MECHANICS AND ENERGETICS OF WALKING WITH A POWERED ANKLE EXOSKELETON USING NEUROMUSCULAR MODEL-BASED CONTROL - A PARAMETER STUDY

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INTRODUCTION

Powered exoskeletons are beginning to break new ground in enhancing locomotion performance for both able-bodied users [1] and individuals with pathologies such as stroke [2]. A major factor in determining exoskeleton performance is the control architecture that is used to generate the commands to motors that apply torques to the lower-limb joints. Approaches to torque control include using preset stiffness and damping values set as a function of joint angle or stride percentage (*i.e.*, impedance control) [1], or using muscle activity of the user (*i.e.*, myoelectric control) [2] to generate a reference signal for the exoskeleton actuators to follow.

Model-based control is another option that may lead to more robust behavior in response to changes in the state of the user or the environment. For example, previous research on a powered ankle-foot prosthesis demonstrated that, with optimized parameter settings, a neuromuscular model (NMM) based on the biological plantarflexors can normalize mechanics and energetics for amputees across a range of walking speeds [3]. It remains to be seen, whether a similar approach can be effective on a powered ankle exoskeleton system.

The purpose of this study was to test the effect of varying the reflex feedback parameters within a NMM-based controller designed to emulate the human ankle plantarflexors on a powered ankle exoskeleton. We hypothesized that increasing reflex feedback gain while minimizing the feedback delay would maximize net exoskeleton work and produce the largest reductions in users' metabolic cost.

METHODS

Exoskeletons: We provided bilateral plantarflexion assistance via a tethered ankle exoskeleton device. Off-board motors and Bowden cable transmission delivered torque to the custom carbon fiber exoskeletons.

Controller: We designed the NMM based controller in Simulink (MathWorks, USA) and implemented it through a dedicated real-time control system which also handled signal IO (500 Hz, dSPACE, Germany). We calculated applied exoskeleton torque from a load cell (500 Hz, LCM Systems Ltd, UK) placed in series with the applied assistance, and a goniometer (500 Hz, Biometrics, UK) attached to the exoskeleton joint provided real-time ankle angle.

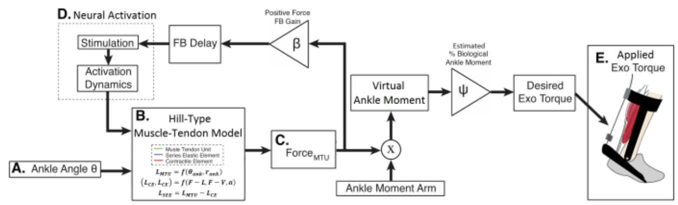

Figure 1: Neuromuscular model controller block diagram. Biological force, as computed by the internal muscle-tendon state, is scaled and applied across a moment arm to calculate desired exoskeleton torque.

The NMM based controller implemented in our system was similar to a reflex-based force feedback controller previously demonstrated [3]. A Hill-type muscle-tendon model was the basis for the emulated muscle-tendon unit (MTU) consisting of a contractile element (CE) with both active and passive properties and a series elastic element (SEE) (Fig.1B). We calculated MTU length from ankle angle and musculoskeletal geometry (1.1) and CE dynamics was subject to force-length, force-velocity and activation (1.2). We calculated SEE length as the difference in length of the CE from the MTU (1.3).

$$L_{MTU} = f(\theta_{ank}, r_{ank}) \quad (1.1)$$
$$(L_{CE}, \dot{L}_{CE}) = f\,(F\text{-}L, F\text{-}V, a) \quad (1.2)$$
$$L_{SEE} = L_{MTU} - L_{CE} \quad (1.3)$$

MTU force (F_{MTU}) was a function of the model's SEE stiffness and strain. In the reflex pathway, we normalized MTU force to Fmax and multiplied by a feedback gain. A delay was added to emulate a positive force feedback neural reflex signal (Stim) and CE activation dynamics (ACT) were modeled to close the feedback loop (Fig.1D). We calculated desired exoskeleton torque as a portion of the 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. We calculated and recorded internal model states (FMTU, LMTU, LCE, STIM, ACT) in dSpace for 5 second periods for offline analysis.

Testing Protocol: Three healthy-young adults (1 male; average mass 72.2 ± 6.1 kg) completed the IRB approved protocol. Each subject walked at 1.25 m/s with the exoskeletons unpowered, and then powered with four different gains (0.8-2.0 gain sweep) at a set delay (10ms) and four different delays (10-40ms delay sweep) at a set gain (1.2). Metabolic power was estimated from indirect calorimetry data collected in last two minutes of each trial (Carefusion, USA).

