Characterizing human leg force control

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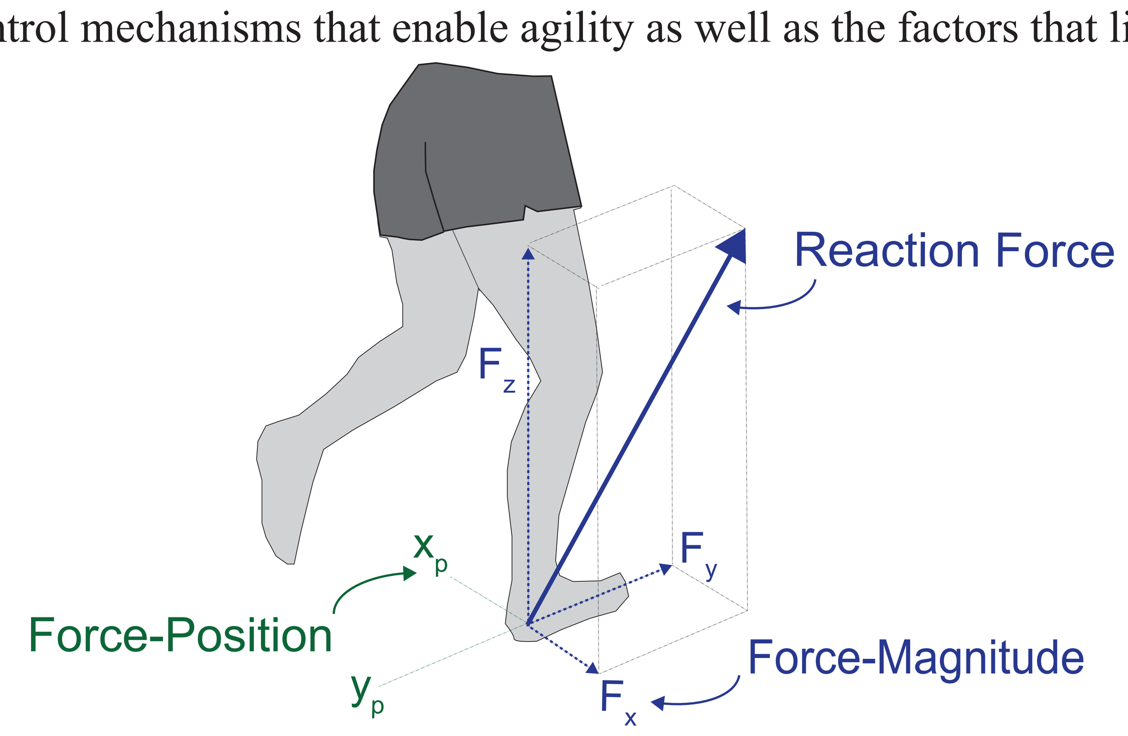
I. Introduction

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 acting at a point on the body, which we refer to as its force-position. Alteration in the force-magnitude of the force can result in linear changes to our motion. A runner who wishes to increase their linear speed, does so by increasing force-magnitude. Alteration in the force-position results 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.



