Omnics Exo: Lightweight Personal Wearable Robot

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Abstract—Lower limb exoskeletons have great potential in injury prevention for workers, but the current lower-limb exoskeletons are typically heavy, bulky and challenging to provide good safety for complex environmental conditions. This paper presents two versions of lightweight and high-torque knee exoskeletons, primarily for squat assistance for injury prevention. We employ high-torque-density motor and quasi-direct-drive actuation in exoskeleton design to achieve light weight and high-torque output. A tethered knee exoskeleton platform is developed to study biomechanics and understand control to optimize human-robot interaction. A portable knee exoskeleton platform is developed to translate the knowledge gained from the tethered platform for onsite knee injury prevention.

Keywords—Knee exoskeleton, squat assistance, high-torque-density motor, quasi-direct-drive actuation

I. INTRODUCTION

Musculoskeletal disorders (MSDs) are a leading cause of injury among various individuals [1]. It is estimated that the direct costs of injuries due to overexertion from lifting, pushing, pulling, turning, throwing, or catching to be $15.1 billion in 2016 [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 [3]. However, state of the art exoskeletons is excessively heavy and bulky [4], and cannot output high torque.

Fig. 1 (Left) tethered soft exoskeleton. (Right) portable soft exoskeleton.

Quasi direct-drive actuation consisting of high torque motors and low gear ratio transmission mechanism represents an improved solution to obtain a lightweight structure and high torque output. [5-7] designed tethered exoskeletons following this paradigm and proved its performance. Inspired by the superior performance of proprioceptive actuators for legged locomotion [8], this paper presented two knee exoskeletons using quasi-direct actuation paradigm based on our high-torque-density motors.

Table 1 Specifications of portable and tethered knee exoskeletons

<table>
<thead>
<tr>
<th>Properties</th>
<th>Tethered</th>
<th>Portable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuation type</td>
<td>Tethered</td>
<td>Portable</td>
</tr>
<tr>
<td>Motor Nominal Torque</td>
<td>2 Nm</td>
<td>2 Nm</td>
</tr>
<tr>
<td>Motor Speed</td>
<td>1500 RPM</td>
<td>1500 RPM</td>
</tr>
<tr>
<td>Motor Voltage</td>
<td>42 V</td>
<td>42 V</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>36:1</td>
<td>36:1</td>
</tr>
<tr>
<td>Output Torque</td>
<td>72 Nm</td>
<td>72 Nm</td>
</tr>
<tr>
<td>Range of Motion</td>
<td>127 degree</td>
<td>127 degree</td>
</tr>
<tr>
<td>Max joint speed</td>
<td>4.4 rad/d</td>
<td>4.4 rad/s</td>
</tr>
<tr>
<td>Total Weight</td>
<td>1.1 kg</td>
<td>2.8 kg</td>
</tr>
</tbody>
</table>

II. TETHERED KNEE EXOSKELETON TO UNDERSTAND BIOMECHANICS AND CONTROL

We developed a tethered knee exoskeleton, as shown in Fig. 1, to study the biomechanics of squatting and evaluation of control algorithms. The specifications are listed in Table 1. A high-torque-density motor and quasi-direct-drive actuation are employed to achieved light weight and high backdrivability. After the validation on the tethered knee exoskeleton, the biomechanical model and control algorithms will be transferred to the portable knee exoskeleton for onsite use.

A. Exoskeleton Design

The soft exoskeleton design approach proposed in this paper 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). Our hybrid soft exoskeleton has a larger moment arm (distance between human joint and the lumped center of the wearable structure, the same as rigid exoskeletons [10]) than textile soft exosuits [11] (approximately the radius of the attached limb) and avoids shear forces to human. Thus, the hybrid soft exoskeleton requires much less force from the cable system to deliver the same amount of torque than textile soft exosuits. It presents one
solution to reduce forces applied to limbs (because of its large moment arm) and pressure concentration (3D scanning and 3D printing based orthotic brace with foam padding are conformable and conformal vs. textile interface [12]). The soft exoskeleton is implemented with a high torque density motor, a bidirectional Bowden cable transmission mechanism, and a low-profile knee joint mechanism.

C. Injury Prevention Demonstration with EMG Sensors

The effectiveness of muscle activity reduction using assistive control was evaluated in six robot loading scenarios. The knee extensors (rectus femoris, vastus lateralis, vastus medialis) and the knee flexor (biceps femoris and semitendinosus) are measured and compared to without exoskeleton, power-off, zero torque control. But EMG in power-off condition had the highest amplitude. Compared to without-exoskeleton condition, peak EMG of the knee extensors (rectus femoris, vastus lateralis, and vastus medialis) in 50% assistance were reduced by 87.5% (from 400 μV to 50 μV), 80% (from 500 μV to 100 μV) and 70% (from 500 μV to 150 μV) separately. However, we also observed that the muscle activities of knee flexor (biceps femoris and semitendinosus) slightly increased. This is possibly due to the lack of training of the exoskeleton device of those novice users. We will study if training and adaptation of the exoskeleton device may alleviate this minute side effects.

III. PORTABLE KNEE EXOSKELETON FOR ONSITE KNEE INJURY PREVENTION

We developed a portable knee exoskeleton using the same actuation paradigm with that of the tethered one such that the light weight and high torque output are guaranteed. It can assist onsite squat with high torque for knee injury prevention.

A. Exoskeleton Design

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. The specifications are listed in Table 1.

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. This design significantly reduces the inertia and
mechanical impedance of the actuator while increasing its control bandwidth.

B. High Torque Density Motor

To enable high torque density actuation, it is crucial to design high torque density motors. Our custom designed BLDC motors optimize the mechanical structure, topology, and electromagnetic properties. It uses high-temperature resistive magnetic materials and adopts an outer rotor, flat and concentrated winding structure. Unlike conventional BLDC motors that place windings around rotors, our rotor consists of only the permanent magnet and rotor cover while the winding is attached to stators. This design significantly reduces the inertia and mechanical impedance of the motor while increasing its control bandwidth. Fig. 4 shows the continuous torque density versus air gap radius distribution of our motor and commercial ones [9]. The continuous torque of our motor is 2 Nm and its mass is 256 g. Maxon EC Flat 90 (#323772) has 0.45 Nm continuous torque with 600 g mass. In the 35-40 mm air gap radius domain, the continuous torque density of our motor is 7.81 Nm/Kg while T-motor U8 is 3.5 Nm/Kg, and Maxon EC Flat 90 (#323772) is 0.75 Nm/Kg. The high torque density actuation was implemented with a tethered actuation platform shown in Fig. 3. Using 2-stage planetary gears with 36:1 ratio and 290 g mass, the actuator generates 72 Nm continuous torque and 4.36 rad/s angular velocity.

IV. CONCLUSION AND FUTURE WORK

This paper presents two embodiments of lightweight and high-torque knee exoskeletons for squat assistance. Both the portable and tethered knee exoskeletons are designed using quasi-direct-drive actuation based on the high-torque-density motor, leading to the performance of light weight and high torque output. The biomechanics and control algorithms on squat assistance were researched and tested on the tethered version. They will be transferred to the portable version for onsite use in our future work.

REFERENCES


