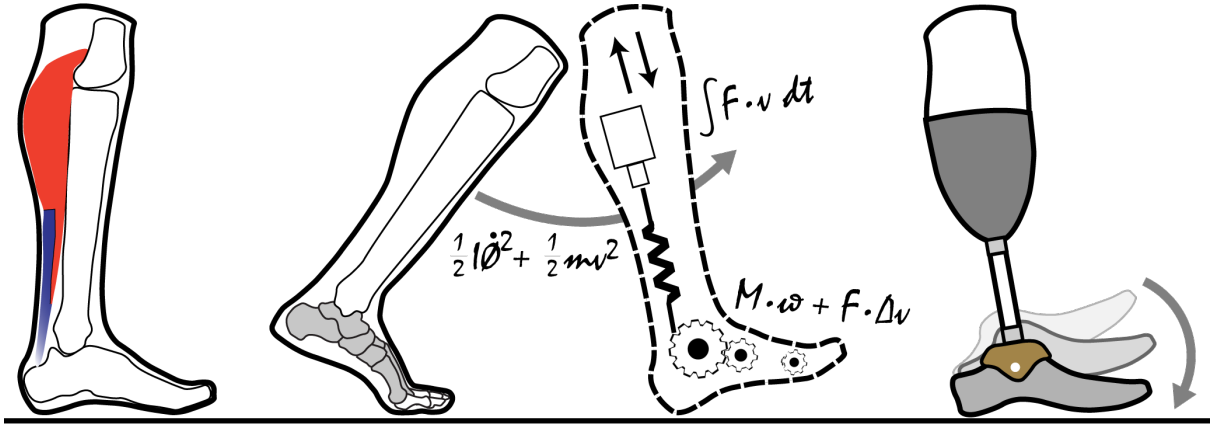
CENTER FOR
REHABILITATION ENGINEERING
+ ASSISTIVE TECHNOLOGY



Biomechanics to bionics:

how scientific insights can unleash our imagination, inspire new tech & broaden use of wearable robots

