Lightweight and Modular Hip and Knee Exoskeletons for Mobility Assistance in Community Settings

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***Abstract*— Exoskeletons have received considerable recognition as a potential technology for augmenting human abilities and supporting rehabilitation. State-of-the-art lower-limb exoskeleton designs have primarily concentrated on individual joints, and due to the intricate nature of their designs and the absence of a standardized mechatronics framework, the majority of existing exoskeleton designs are non-modular and incompatible with each other. In this work, we present the modular mechatronics design of a lightweight exoskeleton for the knee and hip joints.**

I. Introduction

Current exoskeleton designs suffer from non-modularity, making it costly and difficult to tailor to individual user needs [1], [2]. In this work, we aim to address this limitation by presenting the mechatronics design of lightweight and modular exoskeletons specifically targeting the knee and hip joints (Fig. 1). Our lightweight exoskeleton minimizes the metabolic penalty for the user, reducing the energy expenditure required to operate the exoskeleton. In addition, our exoskeleton is highly compliant and does not resist the natural movement of the user. Furthermore, users require different levels of assistance to satisfy their needs, and our exoskeleton can provide as-needed assistance levels based on real-time feedback from the user thanks to its high torque capability (18 Nm peak torque).

II. Portable and Compliant Hip Exoskeleton

The lightweight feature of this exoskeleton (total mass 3.2 kg) reduces weight penalty due to excessive mass (Table I). The actuators are aligned with the wearer's hip joints via a rigid frame that also holds the electronics. The frame has a reserved connector that can link to our modular knee exoskeleton as needed to function as a whole. The control board also has reserved ports to drive actuators and read sensors from the knee exoskeleton. The hip exoskeleton is controlled by 1 IMU sensor on each thigh.

TABLE I

Hip exoskeleton specifications.

Specifications	Value
Total mass (including battery and wearables)	3.2 kg
Actuation torque	18 Nm
Torque density	5.6 Nm/kg
Battery life	3 hrs

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Fig. 1. (a) Our hip exoskeleton has high torque capability while providing optimal comfort and compliance. (b) Our lightweight knee exoskeleton is designed to enhance mobility and provide support for different activities while remaining compliant. It can also integrate with the hip module. (c) Our compact electronics architecture enables simultaneous control of our hip and knee exoskeletons, enhancing their coordination and functionality.

III. Portable and Compliant Knee Exoskeleton

Our lightweight knee exoskeleton has a similar mass (3.3 kg) as our hip exoskeleton and they both have 18 Nm peak output torque (Table II). Its lightweight nature is further appreciated as knee exoskeletons have larger weight penalties than hip exoskeletons due to larger distal mass. The exoskeleton is fixed to the wearers using three braces on each leg. Fitting the three braces is crucial in providing proper assistive forces. Similar to the hip module, the three braces can be switched with varying sizes to better tailor the exoskeleton to the user. It also uses the same thigh IMUs as with the hip module to generate the assistance torque.

TABLE II

Knee exoskeleton specifications.

Specification	Value
Total mass (including battery and wearables)	3.3 kg
Actuation torque	18 Nm
Backdrive (resistive) torque	0.5 Nm (low)
Battery life	3 hrs

IV. Results and Discussions

We evaluated the performance of both exoskeletons on 8 able-bodied subjects. For the hip exoskeleton, it reduced the metabolic cost of treadmill walking at 1.25 m/s and running at 2.5 m/s by 24.3% and 15.2% respectively. For the knee exoskeleton, it reduced the metabolic cost of squatting by 22.2% average compared with no-exo condition. The findings underscore the versatility and advantageous impact of incorporating the exoskeleton in enhancing human performance.

References

[1] K. A. Witte, P. Fiers, A. L. Sheets-Singer, and S. H. Collins, "Improving the energy economy of human running with powered and unpowered ankle exoskeleton assistance," *Science Robotics*, vol. 5, no. 40, p. eaay9108, 2020.

[2] S. Yu, T.-H. Huang, X. Yang, C. Jiao, J. Yang, Y. Chen, J. Yi, and H. Su, "Quasi-direct drive actuation for a lightweight hip exoskeleton with high backdrivability and high bandwidth," *IEEE/ASME Transactions on Mechatronics*, vol. 25, no. 4, pp. 1794–1802, 2020.