The Cost of Asymmetry during Healthy and Pathological Gait

James M. Finley, PhD

Assistant Professor

Director, Locomotor Control Lab

@FinleyLabUSC, @jamesmfinley

USC Division of Biokinesiology and Physical Therapy

University of Southern California

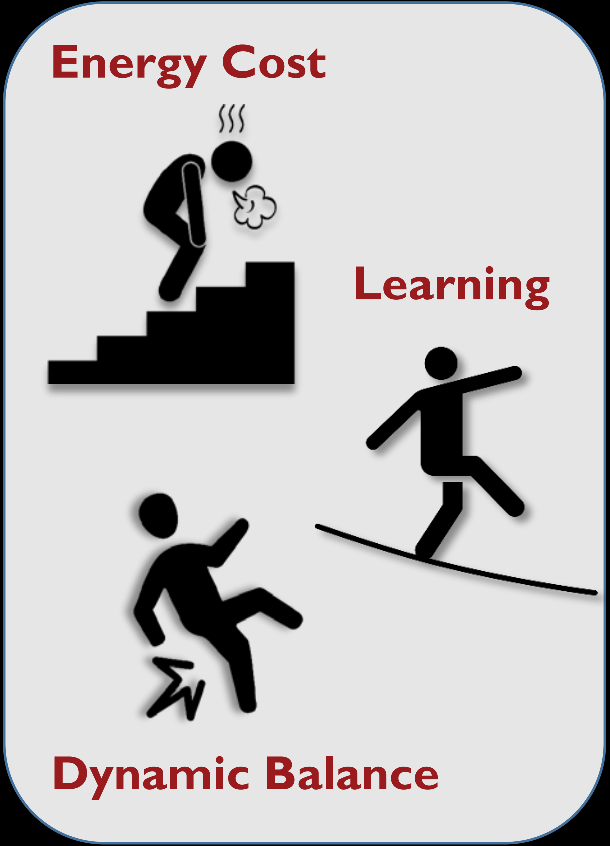
Locomotor Control Lab

Neurological Impairments

Stroke

Parkinson’s disease

Locomotor Function



Energy Cost

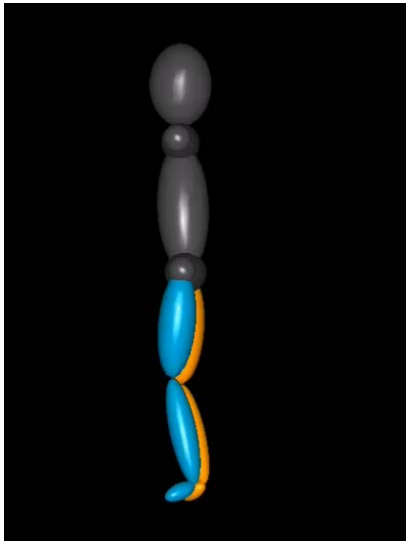
Learning

Dynamic Balance

Context and Content of Therapy

Asymmetries are a hallmark of locomotion in many impaired populations

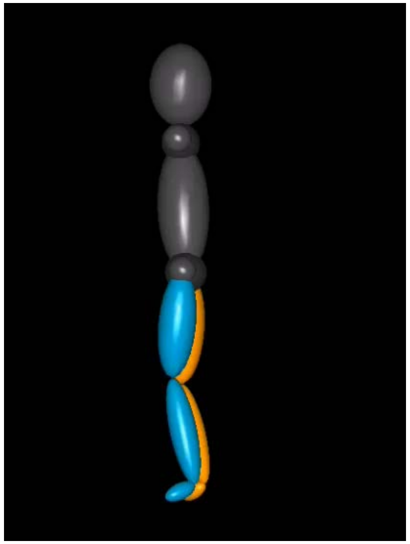
Amputees



People post-stroke

Asymmetries are a hallmark of locomotion in many impaired and *unimpaired* populations

Amputees



People post-stroke

Home

The New York Times

SPORTS

Something Strange in Usain Bolt's Stride

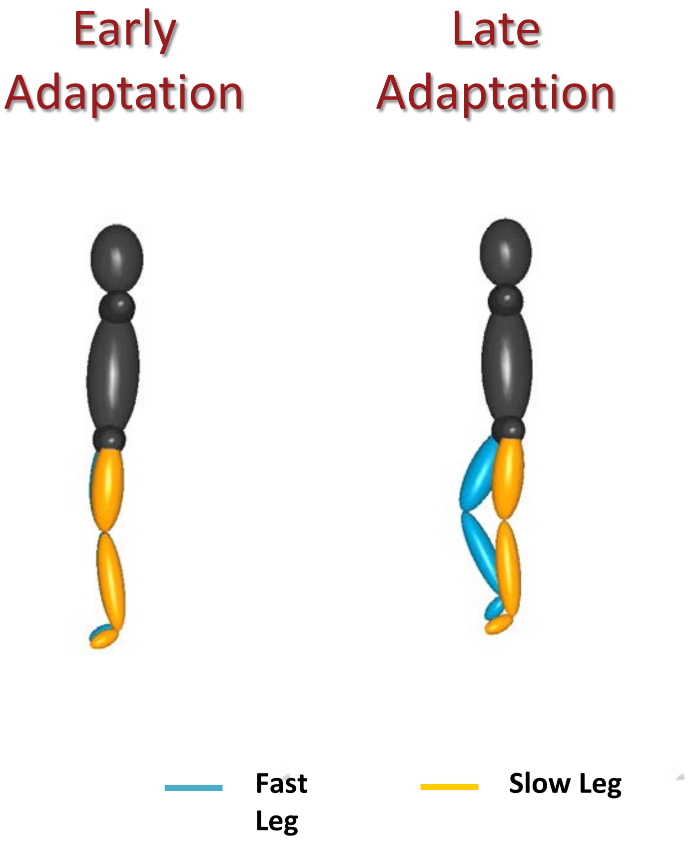
Bolt is the fastest sprinter ever in spite of — or because of? — an uneven stride that upends conventional wisdom.

By JERÉ LONGMAN JULY 20, 2017

New York Times & SMU Performance Lab

- How do people regulate symmetry during walking?
- What are the functional consequences of asymmetry?
- Do reductions in asymmetry lead to enhanced function?

Exploring adaptation to imposed asymmetries using a dual-belt treadmill



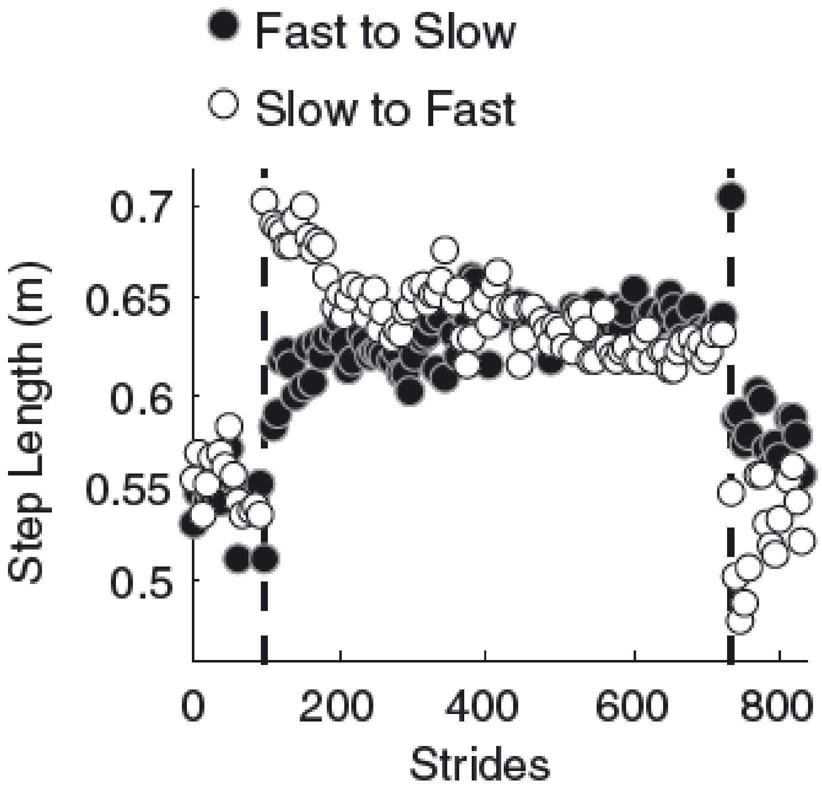
Early Adaptation

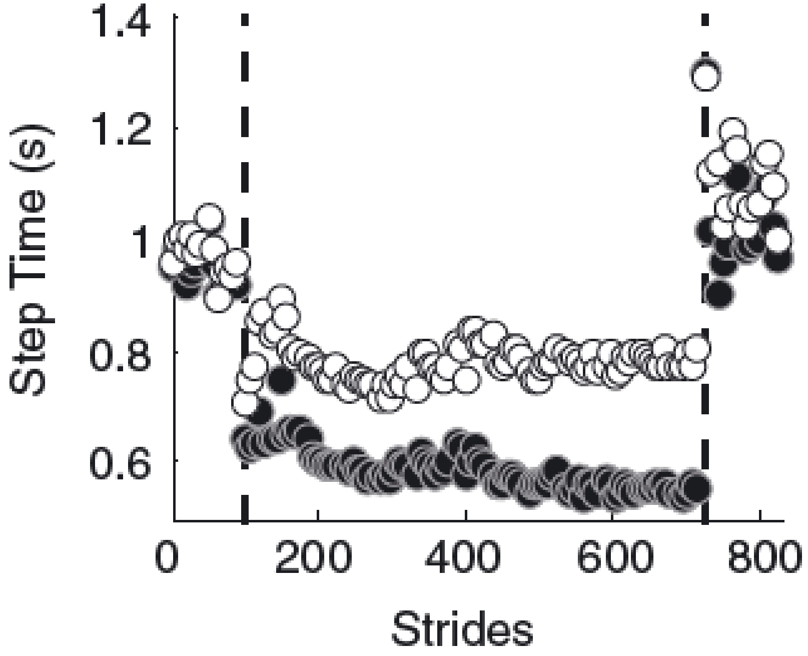
Late Adaptation

Dietz et al., 1994, Exp Brain Res
Reisman et al., 2005, J Neurophys
Finley et al., 2013, J Physiol

