EMBODYING HUMAN PLANTARFLEXOR MUSCLE-TENDON PHYSIOLOGY FOR NEUROMUSCULAR MODEL-BASED CONTROL OF A POWERED ANKLE EXOSKELETON

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INTRODUCTION

Powered exoskeletons show promise for both enhancing able-bodied gait and increasing mobility for individuals with pathologies such as stroke or other neuromuscular diseases. Central to effective exoskeleton control design is the interaction of the robotic device with the human user. This requires the device to be adaptable to the behavior of the lower-limb over in variable conditions of speeds, terrains, and even gaits. However, current exoskeleton controllers are constrained by control parameters that are often defined *a priori* or optimized for select sets of conditions, which in many cases is confined to level ground walking at preferred walking speed. Previously a neuromuscular model based controller was implemented in powered ankle-foot prosthesis (1). By virtually emulating a Hill-type muscle *in silico*, implementing positive force feedback within the controller, the model was capable of embodying aspects of human physiology that may be more adaptable when responding to variable conditions.

The purpose of this work was to develop and test a neuromuscular model (NMM) based controller for powered ankle-foot exoskeletons. We hypothesized that the NMM would have similar dynamics to the biological muscle-tendon units (MTUs) of the ankle plantarflexors that have previously been observed in vivo, in ultrasound studies (2).

METHODS

Controller:

Exoskeleton assistance was provided using our lab based exoskeleton emulator where force was delivered from the off-board motors to bilateral carbon fiber ankle exoskeletons via a Bowden-cable transmission system. The neuromuscular model was designed in Simulink and control was implemented in a real- time computer which also handled signal IO (500 Hz, dSPACE, Germany).

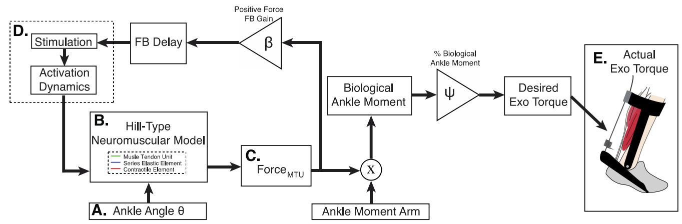

Figure 1: Block diagram of the NMM controller. Torque is applied to the exoskeleton as a percentage of the biological torque.

The neuromuscular model (Fig. 1) was a reflex-based feedback controller similar to Eilenberg et al (1). The emulated plantarflexor muscle tendon unit (MTU) was based off a Hill-type muscle model that consisted of a contractile element (CE), possessing both active and passive properties, in series with a series elastic element (SEE). The internal states of the muscle-tendon model (Fig.1B&2B) were calculated such that the length of the MTU was a function of modeled musculoskeletal geometry and ankle angle (Fig.1A&2A)(1.1), the CE length and velocity were subject to force-length, force-velocity, and activation dynamics (1.2), and the length of the SEE was the difference between MTU and CE lengths (1.3).

$$L_{MTU} = f\left(\theta_{ank}, r_{ank}\right) \quad (1.1)$$

$$(L_{CE}, \dot{L}_{CE}) = f\left(\text{F}-\text{L}, \text{F}-\text{V}, a\right) \quad (1.2)$$

$$L_{SEE} = L_{MTU} - L_{CE} \quad (1.3)$$

The force developed in the MTU (F_{MTU}) (Fig.1C&2C) was a function of the modeled non-linear stiffness of the SEE and the calculated strain in the SEE. In the reflex pathway, the MTU force was normalized to F_{max}, multiplied by a feedback gain, and delayed to emulate a neural positive force feedback neural signal (Stim) (Fig. 1D&1D). The feedback loop was closed by modeling the activation dynamics (ACT) of the CE.

The desired exoskeleton assistance was calculated as a percentage of estimated biological moment.

$$\tau_{exo} = F_{MTU} \times r_{ankle} \times \psi \quad (1.4)$$

where ψ represented a percentage of the estimated biological torque.

Testing Protocol: One able-bodied subject (male, 75 kg) completed the IRB approved protocol. The subject walked at 1.25 m/s while assistance was supplied with the exoskeleton. Ankle angle data were measured from a goniometer (960 Hz, Biometrics, UK) on the device. Internal states from the controller $\left(F_{MTU}, L_{MTU}, L_{CE}, STIM, ACT\right)$ were calculated and recorded in dSpace for 10 seconds (1000 Hz). Applied exoskeleton torque was calculated from a load cell data (500 Hz, LCM Systems Ltd, UK) placed in series with the applied assistance.

