A Portable Powered Soft Exoskeleton for Shoulder Assistance During Functional Movements: Design and Evaluation

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Work-related musculoskeletal disorders represent a leading cause of exclusion from the workforce that poses a significant socio-economic problem for individuals and society [1]. Recently, upper-limb wearable robots have gained high interest in the industry as a means to reduce the risk of developing these disorders. However, assisting the shoulder joint can be challenging due to its complex anatomical structure and its high mobility. Current powered devices for shoulder assistance are mostly bulky and tethered, being appropriate for in-clinical rehabilitation but unsuitable for use in daily activities. Existing portable exoskeletons, on the other hand, are typically passive, i.e., based on spring mechanisms. While this solution enables for a lighter design, the lack of automatic adaptation and smart human-centered control limits its versatility for use in activities of daily life.

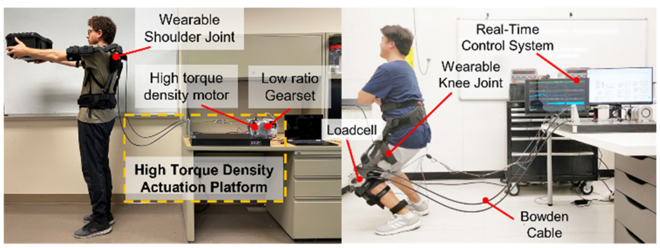

Fig. 1 Our high-torque (peak torque 100 Nm) tethered actuation system can acuate both upper and lower limb exoskeleton systems. (Left) The proposed soft shoulder exoskeleton; (Right) our soft knee exoskeleton [2].

To address the challenges above, we designed a portable powered soft shoulder exoskeleton. Our design combines a lightweight and rigid frame made of carbon fiber rods with soft textile components for a comfortable human-robot interface and leverages the novel paradigm of quasi-direct drive actuation. The quasi-direct drive actuation consists of the combination of our customized high-torque density motor and low gear ratio transmission, ensuring high compliance and an advantageous assistance-to-mass ratio [3]. A Bowden cable-driven mechanism is used to transfer mechanical power from the actuation to the shoulder joint., which can help to minimize weight penalty by remoting the actuators to wearer's waist. Additionally, we designed a passive free hinge mechanism acts in parallel with the human glenoid and a gravity compensation controller to provide the wearer with assistive torque to aid with the arm elevation for both degrees of freedom of shoulder joint: extension-flexion (sagittal plane), and shoulder abduction-adduction (coronal plane). Fig. 1 shows our high torque tethered actuation system, which was used for controller development and biomechanics investigation. This tethered actuation system can acuate both upper and lower limb exoskeleton systems [2]. We translated our control strategies developed with tethered system to our portable soft shoulder exoskeleton system, as shown in Fig. 2.

(a) Holding (b) Overhead drilling (c) Overhead placing

Fig. 2. Our portable soft shoulder exoskeleton during tasks of (a) object holding, (b) overhead drilling, and (c) overhead object placing (c). It assists arm lifting in two degrees of freedom of the shoulder joint (extension/flexion, adduction/abduction) while imposing no restriction on natural movements of the wearer.

Hysteresis and the backlash of the Bowden cable system cause major losses in force transmission, and it affects the output torque, velocity, and position control performance. We minimized the deflection angle of the cable to minimize the friction and applied a pretension force on the cable to minimize the backlash. As shown in the Fig. 3, our biomechanics model-based control enables high accuracy in torque tracking, with a root mean square error of only 1.4% of the reference peak torque set at 10 Nm.

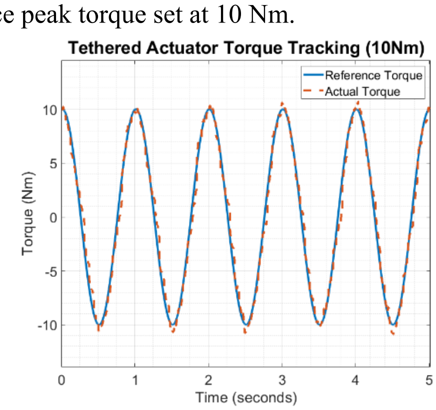

Fig. 3. Our high torque density actuation system shows great torque tracking accuracy. The RMSE absolute value between the desired and actual torque trajectories is 0.14 Nm under 10 Nm peak assistive torque, which is about the arm gravitational torque around the shoulder.

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