Towards a Cohesive, Multi-Scale Understanding of Biomechanics

Karl E. Zelik
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Tutorial: modeling multi-scale biomechanics

molecular  cellular  muscle
GRAND CHALLENGE IN BIOMECHANICS

Developing a cohesive, multi-scale understanding

molecular  cellular  muscle
Developing a cohesive, multi-scale understanding

molecular  cellular  muscle  muscle-tendon  joint-
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!
Main Premise of Presentation

Estimates at one scale should be consistent with others.
Whole-Body
Estimate energy changes on/about body’s center-of-mass

\[ \int F_{grf} \cdot v_{COM} \, dt \]
Whole-Body

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

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

\[ \int F_{grf} \cdot v_{COM} \, dt \]

Peripheral energy change
(motion relative to COM)

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

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

**Graph:**
- **Title:** Net Work or Energy Change (J)
- **X-axis:** Walking Speed (m/s)
- **Y-axis:** Net Work or Energy Change (J)
- **Data:** Zero Net Work
Trust whole-body biomechanics b/c they add up properly

WholeBody Energy = ΣCOM + Peripheral

Zelik & Kuo 2010
Trust whole-body biomechanics b/c they add up properly

\[
\text{Net Work or Energy Change (J)} = \Sigma \text{Joint Work} = \Sigma \text{Hip} + \text{Knee} + \text{Ankle}
\]

\[
\text{WholeBody Energy} = \Sigma \text{COM} + \text{Peripheral}
\]

Zelik & Kuo 2010
Joint-Segment ↔ Whole-Body
Due to motion of the body’s CoM

Due to segmental motion relative to the CoM

Center-of-Mass + Peripheral

König’s Theorem

Zelik & Kuo 2010 & 2012
Due to muscles, tendons and ligaments about each joint
Whole-Body Energy Change

Joint

Due to muscles, tendons and ligaments about each joint

Unmeasured

Everything else, notably work due to deformations of soft tissues

Zelik & Kuo 2010 & 2012
Unmeasured

Everything else, notably work due to deformations of soft tissues
Whole-Body Energy Change

Joint

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

1.25 m/s

Power (W/kg)

% Gait Cycle

COM Power

Zelik & Kuo 2010
\[ F_{grf} \cdot v_{COM} \]

Center-of-Mass

1.25 m/s

Peripheral

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

Power (W/kg)

% Gait Cycle

COM Power

Peripheral Power

Zelik & Kuo 2010
Whole-Body

1.25 m/s

Summed Ankle-Knee-Hip

\[ \sum_{j} M_j \cdot \omega_j \]

Total Power
Joint Power

Zelik & Kuo 2010
Whole-Body

\[ \sum_{j} M_j \cdot \omega_j \]

1.25 m/s

Power (W/kg)

Collision
Rebound
Preload
Push-off
Swing

% Gait Cycle

Joint Power
Total Power

Zelik & Kuo 2010
Whole-Body

1.25 m/s

Power (W/kg)

Collision  Preload  Push-off  Swing

% Gait Cycle

-2 -1 0 1 2 3 4

Total Power

Unmeasured

Zelik & Kuo 2010
Whole-Body

Collision Work (J)

Walking Speed (m/s)

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

Joint-Segment ↔ Whole-Body

- ankle, knee & hip joint work

- center-of-mass energy change
  + peripheral energy change (relative to center-of-mass)
Bad news: feet deform & absorb energy
Bad news: feet deform & absorb energy

Power

Stride Cycle (%)

[50 W]

Ankle (Zelik, Takahashi & Sawicki 2015)

Push-off

rigid foot
Bad news: feet deform & absorb energy

- Ankle (Zelik, Takahashi & Sawicki 2015)
- Foot (Method: Takahashi, Kepple & Stanhope 2012)
Bad news: feet deform & absorb energy

- Ankle (Zelik, Takahashi & Sawicki 2015)
- Foot (Method: Takahashi, Kepple & Stanhope 2012)
- Foot (Method: Prince & Winter 1994)
Bad news: feet deform & absorb energy

- **Ankle** (Zelik, Takahashi & Sawicki 2015)
- **Foot** (Method: Takahashi, Kepple & Stanhope 2012)
- **Foot** (Method: Prince & Winter 1994)
- **Toes** (MacWilliams, Cowley & Nicholson 2003)
Joint-Segment ↔ Whole-Body

Problem: Work sources no longer explain energy change

Joint-Segment ↔ Whole-Body

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

ankle, knee & hip joint work
+ foot work
Problem: Work sources no longer explain energy change

Joint-Segment ↔ Whole-Body

Zelik, Takahashi & Sawicki 2015
Non-obvious culprit: conventional 3DOF inverse dynamics

3DOF inverse dynamics

How much work to rotate body segments?

\[ W_{\text{joint}} = \int \left( M_{\text{joint}} \omega_{\text{joint}} \right) dt \]
Non-obvious solution: 6DOF analysis of hip+knee+ankle+foot

6DOF inverse dynamics

How much work to move body segments?

