Exploiting Quasi-Direct Drive Actuation in a Knee Exoskeleton for Effective Human-Robot Interaction

Peter Phung
Department of Mechanical Engineering, The Grove School of Engineering
The City University of New York, City College
New York, NY, USA
pphung000@citymail.cuny.edu

Advisor: Sainan Zhang, Hao Su*

***Abstract*—Wearable robots offer promising opportunities to enhance mobility both for healthy and impaired people. However, their application in community scenarios is still limited because current portable systems do not meet the requirements foreffective human-robot interaction. To tackle this challenge, here we present the design of a knee exoskeleton that is able to provide enhanced performance thanks to the use of a Quasi-Direct Drive actuation paradigm. The exoskeleton is versatile and shows excellent results in terms of torque density, backdrivability and control bandwidth, disclosing new opportunities for the usability of wearable robots.**

Keywords—Wearable robotics, knee exoskeleton, quasi-direct drive actuation

I. Introduction

Powered exoskeletons have demonstrated great potential for both ambulation restoration in people with gait impairments and for walking augmentation in healthy individuals [1]. However, up to now their diffusion for mobile application is limited, because state-of-the-art portable devices are still significantly heavy and bulky, resulting in rather obtrusive structures that typically provoke discomfort and fall risk. In particular, the lack of high-performance smart actuators represents the major obstacle towards an effective human-robot interaction. As wearable devices, exoskeletons are meant to provide relevant assistance without imposing hindrances or restrictions on human movements [2]. This scope translates into requirements that typically involve a trade-off among diverse factors such as weight, power, compliance and safety. In this context, we propose the design of a knee exoskeleton that offers enhanced performance in terms of torque density, backdrivability and control bandwidth thanks to the employment of a new actuation paradigm.

II. Methods

Unlike conventional actuation methods that rely on low torque (and high speed) motors coupled to high gear ratio transmissions, our knee exoskeleton takes advantage of a customized actuator based on high torque density motor and 6:1 low gear ratio transmission. Thanks to its optimized design with low inertia, this actuation paradigm ensures also high backdrivability (0.4 Nm back-drive torque) and high control bandwidth (40 Hz), which are useful indicators of the compliance and the safety of the system, respectively [3].

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. Proposed portable knee exoskeleton (left) and its electromechanical specifications (right).

Specifically, the backdrivability represents a measure of the mechanical impedance between the exoskeleton and its wearer, such that high backdrivability means that the device is capable to promptly respond to human intentions, while high control bandwidth is desirable for handling unexpected movements (e.g., tripping, slipping) that require to operate at frequencies much higher than those adopted for walking (relatively slow movement at 1-2 Hz frequency) [4]. Therefore, all these properties are of great benefit for a portable system and contribute to advanced usability of the wearable robot.

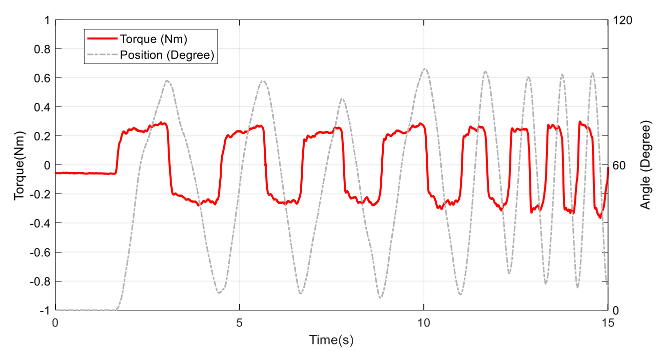

Fig. 2. Backdrivability performance in unpowered mode: the back-drive torque is measured during the motion imposed by the user while the actuator is turned off. The maximum back-drive torque is about 0.4 Nm, demonstrating the low mechanical impedance of the system.

The knee exoskeleton is reported in Fig. 1 together with its electromechanical specifications. The quasi-direct drive

Sainan Zhang, and Hao Su are with the Lab of Biomechatronics and Intelligent Robotics, Department of Mechanical Engineering, The City University of New York, City College, New York, NY, 10023, US. *Corresponding author. Email: hao.su@ccny.cuny.edu

This project was supported by moxie foundation, Mr. Irwin Zahn.

actuator is aligned with the knee joint, and a thigh and shank braces are used to connect the wearable structure to the lower limb of the user. A backpack mounted at the waist hosts the control components and the battery pack [5].

III. Results

The proposed exoskeleton is lightweight and versatile. Its total weight is 2.5 kg including the battery, and it satisfies the range of motion of the daily human movement, from 0° to 160°.

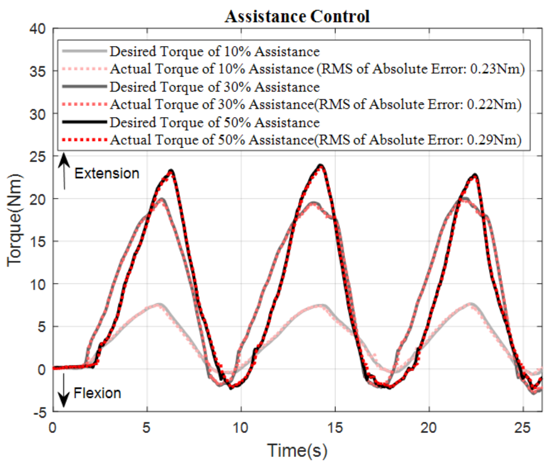

Fig. 3. Assistance torque tracking performance in three squatting cycles. RMSE between the desired and actual torque trajectories is 0.3 Nm, 0.22 Nm, and 0.29 Nm in 10%, 30%, and 50% level of assistance, respectively.

Moreover, thanks to its quasi-direct drive actuation, it presents high torque capabilities, being able to generate a nominal torque of 20 Nm, whereas low resistance is opposed to the free motion of the user, as indicated in Fig. 2. Finally, Fig. 3 demonstrates also excellent torque tracking performance for different levels of assistance during squatting motion.

IV. Conclusions

We presented the design of a knee exoskeleton that leverages a quasi-direct drive actuator to push the boundaries of portable wearable robots. Results demonstrate high performance in torque density, backdrivability and control bandwidth, paving the way towards enhanced human-robot interaction.

References

[1] Young AJ, Ferris DP. State of the art and future directions for lower limb robotic exoskeletons. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2016 Jan 27;25(2):171-82.

[2] Mohammed S, Amirat Y, Rifai H. Lower-limb movement assistance through wearable robots: State of the art and challenges. Advanced Robotics. 2012 Jan 1;26(1-2):1-22.

[3] Wensing PM, Wang A, Seok S, Otten D, Lang J, Kim S. Proprioceptive actuator design in the MIT Cheetah: Impact mitigation and high-bandwidth physical interaction for dynamic legged robots. IEEE Transactions on Robotics. 2017 Jan 19;33(3):509-22.

[4] Yu S, Huang TH, Wang D, Lynn B, Sayd D, Silivanov V, Park YS, Tian Y, Su H. Design and Control of a High-Torque and Highly Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention During Squatting. IEEE Robotics and Automation Letters. 2019 Jul 26;4(4):4579-86.

[5] Wang J, Li X, Huang TH, Yu S, Li Y, Chen T, Carriero A, Oh-Park M, Su H. Comfort-centered design of a lightweight and backdrivable knee exoskeleton. IEEE Robotics and Automation Letters. 2018 Aug 8;3(4):4265-72.