Design and Validation of a Backdrivable Powered Knee Orthosis for Partial Assistance of Lower Limb Musculature

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***Abstract*—We will present the mechatronic design and validation of a partial-assist powered knee orthosis based on a quasi-direct drive actuator with a low-ratio transmission (7:1) that minimizes reflected inertia for low backdrive torques (< 2 Nm during walking) while maintaining high output torque capabilities (23.9 Nm peak). Able-bodied human subjects experiments (N=3) demonstrate overall reduced quadriceps activation with orthosis assistance during multiple demanding activities (sit-stand, stairs, and lifting-lowering), when using a quasi-stiffness controller. Potential benefits for populations including knee-osteoarthritis and lower-back pain will be discussed.**

***Index Terms*—partial-assistance, backdrivable, exoskeletons**

I. INTRODUCTION

Traditionally, exoskeletons aid paraplegic individuals with little to no voluntary movement, by providing complete assistance via designs focused on providing high torque output. To achieve this, high-ratio transmissions are used, resulting in stiff actuators that are not suitable for assistance of those with significant remnant voluntary movement. This work focuses on providing partial assistance to the latter population. For example, partially assisting the quadriceps can mitigate pain at the osteoarthritic patelo-femoral joint that is aggravated by high muscle tension, and reduce the incidence of overuse lower-back injuries by supporting the recommended squat-lift technique. We improve the implementation of several design goals set in our prior work [1]: 1) facilitation of non-hindered voluntary movement of the user (high backdrivability), 2) a non-cumbersome design (light weight, compact), and 3) capability to provide effective torque assistance to the user.

II. METHODOLOGY

First, we designed a custom BLDC motor with encapsulated windings to improve its thermal environment and thus increase its torque output capabilities, allowing the use of a smaller gear ratio (7:1), which greatly increased backdrivability. Second, we custom made all core components of the actuator and designed the planetary gears inside the stator, thereby decreasing the actuator's size and also reducing its total mass to 1.5 kg. We performed benchtop experiments to determine various important characteristics of the actuator. By measuring electromyography (EMG) from the quadriceps muscles, the human subjects (N=3) experiment validated the assistance delivered by the exoskeleton during multiple demanding tasks: sit-stand (STS), lifting and lowering (L&L), stairs ascent, and stairs descent. A quasi-stiffness high-level controller (k = 0.25 Nm/deg) was used for this purpose. Effort was quantified by taking the time integral of EMG normalized by maximum voluntary contraction (MVC).

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Research supported by NIH Award DP2HD080349 and NSF Award 1637704. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH or the NSF. Robert D. Gregg, IV, Ph.D., holds a Career Award at the Scientific Interface from the Burroughs Wellcome Fund.

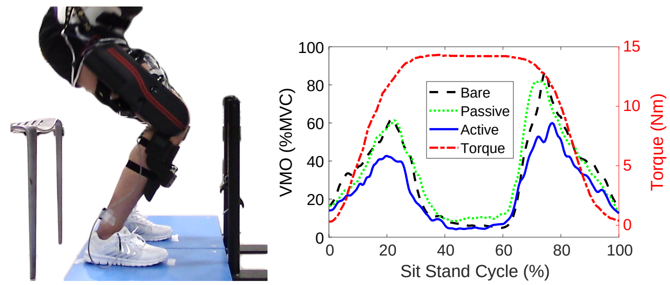

Fig. 1. Exoskeleton assisting a subject during STS (left), and mean ensemble averaged EMG plots for bare, passive, and active modes with assistance torque overlayed (right).

III. RESULTS

The custom actuator has a torque constant of 0.71 Nm/A, approximately 23.9 Nm peak torque and 12.78 Nm continuous torque, less than 0.5 Nm static and 2 Nm dynamic backdrive torques, and non-significant acoustic levels compared to ambient noise. For all activities tested other than stair descent, we found a reduction in mean effort of the vastus medialis oblique (VMO), rectus femoris (RF), and vastus lateralis (VL) when using the orthosis compared to not using it. Further, we found that the peaks of the ensemble averaged quadriceps' EMGs were smaller when using the orthosis for all activities tested. Fig. 1 shows the reduction in EMG of the VMO during sit-stand due to orthosis assistance torque (overlaid).

IV. DISCUSSION AND CONCLUSION

By implementing a custom actuator to reduce mass and improve thermal conductivity, we achieved a light weight, highly backdrivable exoskeleton that was able to assist healthy human subjects in multiple daily activities. Future work will involve patient subjects as well as implementation of a task-invariant energy shaping control strategy [2].

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