Characterizing the nervous system's control of human leg external forces

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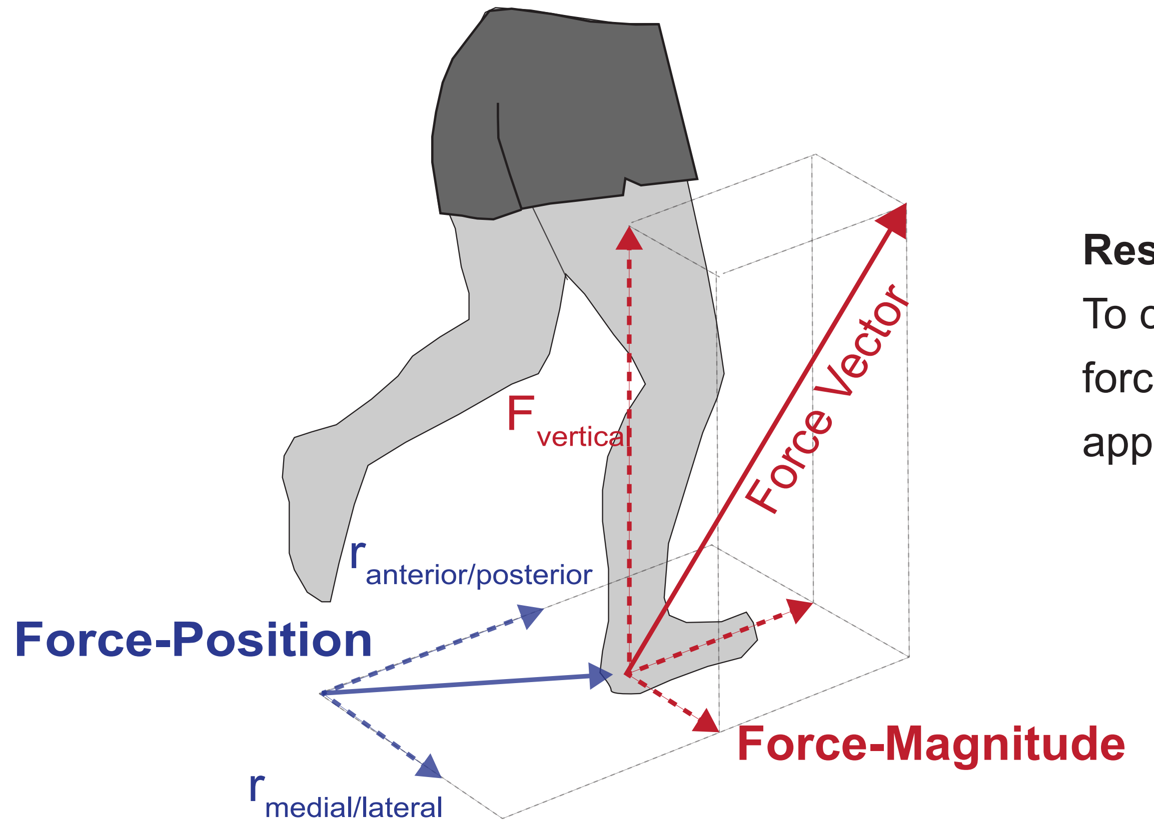
Introduction

Humans are remarkably agile [1]. Our legs, which are the primary point of contact with the environment, enable us to perform agile tasks such as sprinting, jumping, and rapidly changing direction. The ability to modulate external force vectors involving both force-magnitude and force-position control is a determinant in the ability to be agile. Effective control of these force properties may help explain differences between humans, between humans and other animals, and between humans and engineered systems.



Research Objective

To characterize the performance of controlling the force-magnitude and force-position of an externally applied force by the human leg.

