: lower-limb prosthesis users

Relevance: lower-limb prosthesis users

Mobility

63% back pain
(Gailey et al. 2008)

46% residual limb pain
(Struyf et al. 2009)

55% hip pain
(Gailey et al. 2008)

27% knee osteoarthritis
(Struyf et al. 2009)

Relevance: lower-limb prosthesis users

Mobility

63% back pain
(Gailey et al. 2008)

46% residual limb pain
(Struyf et al. 2009)

55% hip pain
(Gailey et al. 2008)

27% knee osteoarthritis
(Struyf et al. 2009)

Livelihood

20-30% depression
(Rybarczyk et al. 1995)

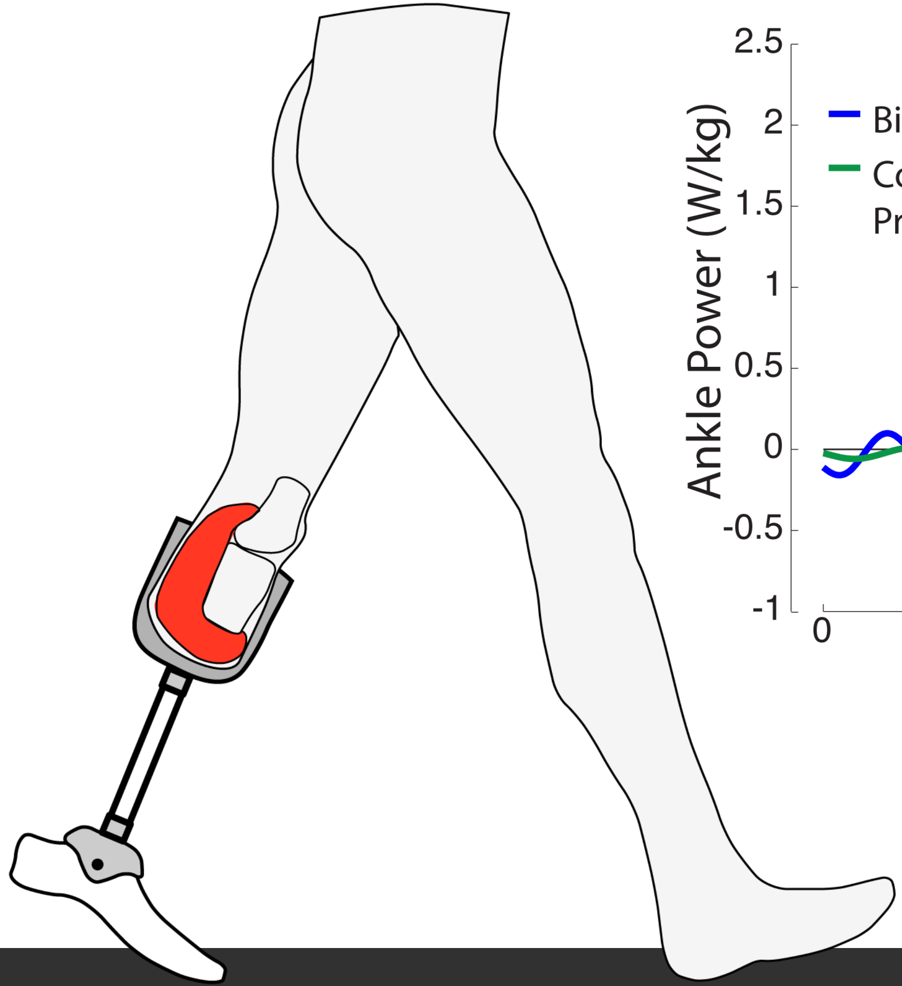
25-40% anxiety issues
(Seidel 2006, Hawamdeh 2008)

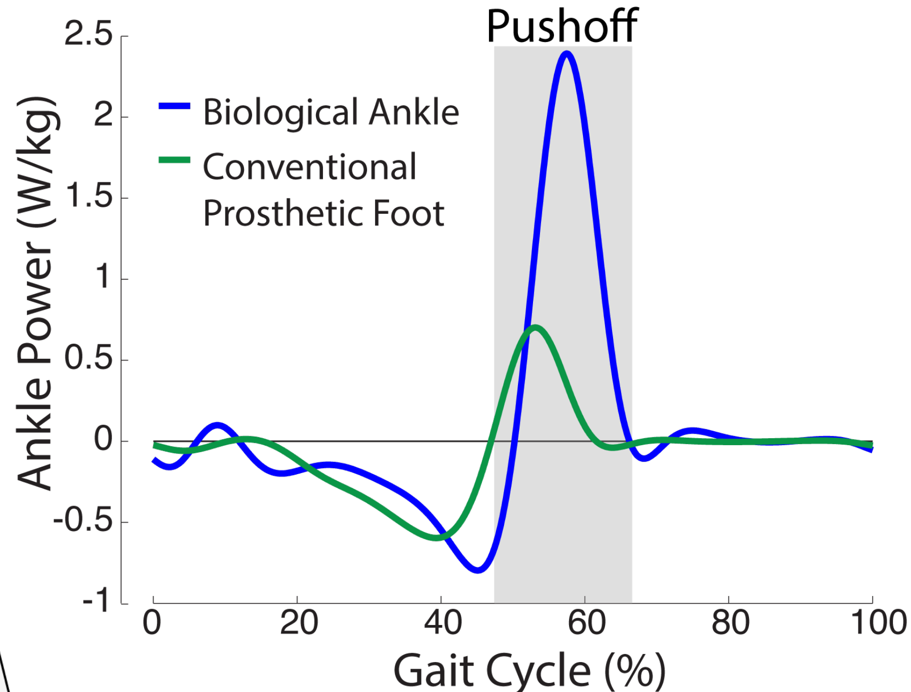
34% need help at home
(Pohjolainen 1990)

65% fatigue
(Hoogendom & Werken 2001)

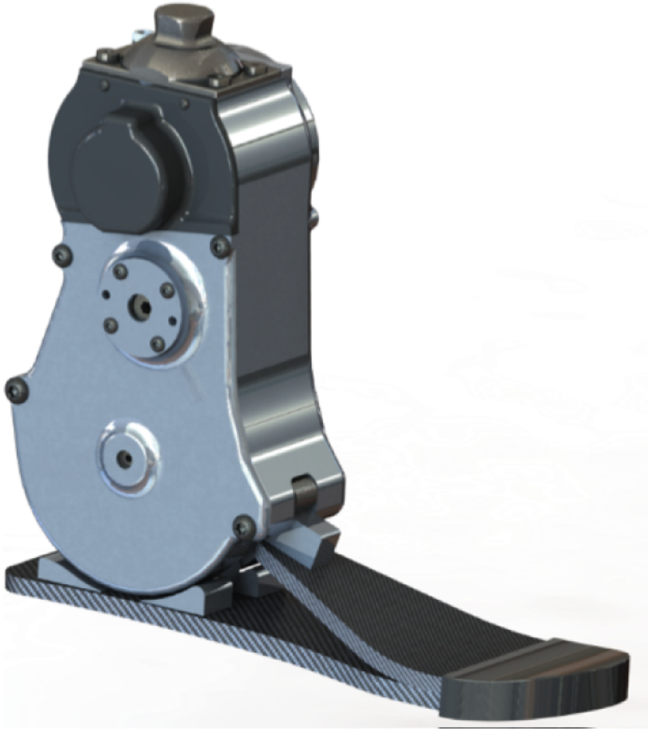
Prevailing Belief

Reduced ankle push-off is factor underlying impaired mobility





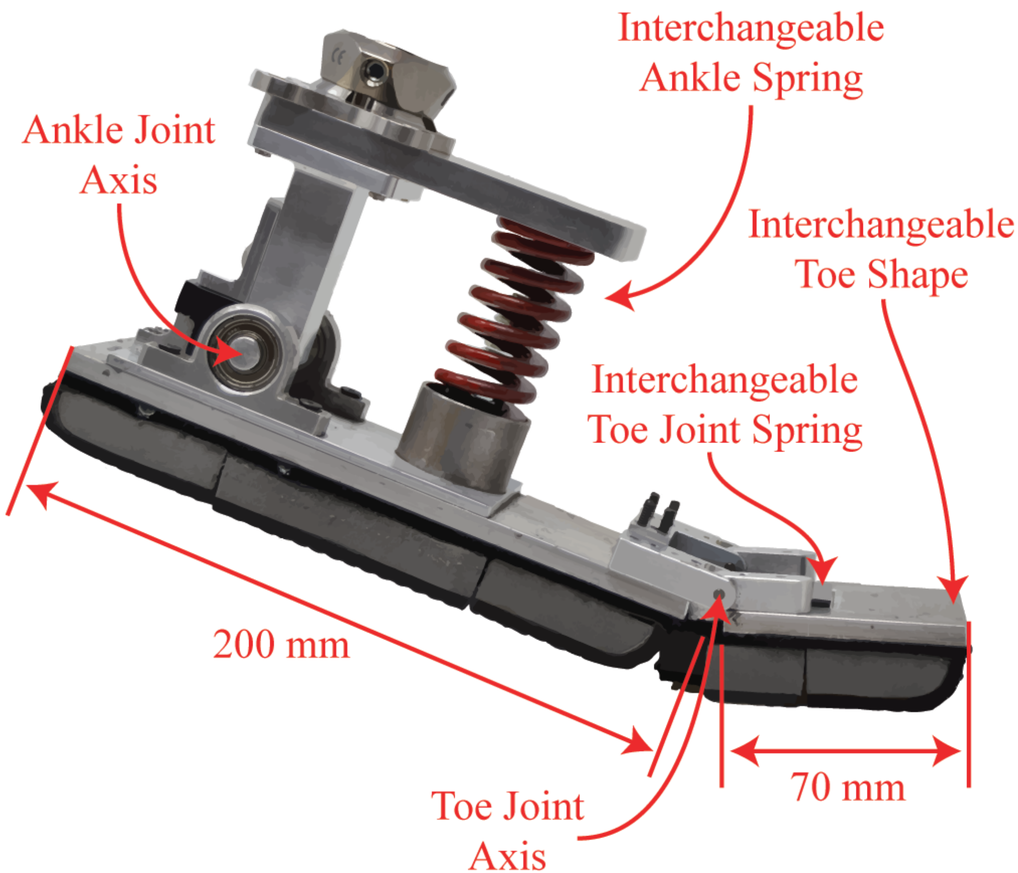
Powered prostheses can restore push-off, but are $$$



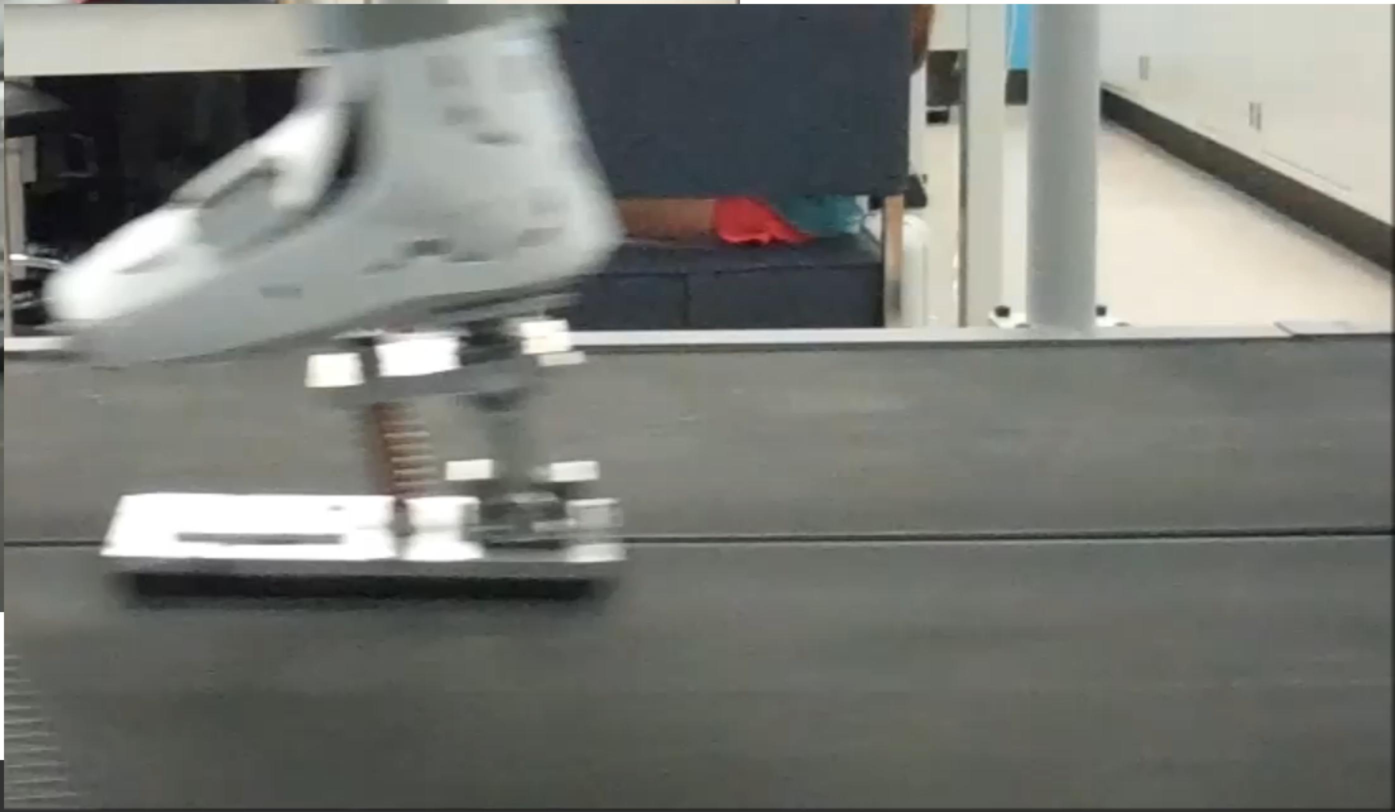
Conventional prosthesis: carbon fiber keel in rubber shell

Leverage toe dynamics to improve push-off capabilities?

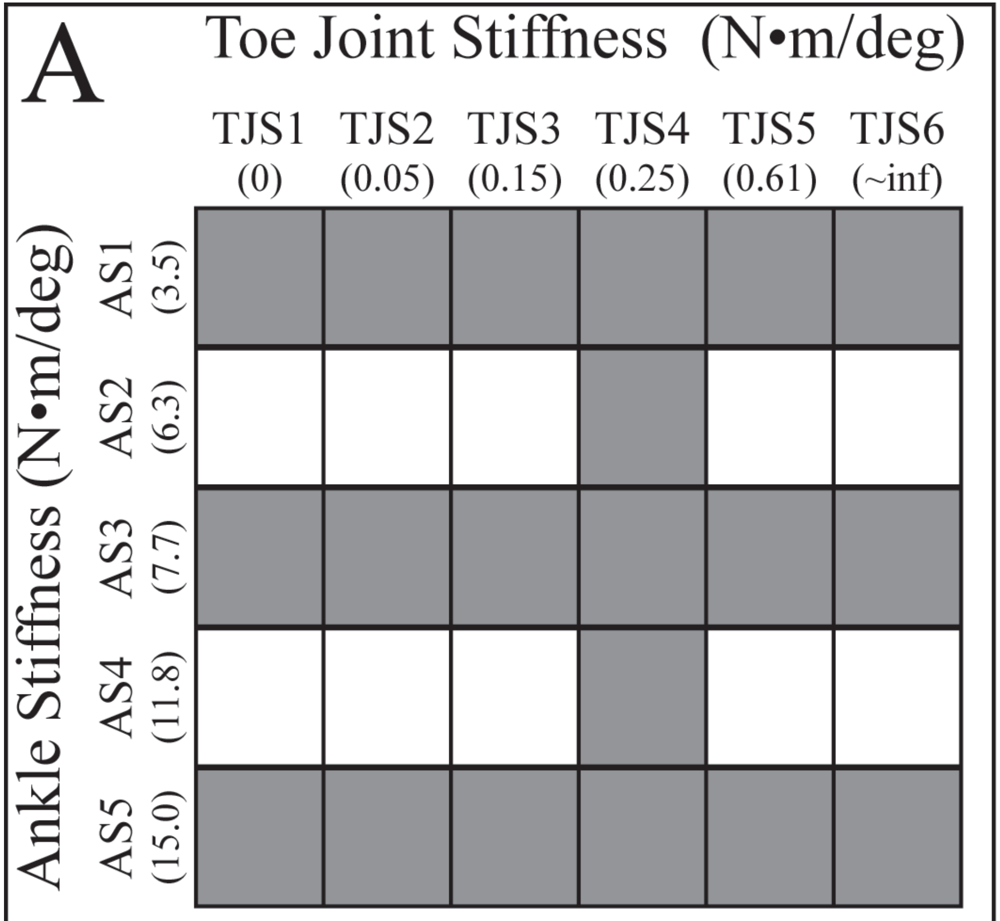
Leverage toe dynamics to improve push-off capabilities?



Leverage toe dynamics to improve push-off capabilities?



