Simulating the impact of sensorimotor deficits on reaching performance

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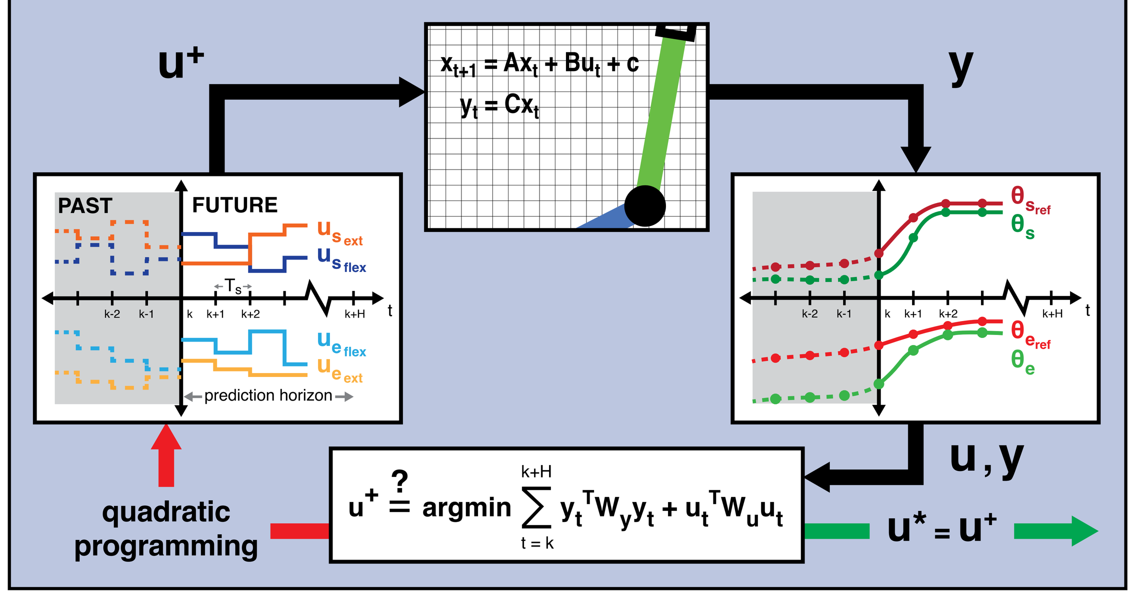
Introduction

Stroke can result in a variety of sensorimotor deficits including muscular weakness, abnormal muscle tone and spasticity, and sensory deficits. Although these deficits are often characterized after a stroke, the complexity of the human neuromusculoskeletal system makes it difficult to understand how they impact motor performance, both individually and in combination. Our lack of understanding is a barrier to designing therapies that efficiently and safely improve sensorimotor performance. To deepen understanding of the factors that lead to disability, we model the human upper extremity and nervous system as an optimal-feedback-controlled planar arm to which we systematically apply stroke-like sensorimotor deficits. We then evaluate the extent to which motor performance is impaired by each sensorimotor deficit.