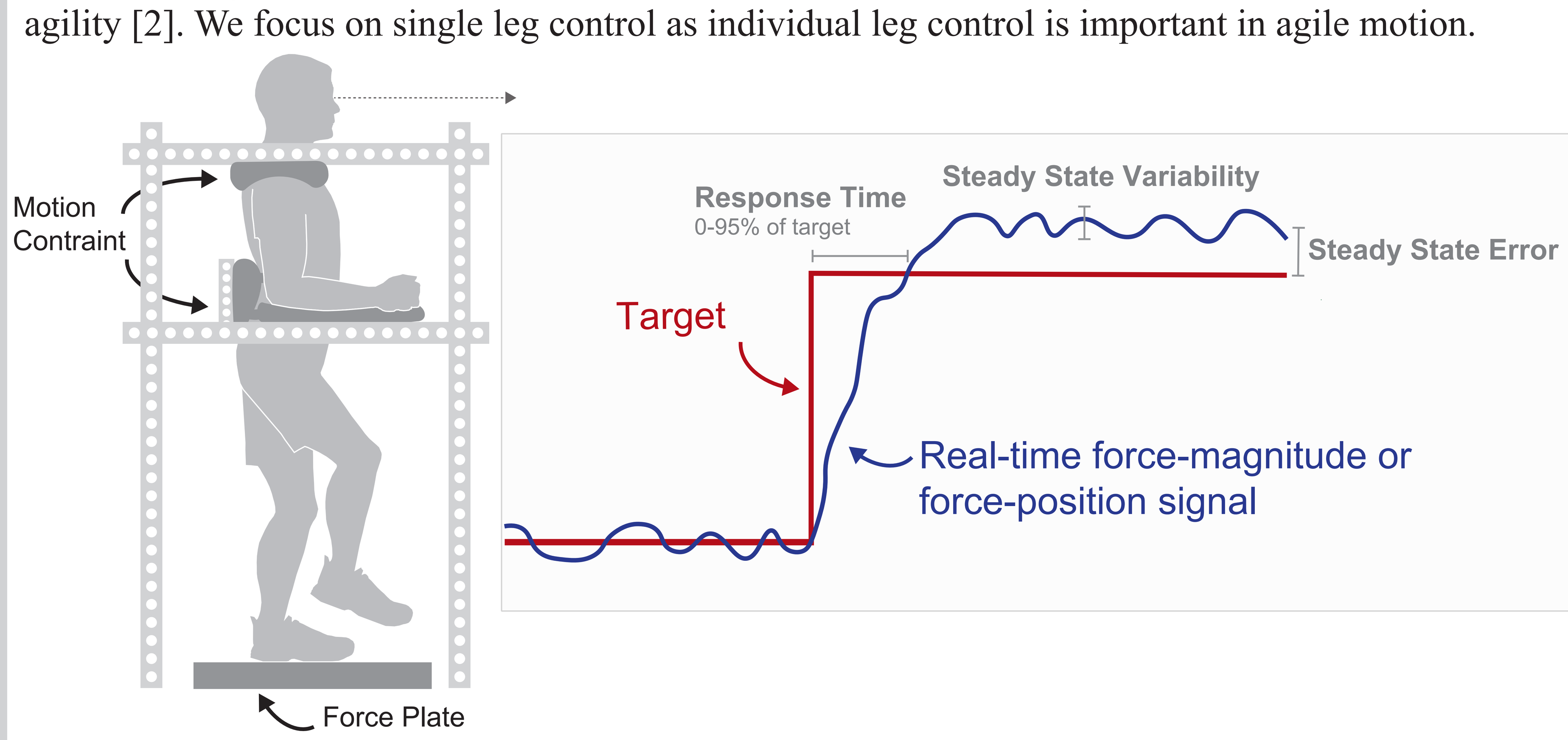
The goal of this research is to quantify the control performance (response time, steady state error and steady state variability) of humans using their legs to voluntarily control the force-magnitude and force-position of external forces.

II. Study Design

To study the performance of our legs controlling force-magnitudes and force-positions, we are designing an apparatus that situates subjects into a standing posture with their upper body constrained from moving in any direction. We mount a force plate in the ground below the subject's feet to measure the three-dimensional force-magnitudes that are applied to the ground. To estimate the force-position, we use the force-magnitudes in each direction F_z, F_y and F_x and the force moments M_y and M_x, to determine the force-position in a local force plate coorindate system [2] :

$$x_p = \frac{-h \cdot F_x - M_y}{F_z} \qquad y_p = \frac{-h \cdot F_y - M_y}{F_z}$$

Were h is the thickness of the force plate cover. We send signals from the force-plate to a data acquisition unit programmed in MATLAB which then display to subjects' real-time feedback of the vertical force-magnitude (F_z) and of the medial-lateral (x_p) and anterior-posterior (y_p) force-position of the external force being applied to the ground. In current pilot experiments, We focus on sub-maximal forces to study the limits to control, not the limits to maximum force generation which can also affect agility [2]. We focus on single leg control as individual leg control is important in agile motion.



In ongoing pilot experiments, we use prescribed step functions to characterize the voluntary control of force-magnitudes and force-positions. For force-magnitude control, subjects use their leg to selectively try and match the magnitude of a prescribed force by pushing or not pushing against the ground. For force-position control, we have subjects place their foot firmly on the force plate and ask them to match prescribed changes in the medial-lateral (x_p) and anterior-posterior (y_p) force-position. We compare the prescribed singal to the emprical data and quantify control performance criteria which includes: response time, steady state error and steady state variability using system identification tools in MATLAB. In brief, we find the transfer function G(s) that best relates the empircal data to the inputted step function by minimizing least squares error:

$$G(s) = \frac{K_p e^{T_d \cdot s}}{1 + T_p \cdot s}$$

Where K_p is the proportional gain, T_d is the time constant, and T_p is a fixed time delay. We then use these model parameters to estimate our control performance variables.

