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Performance Evaluation of a Lower Limb Exoskeleton for Stair Ascent and Descent with Paraplegia*

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Abstract— **This paper describes the application of a powered lower limb exoskeleton to aid paraplegic individuals in stair ascent and descent. A brief description of the exoskeleton hardware is provided along with an explanation of the control methodology implemented to allow stair ascent and descent. Tests were performed with a paraplegic individual (T10 complete injury level) and data is presented from multiple trials, including the hip and knee joint torque and power required to perform this functionality. Joint torque and power requirements are summarized, including peak hip and knee joint torque requirements of 0.75 Nm/kg and 0.87 Nm/kg, respectively, and peak hip and knee joint power requirements of approximately 0.65 W/kg and 0.85 W/kg, respectively.**

I. Introduction

In an effort to facilitate legged locomotion in individuals with paraplegia, several computer-controlled lower limb orthoses and exoskeletons have been, and are being, developed and described in the research literature. These include hybrid FES-systems [1-5], which supplement functional electrical stimulation (FES) of leg muscles with a computer-controlled orthosis; and fully powered lower limb exoskeletons [6-12], which utilize electric motors as the primary form of motive assistance, in addition to the commercially emerging powered lower limb exoskeletons being developed by Argo Medical Technologies and Ekso Bionics, respectively.

Among the important criteria in the design of such gait assistance exoskeletons (and computer-controlled orthoses) is the amount of torque and power required at the enabling joints (which are typically the hip and knee joints). In fact, it can be argued that the joint torque and power requirements in a lower limb exoskeleton are the single most important design specifications in such systems, since nearly all other design decisions propagate from these considerations (e.g., actuator type and size, transmission type and size, power system type and size, structural considerations, etc.). Further, one can reasonably assert that, of all the movements that such systems should enable, stair ascent and descent is the most demanding with regard to hip and knee joint torque and power. As such, one would expect the joint torque and power required for stair ascent and descent to define the joint torque and power requirements for such systems.

In this paper, the authors have implemented stair ascent and descent capability in a lower limb exoskeleton, and tested the functionality of the system on a paraplegic individual with a T10 complete injury. A series of trials was conducted, and experimental data is presented that describes the body-mass-normalized hip and knee joint torque and power required by the exoskeleton during stair ascent and descent.

II. Hardware and Implementation

The Vanderbilt lower limb exoskeleton, shown in Fig. 1, provides powered assistance in the sagittal plane at both hip and knee joints. The exoskeleton consists of a hip segment, a right and left thigh segment, and a right and left shank segment. The hip segment contains a lithium polymer battery which powers the exoskeleton, while each thigh segment contains a pair of brushless DC motors, which actuate the hip and knee joints respectively through speed reduction transmissions. Although the exoskeleton does not explicitly contain a foot segment or ankle joint, it is designed to be used in conjunction with a standard ankle foot orthosis (AFO), which provides stability at the ankle and precludes foot drop during the swing phase of gait. The total mass of the exoskeleton, including the battery, is 12.3 kg (27.0 lb). A more detailed description of the exoskeleton design, including a description of the embedded electronics system, is given in [13].

Figure 1. Vanderbilt lower limb exoskeleton.

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The powered lower limb exoskeleton enables sit-to-stand transitions, stand-to-sit transitions, standing, stand-to-walk transitions, walking, walk-to-stand transitions, and stair ascent and descent. Details regarding the control structure and approach are given in [13], although a brief overview is given here. In order to enable the user to have autonomous control of these maneuvers, a user interface approach was developed based on the user's ability to affect his or her center of pressure via the use of his or her upper body, in combination with a stability aid. Specifically, based on sensors embedded in the exoskeleton, the control system estimates the location of the user's center of pressure (CoP), defined as the user's center of mass projection onto the (assumed horizontal) ground plane, and uses the distance between the CoP and the location of the forward ankle joint as the primary command input. As such, the act of leaning forward or backward at various points in the gait cycle indicates user intent to perform the next movement in a given activity. In the case of stair ascent, each step is ascended in a two-stage sequence. In the first part of the sequence, a forward shift in the CoP estimate lifts the right leg to the subsequent stair tread; in the second part of the sequence, a forward shift in the CoP estimate brings the (lagging) left leg onto the same tread as the (leading) right leg. At this point, a subsequent forward shift in the CoP will repeat the sequence, thus enabling the user to ascend the next stair tread. Figure 2 illustrates the sequence of movement during stair ascent, including the starting posture (Fig. 2a); leaning forward for the first CoP trigger (Fig. 2b); lifting of right leg to subsequent stair tread (Fig. 2c), leaning forward for the second CoP trigger (Fig. 2d); and lifting of body and placement of left foot on subsequent stair tread, next to right (Fig. 2e). Unlike stair ascent, the stair descent procedure requires only an initial CoP trigger. Figure 3 illustrates the sequence of movement involved in stair descent, including the starting posture (Fig. 3a); leaning forward for the CoP trigger (Fig. 3b); extension of right leg over subsequent stair tread (Fig. 3c); lowering of body and right foot to subsequent stair tread (Fig. 3d); and movement of left foot onto subsequent stair tread, next to right foot (Fig. 3e).