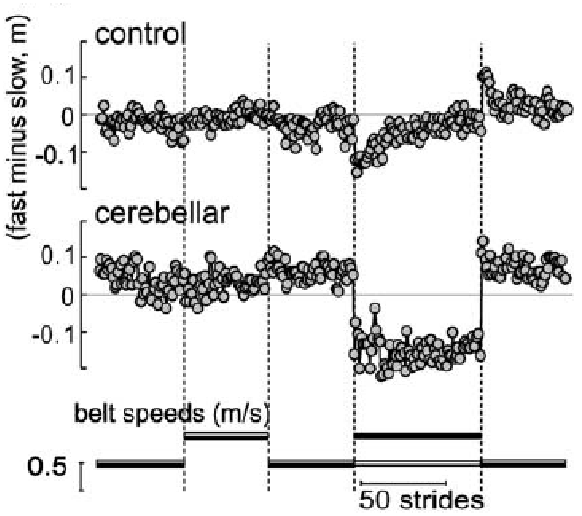
Adaptation results in **steps of equal length**…

and ***asymmetries* in step time** …



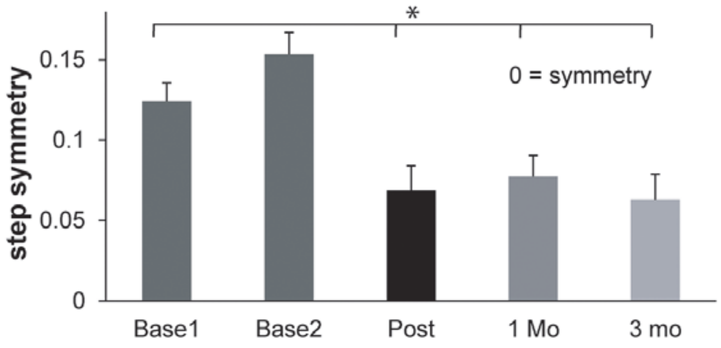


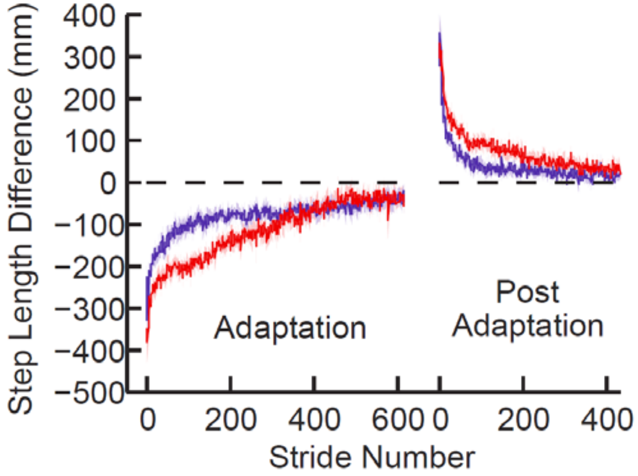
Finley et al., 2013, J Physiol



- Damage to the cerebellum impairs adaptation (Morton and Bastian, 2006)

- Repeated split-belt adaptation can lead to long-term reductions in asymmetry post-stroke (Reisman et al., 2013)





- Adaptation can be induced on a standard treadmill if one foot marches in place (Long et al., 2015)

Is asymmetry energetically costly?

Why are **symmetric** step lengths preferred given **asymmetric constraints** (belt speeds)?

Is asymmetry associated with reduced stability?

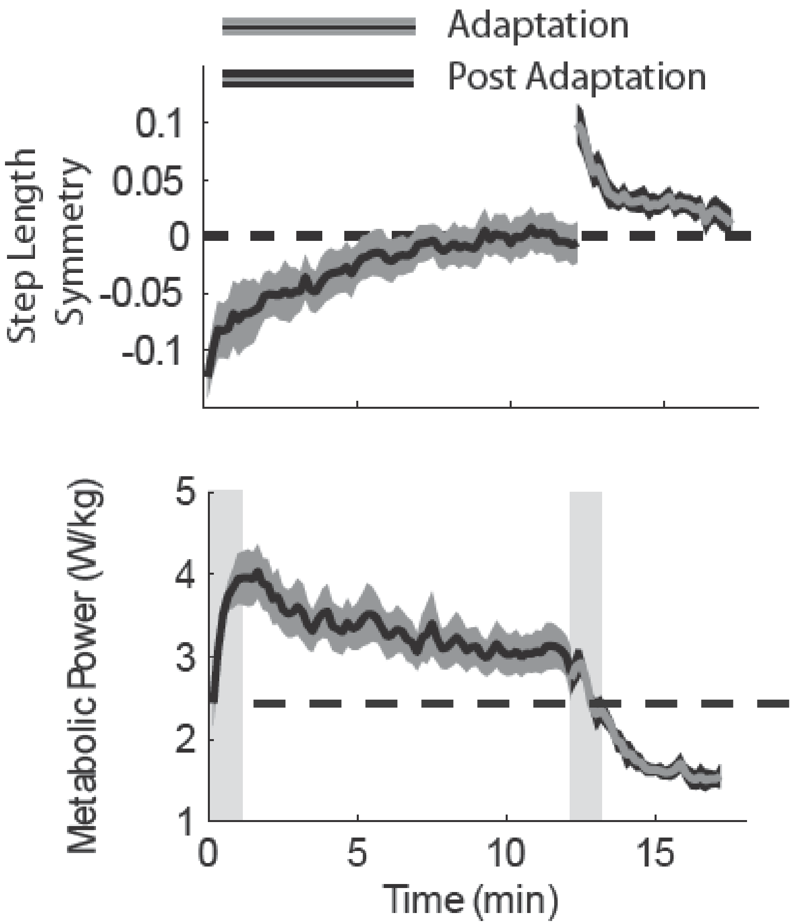
Evidence of energy minimization in human locomotion

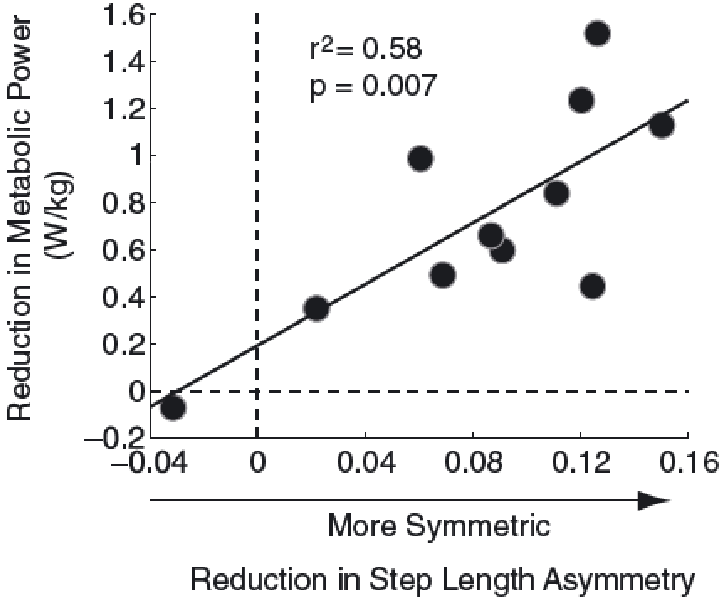
1. Preferred **speed** typically near theoretically optimal speed of 1.3 m/s (Zarrugh et al., 1974; Ralston, 1976, Bastien et al., 2005)

2. Preferred **stride length** across multiple speeds minimizes energetic cost (Cavanagh and Williams, 1982; Bertram and Ruina, 2001; Kuo, 2001)

3. Preferred **step width** is energetically optimal (Donelan et al., 2001)

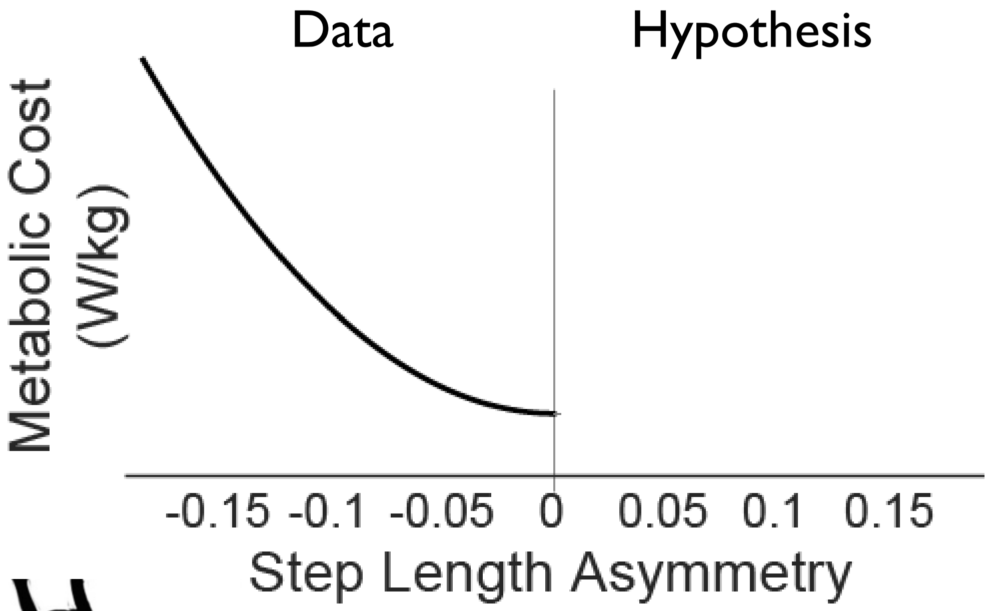
Reduction of asymmetry is associated with a reduction in metabolic cost

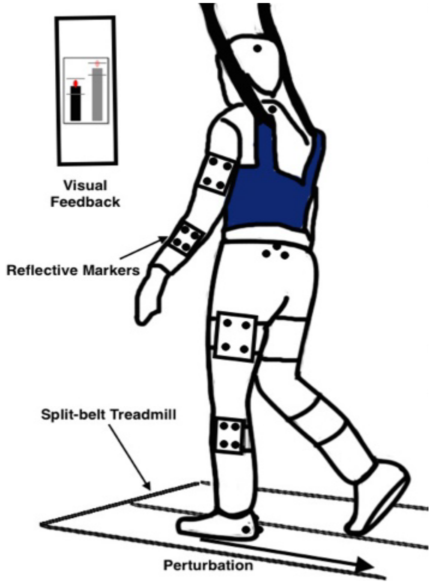


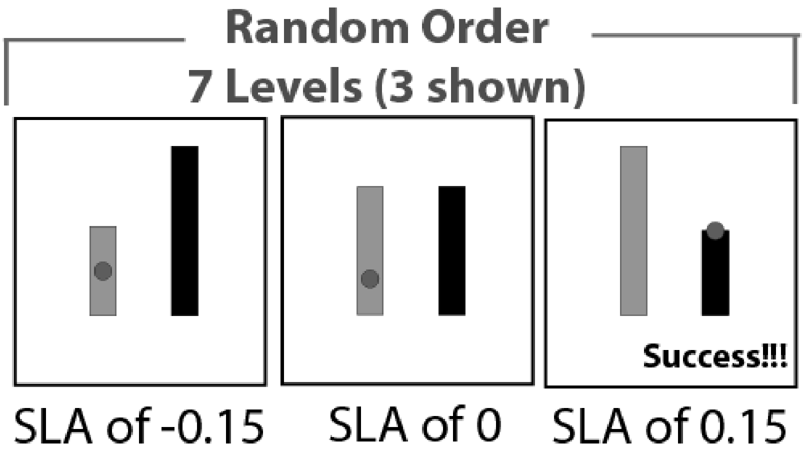


Finley, Bastian, and Gottschall, 2013, J Physiology

Do symmetric step lengths *minimize* energetic cost?

