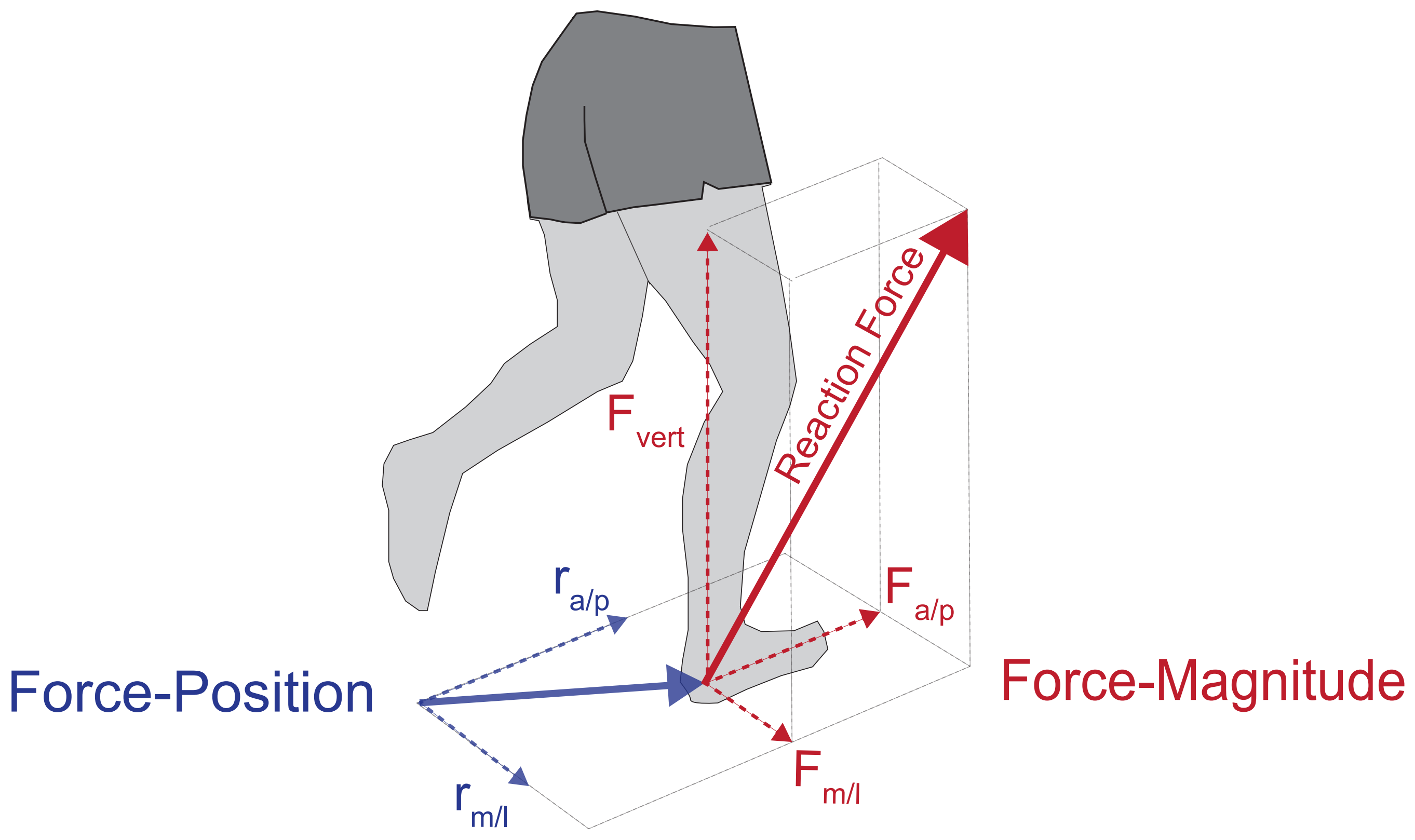
Characterizing human leg force control

Pawel Kudzia[1], Steve N. Robinovich[1,2] and Max Donelan[1,2]
School of Engineering Science[1] and Dept of Biomedical Physiology and Kinesiology[2] , Simon Fraser University, Burnaby, BC, Canada