RESULTS

Increases in the NMM controller gain resulted in systematic increases in exoskeleton torque and power output (Fig. 2A, C-D green). The exoskeleton produced net negative work at low gain and net positive work at high gain (Fig.2B, green). In contrast, increasing NMM controller delay generated a decrease in exoskeleton net work (Fig. 2B, blue) and increased torque output to a point of diminishing returns (Fig.2D, blue). Users' metabolic energy consumption was reduced by 4% from the unpowered condition with a 1.2 feedback gain and 10ms delay. All other NMM controller settings increased metabolic demand – 6% in the worst case (Fig. 3).

DISCUSSION AND CONCLUSIONS

From a mechanical standpoint, the NMM controller functioned as expected with the highest gain and smallest delay providing the most assistance. Surprisingly, this condition did not result in the largest metabolic reduction. Net work delivered by an exoskeleton may not be the only determinant of metabolic benefit to the user. More data and further analysis to examine changes in joint mechanics at the knee and hip, as well as muscle activation patterns may reveal underlying mechanisms driving these observations.

REFERENCES

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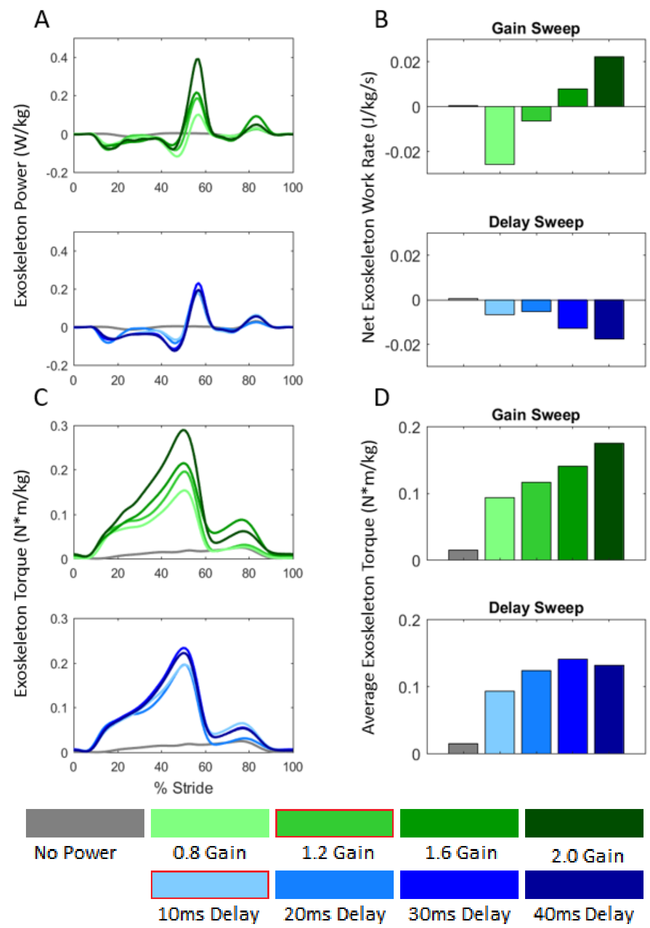

Figure 2: In the gain sweep, exoskeleton power **(A)** and net work rate **(B)** increased across conditions by increasing the torque profile **(C)** and average torque **(D)**. In the delay sweep, average torque peaked, before decreasing and net work rate was entirely negative. Darker colors indicate higher values. Red outline indicates base parameters (Gain: 1.2, Delay: 10ms). Curves are study average trajectories.

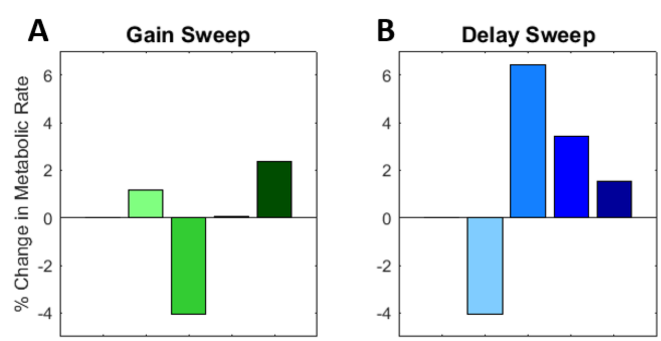

Figure 3: Average change in metabolic rate across gain **(A)** and **(B)** delay sweeps. Metabolic rate decreased at base (Gain: 1.2, Delay: 10ms) condition, but increased with all other parameter values.