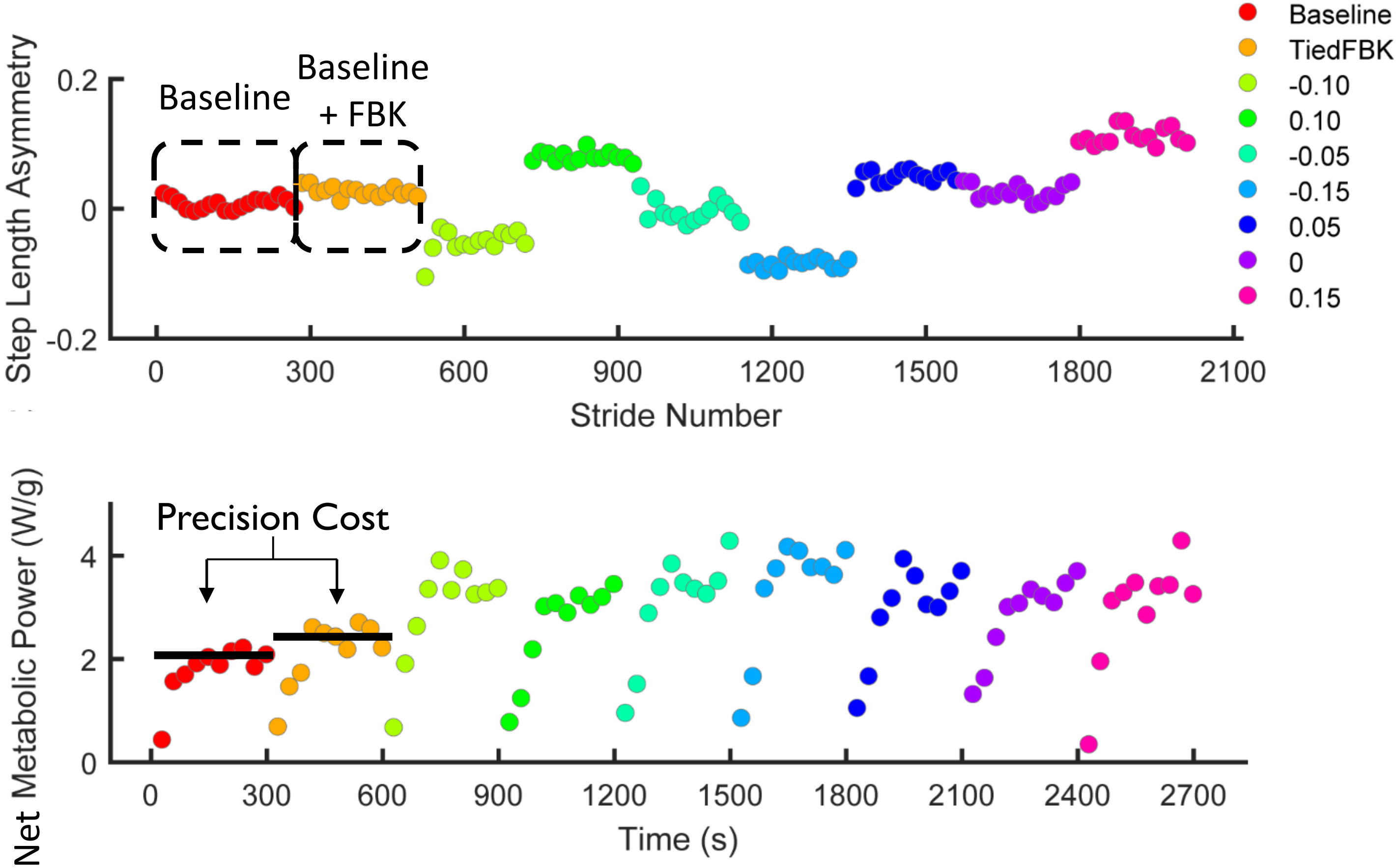






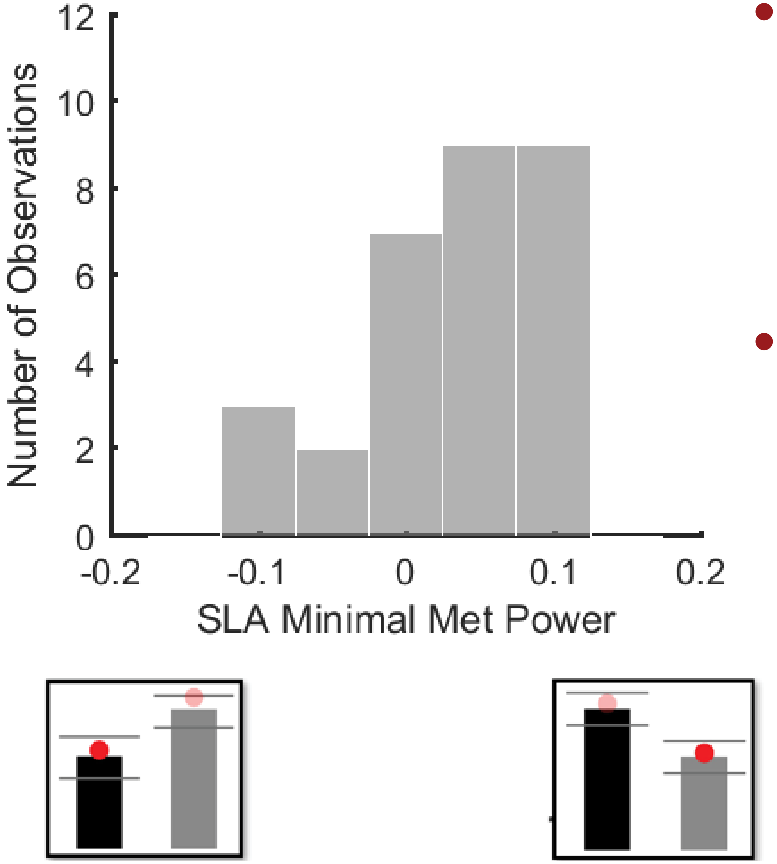
Sanchez, Park, and Finley, 2017, Scientific Reports

Experimental protocol



Sanchez, Park, and Finley, 2017, Scientific Reports

Symmetry is ***not the metabolically optimal solution*** for walking on a split-belt treadmill



- Positive asymmetries, which are ***not observed during adaptation***, were frequently optimal
- The optimal strategy had a cost savings of ~0.25 W/kg relative to symmetry (~6%)

Sanchez, Park, and Finley, 2017, Scientific Reports

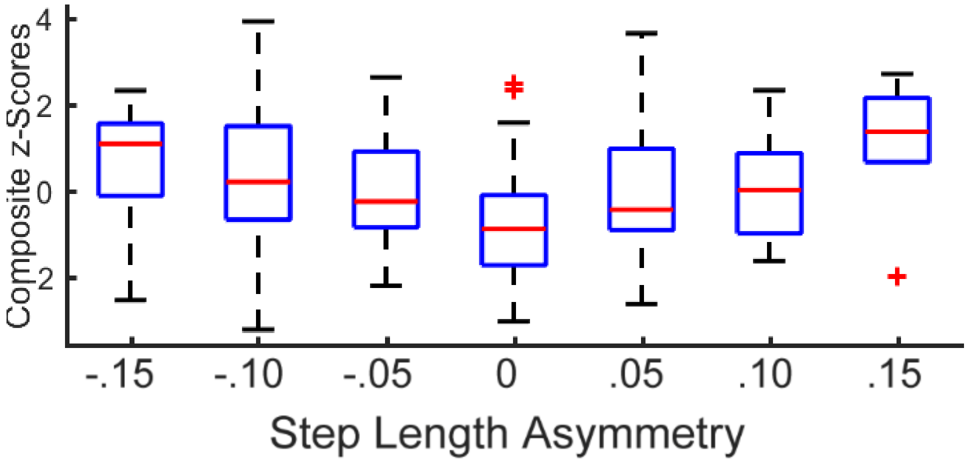
What is the best proxy of how the brain represents effort?

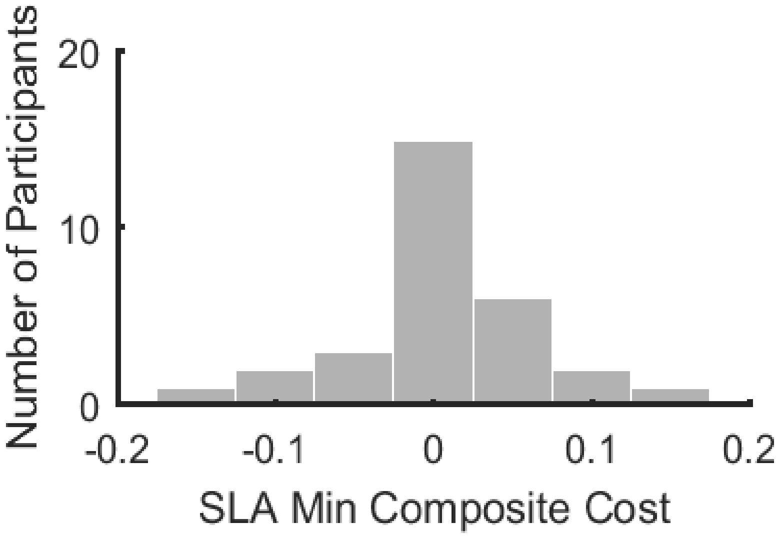
- Potential neural correlates of effort
  - Estimates of blood gas concentration (Bellville et al. 1979; Smith et al. 2006)
  - Corollary discharge or efference copy: Internal representation of the magnitude of descending motor commands (Sperry, 1950; von Holst and Mittelstaedt, 1950)
  - Estimates of cognitive effort (Chong et al., 2017; Schmidt et al., 2012)
  - Peripheral sensory feedback
    - Cutaneous receptors: pressure
    - Golgi tendon organs: muscle force
    - Group IV afferents: muscle metabolism

Effort is a neural/psychological construct and may be better represented using **composite estimates**

Symmetry is optimal when effort is represented as a **composite of mechanical and metabolic cost**

- Composite cost computed by summing z-score normalized measures of metabolic cost and propulsive impulses

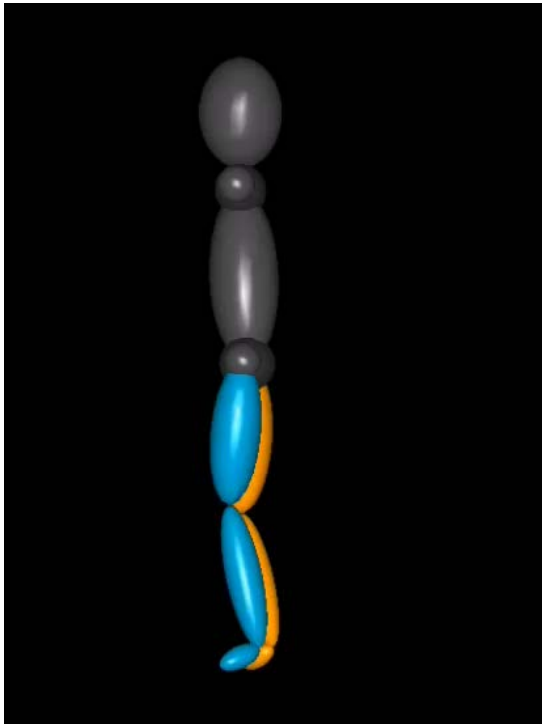




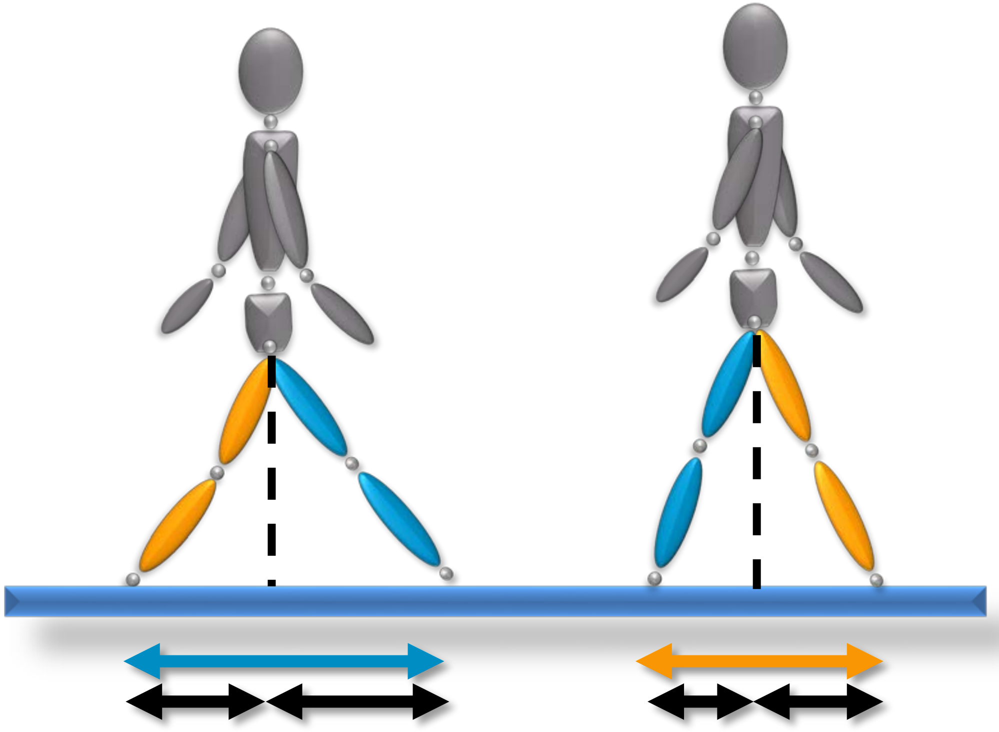
Sanchez, Park, and Finley, 2017, Scientific Reports

Is spatiotemporal asymmetry sub-optimal post-stroke?