1. Introduction

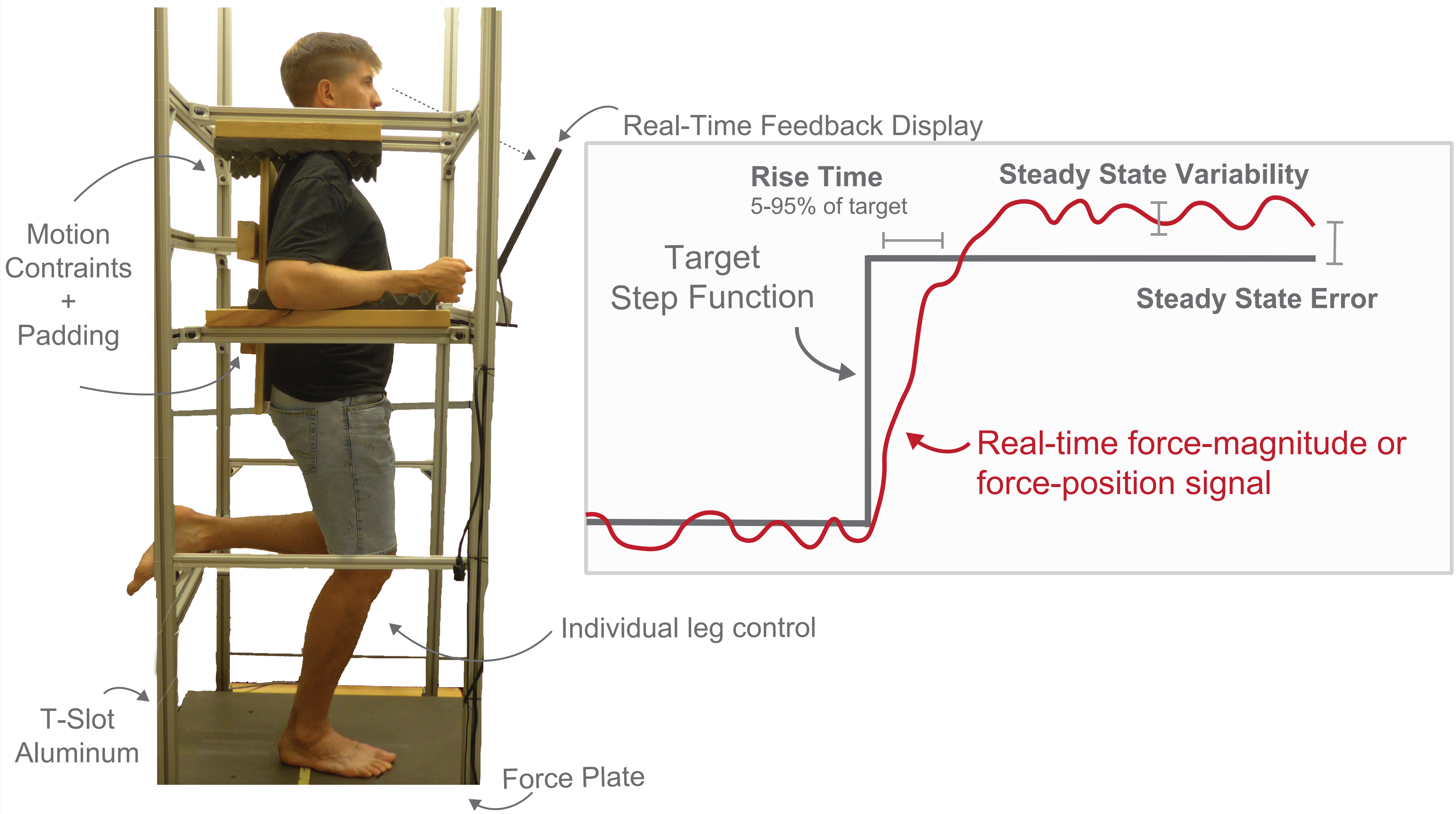
Humans are remarkably agile [1]. We think of agility as the ability to rapidly execute motor control strategies that redirect body motion and reposition our limbs. When we navigate the environment, our legs interact with the ground producing reaction forces that either maintain or change the state of our motion. Each reaction force is a vector quantity with a force-magnitude and a force-position acting at a point on the body. Varying the force-magnitude of the force can result in linear changes to our motion. A runner seeking to increase their linear speed does so by selectively increasing the force-magnitude. Varying the force-position of the force can result in changes in the moment of the force, which has rotational effects on our motion. A gymnast wishing to initiate a front flip does so by selectively shifting the force-position. **A greater control of agile motion is achieved through greater control of leg reaction force-magnitude and force-position. Modulating force rapidly and accurately contributes to greater agility.** If we seek to design robots that exceed the agility of humans, it helps to understand the neuromechanical control mechanisms that enable agility as well as the factors that limit it.