Systematically assessing effects of toe & ankle joint stiffness



- 10 healthy subjects
- Simulator boots
- Treadmill at 1 m/s
- Randomized order
- Motion capture & ground reaction forces

- Toe stiffness range: zero to ~infinity

- Ankle stiffness range: spanned commercial prosthetic feet

Center-of-Mass (COM) Push-off Work (N=10)

Joint Stiffness (N·m/deg)	AS1 (3.5)	AS2 (6.3)	AS3 (7.7)	AS4(11.8)	AS5 (15.0)
TJS1 (0)	11.6 ± 1.5 J	-	12.6 ± 1.4 J	-	11.3 ± 1.7 J
TJS2 (0.05)	9.2 ± 1.4 J	-	11.6 ± 1.6 J	-	10.7 ± 1.3 J
TJS3 (0.15)	11.4 ± 1.6 J	-	13.4 ± 1.6 J	-	12.6 ± 1.8 J
TJS4 (0.25)	11.3 ± 2.1 J	12.1 ± 2.7 J	13.6 ± 1.7 J	13.21 ± 2.1 J	13.2 ± 2.0 J
TJS5 (0.61)	11.5 ± 2.0 J	-	14.8 ± 1.9 J	-	13.8 ± 1.9 J
TJS6 (~∞)	12.1 ± 2.3 J	-	17.7 ± 2.6 J	-	17.2 ± 2.7 J

Center-of-Mass (COM) Push-off Work (N=10)

Joint Stiffness (N·m/deg)	AS1 (3.5)	AS2 (6.3)	AS3 (7.7)	AS4(11.8)	AS5 (15.0)
TJS1 (0)	11.6 ± 1.5 J	-	12.6 ± 1.4 J	-	11.3 ± 1.7 J
TJS2 (0.05)	9.2 ± 1.4 J	-	11.6 ± 1.6 J	-	10.7 ± 1.3 J
TJS3 (0.15)	11.4 ± 1.6 J	-	13.4 ± 1.6 J	-	12.6 ± 1.8 J
TJS4 (0.25)	11.3 ± 2.1 J	12.1 ± 2.7 J	13.6 ± 1.7 J	13.21 ± 2.1 J	13.2 ± 2.0 J
TJS5 (0.61)	11.5 ± 2.0 J	-	14.8 ± 1.9 J	-	13.8 ± 1.9 J
TJS6 (~∞)	12.1 ± 2.3 J	-	17.7 ± 2.6 J	-	17.2 ± 2.7 J

2J range due to ankle stiffness

Effect of toe joint stiffness on COM Push-off is greater!

5J range due to toe stiffness

Joint Stiffness (N·m/deg)	AS1 (3.5)	AS2 (6.3)	AS3 (7.7)	AS4(11.8)	AS5 (15.0)
TJS1 (0)	11.6 ± 1.5 J	-	12.6 ± 1.4 J	-	11.3 ± 1.7 J
TJS2 (0.05)	9.2 ± 1.4 J	-	11.6 ± 1.6 J	-	10.7 ± 1.3 J
TJS3 (0.15)	11.4 ± 1.6 J	-	13.4 ± 1.6 J	-	12.6 ± 1.8 J
TJS4 (0.25)	11.3 ± 2.1 J	12.1 ± 2.7 J	13.6 ± 1.7 J	13.21 ± 2.1 J	13.2 ± 2.0 J
TJS5 (0.61)	11.5 ± 2.0 J	-	14.8 ± 1.9 J	-	13.8 ± 1.9 J
TJS6 (~∞)	12.1 ± 2.3 J	-	17.7 ± 2.6 J	-	17.2 ± 2.7 J

2J range due to ankle stiffness

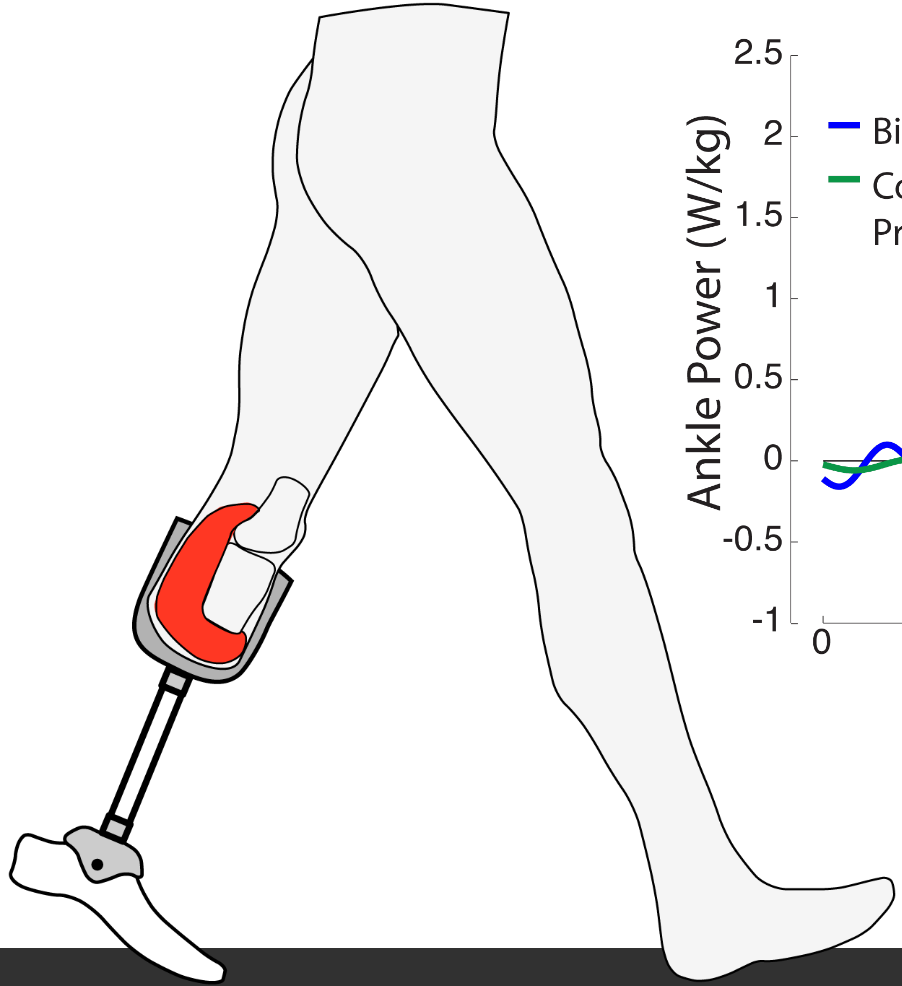
Effect of toe joint stiffness on COM Push-off is greater!

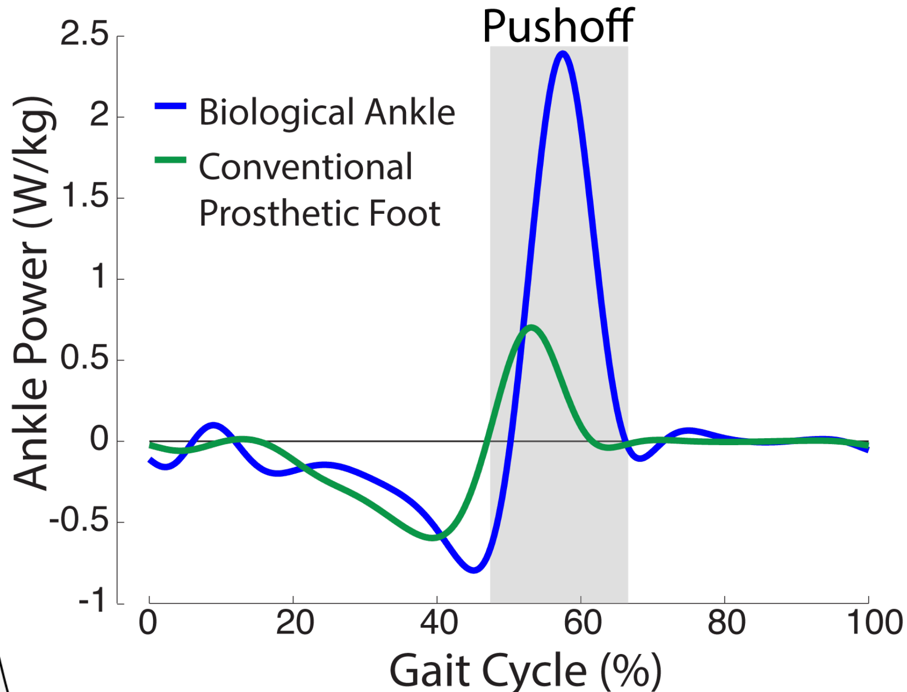
6.5J range due to toe stiffness

Joint Stiffness (N·m/deg)	AS1 (3.5)	AS2 (6.3)	AS3 (7.7)	AS4(11.8)	AS5 (15.0)
TJS1 (0)	11.6 ± 1.5 J	-	12.6 ± 1.4 J	-	11.3 ± 1.7 J
TJS2 (0.05)	9.2 ± 1.4 J	-	11.6 ± 1.6 J	-	10.7 ± 1.3 J
TJS3 (0.15)	11.4 ± 1.6 J	-	13.4 ± 1.6 J	-	12.6 ± 1.8 J
TJS4 (0.25)	11.3 ± 2.1 J	12.1 ± 2.7 J	13.6 ± 1.7 J	13.21 ± 2.1 J	13.2 ± 2.0 J
TJS5 (0.61)	11.5 ± 2.0 J	-	14.8 ± 1.9 J	-	13.8 ± 1.9 J
TJS6 (~∞)	12.1 ± 2.3 J	-	17.7 ± 2.6 J	-	17.2 ± 2.7 J

5.5J range due to ankle stiffness

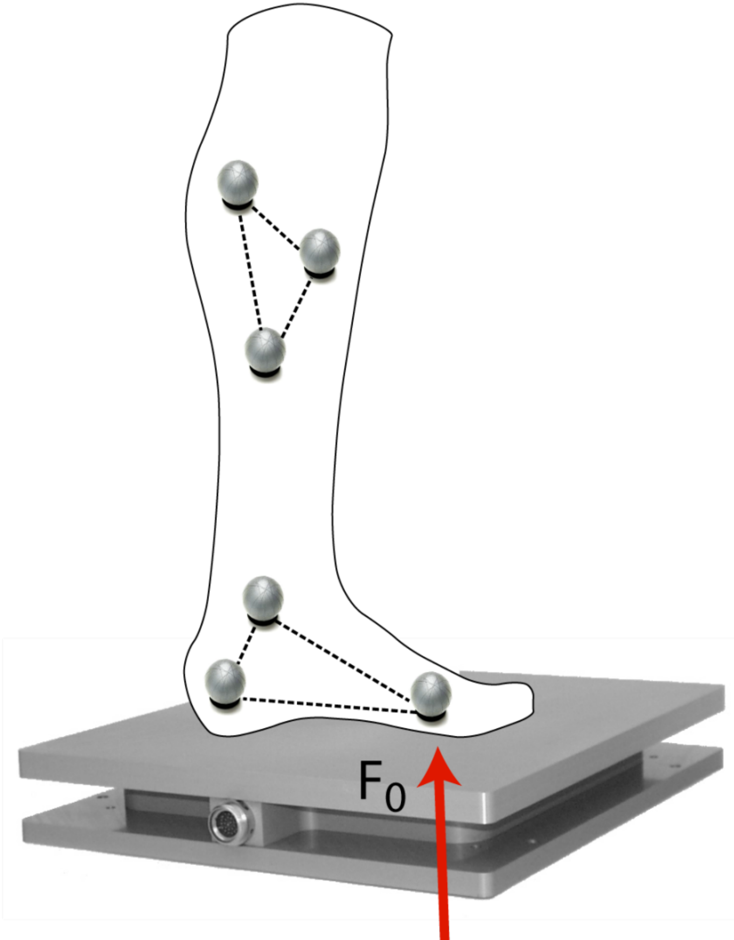
Emphasis on ankle, but foot redesign may also provide benefit

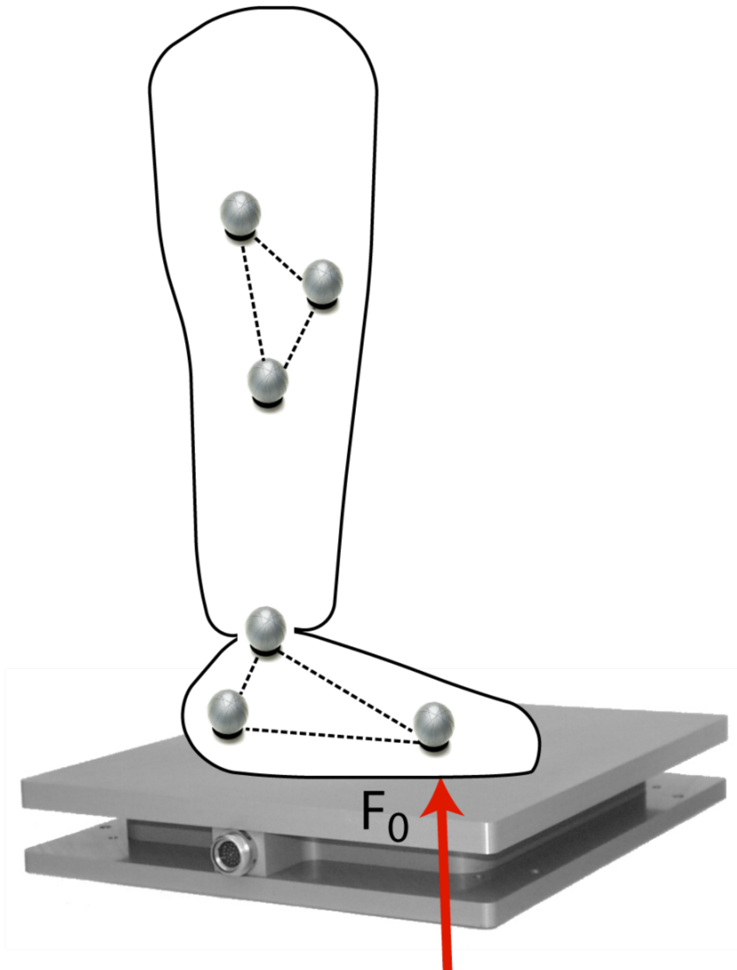




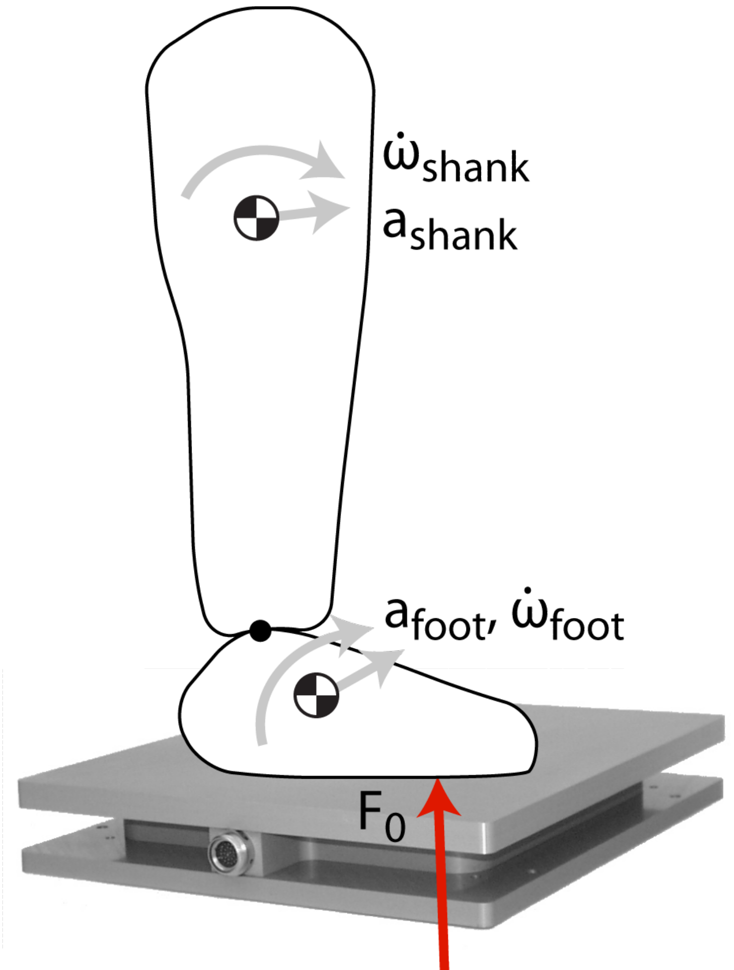
Tests on prosthetic users performing variety of daily tasks