- Asymmetries in foot placement and timing (Chen et al, 2005; Hsu et al, 2003)
- Higher metabolic cost than healthy individuals (Waters and Mulroy, 1999)



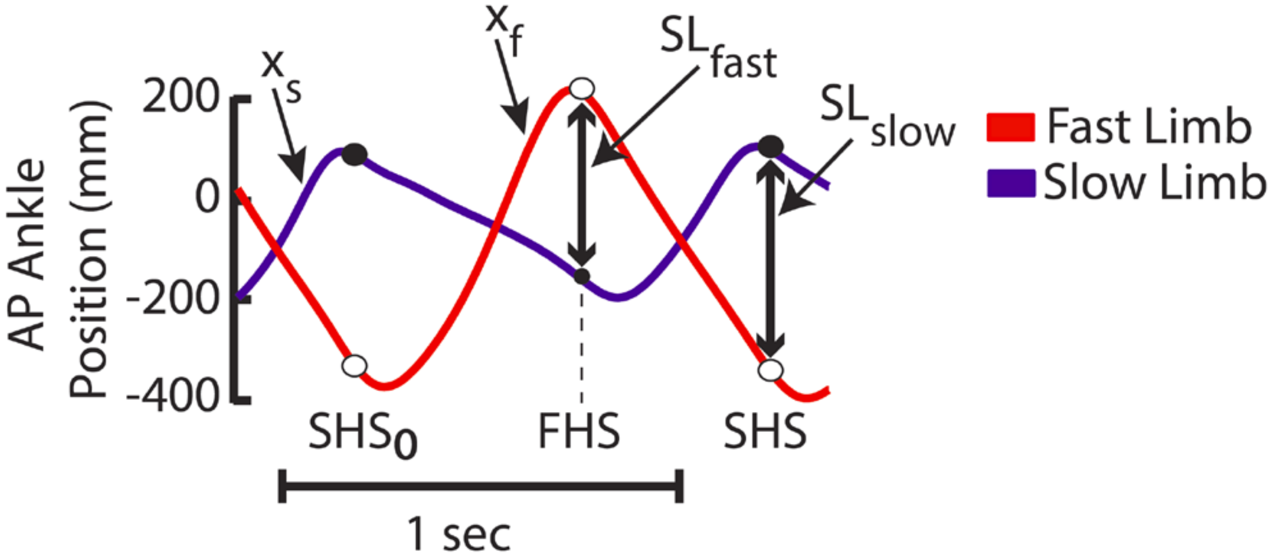
Asymmetries in Step Length



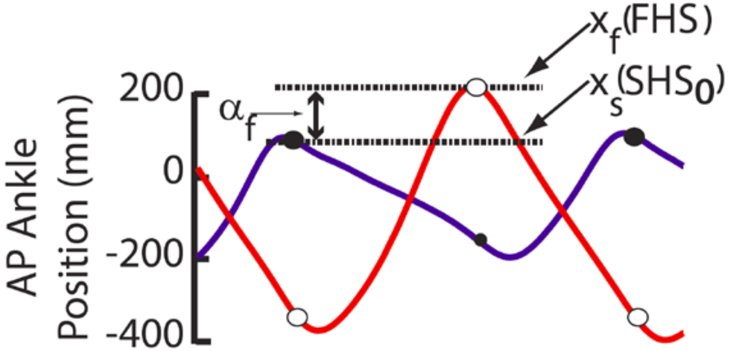
Long step

Short step

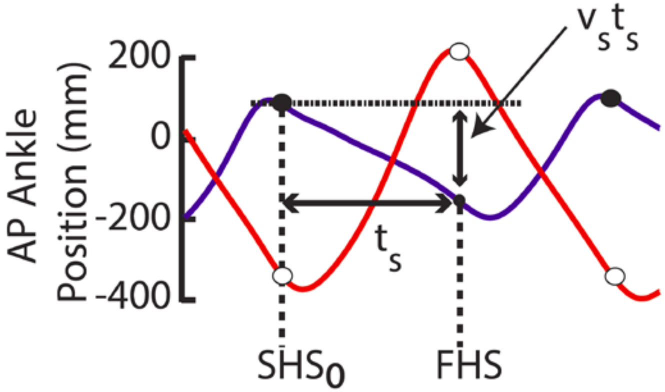
Spatial and temporal contributions to step length asymmetry



Spatial Contribution

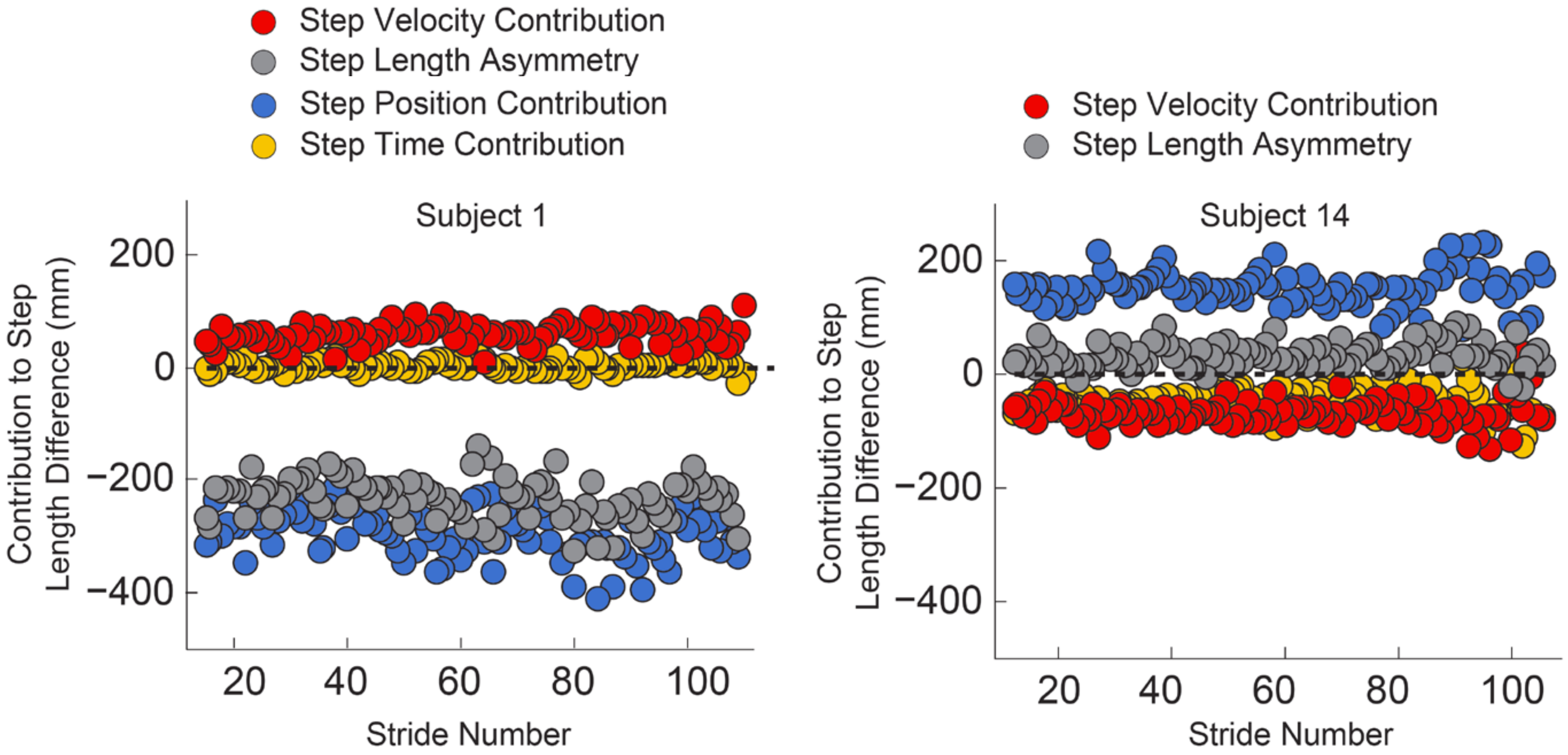


Temporal Contribution



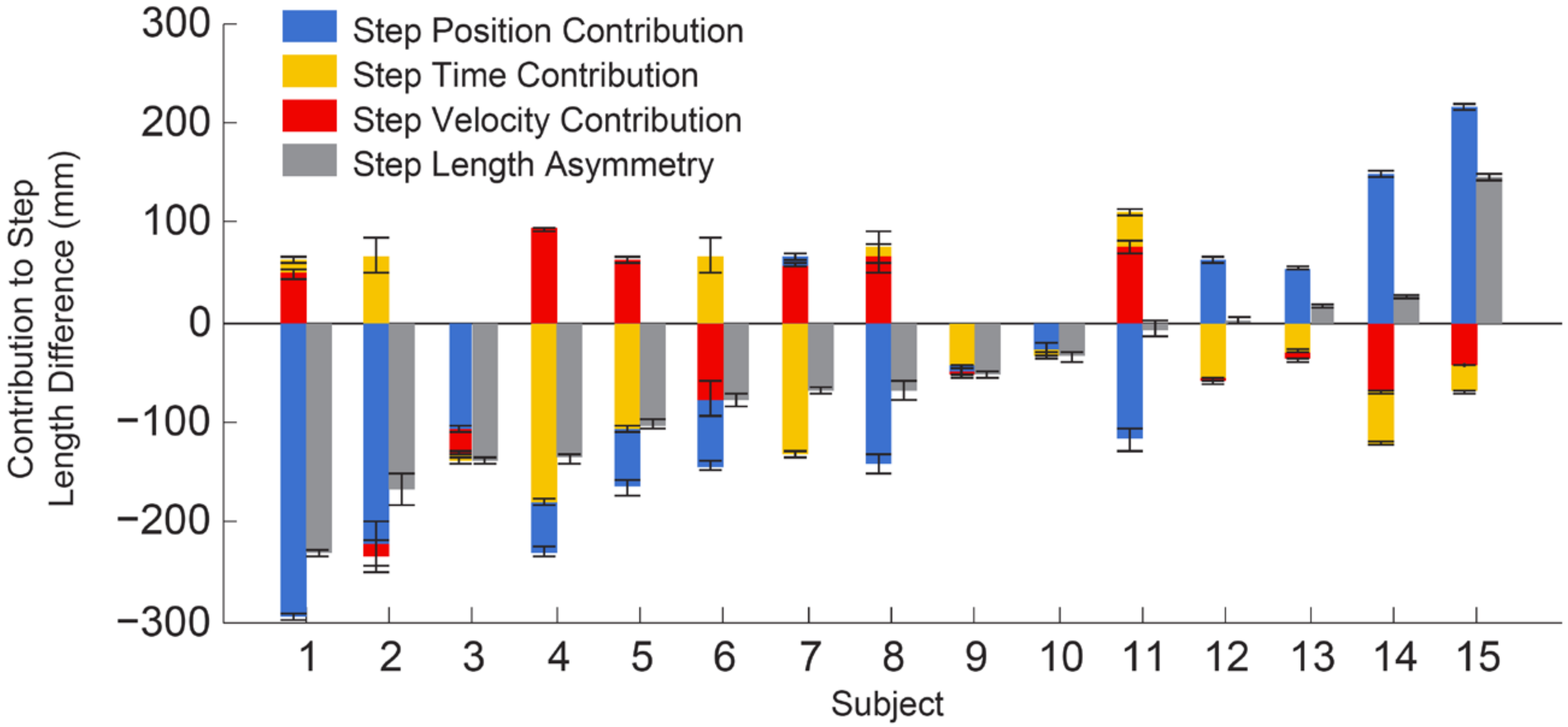
$$SL_{diff} = \underbrace{(\alpha_f - \alpha_s)}_{\text{Step Position}} + [\underbrace{(v_s + v_f)/2 * (t_s - t_f)}_{\text{Step Time}}] + [\underbrace{(t_s + t_f)/2 * (v_s - v_f)}_{\text{Step Velocity}}]$$

