Modeling the Impact of Long-term Exoskeleton Use on Achilles Tendon Mechanical and Morphological Properties

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Summary
Wearable device adoption is on the horizon for various populations, however there has been little consideration of long-term device impacts on the musculoskeletal system. Using a computational model, we investigated the influence of both exoskeleton device parameters and anticipated user behavioral response on tendon remodeling. We found critical differences in tendon remodeling depending on exoskeleton stiffness and predicted human behavior. Behavioral criteria for locomotion dominated remodeling outcomes and dictated the effects of a given exoskeleton stiffness. This work has implications for prescribing exoskeletons with parameters tailored to both an individual’s behavior and their physiology.

Introduction
Reduced metabolic cost is a key parameter for lower limb exoskeletons and has been achieved by decreasing muscle force and/or work during walking. While this unloading improves walking economy, little is known about the long-term effects of these devices on structural properties of the musculoskeletal system. Increased device use may lead to tissue atrophy due to decreased tendon strain, resulting in less economical movement and higher injury risk. Additionally, changes in locomotion behavior in response to long term exoskeleton use are unknown. Models that address these critical aspects of exoskeleton use may provide key insights for effective device design. We developed such a model and hypothesized that user behavior while using a spring-like ankle exoskeleton is a critical driver of long-term tendon remodeling.

Methods
We represented daily locomotion using a neuromuscular model of human hopping with a passive exoskeleton [1]. Tendon stiffness adaptation was incorporated using relationships for cross sectional area and Young’s Modulus changes in response to mechanical loading [2]. A sigmoid function was used to scale these adaptational relationships to account for number of cycles. We modeled two predicted behavioral criteria: one maximized locomotion efficiency and another minimized metabolic cost of transport (COT). Total daily hopping cycles were determined assuming a fixed metabolic budget based on locomotion without an exoskeleton. We simulated 100 days of locomotion and swept exoskeleton stiffness from 10-50% of normal Achilles tendon stiffness (k_t*), over the complete landscape of muscle activation (10-100%) and frequency (2.2-2.5 Hz). Tendon stiffness and number of daily cycles were plotted over time for both behavior regimes (Fig. 1).

Results and Discussion

Assuming users maximize locomotion efficiency, k_exo > 30% k_t* reduced k_t over time. After 100 days, the largest decrease in k_t (26.27%) was observed for k_exo of 50% k_t*. However, k_exo ≤ 30% k_t* had no effect on k_t over time.

Assuming users minimize COT, k_exo ≤ 50% k_t* decreased k_t over time. After 100 days, the largest decrease in k_t (10.72%) was observed for k_exo of 50% k_t*. However, k_exo > 50% k_t* increased k_t over time. After 100 days, the largest increase in k_t (8.63%) was observed for k_exo of 10% k_t*.

These results indicate that tendon adaptation is dictated by both exoskeleton parameters and human behavioral response. As expected, behavioral criterion had a large impact on how k_exo impacts k_t. For example, at k_exo = 40% k_t* the two different behavioral criteria resulted in opposite trends in how k_t remodeled over time.

![Figure 1: Tendon stiffness (k_t) vs. time across exoskeleton stiffness (k_exo=10 (light blue) to 50% k_t*(purple)) and movement criterion (minimized COT (solid); maximized efficiency (dashed))](image)

Conclusions
Our results indicate that it is possible to design exoskeleton control systems that can steer tendon stiffness to a desired value given an adequate time horizon. For example, for older adults with increased tendon compliance, exoskeletons may be tuned to restore young tendon properties over time. Longitudinal human studies will confirm or refute the tendon adaptation relationships used in the model and elucidate behavioral changes in response to exoskeleton use.

References