Quick Aside for Gait Analysis Nerds

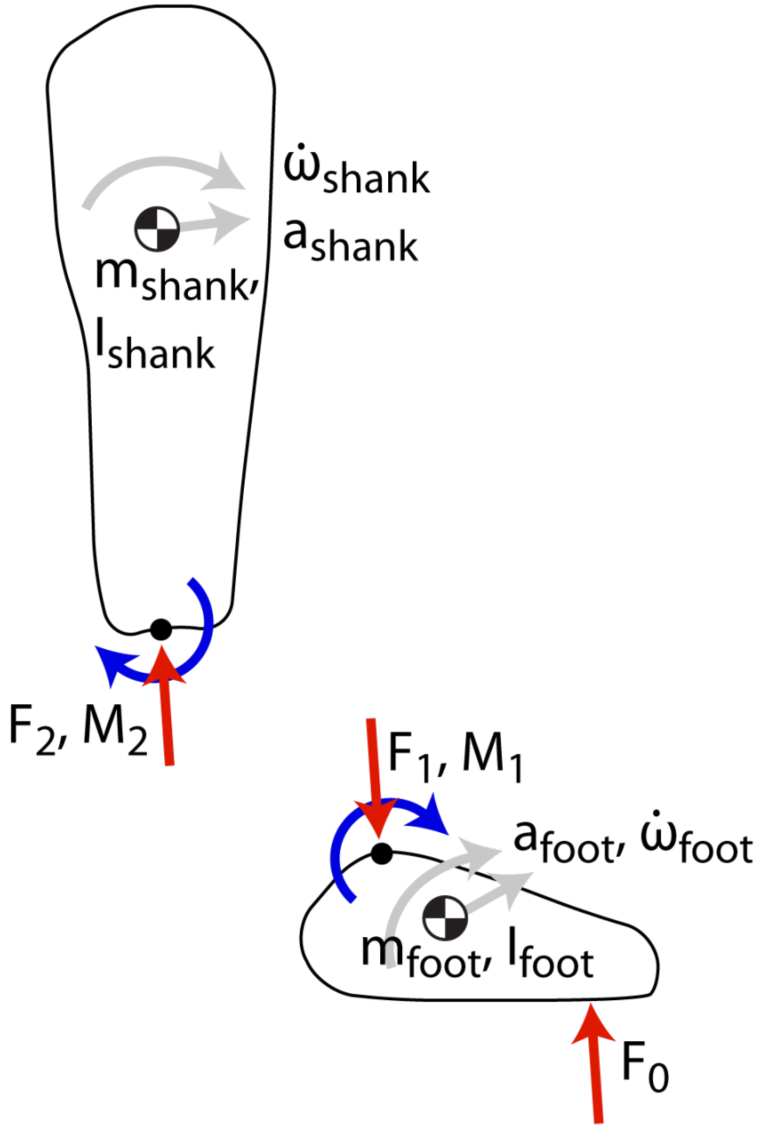

F_0


F_0


VICON

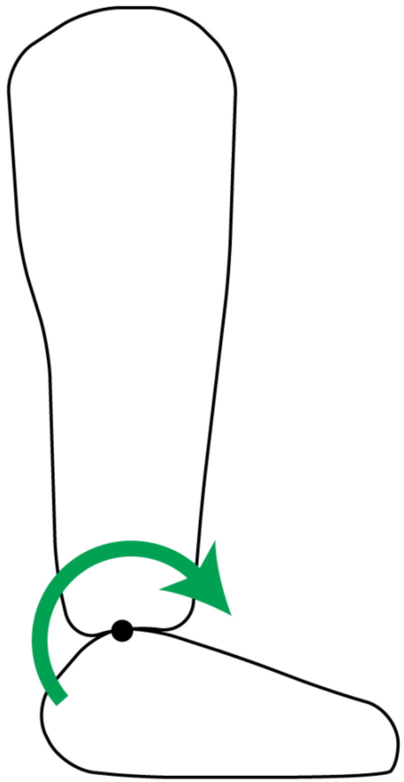


$\dot{\omega}_{shank}$
a_{shank}
a_{foot}, $\dot{\omega}_{foot}$
F_0



$$\sum F = ma$$

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



$$\sum F = ma$$

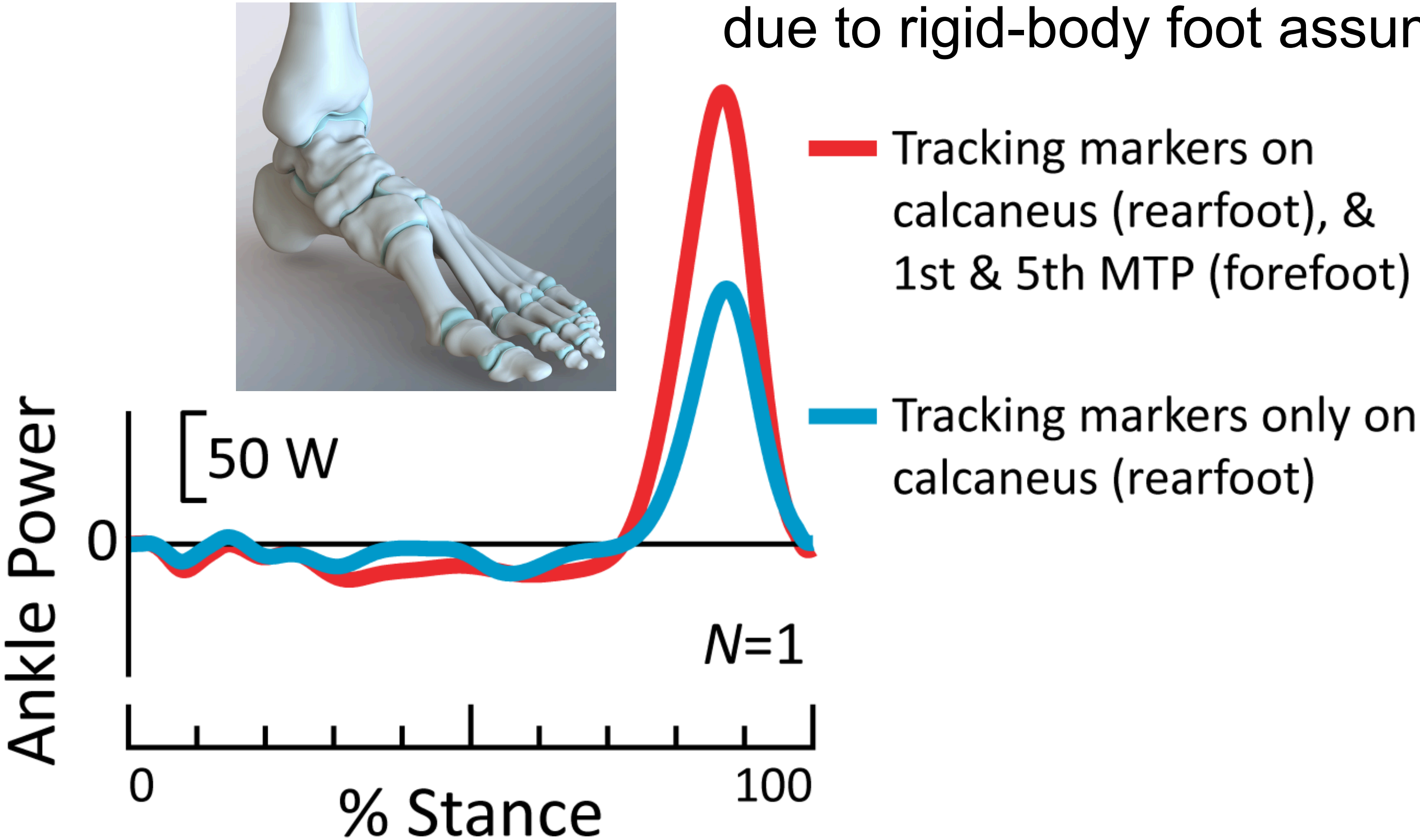
$$\sum M = I\dot{\omega}$$

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

$$W_{joint} = \int P_{joint}\,dt$$

Conventional inverse dynamics ankle power estimates flawed

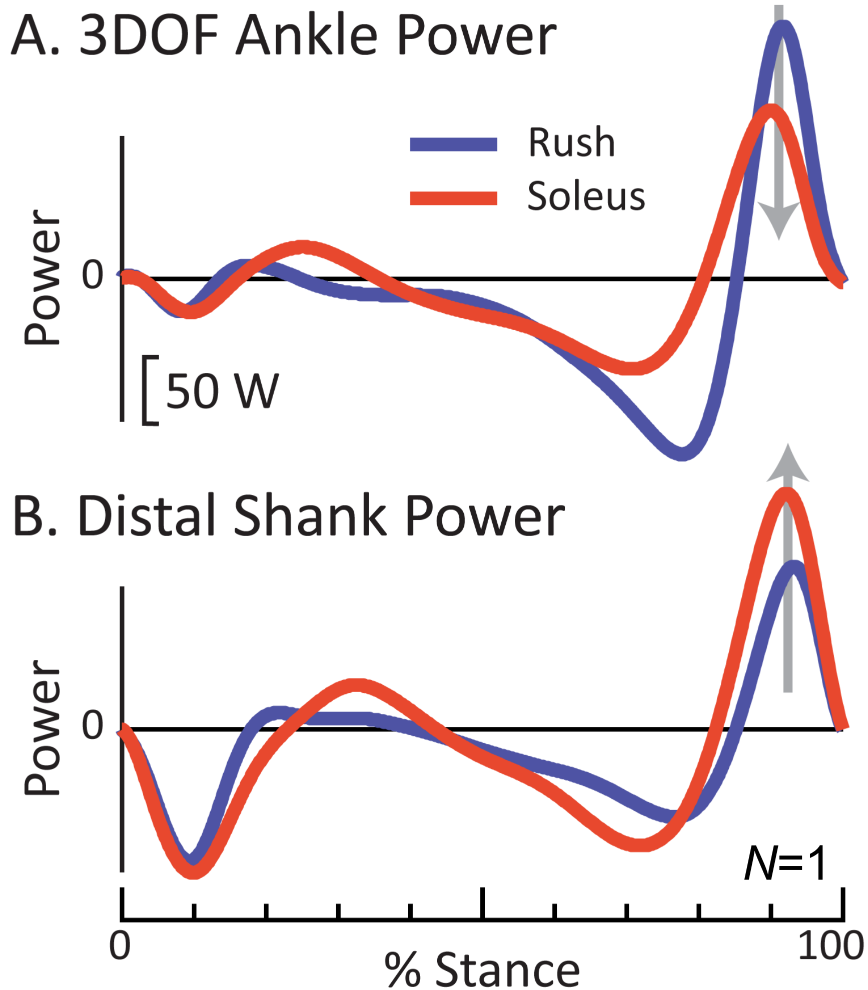
due to rigid-body foot assumptions



Zelik & Honert 2018. *J Biomech.* In Press.

Analogous misestimation with prosthetic ankle power

due to rigid-body foot assumptions

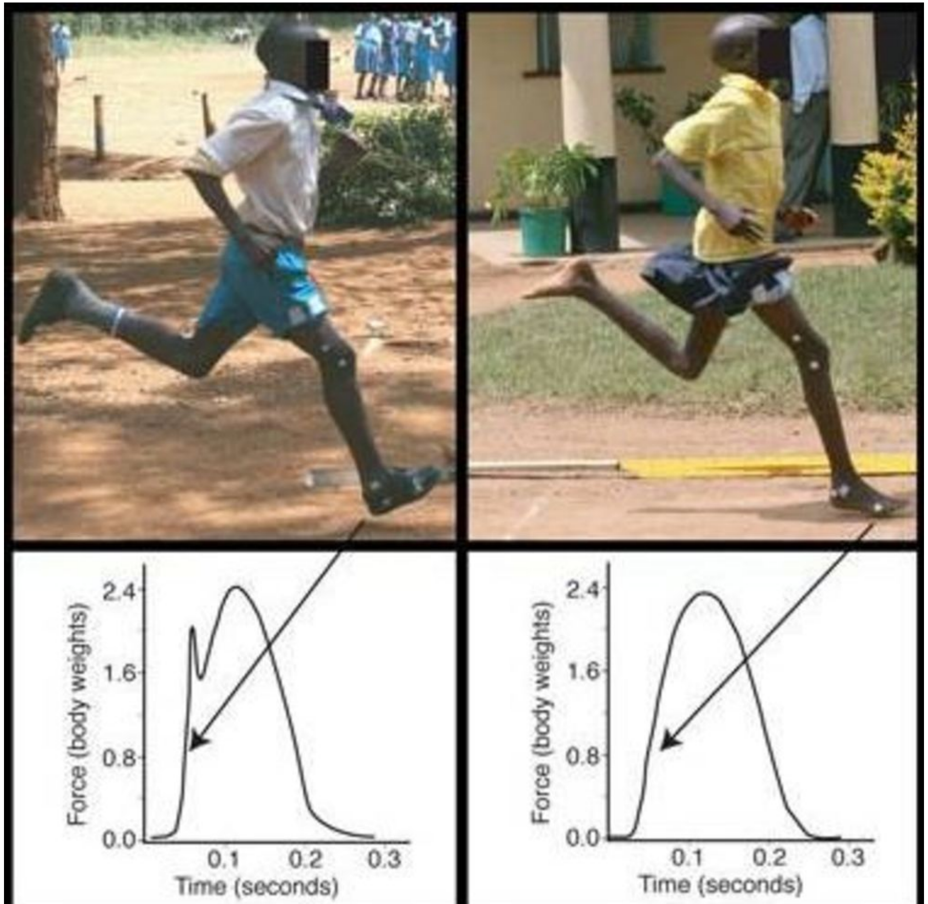


Zelik & Honert 2018. *J Biomech.* In Press.

Running shoes

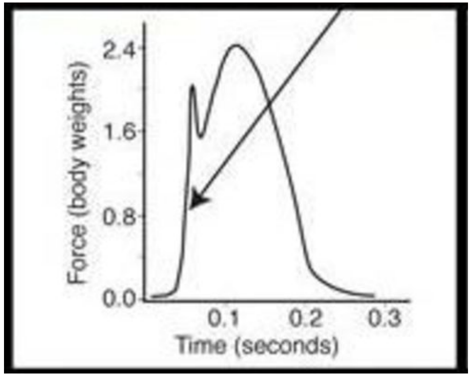
Running shoes: cushioned footwear vs. barefoot?

Running shoes: cushioned footwear vs. barefoot?



Results: Lieberman et al. 2010
Image: Popular Science

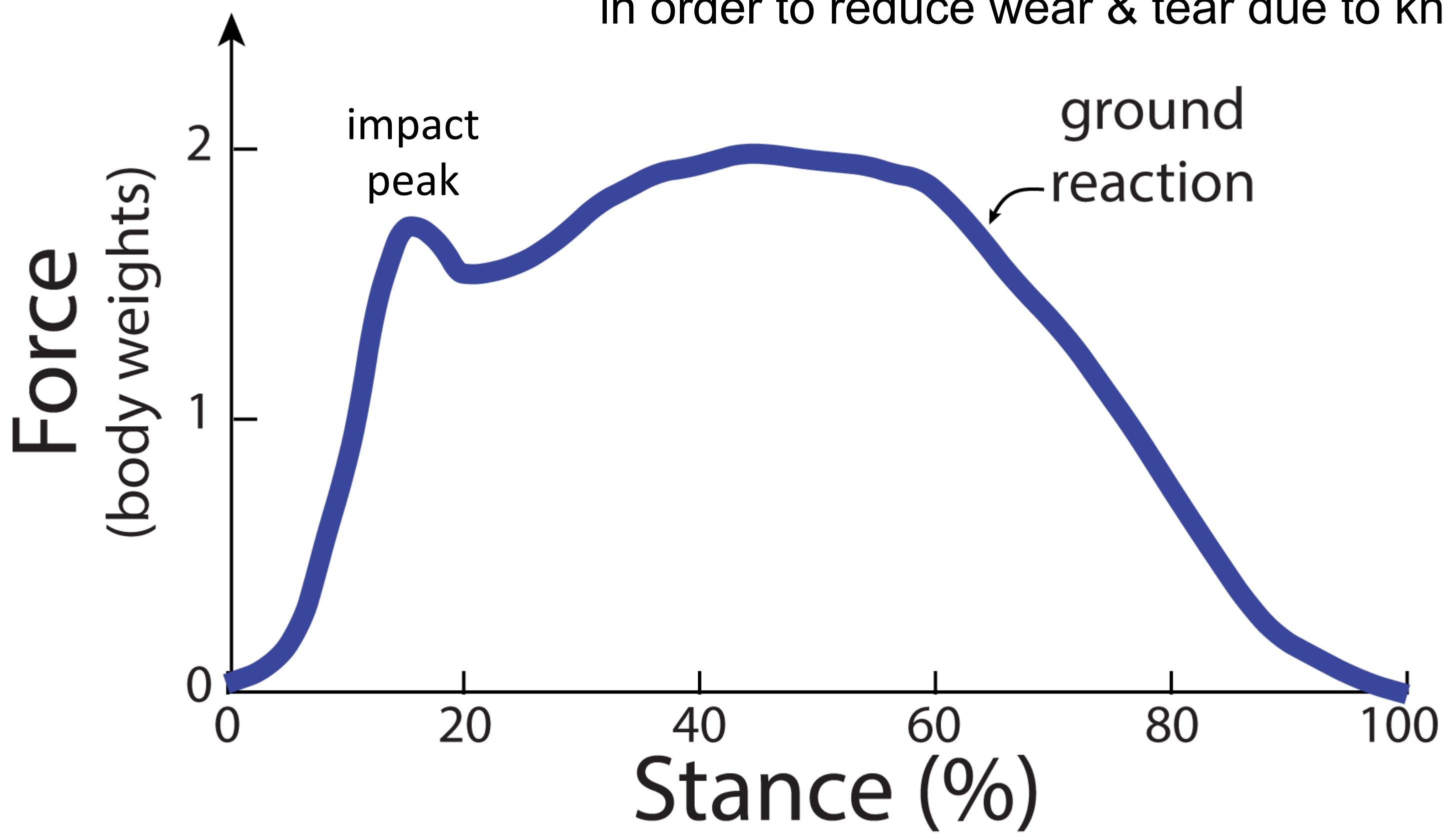
Running shoes: cushioned footwear vs. barefoot?



