Using Portable Physiological Sensors to Estimate Energy Cost for 'Body-in-the-Loop' Optimization of Assistive Robotic Devices

Kimberly Ingraham, Dan Ferris, C. David Remy
Department of Mechanical Engineering
University of Michigan

RAMlab
Robotics and Motion Laboratory

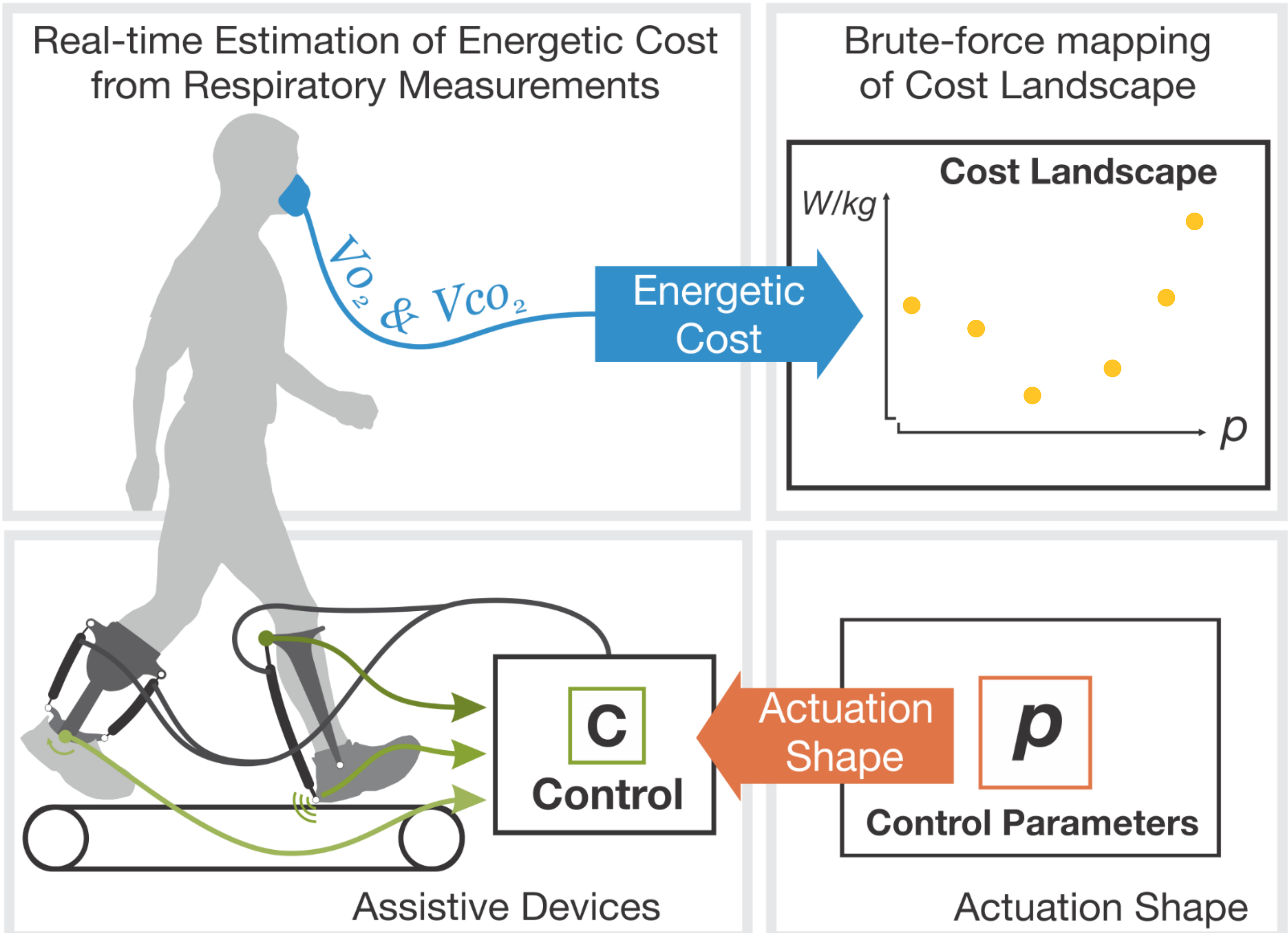
UNIVERSITY OF MICHIGAN

Lower Limb Assistive Robotic Devices

Research Prototypes

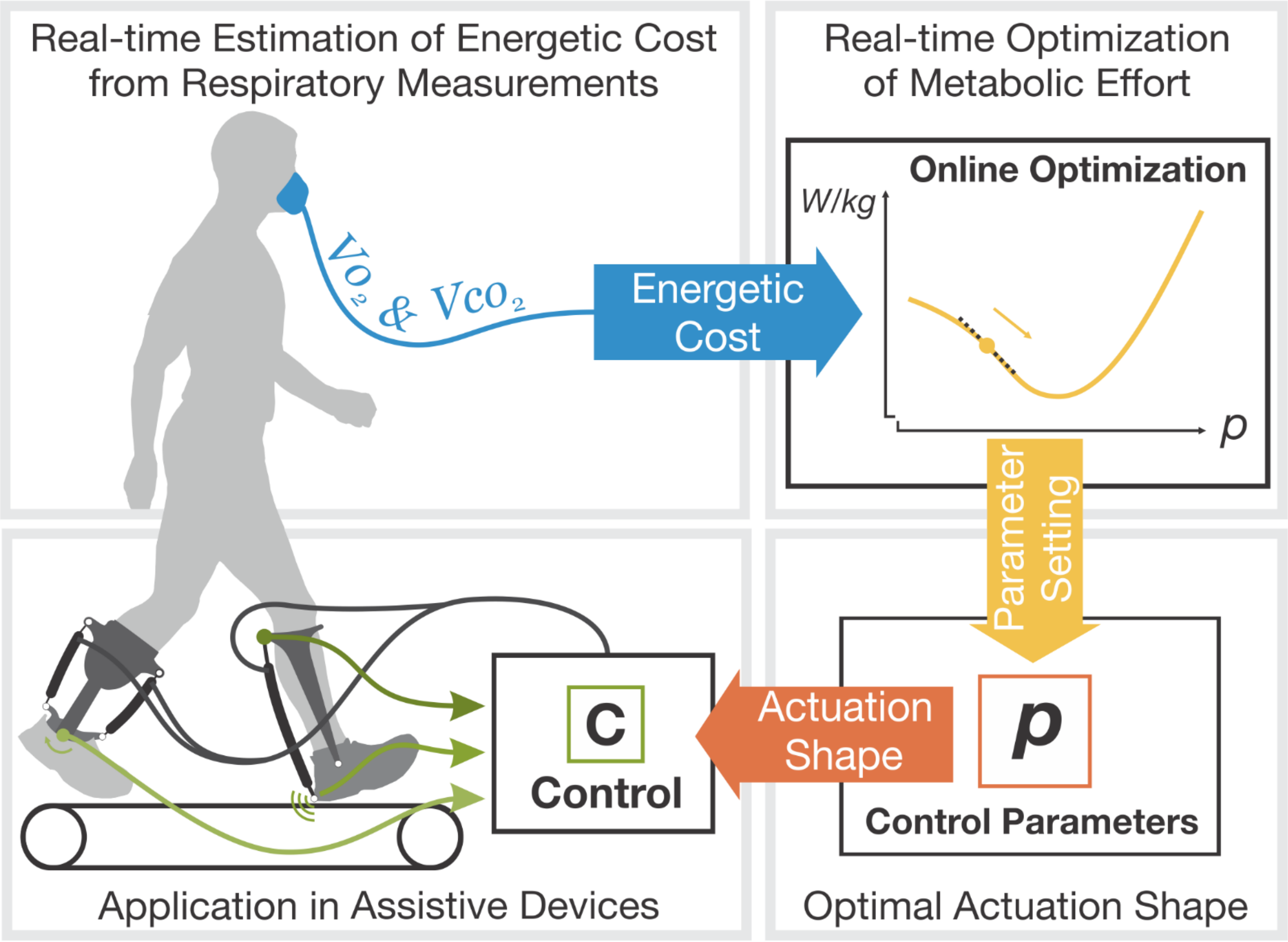
Commercial Devices

Evaluating Assistive Robotic Devices



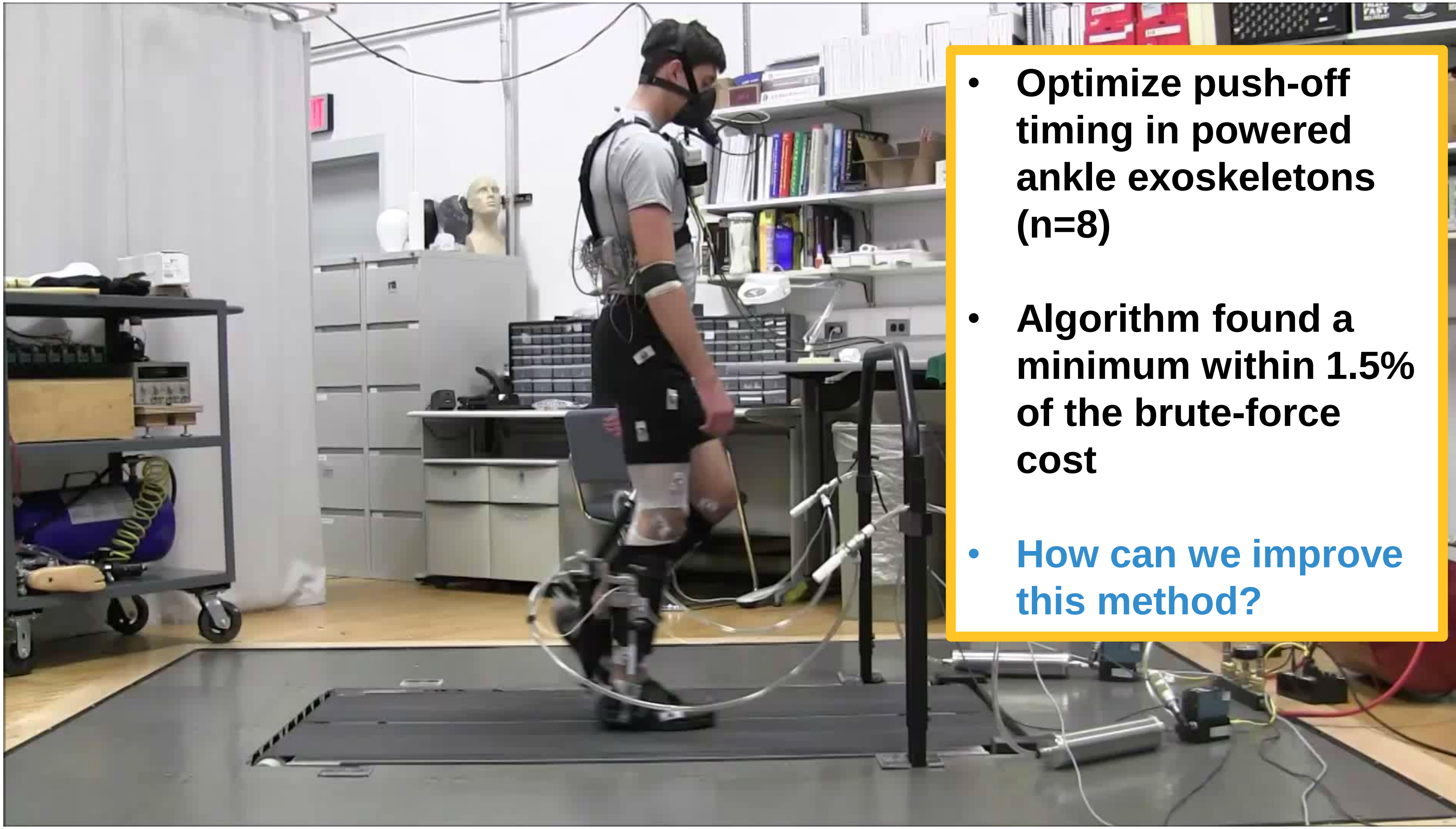
[Malcolm, 2013]