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

rotational work + translational work

DOF = degrees of freedom

Buczek 1994, Duncan 1997
Non-obvious solution: 6DOF analysis of hip+knee+ankle+foot

Joint-Segment ↔ Whole-Body

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

Joint-Segment ↔ Whole-Body

Zelik, Takahashi & Sawicki 2015
Discrepancies → soft tissues; completeness of work estimates

Joint-Segment ↔ Whole-Body

- intervertebral discs
- viscera
- muscles & fat
- joints (cartilage)
- ankle joint
- shoe
- metatarsal joints
- heel pad
- arch

Ankle, knee & hip joint work + foot work

3D, Tot, 6D

Positive work & energy change over stride (J)

CREATE
Whole-Body $\leftrightarrow$ Augmented-Body
Rise of wearable exoskeletons, exosuits & smart clothing
Exoskeletons: $70 million worth sold in 2014

\[ \times 40\% \text{ CAGR} \]
(compounded annual growth rate)

ABI Research Report 2015
Whole-Body ↔ Augmented-Body

Exoskeletons: $2 billion projected for 2025

2014

2025

ABI Research Report 2015
What does this mean for biomechanics community?
Quantifying human augmentation from wearable devices
Quantifying human augmentation from wearable devices
Quantifying human augmentation from wearable devices
Common way to partition human vs. device dynamics

Whole-Body ↔ Augmented-Body
Whole-Body ↔ Augmented-Body

Common way to partition human vs. device dynamics

used to interpret how hard muscles are working
Whole-Body ↔ Augmented-Body

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)

prosimal interface

actuator cable

distal interface

Yandell et al. 2017 (JNER)
Whole-Body ↔ Augmented Body

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

Exosuit loading

Exosuit unloading

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.

Whole-Body ↔ Augmented Body

Yandell et al. 2017 (JNER)
75% of device work assists ankle over stride, but timing delayed
Neglecting interface dynamics affects scientific interpretation.
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
Hard to assess consistency

![Diagram showing muscle-tendon and joint-segment power analysis.](image-url)

- **Triceps Surae**
- **Flexor Dig. & Hal. Longus**
- **Peroneus Longus**

Ankle Power

1 W/kg

% Stride

0 100

Honert & Zelik 2016
What is mechanical function of foot during push-off in walking or running?

Acts like a spring!

Acts like a damper!

Ker et al. 1987
Stearne et al. 2016

Stefanyshyn & Nigg 1997
Takahashi & Stanhope 2013

Hard to assess, but literature suggests discrepancy
Muscle vs. Tendon ↔ Muscle-Tendon Unit (MTU)
Muscle vs. Tendon ↔ MTU

Ultrasound can track muscle fascicles, tendon or junction
Presumption: Tendon spring loaded in series with muscle

muscle = actuator

tendon = series spring
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

Alternative methods → more plausible tendon energy return

Track Muscle Fascicle

$L_m \cos(\alpha)$

$\text{skin}$

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

$1 \text{ J stored, } 2-5 \text{ J returned}$

Zelik & Franz 2017
Alternative methods → more plausible tendon energy return

**Track Muscle Fascicle**

\[ L_{\text{Tendon}} = L_{\text{MTU}} - L_m \cos(\alpha) \]

1 J stored, 2-5 J returned

**Track Muscle-Tendon Junction**

\[ L_{\text{Tendon}} = L_1 + L_{2,\text{MTJ}} \]

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

\[ L_{\text{Tendon}} = L_{\text{MTU}} - L_m \cos(\alpha) \]

1 J stored, 2-5 J returned

Track Muscle-Tendon Junction

\[ L_{\text{Tendon}} = L_1 + L_{2,\text{MTJ}} \]

1 J stored, 0.5-0.9 J returned

Track Local Tendon Elongation

\[ L_{\text{Tendon}} = L_1 + L_{2,T} \]

1 J stored, 0.7-1 J returned

Zelik & Franz 2017
Discrepancy → Partitioning muscle vs. tendon is complicated

suggests need to refine estimation methods

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

Multi-Scale Biomechanics is like IKEA Furniture

1. Human-device interface dynamics
2. Soft tissue contributions & completeness of estimates
3. Hard to assess, but potential knowledge gap
4. Suggest need to refine current methods
Discrepancies between scales provide important insights

Funding: NSF, NIH, DoD, Whitaker International Program, Vanderbilt University
Thanks: Mentors, role models, colleagues, collaborators, family, friends & students
Presentation Slides: Uploaded to my.vanderbilt.edu/batlab