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

Prof. Karl Zelik
You’re not that smart*
relative to complexity of movement

*neither am I
Mechanisms underlying movement are often unexpected & non-intuitive
Non-intuitive mechanisms are key to wearable robot world domination
implantable cardiac devices

Los Angeles
biomechanics & prosthetics
You & I are not that smart relative to complexity of movement
Human Smarts vs. Movement Dynamics

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

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

smarts = ability to quickly reason, understand, intuit or predict
Human Smarts vs. Movement Dynamics

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

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Human Smarts vs. Movement Dynamics

2 linked segments (double pendulum) \(\rightarrow\) maybe we don’t

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

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

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Human Smarts vs. Movement Dynamics

2 linked segments (double inverted pendulum) → hmmm…

Passive Dynamic Walking

smarts = ability to quickly reason, understand, intuit or predict
Human Smarts vs. Movement Dynamics

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

smarts = ability to quickly reason, understand, intuit or predict
Human Smarts vs. Movement Dynamics

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

Just one of the three equations of motion:

\[
\ddot{\theta}_1 = -2((l_3^3 m_3^3 \sin(2\theta_1 - 2\theta_3)(4 I_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 + 4 I_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 + 4 I_3(m_2^2 + 6m_2 m_3 + 8m_3^2)) l_3^2 + 4 I_2 m_3(m_2 + \\
m_3)l_3^2 + 4 I_3(m_2 + 2m_3)) + l_3^2 m_3^2 \sin(\theta_1 + \theta_2 - 2\theta_3)(4 I_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 + 4 I_5(m_2 + 2m_3)) - l_3^2 m_3^2 \cos(\theta_1 + \theta_2 - 2\theta_3)\dot{\theta}_3 + l_3 m_3(\sin(\theta_1 - \theta_3))(8 I_3 m_3^2 l_3^2 + 4 I_2 m_3 l_3^2 + 16 I_2 I_3) + \\
l_2^2 \sin(\theta_1 - 2\theta_2 + \theta_3)(m_2 m_3 l_3^2 + 4 I_3(m_2 + 2m_3))\dot{\theta}_3^2 - 4k_3 l_3 m_3(\cos(\theta_1 - \theta_3)(2m_3 l_3^2 + 4 I_2 - l_2^2 m_2) - l_2^2 m_2(\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_3^2) l_3^2 + 4 I_3(m_2^2 + 6m_2 m_3 + \\
m_1 m_2 + 4m_3 + 4 m_1 m_3)) l_3^2 + 4 I_2 (m_3(m_1 + 2m_2 + m_3) l_3^2 + 4 I_3(m_1 + 2m_2 + m_3))) + l_3^2 m_3^2(\sin(\theta_1 - \\
2\theta_3)(4 I_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 + \\
4 I_3(m_2 + 2m_3))\dot{\theta}_3) / (64 I_1 I_2 I_3 + 8 I_3 l_3^2 l_2^2 m_2 + 8 I_1 l_3^2 l_2^2 m_2 + 8 I_2 l_3^2 l_2^2 m_2 + 32 I_2 l_3^2 l_2^2 m_3 + \\
16 I_2 I_3^2 l_3^2 m_1 + 16 I_1 l_3^2 l_2^2 m_1 + 64 I_2 I_3 l_3^2 m_2 + 16 I_1 I_2 l_3^2 m_3 + 64 I_1 I_3 l_3^2 m_3 + \\
64 I_2 I_3 l_3^2 m_2 + 16 I_1 l_3^2 l_2^2 m_2 + 48 I_1 l_3^2 l_2^2 m_3) + 8 l_1 l_3^2 l_3^2 m_2 m_2 - 8 I_1 l_3^2 l_2^2 m_2 m_2 \cos(2\theta_2 - 2\theta_3) - 2l_1 l_3^2 l_3^2 m_2 m_2 + \\
2l_1 l_3^2 l_2^2 m_2 m_2) - 2l_1 l_3^2 m_2^2 \cos(2\theta_1 - 2\theta_3)(-m_2 l_2 + 4 I_2 + 2l_2^2 l_3^2 m_2 m_2 + 6 I_1 l_3^2 l_2^2 m_2 m_2 + \\
2l_1 l_3^2 l_2^2 m_2 m_2 + l_1 l_3^2 l_3^2 m_2 m_2 - 2l_1 l_3^2 l_3^2 m_2 m_2 \cos(2\theta_2 - 2\theta_3)) - 4 l_1 l_3^2 l_3^2 m_2 m_3 \cos(2\theta_2 - 2\theta_3))
\]
Human Smarts vs. Movement Dynamics

