Ultrasound imaging of plantarflexor muscles during robotic ankle assisted walking: Effects on muscle tendon dynamics and application towards improved exoskeleton and exosuit control

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Abstract— **Ankle exosuits/exoskeletons can improve gait but the assistance needs to be tuned to the individual. We suspect that ankle assistance can affect underlying muscle-tendon dynamics and should be accounted for in the control design. We highlight two complementary studies that begin to address these issues. First, we use ultrasound imaging to directly measure the effect of ankle exoskeleton rotational stiffness on soleus contractile dynamics. With increasing stiffness, the soleus operating length and muscle economy increased in early stance, but this was offset by increased shortening velocity and reduced muscle economy in late stance. Second, we demonstrate an approach to rapidly estimate muscle contractile state and its application in prescribing assistance profiles. These results provide evidence for the importance of muscle dynamics and how it can be used to inform design of wearable devices.**

I. INTRODUCTION

Ankle exoskeletons/exosuits are capable of improving metabolic demand [1], but the correct assistance timing and magnitude must be provided for the user to effectively interact with the device. Models of walking predict that assistance can disrupt the normally tuned interaction of the ankle plantarflexors and Achilles Tendon [2], but no study had validated the effect of exosuit assistance on muscle dynamics experimentally. Understanding how assistive devices affect muscle dynamics is crucial because the coordinated interaction of the ankle plantarflexors and the Achilles tendon allows for efficient force and power production during walking.

In the PoWeR Lab (Sawicki), we directly measured soleus muscle fascicle dynamics using B-mode ultrasound imaging during exoskeleton assisted walking [3]. We hypothesized that increasing exoskeleton stiffness would result in longer fascicle lengths, increased shortening velocity, and altered soleus muscle economy. Furthermore, we expected that the change in fascicle dynamics would help explain why too much assistance is detrimental to exoskeleton effectiveness.

In a later study in the Harvard Biodesign and Biorobotics Lab (Walsh, Howe), we extended these ideas towards development of exosuit assistance profiles that account for muscle dynamics [4]. We hypothesized that we could measure the onset time of muscle concentric contraction using B-mode ultrasound imaging, and use that time to inform individualized exosuit control for level and incline walking.

II. MATERIALS AND METHODS

A. PoWeR Lab

Eleven individuals walked at 1.25 m s^{-1} for 5 exoskeleton stiffnesses (0, 50, 100, 150 and 250 Nm rad^{-1}). We measured metabolic demand, joint dynamics, and muscle activation. We calculated force per activation by dividing the estimated muscle force (derived from joint dynamics) by activation. We recorded B-mode ultrasound images of the soleus with a low-profile ultrasound probe. We tracked the fascicles using an automated tracking software [5] and calculated the length and velocity of the soleus fascicles for the 5 conditions.

B. Harvard Biodesign and Biorobotics

Our sensing/measurement approach used B-mode ultrasound to detect, at real-time rates, when the muscle begins to concentrically contract and generate positive power before push-off. For this, we modeled the ankle soleus-AT complex as an elastic element and contractile element in series. While subjects walked on a treadmill, we captured B-mode images of the soleus (n=7 at 1.5 m s^{-1} on level ground; n=4, 1.25 m s^{-1} level and 10% incline). We then calculated the optical flow velocity of the soleus along the superficial aponeurosis to determine when the muscle was displacing proximally (away from the ankle) and shortening against the distal Achilles tendon. Finally, we performed an initial (n=1) exosuit evaluation where we generated assistance profiles based on the detected onset of muscle contraction.

III. RESULTS

A. PoWeR Lab

Increasing exoskeleton rotational stiffness resulted in an increase in fascicle operating lengths by 4.4 mm and an increase in force per activation by 27% in the highest stiffness compared to no assistance (Fig. 1) [3]. Increasing stiffness also resulted in an increase in shortening velocity by

Part of this work was supported by grants to G.S.S from the National Institute of Nursing Research of the National Institutes of Health (R01NR014756) and the U.S. Army Natick Soldier Research, Development and Engineering Center (W911QY18C0140). Part is based upon the work supported by the Harvard John A. Paulson School of Engineering and Applied Sciences TEAM initiative, National Institutes of Health (BRG R01HD088619) and the National Science Foundation (CNS-1446464) to C.J.W and the Wyss Institute for Biologically Inspired Engineering. K.S. is also supported by a National Science Foundation Graduate Research Fellowship, and S.L. is supported by Samsung Scholarship.

