Design of a Comfortable Pure Moment Knee Exoskeleton

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1 Introduction

Lower-limb exoskeletons have the potential to enhance rehabilitation [1], assist in walking with gait impairments [2], reduce the metabolic cost of normal [3] and load-bearing walking [4], improve stability [5] and probe interesting questions about human locomotion [6]. The ankle produces larger peak torques and performs more positive work than either the hip or the knee during locomotion [7], and this makes it an effective location for applying assistance through an exoskeleton. However, it is difficult to assist a single joint without affecting other joints. Active plantarflexion causes a forward shift in ground reaction force, which extends the knee. This extension torque is resisted by the gastrocnemius as it acts as both a plantarflexor and a knee flexor. Forces in the gastrocnemius may be reduced when applying external torque to the ankle during push off, while knee extension torque resulting from ground reaction forces remains unchanged. This may cause hyperextension of the knee or increased activity of other knee flexors, thereby reducing the benefits of using an ankle exoskeleton. A knee exoskeleton may therefore be useful not only alone, but also in conjunction with an ankle exoskeleton to resist hyperextension during push off.

While often treated as a simple rotational joint, the knee has a moving center of rotation, an issue sometimes addressed by using a four bar linkage to approximate the subject's natural joint trajectory. Such a solution may be problematic as joint trajectories vary across subjects and depend on the assumption that the exoskeleton does not shift. Our goal was to develop an exoskeleton capable of delivering high torque at high bandwidth without enforcing a particular joint trajectory thus allowing less inhibited motion, high tolerance for error in placement, greater reduction in human joint forces, and comfortable fit for a wider range of users.

2 Methods

Inspired by a similar exoskeleton [8], our device was developed to reduce forces in the human knee by providing a near pure moment to the thigh and shank via a tethered emulator system with minimal medial obstruction. It can be used alone or in conjunction with an ankle exoskeleton [described in 9]. Series elasticity provides improved torque control and comfort.

2.1 Mechanical Design

The knee exoskeleton was actuated by two off-board motors with flexible transmissions and a real time controller (Fig. 1 A), described in detail in [10].