Prof. Karl Zelik

VANDERBILT®
SCHOOL OF ENGINEERING

You're not that smart*

relative to complexity of movement

*neither am I

Takeaway 2

Mechanisms underlying movement are often unexpected & non-intuitive

Takeaway 3

Non-intuitive mechanisms are key to wearable robot world domination

Pittsburgh

Washington University in St. Louis

biomedical engineering

St. Louis

Los Angeles

implantable cardiac devices

biomechanics
& prosthetics

Ann Arbor

UNIVERSITY OF MICHIGAN

Rome

FONDAZIONE SANTA LUCIA

SCIENTIFIC INSTITUTE FOR RESEARCH, HOSPITALIZATION AND HEALTH CARE

Nationally renowned hospital for neuromotor rehabilitation

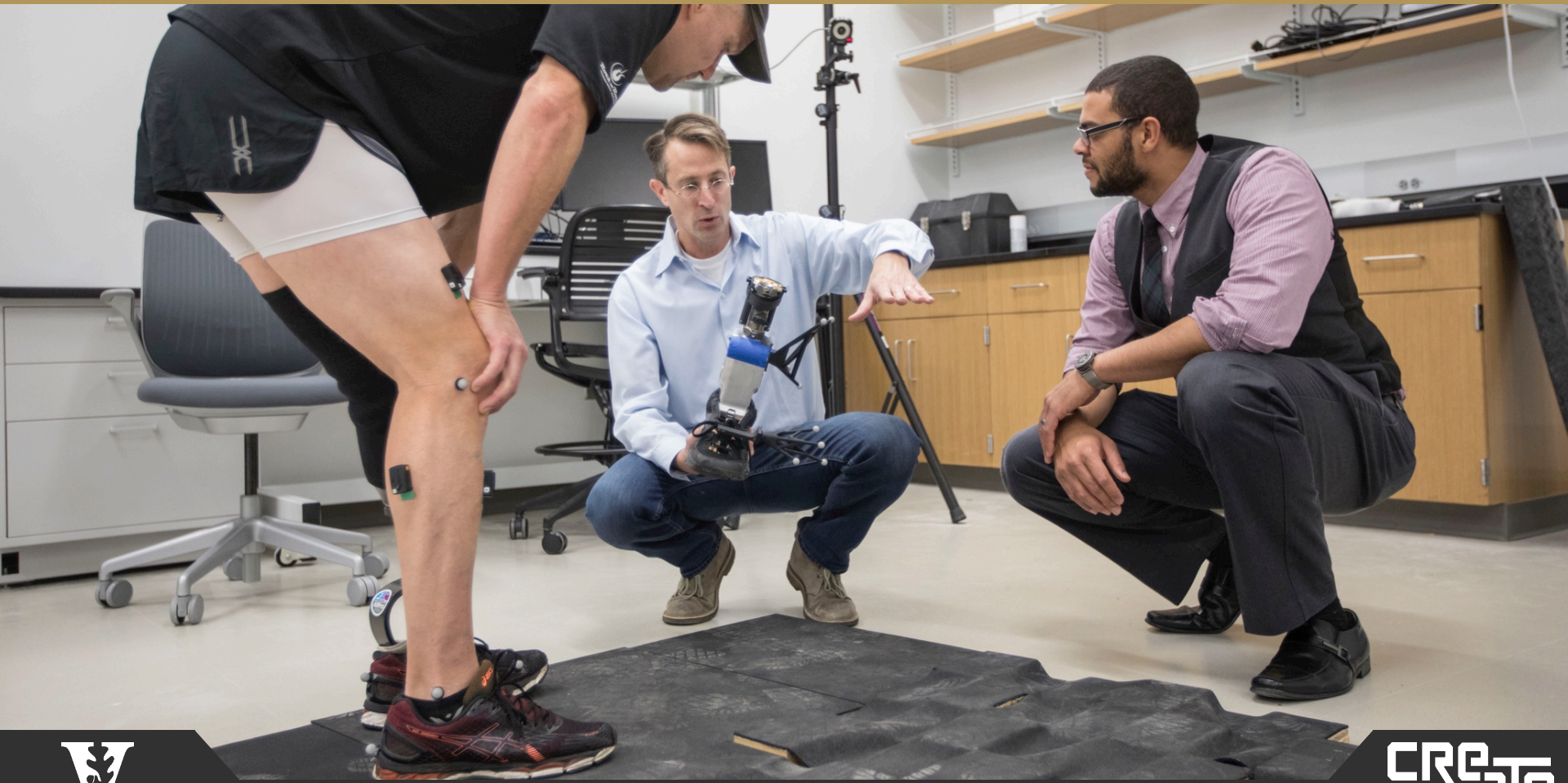
neuromotor control

CREATE

Nashville

CENTER FOR

REHABILITATION ENGINEERING + ASSISTIVE TECHNOLOGY

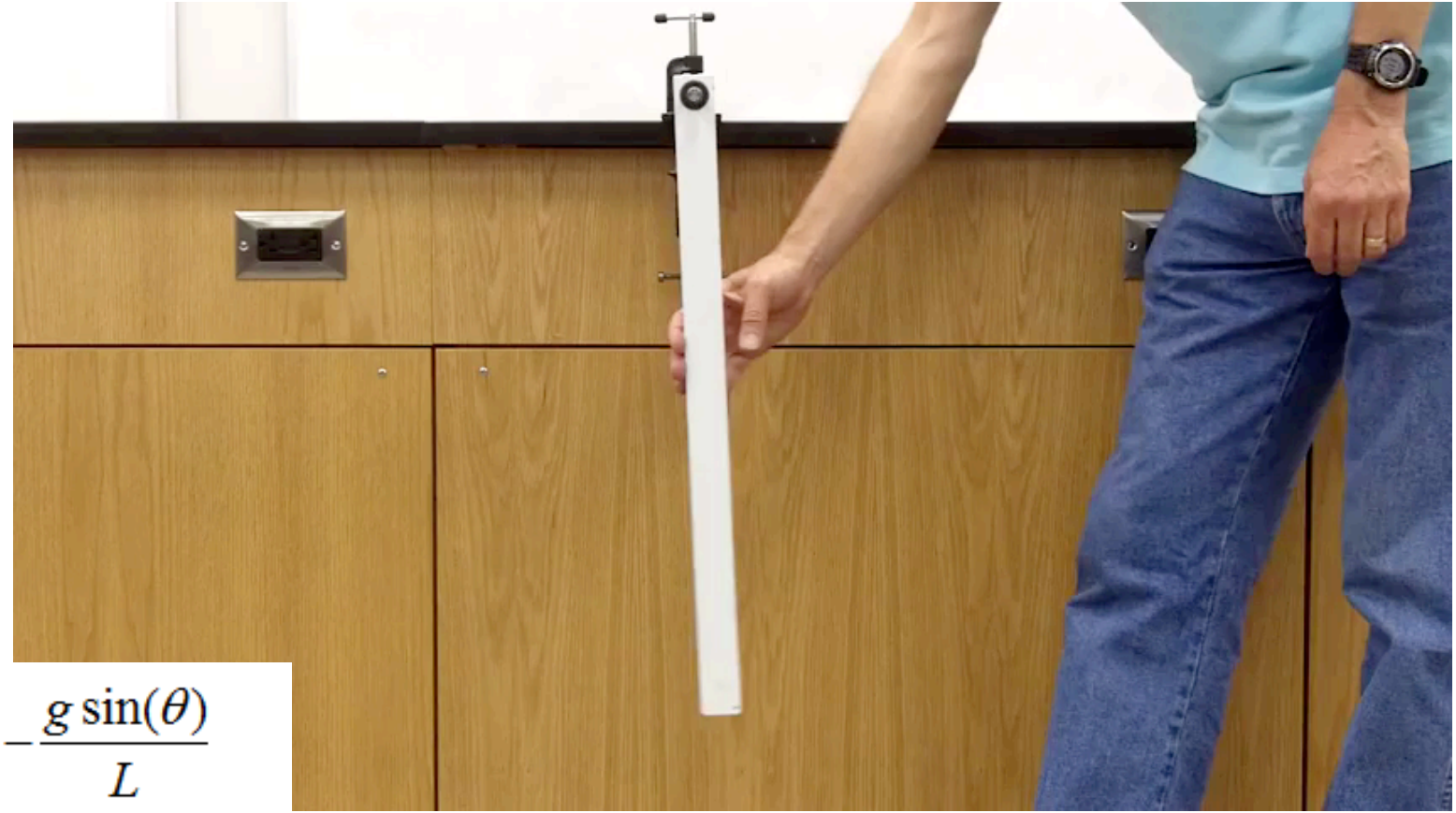


Takeaway 1

You & I are not that smart

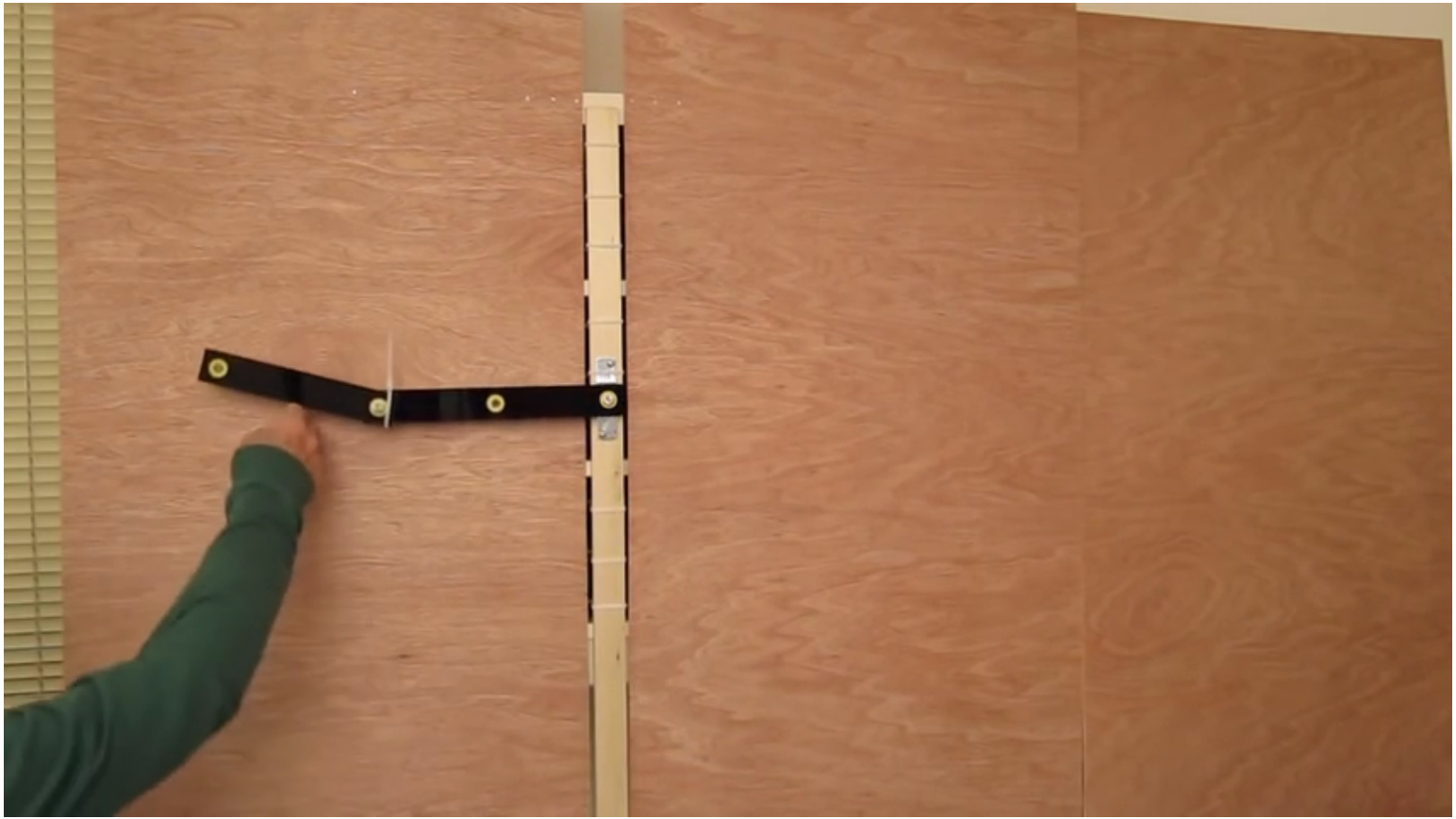
relative to complexity of movement

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

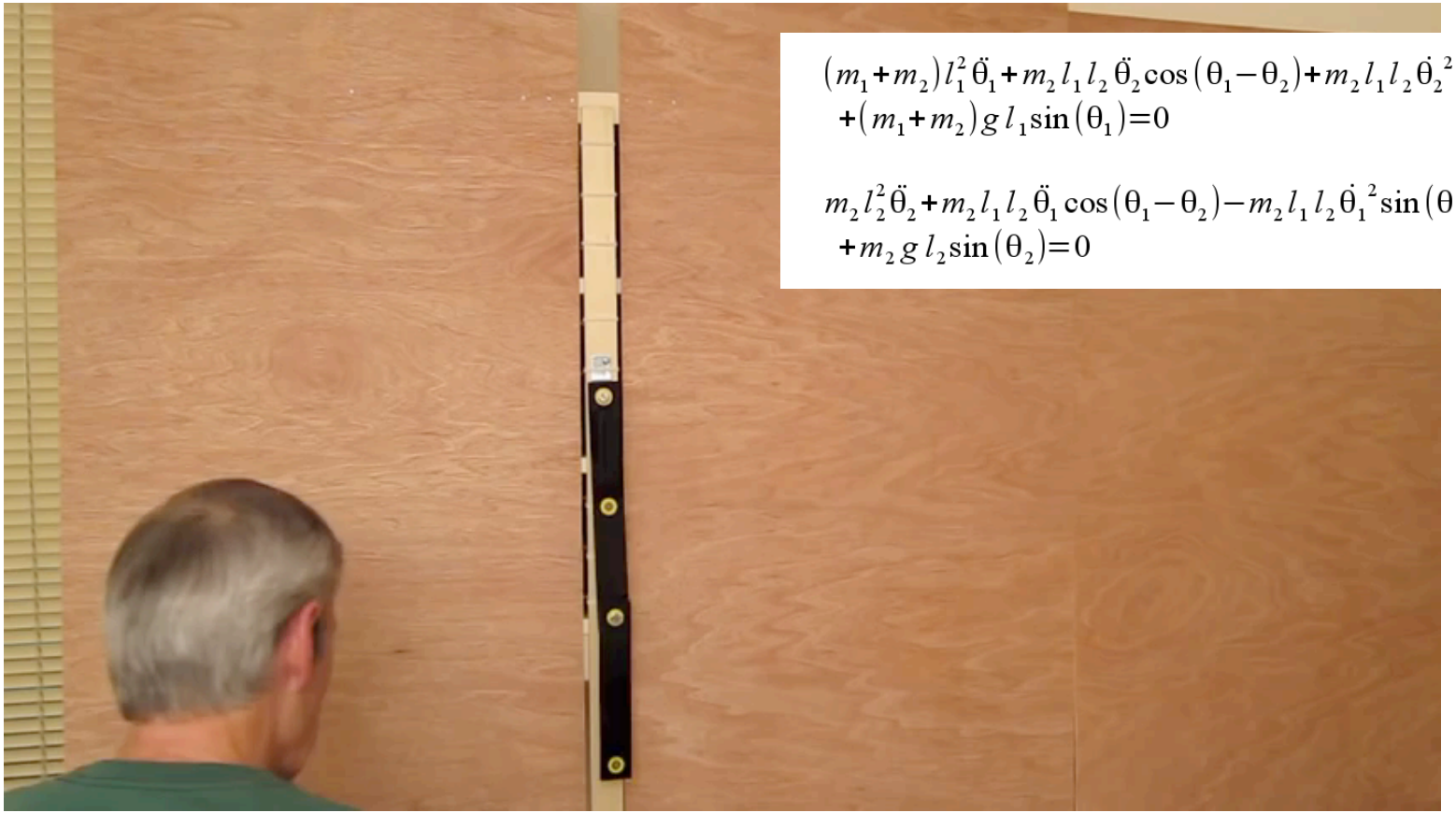


$$\frac{d^2\theta}{dt^2} = -\frac{g\sin(\theta)}{L}$$

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



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



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

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

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

2 linked segments (double inverted pendulum) → hmmm…

Passive Dynamic Walking

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

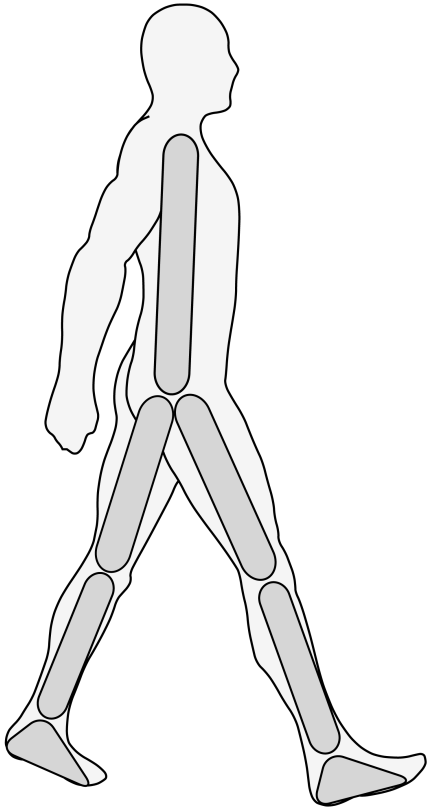
3 linked segments (triple pendulum) → well #%$&

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

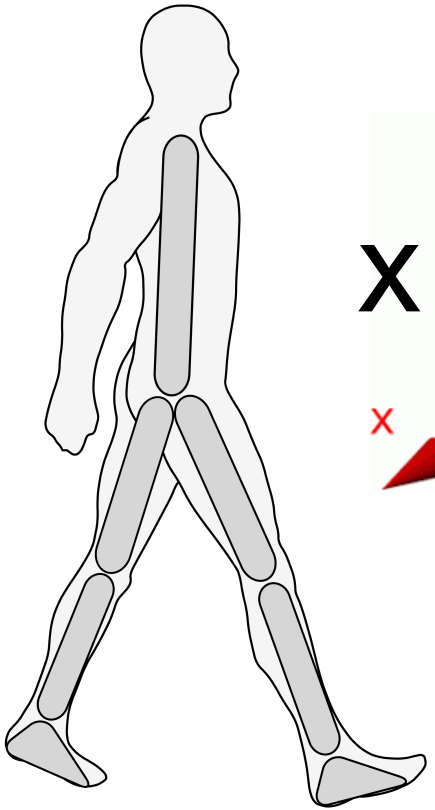
Just one of the three equations of motion:

$$\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))$$

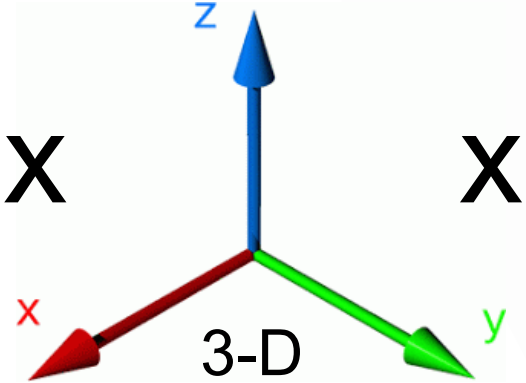
Human: multiple linked segments



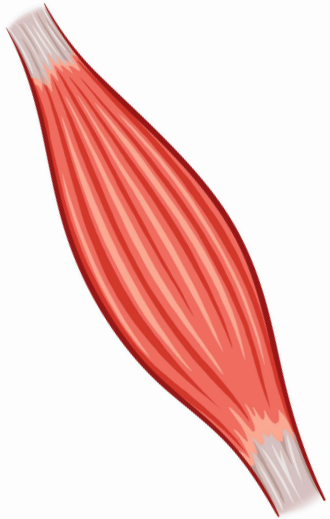
Human: multiple linked segments x 3-D x muscles x control



X

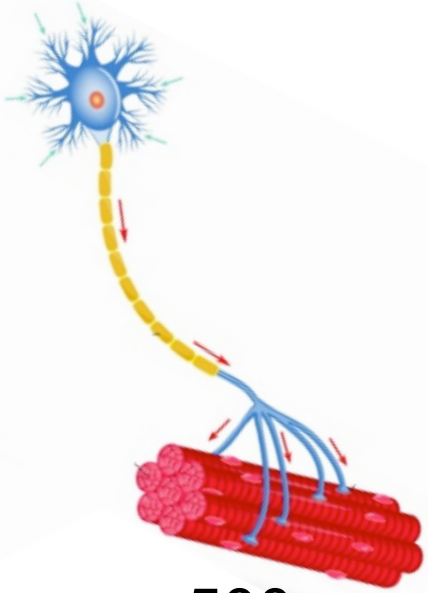


X



600
skeletal
muscles

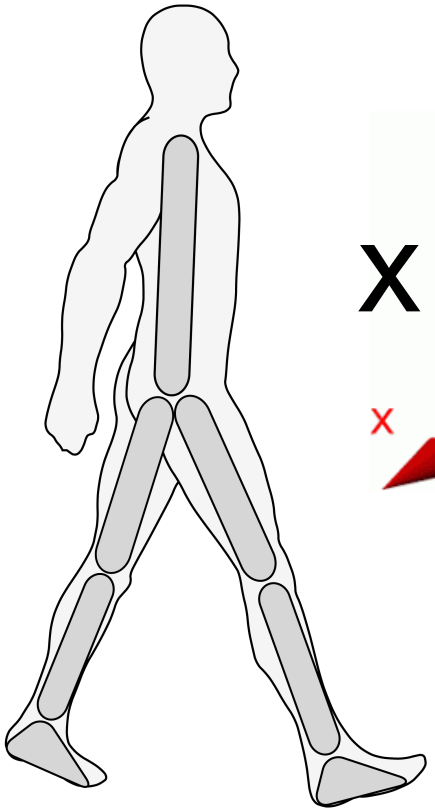
X



500
motoneuron/
muscle

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

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



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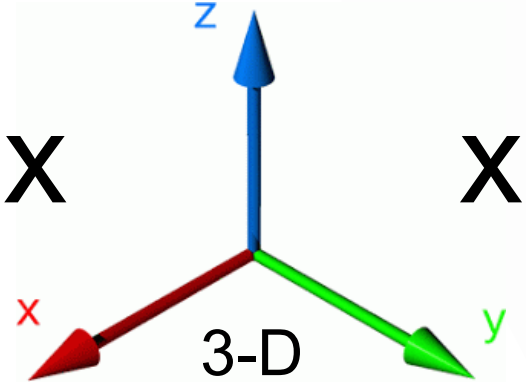
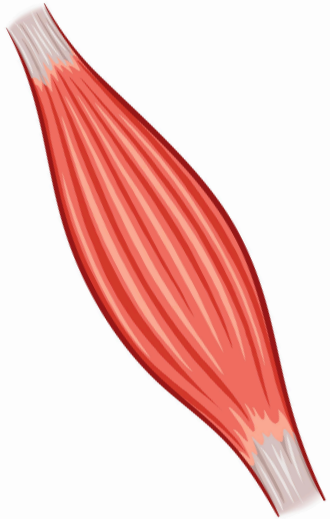
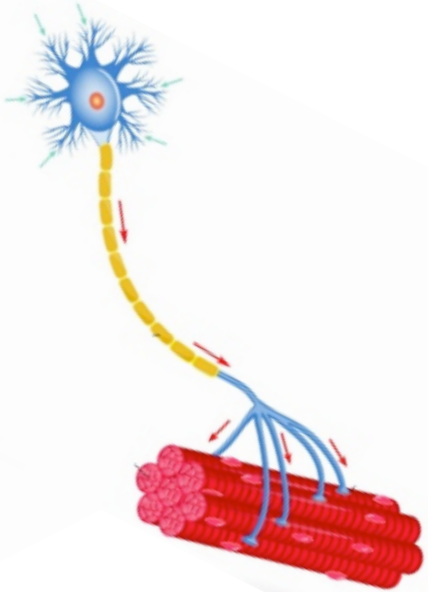


X



X



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

smarts = ability to quickly reason, understand or intuit

People are squishy when forces are applied to body

Yandell et al. 2017

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

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

Takeaway 2

Mechanisms underlying movement are often unexpected & non-intuitive

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 changes has big impact!