Body-in-the-Loop Optimization



[Koller, 2016; Felt, 2015]

Body-in-the-Loop Validation Study



- **Optimize push-off timing in powered ankle exoskeletons (n=8)**
- **Algorithm found a minimum within 1.5% of the brute-force cost**
- **How can we improve this method?**

[Koller, 2016]

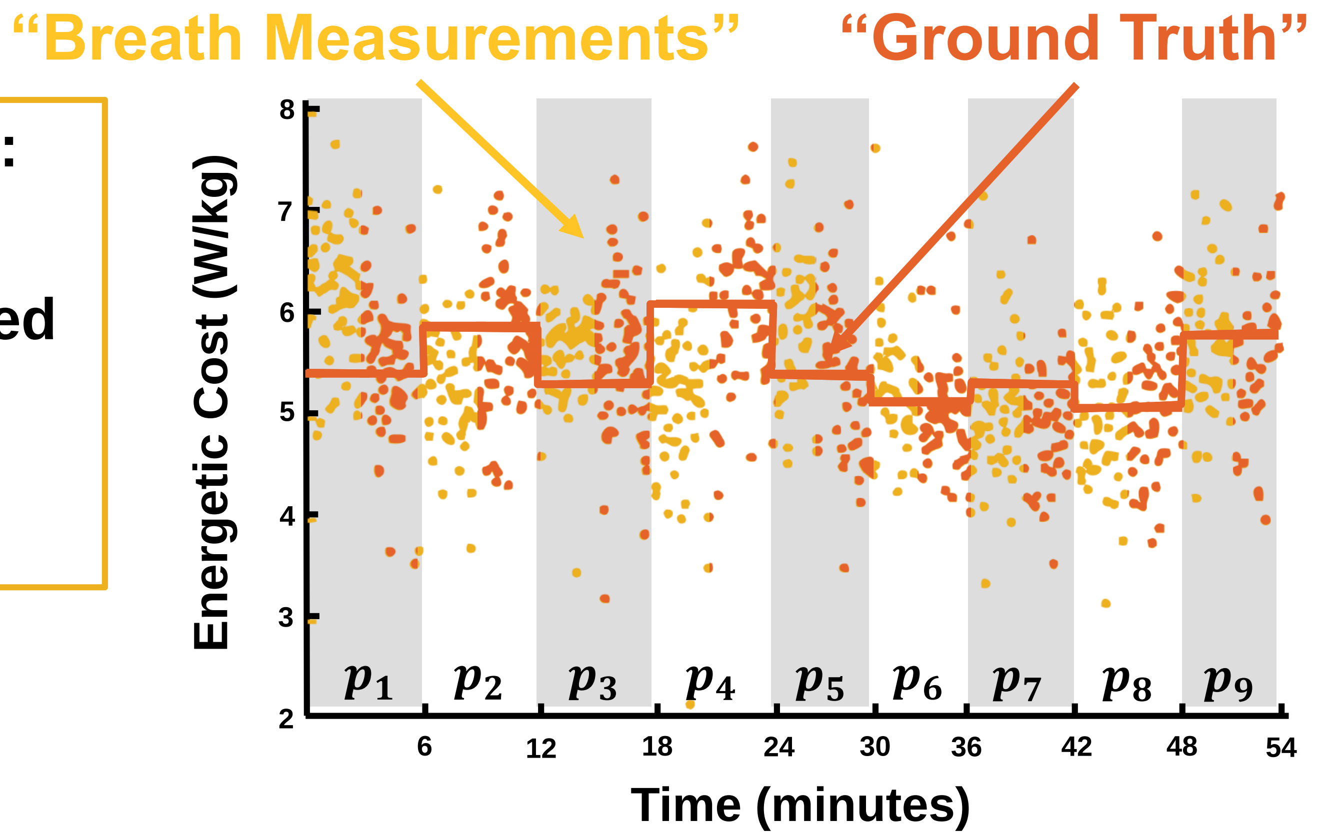
Challenges: Indirect Calorimetry

CHALLENGES:

Noisy

Sparsely sampled

Dynamically delayed



[Selinger, 2014; Lamarra, 1967]

Challenges: Indirect Calorimetry

<u>CHALLENGES</u>:

Noisy

Sparsely sampled

Dynamically delayed

Bulky Equipment

[Selinger, 2014; Lamarra, 1967]

RAMlab
Robotics and Motion Laboratory

Challenges: Indirect Calorimetry

<u>CHALLENGES</u>:

