Exoskeletons for Gait Assistance and Training of the Motor-Impaired

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Abstract—Robotics is emerging as a promising tool for training of human functional movement. The current research in this area is focused primarily on upper extremity movements. This paper describes novel designs of three lower extremity exoskeletons, intended for gait assistance and training of motor-impaired patients. The design of each of these exoskeletons is novel and different. Force and position sensors on the exoskeleton provide feedback to the user during training. The exoskeletons have undergone limited tests on healthy and stroke survivors to assess their potential for treadmill walking. GBO is a Gravity Balancing un-motorized Orthosis which can alter the gravity acting at the hip and knee joints during swing. ALEX is an Actively driven Leg Exoskeleton which can modulate the foot trajectory using motors at the joints. SUE is a bilateral Swing-assist Un-motorized Exoskeleton to propel the leg during gait.

I. INTRODUCTION

In the past decade, robotics has been used to evaluate and treat upper extremity functions in individuals with severe motor impairments. The MANUS, MIME, and ARM [1,2,3] represent early advances in upper extremity devices which demonstrated the usefulness of robotics in functional training by exploiting the built-in neural plasticity in humans. In recent years, a variety of powered arms [4,5,6] and un-powered arms have been developed and tested [7,8,9].

Machines for functional training of the lower extremity are far more challenging to design compared to those for the upper extremity due to issues such as posture and balance during walking. From an engineering perspective, the designs must be flexible to allow both upper and lower body motions, once a subject is in the exoskeleton, since walking involves synergy between upper and lower body motions. From a neuro-motor perspective, an exoskeleton must be adjustable to anatomical parameters of a subject and should facilitate human learning under subject’s control. Lokomat is a motorized lower extremity exoskeleton, now commercially available, for spinal cord injury patients on a treadmill [10]. Mechanized Gait Trainer (MGT) is a one degree-of-freedom powered machine that drives the foot [11]. However, due to limited performance and excessive costs, these machines are not common in rehabilitation clinics. These machines drive patients on a specified trajectory but do not provide flexibility to subjects to move under their own neuro-motor control. Training with fixed trajectories has been known to result in “learned helplessness”, i.e., habituation to given sensory inputs and poor motor response to variations in these inputs [12]. Other current trends in motorized exoskeletons include human strength amplification [13, 14] or targeting assistance at specific joints [15, 16, 17, 18].

In the last five years, our group at the University of Delaware has fabricated and tested three lower extremity un-motorized and motorized exoskeletons for human motor training [19, 20, 21, 22]. Each of these exoskeletons has a unique design principle and addresses the issue of providing a flexible motor-learning environment. The un-motorized exoskeletons can be fabricated at a very reasonable cost, thereby, making these accessible to users from different socio-economic backgrounds. We believe that these exoskeletons have the potential to make an impact on the emerging field of lower extremity gait rehabilitation of motor-impaired patients.

The rest of this paper is organized as follows: Section II summarizes the design principles and features of these exoskeletons. Section III presents a brief summary of preliminary results obtained with these exoskeletons on healthy persons and a person with stroke. These are followed by concluding remarks.

II. EXOSKELETON DESIGNS FOR THE LOWER EXTREMITY

A. Gravity Balancing Orthosis (GBO)

Gravity balancing Orthosis (GBO) is an un-motorized exoskeleton for right hemiparetic patients that can alter the level of gravity acting at the hip and knee joints during motion. Gravity plays an important role in human movement. It assists (or resists) the motion of a joint, such as the hip and knee, over different parts of the swing. With an orthosis that alters the gravity at the joints, i.e., provides partial or full gravity assistance during motion, the hip and knee joints can swing through a larger range of motion for the same nominally applied human joint torques (See Fig. 1). As a
result, a person with a weak musculature or poor motor-
control, when wearing such an exoskeleton, may be able to
attain a larger swing and adapt to it as the gravity is altered
during training (see data in Fig.??). This provides the
guiding principle behind the design of the gravity balancing
orthosis.

The GBO is a simple device composed of rigid links,
joints and springs, which are adjustable to the geometry and
inertia of the leg of a human wearing it. The GBO does not
use any motors or controllers, yet can still unload the joints
of the leg joints from gravity over the full range of motion of
the leg [19]. The mechanical design aims to make the
potential energy of the combined system invariant with
configuration of the leg. Additionally, parameters of the
GBO can be changed to achieve a prescribed level of partial
balancing, between 0-gravity and 1-gravity (See Fig. 2).

