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Soft exosuit for hip assistance

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HIGHLIGHTS

- Soft exosuit to actuate hip extension.
- Applies 30% of thenominal biological torques during walking at 1.25 m/s.
- New spooled-webbing actuator.

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ABSTRACT

Exoskeletons comprised of rigid load-bearing structures have been developed for many years, but a new paradigm is to create "exosuits" that apply tensile forces to the body using textiles and utilize the body's skeletal structure to support compressive forces. Exosuits are intended to augment the musculature by providing small to moderate levels of assistance at appropriate times in the walking cycle. They have a number of substantial benefits: with their fabric construction, exosuits eliminate problems of needing to align a rigid frame precisely with the biological joints and their inertia can be extremely low. In this paper, we present a fully portable hip-assistance exosuit that uses a backpack frame to attach to the torso, onto which is mounted a spooled-webbing actuator that connects to the back of the users thigh. The actuators, powered by a geared brushless motor connected to a spool via a timing belt, wind up seat-belt webbing onto the spool so that a large travel is possible with a simple, compact mechanism. Designed to be worn over the clothing, the webbing creates a large moment arm around the hip that provides torques in the sagittal plane of up to 30% of the nominal biological torques for level-ground walking. Due to its soft design, the system does not restrict the motion of the hip in the ab- and adduction directions or rotation about the leg axis. Here we present the design of the system along with some initial measurements of the system in use during walking on level ground at 1.25 m/s, where it creates a force of up to 150 N on the thigh, equivalent to a torque of 20.5 Nm to assist hip extension.

1. Introduction

A large number of lower limb exoskeletons have been developed over the years, usually with the purpose of assisting or augmenting human walking. For individuals needing to carry heavy loads such as soldiers or recreational backpackers, the promise of a mechanical assist is welcoming, potentially reducing muscle fatigue, metabolic expenditure, or injury rates. For individuals needing assistance with walking such as the elderly or paraplegic, or patients requiring gait rehabilitation, such devices could potentially restore walking function.

Many previous exoskeletons have comprised of rigid load-bearing structures, designed to transmit forces to the ground while tracking or applying torques to the wearer's joints at points along the structure. Some of these use the exoskeleton to support the weight of a hiker's backpack [1–4], while others support a paraplegic's bodyweight [5–10].

An alternative approach that has been applied to assist walking is to apply torques to the user's joints in parallel with the musculature, but without transmitting a load to ground. In particular, devices have been constructed to augment the strength of the hip and knee in healthy individuals [11,12]. Many other such devices are powered orthoses [13–15] that are designed to support disabled individuals by providing assistance at both the hip and knee to compensate for reduced muscle strength. These systems are also rigid, and may require an ankle–foot orthosis to be used with them to provide stability for the ankle joint and prevent migration of the

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rigid components that can often have significant weight. Two previous devices for assisting the hip in flexion used pneumatic actuators [16–18] along with rigid plastic orthoses to secure to the leg and pelvis such that a pin joint was approximately colocated with the hip. Several other devices have been made to provide assistance to the ankle alone, both for plantarflexion and dorsiflexion [19,20]. These units offer the potential to increase power generation capability at the ankle to support forward propulsion in addition to ensuring sufficient toe clearance from the ground during swing.

A more recent rigid exoskeleton is the Honda Walking Assist Device with Stride Management System [21,22], which actuates the hip joint in both flexion and extension. This device consists of a hybrid soft–rigid waist belt and struts that extend partially down the thigh, where they attach with narrow straps. It is powered by a motor approximately colocated with the wearers hip joint in the sagittal plane and includes a passive joint just above the motor to permit small amount of hip ab-/adduction. It functions differently from the previously-discussed examples, in that it only applies small forces and serves primarily to regulate the cadence of the wearer. Humans are known to walk most efficiently at a certain cadence (steps per minute) for a given forward velocity, and the Honda system applies small torques to the hips to entice the user into walking at that cadence.

As an alternative to rigid exoskeletons, a new paradigm is to create "exosuits" that are comprised of fabrics and utilize the body's skeletal structure to support compressive forces. Exosuits are used to augment the musculature by providing small amounts of assistance at crucial times in the walking cycle, as opposed to being able to apply large torques or support significant weight. These systems have a number of substantial benefits: with their fabric construction, exosuits eliminate problems of needing to align a rigid frame precisely with the biological joints and their inertia can be extremely low. These two features virtually eliminate resistance to motion, thus permitting close to natural kinematics. Furthermore, exosuits can be light and sleek, permitting them to be worn constantly; thus enabling rehabilitation or strength augmentation to occur for longer periods of time throughout the day. However, while these systems do offer potential benefits over rigid exoskeletons, there are limitations related to controllability and maximum applied force and thus much research remains to characterize them and understand their capabilities.