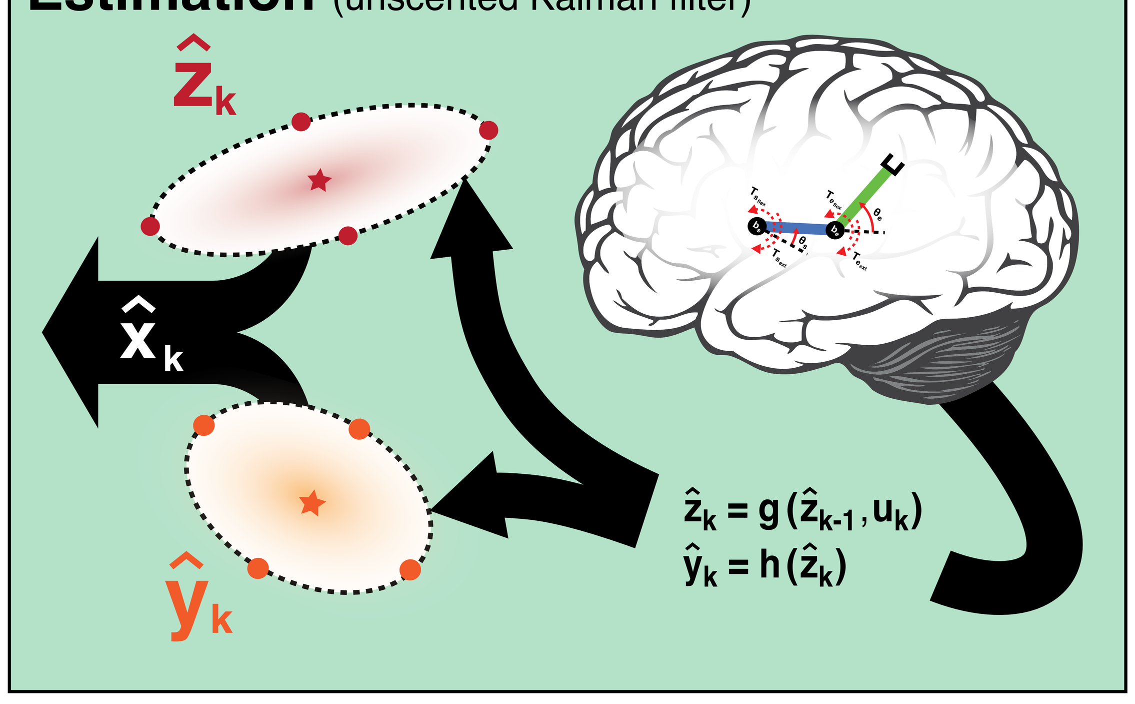
Methods

We model the human neuromusculoskeletal system as an optimal-feedback-controlled[1] two-degree-of-freedom planar arm with physiologically based parameters (e.g., mass, inertia, time delays)[2]. We then simulate point-to-point reaches and systematically apply sensorimotor deficits commonly observed after a stroke.

Control (model predicitive control)



Estimation (unscented Kalman filter)