Noisy

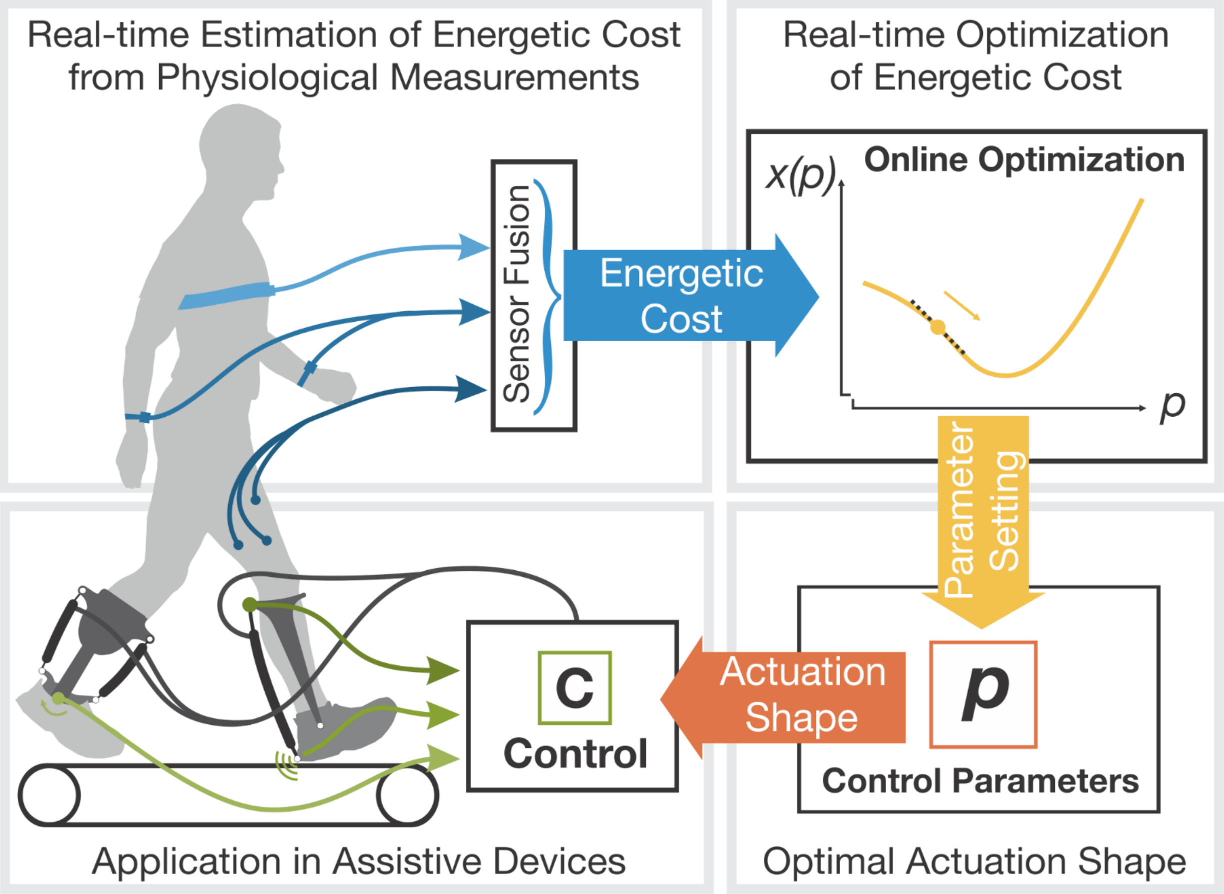
Sparsely sampled

Dynamically delayed

Bulky Equipment

<u>GOAL:</u>

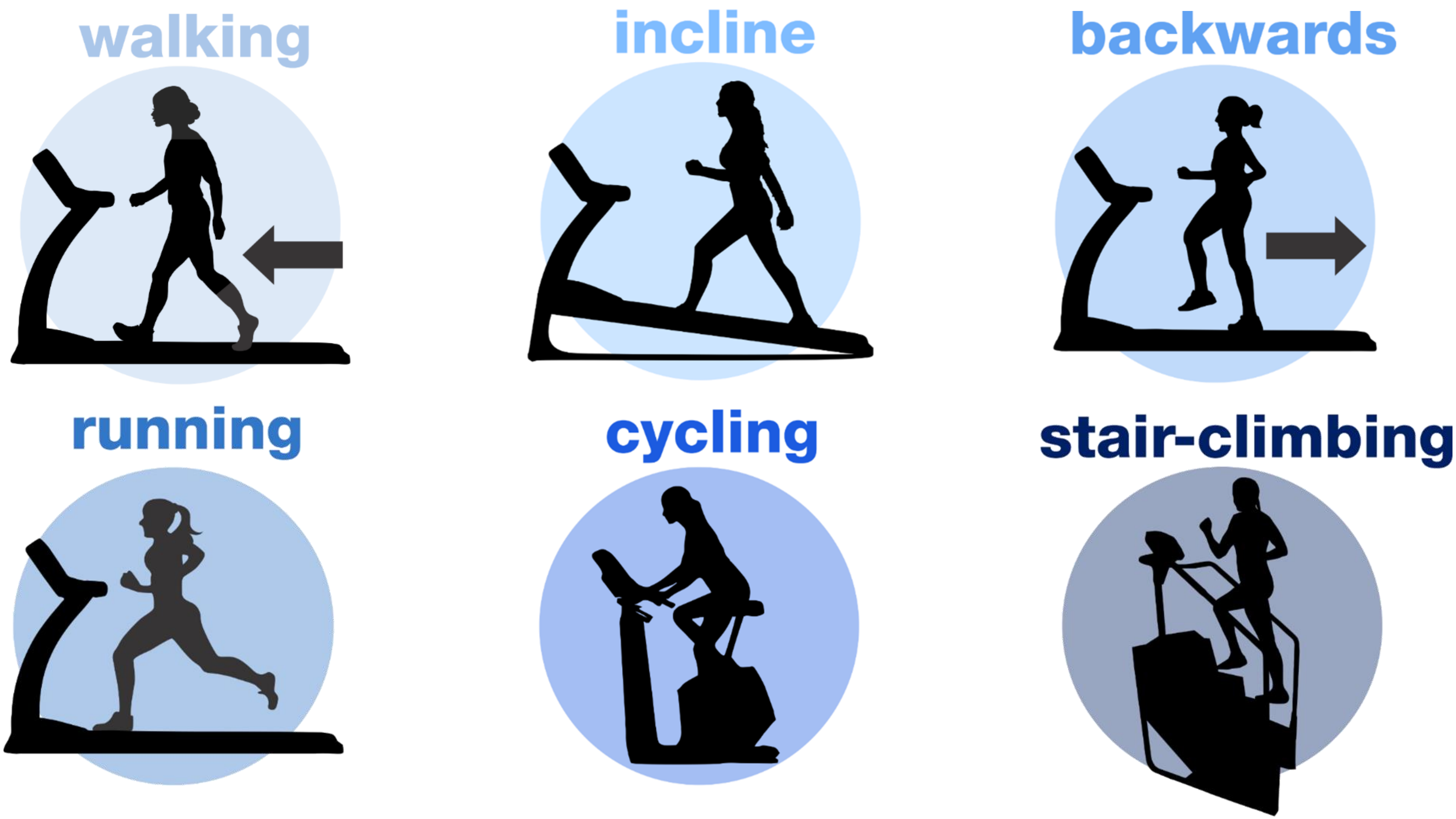
Investigate sensor alternatives for estimating energy cost



