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Passive Dynamics of a Hybrid Neuromechanical Joint Incorporating Living Muscle

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Abstract—**We have developed a hybrid neuromechanical joint to investigate the nonlinear properties of muscle in a physiologically relevant context. We constructed the hybrid system by connecting a live frog gastrocnemius muscle to a joint which is simulated as an inverted pendulum. We first tested this hybrid system with a spring as the actuator to ensure that the perturbation-response trajectories using living muscle would accurately describe the mechanical properties of the muscle. This hybrid neuromechanical system, with muscle as the actuator, responded to impulse torque perturbations with stable damped oscillations. Joint settling times to perturbations were measured while the joint mass and the initial muscle length were varied. Passive muscle alone stabilized small perturbations. With heavier joint masses and shorter initial muscle lengths the system became increasingly unstable. We found that the hybrid neuromechanical joint is an accurate tool to study the neuromuscular system.**

I. INTRODUCTION

THE animal neuromuscular system has the remarkable ability to accomplish a variety of motor tasks under different environmental conditions. The organizational principles that govern the neuromuscular system may offer an elegant solution for a robust control system. Engineers may be well served to mimic the neuromuscular system in order to build versatile robotic and prosthetic systems.

The neuromuscular system can be organized in a hierarchy consisting, from top to bottom, of higher-brain centers, spinal reflexes, and the musculoskeletal plant [1]. Since neural control is subject to time delays, the mechanical properties of the musculoskeletal plant may reduce the load and even simplify the architecture of neural controllers. The interactions between the mechanical properties of the musculoskeletal plant and neural control can be studied during stability tests [2].

The mechanical properties of muscle can provide some level of stability to a skeletal joint [3]. When a joint is perturbed, the intrinsic properties of the muscles produce an instantaneous restoring force. These forces arise from changes in muscle length and velocity while the muscle is under constant activation by the central nervous system. This response can stabilize small perturbations, resulting in damped oscillations. If the muscle is not activated, the instantaneous forces are due to the passive muscle properties. Robotic actuators and controllers that emulate muscle might be a favorable design for autonomous stability.

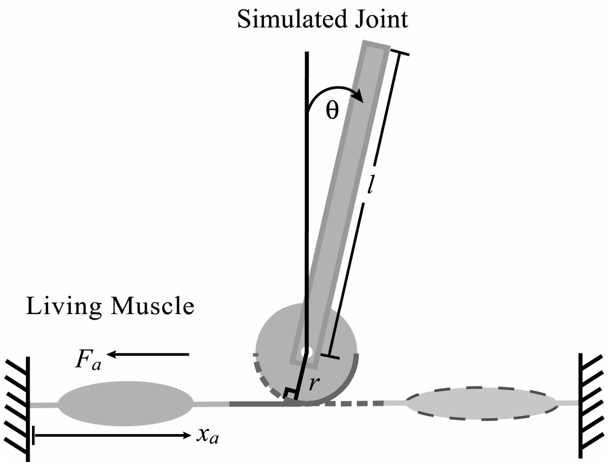

Fig. 1. Schematic of the hybrid neuromechanical joint. The joint was simulated as an inverted pendulum with a constant moment arm for actuation. Forces produced by the muscle were referenced to an initial background force requiring only one muscle to actuate the joint in either direction.

The stability provided by the neuromuscular system is often studied using either computational models [4] or animal preparations [5]. The computational approach offers experimental controllability but relies on simplified models. Animal preparations have the clear advantage of using the intact neuromuscular system, but are often difficult to control. The *hybrid* system is an innovative approach that combines an *in vitro* animal model with a computational or physical model [6]. The combination allows for increased experiment controllability with an animal preparation.