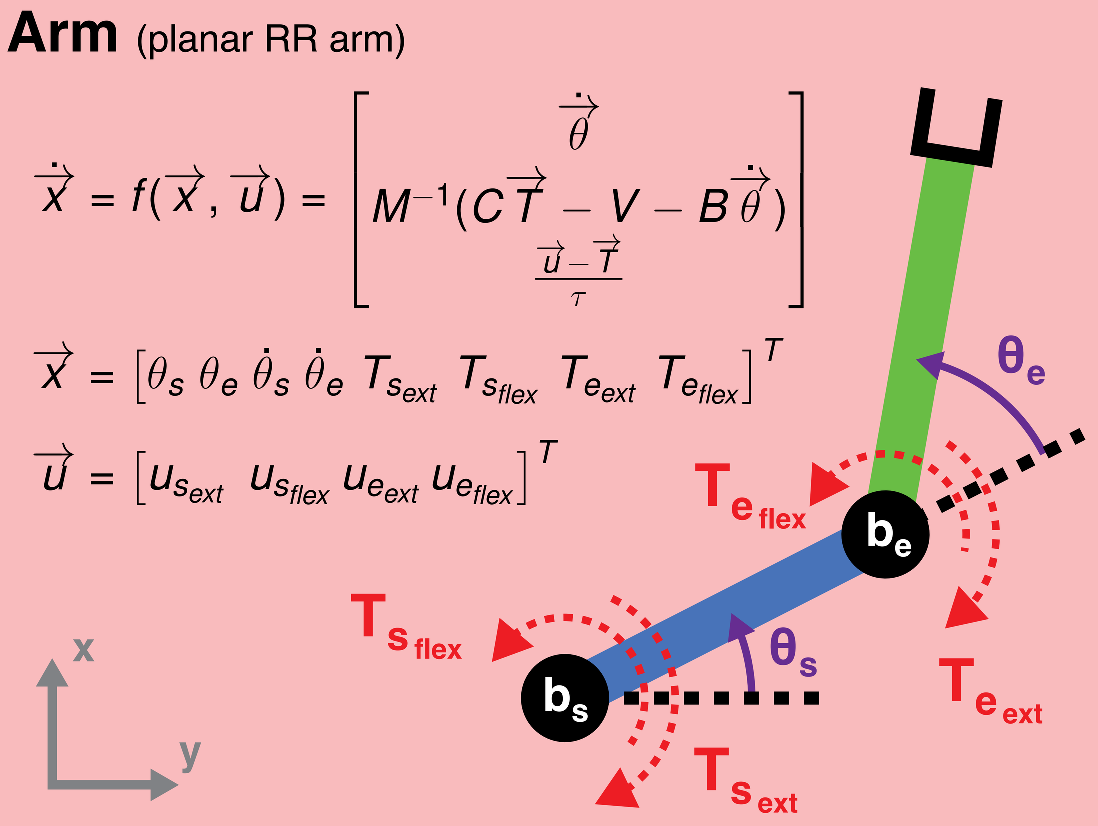


Arm (planar RR arm)

$$\dot{\vec{x}} = f(\vec{x}, \vec{u}) = \begin{bmatrix} \dot{\vec{\theta}} \\ M^{-1}(C\vec{T} - V - B\dot{\vec{\theta}}) \\ \frac{\vec{u} - \vec{T}}{\tau} \end{bmatrix}$$

$$\vec{x} = [\theta_s\ \theta_e\ \dot{\theta}_s\ \dot{\theta}_e\ T_{s_{ext}}\ T_{s_{flex}}\ T_{e_{ext}}\ T_{e_{flex}}]^T$$

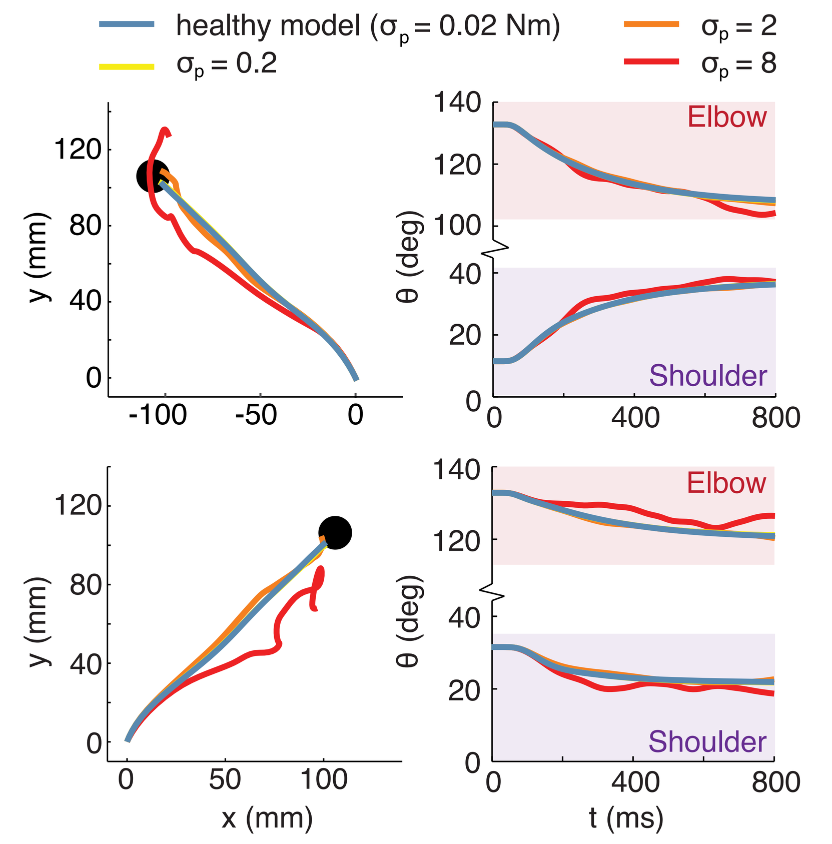
$$\vec{u} = [u_{s_{ext}}\ u_{s_{flex}}\ u_{e_{ext}}\ u_{e_{flex}}]^T$$