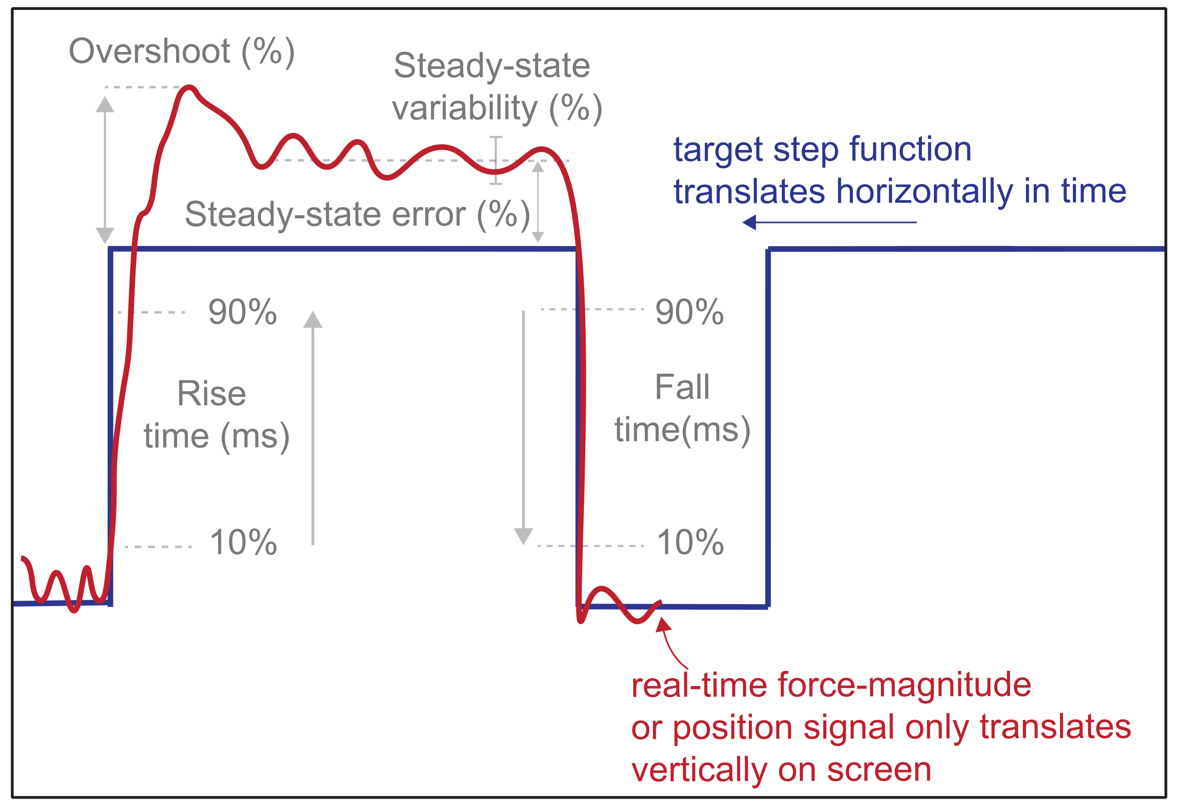
Study Design

We built an apparatus that constrained the body while allowing one leg to isometrically push on a force plate, and a real-time visual feedback system that specified target force-magnitudes, or positions, that the leg should exert. (Participants = 4 female and 10 male; mass: 72.2±6.1 kg; mean±std) .

Force-magnitude exp : target step sizes of 0.25, 0.45, 0.85, and 1.25 x bodyweight

Force-position exp : target step size of +2.5, +4.0, -1.0, -2.5 cm (anterior (+) / posterior (-)) and +1.0, +0.5, -0.5, -1.0 cm (medial (+) / lateral (-)). Each target was 6 seconds in length and repeated 60x times

Real-time feedback display



We modelled the system dynamics and used system identification to estimate the unknown parameters. To fit this model to our data, we solved for the unknown model parameters using sequential quadratic programming minimizing the least-squares between the model predicted and actual empirical response [2].

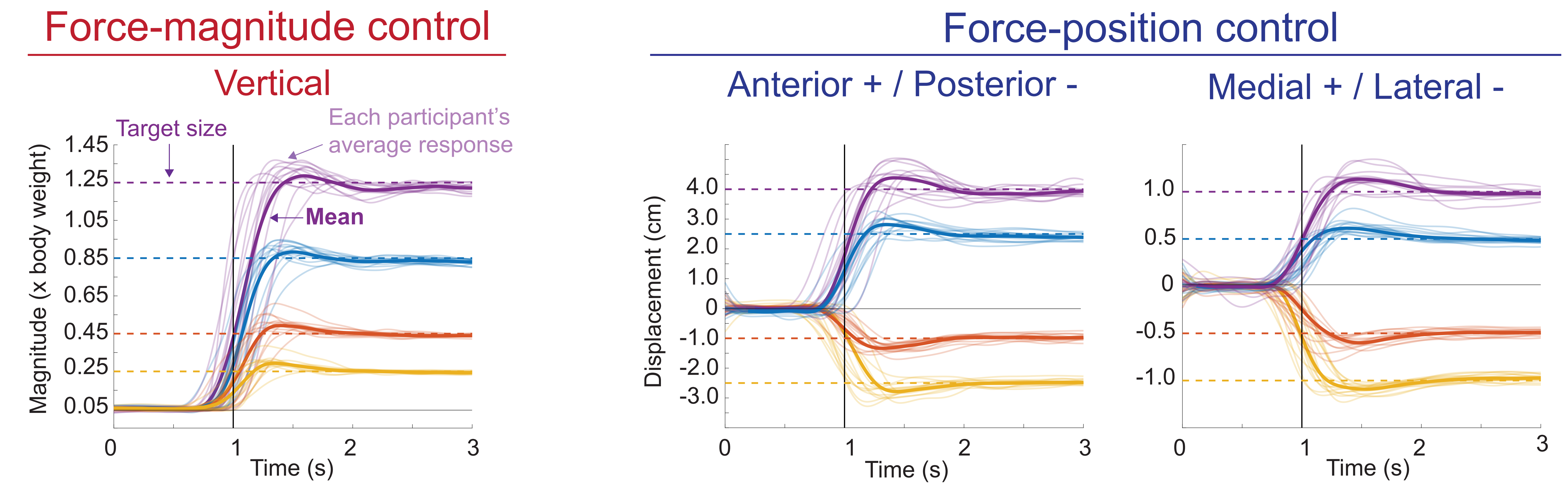
$$Y(s) = \frac{\overset{\text{process gain}}{K_p}}{(1 + 2\,\underset{\text{damping}}{Z_d} T_1 s + (\underset{\text{rate of change}}{T_1} s)^2)} \overset{\text{dead time}}{e^{-T_d s}} X(s)$$