Examples of spatial and temporal contributions to step length asymmetry post-stroke



Finley et al., 2015, Neurorehab and Neural Rep

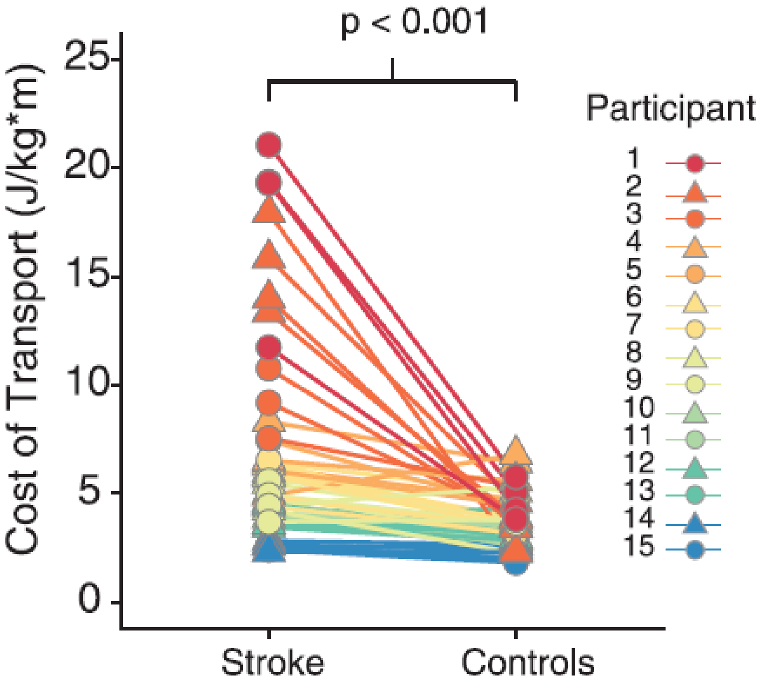
Spatiotemporal asymmetries are heterogeneous post-stroke

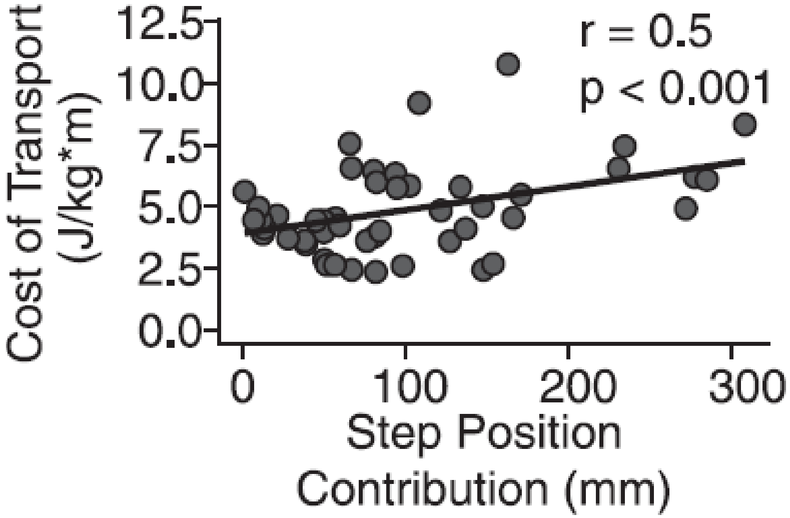


- Spatiotemporal asymmetries in people post-stroke differ in direction, magnitude, and **composition**

Finley et al., 2015, Neurorehab and Neural Rep

Asymmetries during walking in people post-stroke are associated with increased energetic cost



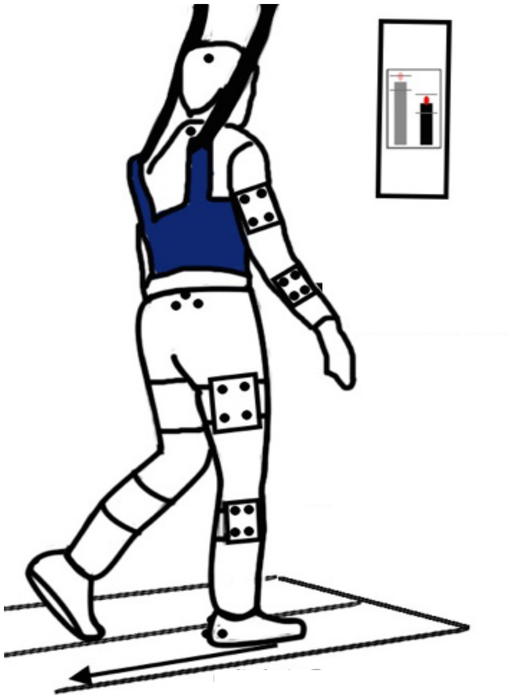


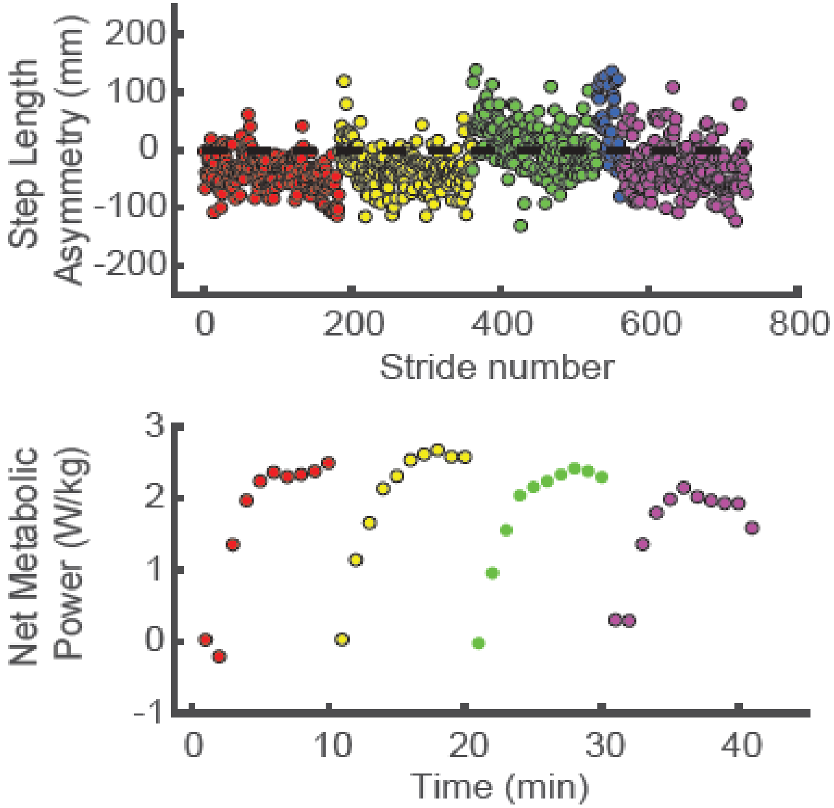
1. Can people post-stroke voluntarily reduce asymmetry?
2. Do *reductions in asymmetry* reduce metabolic cost?

Finley and Bastian, 2017, Neurorehab and Neural Rep

People post-stroke retain the capacity to *voluntarily* reduce step length asymmetry

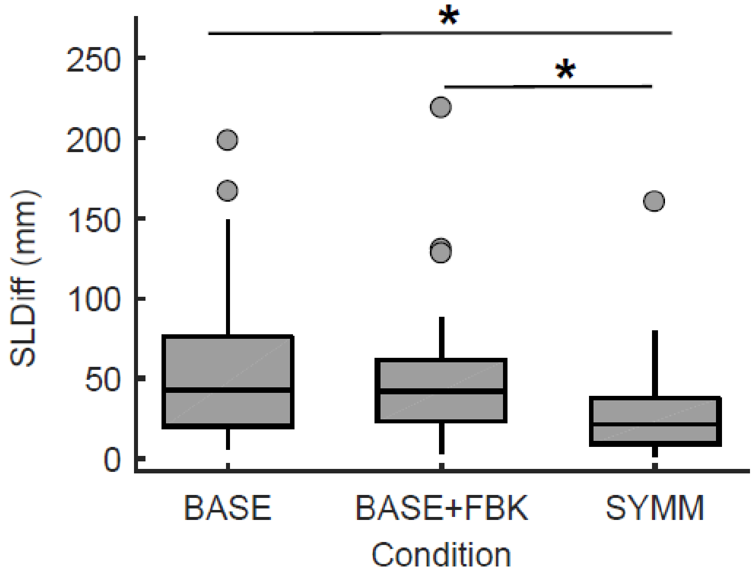
- 24 chronic stroke survivors (1-30 yrs post-stroke)
- 14 right hemi-paretic
- LE Fugl-Meyer ranged from 7-32

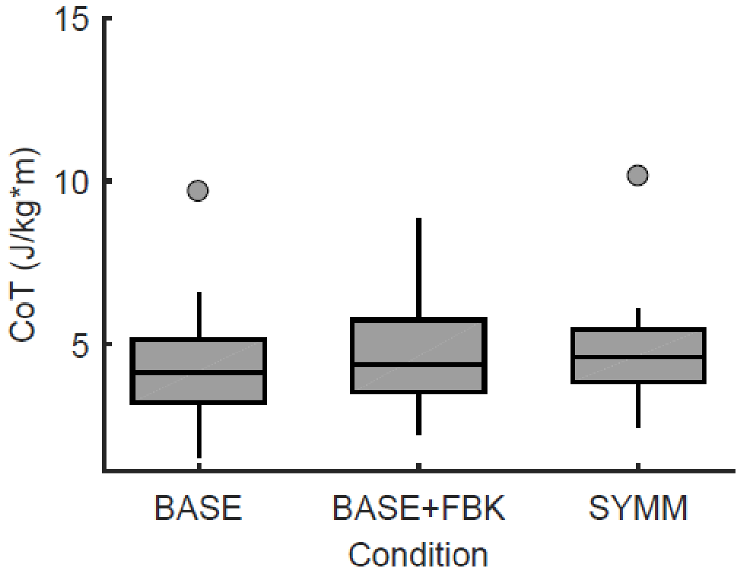




Sanchez and Finley, 2017, bio*Rχiv*

Metabolic cost was not affected by *reductions* in step length asymmetry in people post-stroke

