A Quasi-Direct-Drive Cable Actuation System for Interaction-Safe Knee Exoskeleton Design

Yanjun Li, Shuangyue Yu, Tzu-Hao Huang, Junlin Wang, Xiao Li, Hao Su*, *IEEE Member*

***Abstract*— Quasi-direct drive paradigm can effectively improve the torque density and torque control performance, which are two vital points for a safe and comfortable exoskeleton. This paper introduces a novel knee-exoskeleton design combining the advantages of a high torque density motor and a bi-directional cable transmission system. The knee exoskeleton is lightweight, highly backdrivable and has high torque control bandwidth.**

I. INTRODUCTION

To ensure safety and comfortability, it is well known that an exoskeleton should be as light as possible [1], which indicates that an intrinsically safe exoskeleton should have considerable torque density. Besides weight, the interaction torque between human and device should be highly controllable. An ideal exoskeleton can be viewed as a pure torque source by the user. It has been proved that adopting high torque density actuator and low reduction ratio (in some papers, this paradigm is called quasi-direct drive or QDD) can notably increase the torque density [2]. Although this design cannot influence the reflected rotor inertia, the resultant simplification in transmission can reduce the Coulomb friction and gear inertia instead, which are also important for the torque control performance [3]. Therefore, the quasi-direct drive is both beneficial for weight and controllability. This paper introduces our quasi-direct drive knee exoskeleton design which is shown in Fig. 1, and mainly focus on: (1) the high torque density motor which is suitable for the quasi-direct drive (2) Our bi-directional cable transmission system, and (3) the performance evaluation of the knee exoskeleton.

II. HIGH TORQUE DENSITY MOTOR

To obtain higher torque density, motor characteristic plays a key role in actuator design. This paper presents a high torque density motor with a series of mechanical optimization and electromagnetic optimization. Fig. 2 shows the specific continuous torque versus air gap radius distribution of our motor and other commercial selections (Allied, Parker, Maxon, and T-motor). Our motor has higher specific continuous torque than other commercial selections around 35 to 40 mm air gap radius and even has higher specific continuous torque than Parker K178, which air gap radius is about 55 mm.

Fig. 1 Our knee exoskeleton based on QDD design

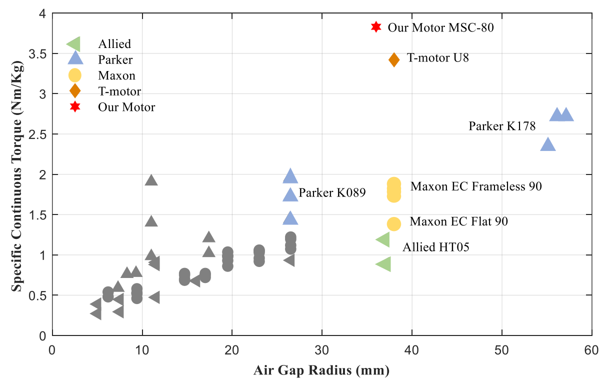


Fig 2. Specific continuous torque versus gap radius distribution of our motor and other commercial selections (Allied, Parker, Maxon, and T-motor)

Besides its high torque density, the design of the motor also makes a good balance of output continuous torque, overload ability, and continuous speed. Fig. 3 shows the operating range of the motor. Under 42 V voltage and 25 centigrade lab environments, the motor maximum speed is about 4000 rpm, the red area shows the motor continuous operation range with 660 mNm maximum continuous torque, the pink area shows the motor 5 seconds overloaded operation range with about 2000 mNm peak torque, and the white area shows the motor can work in a very short-term operation.

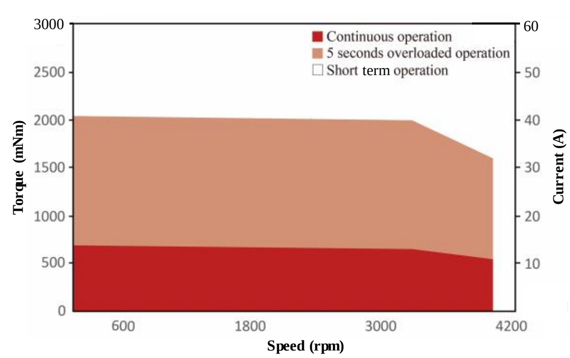


Fig 3. Operating range of our motor.

Shuangyue Yu, Yanjun Li, Tzu-Hao Huang, Junlin Wang, Xiao Li, Hao Su are with the Biomechatronics and Intelligent Robotics Lab, Department of Mechanical Engineering, City University of New York, City College, NY, USA. *Corresponding author: hao.su@ccny.cuny.edu

III. BI-DIRECTIONAL CABLE TRANSMISSION

The goal of the transmission mechanism is to meet the requirements of the lightweight design and high torque control bandwidth. With the high torque density actuator, the design specifications result in a low gear ratio (8:1) of the transmission. We adopt a bi-directional cable transmission system to transfer the power from actuator to the lower linkage of the exoskeleton. By exploiting the characteristics of the cable, this transmission system has high stiffness, low backlash, and low friction, which are essential for the torque control performance. Moreover, using a block and tackle which is close to the joint as a reduction mechanism further increase the transmission stiffness, and thus improve the torque control bandwidth. As a result, this lightweight mechanism guarantees a safe and comfortable interaction with the user. The high power density motor and the simple cable transmission keeps the total measured weight of the exoskeleton around 1.8 kg. Other design specifications are also given in Table I.