TABLE I
MECHANICAL QUANTITIES OF THE HYBRID JOINT

Symbol	Quantity	Value
θ	joint angle	output
M	joint mass	varied
l	length, joint	10 cm
r	length, joint moment arm	2 cm
F_a	force, muscle	output
F_i	force, initial muscle	varied
x_a	length, muscle	output
x_d	length, desired muscle	output
x_i	length, initial muscle	varied

We constructed a hybrid neuromechanical joint by

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TABLE II

EXPERIMENT VARIABLE VALUES

Quantity	Range	Resolution
Initial Muscle Length, x_i	-1 mm to -2 mm*	0.5 mm
Joint Mass, M	50 g to 100 g	25 g
Initial Angular Velocity (Perturbation)	-57.3 °/s to 57.3 °/s	11.5 °/s

* Referenced from the maximum physiological length.

actuating a computational joint with a live frog (*Rana pipien*) gastrocnemius muscle. The skeletal joint is simulated as an inverted pendulum with a circular base allowing a constant moment arm for actuation (Fig. 1). The inverted pendulum is a classical unstable system that is used to study controller efficiency. This allowed us to investigate the stability that passive muscle properties provide. We studied the response of the hybrid system to impulse torque perturbations. In particular, we examined the effects of changing initial muscle length and joint mass on the joint settling time. We hypothesize that passive muscle can stabilize small perturbations and that decreasing initial muscle length and increasing joint mass will increase joint settling time.

II. HYBRID DESIGN

The hybrid neuromechanical joint is a closed-loop system that allows living muscle tissue to actuate a computational joint (Fig. 2). The system uses force feedback and muscle-length control to create the hybrid connection.

A. Joint Model

A joint model was developed in MATLAB® Simulink® and configured to run on a real-time processor. The joint was simulated as a single degree-of-freedom solid thin inverted pendulum. The muscle actuated the pendulum via a constant torque arm. Table I lists all the mechanical parameters and measured quantities. The equation of motion for the joint is

$$I\ddot{\theta} = \frac{Mgl}{2}\sin(\theta) + (F_a - F_i)\cdot r \tag{1}$$

where g is the gravitational constant and I is the moment of inertia. Forces produced by the living muscle (F_a) are referenced to an initial background force (F_i). This allows the muscle to apply positive and negative changes in force requiring only one muscle to actuate the joint in either direction. The model input is muscle force (F_a) and muscle length (x_a). The model output is desired muscle length (x_d). The relationship between joint angle and muscle length is

$$x_j - x_i = -r\theta \tag{2}$$

where $j \in \{a,d\}$. The current muscle length (x_a) was used to calculate the current joint position (θ). The current joint position (θ) and muscle force (F_a) was used to calculate the desired muscle length (x_d).

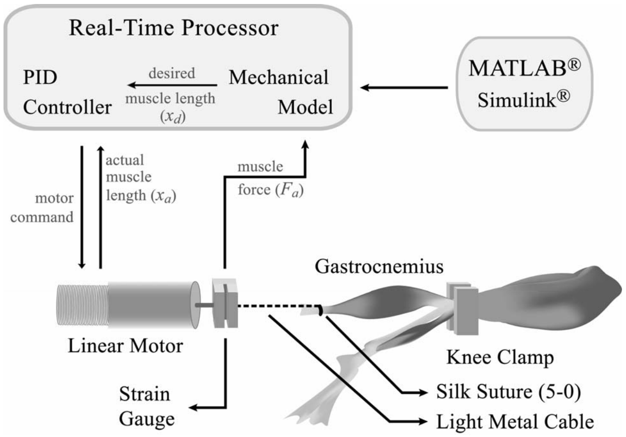

Fig. 2. Design of the hybrid neuromechanical joint. A closed-loop configuration was used to connect a living muscle to the computational joint. A real-time processor was used to implement the joint model and a PID controller that controlled the length of the muscle.