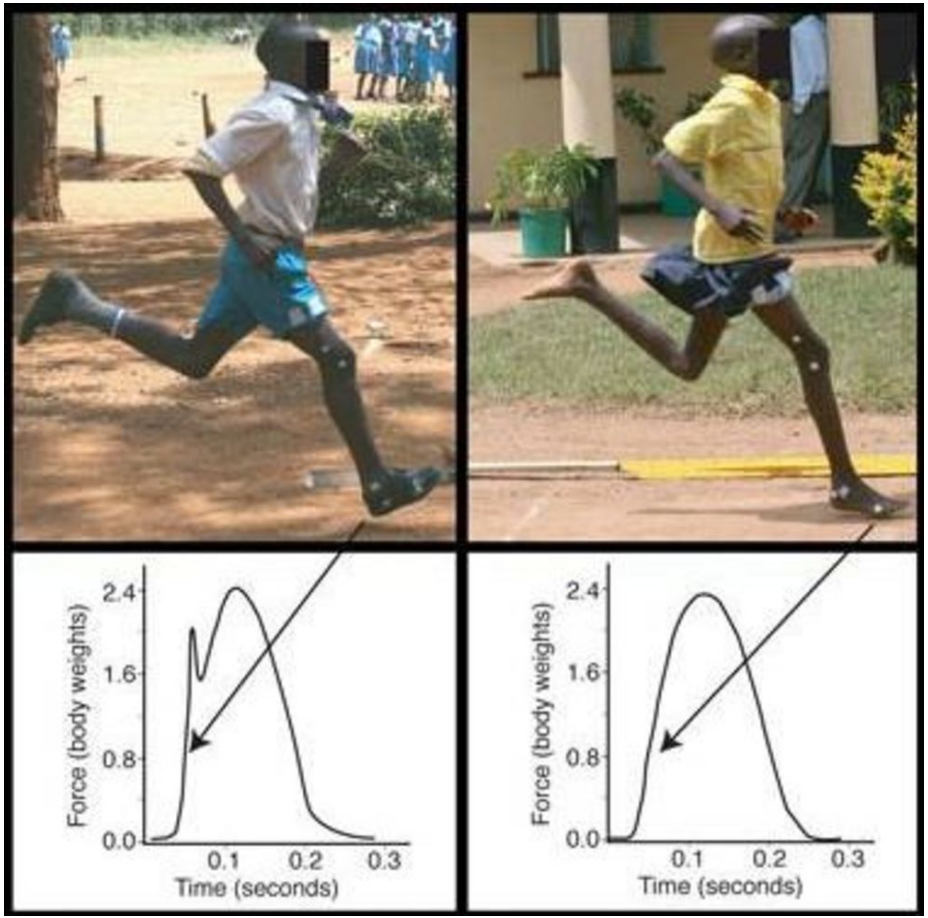
1998 Olympics: Records broken in every single speed skating event (men’s & women’s)

1700 1800 1900

Running shoes

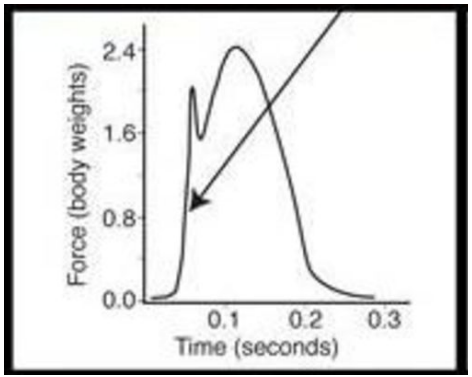
Running shoes: cushioned footwear vs. barefoot?

Running shoes: cushioned footwear vs. barefoot?



Results: Lieberman et al. 2010
Image: Popular Science

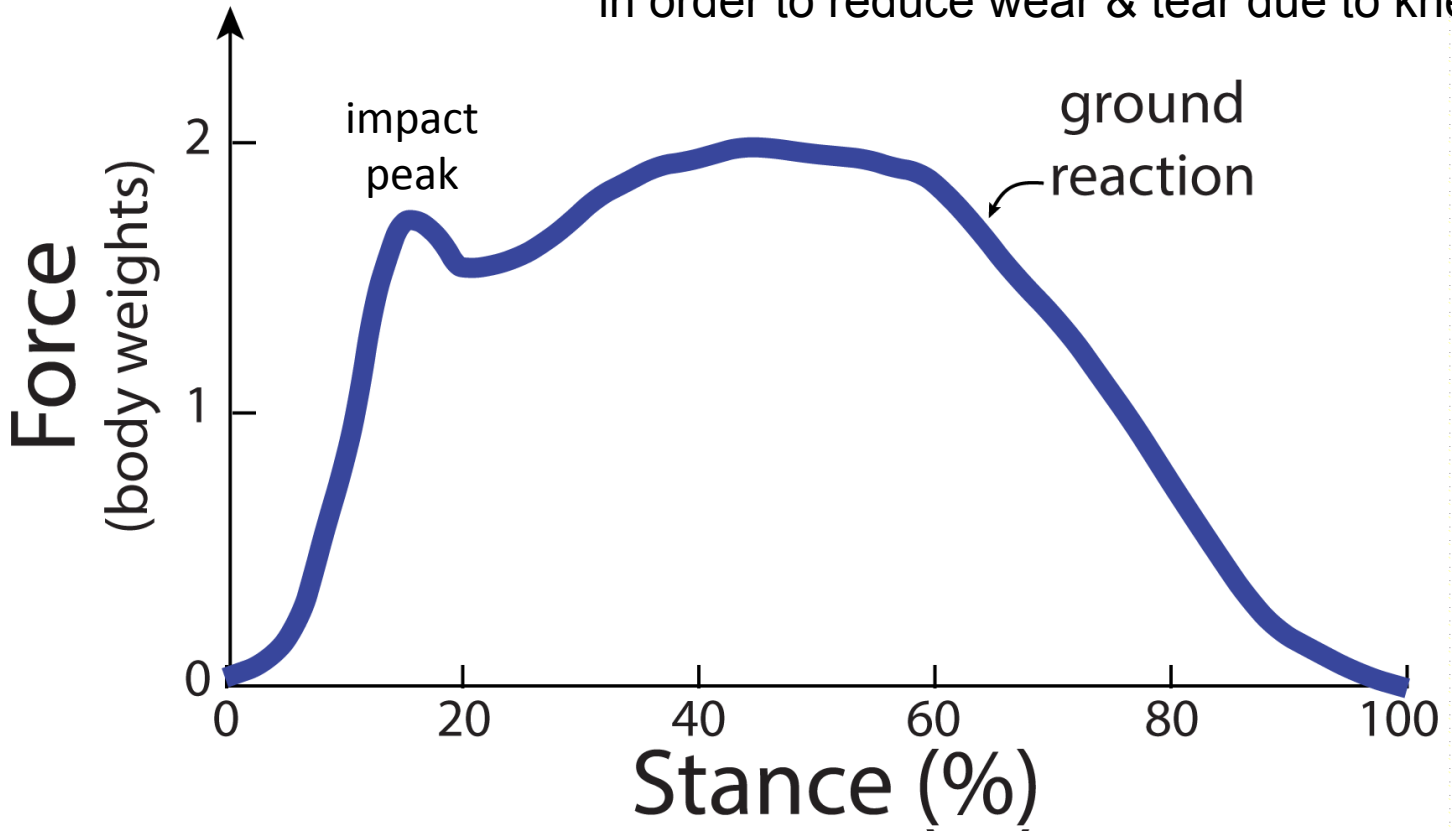
Running shoes: cushioned footwear vs. barefoot?



Results: Lieberman et al. 2010
Image: Popular Science

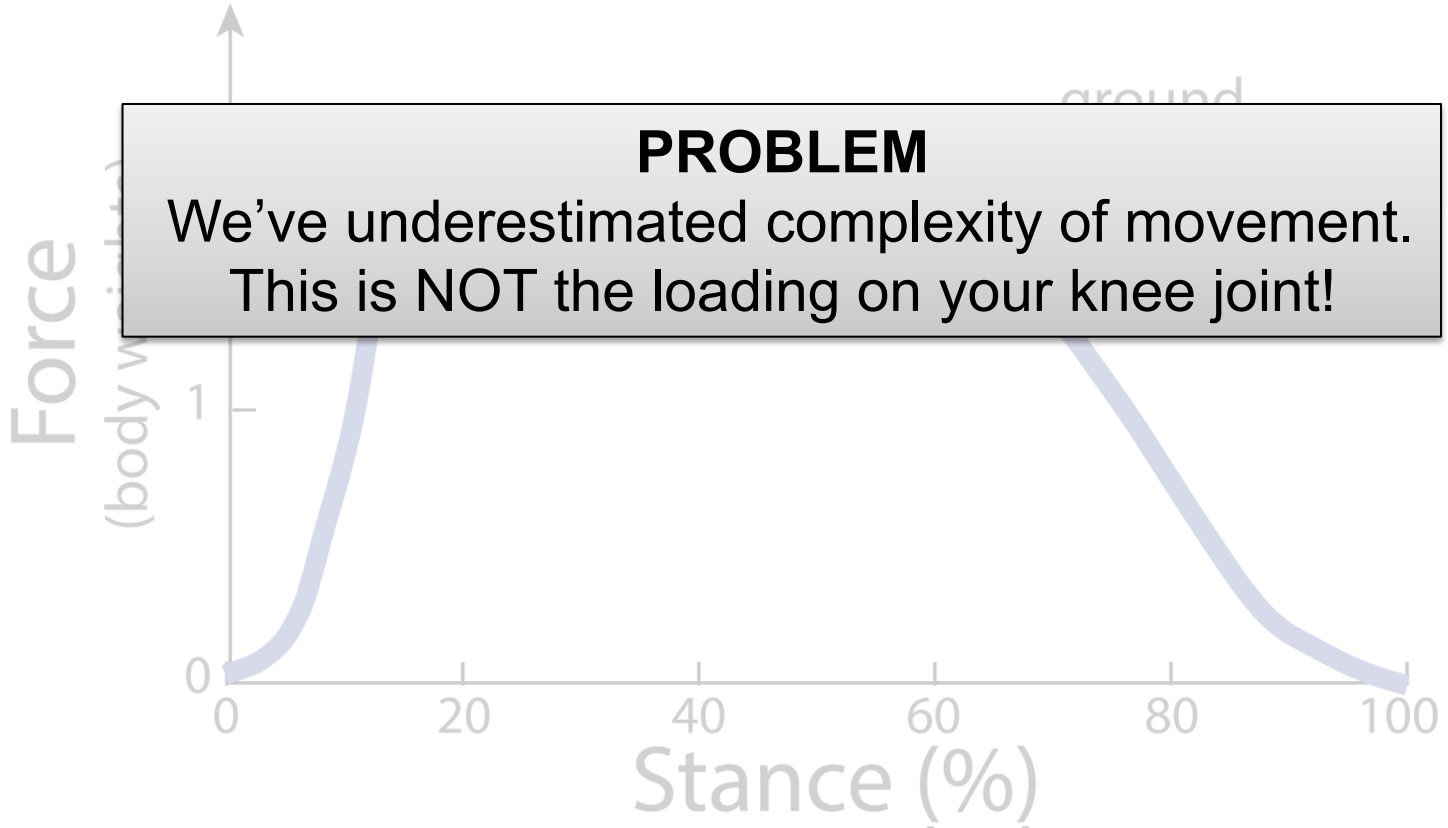
Reasonable thought process → try barefoot to reduce impacts

in order to reduce wear & tear due to knee loading



Scott & Winter 1990

Reasonable thought process → try barefoot to reduce impacts

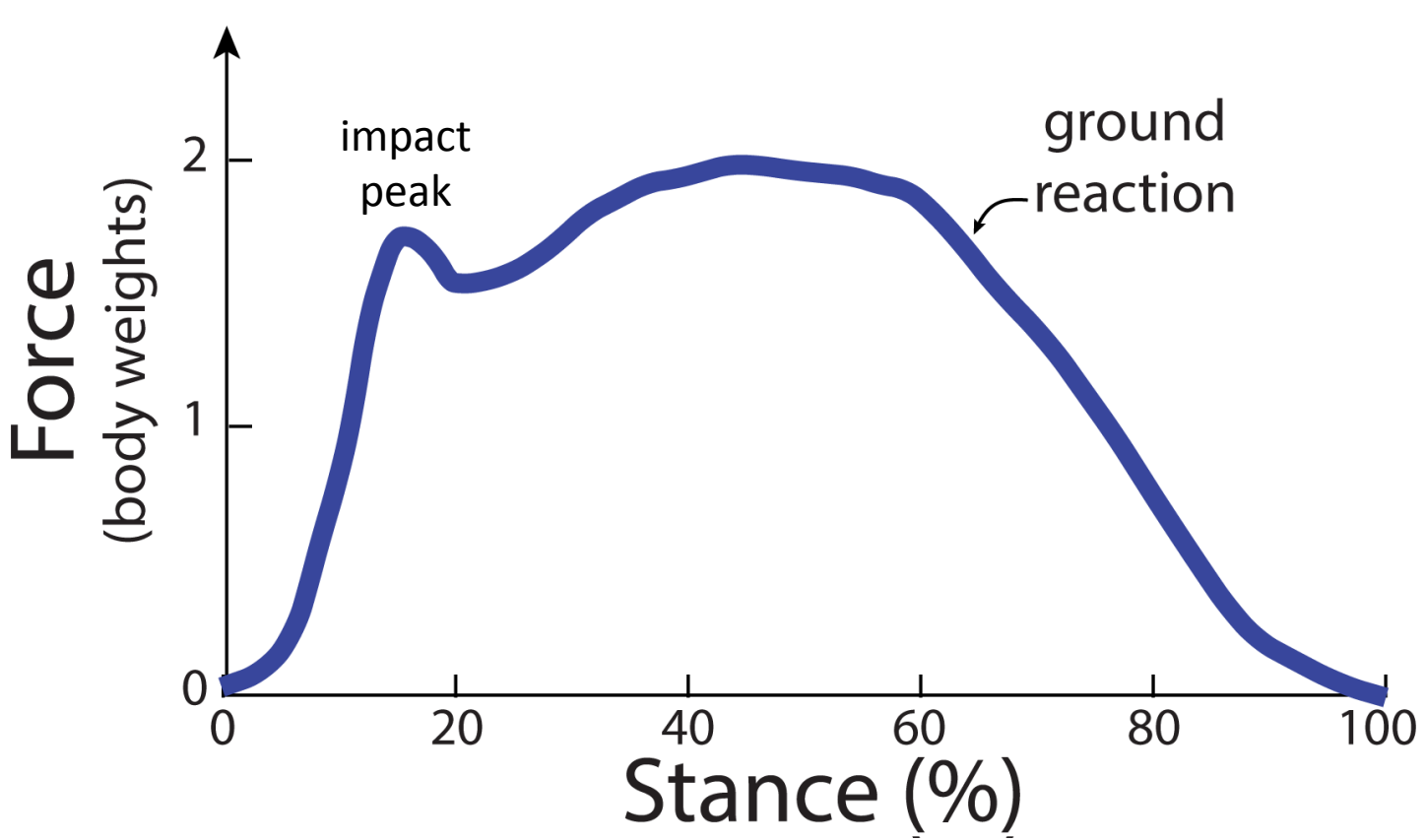


PROBLEM

We've underestimated complexity of movement.
This is NOT the loading on your knee joint!

