Lightweight, Backdrivable, and High-Bandwidth Knee Exoskeleton with Quasi-Direct Drive Actuation

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Summary

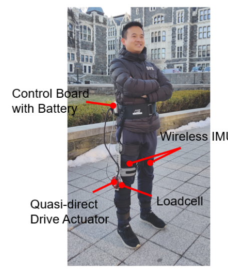
Abstract— Powered exoskeletons have demonstrated great potential both for ambulation restoration in people with gait impairments and for walking augmentation in healthy individuals. However, their diffusion for mobile applications is still limited, because state-of-the-art portable powered exoskeletons are not only excessively heavy and bulky but also typically obtrusive to human movements, causing both discomfort and fall risk. This paper presents the design of a lightweight and high-torque knee exoskeleton for versatile applications in real-world environments. It weighs 2.5 kg including a battery and is able to generate a 20 Nm nominal torque. Unlike conventional actuation methods that rely on high speed, low torque motors coupled to high gear ratio transmissions, our knee exoskeleton takes advantage of a quasi-direct drive actuation paradigm based on high torque density motor and 6:1 low gear ratio transmission. This actuation paradigm enables wearable robots with high backdrivability (0.4 Nm back-drive torque) and high bandwidth (40 Hz) for versatile applications.

Introduction

As wearable devices, exoskeletons should impose no restrictions on human movements. For this purpose, the key features of high-performance wearable robots are high backdrivability and high control bandwidth [1]. Backdrivability represents a measure of the mechanical impedance between the exoskeleton and its wearer. To enhance the responsiveness of the device to human intentions, it is crucial to minimize its resistance to the user during physical human-machine interaction [2]. On the other side, high control bandwidth of wearable robots is critical for human safety, as most exoskeletons designed for assistance during walking (relatively slow movement at 1-2 Hz frequency) are incapable of handling unexpected movements (e.g., human tripping). From the design perspective, the mechanical system of powered exoskeletons is comprised of motors, transmission mechanisms, and wearable structures [3]. Since motors and transmission mechanism predominantly determines backdrivability and control bandwidth of an exoskeleton, our approach focuses on them.

Methods

To address the challenges of excessive mass and restriction of natural movement, we present a unilateral knee exoskeleton design that satisfies the range of motion of the daily human movement, from 0 to 160 degrees, and also presents the advantages of rigid exoskeletons, related to high torque capabilities. The system is based on a quasi-direct drive actuator aligned with the knee joint of the human body. A thigh and shank braces were used to connect the wearable structure to the lower limb of the user, while a backpack-mounted at the waist host the control components. The total weight of the device including a battery pack is 2.5 kg. Fig. 1 shows the overview of the knee exoskeleton and its detail specifications.



Robot Specifications	
Property	Value
Motor continuous Torque	6.6 Nm
Motor Speed	250 RPM
Motor Voltage	42V
Output Peak Torque	20 Nm
Output Speed	26.2 rad/s
Mass (unilateral with battery)	2.5 kg
Gear ratio	6:1
Range of motion	0-160°
Actuation type	portable
Battery life	2 hours

Fig. 1 (Left) Proposed portable hybrid soft exoskeleton. (Right) Device specifications.

Results and Discussion

This paper presents a lightweight knee exoskeleton for personal mobility assistance. The designed exoskeleton is versatile and presents high backdrivability thanks to its high torque density quasi-direct drive actuation. Fig. 2 shows the backdrivability evaluation results, while in Fig. 3 the torque tracking performance is reported for different levels of assistance.

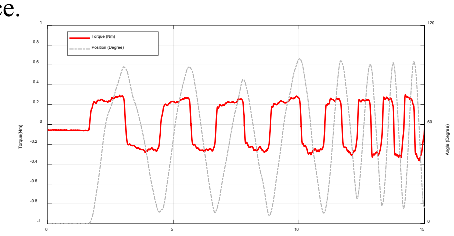


Fig. 2. Backdrivability performance for unpowered mode. The maximum backdrive torque is about 0.4 Nm, demonstrating the low mechanical impedance of the system.

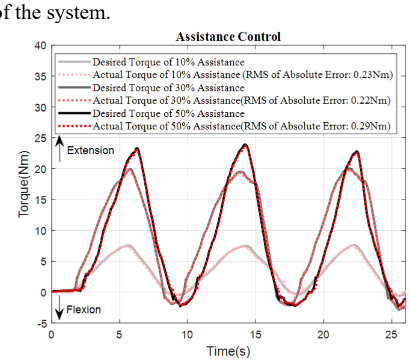


Fig. 3. The tracking performance of the 10%, 30%, 50% knee torque assistance in three squatting cycles. The RMSE between the desired and actual torque trajectories is 0.3 Nm, 0.22 Nm, and 0.29 Nm in 10%, 30%, and 50% knee assistance, respectively.

References

[1] P. M. Wensing, et al., IEEE Transactions on Robotics, 2017
[2] S. Yu, et al., IEEE Robotics, and Automation Letters. 2019.
[3] J. Wang, et al., IEEE Robotics and Automation Letters, 2018