B. Experimental Setup

All surgeries were performed according to procedures approved by the Institutional Animal Care and Use Committee at the Georgia Institute of Technology (Protocol #A04010). Surgeries were performed under standard tricaine anesthesia. The frog was double pithed, and the distal end of the gastrocnemius muscle was severed. The sciatic nerve was cut to ensure that no reflexes were present. The distal tendon was tied to a light and stiff steel cable using a minimal amount of silk suture (size 5-0), and the knee was clamped. The other end of the steel cable was fastened to a strain gauge which was connected in series to a linear motor. The muscle was oriented to pull along its physiological axis. Ringer solution was periodically applied to keep the muscle moist.

C. Closed-Loop Implementation

The hybrid system used the muscle force to determine the angle of the joint. In turn, the angle of the joint determined the length of the muscle. This loop ran in real-time to allow the model to interface with the living muscle. The real-time processor used a fixed-step ode5 solver with a sampling frequency of 10 kHz to solve the joint model for the muscle length. The strain gauge measured the muscle force and fed it into the joint model.

A PID controller was constructed to control the muscle length via a linear motor. The PID gains were tuned to work with a physiological frequency range (3-6 Hz) [7]. The controller compared the desired length to the actual length and issued the appropriate command to the linear motor. The actual length is measured using a 1 μm resolution optical encoder.

III. METHODS

A. Experimental Protocol

The primary experimental aim was to measure joint settling time after a perturbation. The hybrid joint was subjected to a set of torque impulses and the resultant trajectory was measured. A torque impulse is analogous to an initial angular velocity. We transformed the initial angular velocities to linear velocities, which we then applied to the muscle. For each set of initial velocity perturbations, initial muscle length and joint mass were varied. Table II lists the range and resolution of perturbations, muscle lengths, and joint masses. The values were chosen to result in physiologically relevant trajectory amplitudes and frequencies.

For each set of perturbations, the gastrocnemius muscle was stretched to a prescribed length. The muscle was held at that length for 30 s to minimize any effects due to prior movement, and to reach a steady-state. The initial background muscle force was measured (F_i) and used to reference all future muscle forces (F_a). The joint mass was set to the desired value. Each perturbation was applied, and the resultant joint angle and muscle-force trajectories were measured. Between each perturbation, the muscle was allowed to rest for 20 s and a new background force (F_i) was measured. Joint settling times were measured to quantify the stability provided by passive muscle properties

B. *Validation*

The trajectories produced by the hybrid neuromechanical system needed to be validated before we could examine muscle properties. To validate the hybrid neuromuscular joint, we used a steel spring (~0.4 N/mm) to actuate the joint. Two different joint masses were used and two different perturbation amplitudes were applied. The values chosen simulated the frequency and amplitude response expected in the living muscle. The entire system was also simulated using MATLAB® Simulink®.

IV. RESULTS

A. *Validation*

The perturbation response of the hybrid system, actuated by a spring, was comparable to simulated data (Fig. 3). Changes in joint mass and perturbation amplitude caused appropriate changes in frequency and peak amplitude. On closer examination, we found that oscillations had a maximum DC offset of ±0.01°. This was caused by a slight drift in the strain gauge. Oscillations changed in amplitude over the 1 s course by ±0.003° due to the frequency response of the PID controller. The validation procedure used was a sensitive test, and the hybrid system responded with minimal errors. These errors may be further reduced if damping is introduced, as in the case of living muscle. As a result, we believe that the hybrid neuromuscular joint accurately models the response of an inverted pendulum driven by living muscle tissue.

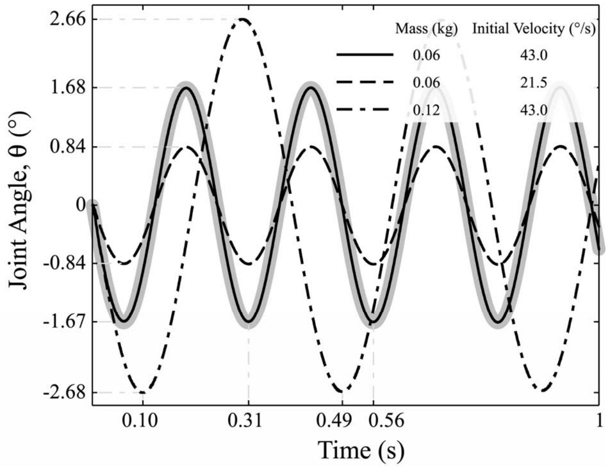

Fig. 3. The validation of the hybrid neuromechanical joint. With a spring as the actuator, the hybrid system responded to perturbations with the appropriate amplitude and frequency. The real spring matched our estimate of the spring and joint (thick grey line) well.