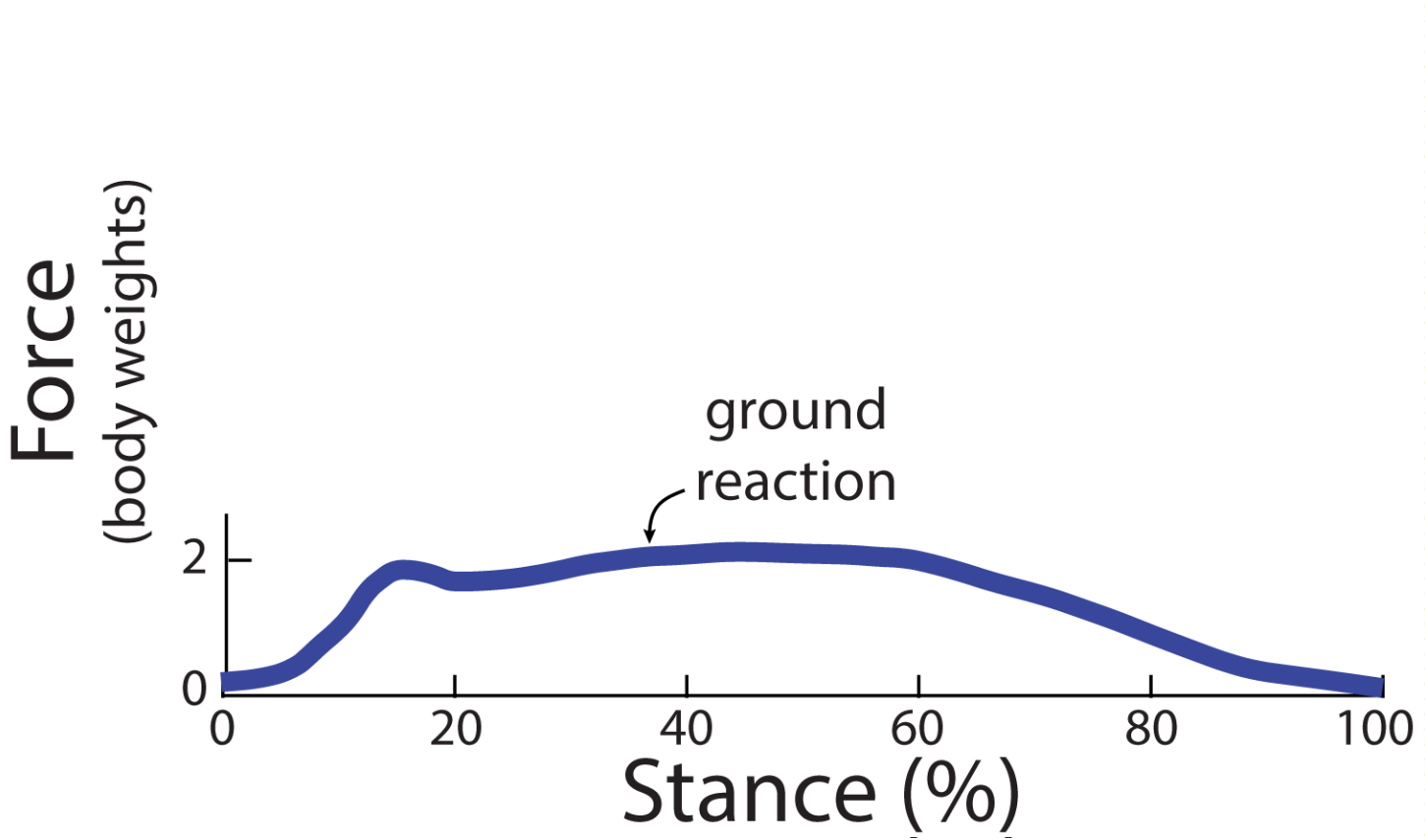
Scott & Winter 1990

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



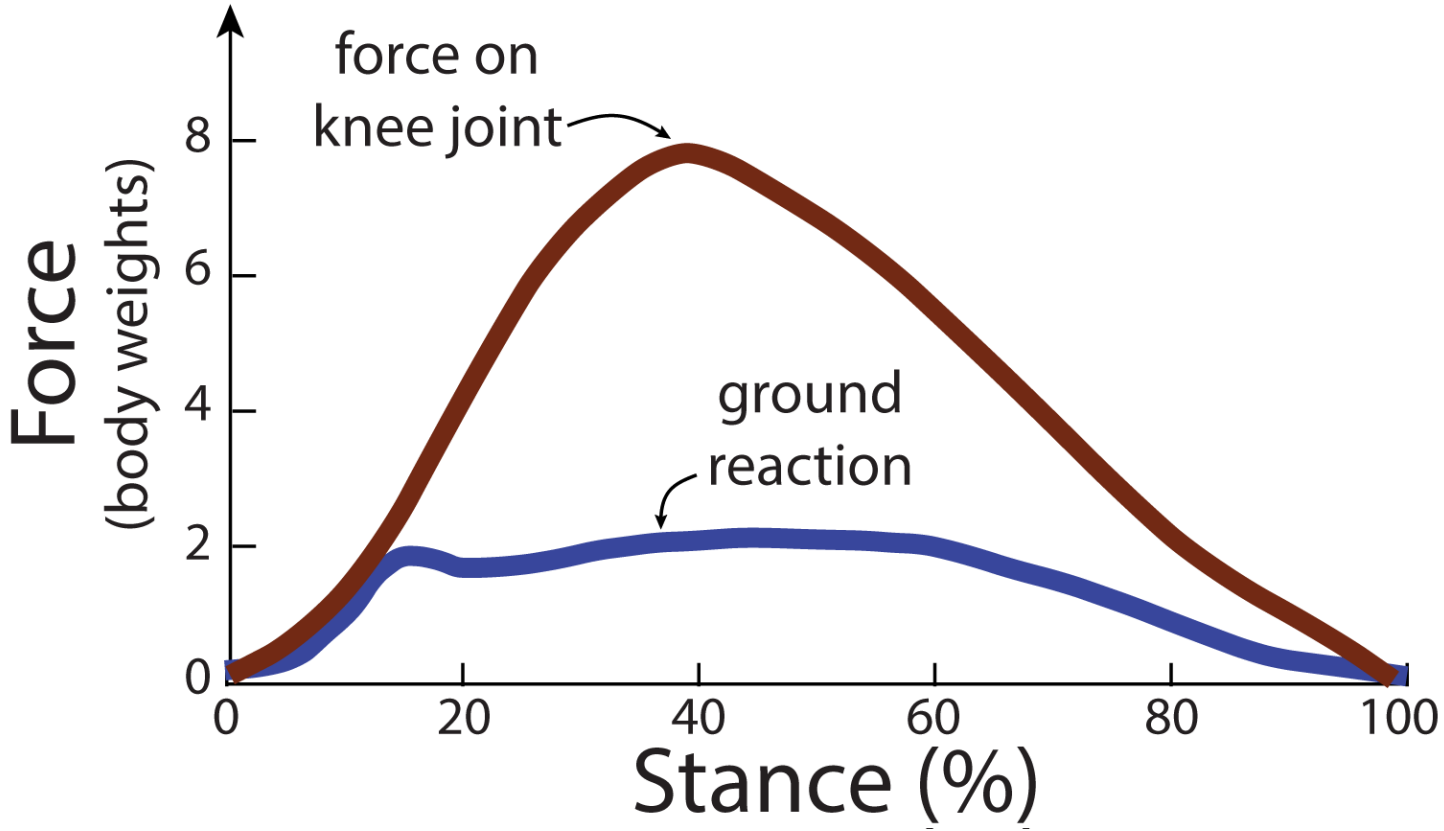
Scott & Winter 1990

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

My own story: repetitive lifting & leaning

Life with small kids

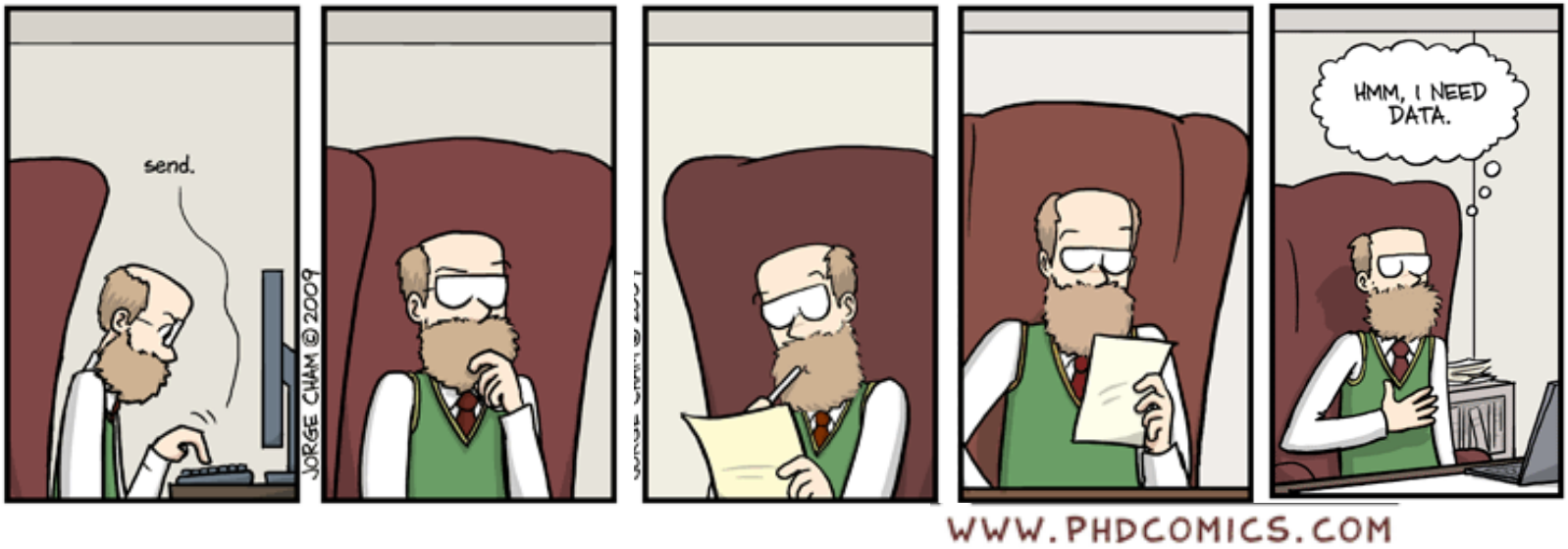
Life with small kids

Life with small kids

Life with small kids & trying to be an adult

Life as a professor

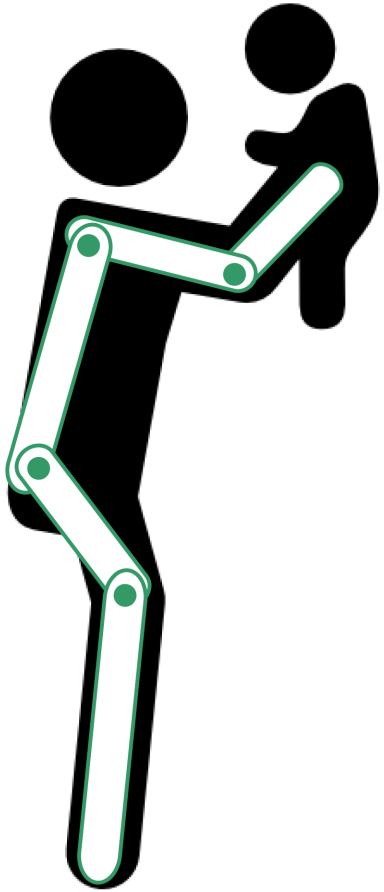
Life as a professor



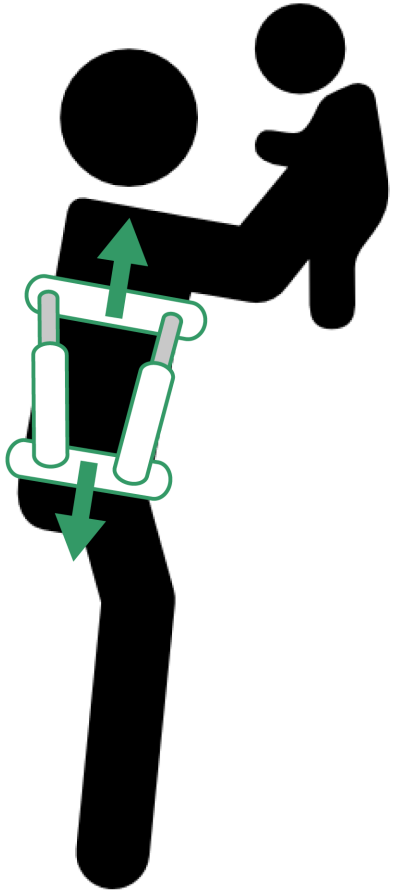
My own story: repetitive lifting & leaning