Human: multiple linked segments

smarts = ability to quickly reason, understand, intuit or predict
Human Smarts vs. Movement Dynamics

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

*smarts* = ability to quickly reason, understand, intuit or predict
Human Smarts vs. Movement Dynamics

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

smarts = ability to quickly reason, understand or intuit
Bonus Challenge

People are squishy when forces are applied to body

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

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

Yandell et al. 2017
Mechanisms underlying movement are often unexpected & non-intuitive
Non-Intuitive Mechanisms

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

Simple modification to traditional skate enhances speed

“a rigid blade fixed below a boot”
Non-Intuitive Mechanisms

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

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

Running shoes
Non-Intuitive Mechanisms

Running shoes: cushioned footwear vs. barefoot?
Non-Intuitive Mechanisms

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Results: Lieberman et al. 2010
Image: Popular Science
Non-Intuitive Mechanisms

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Non-Intuitive Mechanisms

Reasonable thought process → try barefoot to reduce impacts in order to reduce wear & tear due to knee loading

Scott & Winter 1990

![Graph showing force vs. stance percentage](image)
Non-Intuitive Mechanisms

Reasonable thought process → try barefoot to reduce impacts

PROBLEM
We’ve underestimated complexity of movement.
This is NOT the loading on your knee joint!
Non-Intuitive Mechanisms

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

Scott & Winter 1990
Non-Intuitive Mechanisms

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

Scott & Winter 1990
Non-Intuitive Mechanisms

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

Scott & Winter 1990
Non-Intuitive Mechanisms

My own story: repetitive lifting & leaning
Non-Intuitive Mechanisms

Life with small kids
Non-Intuitive Mechanisms

Life with small kids
Non-Intuitive Mechanisms

Life with small kids
Non-Intuitive Mechanisms

Life with small kids & trying to be an adult
Non-Intuitive Mechanisms

Life as a professor
Non-Intuitive Mechanisms

Life as a professor

Send.

Hmm, I need data.
Non-Intuitive Mechanisms

My own story: repetitive lifting & leaning
Potential Wearable Tech Solutions
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Concept 1: load path to ground
Potential Wearable Tech Solutions

Concept 2: traction device
Potential Wearable Tech Solutions

Concept 3: torsion/scissor mechanism
Potential Wearable Tech Solutions

Not aware of any solutions (existing or theorized) that work for me
Non-Intuitive Mechanisms

Stopped thinking about tech, started thinking about science
Non-Intuitive Mechanisms

What causes high forces on the low back? It’s all about levers!
Head
Arms
Trunk
(0.5 BW)

Weight of Child
(0.1 BW)

50 cm
Muscle Force = 0.1 BW * 50 cm / 5 cm = 1 BW
Non-Intuitive Insight

spine force mostly self-inflicted from your own muscles
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Historical Aside

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!

Historical Aside

Borelli (17th 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
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 pain.
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)

- adjustable clasp
- upper-body interface
- elastic bands
- lower-body interfaces

Lamers, Yang & Zelik 2017
14-43% reduction in low back muscle activity (N=8)

Lamers, Yang & Zelik 2017
Implications

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
Final Thoughts

1900 yrs after Galen, underlying mechanism still non-intuitive
Final Thoughts: Academic-Industry Partnership

Exploring non-intuitive wearable tech solutions
Evaluating & optimizing wearable robotic devices

Human-Device Interaction
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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