RESULTS AND DISCUSSION

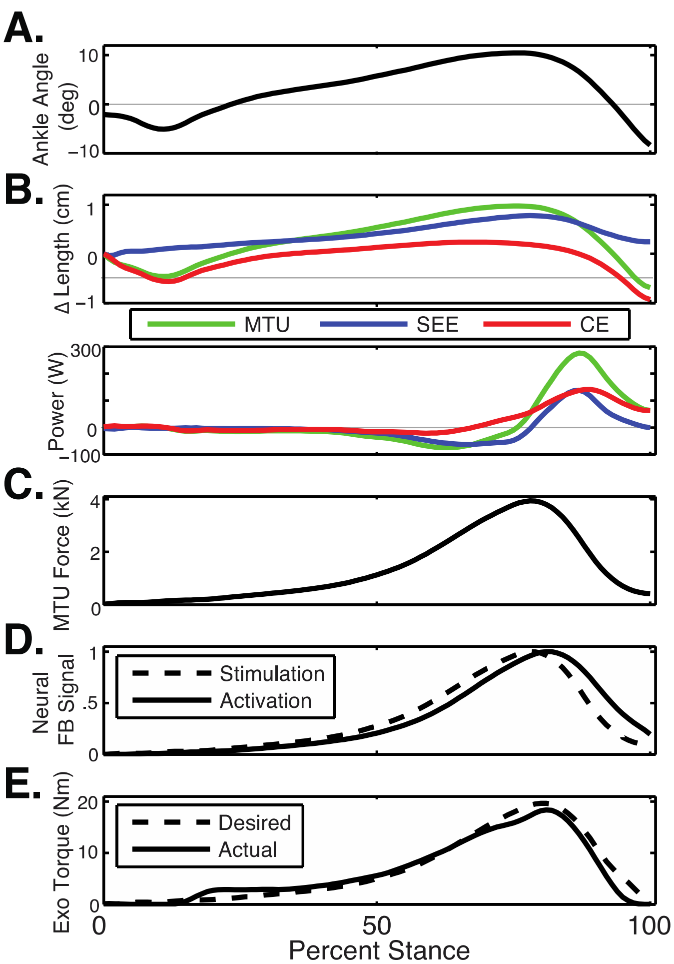

Figure 2: Results of NMM controller of a single subject walking at 1.25 m/s. **A.** Ankle angle during stance phase. **B.** Length changes in virtual MTU and corresponding power output. **C. Calculated** MTU force .**D.** Stimulation and activation signals FB signals . **E.** Desired and actual torque profiles.

Ankle kinematics were typical of walking gait with a long period of dorsiflexion followed by rapid plantar flexion (Fig 2A). At initial heel strike, there was slight plantar flexion which resulted in shortening of the MTU and contraction of the CE (Fig 2B). In early to midstance, the CE contracts nearly isometrically and behaves like a strut for the SEE to lengthen against. Finally, in late stance, the CE begins to contract concentrically and the tendon recoils during plantar flexion. The dynamics result in a period of energy storage (SEE) followed by energy recovery (SEE) and addition of net positive power (CE). Similar muscle tendon dynamics have been observed in ultrasound studies of humans walking where large excursions in the SE allowed for low velocities in medial gastrocnemius fascicles (3). The muscle tendon dynamics resulted in a virtual MTU force (Fig. 2C), which generated a positive force feedback signal and enhanced muscle activation (Fig. 2D). We calculated the desired peak exoskeleton torque to represent 10% of the biological ankle moment (Fig. 2E).

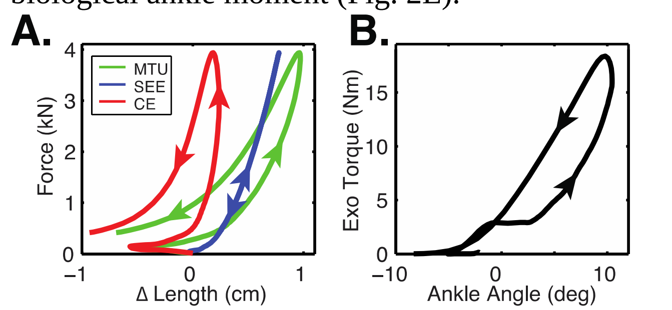

Figure 3: Workloops for the **A**. Virtual MTU of the NMM controller and **B**. Applied exoskeleton torque assistance.

Work loops representing muscle-tendon dynamics and ankle joint torque-angle behavior also closely matched observed patterns in humans (Fig.3A&B). Net positive work was added to the MTU through the concentric action of the CE.

This biologically inspired model can then be used to improve passive exoskeletons, reduce metabolic cost of walking, and serve as a controller in powered exoskeletons.

REFERENCES

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2. Farris DJ, Sawicki GS. Proc Natl Acad Sci U S A. 2012; 109(3):977-82.

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