Investigating the role of muscle dynamics in individual response to soft exosuit assistance

Richard W. Nuckols, Krithika Swaminathan, Sangjun Lee, Dheepak Arumukhom Revi,
Conor J. Walsh, and Robert D. Howe

Paulson School of Engineering and the Wyss Institute at Harvard,
MA, USA.

***Abstract*—Wearable robotic devices (exosuits, exoskeletons) for augmenting gait can reduce group level metabolic demand. However, at the individual level, metabolic response is variable and the mechanisms behind this inconsistency is unclear. In this work, our aim is to investigate the effect of muscle tendon dynamics on individual response to exosuit assistance. To this end, we measured muscle contraction state of the soleus and medial gastrocnemius using B-mode ultrasound while naïve subjects walked with exosuit assistance. We also sub-categorized subjects into good and poor responders. We found that subjects that responded well (15% reduction) to the assistance began soleus muscle contraction prior to the onset of assistance. Conversely, the soleus muscle contraction began after the onset of assistance in subjects that responded poorly (2% reduction). We also found that the medial gastrocnemius was lengthening at the time of assistance onset in subjects that responded poorly which may highlight the impact of knee mechanics. These findings suggest the importance of energy exchange between the muscle, tendon, joint and environment towards efficient walking and how exosuit assistance might affect those dynamics. Ongoing and future work will expand upon this work and will incorporate EMG, kinematic, and kinetic analysis.**

Keywords—exosuit, exoskeleton, muscle, tendon, gait, walking

I. Introduction

Studies demonstrating efficacy of wearable devices for gait augmentation have largely been dominated by the goal of maximizing the average reduction in metabolic cost across individuals [1]. From a biomechanics perspective, the studies suggest that, as a group, metabolic improvement is driven by reduction in biological joint moment and muscle activation [2],[3]. However, what remains unclear is the reason for inconsistency in individual response. At the level of the individual, human metabolic response to exoskeleton assistance during walking is variable and individuals that appear to have similar biomechanical trends can have very different whole-body metabolic response. Little effort has gone into understanding the biomechanics underlying the variability in metabolic response among individuals, and so far, the methods fail to provide a mechanistic explanation for differences in individual response which could be used to improve exosuit design and function.

K. Swaminathan is supported by the NSF, and S. Lee is supported by Samsung. This material is based upon the work supported by the NSF (grant #CNS-1446464), the Wyss Institute, the Paulson School at Harvard and the Technology for Equitable and Assessable Medicine initiative at Harvard.

Our aim in this work is to evaluate whether muscle contraction dynamics of the triceps surae can help explain individual response to ankle exosuit assistance. The efficiency of walking is heavily reliant upon proper function of the ankle joint and the muscle-tendon unit (MTU). Efficient and powerful ankle plantarflexion is generated only through properly timed energy exchange between the muscle, the series elastic tendon, the joint, body, and environment. Therefore, understanding and maintaining effective MTU dynamics is also crucial for efficient walking. We suggest that ultrasound-based measurement of muscle dynamics can provide improved metrics for understanding exosuit performance compared to kinematic, kinetic, and EMG-based measurements. We hypothesize that initial response to exosuit assistance will be predicted by similarity between baseline muscle contraction timing and the onset timing of exosuit assistance.

II. Material and Methods

A. System Details

We applied active ankle plantarflexion, and passive hip and knee flexion assistance to the user with a portable multi-articular body-mounted soft exosuit (Figure. 1). The controller commanded a force-based position profile with assistance onset at 42.5% of gait cycle and a peak force of 350N. See [3] for details on suit design.

B. Protocol Overview

We recruited only naïve subjects for this study (no prior exosuit experience). The protocol had three bouts: No suit (NS), suit donned and components slack (Slack), and suit donned and providing assistance (Active). Subjects walked at 1.5 m/s on a split-belt treadmill (Bertec, Columbus, OH) while we collected multi-level biomechanics data, from whole body down to muscle dynamics.

C. Collected Measurements

We measured whole-body energetics with a portable metabolic device (K4b2, COSMED, Italy), lower limb kinematic/kinetic data using a motion capture system (Qualisys, Sweden), and ground reaction forces from an instrumented treadmill. Load cells (Futek, Irvine, CA) on the suit measured applied force from suit actuation. We collected muscle activation data from eight lower leg muscles with wired surface electrodes (Delsys, Natick, MA), and muscle dynamics data with B-mode ultrasound obtained at 120Hz (microUS,Telemed, Lithuania).We analyzed the velocities of the soleus and gastrocnemius in the mid to late phase of stance when the muscles concentrically contract to stretch the Achilles tendon and give rise to the ‘catapult mechanism’ of the ankle (Fig 1).