Results: Lieberman et al. 2010
Image: Popular Science

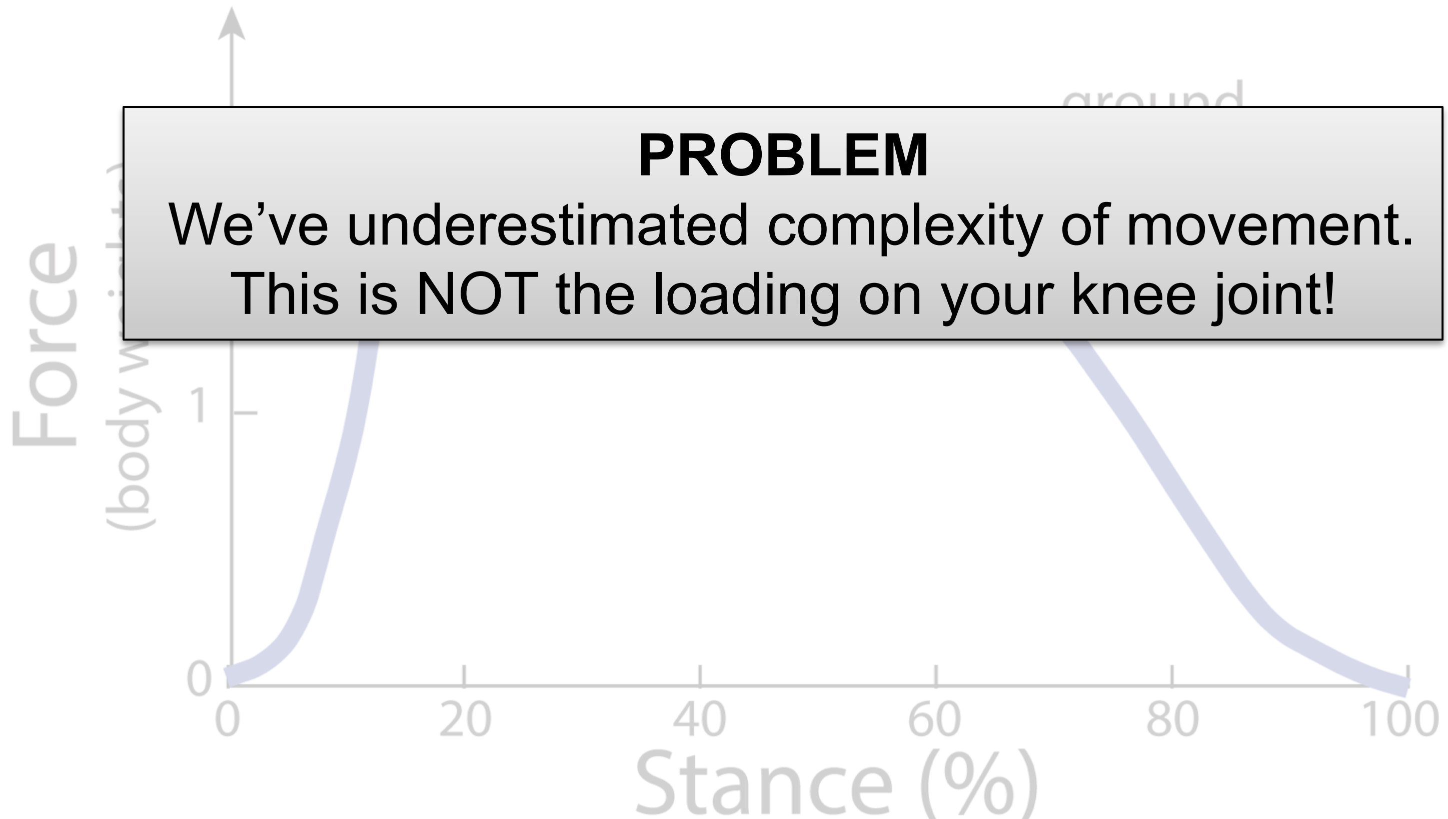
Reasonable thought process → try barefoot to reduce impacts

in order to reduce wear & tear due to knee loading



Scott & Winter 1990

Reasonable thought process → try barefoot to reduce impacts



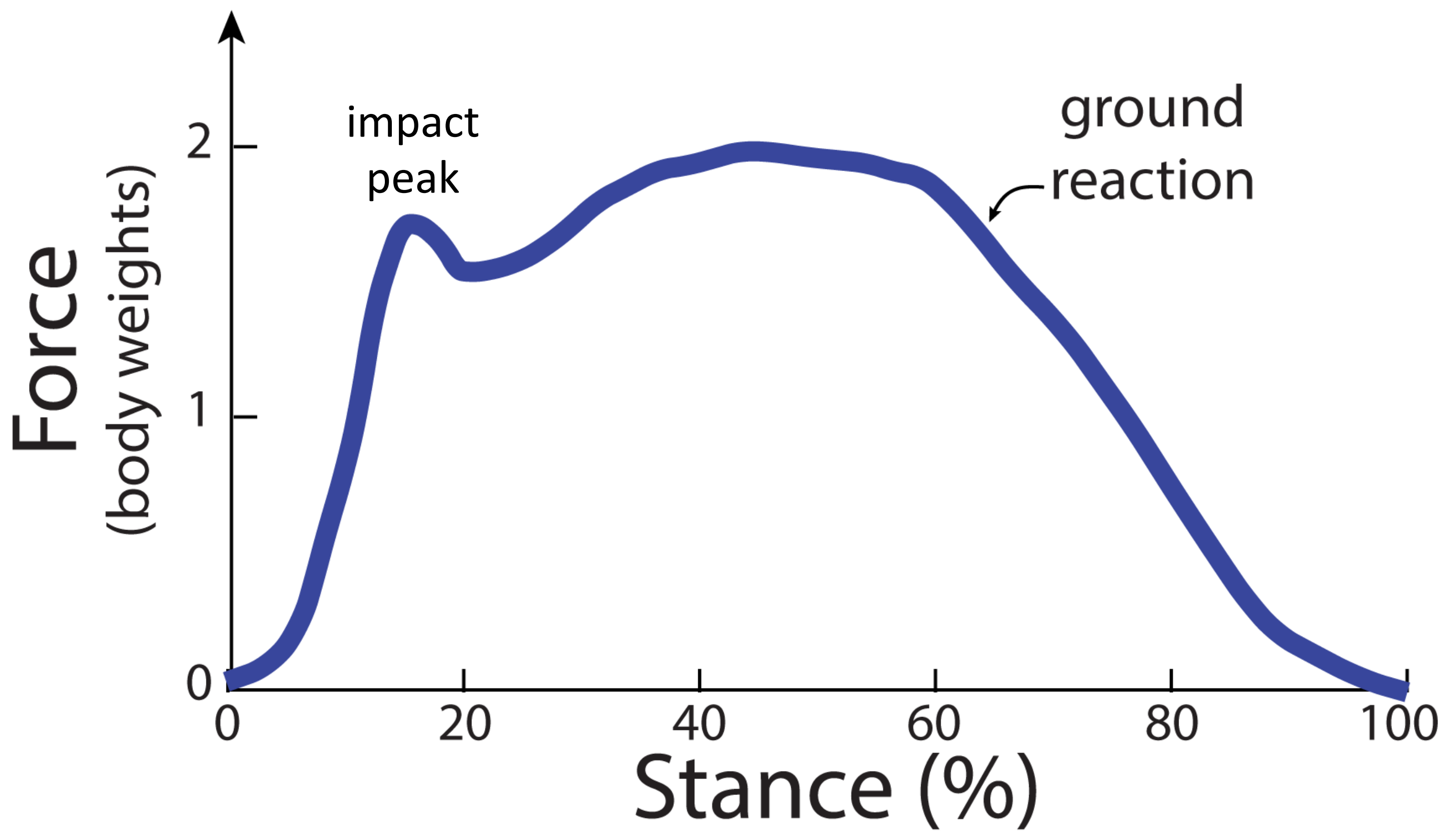
PROBLEM

We've underestimated complexity of movement.

This is NOT the loading on your knee joint!

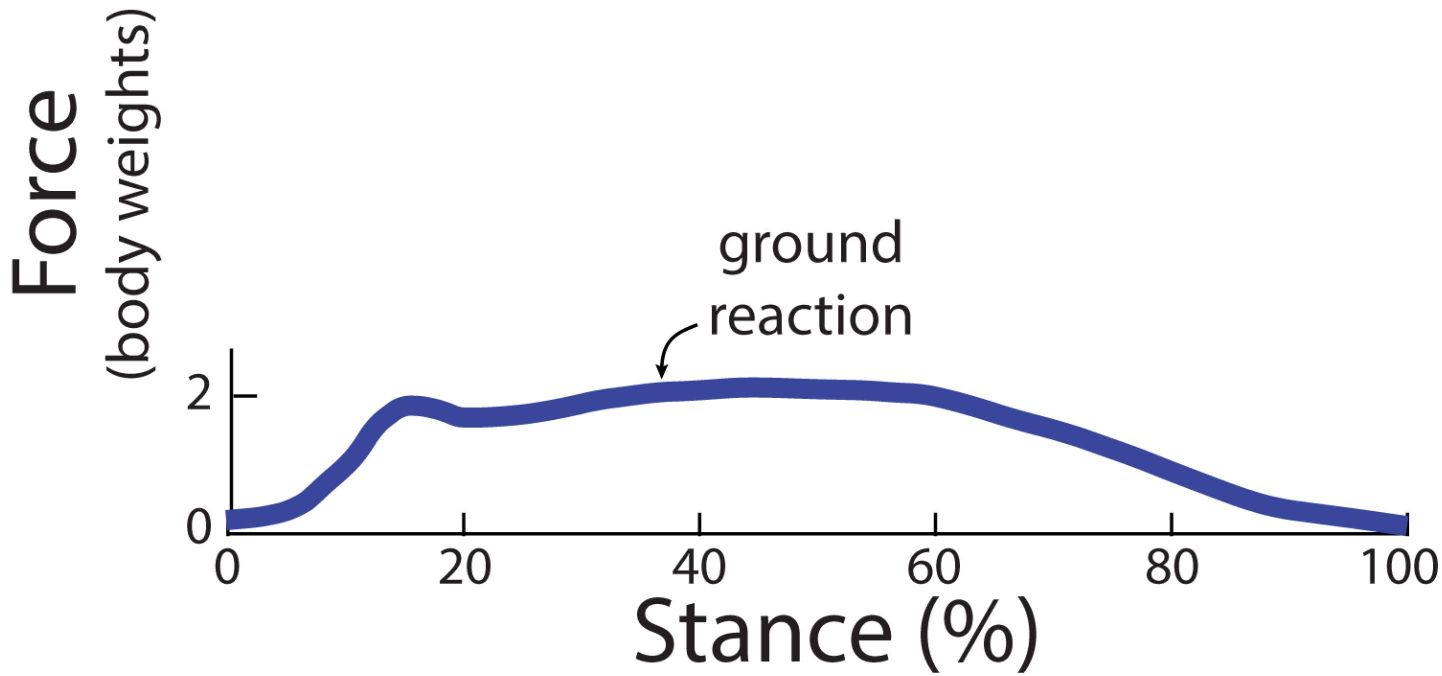
Scott & Winter 1990

How does knee force compare? Shifted left, right, up, down?



