A Lightweight and High Torque Hip Exoskeleton with Quasi-Direct Drive Actuation for Independent Living Assistance

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Summary

Abstract— Recent research has demonstrated the benefits of hip exoskeletons for human movement assistance in lab settings with the improved metabolic economy and gait kinematics, but its adoption in community settings has been restricted by factors like the device mass and its torque capabilities. This paper presents the design of a lightweight and high-torque hip exoskeleton with quasi-direct-drive actuation using compact and high torque density motors. The portable hip exoskeleton including battery weighs 3.4 kg and can generate 45 Nm peak torque. Unlike conventional actuation method using high speed and low torque motor with high gear ratio transmission, our hip exoskeleton uses a quasi-direct drive actuation paradigm with high torque density motor and 8:1 low gear ratio transmission to achieve high backdrivability (0.4 Nm) and high control bandwidth (62.4 Hz) which provides physical intelligence (e.g. high backdrivability and high bandwidth) without active control for versatile applications in real-world environments.

Introduction

Recent research has demonstrated the benefits of hip exoskeletons for human movement assistance in lab settings with an improved metabolic economy and gait kinematics [1-3]. The widespread adoption of the devices in community settings has been restricted by factors like the device mass and its torque capabilities. In general, the performance is restricted by the trade-off between the device mass and output torque ability. In addition to fully-integration and lightweight design of the wearable structure and electronics, motor performance and mechanical design of the robot have a major impact on the device output torque density. One classic design solution to achieve high device torque density is to use a high gear ratio transmission with a high-speed and low-torque motor. Due to the large gear ratio transmission, the actuator output has large rotor inertia and significantly reduces backdrivability of the robot. The series elastic actuation (SEA) paradigm overcomes the backdrivability limitation but also sacrifices control bandwidth and causes excessive weight. To achieve device high torque density and maintain high backdrivability, this paper presents a hip exoskeleton design solution that is based quasi-direct drive actuation. The actuator consists of a customized high torque density motor, a low gear ratio transmission and low-power electronics. The actuator weights 777 g and has high output peak torque density (58 Nm/kg), high backdrivability (0.4 Nm back drive torque in 2 Hz test), and high control bandwidth (62.4 Hz).

Results and Discussion

This paper presents a lightweight hip exoskeleton using compact quasi-direct drive actuator. It provides 45 Nm peak torque can achieve 13.2 Nm/kg high torque density. It also has low impedance and high backdrivability performance to make the system intrinsically safe. Table 1 shows our design specification and comparison with benchmarked hip exoskeletons. The hip exoskeleton has potential as a personal mobility assistance device to support independent living and we will conduct experiments to evaluate its performance in community settings.

TABLE. 1 HIP EXOSKELETON SPECIFICATION AND COMPARISON

Parameters	[1]	[2]	[3]	This work
Degree of Freedom	Ext	Flex/Ext	Flex/Ext	Flex/Ext
Peak Torque (Nm)	32	60	12	45
Mass (kg)	5	7	2.5	3.4
Torque Density (Nm/kg)	6.4	8.6	4.8	13.2

The designed exoskeleton is versatile in terms of high bandwidth and high backdrivability thanks to its high torque density quasi-direct drive actuation. Fig. 1 shows the control bandwidth test result. The control test with 22% of biological hip joint movement during walking and squatting was performed to investigate the tracking performance. An able-bodied adult subject (26-year-old, male, 70 kg) wore the hip exoskeleton and walked on a treadmill with the speed varying from 0.8 to 1.4 m/s and squatted on the ground with 2 s cadence. As shown in Fig. 2, the average RMS error between the desired and actual torque trajectory in 60 tests is 1.09 Nm (5.4% error of the maximum desired torque). The results indicate that the torque controller can follow the torque profile with high accuracy to assist human walking and squatting.

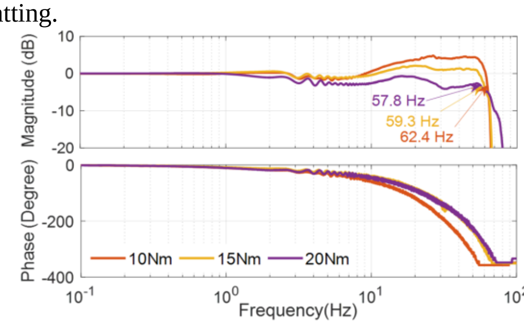

Fig. 1 The Bode plot of the 10 Nm, 15 Nm, and 20 Nm torque control. The bandwidth is 62.4 Hz.

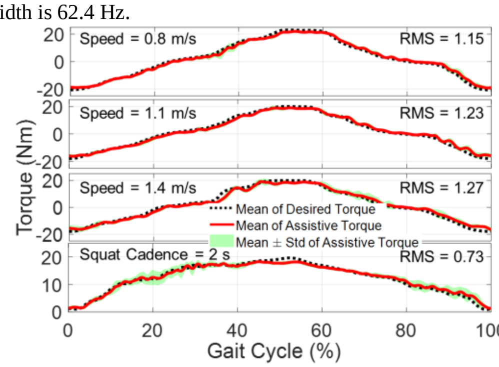

Fig. 2 Torque tracking performance of ±20 Nm assistance during walking and squatting tests. The mean of actual assistive torque (red) tracked the desired torque (black dash) well.

References

[1] J. Kim, et al, Science, 2019.
[2] H. J. Lee, et al, TNSRE, 2017.
[3] K. Seo, et al, ICRA, 2016.