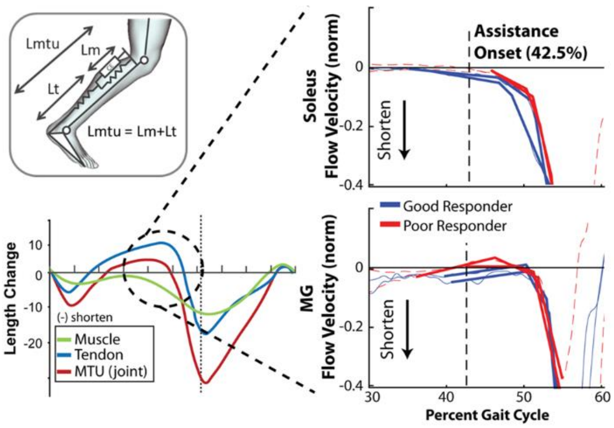

Figure 1: **Left Top** Ankle plantarflexor MTU is composed of the muscle and tendon in series. The compliant tendon decouples the movement of the muscle from the ankle joint. **Left Bottom:** Representative length change of the muscle, tendon, and MTU in walking. Muscle shortening typically occurs between 30 and 50 percent of the gait cycle and kinematics are decoupled from joint through the tendon [4] **Right Top:** Soleus flow velocity during 30-60% stance where negative represents shortening. The velocity profile overlaid with piecewise linear estimates of the flow velocity around the time of assistance for good responders (blue) and poor responders (red). Onset of concentric contraction for good responders begins prior to assistance. **Right Bottom:** MG flow velocity during stance. MG is lengthening at the time of assistance in poor responders.

III. RESULTS

From the seven participants, we sub categorized the two subjects with the best metabolic response to the exosuit as good responders and the two subjects with worst metabolic response as poor responders. Good responders average metabolic rate changed by -15% (-11% and -19%) relative to Slack and -12% (-8% and -16%) relative to NS. Poor responders had an average metabolic reduction change of -2% (-3% and -0%) relative to Slack and +3% (0% and +7%) relative to NS.

From velocity measurements of the soleus, the contraction of the soleus in the good responders began at 34.5% and 36.7% of the gait cycle which is prior to the onset of mechanical assistance (42.5%). The poor responders conversely initiated rapid concentric contraction of the soleus at 45.4% and 45.3% of the gait cycle which is after the onset of exosuit assistance (Fig 1). The profile of contraction in the good responders was more prolonged compared to the poor responders which had a rapid transition to the onset of concentric contraction. For the medial gastrocnemius, in the good responders, the MG was shortening at the time of assistance onset while in the poor responders, the MG did not begin shortening until 46% and 49% of the gait cycle (Fig 1).

IV. DISCUSSION AND CONCLUSION

Previous literature has suggested that efficient exchange of energy between the muscle, tendon, and joint is crucial for energetically efficient walking [5]. Here we show that an important feature that distinguishes poor and good response to exosuit assistance is the state of the triceps-surae muscles at the time assistance is provided suggesting that exosuits impact the energy exchange in the muscle tendon system. In this dataset, the good and bad responders exhibited different responses in both soleus and gastrocnemius contraction. In the good responders, the soleus and gastrocnemius are concentrically contracting at the time in which assistance is given. Conversely, in poor responders, the soleus begins the rapid concentric contraction after the onset of assistance and the gastrocnemius is lengthening at the time of assistance. The exchange of energy among the muscle, tendon, and ankle can be affected by the time the contraction begins relative to the assistance onset. Because assistance is expected to reduce the force in the MTU, then energy storage in the tendon and the resulting catapult mechanism might be disrupted to a greater extent when muscle contraction has not begun such as in the case of poor responders. The dynamics of the knee also likely plays a major role in the state of the gastrocnemius. Lengthening of the gastrocnemius could suggest increased extension of the knee in poor responders compared to good responders. We acknowledge certain limitations. These data need to be and will be compared and analyzed against the EMG and joint kinetic and kinematic data. Kinematic data will provide important insight into tendon energetics. Our current sample size is small particularly when we sub-categorize groups.

In conclusion, the data suggest that assistance should be provided after or at the time when the muscle has started the rapid concentric contraction phase. We hypothesize that by providing assistance prior to the onset of contraction we potentially remove energy from the Achilles tendon and disrupt the normal muscle-tendon resonance. Additionally, knee dynamics is important and can additionally affect the gastrocnemius muscle and energy in the MTU structure even when assistance is not directed at the knee. Future work will be targeted at addressing these topics in further detail.

REFERENCES

[1] L. M. Mooney and H. Herr, “Biomechanical walking mechanisms underlying the metabolic reduction caused by an autonomous exoskeleton.” J Neuroeng Rehabil, vol. 13, no. 1, p. 1, 2016

[2] G. S. Sawicki and D. P. Ferris. “Mechanics and Energetics of Level Walking with Powered Ankle Exoskeletons.” J Exp Biol, vol. 211, no. 9, pp. 1402–1413, 2008

[3] S. Lee et al., “Autonomous Multi-Joint Soft Exosuit for Assistance with Walking Overground,” in ICRA, 2018, pp. 2812-2819.

[4] D. J. Farris and G. S. Sawicki, "Human medial gastrocnemius force-velocity behavior shifts with locomotion speed and gait," *PNAS*, vol. 109, no. 3, pp. 977-982, 2012.

[5] B. D. Robertson and G. S. Sawicki, "Unconstrained muscle-tendon workloops indicate resonance tuning as a mechanism for elastic limb behavior during terrestrial locomotion," *Proc Natl Acad Sci U S A*, vol. 112, no. 43, pp. E5891-8, Oct 27 2015.