The goal of this research is to quantify the control performance (rise time, steady state error and steady state variability) of humans using their legs to voluntarily control the force-magnitude and force-position of external forces.

2. Study Design

To study the performance of controlling force-magnitudes and force-positions with our legs, we have designed and built a rig that constrains subjects from motion while allowing them to exert variable forces onto the ground . We mount a force plate below the subject's feet to measure the ground applied force-magnitudes and derive the medial-lateral and anterior-posterior force-positions [2]. We send signals from the force-plate to a data acquisition unit which displays to subjects' real-time feedback of the vertical force-magnitude and of the medial-lateral and anterior-posterior force-position of the force applied to the ground.



Human Subject Experiments

We adjust the rig to fit subjects comfortably such that their torso is constrained and their arms and shoulders can selectively push against the rig. We constrain the height of the rig such that the subjects adapt a running stance posture. For force-magnitude control, we have subjects use their foot to selectively try and match the magnitude of a prescribed step function by pushing or not pushing against the ground as the target trace appears on their screen. For force-position control, we have subjects place their foot firmly on the force plate and ask them to match prescribed changes in either the medial-lateral or the anterior-posterior force-position by selectively shifting the pressure under their foot. We compare the prescribed signal to the empirical data to quantify control performance criteria which includes: rise time, steady state error and steady state variability using system identification tool in Matlab.