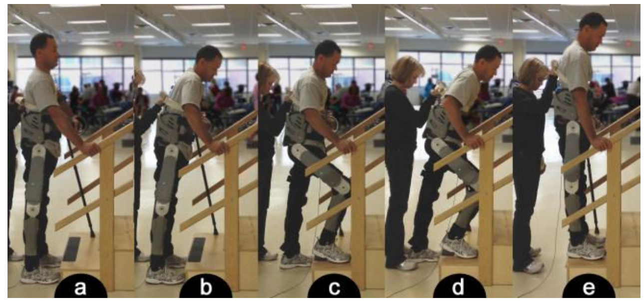

Figure 2. Stair ascent sequence, including a) starting posture, b) leaning forward for initial CoP trigger, c) lifting of right leg to subsequent stair tread, d) leaning forward for second CoP trigger, and e) lifting of body and placement of left foot on subsequent stair tread, next to right foot.

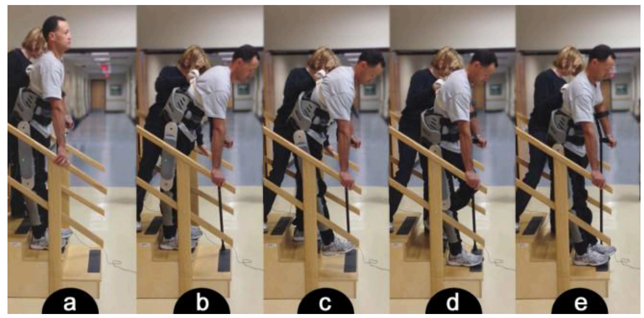

Figure 3. Stair descent sequence, showing a) starting posture, b) leaning forward for CoP trigger, c) extension of right leg over subsequent stair tread, d) lowering of body and right foot to subsequent stair tread, and e) movement of left foot to subsequent stair tread.

III. Data Collection

The stair ascent and descent functionality was implemented in the Vanderbilt lower limb exoskeleton, and trials were conducted on a paraplegic subject (1.85 m tall, 73 kg) with a T10 motor and sensory complete injury (i.e., American Spinal Injury Association, ASIA, A classification), 9 years post injury. Testing was performed at the Shepherd Center (Atlanta, GA, USA), a rehabilitation hospital specializing in spinal cord injury. A physical therapist was present for all trials, in accordance with the approved Institutional Review Board protocol. All trials were performed on a standard staircase, characterized by a step height 15 cm (6 in) of and a step depth of 29 cm (11.5 in). All tests were performed with a handrail support on the right side, and a forearm crutch on the left side. The subject was allowed to practice stair ascent and descent until he felt accustomed to and comfortable with the respective movements, and until the therapist reported that the subject was able to complete the respective movements without assistance from her (i.e., which she classified as contact guard assist). Following this practice, the exoskeleton hip and knee joint torques and power, as measured by instrumentation on the exoskeleton, were recorded during 12 successive stair ascent movements, and 12 successive stair descent movements.

IV. Results and Discussion

A. Stair Ascent

The averaged right and left hip and knee joint torques and power from the stair ascent trials are shown in Figs. 4, and 5, respectively. Specifically, Fig. 4 shows the averaged measured body-mass-normalized joint torque for the right and left hip and knee joints for 12 successive stair ascent movements. Note that the torques are positive in flexion and negative in extension. The dashed vertical line in the figure represents the time between the completion of the first phase of movement, and the initialization of the second phase of movement, as triggered by a second forward shift in the CoP. Based on the averaged torques across these trials, the largest knee joint torque required during the stair ascent movement was 0.87 Nm/kg (in extension), required at the right knee joint during the process of lifting the body up to the next stair tread, while the largest hip joint torque was approximately 0.75 Nm/kg (in flexion), required during the process of lifting the right leg onto the successive stair tread.

