# Force-velocity property of muscle is critical for stabilizing a tendon-driven robotic joint controlled by neuromorphic hardware

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OUR overall aim is to understand which minimal features of the human sensorimotor nervous system are sine-qua-non for natural function and pathology. To this purpose, we designed and implemented a tendon-driven robotic system resembling human joints, which allows us to examine the functional significance of neuromuscular structures using a synthetic analysis approach. In our first setup (Figure 1a), we have built a single D.O.F. joint driven by two antagonistic tendons actuated by DC motors programmed to implement biologically plausible muscle models. Real-time hardware simulates spindle afference as in [1]; and 16,000 simulated Izhikevich spiking neurons [2] to implement multiple proprioceptive closed-loop pathways in parallel, resembling the concurrent monosynaptic pathways in human spinal cord [3].

In principle, the monosynaptic spinal pathways can provide fast, continuous feedback control that presumably has a stabilizing effect on human joints. It is, however, not clear which structures and features in the abundant neuromuscular physiology literature, are essential for joint stabilization. Specifically, we ask whether and how the level of detail of the muscle model affects the ability of the joint to regain its original angle when perturbed.

A Phantom Desktop haptic robot perturbs the joint with a 4.0 N force pulse lasting 20ms while we record joint angle and muscle eletromyograph (EMG, Figure 1b). For a same proprioceptive spinal circuitry, we compared the responses from a Hill-type model with spike interfaces and a simple twitch model. In the former, the joint returns to the original angle with minimal oscillations after ~200 ms. In the latter, however, the joint overshoots out of the working range and invalidates subsequent simulations. We argue that this is due to the force-velocity relationship [4] captured in Hill's model, which effectively provides dynamic damping induced by muscle shortening and lengthening.

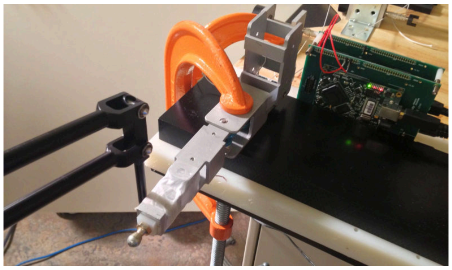

Figure 1a Demonstration of the tendon-driven finger connected to FPGA neuromorphic controllers. A Phantom robot is delivering torque perturbations

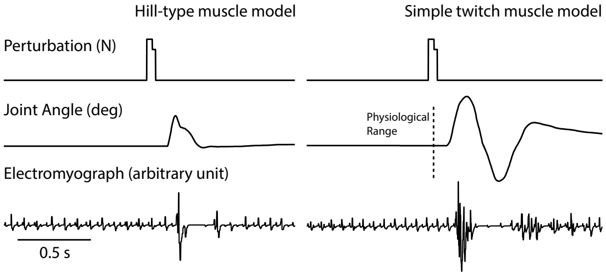

Figure 1b The torque perturbation increased the joint angle but is rapidly compensated by the reflex loop when using Hill-type model. The same perturbation elicited large oscillation when using simple twitch model. EMGs are shown as verification.

Expanding on this initial work in the development of neuromorphic tests beds, we will systematically explore alternative implementations of known neuromuscular and spinal physiology. This will eventually allow us to test what really is required to achieve hand control, and the origins of upper-limb neuropathology, by driving the tendons of cadaveric hands [5] with real-time hardware implementing physiologically plausible muscle and spinal neuromorphic models.

## REFERENCES

[1] M. P. Mileusnic, I. E. Brown, N. Lan, and G. E. Loeb, "Mathematical models of proprioceptors. I. Control and transduction in the muscle spindle.," *J. Neurophysiol.*, vol. 96, no. 4, pp. 1772–1788, Oct. 2006.

[2] E. M. Izhikevich, "Simple model of spiking neurons.," *IEEE Trans Neural Netw*, vol. 14, no. 6, pp. 1569–1572, 2003.

[3] C. M. Niu, S. K. Nandyala, W. J. Sohn, and T. D. Sanger, "Multi-scale Hyper-time Hardware Emulation of Human Motor Nervous System Based on Spiking Neurons using FPGA," pp. 37–45, 2012.

[4] T. A. McMahon, *Muscles, Reflexes, and Locomotion*. Princeton, NJ: Princeton University Press, 1984.

[5] J. J. Kutch and F. J. Valero-Cuevas, "Challenges and new approaches to proving the existence of muscle synergies of neural origin.," *PLoS Comput Biol*, vol. 8, no. 5, p. e1002434, 2012.

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