Potential Wearable Tech Solutions

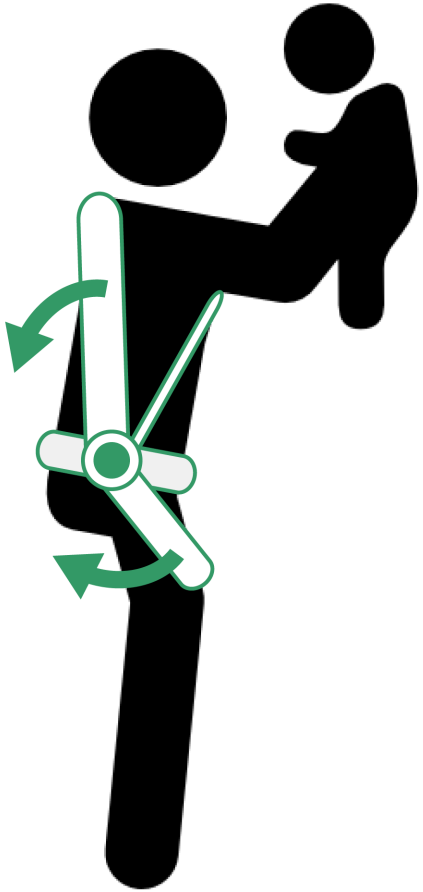
Concept 1: load path to ground



Concept 2: traction device



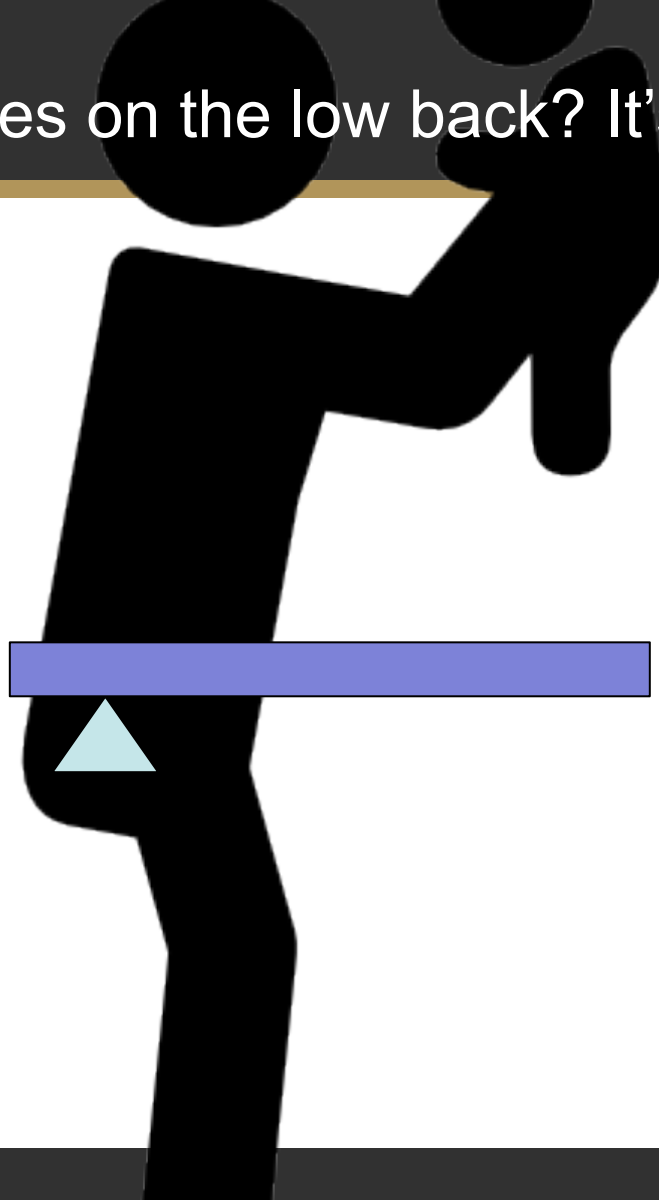
Concept 3: torsion/scissor mechanism

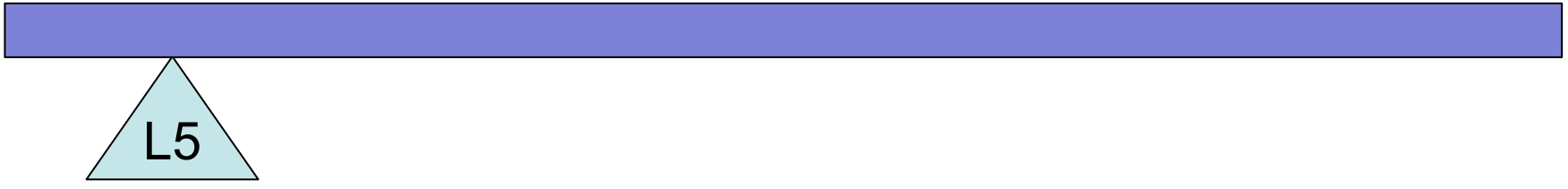


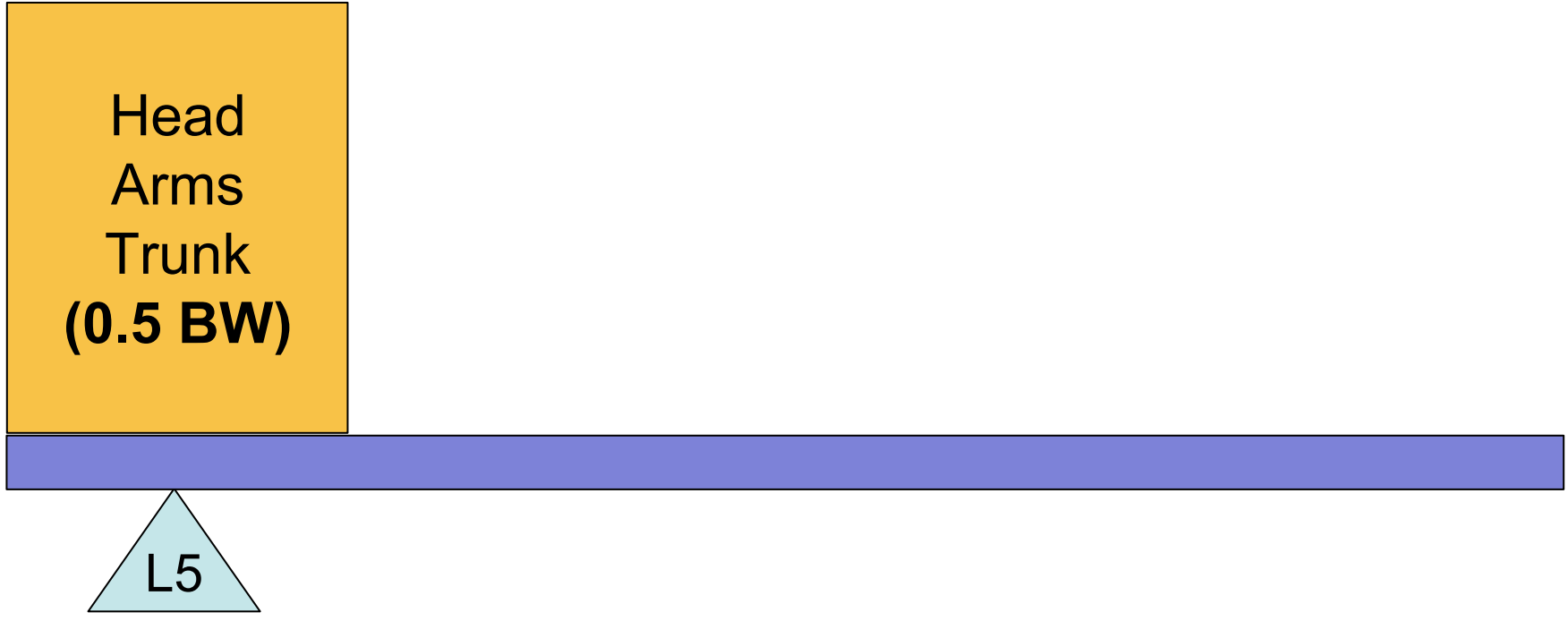
Not aware of any solutions (existing or theorized) that work for me

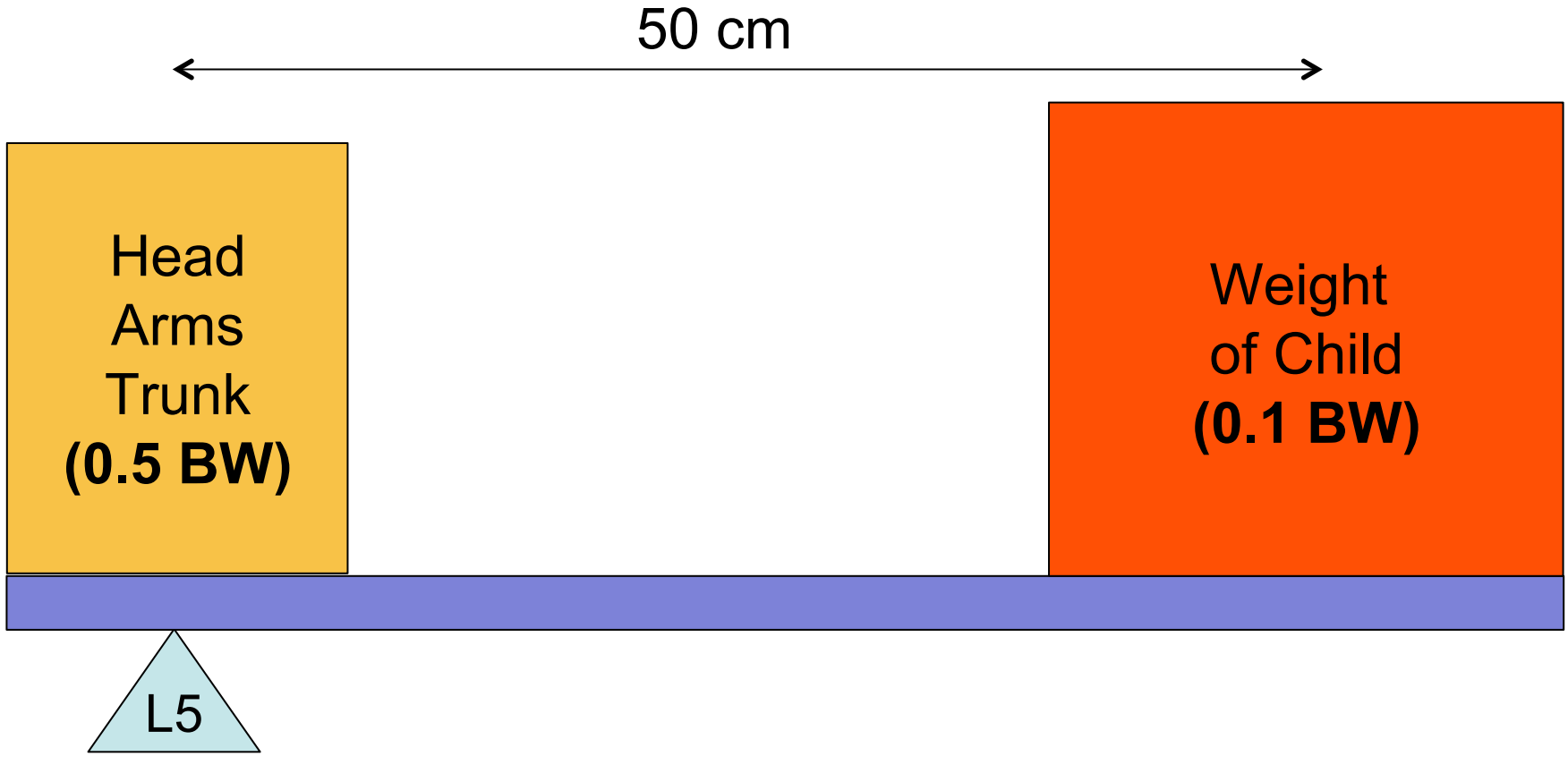
Stopped thinking about tech, started thinking about science

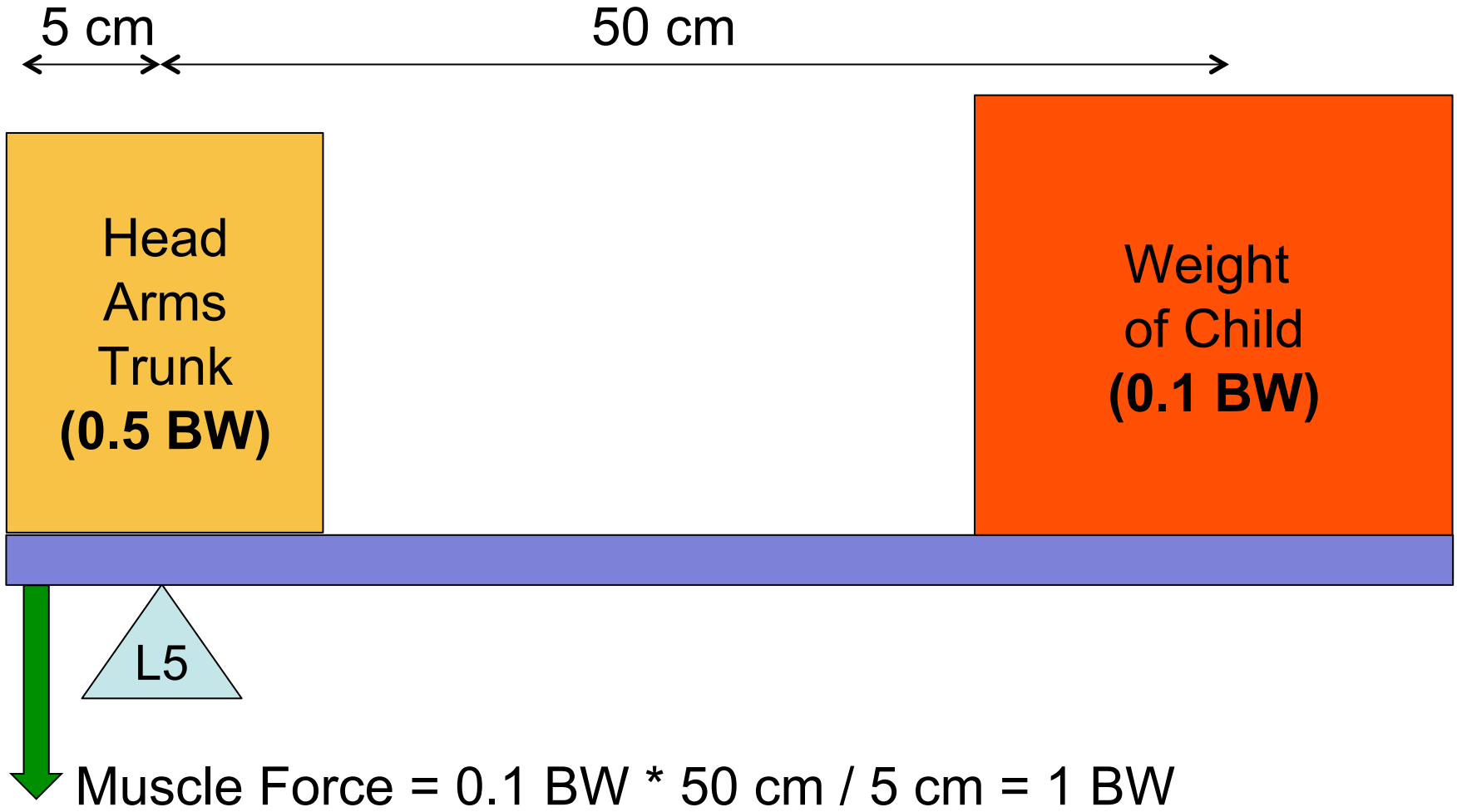
What causes high forces on the low back? It's all about levers!

