TUNED OR NOT? ULTRASOUND MEASUREMENTS OF SOLEUS FASCICLE DYNAMICS DURING HUMAN WALKING WITH ELASTIC ANKLE EXOSKELETONS

Taylor J.M. Dick, Richard W. Nuckols, Gregory S. Sawicki

Joint Department of Biomedical Engineering, North Carolina State University and University of North Carolina-Chapel Hill, NC, USA
email: tjdick@ncsu.edu

INTRODUCTION

Biologically inspired robotic devices assisting the ankle joint have the potential to augment healthy locomotion [1] and restore impaired neuromuscular deficits as a result of age or disease [2]. Most efficacy studies focus at most on whole body and joint level dynamics, but to date we have a limited understanding of how these devices alter the underlying muscle-tendon behaviour in walking.

Previous work done in our lab has shown that at intermediate stiffnesses, passive ankle exoskeletons reduce the energetic cost of walking by up to 7% [1]. However, at stiffnesses below or above this optimal value metabolic demands are greater than unassisted walking. We theorize that these aforementioned changes in metabolic cost due to stiffness are directly linked to the underlying muscle-tendon dynamics [3]. In this study, we aimed to determine how elastic ankle exoskeletons affect joint mechanics and plantarflexor fascicle dynamics in relation to metabolic cost during human walking. We hypothesized that the stiffest ankle exoskeletons 'de-tune' muscle force-length behaviour and offset the benefits of decreased muscle force, leading to suboptimal improvements in metabolic cost. Specifically, we hypothesized that a reduction in the plantarflexor force requirements would result in a compensatory increase in soleus fascicle lengths due to the decreased stretch of the series elastic element (Achilles tendon).

METHODS

Eleven subjects (7M, 4F; mean: 27.5y; 74.2kg) completed the IRB approved protocol. We used an exoskeleton emulator to apply a range of ankle exoskeleton rotational stiffnesses (k_{exo}) to the user (0, 50, 100, 150, 250 Nm rad^{-1}). The emulator provided torque from benchtop motors to bilateral ankle exoskeletons through a Bowden cable transmission while subjects walked on an instrumented treadmill at 1.25 m s^{-1} (Fig. 1A). A torque-angle relationship was imposed to emulate rotational stiffness at the ankle. Following an initial training day, we collected a comprehensive set of kinetic (Bertec), kinematic (Vicon), B-mode ultrasound (Telemed), EMG (Biometrics), and metabolic data (OxyCon Mobile). We performed inverse dynamics analysis (Visual3D) to determine joint moments. Soleus ultrasound images were analyzed [4] to determine time-varying fascicle lengths during walking at the five exoskeleton stiffnesses. We performed an ANOVA to test the effect of k_{exo} on soleus fascicle length during walking.

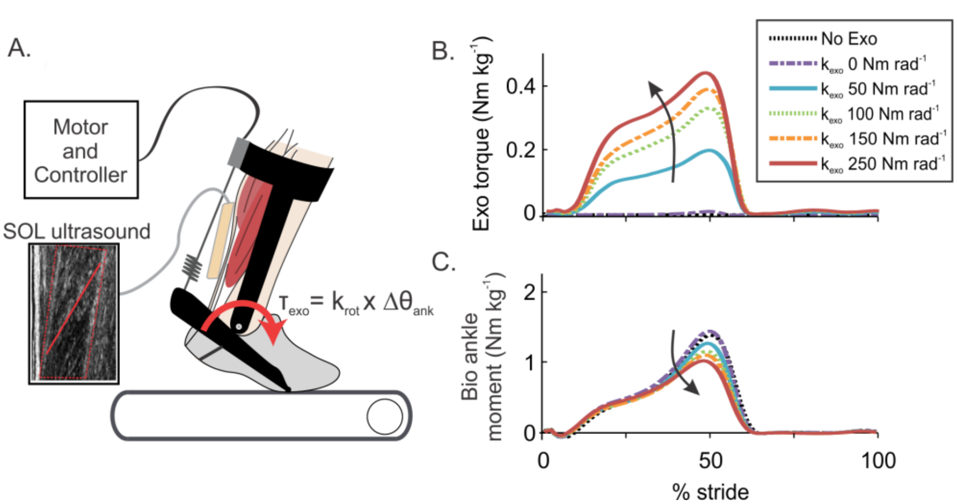

Figure 1: (A) Experimental setup. During exoskeleton assisted walking at five stiffnesses, we imaged soleus (SOL) fascicles using B-mode ultrasound. (B) Exoskeleton torque increased with spring stiffness (k_{exo}). (C) Biological contributions to the ankle moment, averaged across the 11 subjects and normalized to body mass, decreased with increased exoskeleton stiffness.

