A Quasi-Passive Knee Exoskeleton to Assist During Descent

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***Abstract*— A pneumatic exoskeleton intended to decrease the muscle activity of the knee extensors during walking on a negative slope is presented. The device consists of an air spring that can be engaged and disengaged via a solenoid valve. When engaged, the air spring resists knee flexion. A preliminary evaluation of the device was conducted with a single healthy subject. During testing, the EMG activity of the rectus femoris decreased by 15%, while the EMG activity of the vastus medialis increased by 8%.**

I. Introduction

THIS paper presents the design and preliminary evaluation of a quasi-passive knee exoskeleton to assist during walking on negative inclines. During the stance phase of descent, when the knee is in flexion while supporting the weight of the body, the knee extensor muscles contract eccentrically to counteract large moments around the knee [1]. In other words, the knee effectively acts as a torque dampening mechanism during downhill walking. These large extensor forces can lead to muscle fatigue and high stresses on the knee joint in the short term and increased risk of degenerative joint diseases in the long term [2]. Quasi-passive exoskeletons have previously been evaluated for assisting the knee during level walking [3], load-carrying [4] and running [5]. To the best of our knowledge, this paper presents one of the first evaluations focused on quasi-passive knee assistance during descent.

II. Materials and Methods

The prototype presented here (Fig. 1) consists of three modules: two air springs that provide resistive torques at either knee, a fabric interface to attach the device to the body, and an integrated sensing and control system to detect the user's gait and control the device accordingly. When heel strike is detected, the corresponding air spring is sealed and acts to resist flexion. When opposite heel strike is detected, the air spring is disengaged so that it does not resist flexion or extension during the late stance and swing phases.

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Fig. 1. Left: (a) control system, (b) air spring, (c) fabric interface. Right: during early stance phase, a solenoid valve seals the air chamber and restricts flexion. When opposite heel strike is detected, the valve opens and the knee can flex freely.

The air spring is the most critical component of the exoskeleton. By resisting compression when sealed on one end, the air spring generates a resistive torque about the knee to assist the extensor muscles during downhill walking. A motion capture study was performed to define the test subject's knee kinematics during descent. The resulting data were combined with a simple model to calculate the air spring dimensions and attachment points required to produce the necessary knee extension moment. A low-friction glass cylinder with a graphite piston was used to create the air spring (Stock Piston and Cylinder Sets #2KS444-CP, Airpot Corp, Norwalk, CT). A protective PVC cylinder was added around the glass cylinder, custom end caps were designed and 3D printed, and a steel rod was connected to an alignment coupler, to ensure straight travel of the rod and piston within the cylinder and reduce undesired kinematic constraints on the user.

Two valves at the proximal end of the air spring allow for control of air flow. The first valve is a one-way check valve, that allows air to enter the air spring during extension (swing phase), while preventing air from escaping during flexion. A high-flow check valve with a low cracking pressure (0.062 PSI) was used, allowing air to enter the air spring with minimal extension force from the knee (High flow check valve, #91030, Qosina, Edgewood, NY). This reduces the amount of resistance to the user during the swing phase. Flow through the second valve is controlled by a solenoid. This control valve is closed during stance to provide a resistive torque, and open during swing so as not to interfere with the natural gait.

The sensing system consists of a foot switch in each shoe connected to a microcontroller, which regulates a solenoid valve that engages the air spring. When heel strike is detected by one of the foot switches, the signal is passed to the microcontroller and the valve is controlled appropriately.