Table I: The Specifications of the Exoskeleton

Base structure material	Al 7075 T6
Output gear ratio	8:1
Max. the output torque	20 Nm
Total weight*	1.8 kg

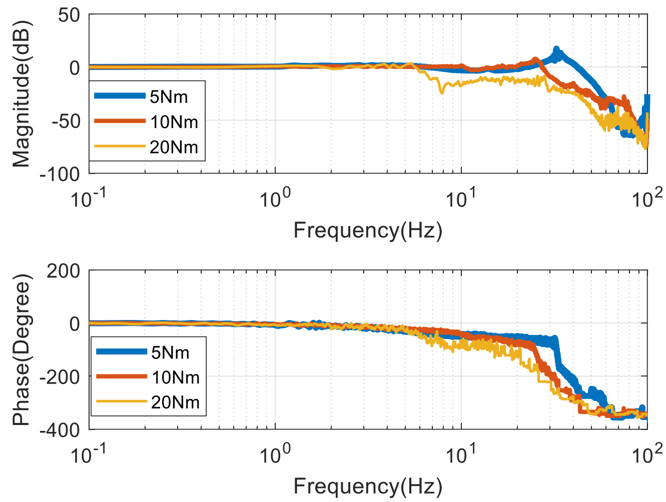
*The weight was measured including the motor and braces.

IV. PERFORMANCE EVALUATION

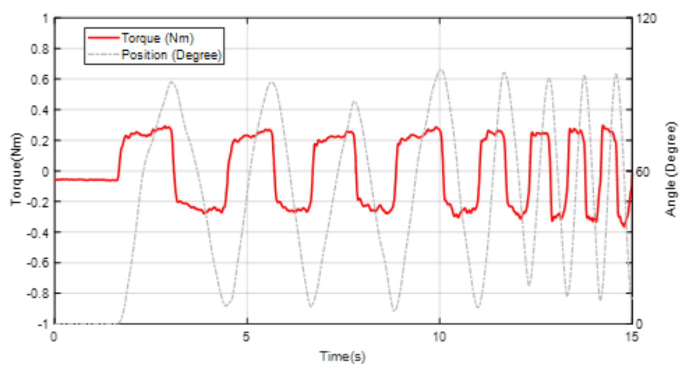
The frequency response test of our knee exoskeleton was conducted on a testbed (as shown in Fig. 4) to analyze the torque control performance. Fig. 5(a) shows that for 10 Nm, the torque control bandwidth is 28 Hz, the gain margin is 7.5 dB, and the phase margin is 8.6°. The maximum bandwidth of knee joint torque is approximate to 8 Hz, which means that the bandwidth of the torque control is sufficient to assist the human.

Our quasi-direct drive design and cable-driven transmission mechanism lead to a system with low output impedance. No-load impedance test demonstrated that the maximum backdriving torque is approximate to 0.8 Nm, as shown in Fig. 5(b). Zero-impedance control can be implemented to further eliminate the mechanical impedance and allow the human to percept little resistance as wearing the exoskeleton. In our zero impedance control test, the maximum amplitude of the resistance torque reduced from 0.8 Nm to 0.2 Nm, which can guarantee the human energy consumption will not increase significantly with the exoskeleton.

Fig. 4. The torque control testbed



(a)



(b)

Fig. 5. (a) Bode plot of torque control system. (b) Backdriving torque of the exoskeleton

V. CONCLUSION

An intrinsically safe knee exoskeleton is developed following the QDD design paradigm. We selected a high torque density motor as the basis of QDD. Then, a bi-directional cable transmission system is designed, which has merits like a simple structure, light weight, and high stiffness. Our exoskeleton has light-weight and good torque control performance.

REFERENCE

[1] Y. J. Jeong and H. Kazerooni, "Design of Low Profile Actuators for Medical Exoskeletons," in Volume 3: Biomedical and Biotechnology Engineering, 2015, vol. 2, p. V003T03A094.

[2] P. M. Wensing, A. Wang, S. Seok, D. Otten, J. Lang, and S. Kim, "Proprioceptive actuator design in the MIT cheetah: Impact mitigation and high-bandwidth physical interaction for dynamic legged robots," IEEE Trans. Robot., vol. 33, no. 3, pp. 509–522, 2017.

[3] S. Seok et al., "Design principles for energy-efficient legged locomotion and implementation on the MIT Cheetah robot," IEEE/ASME Trans. Mechatronics, vol. 20, no. 3, pp. 1117–1129, 2015.