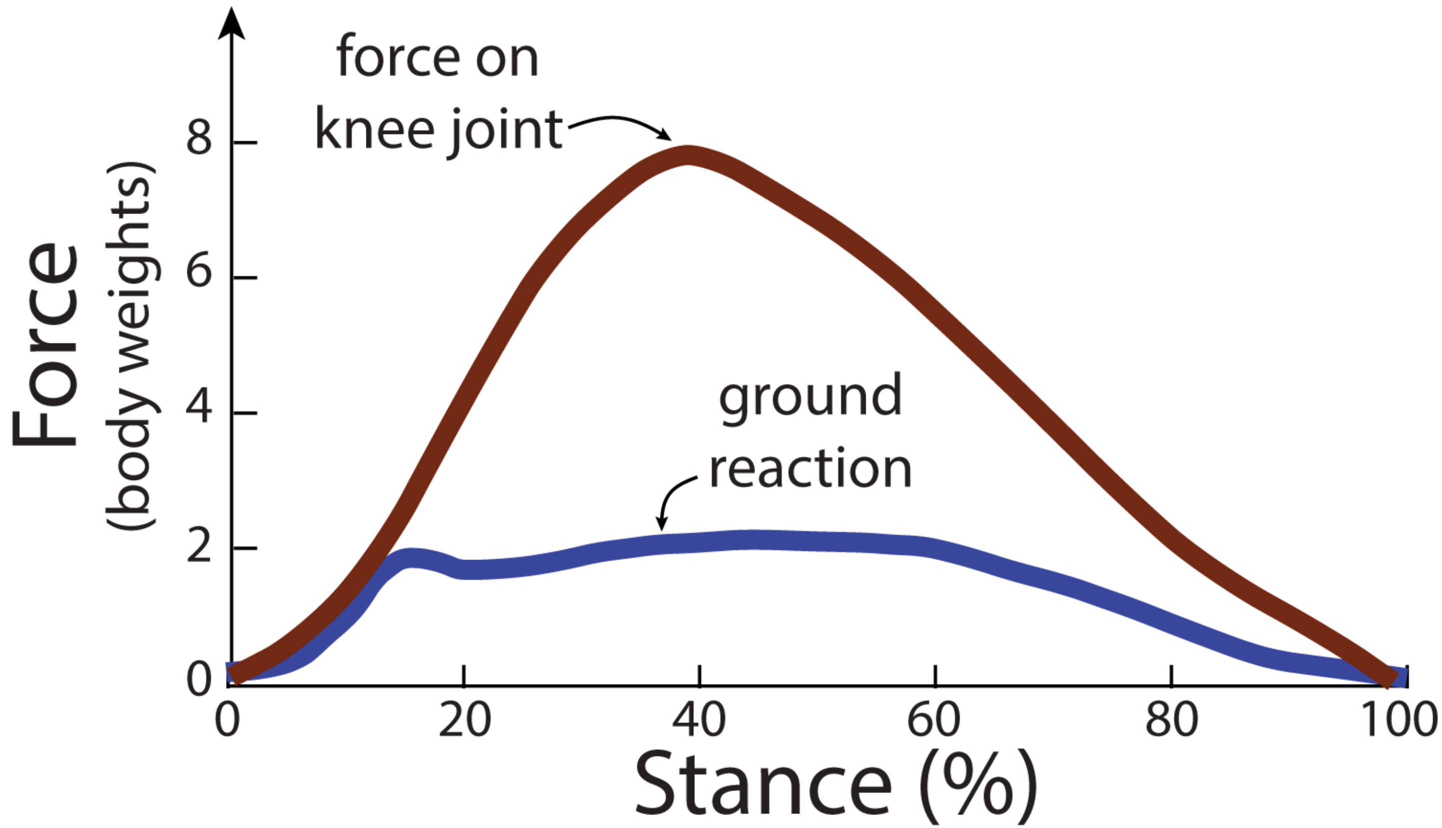
Scott & Winter 1990

Peak ground forces 2-3x BW vs. peak knee loading 6-14x BW



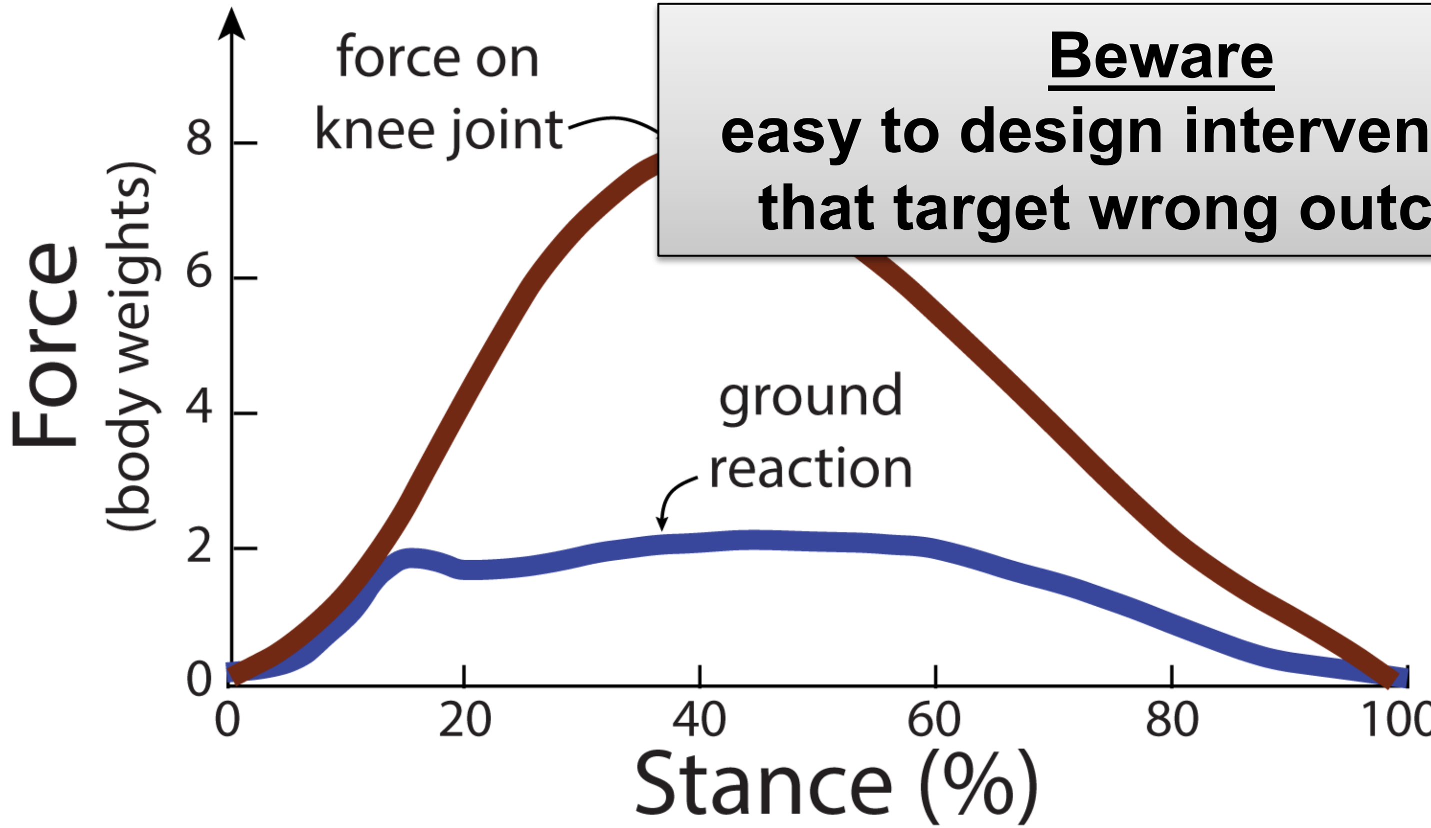
Scott & Winter 1990

Peak ground forces 2-3x BW vs. peak knee loading 6-14x BW



Scott & Winter 1990

Peak ground forces 2-3x BW vs. peak knee loading 6-14x BW

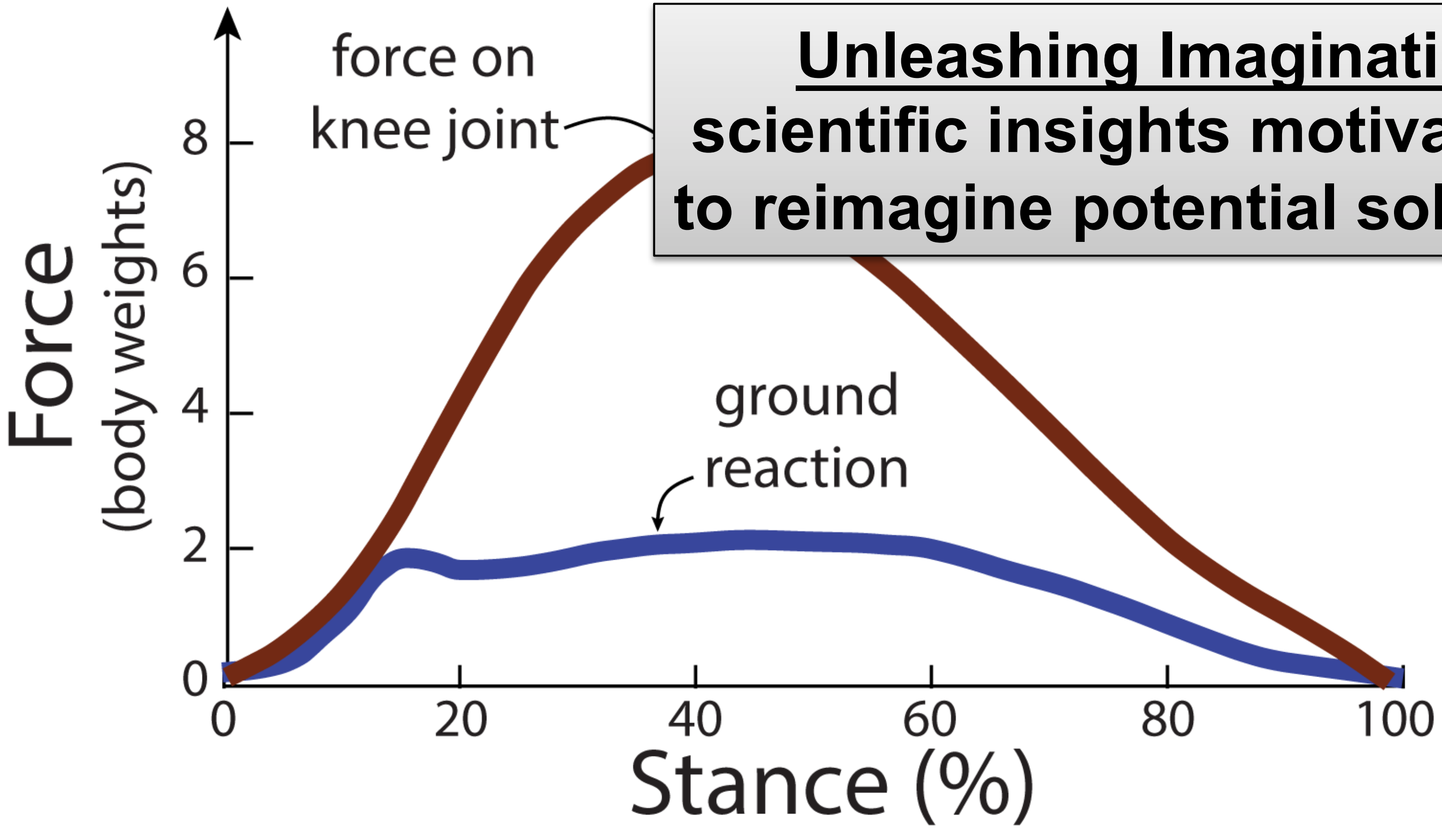


Beware

easy to design interventions that target wrong outcome

Scott & Winter 1990

Peak ground forces 2-3x BW vs. peak knee loading 6-14x BW



Unleashing Imagination

scientific insights motivate us to reimagine potential solutions

Scott & Winter 1990

Low back pain: leading cause of disability; >$200 billion/year

High and/or repetitive forces can increase risk of pain or injury

and increase rate of fatigue

Bernard 1997;
Coenen et al. 2014;
Griffith et al. 2012;
Adams & Hutton 1982

Back belts? Lack evidence of benefits after decades of testing

Studies repeatedly fail to find evidence that back belts reduce low back injury or pain

Steffens et al. 2016; NIOSH 2014; Dawson et al. 2007

Wearable robots are promising solutions for some jobs

Lots of individuals for whom wearable robots are impractical

or unaffordable, or undesirable

Most importantly me… where's my exo?!?

My Daily Routine

Life with small kids

Life with small kids

Life with small kids

Life with small kids & trying to be an adult

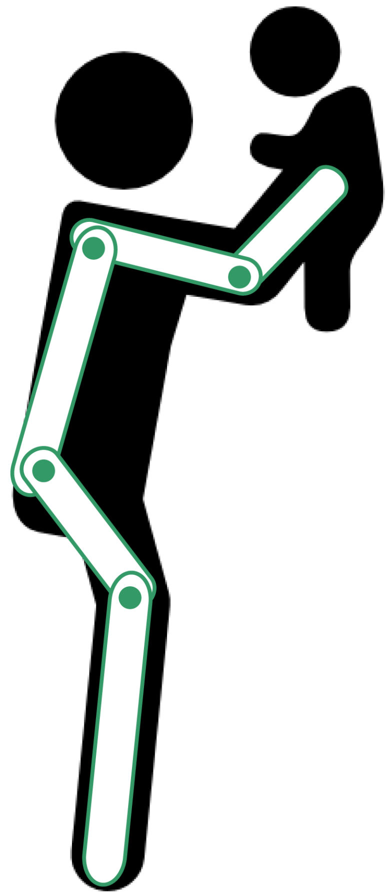
Life as a professor

Life as a professor

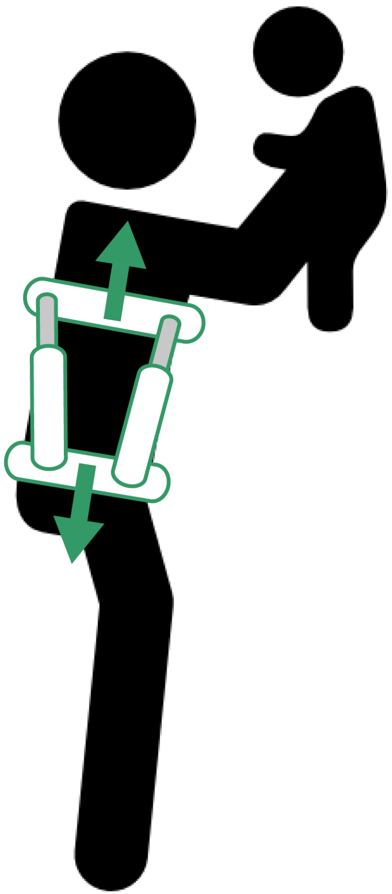
Designs that assist lifting/leaning & fit into my daily routine?

Potential Wearable Tech Solutions

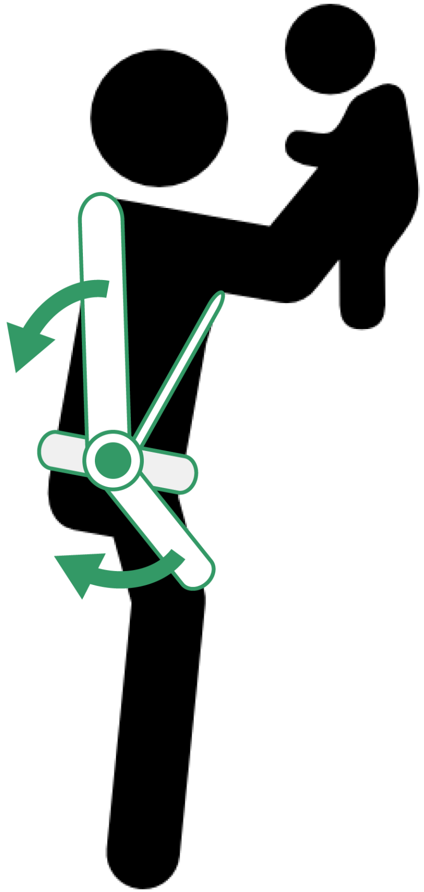
Concept 1: load path to ground



Concept 2: traction device



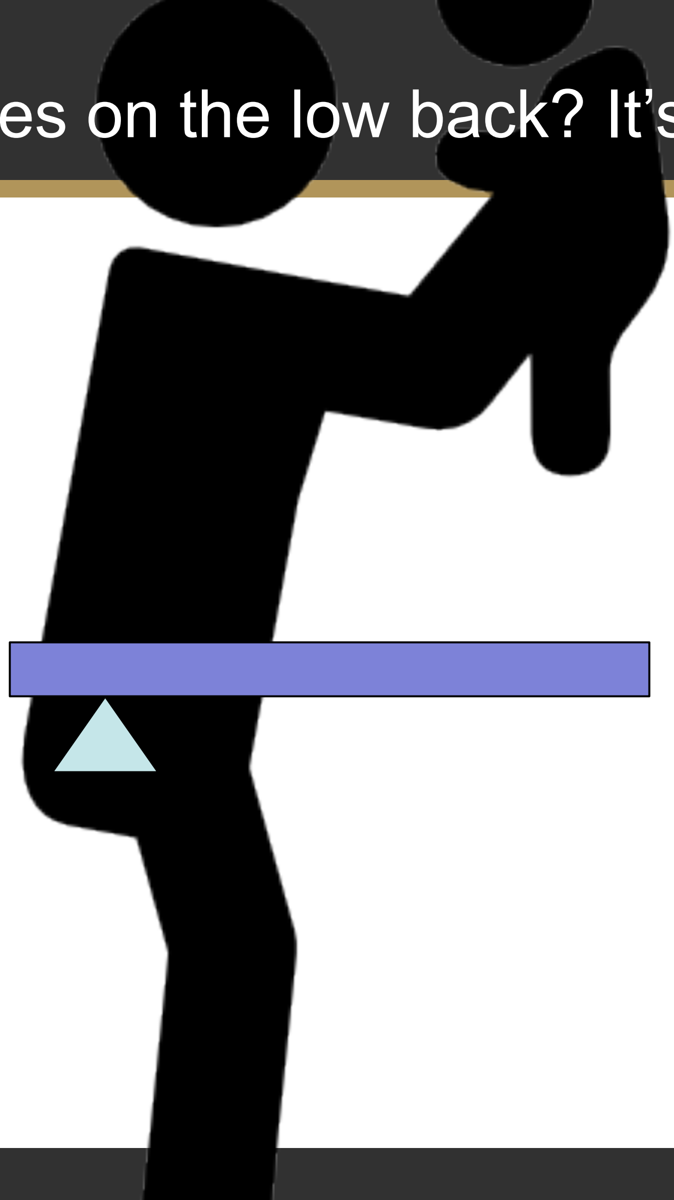
Concept 3: torsion/scissor mechanism

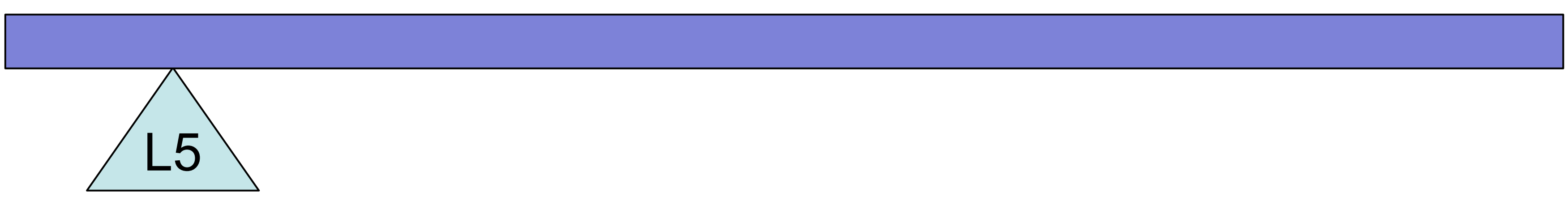


Not aware of any solutions (existing or theorized) that work for me

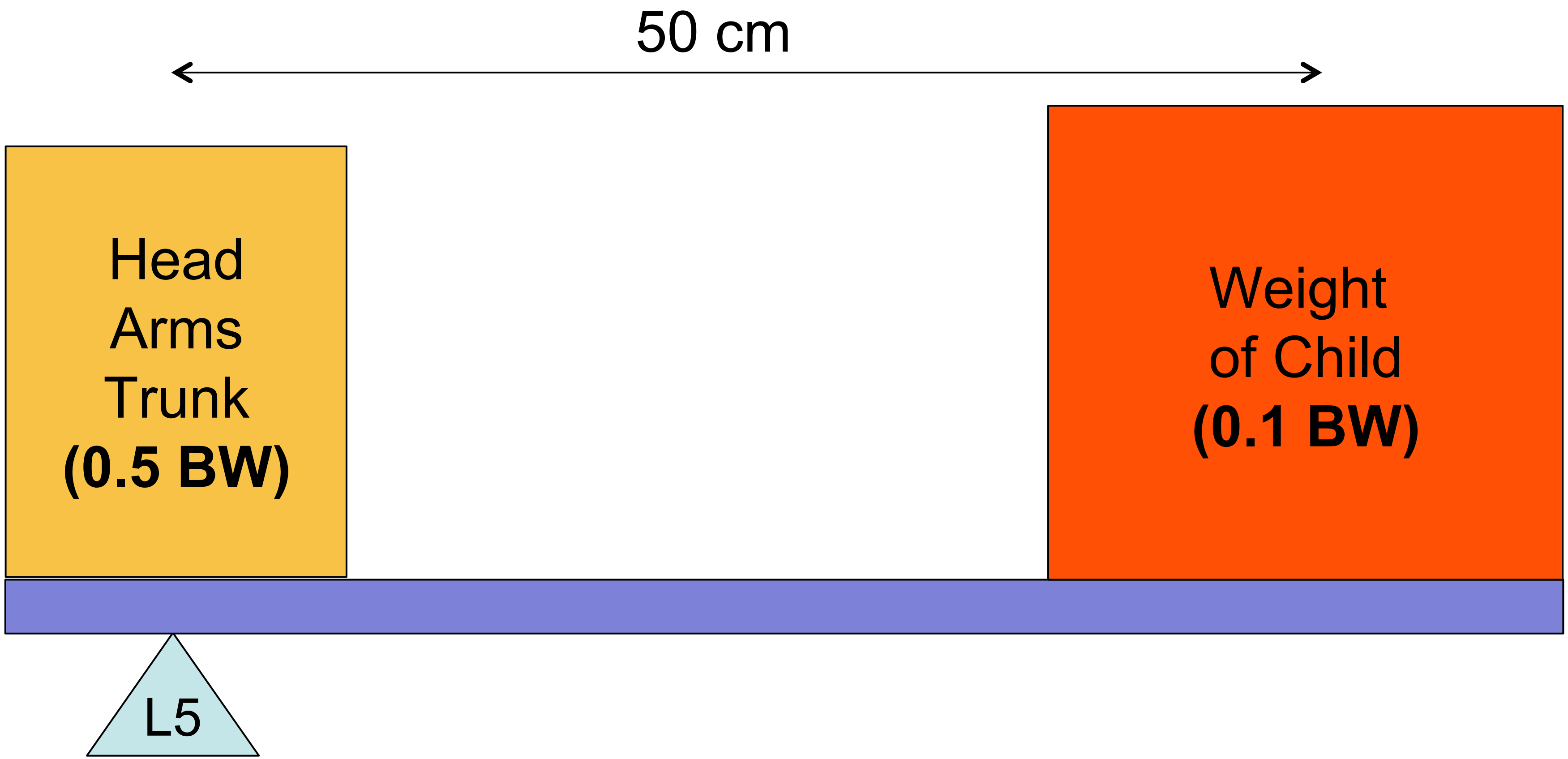
Stopped thinking about tech, started thinking about science