Figure 5 shows the averaged body-mass-normalized joint power for the right and left hip and knee joints for 12 successive stair ascent movements. Note that positive power represents exoskeleton power generation, while negative power represents exoskeleton power absorption (or dissipation). Based on the measured data, the peak knee joint power is approximately 0.85 W/kg (power generation), required while lifting the body, while the peak hip joint power is approximately 0.65 W/kg (power generation), required while lifting the leg up to the next stair tread. Additionally, the maximum root-mean-square (RMS) power during a movement is 0.43 W/kg at the knee joint, sustained for a 2-s period while lifting the body, and 0.33 W/kg at the hip joint, also sustained for a 2-s period, while lifting the leading leg onto the next stair tread. Note that the power required during the approximately 3-s duration of the intermediate CoP trigger is essentially zero.

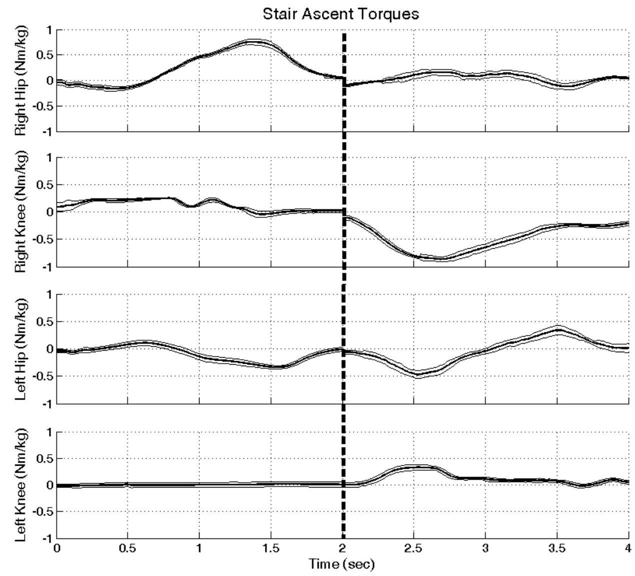

Figure 4. Measured body-mass-normalized joint torques averaged over 12 stair ascents movements, along with plus and minus one standard deviation, all with the right leg leading the movement (and left leg trailing). The dashed vertical line represents a discontinuity in time (of approximately 3 s), during which the subject shifted his CoP forward to trigger the next phase of the movement.

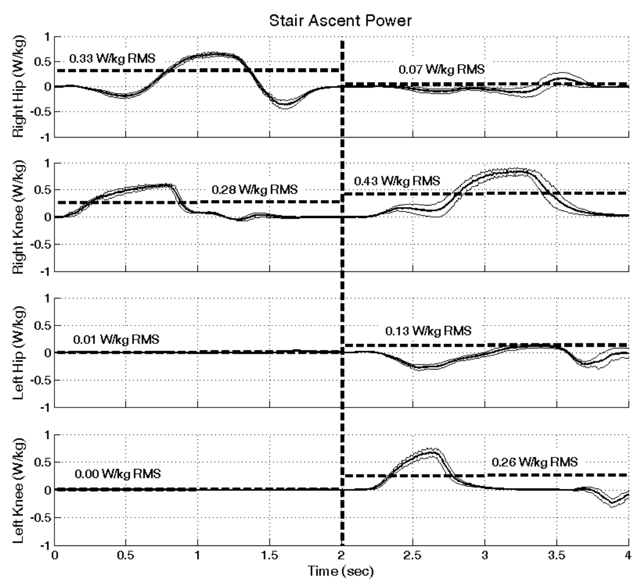

Figure. 5. Body-mass-normalized power averaged over 12 stair ascents movements, along with plus and minus one standard deviation, all with the right leg leading the movement (and left leg trailing). The dashed vertical line represents a discontinuity in time (of approximately 3 s), during which the subject shifted his CoP forward to trigger the next phase of the movement. The dashed horizontal line indicates RMS averaged power during each of the two phases of ascent for each joint.

B. *Stair Descent*

The averaged right and left hip and knee joint torques and power from the stair descent trials are shown in Figs. 6 and 7, respectively. Specifically, Fig. 6 shows the averaged measured body-mass-normalized joint torque for the right and left hip and knee joints for 12 successive stair descent movements. Based on the averaged torques across these trials, the largest knee joint torque required during the stair descent movement was 0.35 Nm/kg (in extension), required at the left knee joint during the process of lowering the body and the right foot to the subsequent stair tread, while the largest hip joint torque was 0.57 Nm/kg (in extension), required during the process of lowering the lagging (left) foot onto the successive stair tread next to the right.

Figure 7 shows the averaged body-mass-normalized joint power for the right and left hip and knee joints for 12 successive stair descent movements. Based on the measured data, the peak knee joint power is approximately 0.55 W/kg (power dissipation), required while lowering the body, while the peak hip joint power is approximately 0.5 W/kg (power generation), required while extending the right leg over the subsequent stair tread and also while lowering the left leg down to the subsequent tread. Additionally, the maximum root-mean-square (RMS) power during the descent movement is 0.22 W/kg at the knee joint, and 0.15 W/kg at the hip joint, both occurring over the 4-s period required for the stair descent maneuver.