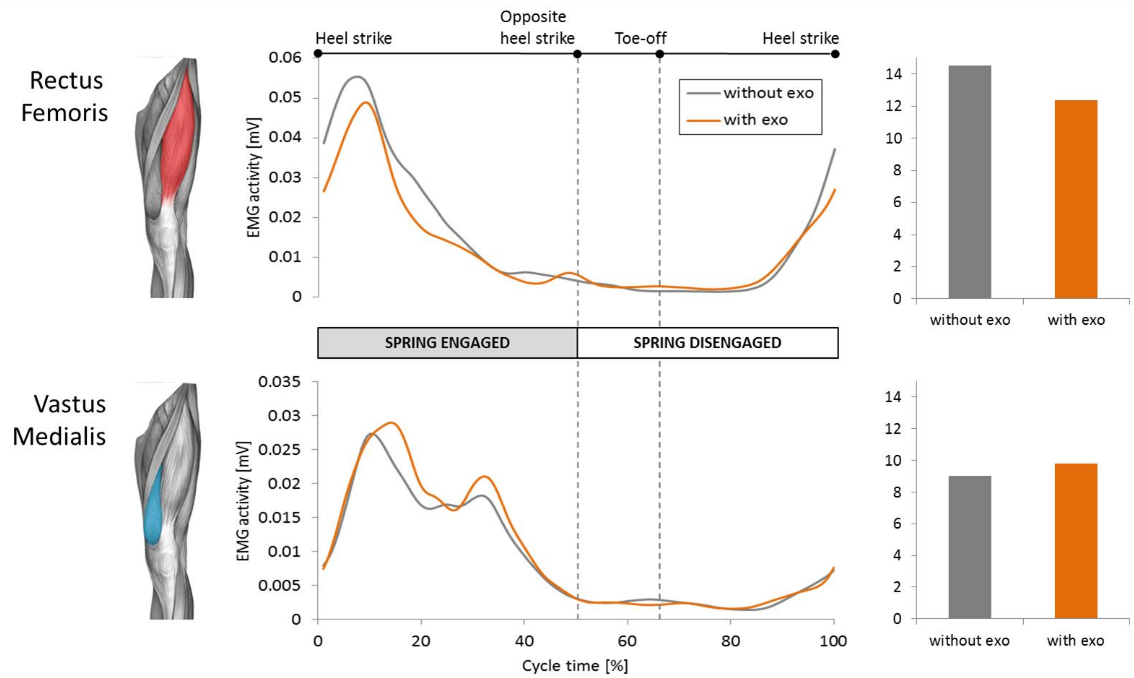

Fig. 2. Left: EMG electrode placement during testing. Centre: EMG activity throughout the gait cycle, averaged over 10 strides. Right: The area under the curves in the EMG plots, giving an estimate of total EMG activity over the gait cycle.

A preliminary evaluation of the prototype's performance was carried out. A single healthy female subject walked on an instrumented treadmill (Bertec, Columbus, OH, USA; 2160 Hz) at a speed of 1.0 m/s and a slope of -5°. Surface electromyogram (sEMG) readings were taken from two knee extensors (rectus femoris, RF, and vastus medialis, VM) using a wired system (Delsys, Natick, MA, USA; 2160 Hz). These muscles were chosen as they are the only muscles whose activity increases during descent [6]. Control data were recorded from the subject walking on an inclined treadmill while not wearing the exoskeleton, and experimental data consisted of the subject walking on the same incline while wearing the device. Ground reaction forces were measured to enable gait segmentation. The resulting data were used to estimate the change in muscle activation while wearing the exoskeleton prototype.

The EMG and GRF data were analyzed in Visual 3D (C-Motion, Rockville, MD, USA). The EMG data were band-pass filtered (4th order Butterworth, cut-off 20-450 Hz), rectified and low-pass filtered (4th order Butterworth, cut-off 6 Hz) to obtain an EMG linear envelope. The last 10 strides of each 1 minute trial were segmented using an automatic gait event detection algorithm based on GRF data (Visual 3D, C-Motion, Rockville, MD, USA) and averaged over the gait cycle.

III. Results & Discussion

Fig. 2 shows muscle activity during the entire gait cycle for the vastus medialis and rectus femoris, averaged over 10 strides. A 15% decrease in EMG activity is seen for the RF, while an 8% increase is seen for the VM. Thus, the device had the desired effect upon the RF but caused an undesirable increase for the VM. While an increase in extensor activity during the swing phase is to be expected, due to the mass added to the leg and the friction of the air spring, the increase in VM activity during the stance phase is surprising. The differences may be due to kinematic constraints at the knee that affect each muscle differently, or to effects of the device on the hip; the RF is a biarticular muscle that crosses both hip and knee, while the VM crosses only the knee joint.

IV. Conclusions

This preliminary design has shown promising results for decreasing RF activity during descent using a quasi-passive knee exoskeleton. Further research is required in order to better understand the effect of the exoskeleton on muscle activity and joint kinetics. Future work will include testing with additional subjects and using inverse dynamics to estimate the device's effect on knee moment during descent.

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