Assessing the role of neuromuscular components using a tendon-driven robotic plant 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 a tendon-driven robotic plant controlled by neuromorphic hardware using Very Large Scale Integrated-circuit (VLSI) technology (Fig.1A). The robotic plant resembles human joints, and the VLSI hardware simulates realistic neurons, spindles, muscles, and their connectivity in real-time. We examined the functional significance of these neuromuscular structures using a synthetic analysis approach. In our first implementation (Fig.1B), we built a single D.O.F. joint driven by two antagonistic tendons actuated by DC motors. Each motor was controlled by a VLSI chip simulating spindle afference as in [1], 16,000 Izhikevich spiking neurons [2], and a Hill-type muscle producing a surface electromyogram (EMG). This setup had multiple proprioceptive closed-loop pathways in parallel, resembling the concurrent monosynaptic pathways in human spinal cord [3]. A total of 8,000 alpha-motoneurons were divided into 6 groups representing motor units with various sizes, therefore Henneman's size principle naturally emerge during simulated voluntary motor unit recruitment. The reflex behavior of the system was tested using force-pulse perturbations delivered by a Phantom Desktop haptic robot (Fig.1C).

This neuromorphic hardware generated realistic multi-scale physiological information that is difficult to obtain in-vivo (Fig.2). The simulated surface EMG was also piped through a speaker and presented to a practicing neurologist to allow visual and auditory validation. When the size principle is violated, the EMG became significantly more abrupt and no longer resembles physiological data (Fig.2, bottom trace).

We further tested and how the level of detail of the muscle model affects the ability of the joint to regain its original angle when perturbed. For a same proprioceptive spinal circuitry, we compared the responses from a Hill-type muscle model (adapted to spike interfaces) vs. a simple twitch model. With the former, the joint returns to the original angle with minimal oscillations after ~200 ms (Fig.3A). With the latter, however, the joint overshoots out of the working range and invalidates subsequent simulations (Fig.3B). We argue that this is due to the force-velocity relationship [4] captured in Hill's model, which effectively provides dynamic damping.

By testing 1) the significance of size principle for producing realistic EMG, and 2) the significance of the force-velocity relationship of muscle for joint stabilization, we show the feasibility and promise of our synthetic approach to understanding neuromuscular control. Our ultimate goal is produce realistic control of a cadaveric hand [5] with multiple neuromorphic actuators to understand the nature of upper-limb neuropathology.

References

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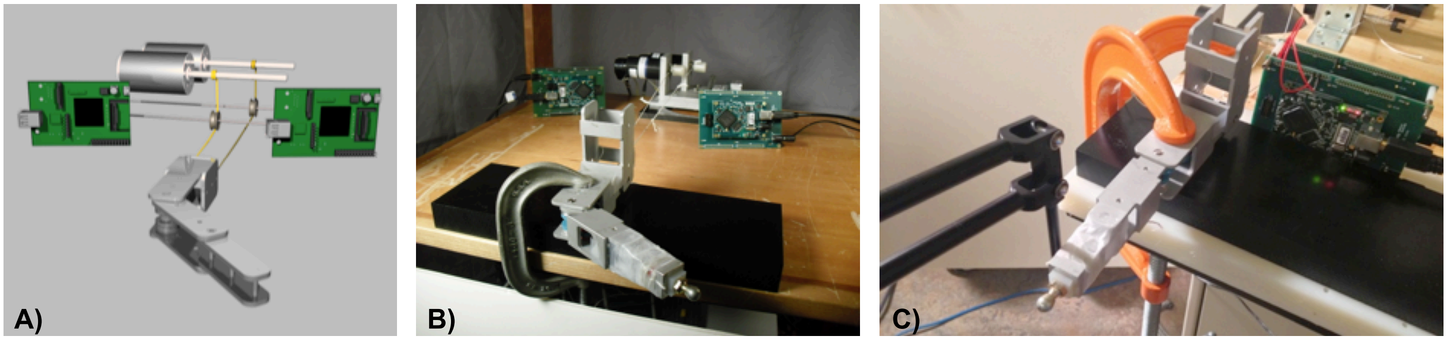

Figure 1. A) Design of the tendon-driven finger connected to VLSI neuromorphic controllers. B) We have built a single D.O.F. joint driven by two antagonistic tendons actuated by DC motors. Each motor is controlled by a VLSI chip simulating spindle afference, 16,000 Izhikevich spiking neurons, a Hill-type muscle and surface electromyograph (EMG). C) A Phantom Desktop robot is delivering torque perturbations.

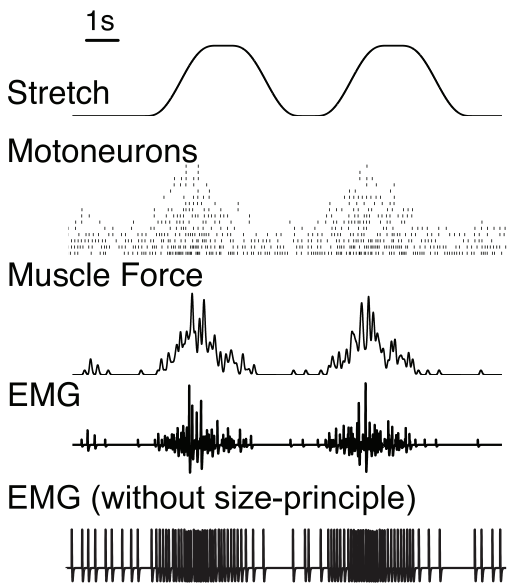

Figure 2. Multi-scale information produced by the simulated reflex when the joint is stretched. The two phases of muscle stretch activate motoneuron pools through the function of simulated spindle. The two peaks in muscle force and EMG correspond to the maximum velocity of stretching. When Henneman's size principle is removed, the EMG no longer shows a burst pattern.

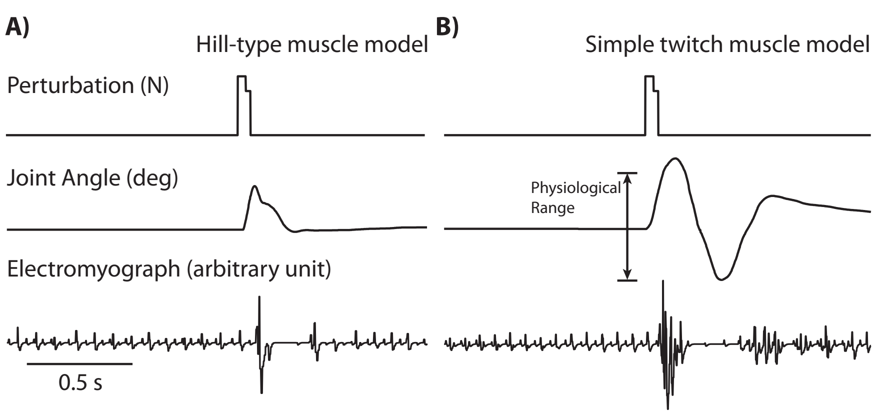

Figure 3. A) The torque perturbation increased the joint angle but is rapidly compensated by the reflex loop when using Hill-type model. B) The same perturbation elicited large oscillation when using simple twitch model. EMGs are shown as verification.

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