Development of a passive ankle exoskeleton and evaluation of the exoskeleton dynamics

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Summary

Wearable assistive devices with spring-based actuators are promising technology to increase gait efficiency. A critical aspect for maximizing the benefits of this technology is to secure high mechanical efficiency. However, this metric is rarely investigated. Here, we developed a lightweight passive assistive device with a spring in parallel to the plantarflexors. The device was primarily built with 3D-printed carbon fiber composites. We performed experiments to examine the exoskeleton's mechanical efficiency and found that ~94% of the absorbed mechanical work is delivered to generate exoskeleton's joint mechanical power. Our results suggest that rapid manufacturing with reinforced materials is suitable for achieving high mechanical work efficiency.

Introduction

Exoskeletons are wearable devices that assist mobility. Active exoskeletons provide assistance using controllable actuators such as electric motors, while passive exoskeletons rely on springs and/or dampers. The use of passive exoskeleton using spring-based actuators to assist gait has shown promise in reducing metabolic costs if appropriate spring stiffness is selected. Reported "optimal" stiffnesses for metabolic cost reduction vary from 50 [1] to 180 Nm/rad [2], varying due to differences in each device's structure geometries, spring moment arms, materials, textile wrapping surfaces, etc. [3] Investigating the mechanical efficiency of the exoskeleton structure is key to securing efficient device energy conservation, maximizing the benefits of the assistance.

Methods

We developed a passive ankle exoskeleton with a structure based on 3D-printed carbon fiber reinforcement. The device objectives were to transmit up to 30 Nm as in prior studies [1][2], be lightweight (<1 kg per leg), and have a high mechanical work efficiency. We quantified the exoskeleton's joint power P_{exo}, the spring's linear mechanical power P_{spring}, and the mechanical power due to the exoskeleton deformation P_{other} as shown in Eq 1, 2, & 3:

$$P_{exo} = P_{spring} + P_{other} \qquad \text{Eq 1}$$

$$P_{exo} = (\boldsymbol{r}_{spring} x \boldsymbol{F}_{spring}).\boldsymbol{\omega}_{exo} \qquad \text{Eq 2}$$

$$P_{spring} = \boldsymbol{F}_{spring}.\dot{x}_{spring} \qquad \text{Eq 3}$$

Where F_{spring} is the spring force, r_{spring} is the moment arm of the spring force to the exoskeleton joint, ω_{exo} is the exoskeleton's joint angular velocity, and $\dot{x}_{spring}$ is the velocity of the spring length changes. We performed experiments where a subject was asked to stand still and then perform 10 squats while using the device with different spring stiffnesses: 6.5, 9.7, and 10.3 KN/m, each in a different trial. This setup allows the examination of the device's force, torque, and power during ~ 0-15 deg dorsiflexion. We computed spring force via a load cell and all related kinematics (e.g., spring excursion, device's joint kinematics) using a motion capture system. We evaluated the efficiency n of the mechanical energy storage, defined, at each trial, as the positive/delivered work divided by the negative/absorbed work, and multiplied by 100% at each element, i.e., $n_{exo}, n_{spring}, and\ n_{other}$.

Results and Discussion

The device weighed 700 g per leg. The computed peak torque was similar across trials, i.e., ~40 Nm. Across all trials, the exoskeleton's joint work efficiency (n_{exo}) was 94.4 +/- 1.1%, the spring's work efficiency (n_{spring}), 98.6 +/- 0.7%, and the exoskeleton deformation's work efficiency (n_{other}), 81.2 +/- 0.3% (mean+/-SD). Hence, the exoskeleton structure delivers most of the mechanical energy absorbed.

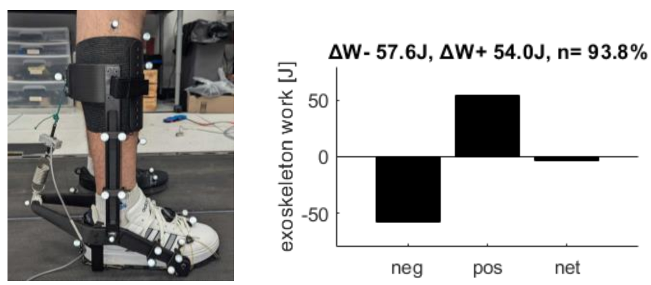

Figure 1: Prototype with markers and a load cell, and computed exoskeleton work at a representative trial, K=9.7 KN/m.

Conclusions

Rapid manufacturing is promising for developing exoskeleton prototypes with high mechanical work efficiency. Future work will investigate the exoskeleton dynamics and its contribution to ankle power augmentation during gait at several walking speeds. We will also assess the adaptation time for the user to take maximal advantage of the exoskeleton .

References

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[3] Yandell et al. (2017). *JNER*, **14**: 40.