Figure 4 depicts example responses to perturbations using the frog gastrocnemius muscle as the actuator. The hybrid system responds to a small perturbation with stable damped oscillations. The offset in steady-state angle is due to the drift in background muscle force. If no perturbation is applied, the joint does not move. Larger perturbations can cause the system to grow unstable. The magnitude of the force in the negative direction is saturated by the magnitude of the initial background force. This limits the ability of the muscle to stabilize large positive initial angular velocities (perturbations that cause the muscle to initially shorten). A hybrid system with two antagonistic muscles would overcome this limitation.

B. *Experiment*

Increasing joint mass and decreasing initial muscle lengths increased the settling time of the hybrid neuromechanical joint (Fig. 6). Lengthened passive muscle has increased stiffness resulting in greater restoring forces when the joint was perturbed. Increased stiffness was also observed in the increased frequency of oscillations in the response to a perturbation (Fig. 5). The greater restoring force helped reduce settling time. As expected, increasing the joint mass reduced the frequency of the perturbation response (Fig. 5)

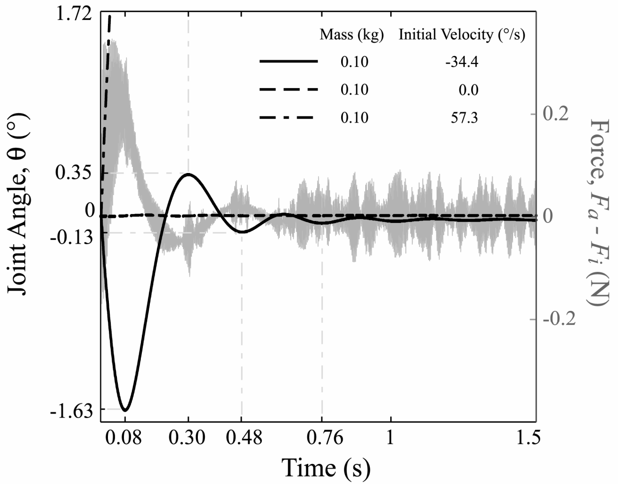

Fig. 4. Example responses of the hybrid neuromechanical system to perturbations. The dark lines in the foreground depict the joint angle trajectory. The force applied to the joint by the muscle during the damped oscillation is shown using a light grey trace. The force is not filtered.

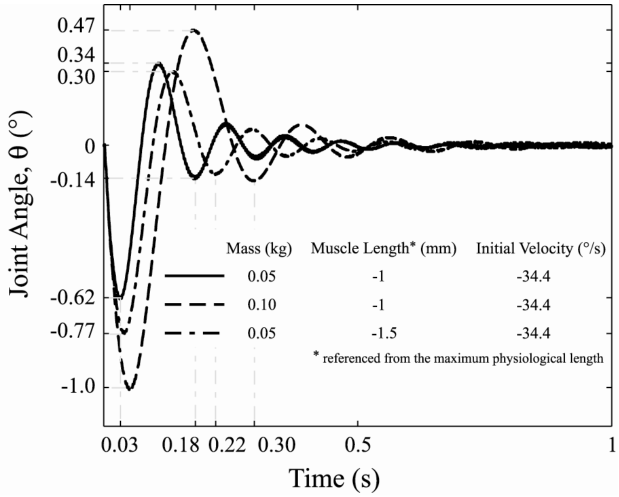

Fig. 5. Perturbation responses with varied muscle length and joint mass. Increasing the muscle length or decreasing the joint mass increased the system frequency and reduced the initial overshoot.

and also led to longer settling times. The asymmetry in settling time between positive and negative perturbations is due to the nonlinear properties of the passive muscle force-length curve. A positive change in muscle length produces a greater change in force than a negative change in muscle length does. The hybrid neuromuscular joint responded to perturbations in a manner that supported our hypothesis. Decreasing initial muscle length and increasing the joint mass increased the joint settling time.