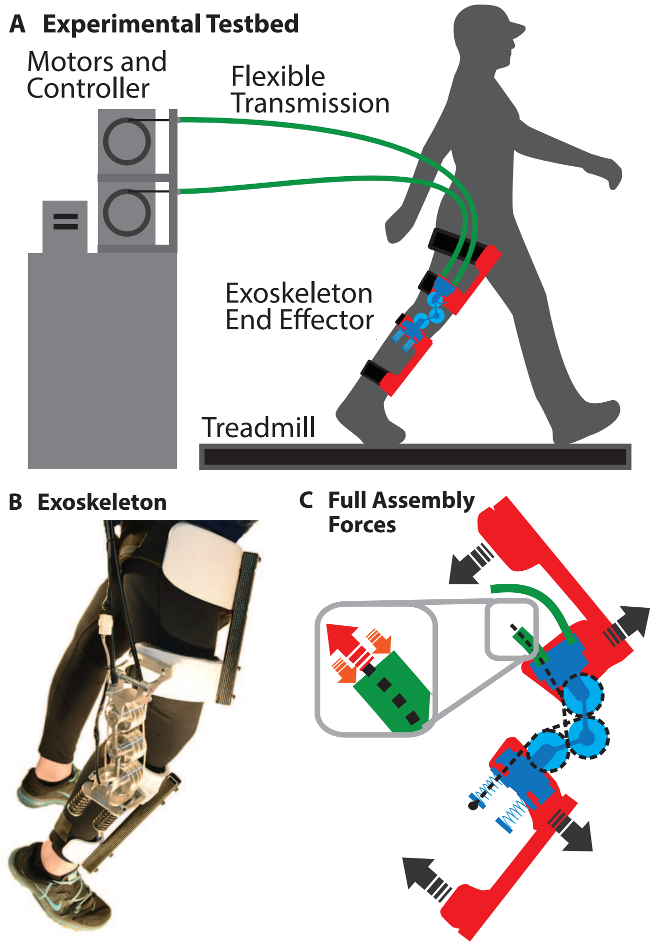

Figure 1: **A** The testbed comprised two off-board motors, a controller, a flexible transmission, and a knee exoskeleton end-effector worn on the user's leg. **B** An image of the knee exoskeleton displaying the aluminum joint, rigid interfaces at the straps, and carbon fiber struts. **C** Free Body Diagram of the full assembly. Forces normal to the user's leg act against the support structures (red) at each strap position. Due to the properties of the pulley system, these forces are equal and opposite resulting in pure moments applied to the thigh and shank. Forces in the Bowden cable conduit and inner rope (inset) are equal and opposite, producing no net external load on the leg.

The device interfaces with the user in four places: the top of the thigh, just above the knee, the shin below the knee, and just above the ankle (Fig. 1 B). Torque is applied to rigid structures at the interfaces closest to the knee (Fig. 1 C), and reaction forces are produced normal to the user at all four interfaces.

The exoskeleton comprises a large aluminum joint, carbon fiber struts, and aluminum and canvas interfaces (Fig. 1 B). The triple pulley design with hinged attachment provides five degrees of freedom, allowing unconstrained thigh and shank movements without concern for shifting. The joint features three sets of three pulleys: one for extension, one for flexion, and one which acts as an adjustable hard stop to prevent hyperextension of the knee in case of malfunction. If bearing friction is neglected, zero net force is expected at the knee joint, resulting in a pure moment applied to the thigh and shank. In reality, friction at the bearings results in small reaction forces in the human knee. Experiments are underway to quantify these forces.

The exoskeleton was designed to provide 120 N·m of torque. It allows 180 degrees of flexion. The triple joint configuration allows the device to be fitted to a range of users of thigh length 0.38 m ± 0.04 m and shank length 0.43 m ± 0.04 m. Users outside this range could be accommodated by manufacturing struts of different lengths. Thermo-conforming padding and Velcro straps allow for variation in thigh, ankle, and calf diameters.

Benchtop tests demonstrated the ability to apply joint torques of at least 120 N·m. Additional tests will quantify resultant human joint forces, closed loop bandwidth, and torque tracking error during walking.

There are no rigid structures on the medial aspect of the leg, which allows for narrower steps. However, this configuration requires large rigid supports at the straps to ensure comfortable and effective transfer of applied loads to the user.

Coil springs were included as series elastic elements to decouple the user from the inertia of the motor, and to improve torque control [11]. It is possible, however, that the Bowden cable and soft tissues of the leg will provide sufficient series elasticity without an explicit spring element.

2.2 Planned Experiments

We plan to quantify the reaction forces in the human joint as a result of applied torques by fixing the exoskeleton to a test stand featuring a joint instrumented with strain gauges. Torque measurement accuracy and bandwidth will also be assessed. Torque tracking accuracy will be quantified during walking trials.

3 Discussion

Human locomotion is a versatile and complex behavior that remains poorly understood, and designing devices to interact usefully with humans during walking is a difficult task. The most effective design is unclear and depends on the end use of the device. Our exoskeleton was designed to reduce resultant forces in the human joint, allow any center of rotation trajectory, minimize medial protrusions, apply high torque, and fit a wide range of users. This was accomplished at the cost of higher mass and transmission forces as a result of the large joint assembly and small radii of the pulleys. The single stay design required complex rigid supports, which were expensive and time consuming to produce. It is difficult to evaluate the effectiveness of these trade-offs without comparison to other designs. A simpler, lighter exoskeleton featuring a pivot joint and supports on medial and lateral aspects of the leg will be produced for comparison and used in parallel during experiments.

Experiments featuring this knee exoskeleton will help identify best practices in knee exoskeleton design and help researchers evaluate numerous assistance strategies during walking. This knee exoskeleton may be used in conjunction with ankle and hip exoskeletons, allowing researchers to explore interactions across joints during walking, running, and jumping.

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