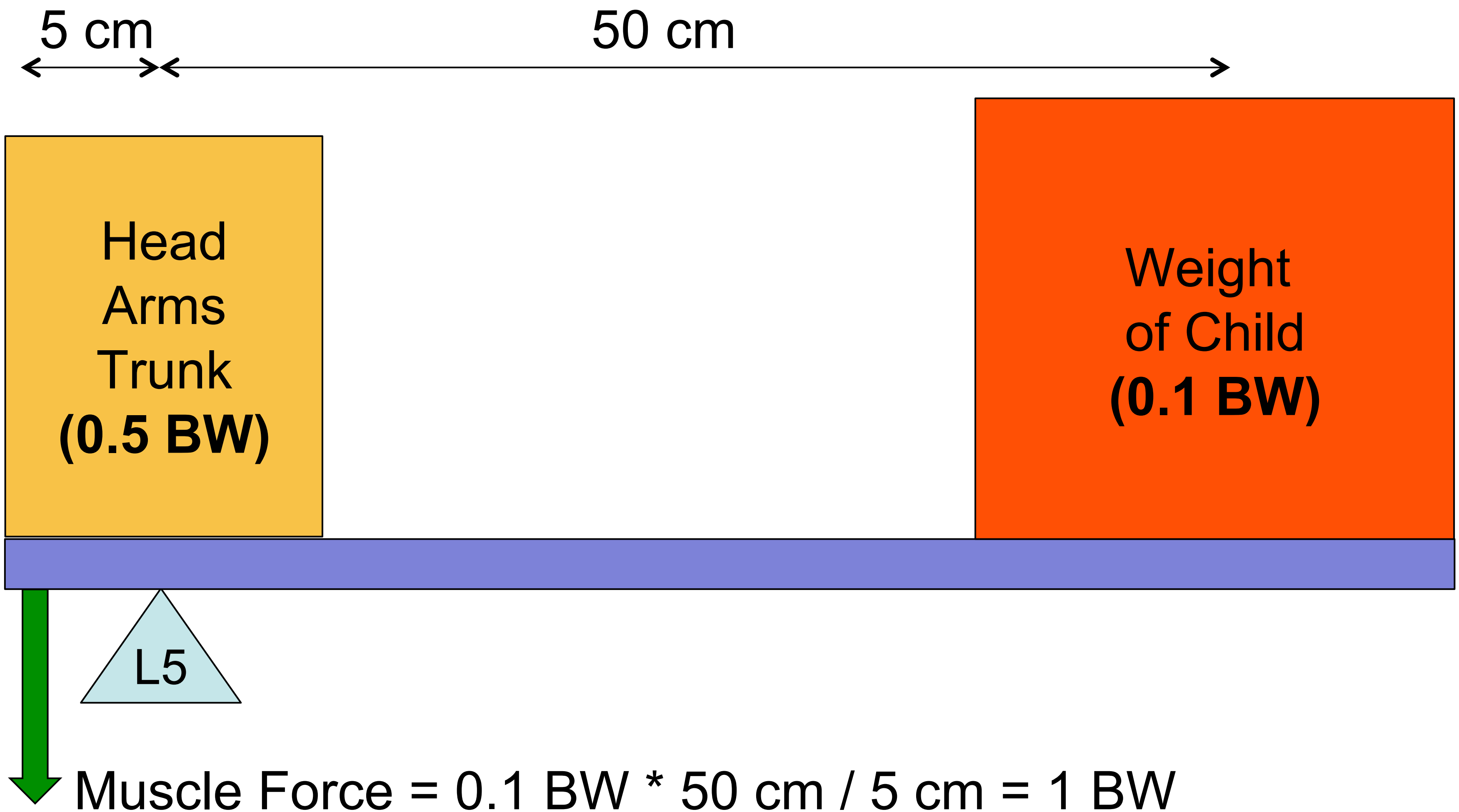
What causes high forces on the low back? It's all about levers!

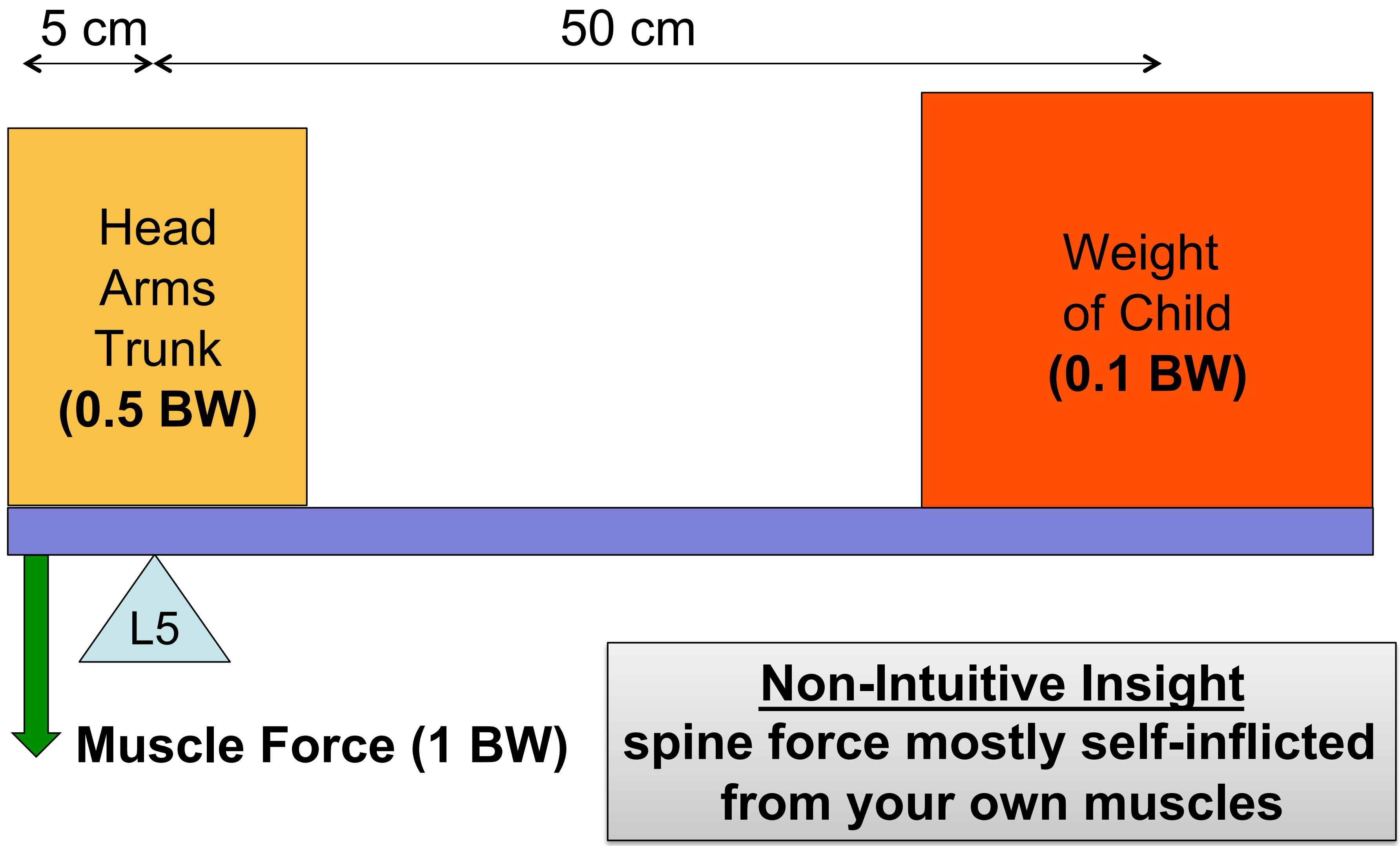



L5


Head
Arms
Trunk
(0.5 BW)
L5


50 cm
Head
Arms
Trunk
(0.5 BW)
Weight
of Child
(0.1 BW)
L5


5 cm
50 cm
Head
Arms
Trunk
(0.5 BW)
Weight
of Child
(0.1 BW)
L5
Muscle Force = 0.1 BW * 50 cm / 5 cm = 1 BW

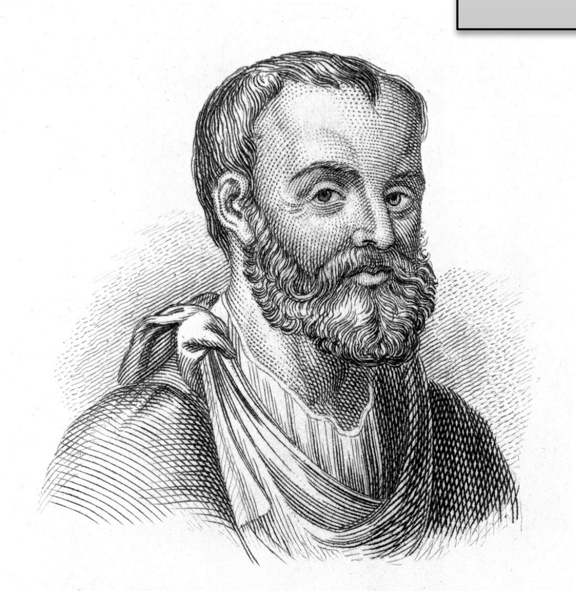

5 cm
50 cm
Head
Arms
Trunk
(0.5 BW)
Weight
of Child
(0.1 BW)
L5
Muscle Force (1 BW)
Non-Intuitive Insight
spine force mostly self-inflicted
from your own muscles

Non-Intuitive Insight

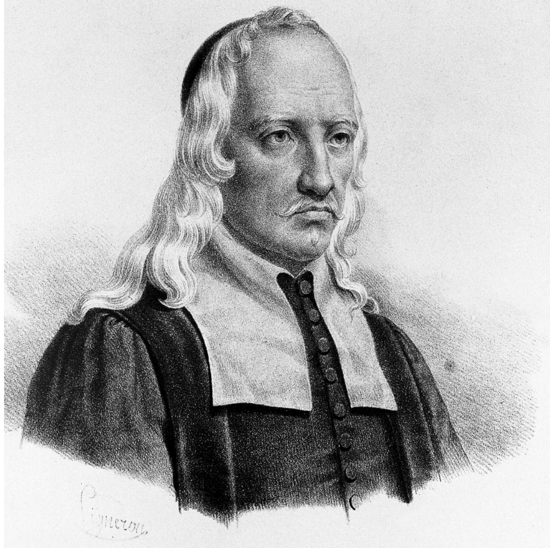
spine force mostly self-inflicted from your own muscles

Simple insight so non-intuitive that it took 1500 yrs to realize!

Non-Intuitive Insight
spine force mostly self-inflicted from your own muscles

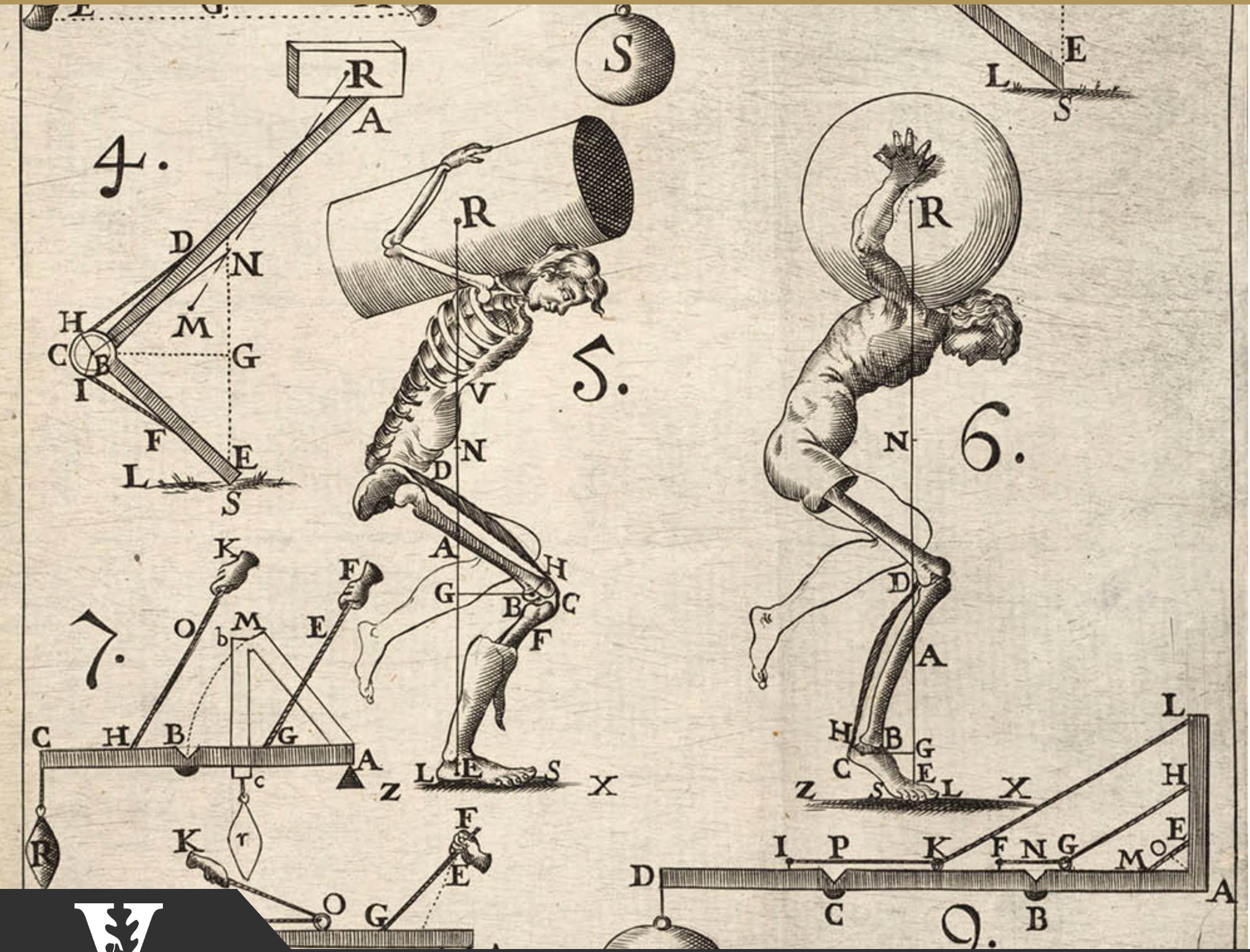


Galen (2nd Century)



Borelli (17th Century)

Simple insight so non-intuitive that it took 1500 yrs to realize!



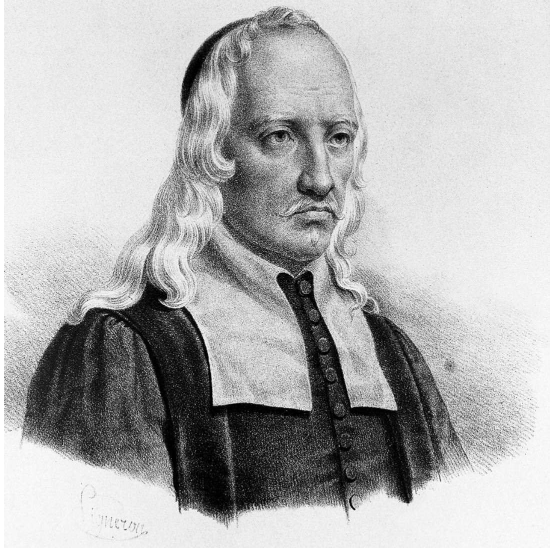
Borelli (17th Century)

Simple insight so non-intuitive that it took 1500 yrs to realize!