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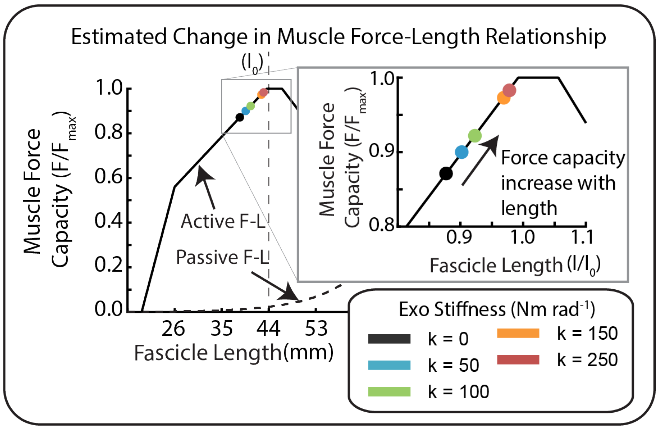

Fig. 1. Effect of exoskeleton stiffness on fascicle length at peak force and and estimated effect of fascicle length change on force production capacity.

3.7 mm s^{-1} and a reduction in muscle force per activation by 24% in the highest stiffness compared to no assistance. User metabolic demand was minimized at an intermediate stiffness of 50 Nm rad^{-1} and increased for the highest stiffness.

B. *Harvard Biodesign and Biorobotics*

The semi-automated routine using optical flow segmented the data to a normalized gait cycle and estimated the onset of concentric contraction at real-time rates (∼130Hz) [4]. Estimation of the onset of concentric contraction had a high correlation (R^2=0.92) and an RMSE of 2.6% gait cycle relative to manual estimation. The onset of muscle contraction at 1.5 ms^{-1} walking ranged from 39.3% to 45.8% of the gait cycle with an average of 42.8% gait cycle. The onset of muscle contraction was estimated to be 7% earlier in 10% incline walking but was variable across individuals (Fig 2). Finally, when comparing to a fixed assistance profile, we found that updating the onset of exosuit assistance using muscle contraction timing improved metabolic energy demand in incline walking.

IV. Discussion

A. *PoWeR Lab*

The results supported the hypothesis that increasing exoskeleton stiffness alters soleus muscle dynamics and helps

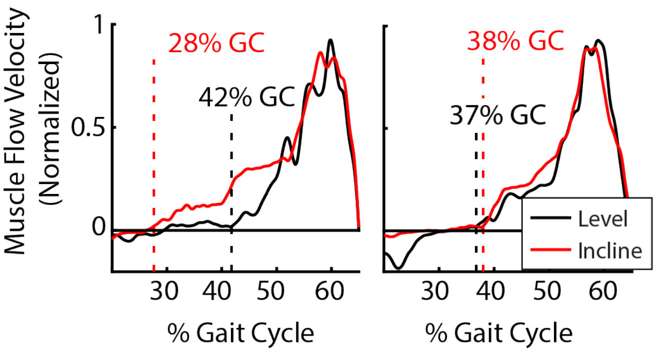

Fig. 2. Estimated onset time of concentric contraction for level and 10% walking for two subjects. Muscle response to incline varied with individuals.

explain why increasing assistance does not continually improve performance. We found that increasing exoskeleton stiffness resulted in increased fascicle lengths and improved muscle economy (force/activation) in early stance; however, the benefit was offset by increased fascicle shortening velocity and reduced muscle economy in late stance. This apparent trade-off resulted in a metabolic 'sweet-spot' at intermediate exoskeleton stiffness where metabolic energy consumption was minimized. For the first time, we are capable of providing experimental evidence that supports previous modeling and simulations studies that predict changes to muscle fascicle dynamics resulting from exoskeleton assistance. These experimental results provides insight into how muscle-tendon dynamics can be incorporated into design for wearable devices.

B. *Harvard Biodesign and Biorobotics*

The transition to muscle concentric contraction shown from this technique aligns with reported group average data from prior studies [6]. The determination that the onset of muscle concentric contraction is variable may help explain why individual response to fixed exosuit assistance is so varied. Though preliminary, the exosuit pilot demonstrates that we may be able to improve exosuit performance by accounting for biomechanical changes in the user's muscle dynamics.

V. Conclusion

This work highlights the importance of understanding muscle-tendon dynamics for developing effective exoskeleton/exosuit controllers. We highlight some recent work that suggest how muscle tendon dynamics might be used for individualized assistance profiles that are adaptive to the task demands. In the future, exosuit controllers that sample the individual's muscle-tendon state may enable muscle-in-the-loop controllers capable of offloading muscle force while maintaining efficient contractile dynamics.

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