Results

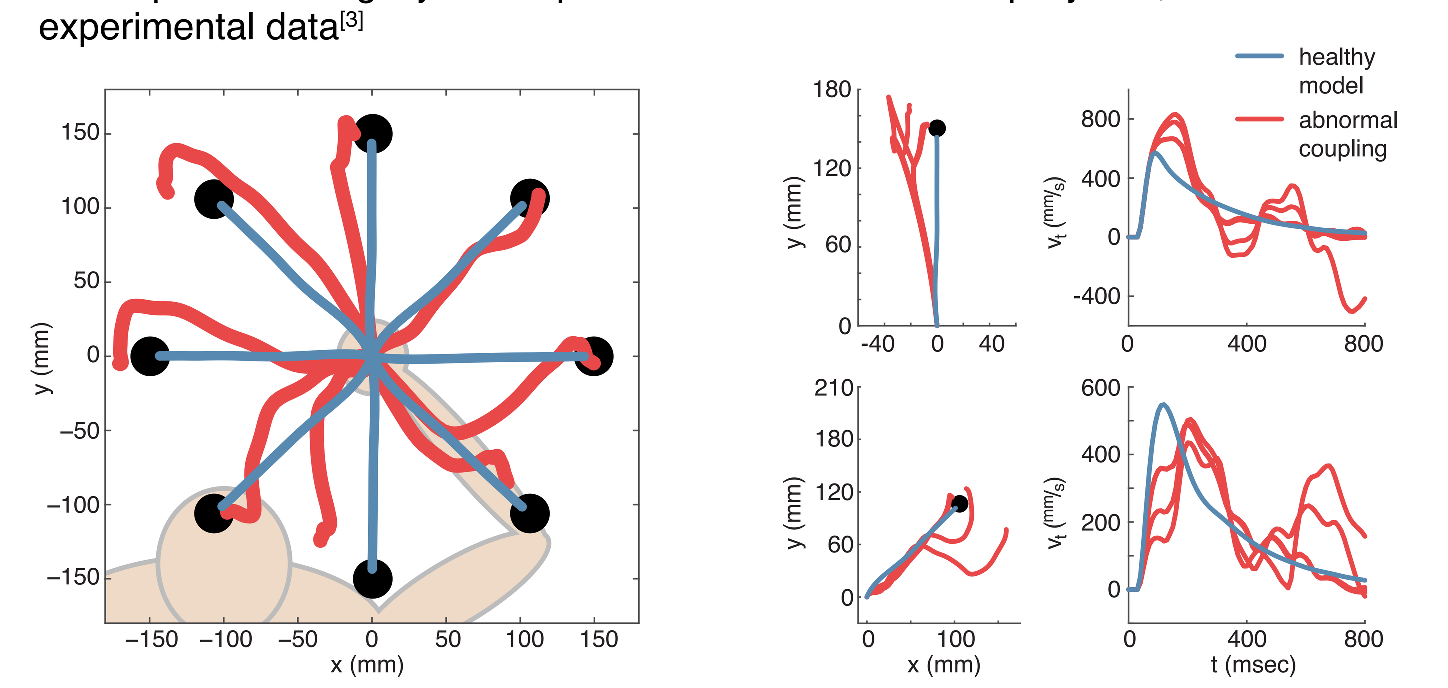
Estimation noise

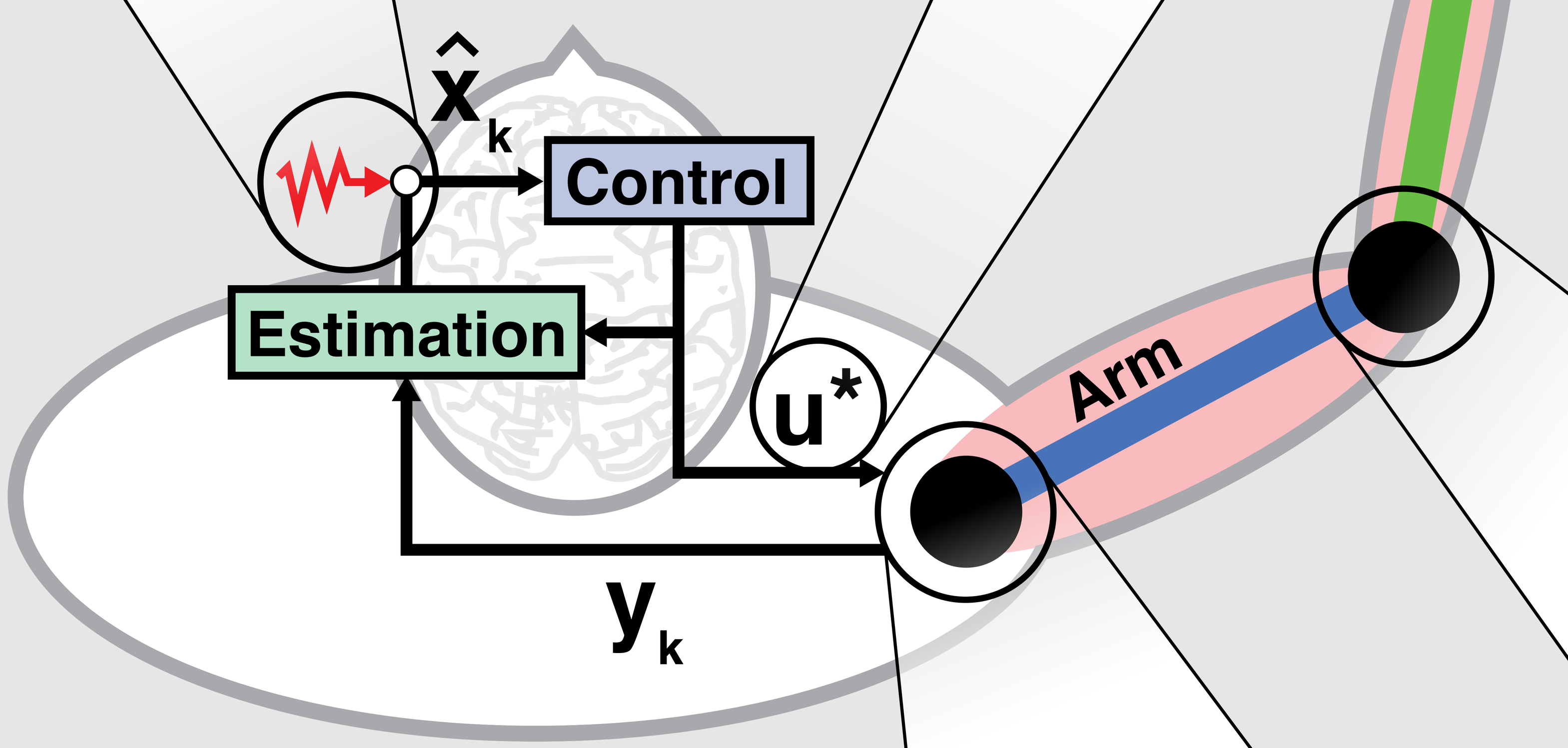
Increase the uncertainty of the state estimates by increasing the standard deviation of Gaussian noise applied to final estimate