RAMlab Robotics and Motion Laboratory

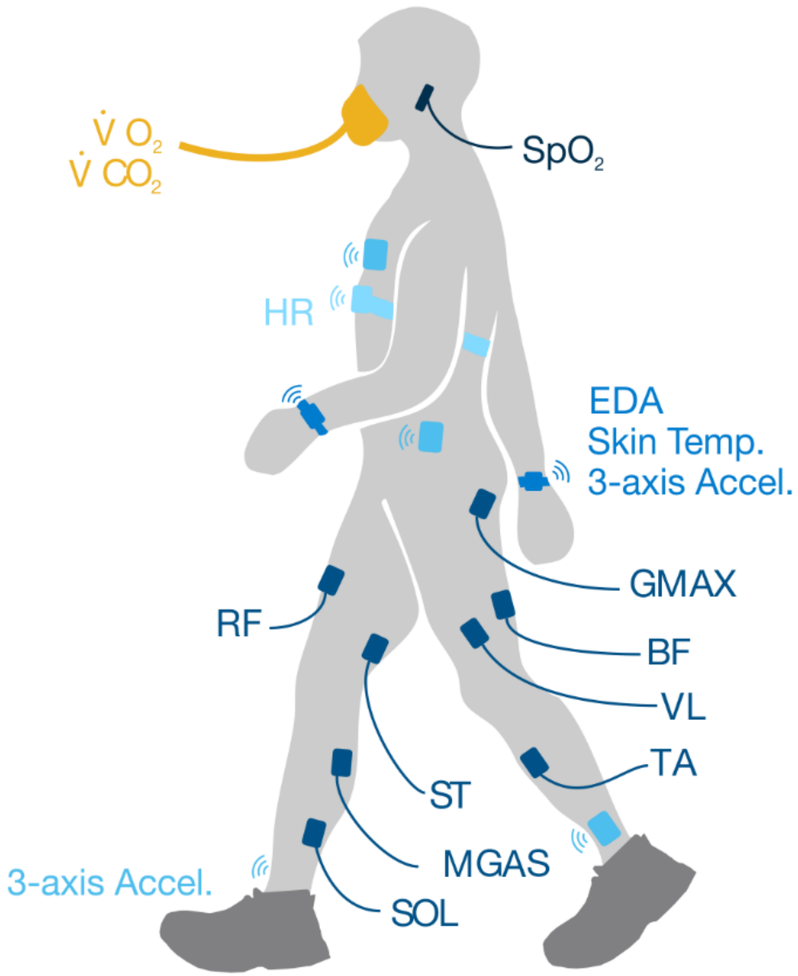
Experimental Data Collection

10 healthy subjects (8 male, 2 female)



RAMlab
Robotics and Motion Laboratory

Experimental Data Collection



- Heart rate monitor
- 3-axis accelerometers
- Wristbands (EDA, skin temp., 3-axis accel.)
- 16 lower-limb EMG
- Pulse oximeter (O_2 saturation)
- Indirect calorimetry

Feature Extraction

Local Signals

- Accelerations (x, y, z)
  - Vector magnitude = $\sqrt{x^2 + y^2 + z^2}$
  - 1-minute, 0.1 Hz Gaussian filter kernel
- EMG
  - Linear envelope = full wave rectify, low-pass filter
  - Composite sum = $\sqrt{\sum_{i=1}^{8} LinEnv(muscle)_i{}^2}$
  - 1-minute, 0.1 Hz Gaussian filter kernel

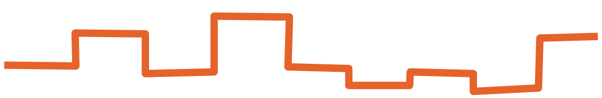
Global Signals

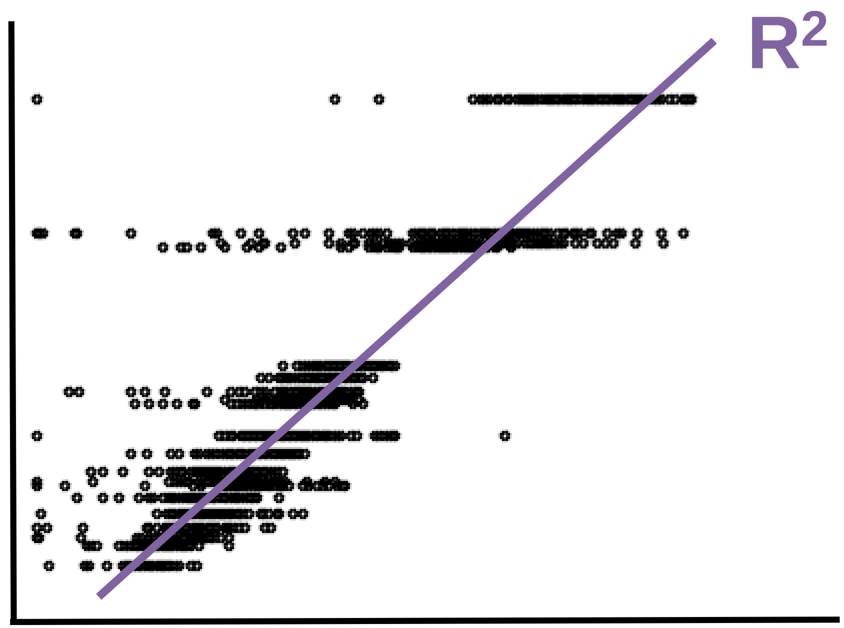
- SpO_2, HR, EDA, Skin temp.
  - 1-minute sliding window average