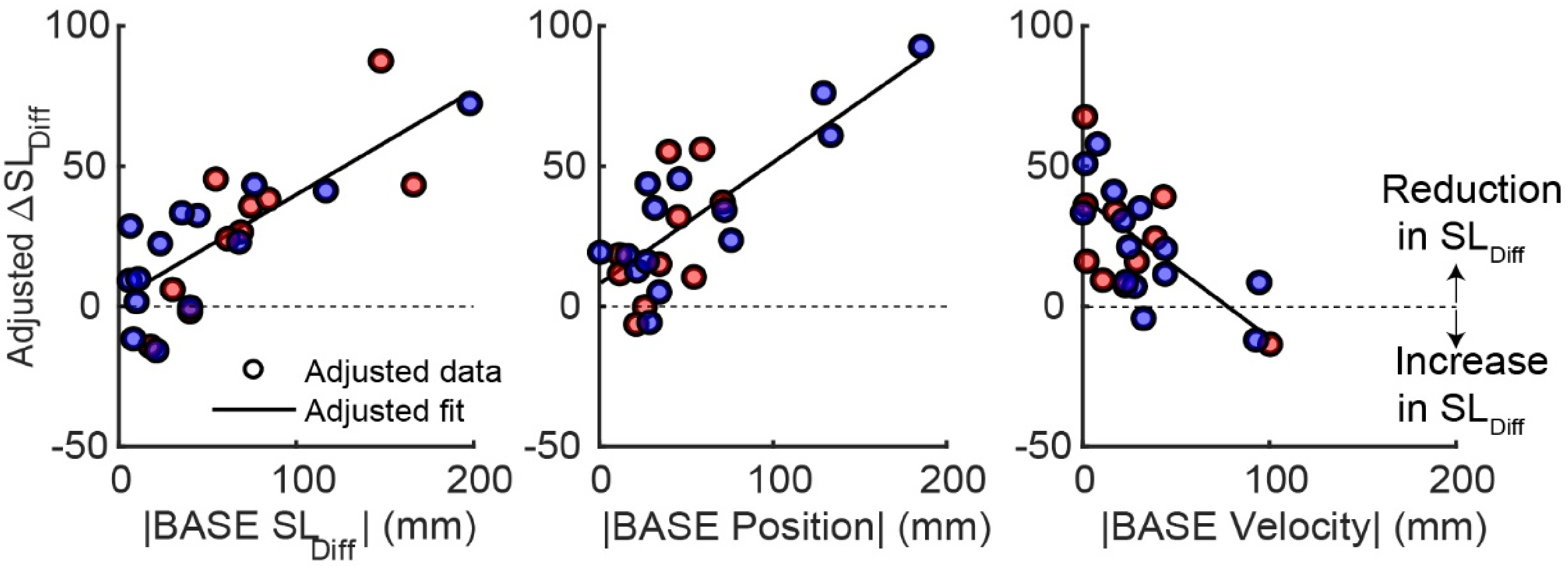




- There was a trend (p = 0.07) toward a higher rating of perceived exertion (RPE) in the Symmetry condition

Sanchez and Finley, 2017, bio*Rχiv*

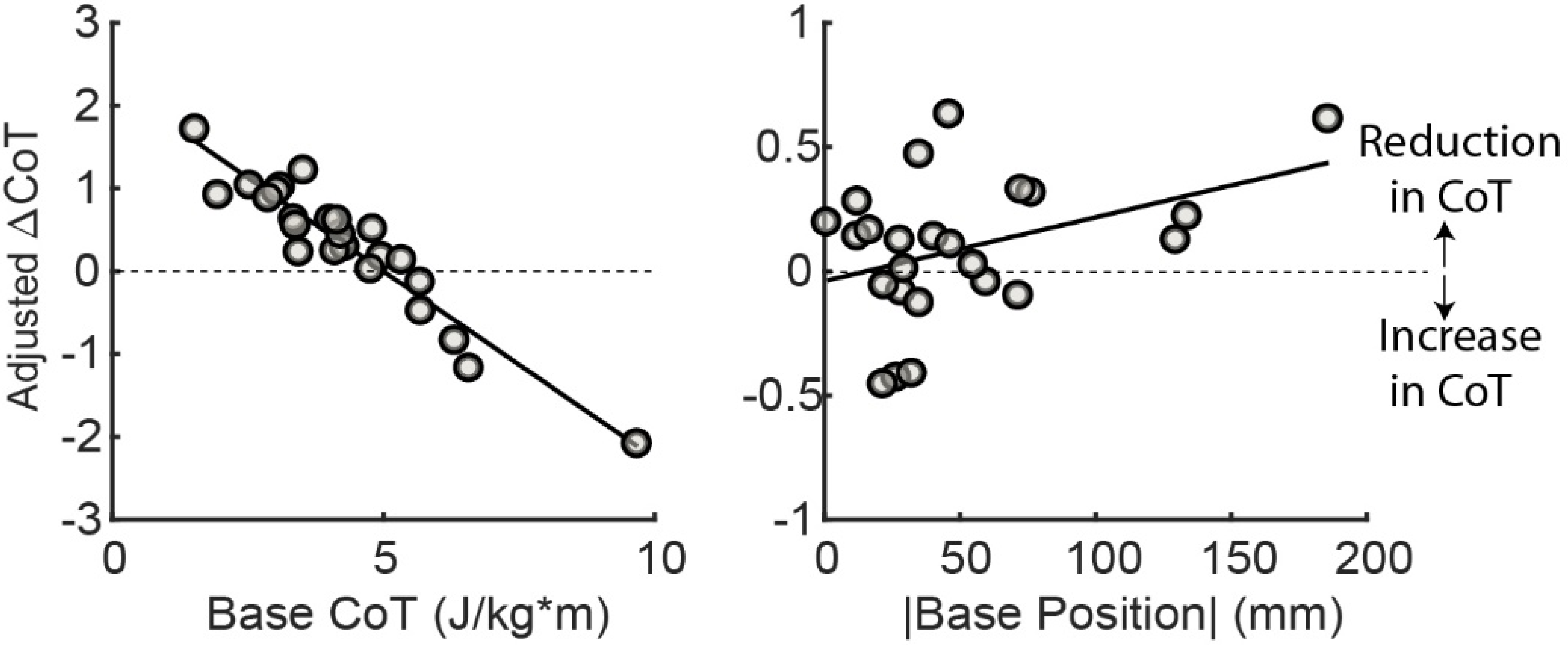
Individual differences in baseline asymmetry were associated with the ability to reduce asymmetry



- Participants with larger baseline asymmetries achieved larger reductions in asymmetry

Sanchez and Finley, 2017, bio*Rχiv*

Individual differences in habitual gait characteristics associated with changes in metabolic cost



- Participants with a naturally high metabolic cost were likely to *increase* metabolic cost when asked to reduce asymmetry
- Reductions in asymmetry were most beneficial for participants who had a lower metabolic cost

Sanchez and Finley, 2017, bio*Rχiv*

Take home points

- Taking steps of equal length (symmetry) is not the *metabolically* optimal strategy for walking on a split-belt treadmill
    - Symmetry appeared to be optimal when cost was estimated using a composite estimate of effort

- Composite estimates of effort may better explain behavioral strategies during adaptive motor learning
    - Most useful when candidate cost components have less than perfect correlation

- Spatiotemporal asymmetries are associated with individual differences in metabolic cost post-stroke
    - Stroke survivors retain the capacity to voluntarily walk more symmetrically
    - Whether reductions in asymmetry reduce metabolic cost depends on individual differences in impairment

Moving forward

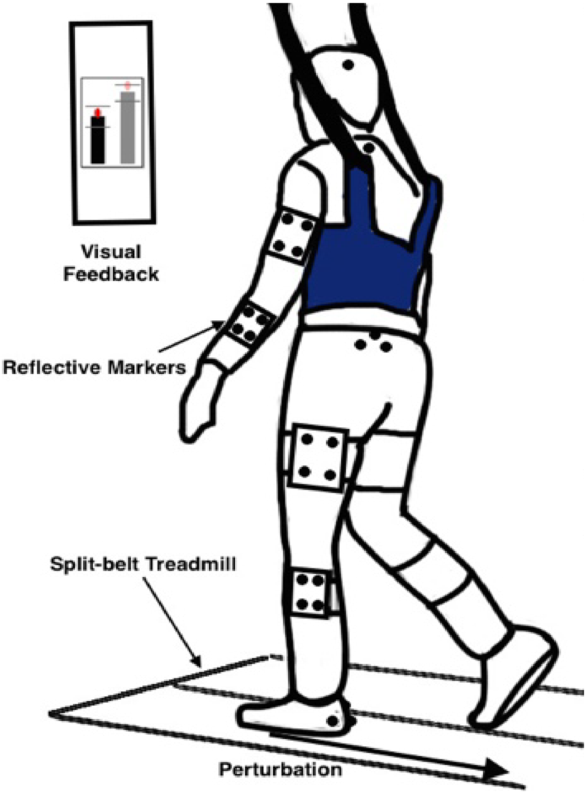
- What about balance?
  - How does asymmetry influence the reactive control of balance?

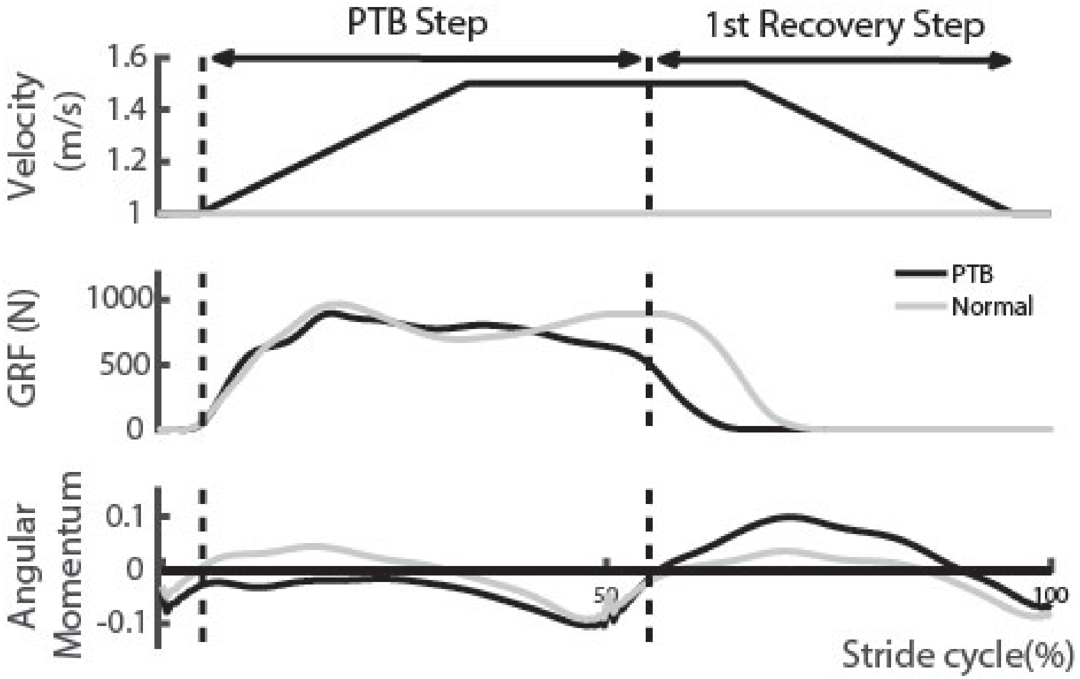
- How do subjective preferences influence the way in which people post-stroke choose to walk?
  - Are biomechanical and physiological measures appropriate estimates of the *cost* of a given locomotor strategy?

