Comparison of Ankle Moment Inspired and Ankle Positive Power Inspired Controllers for a Multi-articular Soft Exosuit for Walking Assistance

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***Abstract*—Mobility can be limited due to age or impairments. Wearable robotics provide the chance to increase mobility and thus independence. A powered soft exosuit was designed that assist with both ankle plantarflexion and hip flexion through a multi-articular suit architecture. So far, the best method to reduce metabolic cost of human walking with external forces is unknown. Two basic control strategies are compared in this study: an ankle moment inspired controller (AMIC) and an ankle positive power inspired controller (APIC). Both controllers provided a similar amount of average positive exosuit power and reduced the net metabolic cost of walking by 15%. These results suggest that average positive power could be more important than assistive moment during single stance for reducing metabolic cost. Further analysis must show if one of the approaches has advantages for wearers comfort, changes in walking kinetics and kinematics, balance related biomechanics, or electrical energy consumption.**

I. Introduction

MOBILITY determines human independence and thus quality of life. It can be affected due to age and/or disease. Next to exercise, wearable robotics can provide solutions for mobility improvements. Several prototypes to assist human movement have been developed and have shown promising results [1]-[5]. However, to date the best configuration and assistance profile is still unknown. The majority of the first studies with exoskeletons intended for metabolic rate reduction prioritized reducing biological positive joint power over joint moment. It might be possible that assistance profiles that follow the biological moment also effectively reduce metabolic rate because it is known that biological muscles can still consume energy even when they do not produce positive joint power [6, 7]. To address this topic, we conducted a study comparing an ankle moment inspired controller (AMIC) and an ankle positive power inspired controller (APIC) using a multi-articular exosuit [5].

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II. Methods

The soft exosuit used in this study has a single actuator per leg which assists with ankle plantarflexion and hip flexion through the multi-articular load path specified by the textile architecture (Fig. 1) [4]. An offboard actuation system was used to generate assistive forces, and Bowden cables were used to transmit the forces to the soft exosuit local to the subject's ankle. On each leg, two gyroscopes and a load cell were attached to measure data from the suit and the wearer.

Seven healthy male adults participated in this study (26.71 ± 4.75 y; 68.43 ± 9.46 kg; 1.74 ± 0.06 m; mean ± SD). While participants walked on a treadmill at 1.50 m s^{-1}, two different control strategies were investigated, each with their own powered-off condition for relative metabolic comparison. Metabolic rates, lower-limb kinematics, and ground reaction forces were measured (Fig. 1).

Ankle moment inspired controller: As shown in Fig. 2 (a) and (b), using an approach similar to [8], the AMIC used the suit-human series stiffness of the exosuit [5] and averaged ankle kinematics and kinetics data to identify a position trajectory that would produce biologically relevant assistive ankle moments during push-off. The system performed a force-based position control on a step-by-step basis to reach a maximum peak force of 5.52 N kg^{-1}.

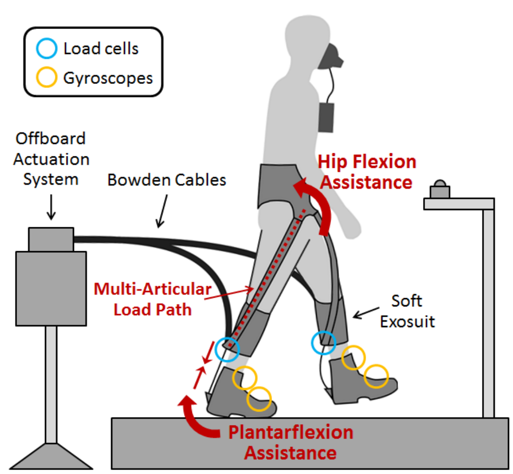

Fig. 1. *Experimental setup with the offboard actuation system and the multi-articular soft exosuit that assists with both ankle plantarflexion and hip flexion*