Galen (2nd Century)

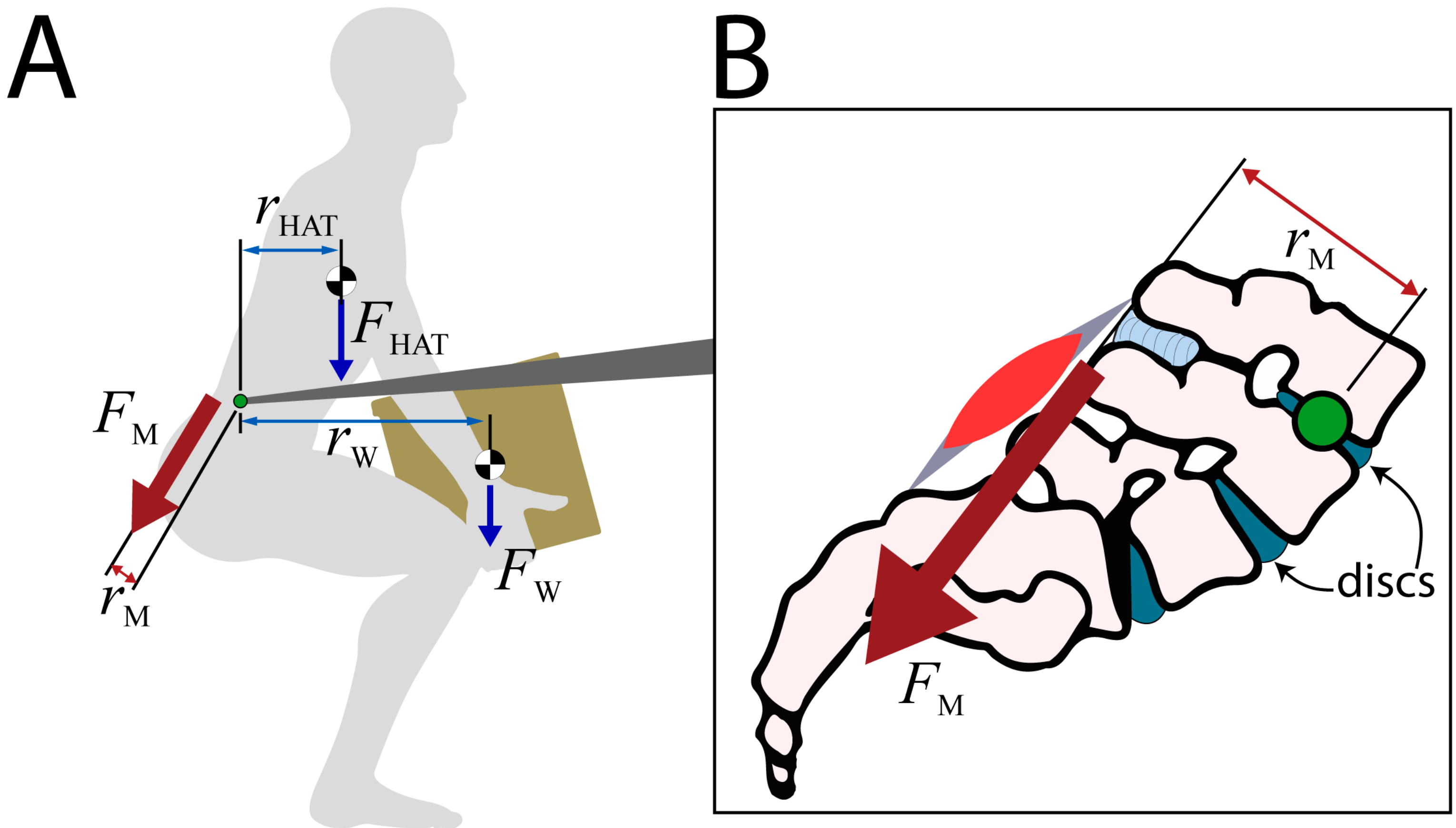
"Galen states that a tendon (muscle working on joint) is like a lever… This has been questioned by nobody. Who indeed would be stupid enough to look for a machine [human body] to move a very light weight with a great force …This seems strange and against commons sense, I agree, but I can convincingly demonstrate that this is what happens…"

- Giovanni Borelli

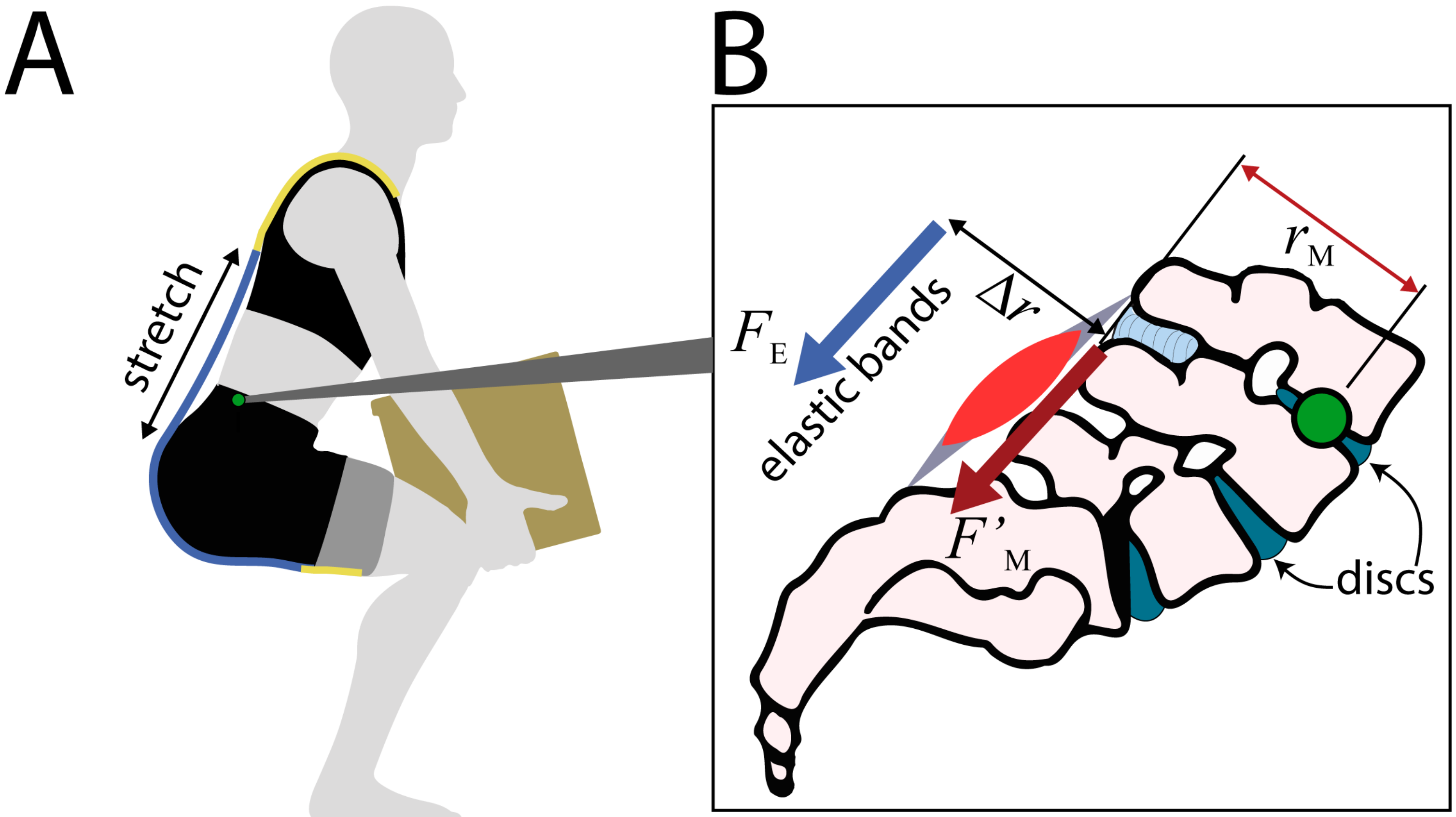


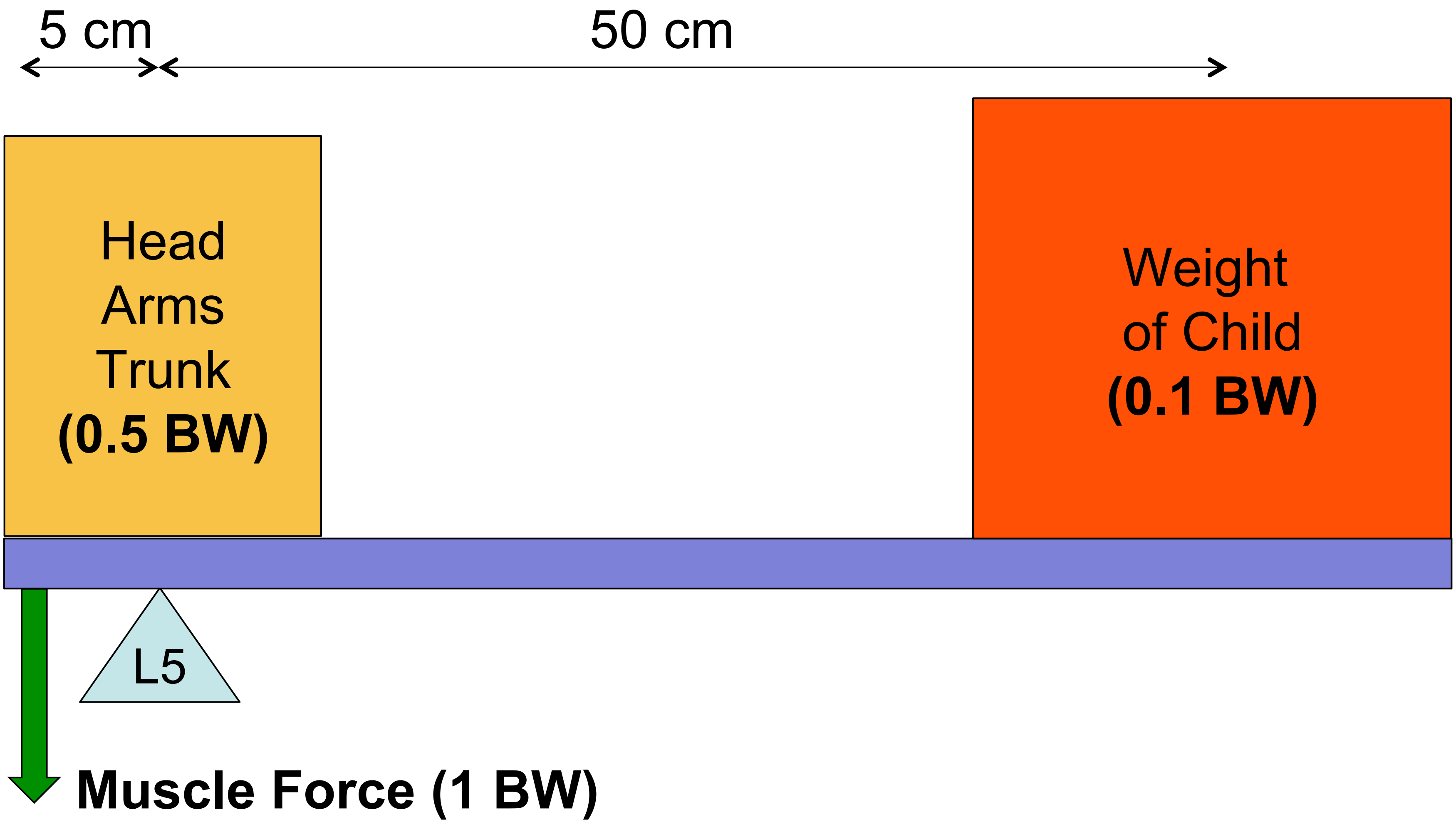
Borelli (17th Century)

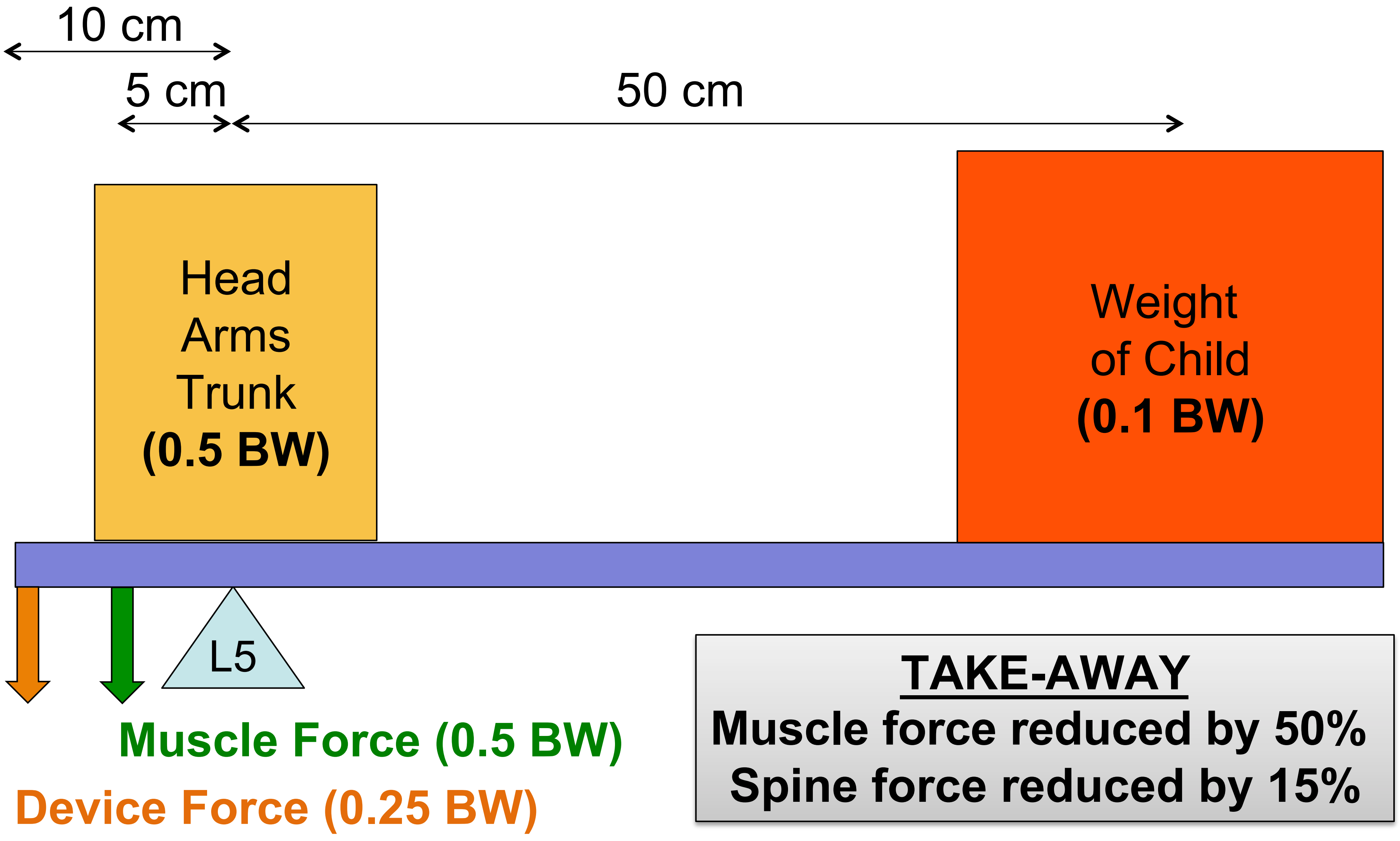
Spine forces are mostly self-inflicted! (from your own muscles)



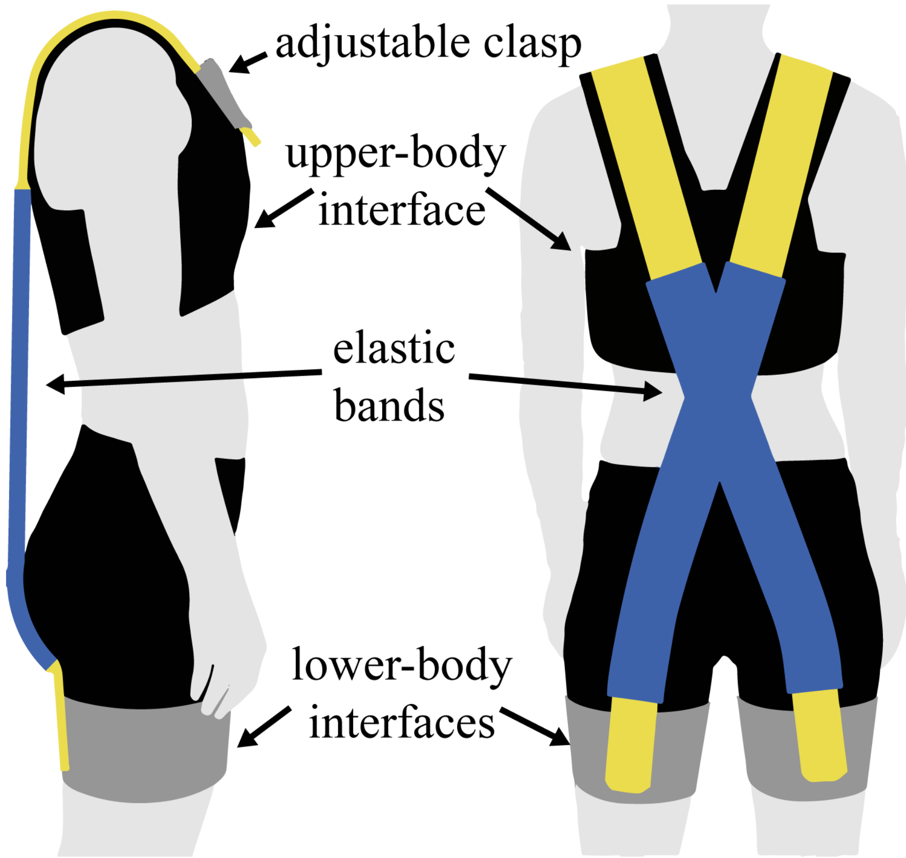
Embed spring-like structures into clothing to offload low back




5 cm
50 cm
Head
Arms
Trunk
(0.5 BW)
Weight
of Child
(0.1 BW)
L5
Muscle Force (1 BW)