Abnormal joint coupling (merged muscle synergies)

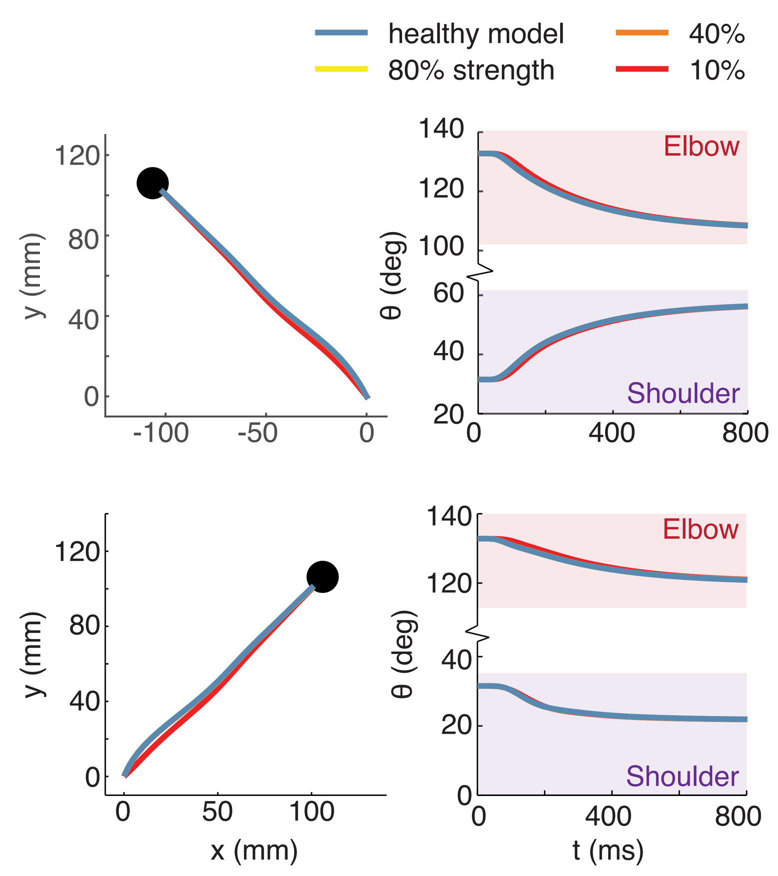
Re-map certain single-joint torque actuators to affect multiple joints, based on experimental data[3]