$$\textbf{Response Time (RT)} = T_d + 3T_c$$

$$\textbf{Steady State Variability (SSV)} = 100 \cdot \frac{SD_{Empirical}}{Mean_{Empirical}}$$

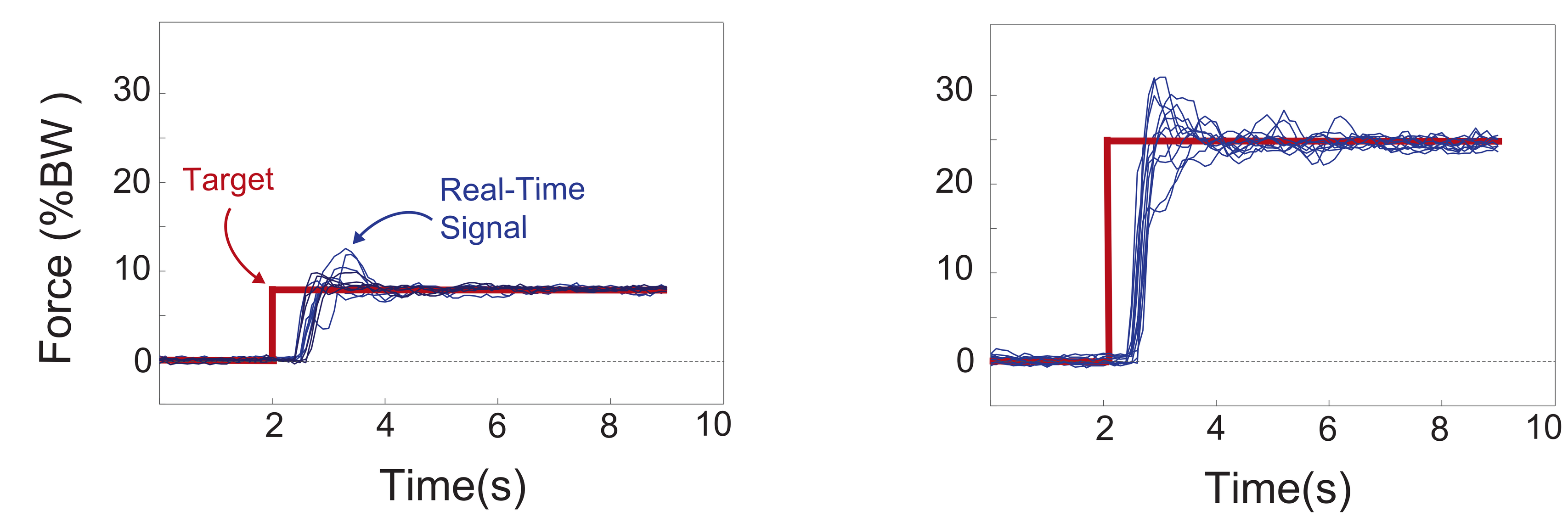
$$\textbf{Steady State Error (SEE)} = 100 \cdot \frac{(Magnitude_{StepFunction} - Mean_{Empirical})}{Magnitude_{StepFunction}}$$

III. Pilot Results

We evaluated preliminary data collected from 2 subjects in our pilot study. We assessed force-magnitude control at three different step functions 8%, 15% and 25% body weight. We assessed force-position control in the medial-lateral (x_p) postions and in the anterior-posterior (y_p) postions with step changes of 3cm and -3cm. Our subjects then performed each condition 12 times, representative trials are shown.