While the concept of an exosuit is relatively new, a number of designs have already been developed. Wehner et al. [23] created a pneumatically-powered system that assists ankle plantarflexion, and uses a garment of cloth and webbing to secure to the legs, waist, and shoulders. Asbeck et al. [24] developed a Bowden-cable-driven biologically inspired exosuit that assists both ankle plantarflexion and hip flexion with a single actuator for each leg. This is achieved with a multi-articular exosuit architecture that transmits forces from the waist and thigh through the knee and to the back of the calf, where it connects to the heel via the Bowden cable. Kawamura et al. [25] made a pneumatically-powered exosuit to assist hip flexion, with the device attaching to the wearer with a wide waist belt and a brace that crosses the knee. In addition to assisting walking, several other exosuits have been developed that support the back and torso while the wearer is lifting heavy loads [26–28].

The system described in this paper is a new example of a soft exosuit that uses the body's bone structure to support compressive forces and does not provide kinematic restrictions to the joints. The design assists hip extension, and is shown in Fig. 1.

In this paper, we focus on the design of the exosuit. In the following sections, we present an overview of the system, model how it applies torques to the body, and compute the requirements for the actuators. We describe and perform analysis for a new spooled-webbing actuator. We also present preliminary measurements of the system in use during walking on level ground, demonstrating its functionality.

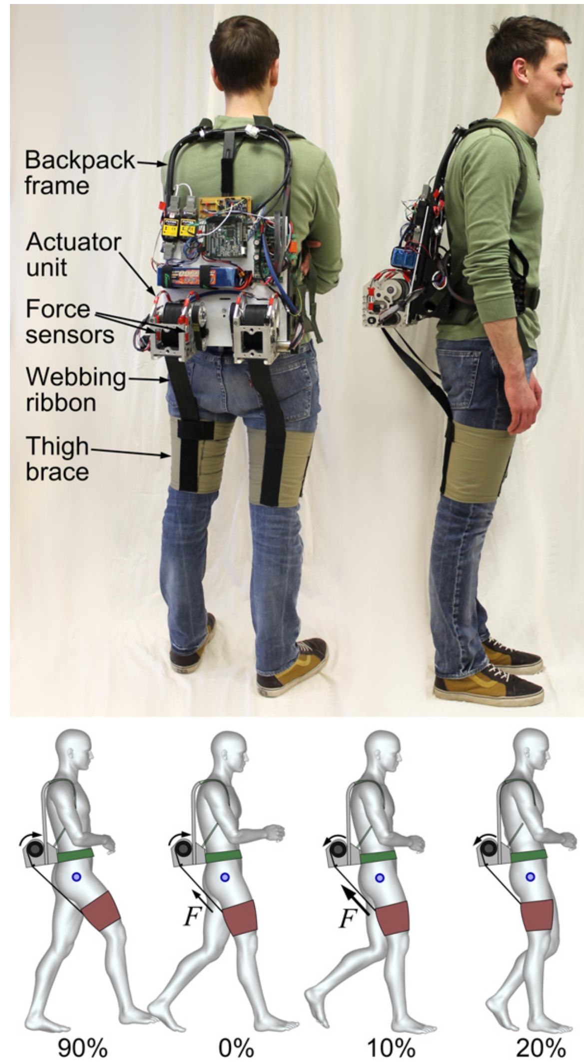

Fig. 1. Top, exosuit to assist hip extension described in this paper. Two actuator units are mounted on a backpack frame, and connect to cloth thigh braces with webbing. Bottom, overview of device operation. Starting at 90% in the gait cycle, which extends from one heelstrike to the next, the actuator units retract the webbing. This produces a force on the thigh that increases until 6% in the gait cycle. The actuator units then spool out the webbing so the force decreases, reaching zero at 20% in the gait cycle. At other times in the gait cycle, the webbing is slack so that no force is applied to the leg.

2. System overview

Our design (Fig. 1) utilizes a backpack frame to attach to the torso, and uses geared motors to retract webbing ribbon connected to a thigh brace on each leg. The actuators wind up the webbing ribbon onto a spool, which permits large (>25 cm) travel with a simple mechanism. The bottom of Fig. 1 shows how the device functions during the walking cycle. The actuators retract the webbing just before heelstrike, which in conjunction with the leg's motion creates forces pulling the thigh back. The force peaks just after heelstrike, concurrent with the wearer extending their hip to support themselves on the newly-planted leg. The actuators then extend the webbing again, so that there is no force in the webbing for the majority of the gait cycle.

This actuation scheme is unique in that the ribbon is wound on top of itself, increasing the spool diameter as the ribbon retracts. Mechanisms that wind or unwind a thin ribbon from a spool with an actuator have been used in several applications previously, including retracting seat belts, reading audio and video magnetic tapes, mopping floors, and deploying drip system tubing [29–32].