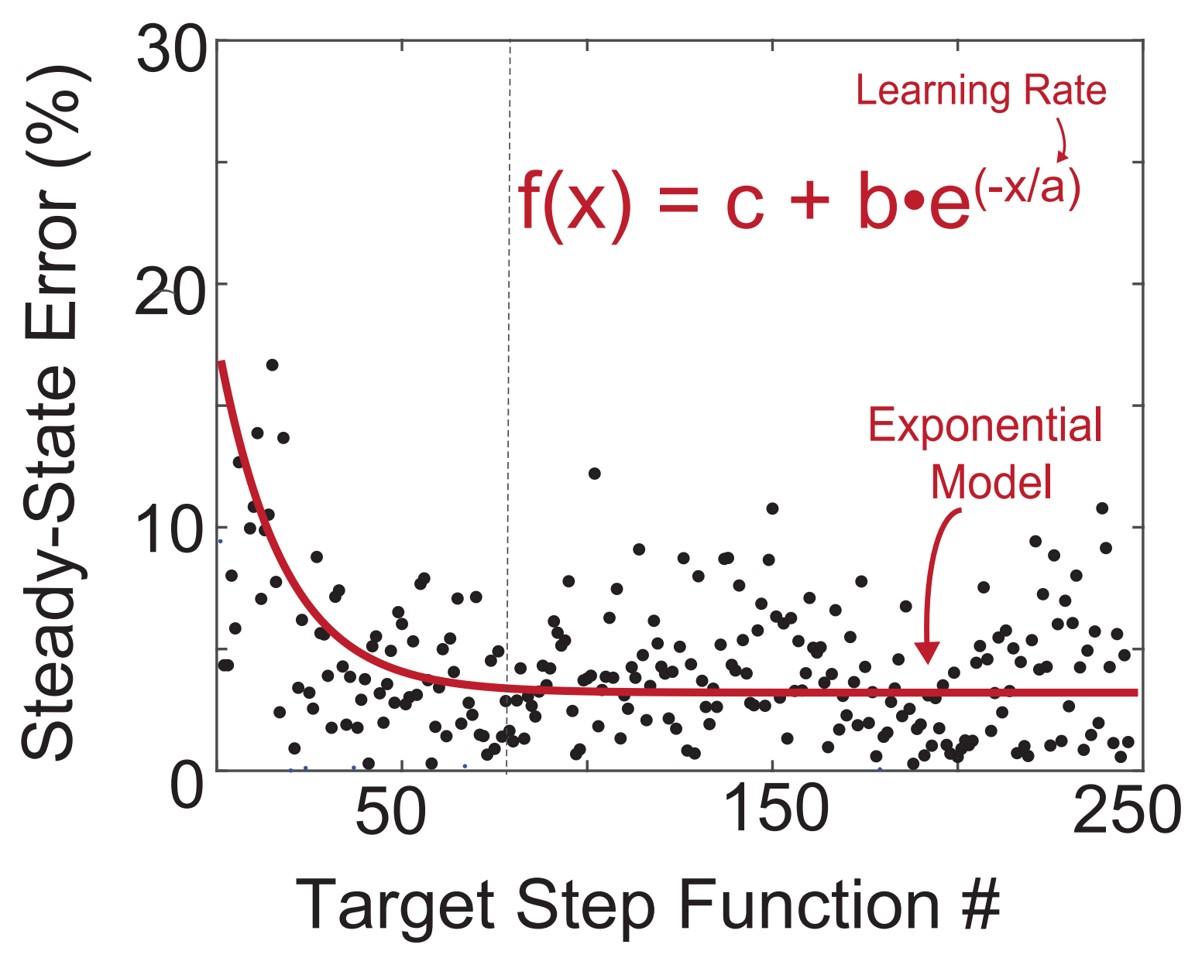
Task Motivation

To keep subjects motivated during the experiment we created a simple game. Every minute (~ 6 target steps per minute) subjects are shown a score board on their screen. The score board shows them an error rate (a weighted measure of our outcomes) of their performance in that minute. We encourage subjects to achieve the lowest score possible (minimizing error) and have them compete against themselves throughout the experiment.

2. Study Design continued

Task Adaptation

We are interested in quantifying the optimal performance of leg force control. To accomplish this, we determine the number of trials it takes for the performance of subjects to plateau. We determine the learning rate by having subjects perform many repeats of the same task (e.g. force-control at 1.5x body weight). We then fit an exponential function to the error data, which gives us the learning rate, and use 3x the learning rate to determine the number of trials until people have stopped adapting [3].

