# THE GOLDILOCKS ZONE: INTERPLAY OF ELASTIC EXOSKELETON ASSISTANCE AND WALKING SPEED ON THE MECHANICS AND ENERGETICS OF WALKING

Richard W. Nuckols and Gregory S. Sawicki

Joint Department of Biomedical Engineering at UNC Chapel Hill and NC State University, Raleigh, NC, USA
email: rwnuckol@ncsu.edu, web: hpl.bme.ncsu.edu

## INTRODUCTION

Application of an intermediate exoskeleton stiffness results in a minimization of metabolic demand during level walking at 1.25 m/s (1). However, this 'sweet spot' in parallel stiffness at other gait speeds has yet to be identified. This study provides insight into the relationship between elastic mechanical assistance at the ankle and walking speed. Previous work suggests that the stiffness of the ankle in able-bodied subjects increases with increasing walking speed (2). Thus, we hypothesized that the optimal rotational stiffness provided by the exoskeleton would increase with increased walking speed.

## METHODS

Ankle exoskeleton assistance was delivered to the user through an exoskeleton emulator consisting of bilateral ankle exoskeletons, benchtop motor and transmission, and a control system (Fig 1).

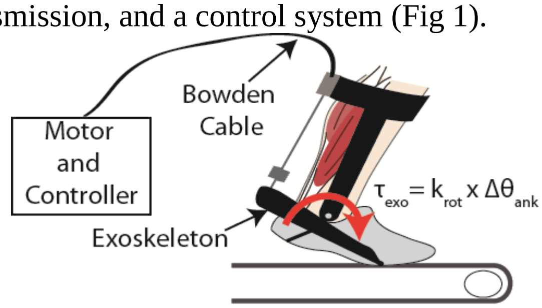


**Figure 1:** The exoskeleton is a lightweight carbon fiber ankle foot orthosis capable of providing plantarflexion moment. Torque is delivered to exoskeleton from the benchtop motors via Bowden cable transmission. The control system is an impedance controller which emulates a passive elastic element by imposing a torque angle relationship (*i.e.,* rotational stiffness) on the ankle exoskeleton.

In the study, we examined the interaction of six exoskeleton conditions with three walking speeds for a total of 18 trials. The six conditions included a no-exoskeleton condition (NE) where exoskeleton was not worn (to evaluate added mass cost) and five stiffness conditions where a range of rotational stiffness was applied by the exoskeleton (0, 50, 100, 150, 250 Nm/rad). We performed a randomized sweep of each stiffness condition at three randomized walking speeds (1.25, 1.5, and 1.75 m/s). Once all stiffness values were evaluated at a set speed, we progressed to the next speed. Finally, at either the beginning or end of the study, we performed the NE trials at each speed.

Three untrained, able-bodied subjects (female =1) completed the IRB approved protocol. During each of the 18 trials, the subject walked for 5 minutes while data monitoring the effect of exoskeleton assistance on mechanical and metabolic effort was collected. Inverse dynamics analysis was performed via a reflective motion capture system (VICON) and an instrumented treadmill (Bertec). Whole body net metabolic power was collected using a portable indirect calorimetry system (OxyCon Mobile).

## RESULTS AND DISCUSSION

<u>Mechanical Effort:</u> At each walking speed, as the rotational stiffness increased, the amount of exoskeleton assistive torque also increased. As a result of increased exoskeleton torque, we observed a decrease in biological moment. This trend can be observed over the stride cycle (Fig 2A) and on average torque charts (Fig 2B). Additionally, we found a decrease in the ankle range of motion as the stiffness increased. This may be indicative of a lack of training, with the subject unable to further reduce the biological moment.

Somewhat unexpected, we did not see an increase in the magnitude of exoskeleton assistance as speed increased. The peak exoskeleton torque and maximum average torque were achieved at the middle walking speed and highest stiffness. For other stiffness values, the trend seems to be reversed as applied exoskeleton torque decreased with increasing walking speed. One factor for the reduced torque at high walking speed was the decrease in ankle joint range of motion.

Metabolic Effort: Our initial findings indicated that in some conditions the metabolic cost of walking could be reduced through application of elastic exoskeleton assistance (Fig 3). The net metabolic cost of walking was reduced (0.4% and 1.4%) with the 150 Nm/rad stiffness condition at 1.25 and 1.75 m/s, respectively.

## CONCLUSIONS

This study is an important step in evaluating the effect of elastic exoskeleton assistance at different walking speeds. Although our subjects were not trained, our results suggest that elastic assistance is capable of reducing biological moments and reducing metabolic effort across speeds. Additional data are required to evaluate the landscape where the maximum benefit is a function of both walking speed and applied exoskeleton assistance. In continuing work, we will provide training to the subjects and collect data on a much larger subject population (n=10).