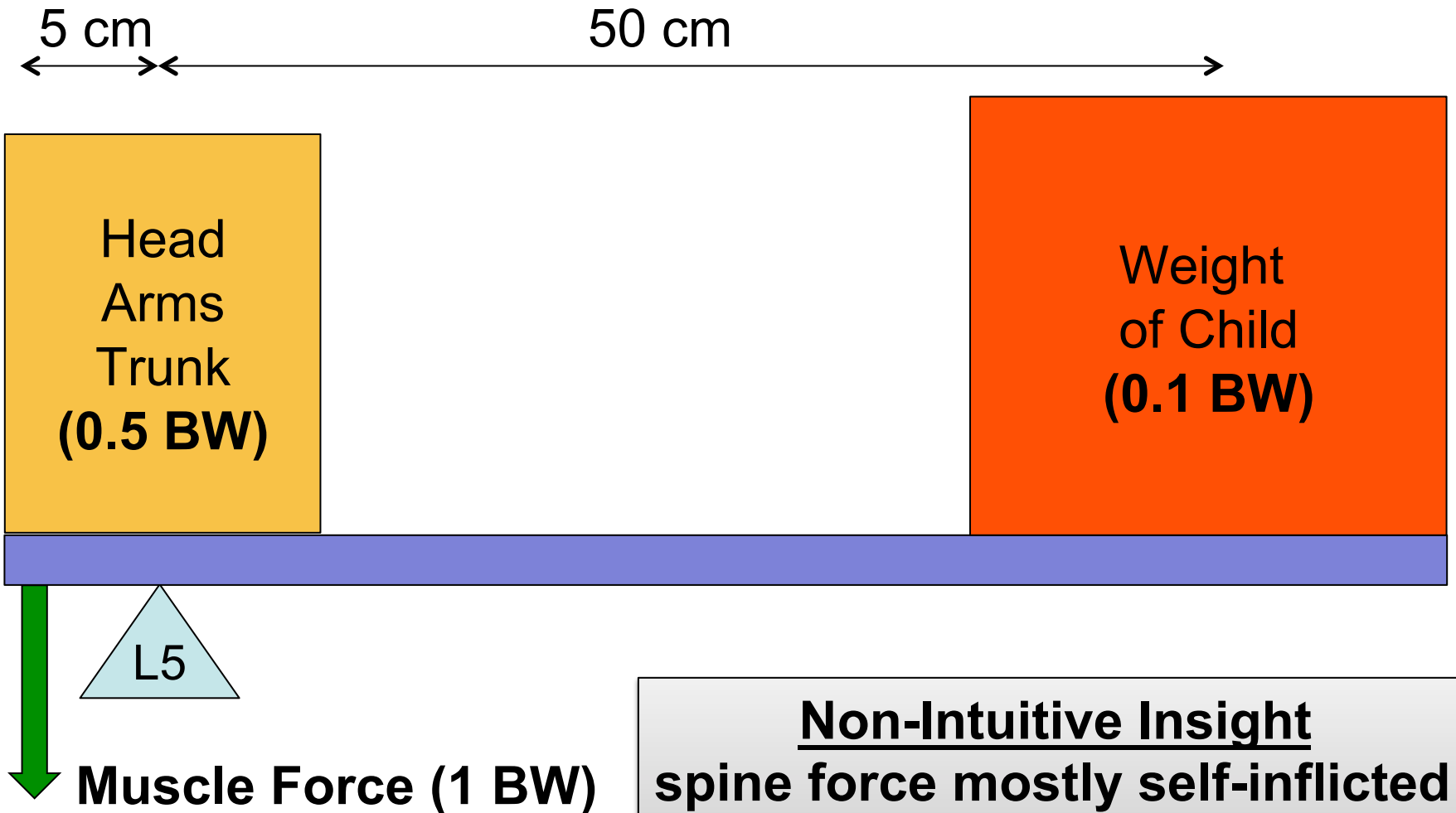



L5


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



Non-Intuitive Insight

spine force mostly self-inflicted from your own muscles

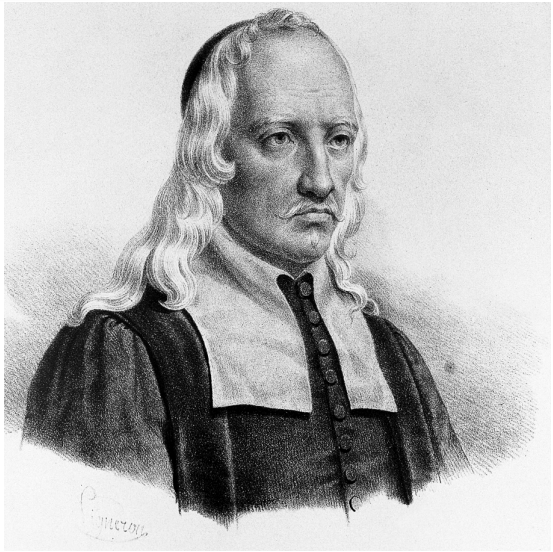
Non-Intuitive Insight

spine force mostly self-inflicted from your own muscles

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

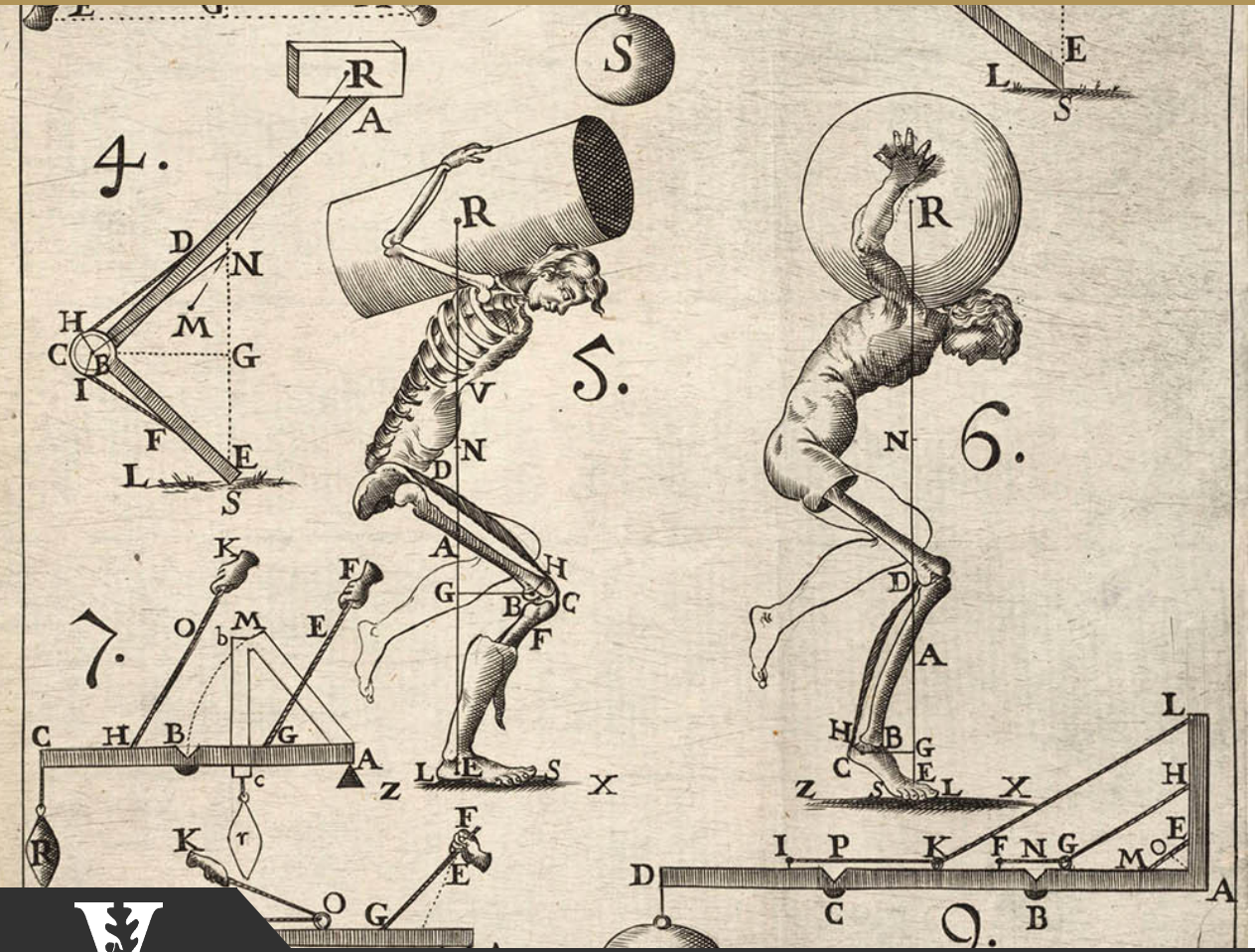
Non-Intuitive Insight
spine force mostly self-inflicted from your own muscles

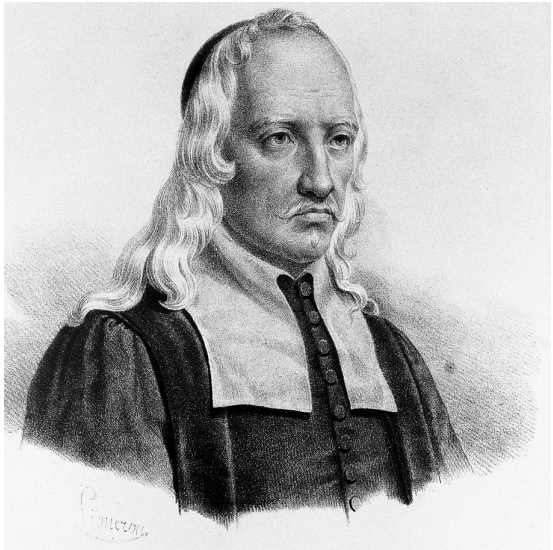
Galen (2nd Century)



Borelli (17th Century)

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





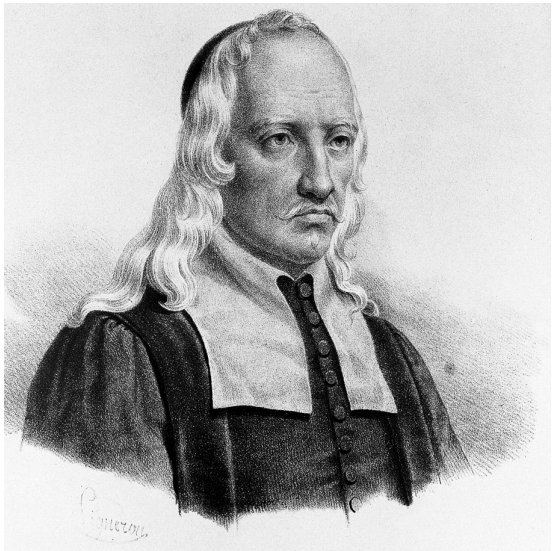
Borelli (17th Century)

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

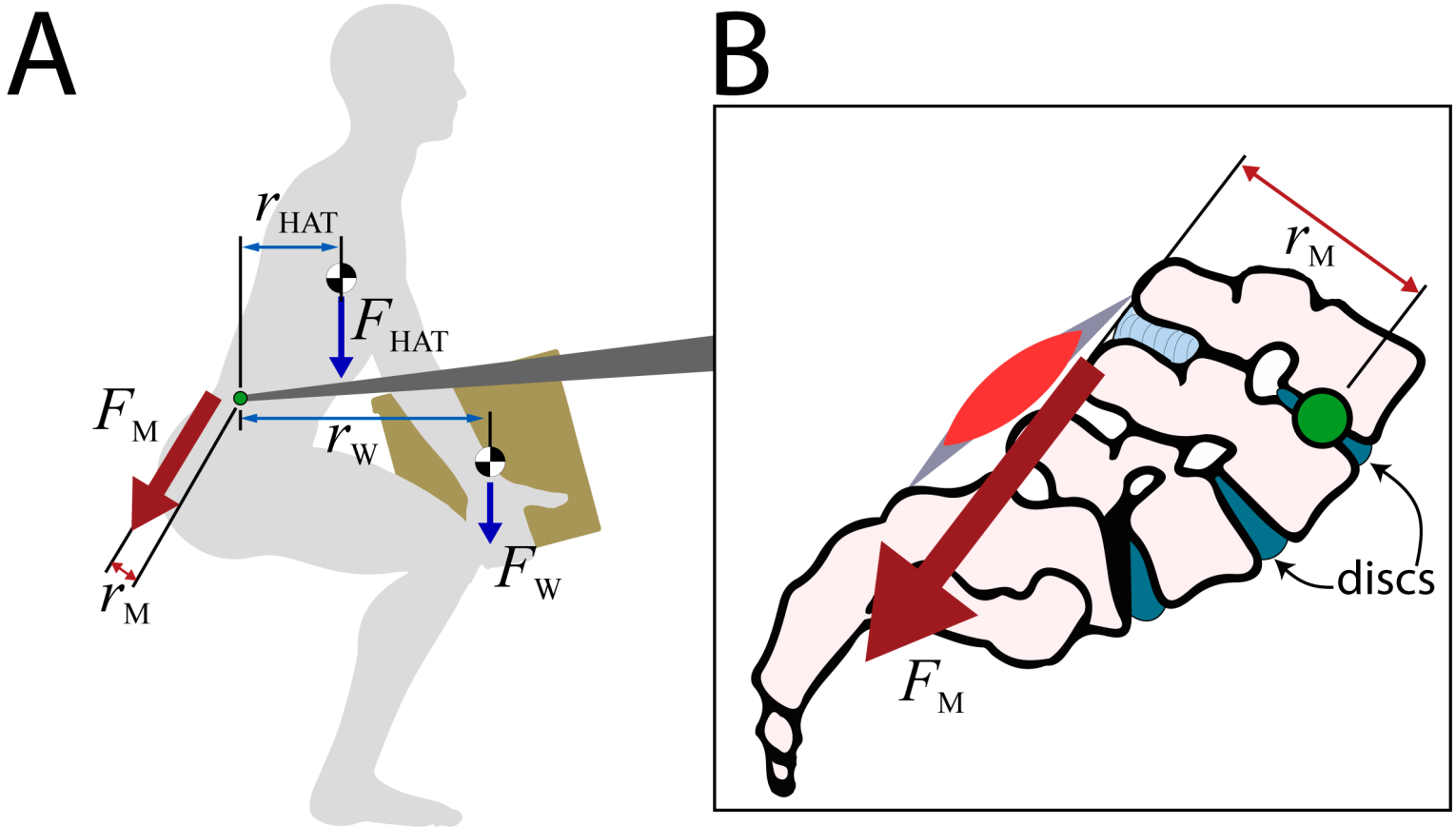


Borelli (17th Century)