V. SUMMARY

We utilized a hybrid system to investigate the stabilizing properties of passive muscle. We validated the hybrid system by using a real spring as the actuator. The hybrid spring-joint system responded to perturbations with the appropriate frequency and oscillation amplitude. With the frog gastrocnemius muscle as the actuator, we examined the influence of muscle length and joint mass on stability. Measured settling times indicated that the system grew more unstable with shorter muscle lengths and joint mass. By utilizing a computational joint, experiments can be performed that would have otherwise been impossible in the natural system. Using a living neuromuscular system allows a study of real biological properties that cannot be achieved in modeling studies alone. Thus, we believe that the hybrid neuromechanical joint is an innovative tool to study the neuromuscular system.

VI. DISCUSSION

For small perturbations, neural centers may not need to exert any control. The stiffness and damping of passive muscle, that without any neural activation, was able to stabilize small perturbations to the joint. In this study, increased muscle stiffness helped reduce joint settling times. Intrinsic muscle properties (muscle under constant activation) may provide even greater stability due to increased stiffness. Intrinsic and passive properties may serve as a distributed local control architecture that helps reduce the control effort required of the central nervous system. These properties may then be amplified by the remaining sections of the neuromuscular system: spinal reflexes and the higher-brain centers.

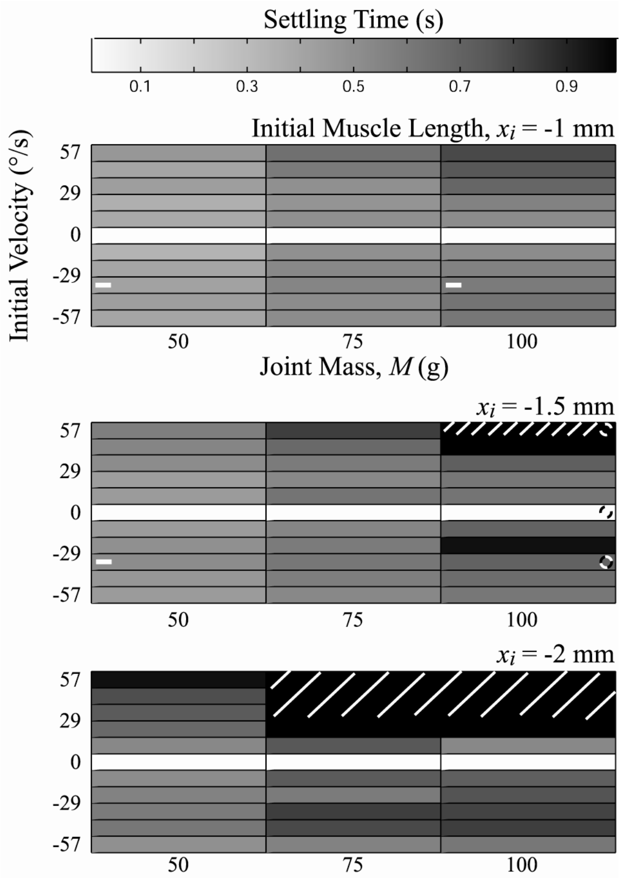

Fig. 6. Settling time of the hybrid neuromechanical joint. Settling times increase with larger joint masses and shorter muscle lengths. Data points with dashed lines indicate unstable trajectories. Data points with a black and white circle indicate trajectories shown in Figure 4. Data points with a white rectangle indicate trajectories shown in Figure 5.

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