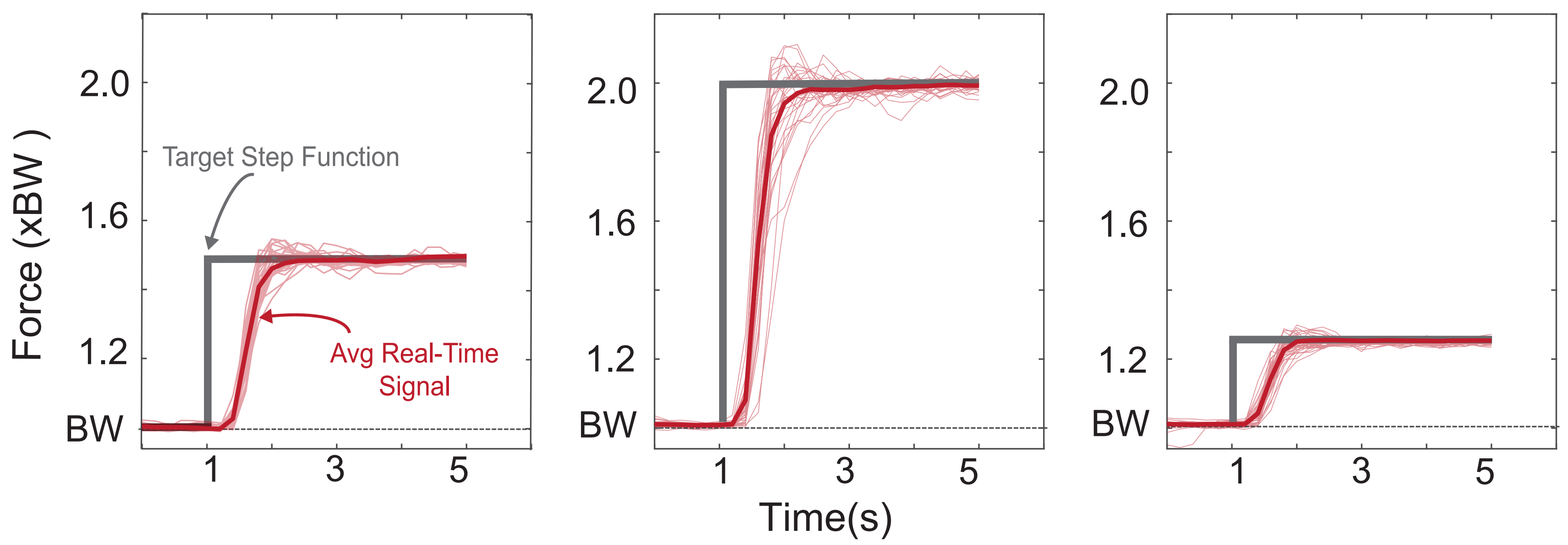


We tested one subject who repeated 250 trials of a force-magnitude experiment at x1.5 body weight. We fitted an exponential model to our outcomes measures and found a learning rate of 17.5 (95% CI [8.8, 26.2]) which corresponds to a subject adaption rate of 53 target steps (95% CI [26.4, 78.6]) at which point performance has plateaued. Shown on the figure is the steady-state error, which we present here as a representative measure of our three outcomes.

3. Results and Discussion

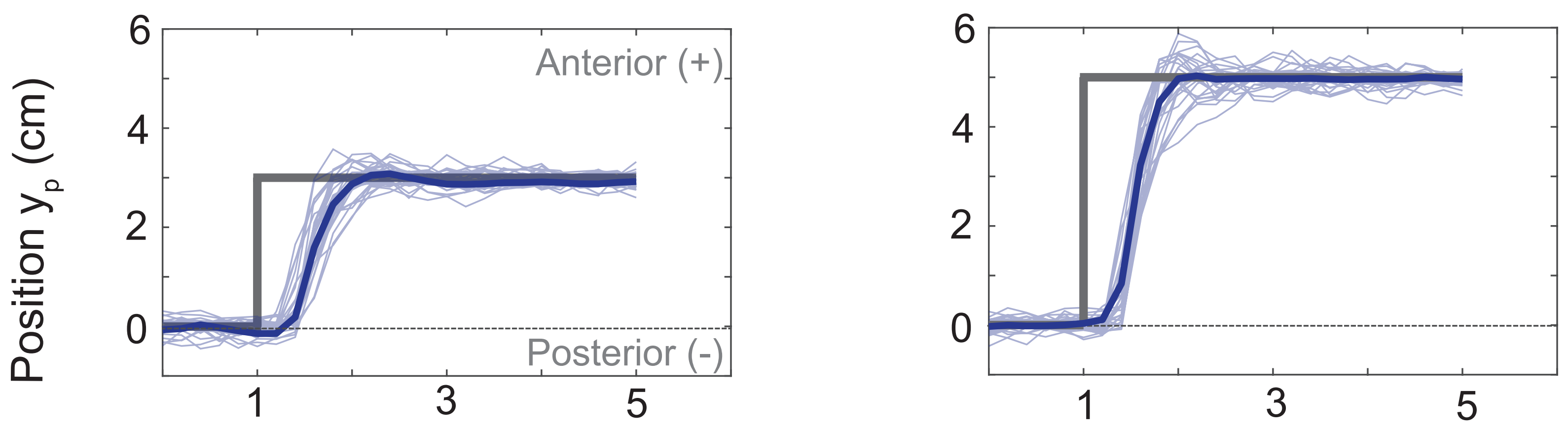
We collected pilot data of one subject performing 3 force-magnitude control experiments at 1.25, 1.5 and 2x bodyweight of force. We also collected force-position control data where one subject performed two anterior-posterior control experiments (3 and 5cm) and two medial-lateral control experiments (0.5 and 1cm). We presented real-time data to the subject such that the target changed roughly every 5s with 6 target steps occuring per minute. We then presented them with their error score and a 30 second break before the next trial. We collected 60 target steps of each condition and used the last 30 for analysis.

