An emulator system to characterize optimal elastic ankle exoskeleton stiffness during human walking and running.

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1 Introduction

Recent work has demonstrated that a passive elastic ankle exoskeleton is capable of reducing the metabolic cost of walking in humans (1). Our initial study focused on walking at preferred speed (1.25 m/s) on level ground without added load. In this 'baseline' condition, we demonstrated a 'sweet spot' in metabolic benefit at intermediate exoskeleton spring stiffness. Our current aim is to characterize the influence of exoskeleton spring stiffness on metabolic performance in conditions of increased mechanical demand (e.g. faster walking, running, inclined surface, load carriage). However, exploring this vast, multi-factorial performance space using custom devices developed for each condition of interest is time consuming and costly. A framework for rapidly and systematically evaluating exoskeleton concepts is necessary.

2 Methods

In collaboration with Carnegie Mellon and based off the work shown in Caputo et al.(2), we have developed an exoskeleton emulator that consists of a benchtop motor and controller tethered to an ankle exoskeleton end-effector via a Bowden cable transmission. Using this system, we are in the initial stages of developing a simple impedance controller capable of emulating a passive elastic element (i.e. rotational stiffness) with high fidelity.

Real-time ankle kinematics and exoskeleton torque are measured by a goniometer and load cell and used as inputs into a hierarchical controller. In the high-level controller, desired exoskeleton torque is calculated from ankle joint angle consistent with a predefined rotational stiffness. The low-level controller drives error in desired torque towards zero using a proportional plus velocity damping feedback.

To evaluate the performance of the ankle exoskeleton emulator system, we performed a preliminary pilot study on a single naïve subject during 2 minute trials across three stiffness conditions (130, 180, and 250 Nm/rad) for walking (1.25 m/s) and one stiffness condition (130 Nm/rad) for running (2.25 m/s). Inverse dynamics analysis was performed from data collected via a reflective marker motion capture system (Vicon) and an instrumented treadmill (Bertec).

3 Results

During walking trials, the exoskeleton emulator system was capable of matching desired stiffness across the three conditions (Figure 1). As expected, the peak torque generated by the exoskeleton increased (0.226, 0.340, 0.359 Nm/kg) with increased stiffness. Ankle kinematics across the three conditions were similar, although peak ankle angle during dorsiflexion was reduced for the stiffest condition. Net exoskeleton work across the conditions was +0.006, +0.016, and 0.018 J/kg representing 26, 38, and 46% of the positive exoskeleton work over the stride.
The exoskeleton emulator system was also able to achieve the desired rotational stiffness of 130 Nm/rad during running (Figure 2). The maximum exoskeleton torque achieved during running was 0.545 Nm/kg compared to 0.226 Nm/kg for the same stiffness during walking. The system also generated more positive and negative work in running compared to walking. Net exoskeleton work for the single running condition was 0.049 J/kg, representing 40% of the positive exoskeleton work over the stride.

4 Discussion

This preliminary study demonstrated that our ankle exoskeleton emulator system was capable of generating desired rotational stiffness across a number of conditions. As expected, an increase in stiffness from 130 to 180 Nm/rad resulted in an increased exoskeleton torque and decreased biological moment. However, when the stiffness was further increased by approximately 33% from 180 to 240 Nm/rad, the generated exoskeleton torque was nearly identical. This is attributed to the decrease in peak ankle angle during dorsiflexion and likely reflects constraints on motor adaptation of the user.

Our preliminary study highlights a few areas that require refinement. As the intention of the system is to emulate a physical elastic element (i.e. torsional spring) with high fidelity, the net exoskeleton work should be zero or slightly negative (i.e. little hysteresis). To address this we plan to tune the low-level control gains and adjust the series elastic actuator compliance to improve the response time of applied stiffness in initial (i.e. onset) and late (i.e. offset) stance.

Once emulator performance is tuned, we will begin to evaluate the effect of rotational stiffness across different speeds, inclines and added backpack loads during walking and running gait.

5 Figures

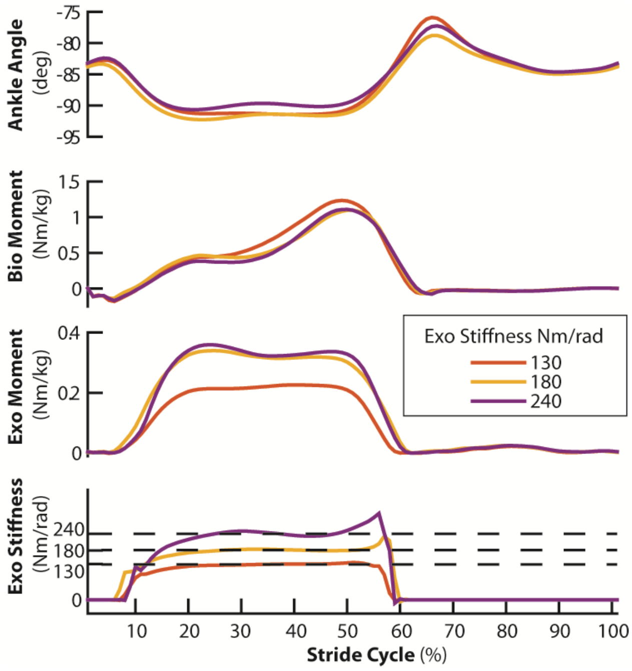

Figure 1: Gait dynamics and ankle exoskeleton emulator (Exo) performance across three stiffness conditions during walking at 1.25 m/s. Dashed lines indicate the desired exoskeleton rotational stiffness.

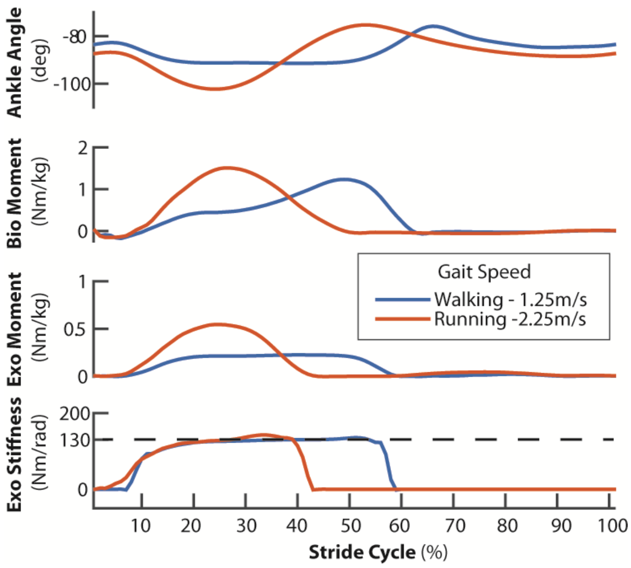

Figure 2: Gait dynamics and ankle exoskeleton emulator (Exo) performance for walking (1.25m/s) and running (2.25 m/s) at a desired exoskeleton rotational stiffness of 130 Nm/rad. Dashed lines indicate the desired rotational stiffness.

References

1. Collins SH, Wiggins M, Sawicki GS. An exoskeleton that uses no energy yet reduces the metabolic cost of human walking. Nature. in press.

2. Caputo JM, Collins SH. A universal ankle-foot prosthesis emulator for human locomotion experiments. J Biomech Eng. 2014 Mar;136(3):035002.