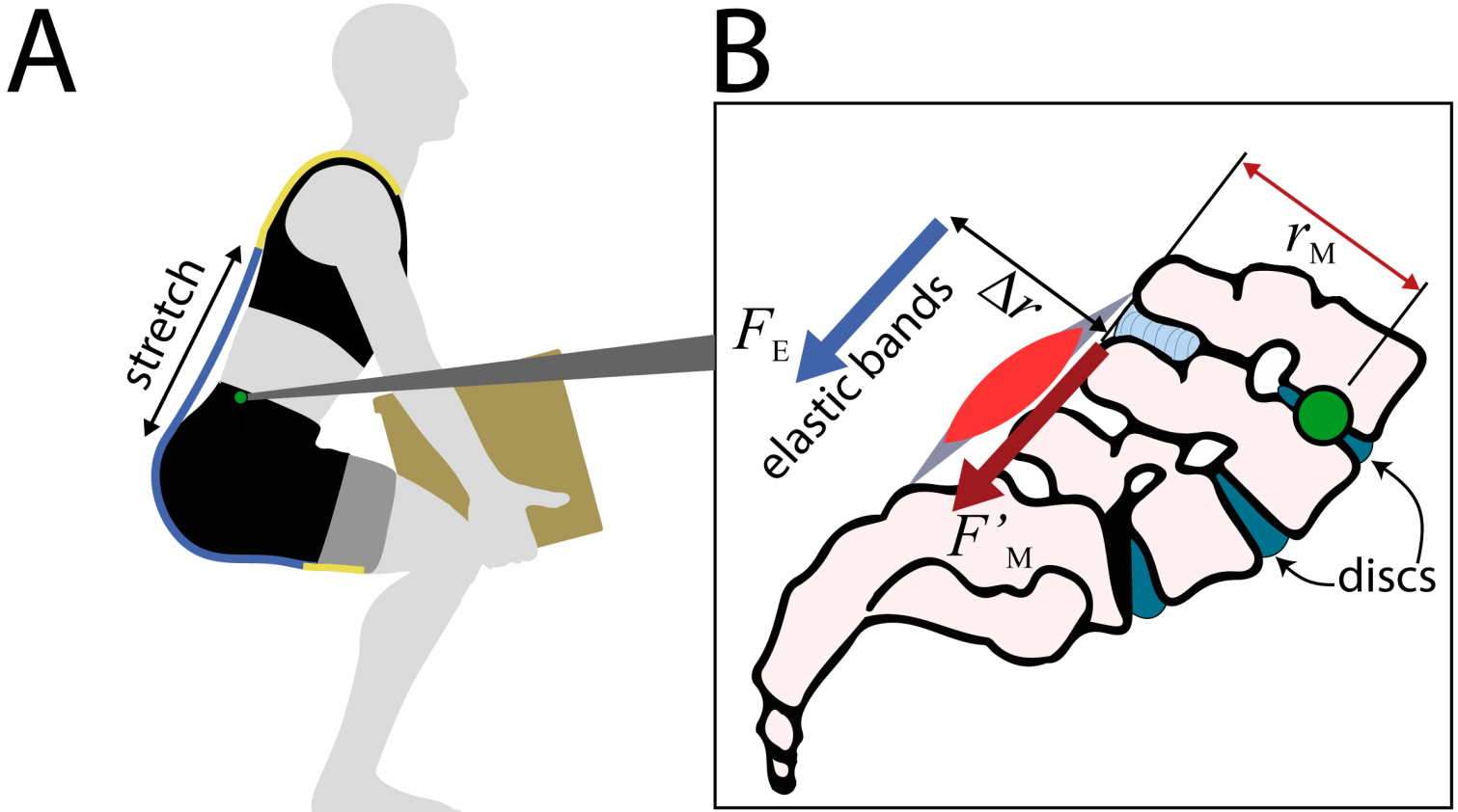
Takeaway 3

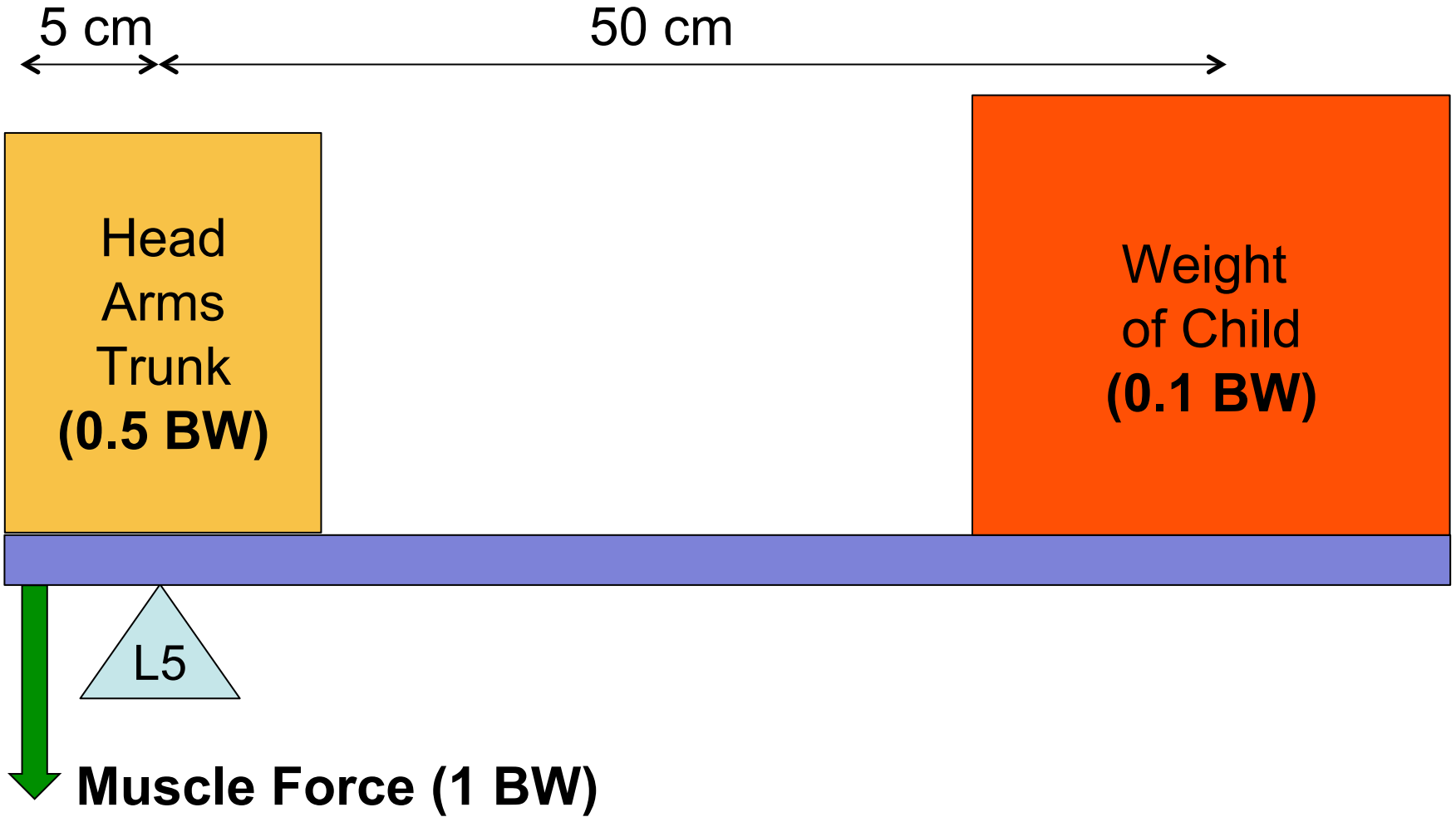
Non-intuitive mechanisms are key to wearable robot world domination

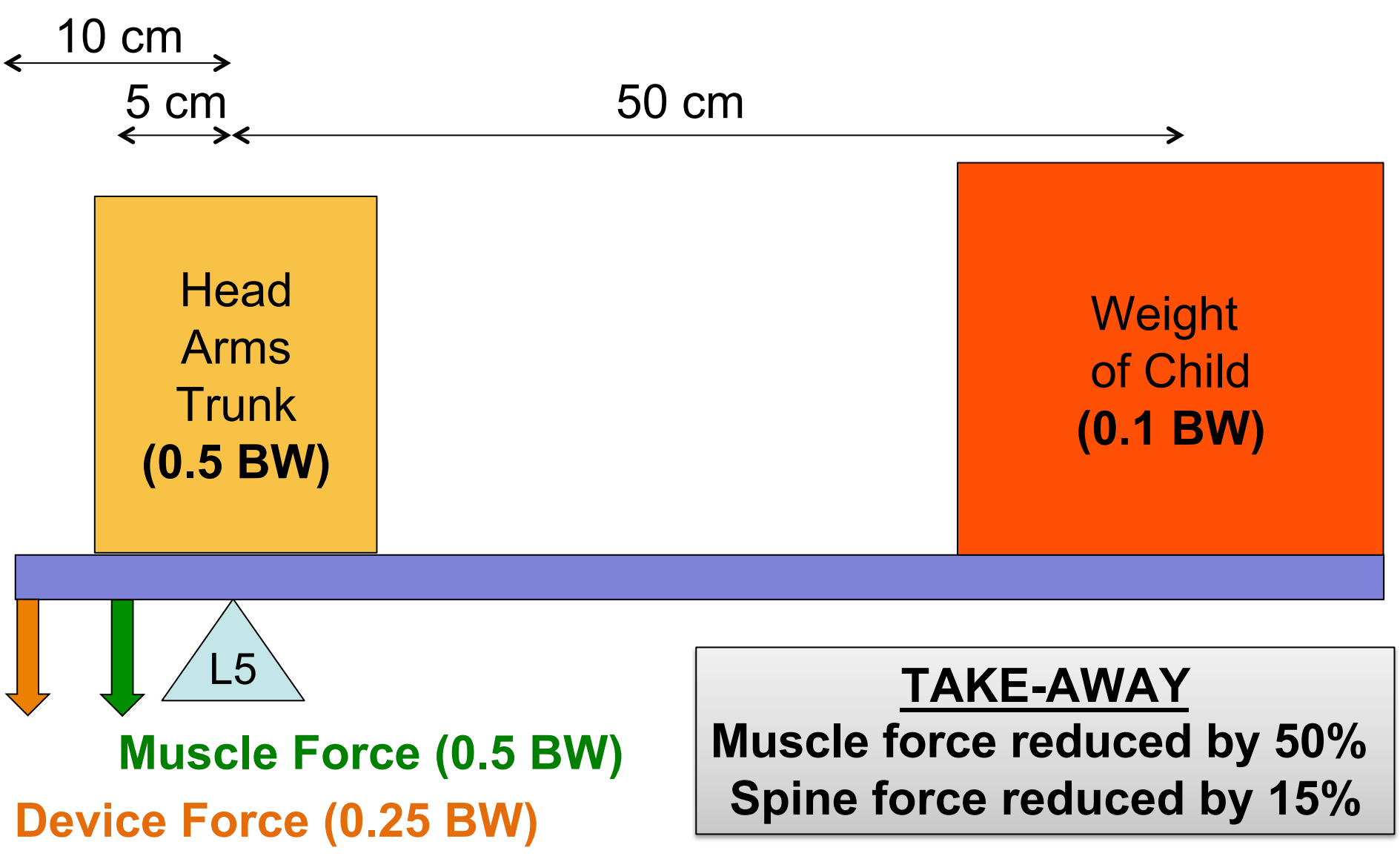
Spine forces are mostly self-inflicted! (from your own muscles)