C. *Nominal Lower Limb Torque and Power Requirements*

Having obtained repeatable stair ascent and descent with a paraplegic individual by means of a powered exoskeleton, it is reasonable to consider the reported normalized torque and power demands as they relate to absolute system performance requirements. The maximum hip and knee joints torques required for stair ascent and descent with the exoskeleton were shown to be 0.75 Nm/kg and 0.87 Nm/kg, respectively. The peak hip and knee joint power was shown to be 0.65 W/kg and 0.85 W/kg, respectively. Considering a reasonable upper bound for subject body mass as 90 kg (~200 lbs), a gait assistance exoskeleton with stair ascent and descent capability would need to provide maximum absolute

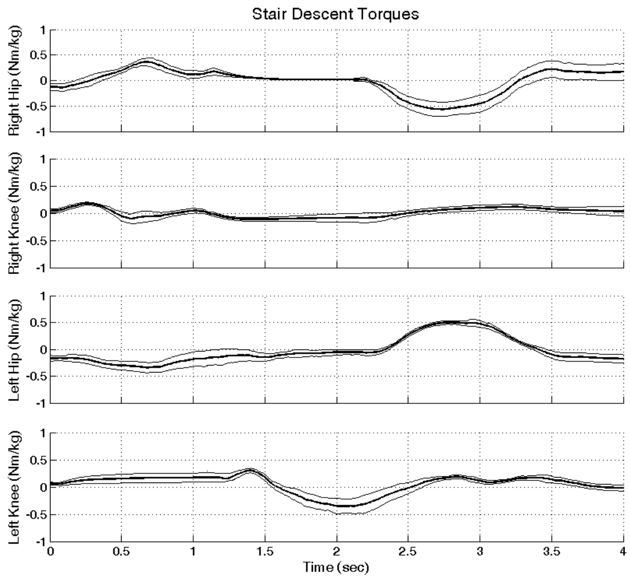

Figure 6. Measured body-mass-normalized joint torques averaged over 12 stair ascents movements, along with plus and minus one standard deviation, all with the right leg leading the movement (and left leg trailing).

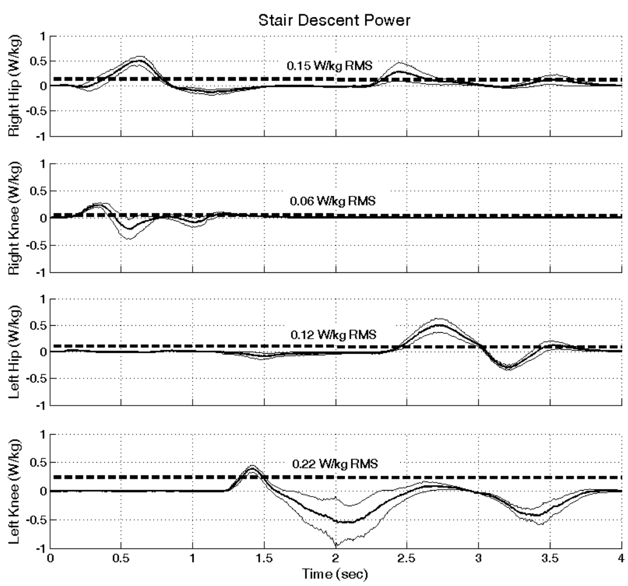

Figure 7. Body-mass-normalized power averaged over 12 stair ascent movements, along with plus and minus one standard deviation, all with the right leg leading the movement (and left leg trailing). The dashed horizontal line indicates RMS averaged power during descent for each joint.

joint torques of 68 Nm and 78 Nm at the hip and knee joints, respectively, and peak joint powers of 59 W and 77 W at the hip and knee joints, respectively.

V. Conclusion

Measured data characterizing the joint torque and power requirements for a lower limb exoskeleton has not previously been published. This paper addresses these issues based on the premise that the largest torque and power requirements on these systems will occur during stair ascent and descent. Averaged results from 12 stair ascents and descents are presented, including body-mass-normalized joint torques and joint power. The peak torque requirement at the hip is 0.75 Nm/kg and at the knee is 0.87 Nm/kg, both occurring during ascent. The peak hip joint power is approximately 0.65 W/kg (power generation), required while lifting the leg up to the next stair tread, while the peak knee joint power is approximately 0.85 W/kg (power generation), required while lifting the body mass. This knowledge of torque and power requirements should provide improved specifications for purposes of designing lower limb exoskeleton systems for facilitating legged locomotion in individuals with paraplegia.

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