A Quasi-Direct-Drive Knee Soft Exoskeleton for Musculoskeletal Injury Prevention

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Musculoskeletal disorders (MSDs) are a leading cause of injury among various individuals [1]. Wearable robots present an attractive solution to mitigate the incidence of injury and augment human performance [2]. 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 [3]. Squatting and kneeling are two of the primary risk factors that contribute to knee disorders. Squatting motion is relatively simpler than walking as it involves fewer muscle groups, but its functional requirements present a new challenge because it needs to overcome the same aforementioned limitations, while the range of motion and the torque assistance during squatting are much greater than walking, as shown in Table.1.

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 system 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 thigh and shank while the ankle and hip exosuits can be anchored to footwear and waist respectively.

TABLE I. DESIGN PARAMETERS OF KNEE EXO FOR DEEP SQUAT

Parameters	Walking	Squat	Our Robot
Range of motion (deg)	10-60	0-130	0-130
Max knee joint moment (Nm)	40	60	72
Max knee joint speed (rad/s)	4.3	2.4	4.4
Exoskeleton moment arm (m)	0.35	0.35	0.35
Exoskeleton weight (kg)	——	——	1.1
Actuator min speed (m/s)	0.22	0.12	0.22
Actuator max force (N)	320	480	1250

To overcome the challenges of the excessive mass and restriction of natural movement, we have developed a quasi-direct drive actuation paradigm using customized high torque density motors and low gear ratio that significantly reduce the mass and mechanical impedance of the wearable robot. By combining with the cable transmission structure and quasi-direct drive actuator, Fig. 1 shows a hybrid soft exoskeleton design approach that combines the advantages of rigid exoskeletons (high torque) and textile-based soft exosuits (no restriction to human movements). It uses a cable transmission (like textile-based soft exosuit) in combination with a rigid wearable structure with interior soft padding (like rigid exoskeletons producing large torque). Thanks to the benefit of the large moment arm, hybrid soft exoskeleton requires less force for the same amount of delivered torque than textile soft exosuit. It presents one solution to reduce forces applied to limbs (because of its large moment arm) and pressure concentration. The hybrid soft exoskeleton is implemented with the quasi-direct drive actuation, a bidirectional Bowden cable transmission mechanism, and a low-profile knee joint mechanism. Fig. 2 shows the torque tracking performance of a biomechanics model-based torque control under 50% torque assistance mode.

As a proof of concept, the tethered exoskeleton demonstrates the design principles and effectiveness of control strategies. All design principles are transferable to portable version. Moreover, the offboard actuator is also lightweight. Our future work will investigate optimal control strategies using this platform and study the effectiveness of a portable version in the field using wearable motion and physiology sensors for injury prevention and human augmentation.

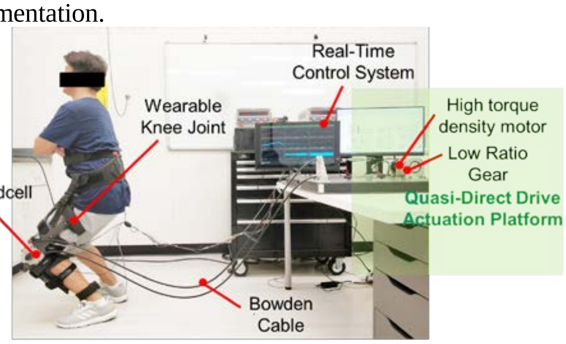

Fig. 1. A healthy subject performs squatting with the hybrid soft exoskeleton that uses soft cable transmission with rigid customized wearable structure. The quasi-direct drive actuation consisting of high torque density motors and low transmission ratio gears makes the exoskeleton lightweight and highly-backdrivable.

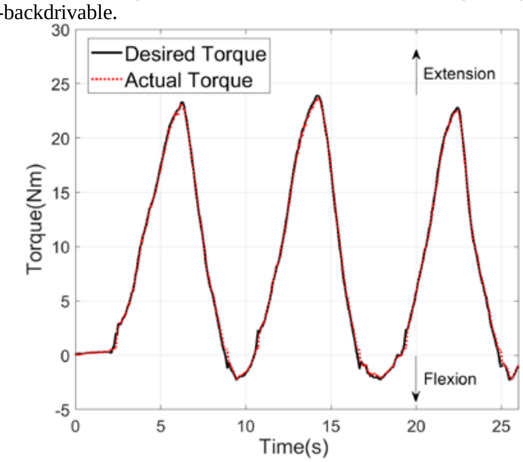

Fig. 2. The desired and actual torque of 50% assistance. A 0.29Nm RMS absolute error demonstrated that the torque controller can accurately and reliably deliver the desired torque profile to assist squatting.

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