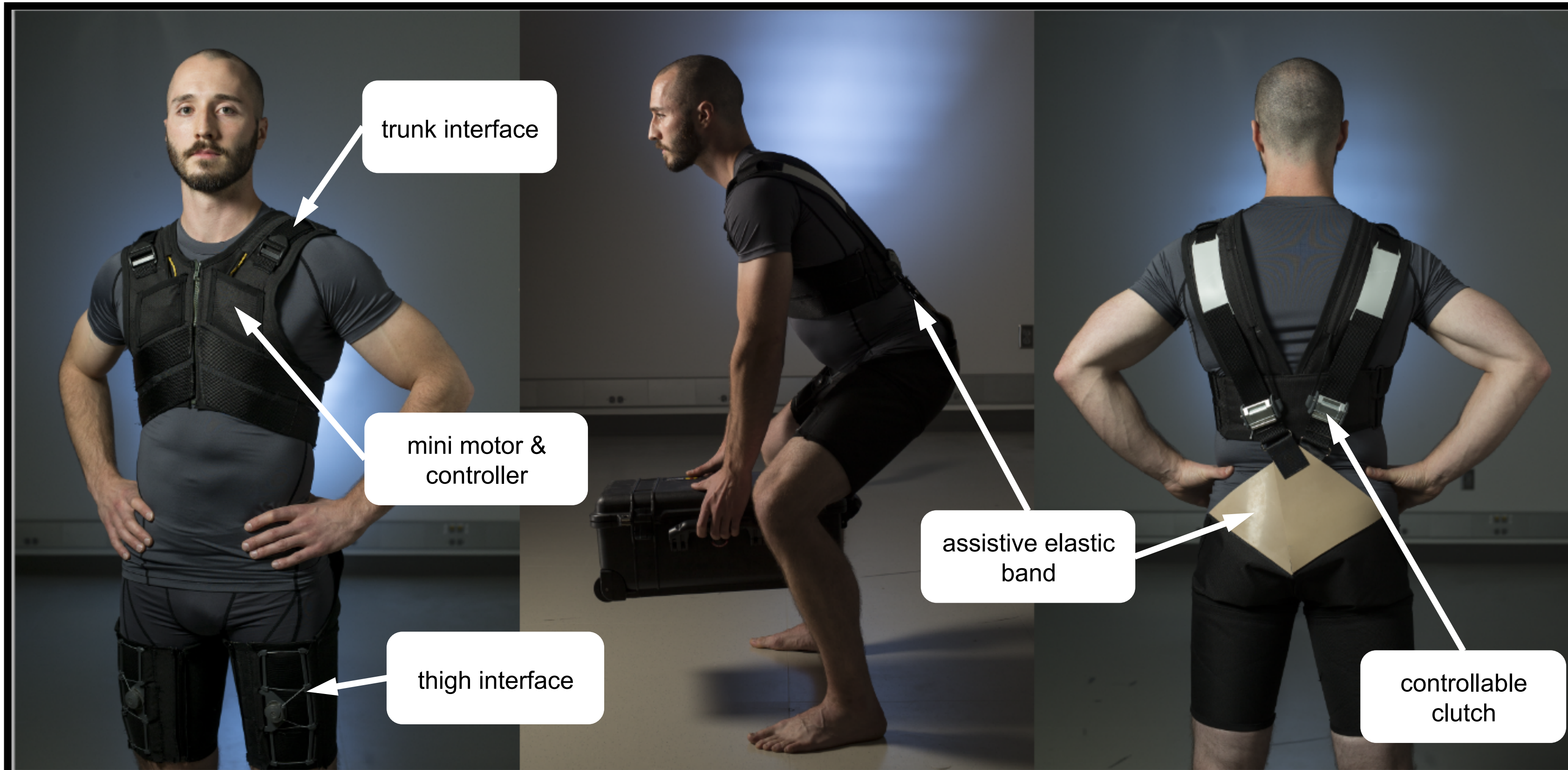

10 cm
5 cm
50 cm
Head
Arms
Trunk
(0.5 BW)
Weight
of Child
(0.1 BW)
L5
Muscle Force (0.5 BW)
Device Force (0.25 BW)
TAKE-AWAY
Muscle force reduced by 50%
Spine force reduced by 15%

Biomechanically-assistive clothing (passive device)



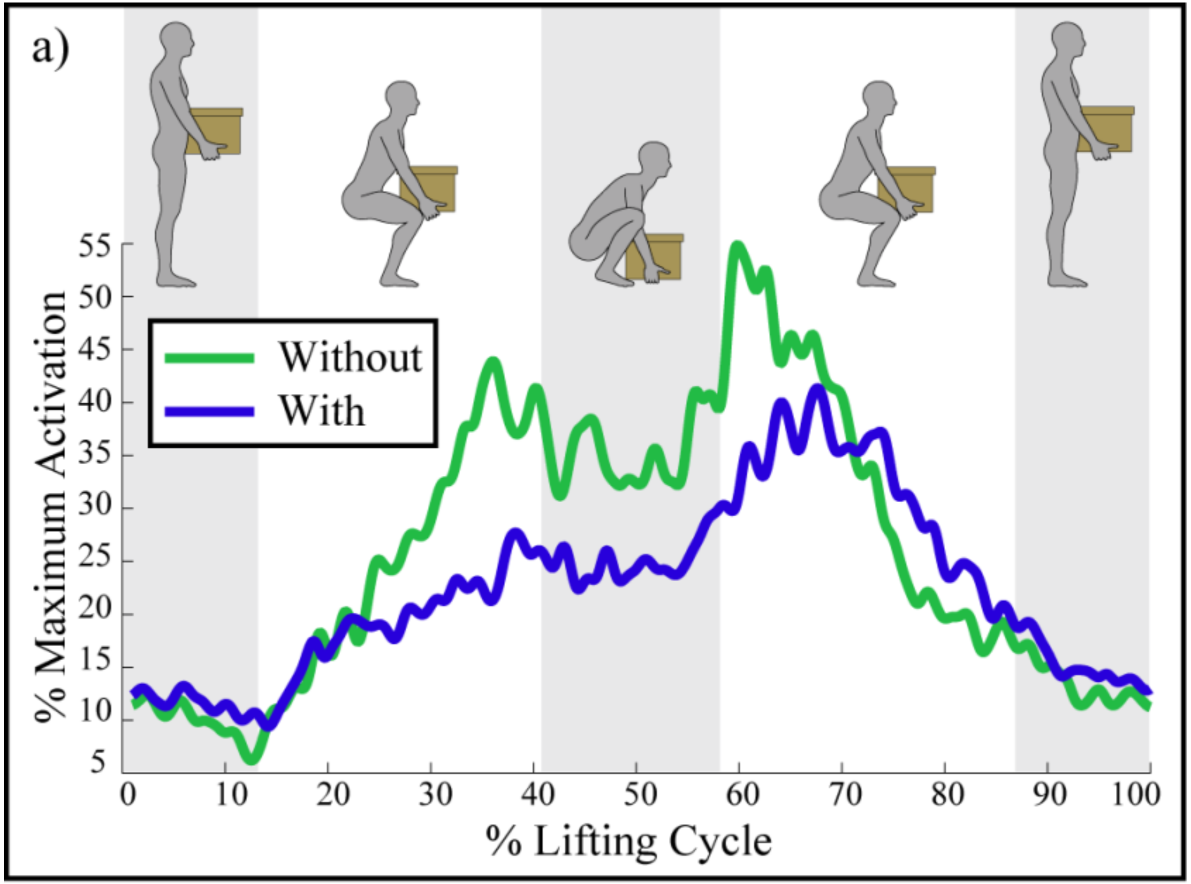
Lamers, Yang & Zelik 2017

Smart underwear (quasi-passive clothing-like device)

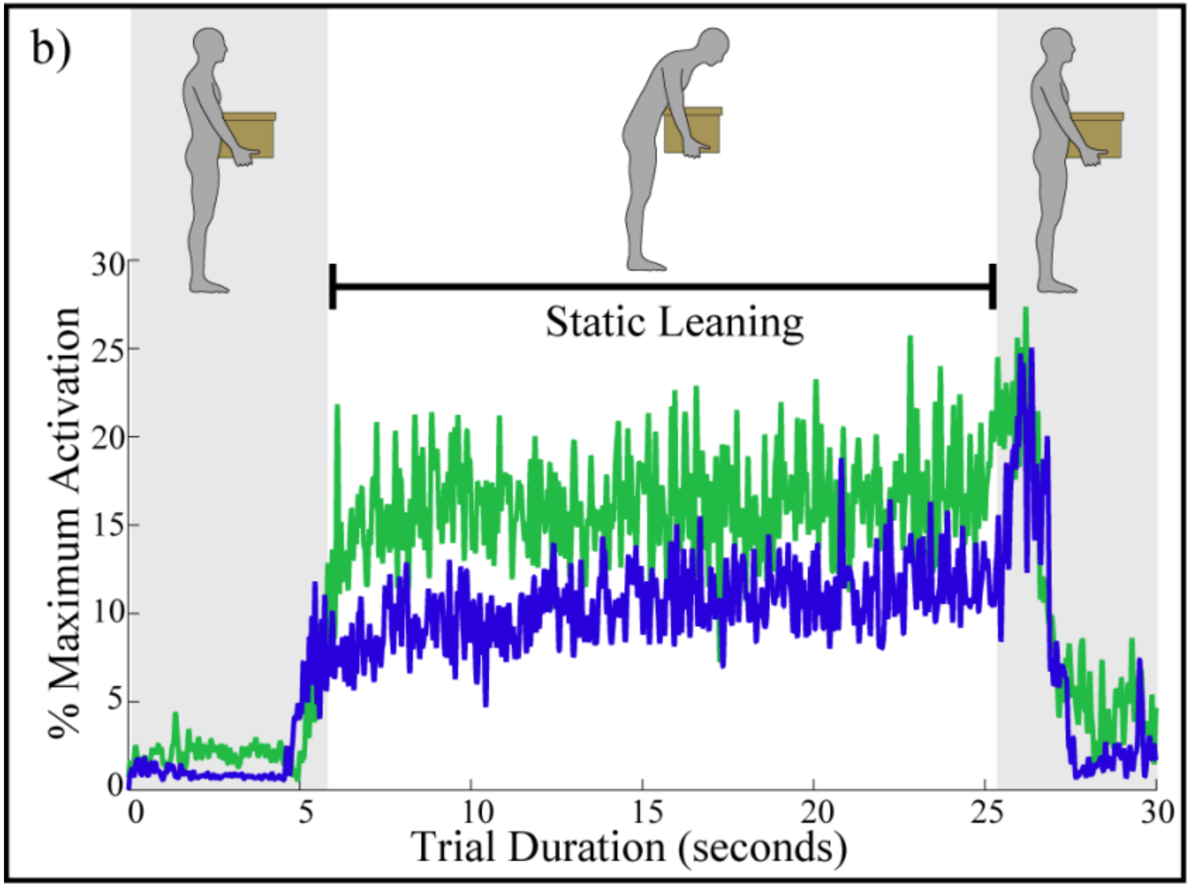


Lamers, Yang & Zelik 2017

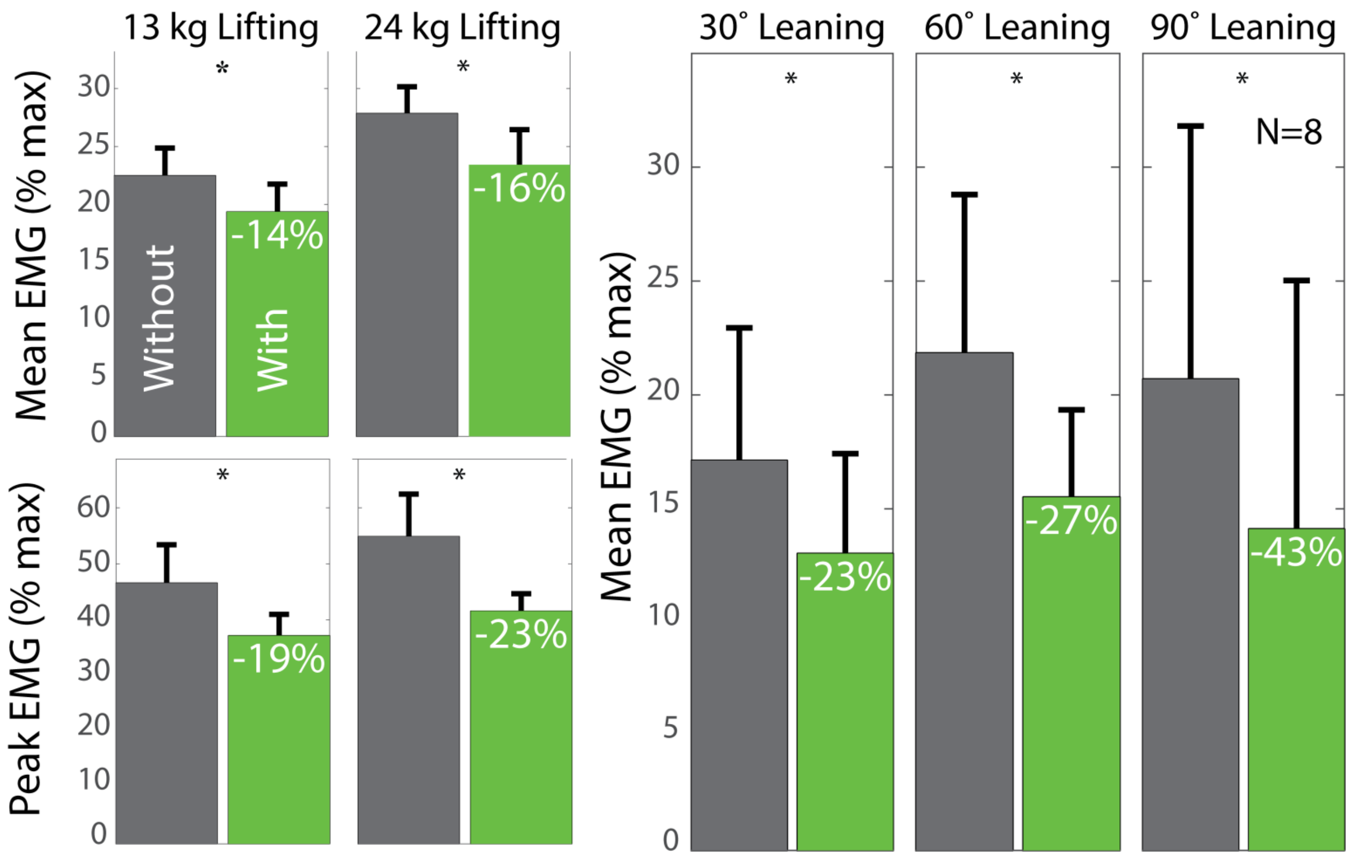
Reduced low back EMG (indicator of muscle force) during lifting



Reduced low back EMG (indicator of muscle force) when leaning



14-43% reductions in low back muscle activity (N=8)



Device can offload my back, fit under my clothes, into my life!

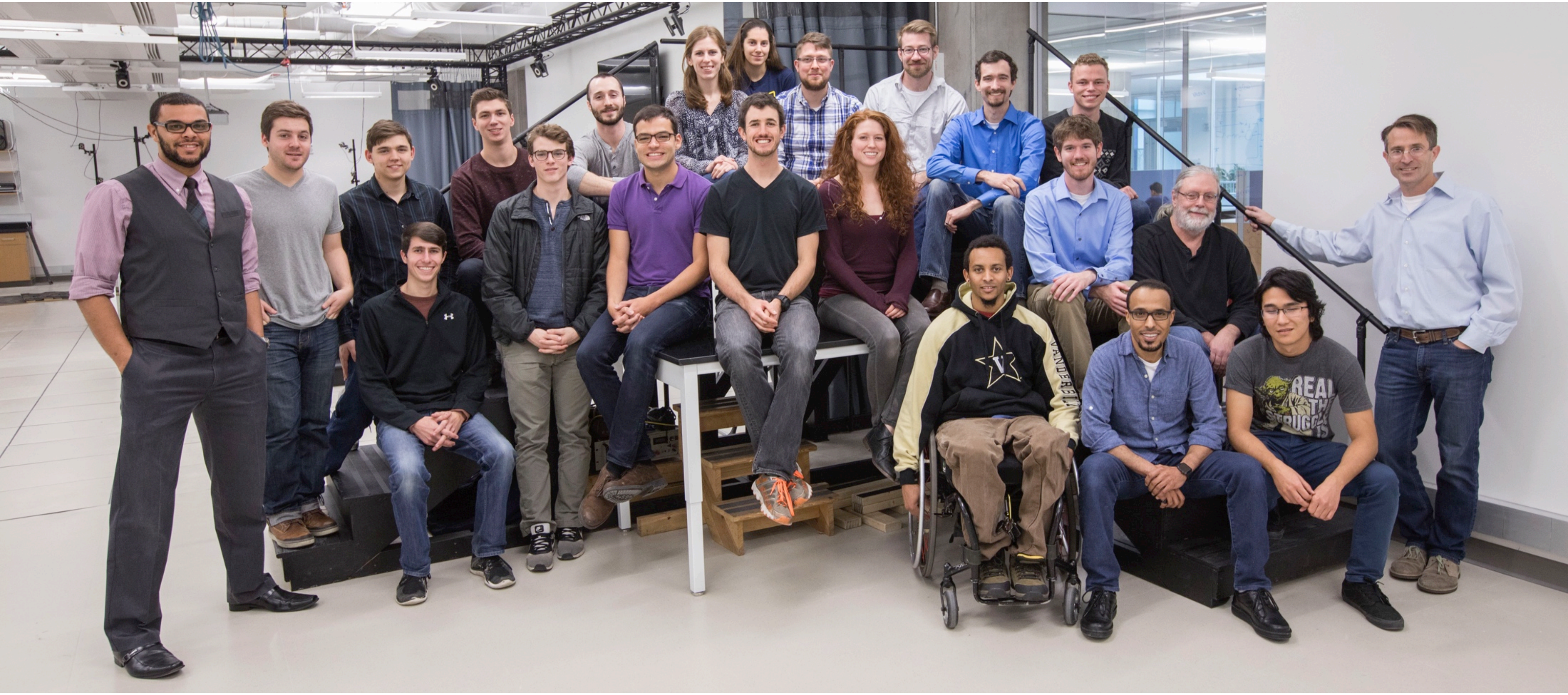
Started project selfishly… later realized broad applications

new markets & new potential end-users

CREaTe

Acknowledgements

Students, post-docs, faculty, staff, collaborators & funding sources



Funding Sources: NSF, NIH, NIDILRR, SEC, Vanderbilt, Industry

From biomechanics to new assistive tech

1. You & I are not that smart (relative to complexity of movement)
2. Mechanisms underlying movement are often unexpected & non-intuitive
3. Non-intuitive mechanisms are key to innovative new assistive tech & broadening societal impact