Force-Magnitude Control



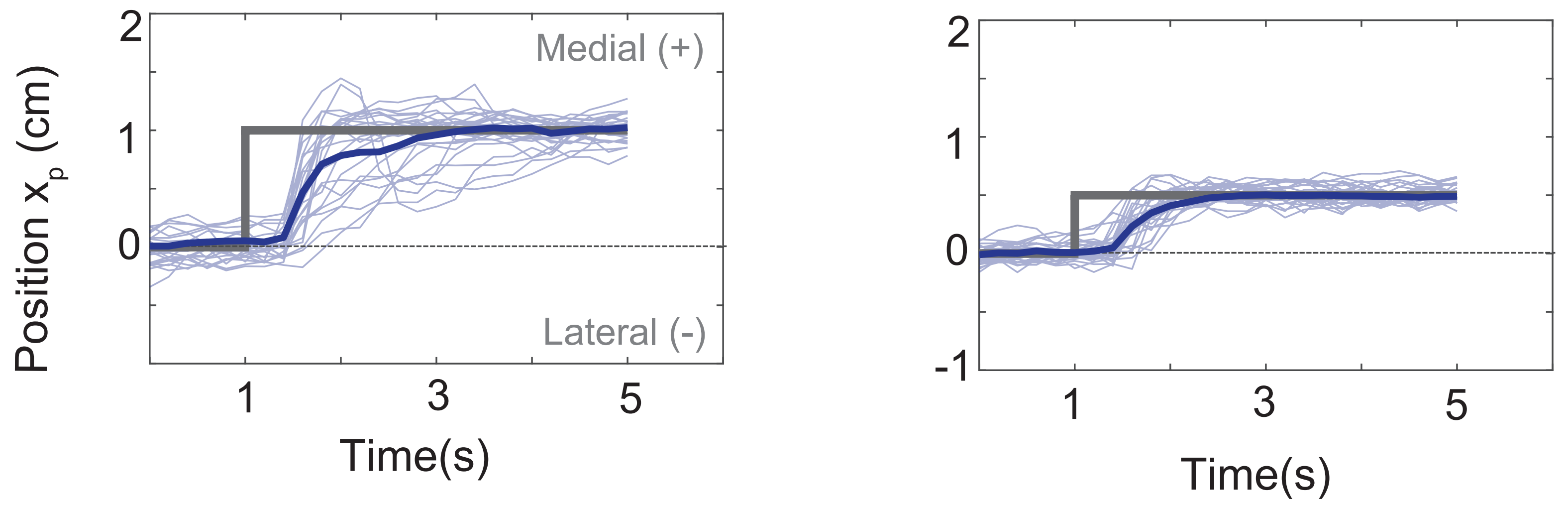
Force-Position Control

Anterior-Posterior Direction



Force-Position Control

Medial-Lateral Direction



	Rise Time (s) mean±sd	Steady-State Error (%) mean±sd	Steady-State Variability(%) mean±sd
Force Magnitude	0.7±0.5	4.3±2.7	12.5±8.0
Force Position a/p	1.3±0.7	2.5±1.9	7.0±6.4
Force Position m/l	2.0±0.7	11.1±8.9	12±15.3

While preliminary, the leg's voluntary control of force seems remarkably poor in the context of the superior agility of humans.

References

[1] A. J. Ijspeert, "Biorobotics: Using robots to emulate and investigate agile locomotion," Science (80-. 96)., vol. 346, no. 6206, pp. 196–203, 2014.
[2] D. A. Winter, "Biomechanics and Motor Control of Human Movement," Libr. Mot. Control, vol. 2nd, p. 277, 2009.
[3] S. J. Abram, J. C. Selinger, and J. M. Donelan, "Energy Optimization is a Major Objective in the Real-Time Control of Step Width in Human Walking," J. Biomech., 2019

NSERC CRSNG
This work was supported by an NSERC discovery grant to MD and a NSERC PGS-D scholarship and a MYF fellowship to PK