- What are the long-term consequences of reducing asymmetry?
  - Reduce the likelihood of developing musculoskeletal impairments?
  - Stimulate neural repair and impairment mitigation?

- Moving beyond step length
  - How do we balance trade-offs between comprehensive, quantitative movement analysis and clinically meaningful interpretation?

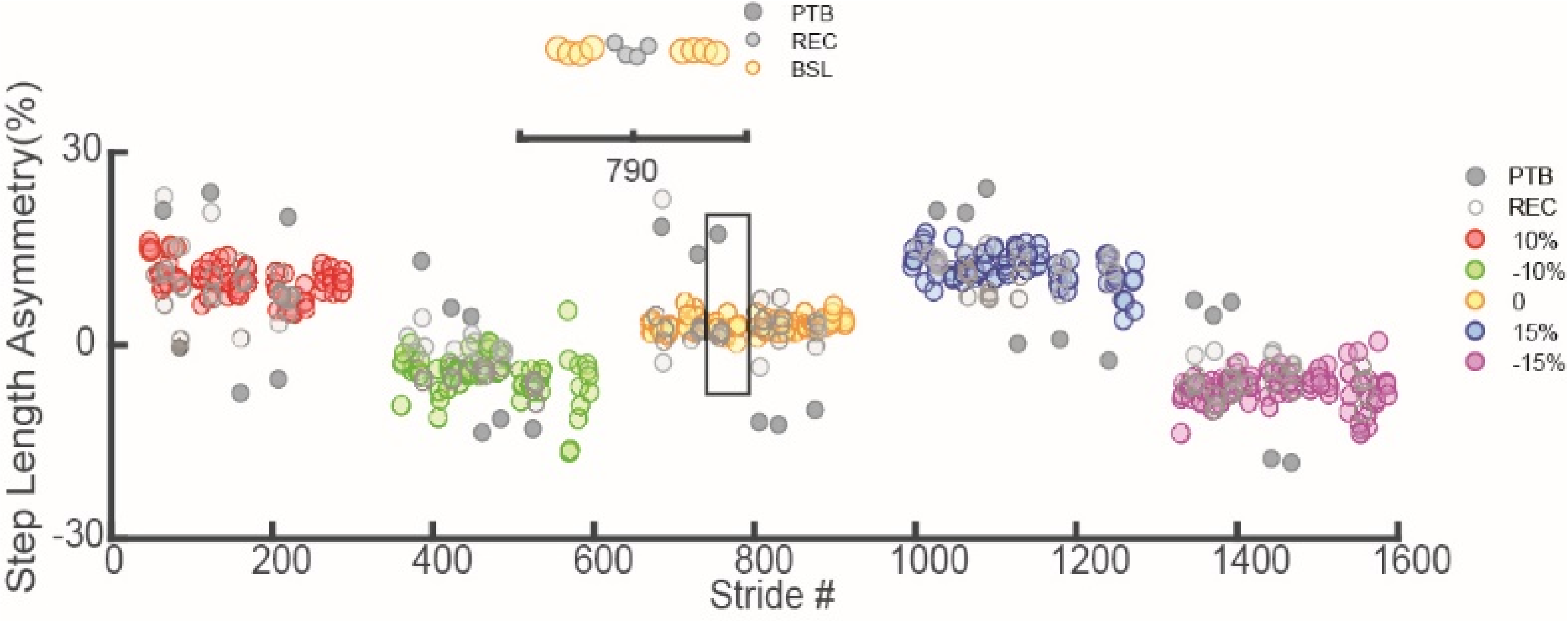
Does asymmetry impair the reactive control of balance?



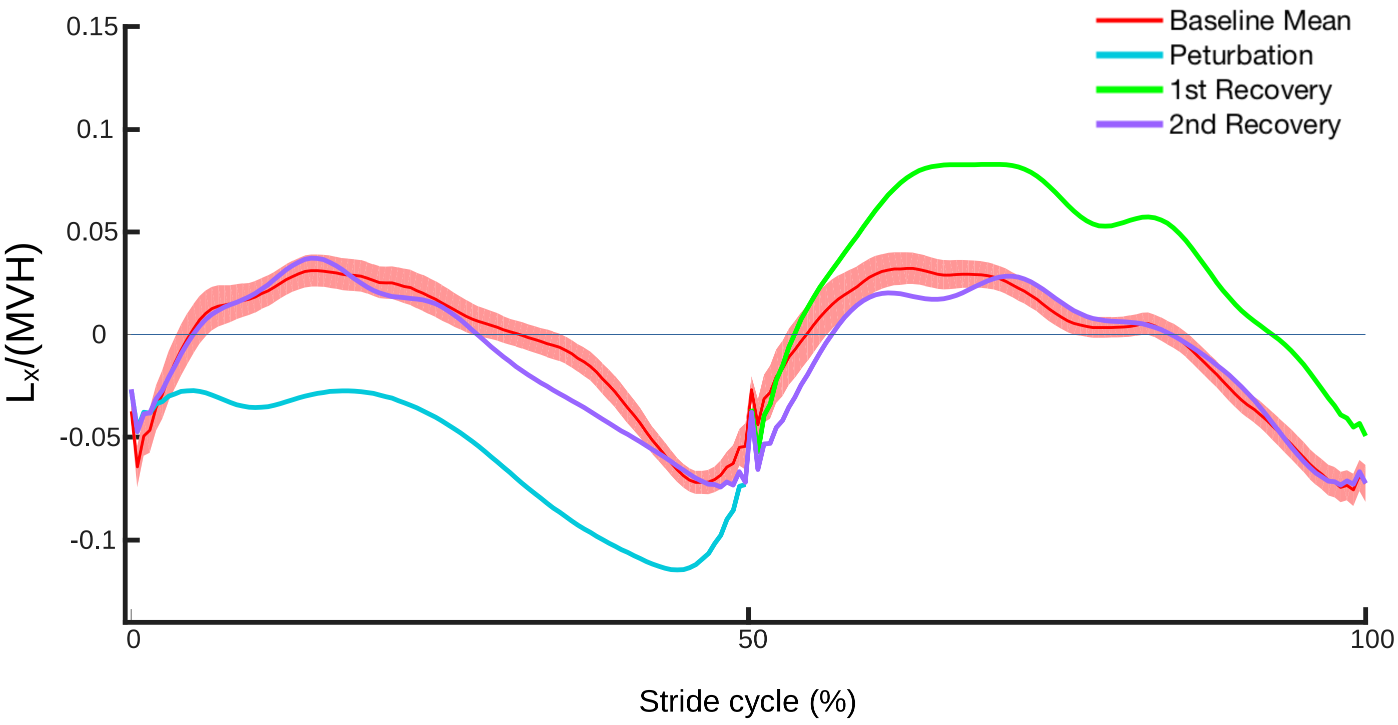


- Whole-body angular momentum can be used to quantify the magnitude of stumbles and the subsequent recovery

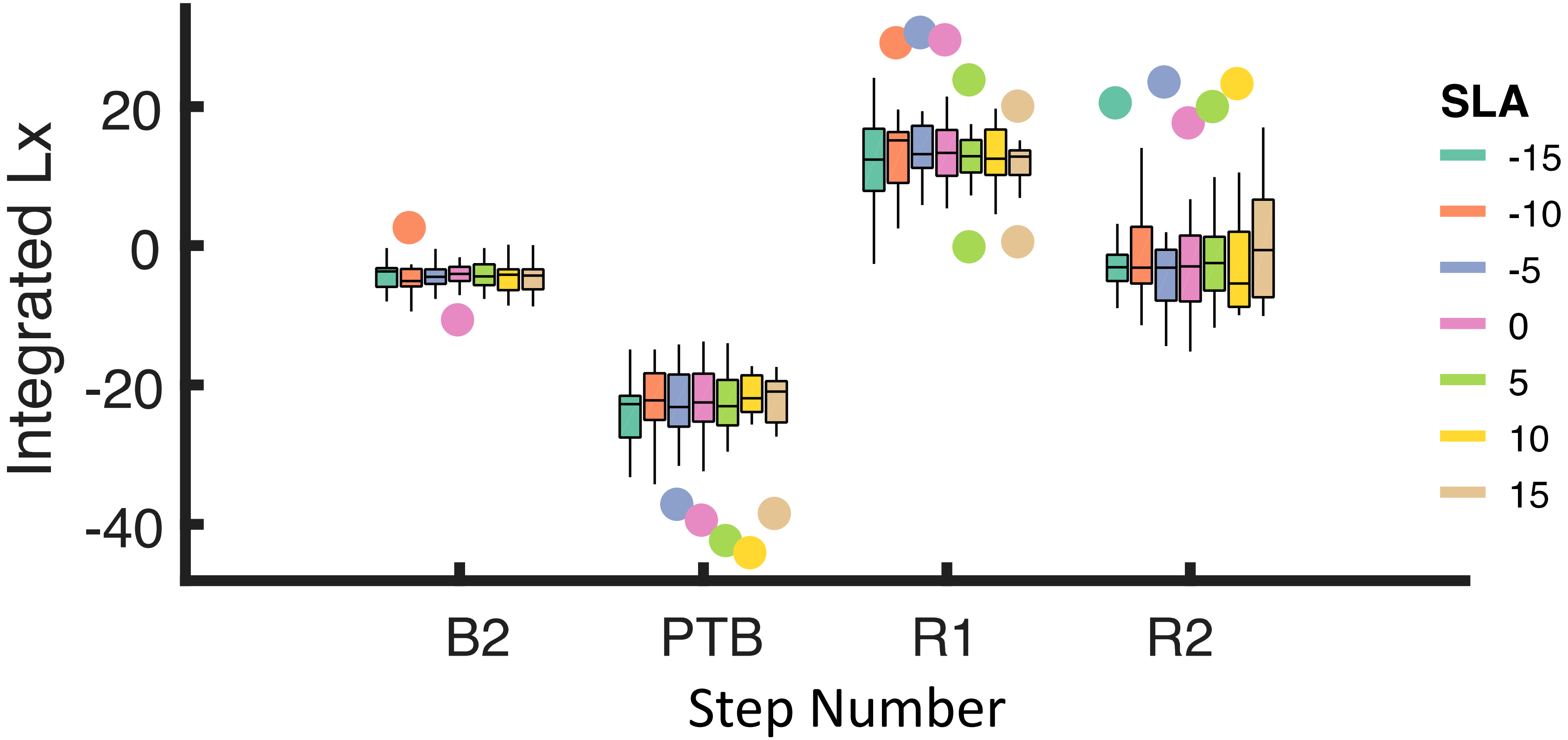
Perturbations elicited systematic changes in asymmetry