Multiple Linear Regression Models

- Multiple linear regression models trained for each subject (concatenated all activities)

Ground Truth Energy Cost (W/kg)



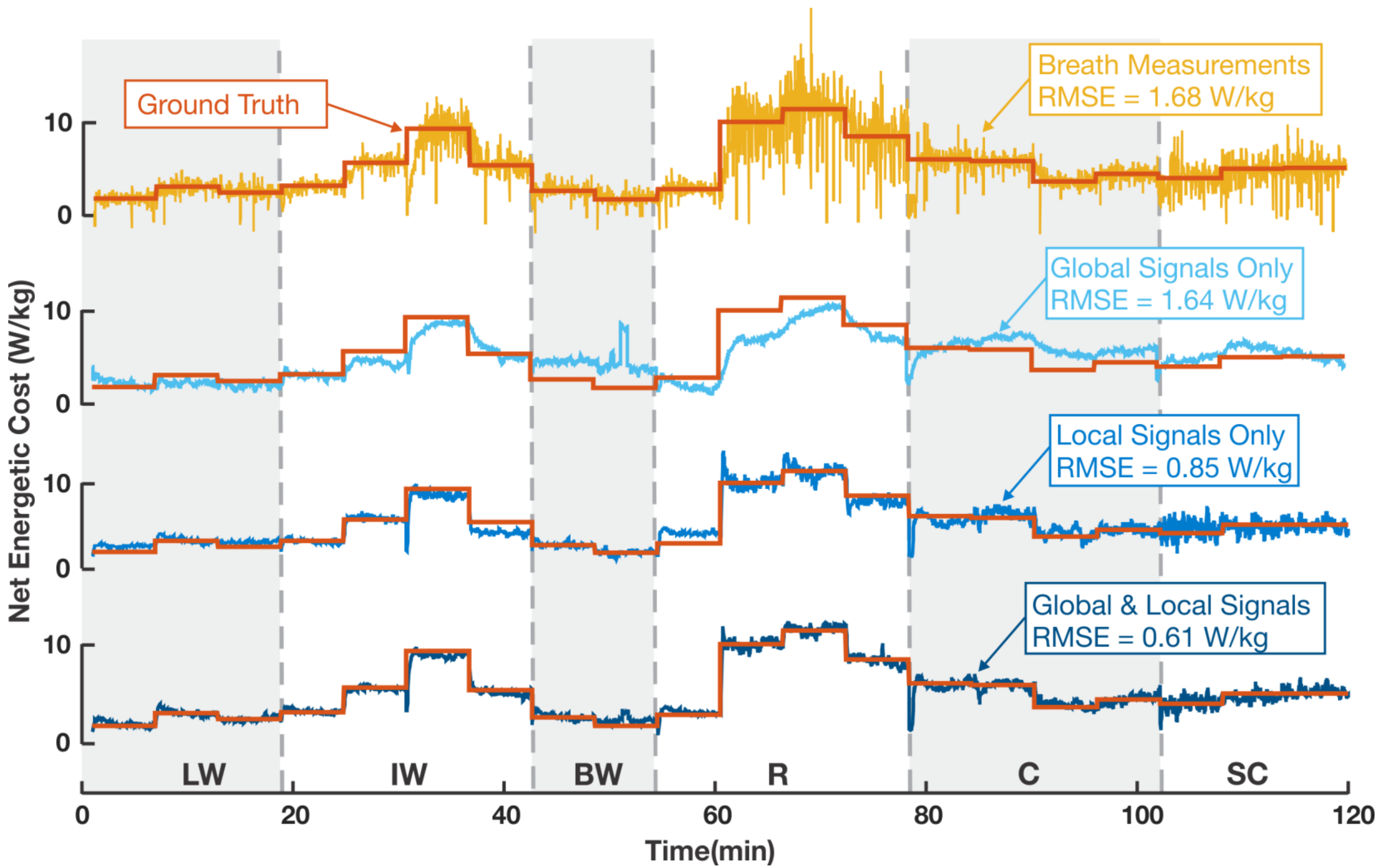


Various Combinations of Physiological Sensors

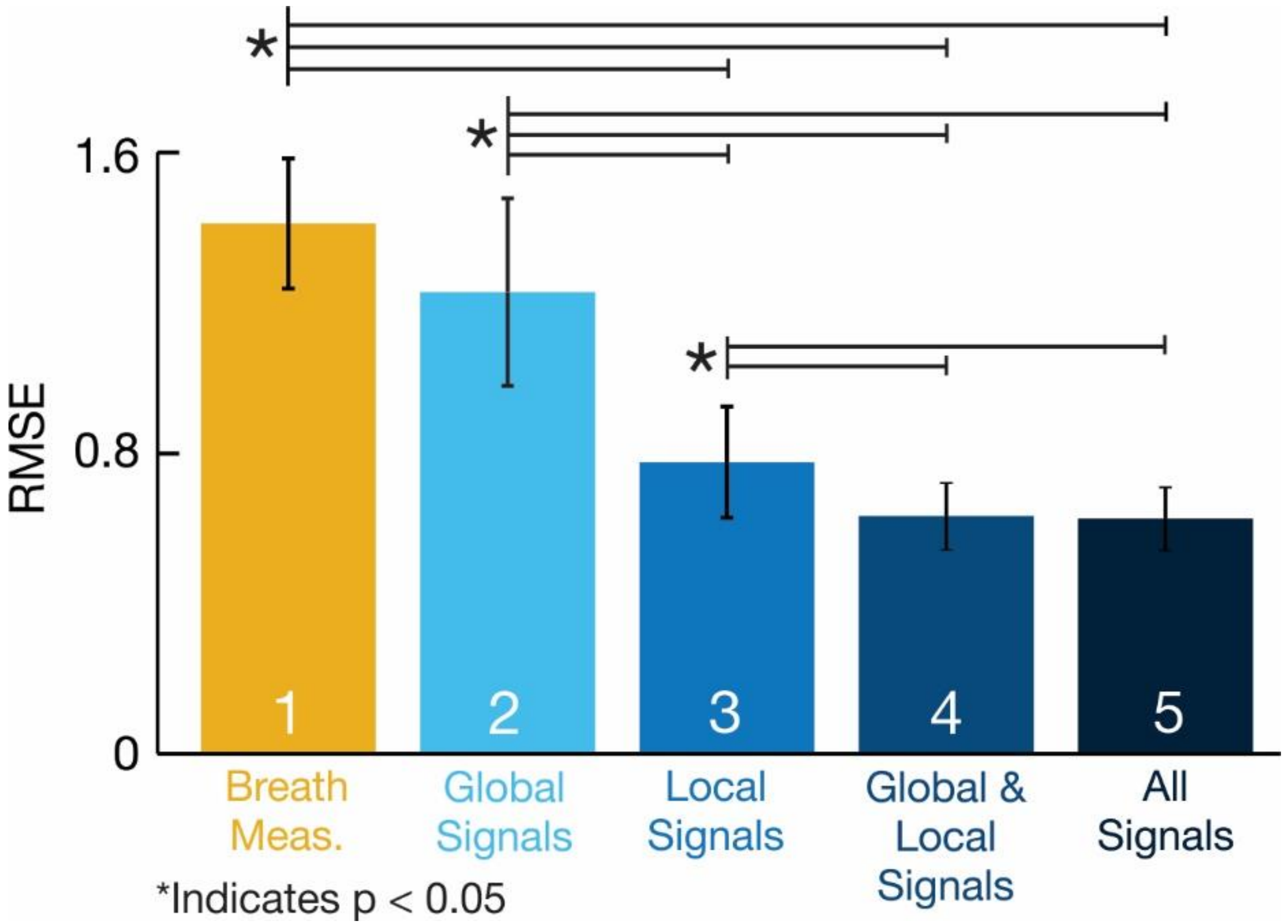
Multiple Linear Regression Models

		Global Signals				Local Signals		
Subset #	Breath Meas.	EDA	Skin Temp.	Heart Rate	SpO_2	Acc. Mag.	EMG Lin. Env.	R^2 Mean±SD
1	X							0.76±0.05
2		X	X	X	X			0.77±0.09
3						X	X	0.91±0.04
4		X	X	X	X	X	X	0.94±0.02
5	X	X	X	X	X	X	X	0.95±0.02

