Series elastic element is critical for stabilizing a tendon-driven robotic joint controlled by physiologically realistic models

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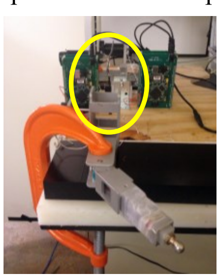
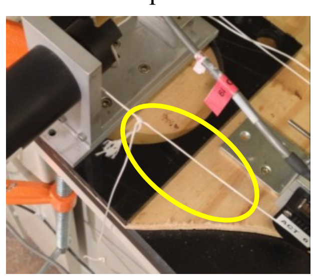
OUR overall aim is to understand which minimal features of the human sensorimotor nervous system are sine-qua-non for natural function and pathology. To this purpose, we designed and implemented a tendon-driven robotic system resembling human joints, which allows us to examine the functional significance of neuromuscular structures using a synthetic analysis approach. In a subset of our overall design (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 human neuromuscular systems, it is important that muscle tendons be tense at all times. This guarantees that muscle spindles can continuously sense the length and lengthening velocity of muscle. In our tendon-driven robotic system, however, it is found that tendons tend to slack when shortened by external perturbations. This will result in immediate instability in the joint. In theory, in order for the tendon to tense during dynamic interactions it requires the motor to rapidly generate torques and rapidly rotate if needed. Due to the design of DC torque motors, however, their torque generation is sufficiently responsive only when no rotation is needed. Thus, during muscle shortening the expected tension will not be reached until the motor speeds up to re-tense the tendon, adding significant delays in the control loop and making the joint difficult to stabilize.

We created the solution of adding a spring between the motor side and the joint side of the string (Figure 1b and c). In quasi-static tasks, this serial elastic component transfers the exact tension that the monosynaptic spinal pathway expects to deliver. In dynamic tasks including muscle shortening, the series elastic component provides immediate force feedback without having to wait for the torque motor to speed up. This solution allows stabilizing the joint even when fusimotor drives to muscle spindles are set to the highest available value, meaning the highest closed-loop gain in monosynaptic control. This also suggests that serial elastic components, as included in Hill-type models [4], are functionally important for joint stabilization. When a joint is driven by two opposing muscles, any movement in the joint will shorten one of the two muscles. Therefore, the serial elastic component helps to keep the shortened muscle tense, such that its muscle spindle can still monitor muscle status to provide continuous spinal-level feedback control.

One of the main conclusions that can be drawn from this is that the implementation of neuromuscular models in control systems is greatly facilitated by the inclusion of a series elastic element for realistic and stable behavior. This should aid future implementations for prosthetics or neuromuscular experiments.





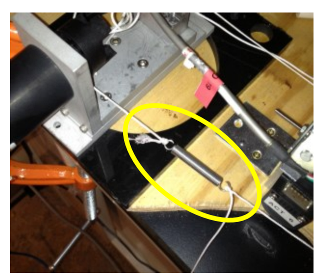


Figure 1

a) Mechanical tendon-driven finger with neuromorphic FPGA controller

b) Direct tendon connection

c) Series elastic element in the tendon connection

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Because of space constraints, numerical data will be included in the poster to corroborate these results as supplemental material.