Lightweight and High Torque Hybrid Soft Exoskeletons for Walking and Squatting Assistance

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Summary

This paper presents a hybrid soft exoskeleton that is lightweight and highly backdrivable with high torque output. The hybrid soft exoskeleton design combines the advantages of rigid exoskeletons (high torque thanks to large moment arm) and textile-based soft exosuits (no restriction to human movement). Leveraging on our high torque density motors that have more than five times higher torque density than Maxon motors, we use quasi-direct drive actuation to achieve high backdrivability and high torque density (90 Nm/Kg for each actuator). It is lightweight (2.8kg) and does not restrict natural movement. We derive a biomechanics model-based controller that generates biological torque profile for versatile control of both walking and squatting movement. Experimental results demonstrate the exoskeleton exhibits low mechanical impedance (1.5 Nm) in unpowered mode. Root mean square (RMS) error of torque tracking is less than 0.29 Nm (1.21% error of 24 Nm peak torque). The subject test result shows the maximum amplitude of the knee extensor muscle activity was reduced during squatting by 30% with 50% biological torque assistance.

Introduction

Wearable robots present an attractive solution to mitigate the incidence of injury and augment human performance [1]. Recently, there is a growing interest in wearable robots for knee joint assistance as cumulative knee disorders account for 65% of lower extremity musculoskeletal disorders [2]. Soft exoskeletons using either pneumatics or cable transmission represent a trend in wearable robot design. Pneumatic actuation operates on a tethered air compressor; thus, it is challenging for portable applications. Textile soft exosuit is a new approach to soft wearable robot design and has been used for ankle and hip joint assistance during walking. There is no knee textile exosuit developed yet, possibly due to the demand to anchor wearable structures to both thigh and shank (both are difficult as attachment fixture due to their geometry) while ankle and hip exosuits can be relatively easily anchored to footwear and waist respectively.

Methods

To overcome the challenges of the excessive mass and restriction of natural movement, we present a lightweight (2.8kg) hybrid soft exoskeleton design that combines the advantages of rigid exoskeletons (high torque thanks to large moment arm) and textile-based soft exosuits (no restriction to human movement) as shown in Fig. 1.

Compared with our previous soft knee exoskeleton design [3] which was relatively bulky and focused on walking assistance and generated 16 Nm continuously torque, our new design provides high torque assistance under the premise of ensuring high backdrivability. Besides the innovation of

hybrid soft exoskeleton design approach, our robot leverages quasi-direct-drive actuation paradigm that uses our custom developed high torque density motors with small transmission ratio gear or pulley. It is comprised of a customized pancake brushless DC motors (274g, 2 Nm continuous torque output), a 36:1 two-stage planetary gearbox. Thus, the actuator can generate 72 Nm continuous torque. Our motor has a five times higher torque density than conventional Maxon EC90 motor [4]. This design significantly reduces the inertia and mechanical impedance of the actuator while increasing its control bandwidth.

In addition, we derive a biomechanics model that explicitly generates a unified biological torque profile to assist both walking and lifting activities in real time. This bio-inspired control profile is biologically meaningful and applicable to squat, stoop and walking activities. We use three wireless IMUs placed on the human torso, thigh, and shank to detect the hip and knee joint angles. A human dynamic model is used to calculate the human knee torque during human motions.

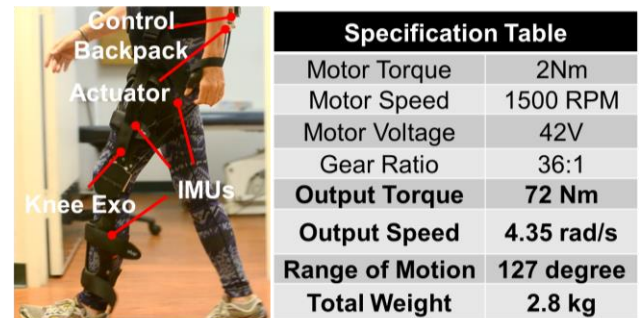| Specification Table	
Motor Torque	2Nm
Motor Speed	1500 RPM
Motor Voltage	42V
Gear Ratio	36:1
Output Torque	**72 Nm**
Output Speed	**4.35 rad/s**
Range of Motion	**127 degree**
Total Weight	**2.8 kg**

Fig. 1 (Left) The portable hybrid soft exoskeleton. (Right) The robot specifications.

Results and Discussion

Experimental results [5] demonstrate that the robot exhibits low mechanical impedance (1.5 Nm torque) when it is unpowered and 0.5 Nm torque with zero-torque tracking control. Root mean square error of torque tracking is less than 0.29 Nm (1.21% error of 24 Nm peak torque). Compared with squatting without exoskeleton, the maximum amplitude of the knee extensor muscle activity (rectus femoris) was reduced by 30% using 50% biological torque assistance in one healthy subject. It can operate autonomously for more than 1 hour with potential as a personal mobility device.

References

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