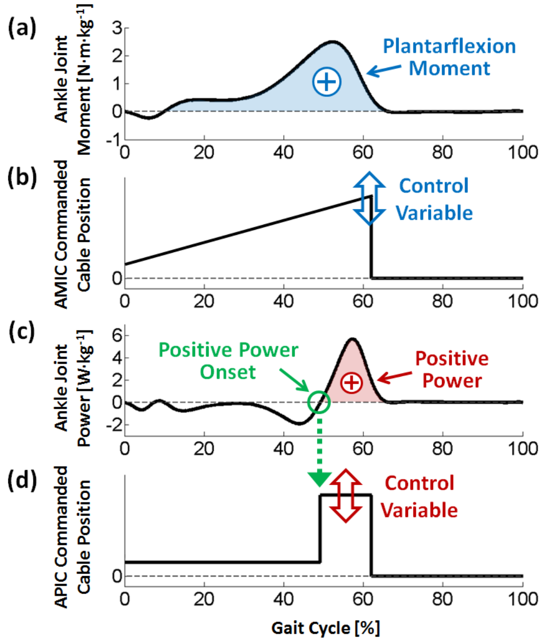

Fig. 2. Example position trajectories of the AMIC and APIC (a & b) The AMIC performs a force-based position control using a position trajectory inspired by a robotic-tendon model [8] that takes into account the suit-human series stiffness and natural ankle kinematics/kinetics in attempt to produce a biologically relevant ankle moment. (c & d) The APIC controller performs power-based position control using the ankle speed zero-crossing to ensure that assistance delivered by the exosuit coincides with the positive biological ankle power.

Ankle positive power inspired controller: As shown in Fig. 2 (c) and (d) and previously described in [4], the APIC delivered assistance predominantly during the positive ankle power phase. Ankle speed zero-crossing, which corresponds to the positive power onset, was estimated using the gyroscopes and used to trigger actuation. The system performed a power-based position control on a step-by-step basis to deliver 8 W of positive exosuit power assistance in parallel to the positive biological ankle power [4].

III. Results

The AMIC and APIC were able to deliver desired power and moment to the ankle joint and reduce the net metabolic cost of walking by 0.72 ± 0.21 W kg^{-1} ($14.78 \pm 3.63\%$) and 0.74 ± 0.30 W kg^{-1} ($15.36 \pm 5.53\%$), respectively. The average peak applied forces were 5.60 ± 0.50 N kg^{-1} and 4.99 ± 1.36 N kg^{-1} (Fig. 3a). The average positive exosuit power was 0.133 ± 0.028 W kg^{-1} and 0.124 ± 0.023 W kg^{-1} for the AMIC and APIC respectively (Fig. 3b). The average negative exosuit power was 0.026 ± 0.017 W kg^{-1} and 0.007 ± 0.002 W kg^{-1}. Using the AMIC, peak ankle dorsiflexion during stance was significantly reduced. For both controllers, ankle peak plantarflexion angle increased and occurs earlier in the gait cycle.

IV. Discussion & Conclusion

APIC produces similar metabolic benefit as AMIC with much lower moment assistance during single stance and similar average positive exosuit power during push-off. This

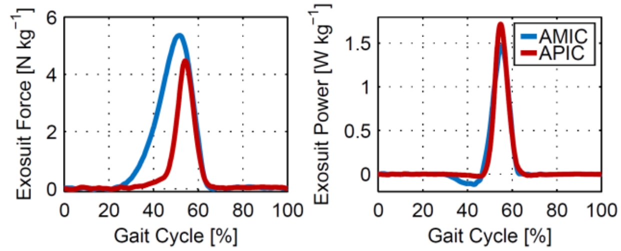

Fig. 3. (a) Average exosuit force and (b) average exosuit power for the AMIC and APIC.

seems to suggest that positive power is more helpful. However, we cannot make strong claims about the specific influence of peak positive power since we did not test the effect of this parameter in isolation from other changes in the actuation profile. Nevertheless, the finding that positive exosuit power could be more important than assistive moment during single stance for reducing metabolic cost aligns well with previous findings [9].

In summary, in this work we showed that the metabolic cost of walking can be reduced using two different controllers, an ankle moment inspired controller and an ankle positive power inspired controller. Further analysis of the data must show if one of the approaches has advantages for wearers comfort, changes in walking kinetics/kinematics, balance related biomechanics or electrical energy consumption. These parameters might give further insight to the benefits of each approach.

Acknowledgment

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