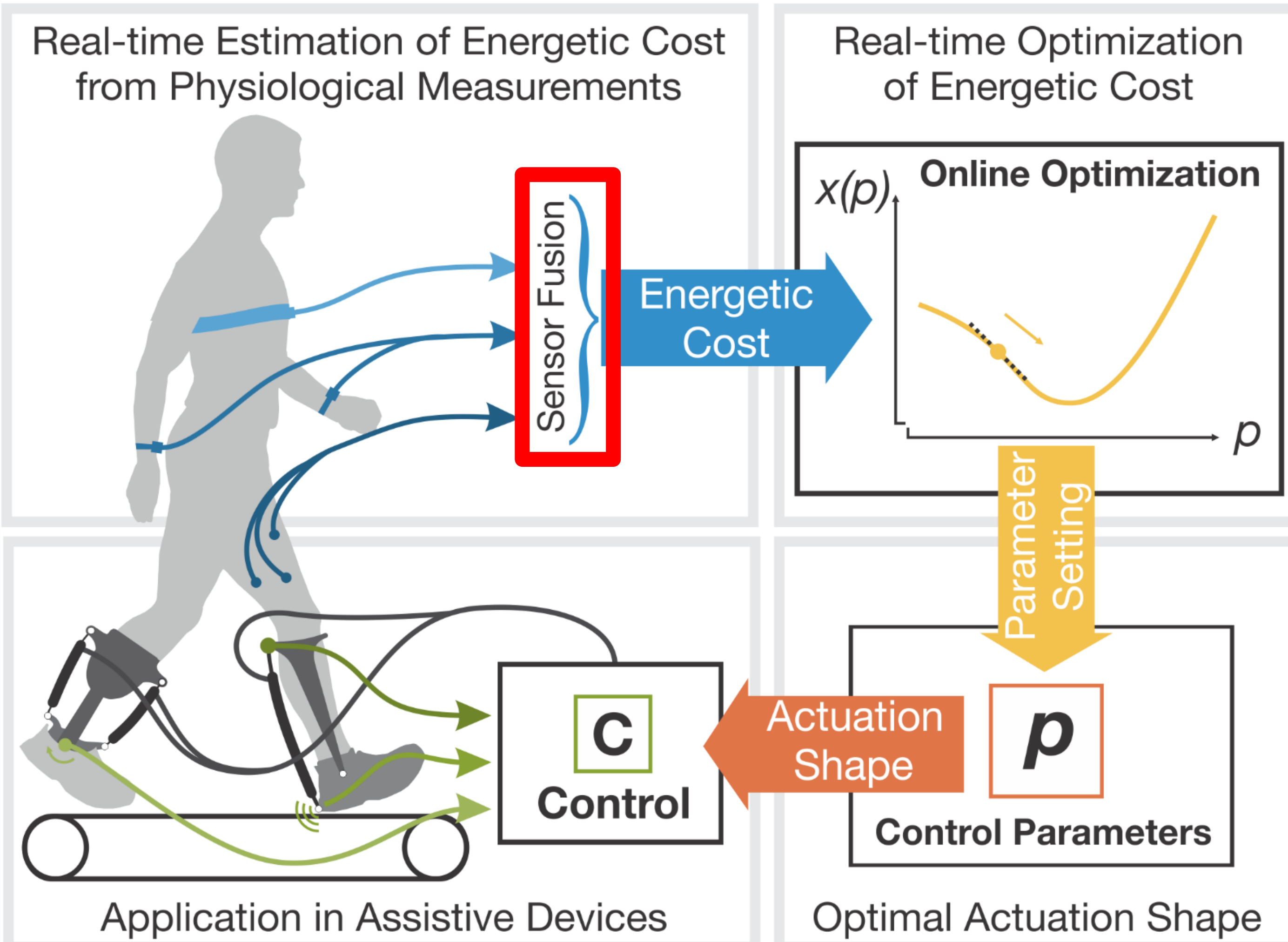
Time Series Predicted Energy Cost



Multiple Linear Regression Models



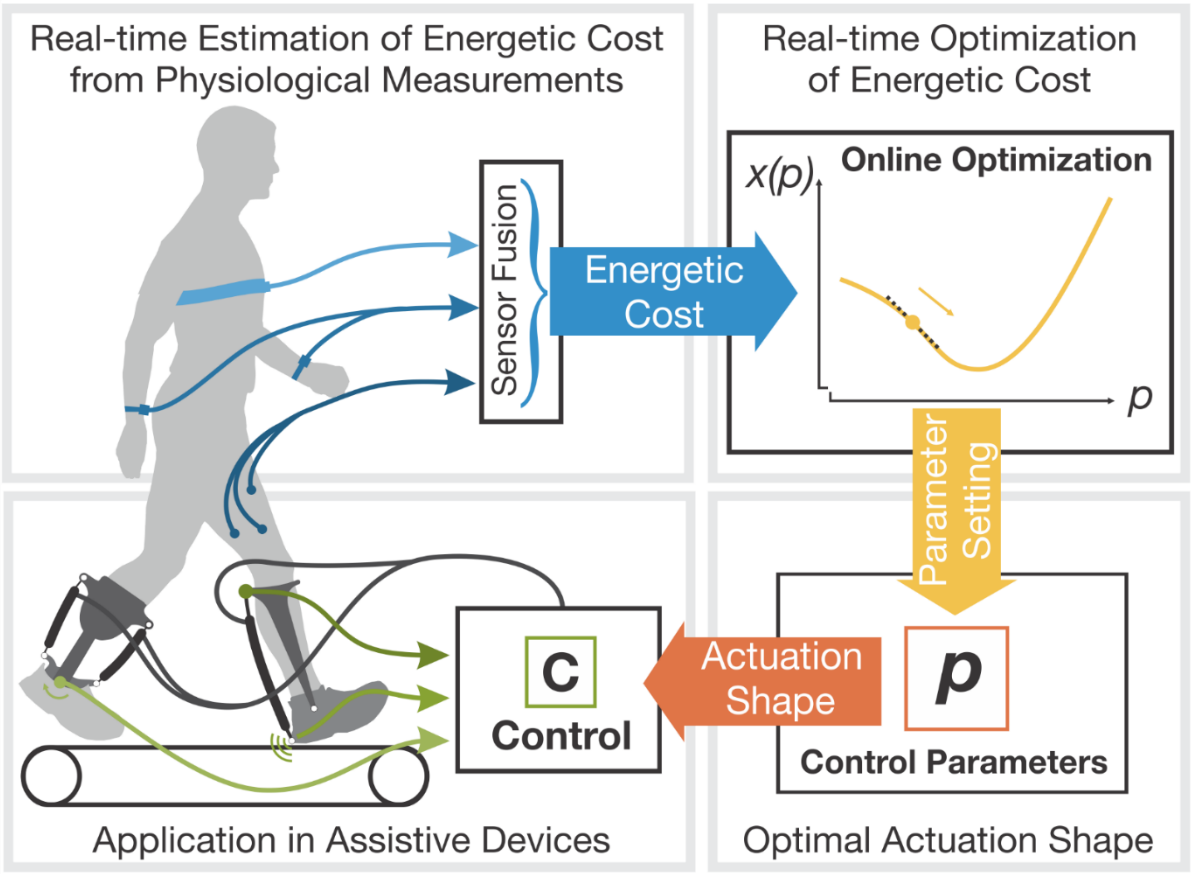
Future Directions



Questions?

Acknowledgements
C. David Remy
Dan Ferris
Jeff Koller

Funding sources



References

Malcolm, P., Derave, W., Galle, S., & De Clercq, D. (2013). A Simple Exoskeleton That Assists Plantarflexion Can Reduce the Metabolic Cost of Human Walking. *PLoS One*, *8*(2), 1–7.

Felt, W., Selinger, J. C., Donelan, J. M., & Remy, C. D. (2015). "Body-In-The-Loop": Optimizing Device Parameters Using Measures of Instantaneous Energetic Cost. *PLoS One*, *10*(8), e0135342.

Koller, J. R., Gates, D. H., Ferris, D. P., & Remy, C. D. (2016). "Body-in-the-Loop" Optimization of Assistive Robotic Devices: A Validation Study. In *Robotics: Science and Systems* (pp. 1–10). Ann Arbor, MI.

Selinger, J. C., O'Connor, S. M., Wong, J. D., & Donelan, J. M. (2015). Humans Can Continuously Optimize Energetic Cost during Walking. *Current Biology*, *25*, 1–5.

Lamarra, N., Whipp, B. J., Ward, S. A., & Wasserman, K. (1967). Effect of interbreath fluctuations on characterizing exercise gas exchange kinetics. *Journal of Applied Physiology*, *62*(5), 2003–2012.