References: [1] J. M. Sheppard and W. B. Young, "Agility literature review: Classifications, training and testing," J. Sports Sci., vol. 24, no. 9, pp. 919–932, Sep. 2006. [2] M. T. Thompson, "Review of Signal Processing Basics," in Intuitive Analog Circuit Design, Elsevier, 2014, pp. 15–52.

Results

Participants were well able to control the external force-magnitude and position by quickly responding to and closely matching the range of commanded target step sizes.

Step up to target



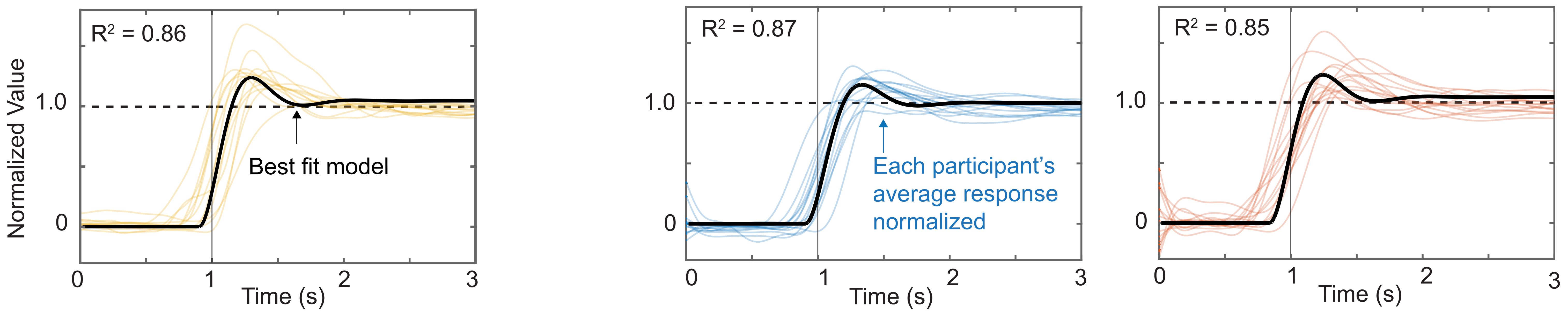
We observed similar control performance in terms of speed and accuracy for both force-magnitude and position control for all target sizes.

Representative Data

	Target Size	Overshoot (%)	Rise Time (ms)	Bandwidth (Hz)	Steady-State Error (%)	Steady-State Variability (%)	Fall time (ms)
Force-magnitude	x0.45 BW	19±11	205±64	1.8±0.5	2.9±1.0	3.1±1.0	374±100
Force-postion	2.5 cm (Anterior)	19±9	226±48	1.6±0.3	6.2±2.1	3.8±2.3	418±111
Force-position	1 cm (Lateral)	19±13	230±46	1.6±0.3	5.9±3.7	4.2±2.5	382±115

A 2^{nd} order model was a good predictor of leg external force control.

2^{nd} order model



This controller, and by extension the human leg, rises to step changes in 165 ms but overshoots targets by 15%. It settles on targets in 170 ms and then exhibits no steady-state error or variability. It can accurately track changes to force-magnitude or position that oscillate twice per second (bandwidth of 2 Hz).

Benchmarking force control performance in young healthy humans will be useful for understanding the effect of age, disease, and injury on force control and human agility.