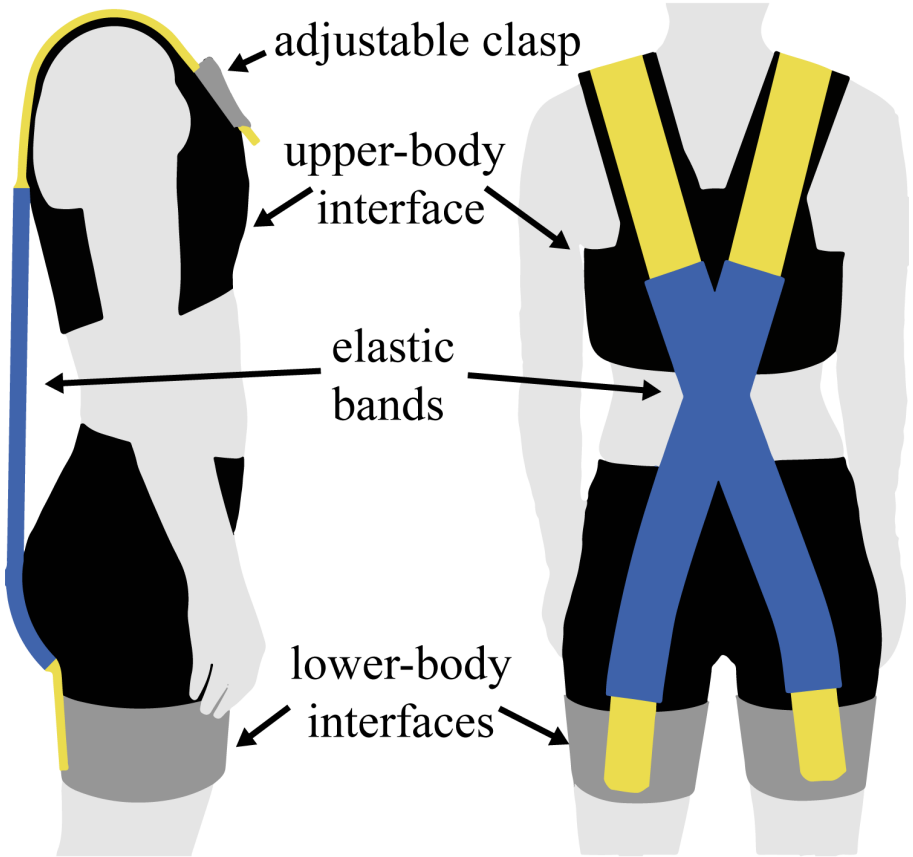
Embed spring-like structures into clothing to offload low back




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

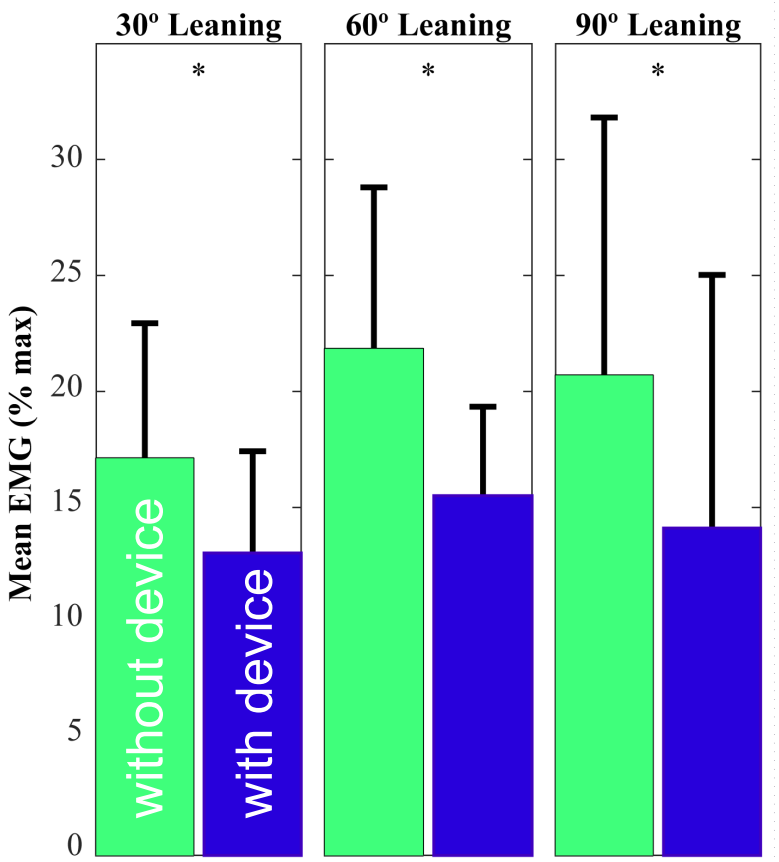

10 cm
5 cm
50 cm
Head
Arms
Trunk
(0.5 BW)
Weight
of Child
(0.1 BW)
L5
Muscle Force (0.5 BW)
Device Force (0.25 BW)
TAKE-AWAY
Muscle force reduced by 50%
Spine force reduced by 15%

Biomechanically-assistive clothing (passive device)



Lamers, Yang & Zelik 2017

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

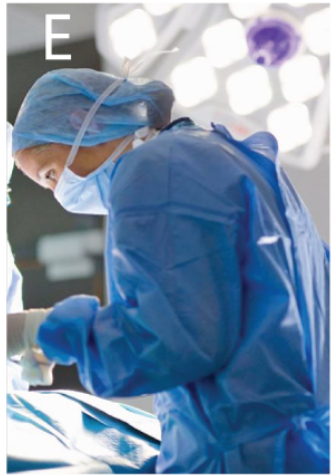


Lamers, Yang & Zelik 2017

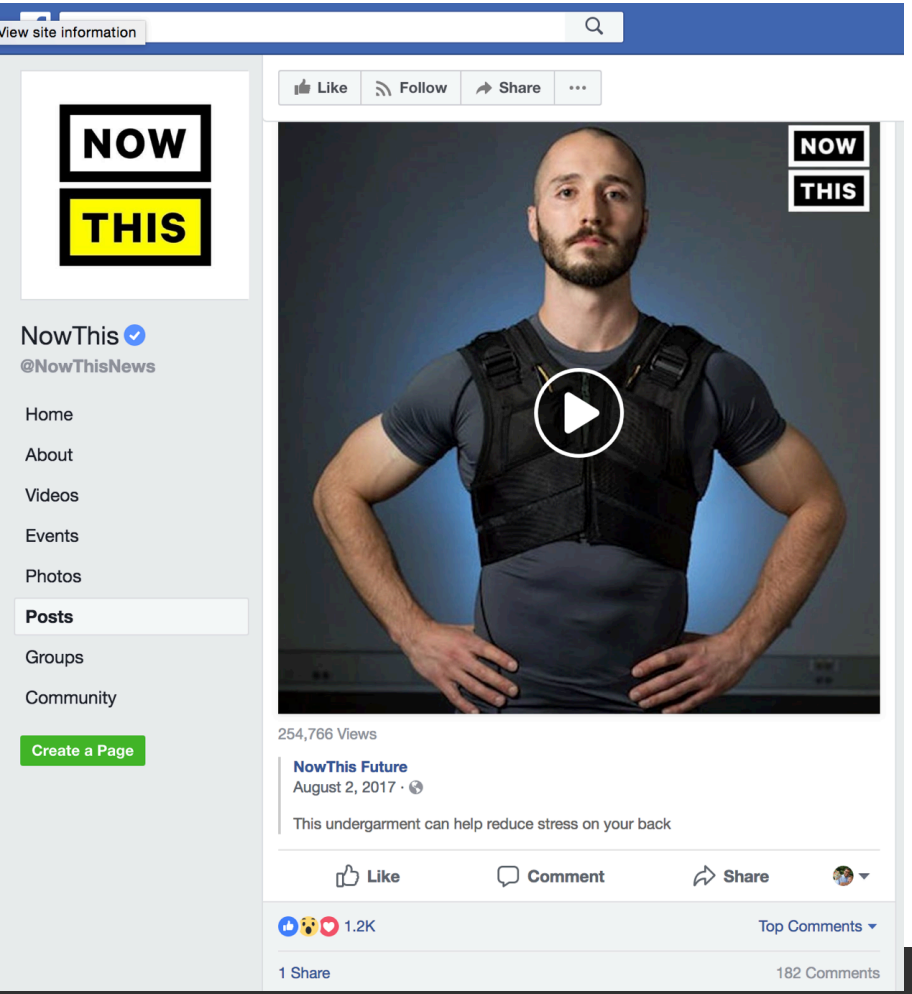
Device can offload my back, fit under my clothes, into my life!

Started project selfishly… later realized broad applications

new markets & new potential end-users



1900 yrs after Galen, underlying mechanism still non-intuitive



I think people are missing the point, this was designed by somebody with no mwchanical background, not only do you have the load compressing your spine but also the so called counter force of the elastic contraption

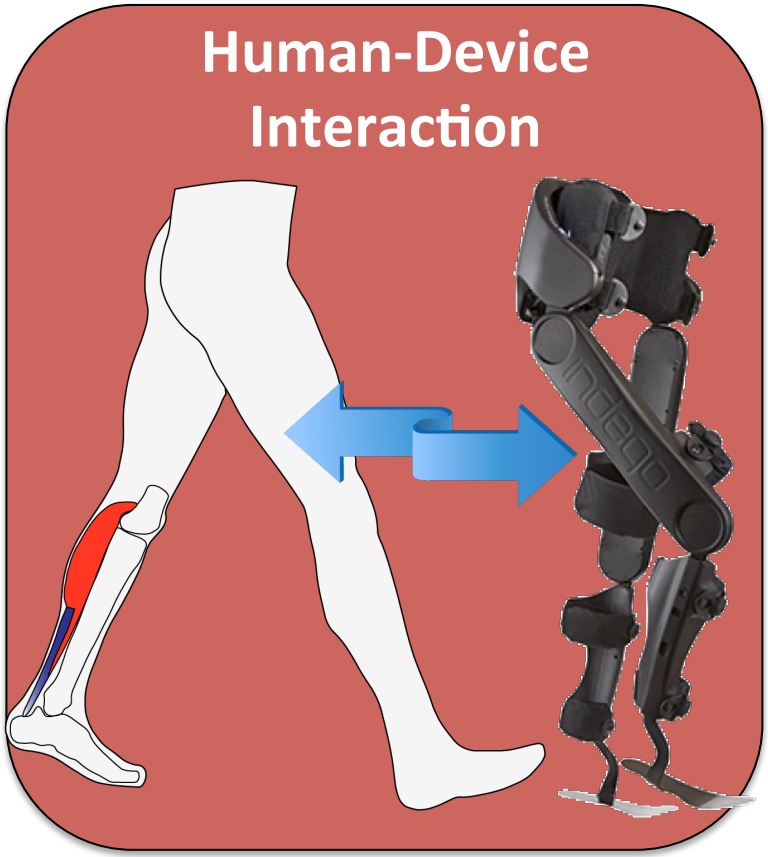
Like · Reply

Worked at Southampton General Hospital UK

Former Rehabilitation Technician at Southampton University Hospitals NHS Trust

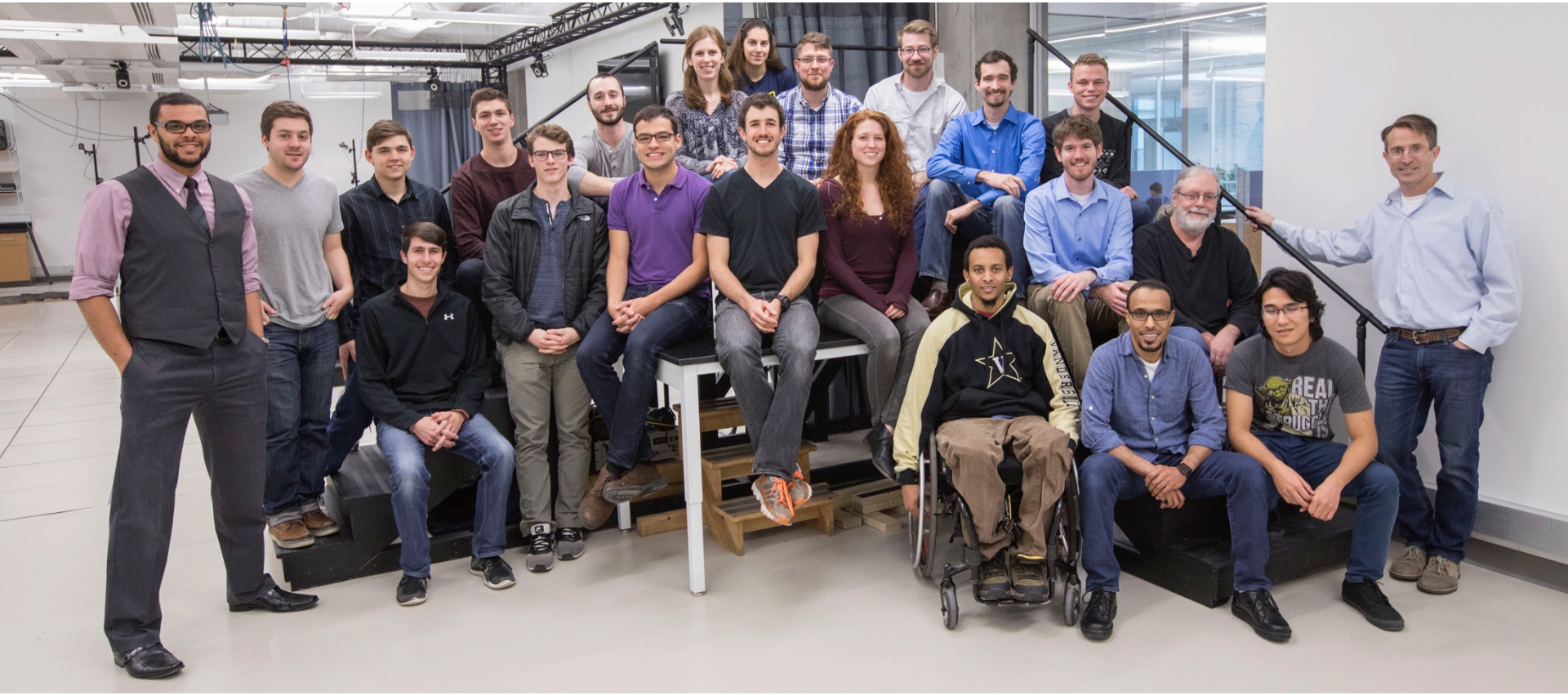
Exploring non-intuitive wearable tech solutions

Evaluating & optimizing wearable robotic devices



Acknowledgements

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



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Thanks. Questions?

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 wearable robot world domination