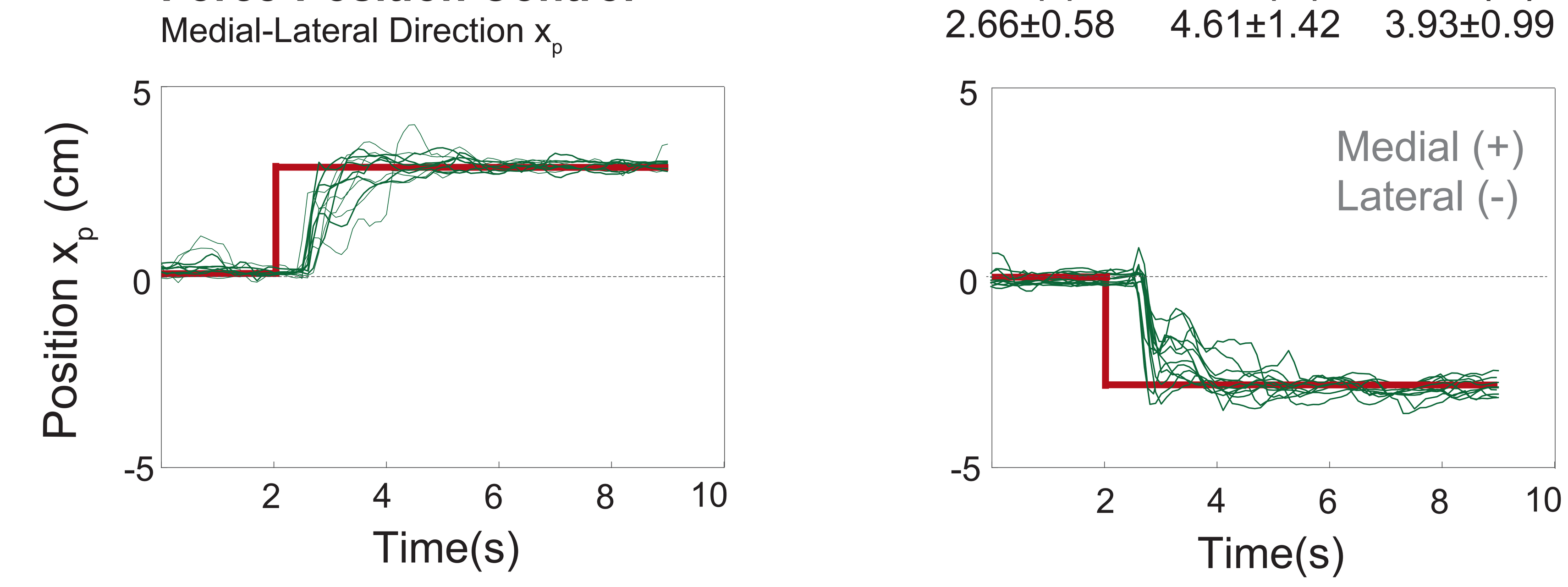
Force-Magnitude Control

RT(s)	SSV(%)	SSE(%)
1.72±0.31	4.47±2.04	2.13±0.85



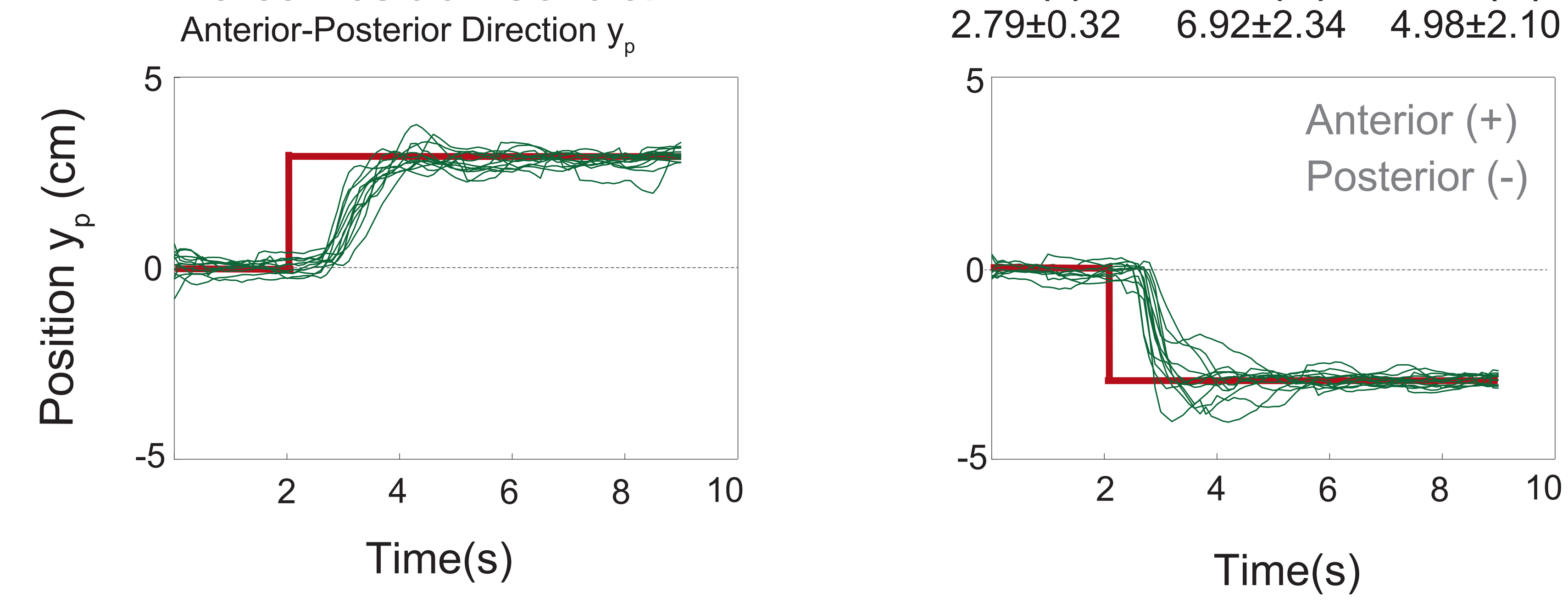
Force-Position Control
Medial-Lateral Direction x_p