Recovery of whole-body angular momentum following a single perturbation



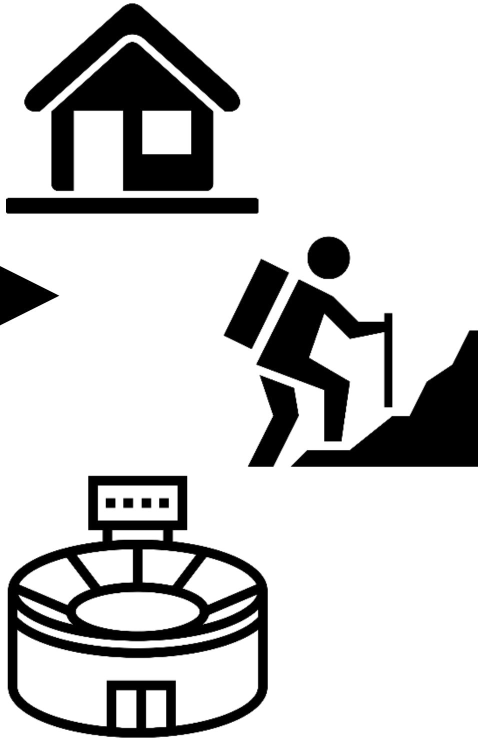
Imposed asymmetries did not affect recovery of whole-body angular momentum



- Neither the immediate effects of the perturbation, nor the time required to recover from the perturbation varied with asymmetry
- Asymmetry in the absence of impairment may have little influence on dynamic stability

Generalization of motor learning in the context of physical therapy

USC Division of Biokinesiology and Physical Therapy



Virtual reality as a platform for multi-context training and graded exposure

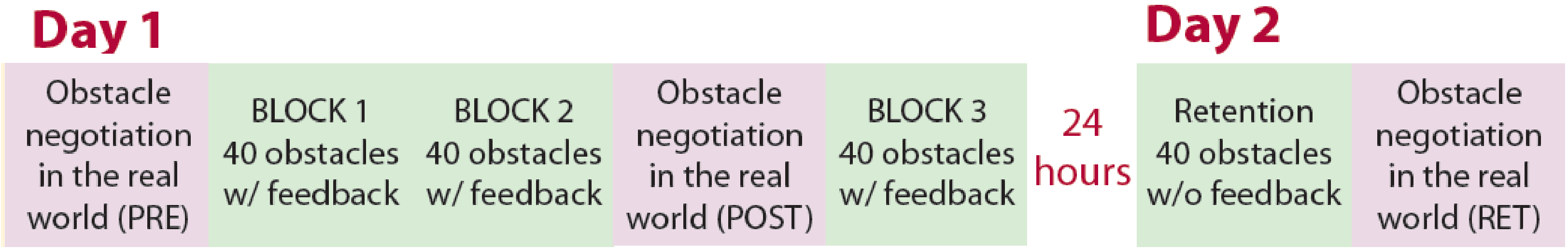
- Enables generation of a **variety of environments** in a safe setting

- Mimics **real-world challenges** (obstacles, crowds, etc.)

- Provides **systematic control over the environment**, distractors, and performance feedback

Obstacle negotiation in immersive virtual reality

Participants learned to reduce clearance during virtual obstacle negotiation



Day 1

Obstacle negotiation in the real world (PRE)

BLOCK 1 40 obstacles w/ feedback

BLOCK 2 40 obstacles w/ feedback

Obstacle negotiation in the real world (POST)

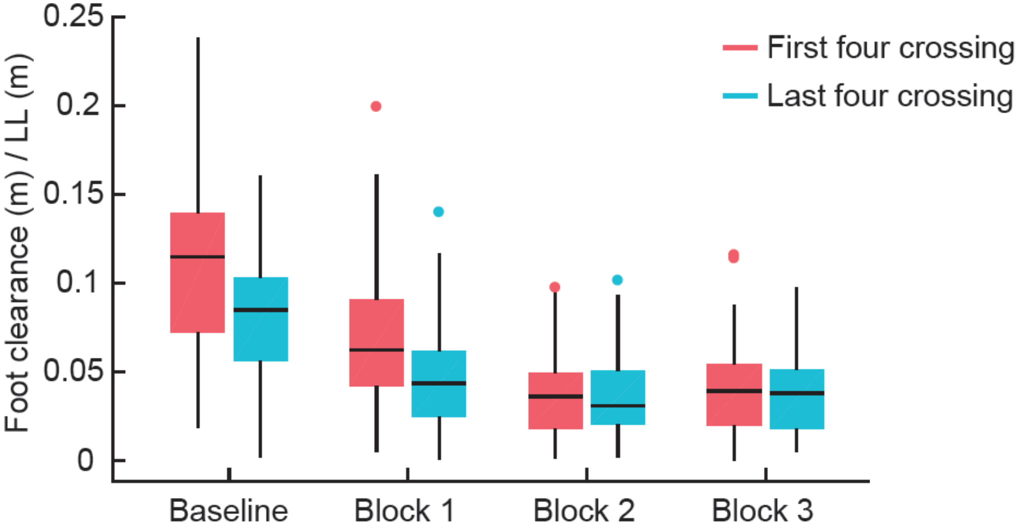
BLOCK 3 40 obstacles w/ feedback

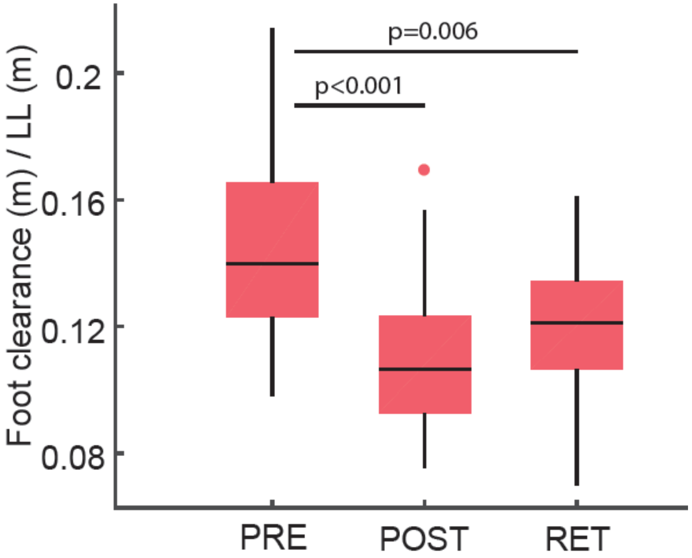
24 hours

Day 2

Retention 40 obstacles w/o feedback

Obstacle negotiation in the real world (RET)





- Improvements in performance in the absence of auditory error feedback were maintained 24 hours later
- Improvements in skill transferred to over-ground walking

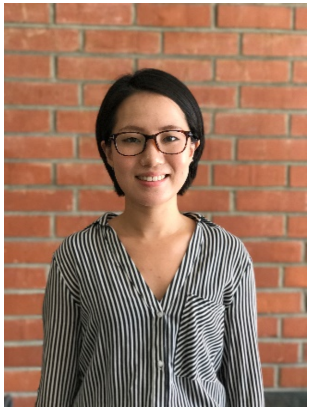
USC University of Southern California


Natalia Sanchez, Ph.D.
Biomed. Engineering


Sungwoo Park
Mech. Engineering


Chang Liu
Biomed. Engineering


Lindsey Trejo
Biomed. Engineering


Aram Kim
PT & Biokinesiology

JOHNS HOPKINS
MEDICINE

Amy Bastian, PT, PhD

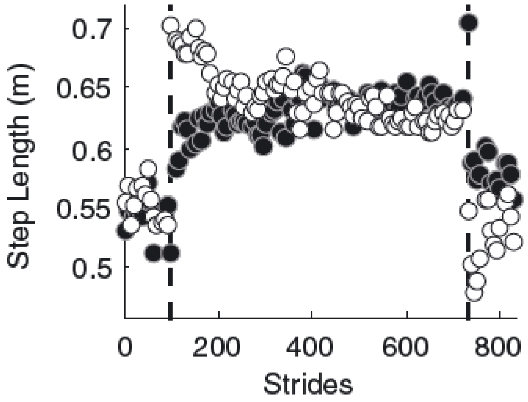
PennState

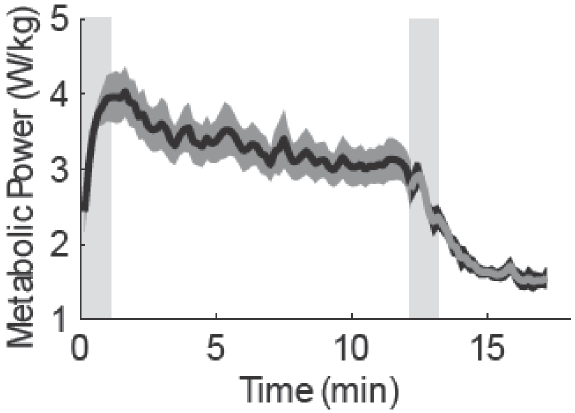
Jinger Gottschall, PhD

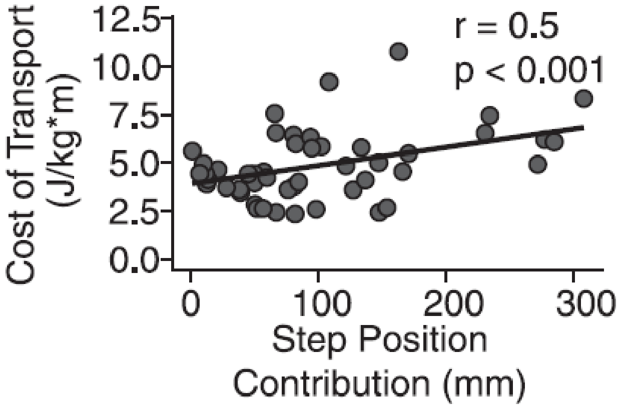
U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
National Institutes of Health

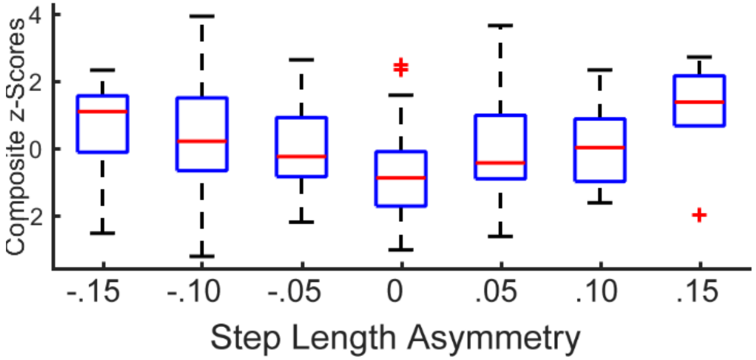
American Heart Association®

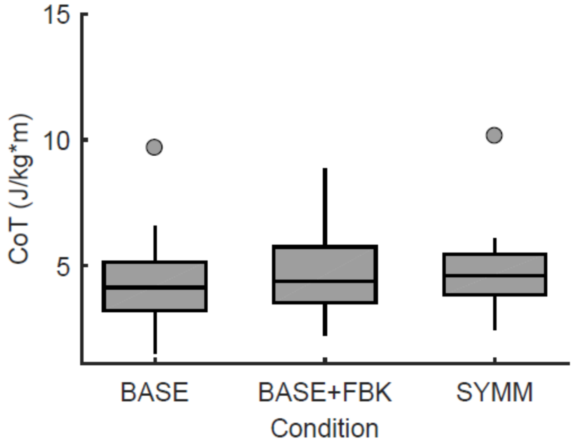
Thank you!


Step Length (m)
0.7
0.65
0.6
0.55
0.5
0
200
400
600
800
Strides


Metabolic Power (W/kg)
5
4
3
2
1
0
5
10
15
Time (min)


Cost of Transport (J/kg*m)
12.5
10.0
7.5
5.0
2.5
0.0
0
100
200
300
Step Position Contribution (mm)
r = 0.5
p < 0.001


Composite z-Scores
4
2
0
-2
-.15
-.10
-.05
0
.05
.10
.15
Step Length Asymmetry


CoT (J/kg*m)
15
10
5
BASE
BASE+FBK
SYMM
Condition