HOW DO ELASTIC EXOSKELETONS INFLUENCE MUSCLE SPINDLE FEEDBACK?

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Introduction

With significant advancement in wearable technologies for assisting locomotion and augmenting balance, there is a growing need to understand the neural mechanisms underlying stable movement. It remains unclear whether exoskeletal devices that provide force either in parallel (e.g., elastic exoboots) or in series (e.g., cushioned running shoes) with muscle tendon units (MTU) interfere with or enhance the natural response of sensory organs during cyclical movement. In part due to the difficulty of directly measuring spindle firing in humans, a theoretical framework that can predict the relationship between muscle afferent feedback and contractile dynamics has yet to be fully validated. Indeed, most models of spindle firing still rely on a kinematic relationship with firing rates driven by fiber length and velocity. However, recent work suggests that the contractile force (F_c) and yank (Y_c) acting on the intrafusal fibers may more accurately predict spindle instantaneous firing rate (IFR) during passive MTU stretches [1]. Here, we aimed to construct a simple modelling framework pitting kinematic vs. kinetic drivers of spindle firing against each other in the context of altered external mechanical loading manifests from assistive technologies. Ultimately, we aim to test our model-based predictions in-vivo in both animal and human experiments to help reveal how spindles work and how exoskeletons alter their behaviour.

Methods

We developed a simple mechanical model (fig. 1a) comprised of series and parallel springs representing active and passive elements of the MTU (orange) and exoskeletal devices in parallel (blue) or in series (green). Sinusoidal length changes (L_{in}) were applied to the model while modulating active stiffness of the muscle to maintain a constant force amplitude, akin to a locomotion cycle. We independently varied parallel (fig. 1b) and series (fig. 1c) exoskeleton stiffness added to the MTU to determine their individual contributions to the predicted spindle IFR. The noncontractile part of the muscle force was determined according to [2]: $F_{NC} = k_{lin}(\Delta L_m) + Ae^{k_{exp}(\Delta L_m)}$, a function of muscle length change (ΔL_m). F_c was the result of subtracting the F_{NC} from the total force signal. F_c was then used to predict $IFR = (F_c + b_F)k_F + (Y_c + b_Y)k_Y + C$ [2].

Results and Discussion

With an exoskeleton (exo) in series (fig. 1b), the force on the MTU remained the same, but the length change of the muscle decreased as stiffness decreased. F_{NC} of the muscle therefore decreased, resulting in an increase in F_c to meet the F_{total}. As a result, IFR increased with added exo series compliance, when determined as a function of F_c, but decreased when determined as a function of L_m (fig. 1B).

With an exo in parallel, the total force was split between the exo and the MTU, and the length change of the muscle decreased as stiffness increased. F_{NC} of the muscle therefore increased, resulting in a decrease in F_c. As a result, IFR decreased as parallel exo stiffness increased, when determined as a function of F_c, but increased when determined as a function of L_m (fig. 1C).

Contrasting predictions from kinematic vs. kinetic models for spindle output IFR, when compared against in-vivo data from future animal and human experiments, should help decode mechanisms underlying spindle firing during cyclic contractions.

Significance

Adding known external mechanics with an exoskeleton either in parallel or series to a biological MTU can help reveal which muscle states contribute to spindle firing. As assistive devices become increasingly complex, a complete model of the human neuromuscular system is critical for human-machine integration. Further work in animal models (e.g., rat gastrocnemius muscle), augmented with exoskeletal assistance, will help clarify the relationship between varying muscle kinematic and mechanical parameters and resulting neural feedback [3]. With an understanding of this relationship, engineers and physiologists can join forces to develop exoskeletons more adept at addressing clinical challenges in motor (re)learning by controlling the neural feedback via exoskeleton tuning.

Acknowledgments

We would like to thank Dr. Tim Cope, Dr. Surabhi Simha, and Paul Nardelli for their feedback in developing this model.

Support form National Institutes of Health (NIH), Eunice Kennedy Shriver National Institute of Child health and Human Development (NICHD), R01HD090642.

References

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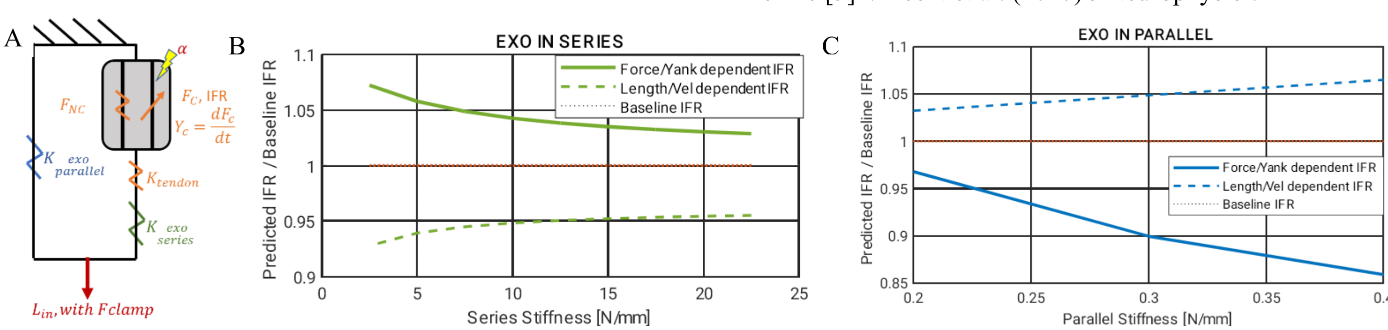

Figure 1: A) Mechanical Model of MTU with added parallel (K_{exo}) and series (K_{series}) elasticity. Comparison between the IFR prediction of a force and yank dependent spindle model vs a length and velocity dependent model with B) added series exoskeleton and C) added parallel exoskeleton.