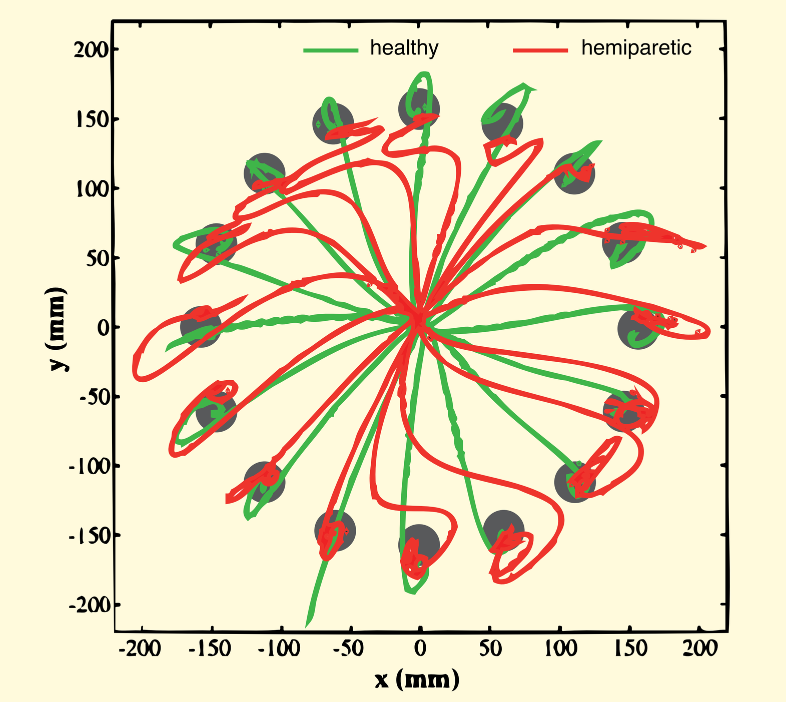


Muscle weakness

Decrease the strength of all muscles by decreasing maximum torque limits



Experimental reach data[3]



Tone and spasticity

Apply a spring-damper model of spastic muscle tone and damping that scales with score on modified Ashworth scale[4,5,6]:

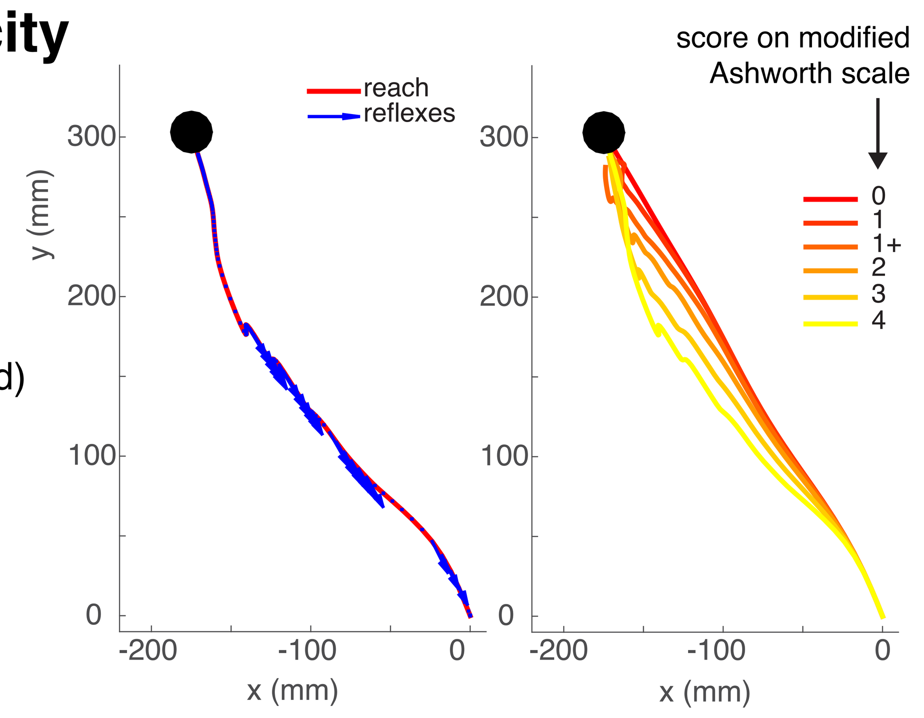
if (arm state > spastic threshold)

$T = T_{command} + T_{reflex}$

$T = T_{command} + \underbrace{k\Delta\theta}_{spring} - \underbrace{b\dot{\theta}}_{damper}$

else

$T = T_{command}$



Discussion

Our results indicate that reaching performance is highly robust to prediction error resulting from increased estimation noise and changes to the plant (decreased muscle strength), but is greatly impaired by unmodeled dynamics (abnormal joint coupling or unexpected spastic events). This result suggests that **while humans are naturally adept at stochastic control, robust control is difficult**. After validating our simulations with experimental data, future work will extend the framework to three dimensions (beyond planar movements), as well as capture de cits caused by other neuromotor injuries or illnesses (e.g., cerebral palsy, spinal-cord injuries, deafferentation). Ultimately, in conjunction with a well-formulated cost function (e.g., maximizing workspace), the framework will be used to design optimal personalized rehabilitation strategies and assistive devices.

References

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