RT(s)	SSV(%)	SSE(%)
2.66±0.58	4.61±1.42	3.93±0.99



Force-Position Control
Anterior-Posterior Direction y_p

RT(s)	SSV(%)	SSE(%)
2.79±0.32	6.92±2.34	4.98±2.10

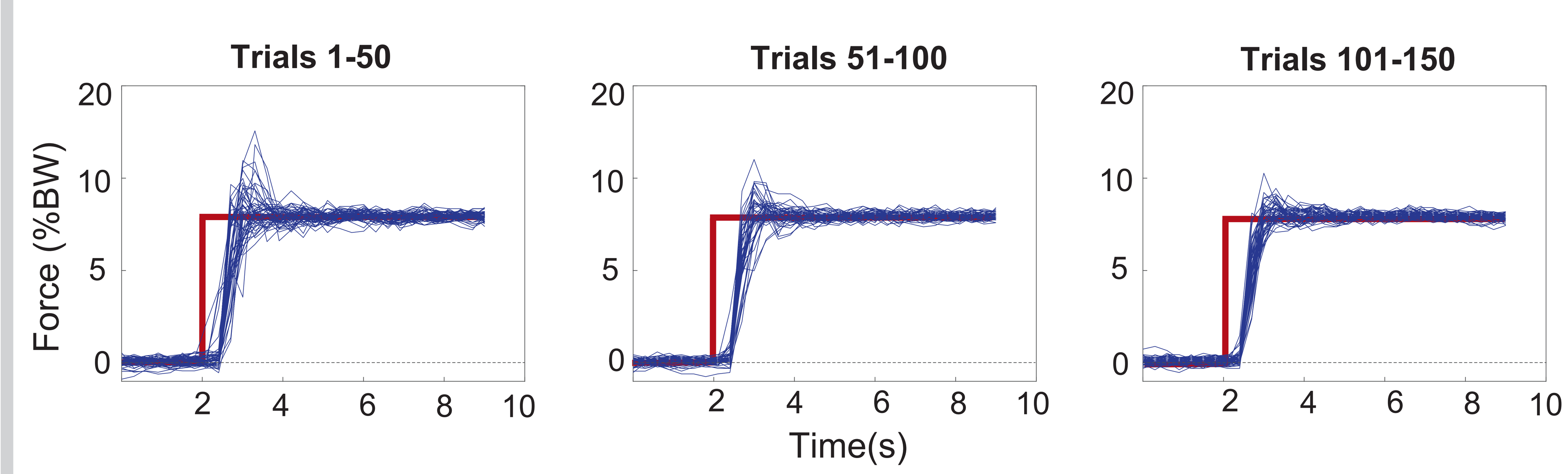


III. Discussion

While preliminary, the leg's voluntary control of force seems remarkably poor in the context of the superior agility of humans. As we move forward and fine tune our methods, our aim is to determine the amount and type of exposure subjects require to maximize performance. We have begun to address this by investigating how performance might change when the subject has a large amount of exposure to the task. We had one subject perform 150+ trials of the force-magnitude control task:

How does motor learning influence performance ?

	RT(s)	SSV(%)	SSE(%)
Trials 1-50	1.77	3.31	1.50
Trials 51-100	1.88	2.52	1.18
Trials 101-150	1.81	2.61	0.91



How does motivation to perform the task influence performance?

Our task is repetitive and challenging in nature. To keep subjects motivated we are considering real-time performance feedback. Feedback not only has an informational function, but also has motivational properties that have an important influence on learning [3]. Our aim is to determine the amount and type of feedback that maximizes motivation and in turn performance. One approach we are considering is providing subjects with a real-time moving average of their performance. This performance metric would encapsulate the control metrics that we are evaluating.

VI. References

[1] A. J. Ijspeert, "Biorobotics: Using robots to emulate and investigate agile locomotion," *Science* (80-.)., 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] G. Wulf, C. Shea, and R. Lewthwaite, "Motor skill learning and performance: a review of influential factors," *Med. Educ.*, vol. 44, no. 1, pp. 75–84, Jan. 2010.

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