Effect of Timing of Hip Extension Assistance with IMU-based Iterative Control during Loaded Walking with a Soft Exosuit

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Summary

In this abstract, we describe an IMU-based iterative controller controls on the onset timing, peak timing and peak magnitude of the force applied to hip extension. The controller was implemented on a mono-articular soft exosuit actuated by a multi-joint actuation platform that enables rapid reconfiguration of different sensors and control strategies (Figure 1, Ding et al., 2014). This iterative controller detects onset timing of hip extension based on an estimation of the maximum hip flexion angle. Timing and magnitude of peak assistance is modulated by generating step-by-step actuator position profiles based on the previously measured assistive force. The average peak assistive force was 197.6 ± 0.2 N (desired 200N), equivalent to an average peak torque of 30.5 Nm. Peak timing error was within 1% of the gait cycle. The force performance shows the robustness of controller on delivering hip extension assistance profiles across different subjects. With this control approach, we evaluated four different hip assistive profiles with different actuation timings: early-start-early-peak (ESEP), early-start-late-peak (ESLP), late-start-early-peak (LSEP), late-start-late-peak (LSLP). All assistive profiles significantly reduced the metabolic cost of walking compared to the unpowered condition by 5.7 ± 1.5% (ESEP), 8.5 ± 0.9% (ESLP), 6.3 ± 1.4% (LSEP) and 7.1 ± 1.9% (LSLP). Biological joint power was also reduced at the hip (ESEP and ESLP) and the knee (ESEP and LSEP) with respect to the unpowered condition. The ESLP profile, which has the highest metabolic reduction, suggests that starting the assistance at terminal swing with a later peak force timing may be the most beneficial strategy.

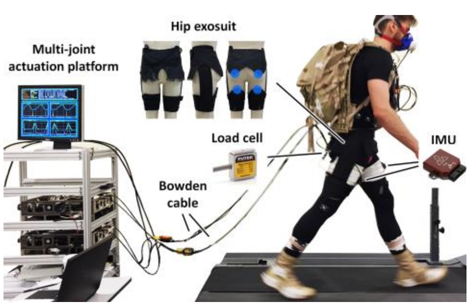

Figure 1. Experimental setup with a participant wearing a soft exosuit that assists hip extension via Bowden cable. The assistive force is transmitted from the multi-joint actuation platform (on the left) to the wearer.

Introduction

Lower limb wearable robots have been developed with the purpose of rehabilitation and augmenting human walking. Both autonomous (Collins et al., 2015, Mooney et al., 2016) and tethered (Malcolm et al., 2013) systems have achieved reductions in the metabolic cost of walking. All these devices provided mechanical assistance only to the ankle joint. Nevertheless, it has been hypothesized that generating a fixed level of mechanical power at the hip may need a higher metabolic cost than at the ankle (Sawicki et al., 2009). Few groups have reported metabolic reduction during walking by only assisting hip joint. The Stride Management Assistance Device reduced metabolic cost of walking ~7% with a peak torque of 3 Nm of hip flexion and extension assistance compared to an unpowered condition (Kitatani et al., 2014). Previous work from our group compared the effect of hip extension assistance during loaded walking with a multi-joint actuation platform and a soft exosuit, finding an average metabolic reduction of 4.6% with an average peak torque of 16 Nm (Ding et al., 2016). However, none of the previous research has studied the biomechanical and physiological effects of different assistive profiles at the hip, a fundamental step in the development of wearable robots for the hip that reduce metabolic cost.

We present the design of an IMU-based iterative hip controller that can deliver a pre-defined assistive profile to assist hip extension. We designed four assistive profiles with the aim of analyzing the effect onset timing and peak force timing during stance. We chose these two parameters because they enable us to regulate the amount of mechanical power delivered during the swing and stance phases respectively, both of which are related to the metabolic cost of walking (Sawicki et al, 2009).

Table 1. Peak force and peak timing across ten measured steps for each subject for the ESEP profile. Peak timing is the time from peak hip flexion to peak force divided by the time between peak hip flexion events. Target peak force and peak timing are 200 N and 23%.

Subject	1	2	3	4	5	6	7	8	Ave
Average Peak Force (N)	200.5	198.7	200.5	195.7	198.1	198	197.3	196.4	198.2 ±1.6
Average Peak Timing (%)	23.2	22.9	22.5	23.1	22.3	23.6	23	21.5	22.7 ±0.6

Methods

Eight participants (age 29.8 ± 5.0 yr., weight 82.6 ± 5.8 kg, height 1.79 ± 0.05 m, mean ± SD) walked on an instrumented treadmill (Bertec, Columbus, OH, USA) at 1.5 m s^{-1} while carrying a 23-kg backpack. We tested five different conditions: four with the assistive profiles described in the summary and one unpowered. We evaluated participants' metabolic cost with a portable gas analysis system (K4b^2, Cosmed, Roma, Italy) and lower limb kinetics and kinematics with a nine-camera Vicon optical motion capture system (Oxford Metrics, Oxford, UK). Biological joing power was calculated as net joint power from inverse kinematics less the power delivered by the exosuit.

Results

The average peak of the assistive force was 197.6 ± 0.2 N. The errors of onset and peak timing were within 1% of the gait cycle. Table 1 presents performance of the ESEP profile from all eight subjects, as one example. All assistive profiles significantly reduced the metabolic cost of walking compared to the unpowered condition by 5.7 ± 1.5% (ESEP), 8.5 ± 0.9% (ESLP), 6.3 ± 1.4% (LSEP) and 7.1 ± 1.9% (LSLP). Biological joint power was also reduced at the hip (ESEP and ESLP) and the knee (ESEP and LSEP) with respect to the unpowered condition.

Discussion

The results demonstrate that this iterative hip controller delivers robust hip extension assistance profiles across different subjects. The metabolic and biological joint power reductions provide insight into how to augment loaded walking via hip extension. Further, the highest metabolic reduction was found in the ESLP condition, suggesting that starting the assistance at terminal swing with a later peak force may be the most beneficial strategy. Future work on autonomous hip exoskeletons may incorporate these considerations when designing control strategies.

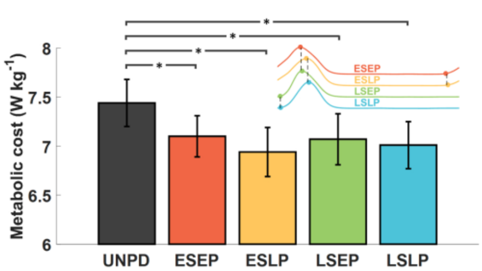

Figure 2. Net metabolic cost. Data are means ±SEM. The small panel on the right corner shows the corresponding assistive profile. Early-start-early-peak (ESEP), early-start-late-peak (ESLP), late-start-early-peak (LSEP), late-start-late-peak (LSLP) in red, yellow, green, blue respectively. The unpowered condition (UNPD) is in black. The * represents statistically difference between conditions (p<0.050).

Acknowledgements

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