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

Our legs act as our primary contact with the surrounding environment, generating external forces that enable agile motion. The control of the magnitude of this force, and of the position where the force is applied by the foot onto the ground are key determinants of translational and rotational acceleration. Effective control of these force properties may help explain differences between humans, between humans and other animals, and between humans and engineered systems. The objective of our work was to characterize the performance of the human leg in controlling the force-magnitude and position of an externally applied force. To accomplish this, we built an apparatus that constrained healthy young participants (f=4,m=10) standing above a ground embedded force platform. The constraints immobilized the body but allowed participants to exert variable but controlled forces onto the ground. This involved selectively pushing either more or less with their leg (force-magnitude) or shifting the position of the force beneath their foot (force-position). We provided real-time visual feedback of either the leg force-magnitude or position that participants were exerting against the force platform and instructed participants to best match their real-time signal to prescribed target step functions. We tested target step functions of a range of sizes and characterized the control of external forces in terms of speed (rise time,bandwidth), overshooting the target, steady-state error, and steady-state variability. We found that when controlling leg force-magnitude for step targets of size x0.45 bodyweight, participants required 205±64ms(mean±std) to approach a new steady-state value (rise time), achieving a bandwidth of 1.8±0.5Hz. Participants overshot the step target by 19±11%, had a steady-state error of 2.9±1.0% bodyweight, and had a steady-state variability of 3.1±1.0% bodyweight. We found similar control performance for a range of target step sizes and the control of force-position. In addition to this control characterization, we modelled the measured control of external forces as a 2nd order control system and used system identification methods to estimate the unknown model parameters. We found that our controller well-described the observed force control characteristics with best-fitted R^2 values for both force-magnitude and position control above 0.85 for the range of tested target step sizes. 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 human agility. It will also be useful for understanding the limits to agility in legged robots, and wearable devices.