Human Augmentation in the Real-World: A Lightweight and Compliant Knee Exoskeleton Design

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***Abstract*— Recent studies have demonstrated the opportunity of using exoskeletons to reduce the amount of energy expended by humans during walking. Yet, one of the primary objectives of robotic augmentation is to enhance human productivity while mitigating human effort, especially for physically demanding tasks. Moving in that direction, we developed a versatile and untethered exoskeleton for augmentation at the knee joint. Experimental results demonstrated that the exoskeleton not only reduced the energy expended by humans but also significantly enhanced productivity in terms of the amount of tasks completed under the same level of perceived exertion.**

I. Introduction

The field of powered exoskeleton technology has considerably advanced in recent years, showing the potential to greatly enhance human mobility. Numerous studies have focused on developing optimized assistance profiles to reduce energy expenditure [1], [2]. However, there has been limited advancement in the design and development of devices that enable untethered operation and versatile assistance, which constitute crucial requirements for real-world applications. Designing an effective exoskeleton entails balancing multiple aspects of the system as a mechatronic ensemble, including weight, power and torque capabilities, compliance, and versatile control. These challenges emphasize the importance of a comprehensive and holistic approach to the design of powered knee exoskeletons for outdoor scenarios.

TABLE I

Knee exoskeleton specifications.

Specification	Value
Total mass (including battery and wearables)	3.5 kg
Unilateral mass (actuator and wearables)	1.4 kg
Actuation torque	14 Nm
Torque density	10 Nm/kg
Backdrive (resistive) torque	0.22 Nm (low)
Battery life	>1.5 hrs

II. Knee Exoskeleton for the Real World

In this study, we present the design of a knee exoskeleton (Fig. 1a) that aims to enhance human capabilities in real-world applications. Our robot is untethered (its battery provides autonomy longer than 1.5 hours) and achieves high torque density (10 Nm/kg) while maintaining a lightweight (total mass: 3.5 kg including battery and wearables, Fig. 1b) and compliant structure (Table I). To verify the effectiveness of the exoskeleton to augment mobility in a real-world setting, we evaluated the metabolic cost and heart rate required to traverse a 1 km hiking route, with a 60 m increase in elevation. Furthermore, we carried out laboratory experiments on 9 able-bodied participants, who performed squatting, stair-climbing, and loaded incline walking tasks.

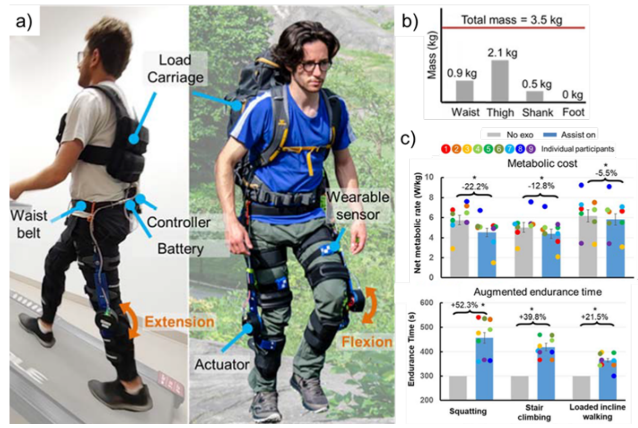

Fig. 1. a) Lightweight and compliant knee exoskeleton design for indoor and outdoor applications, such as treadmill walking and hiking. b) The exoskeleton was designed to minimize the distal mass of the robot. c) For indoor conditions, the assistance provided by the exoskeleton resulted in an average metabolic reduction of 22.2%, 12.8%, and 5.5% and participants were able to squat, climb stairs, and carry a load on an incline for 52.3%, 39.8%, and 21.5% longer time, respectively, before reaching the same exertion level experienced without the device.

III. Results and Conclusions

Our findings revealed that the average metabolic cost of the user during the hiking was reduced by 9.8% with exoskeleton assistance compared to the no-exo condition. Laboratory experiments showed that the exoskeleton assistance enabled an average metabolic reduction of 22.2% for squatting, 12.8% for stair-climbing, and 5.5% for loaded incline walking compared to the no-exo condition (Fig. 1c). Overall, these results demonstrate the effectiveness of the exoskeleton in augmenting human motion and highlight its potential to benefit individuals in outdoor activities, such as hiking. Additionally, along with the importance of effective control, they highlight the crucial role of exoskeleton design in promoting user benefit by reducing mass penalties and optimizing actuator compliance.

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