RESULTS AND DISCUSSION

Exoskeleton torque increased with exoskeleton stiffness (k_{exo}) and resulted in a concomitant decrease in the biological ankle moment (Fig. 1 B/C). Compared to the no assistance condition (0 Nm rad^{-1}), the stiffest exoskeleton condition (250 Nm rad^{-1}) reduced the peak biological plantarflexion moment by 29%. Increases in k_{exo} were also accompanied by a reduction in ankle range of motion and therefore total muscle-tendon unit (MTU) length changes. Range of motion decreased from -17.7 to 15 deg. at 0 Nm rad^{-1} to -7.3 to 14.3 deg at 250 Nm rad^{-1} which translates to, on average, a 7 mm reduction in MTU length change at the highest stiffness.

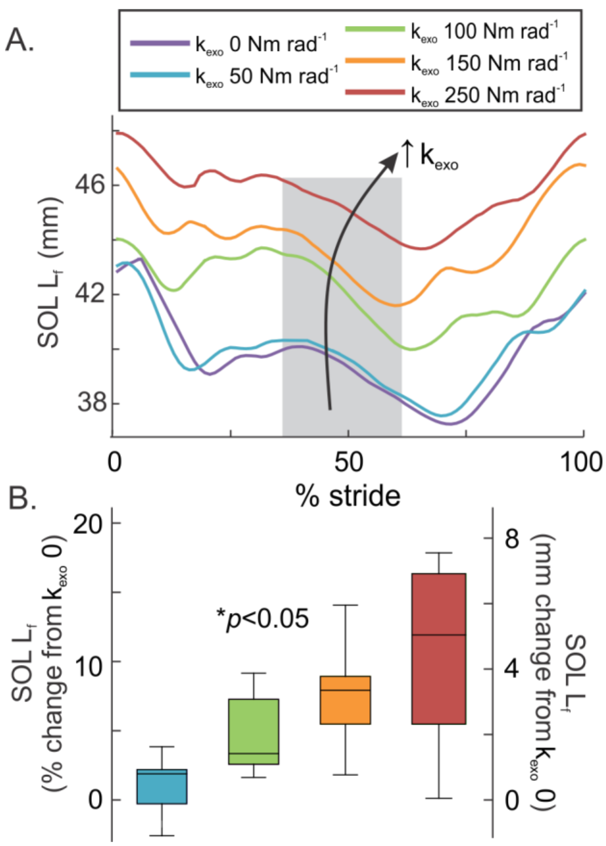

Figure 2: Effect of varying k_{exo} on soleus (SOL) fascicle behaviour during exoskeleton assisted walking. (A) Time-varying fascicle lengths (L_f) for 1 subject, averaged over 5 strides and normalized to the stride period, show increases in fascicle operating lengths with increases in exoskeleton stiffness (k_{exo}). Shaded region depicts timing of peak MTU length during the gait cycle. (B) SOL fascicle length as a function of k_{exo} (normalized to SOL fascicle length at peak MTU length in the k_{exo} = 0 condition) are shown as box and whisker plots (median, interquartile range, range) for the 11 subjects.

Despite this reduced MTU length change, and in support of our hypothesis, we found an increase in SOL fascicle length with increasing k_{exo} (Fig 2A). SOL fascicle length (determined at peak MTU length) increased from 47.5 mm during the no assistance condition (0 Nm rad^{-1}) to 52 mm at the highest stiffness condition (250 Nm rad^{-1}) when averaged across 11 subjects (Fig. 2B). This translates to an average SOL fascicle length increase of 11% when the highest exoskeleton stiffness was applied (Fig. 2B).

We found greatest reduction in metabolic cost (-4.2 % compared to no assistance) at the 50 Nm rad^{-1} condition, which coincides with the condition where SOL fascicle lengths were most similar to unassisted walking (Fig 2A). This suggests that, in young healthy adults, small amounts of added stiffness provide some metabolic benefit, but high levels of stiffness likely interfere with the normally efficient and highly tuned plantarflexor muscle-tendon interaction.

CONCLUSIONS

Our results are consistent with [1] but we now highlight the mechanistic links between disrupted muscle-tendon dynamics and whole body energetic costs during robotically-assisted locomotion. In conclusion, we have shown that exoskeletons which are too stiff shift fascicles towards unfavorable contractile conditions. This effectively 'de-tunes' the plantarflexors normal muscle-tendon mechanical behaviour and is a likely contributor to negating metabolic improvements.

REFERENCES

1. Collins SH et al. *Nature* **522**, 212-215, 2015
2. Takahashi KZ et al. *J Neuroeng Rehabil* **12**, 23, 2015.
3. Sawicki GS & Khan NS. *IEEE Trans Biomed Eng*, **63**(5), 914-923, 2016
4. Farris DJ & Lichtwark GA. *Comput Methods Programs Biomed* **128**, 111-118, 2016.

ACKNOWLEDGMENTS

This project was funded by National Institutes of Health, National Institutes of Nursing Research Award # R01 NR014756 awarded to GSS.