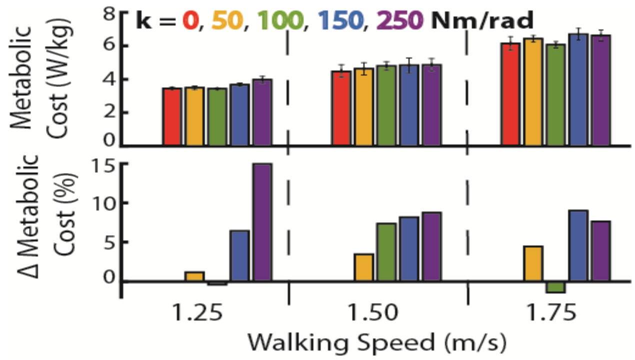


**Figure 3**: (Top) Average (n=3) net metabolic cost of walking for each stiffness condition and walking speed. (Bottom) Percent change in net metabolic cost compared to the 0 stiffness condition.

## REFERENCES


1. Collins SH, Wiggin MB, Sawicki GS. Nature. 2015
2. Shamaei K, Sawicki GS, Dollar AM. PLoS One. 2013


## ACKNOWLEDGEMENTS


Supported by NIH R01 NR014756 to GSS.


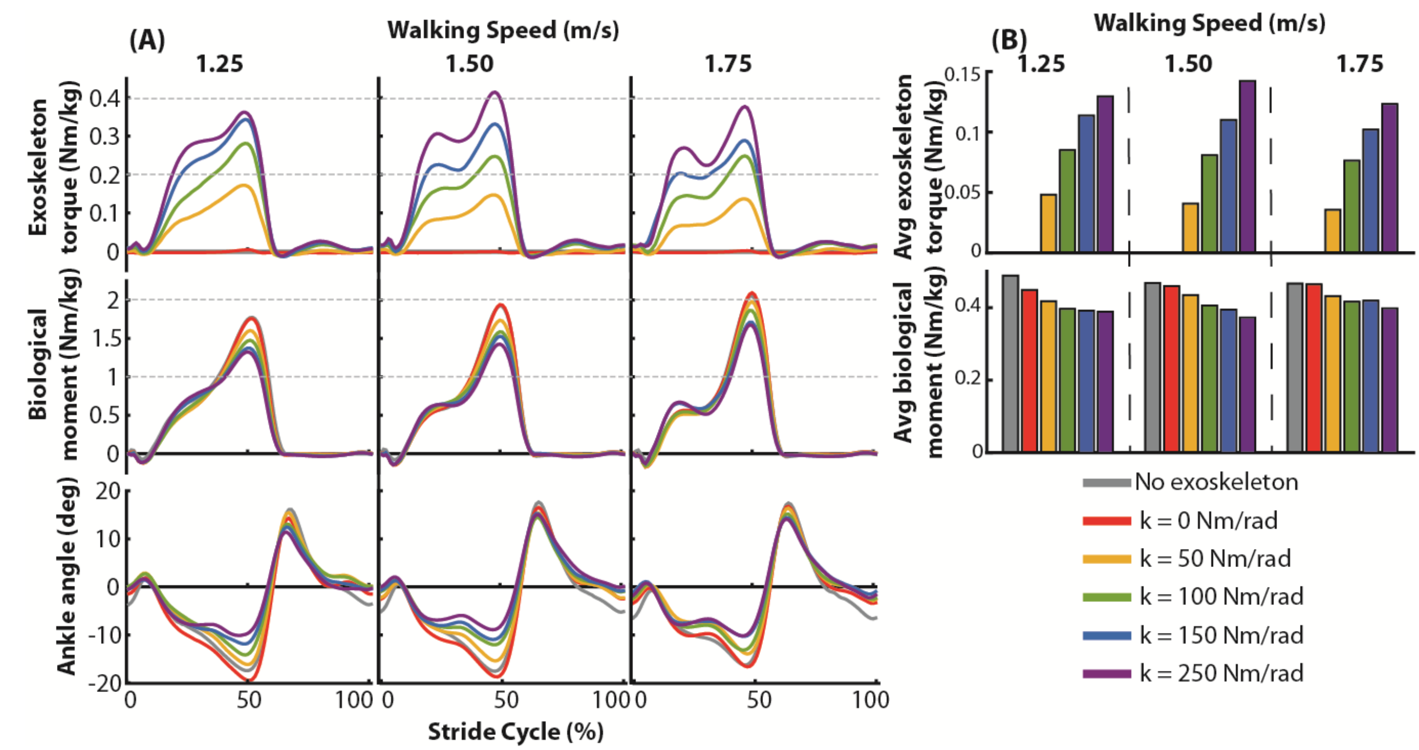


**Figure 2:** (A) Exoskeleton torque (top), biological moment (middle), and ankle angle (bottom) for each stiffness condition and walking speed. As rotational stiffness increased, the exoskeleton torque increased, biological moment decreased, and range of motion of the ankle decreased. (B) Average exoskeleton torque and biological moment over the entire stride. Biological moment decreased by 13, 19, and 14% from the minimum to maximum stiffness condition at each of the three speeds.