During training, the GBO is attached to a walker and is
strapped on to the subject at the trunk and segments of
the leg. The trunk has four degrees-of-freedom with respect to
the walker to allow natural motion of the upper body during
walking. The hip segment can abduct with respect to the
trunk. The thigh and shank segments of the machine are
telescopic to accommodate a range of subjects. The orthosis
is fitted with encoders that record the movement of the trunk
and the leg. In addition, the GBO has two 6-axis force-
torque sensors that record the interaction forces between the
GBO and corresponding segments on the human. The
trajectory of the foot and joint angles, recorded by the joint
encoders, are provided to the subject as visual feedback.

A. The GBO

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B. Active Leg Exoskeleton (ALEX)

ALEX is a motorized exoskeleton designed to assist right
hemiparetic patients. The significant aspect of ALEX is the
nature of assistance it provides to the leg during gait,
designed to maximize human-motor learning. The control
architecture can prescribe a tunnel around the desired foot
trajectory, see Fig.3 [20]. Depending on the current position
of the foot with respect to the tunnel, the controller provides
normal and a small tangential force on the foot to help
achieve this desired foot trajectory. If the foot is within the
tunnel, the normal force is close to zero. As the foot goes
outside the tunnel, the normal force acts as a restoring force
to bring the foot closer to the center line of the tunnel. The
controller allows the user to select the tunnel width and the
nature of the force field outside the tunnel. Unlike Lokomat,
it does not move the leg on a fixed trajectory but allows the
user to modulate it according to their current capability.

The exoskeleton design of ALEX is structurally similar to
the GBO (Fig. 3). The hip and the knee joints are actuated
by servo motors. The human-machine interface of ALEX is
similar to GBO. It is attached to a walker and is adjustable to
a range of subjects. ALEX has sensors to record kinematics
and kinetics of the gait similar to the GBO. A major design
and control challenge in the development of ALEX was to
achieve back drivability of motors while keeping the
required torques small. When we amplified the peak torque
by a large gear reduction, this introduced significant friction
in the gear train that prevented back drivability. This was
resolved by characterizing the friction empirically and
compensating for it using a load cell with a PI control law.
Details of gait training of healthy subjects using this
motorized exoskeleton are presented in Section IIIB.
C. Swing-Assist Un-motorized Exoskeleton (SUE)

SUE is a bilateral un-motorized exoskeleton (SUE) optimized for propulsion of the leg, during treadmill walking [21]. The design is based on a mathematical model of a swinging leg strapped to SUE. The dynamic model provides a framework for optimization of the torsion springs at the hip and knee joints. The optimized design was aimed at achieving a given final configuration with a positive ground clearance during motion. Figure 4(i) shows a subject wearing SUE.

In contrast to GBO and ALEX, it is not attached to a walker. It is un-motorized, light-weight, and portable. Kinematic and kinetic data are collected using joint encoders and interface force-torque sensors similar to the GBO and ALEX. Details of subject data collected with SUE are described in Section IIIIC.

III. RESULTS AND PERFORMANCE EVALUATION

A schematic of the training paradigm, used with GBO and ALEX, is shown in Figure 4 (ii), where a subject is presented with a gait template of the foot, which is made progressively closer to the normal trajectory over sessions. The assistance is in the form of gravity balancing in the GBO, hip and knee joint torque in ALEX, or propulsive force due to springs in SUE. The training exploits the ability of a human, under assistance, to extend the range of motion. GBO and ALEX are well suited to improve the motion of the hemiparetic leg following a stroke, while patients with spinal cord injury would typically benefit from SUE or future bilateral designs of ALEX. A given gait template, in general, can be achieved by multiple combinations of torque inputs applied by the human and is selected by the human motor system.

A. Gravity Balancing Orthosis (GBO)

The first data, presented here, was collected from four healthy young adults and three subjects with right hemiparesis, following a stroke. Stroke patients walked at their preferred speeds, while the healthy subjects walked at 30% and 60% of their preferred speeds to make the speeds comparable to those of the stroke subjects. Five trials of walking were collected and the time duration of each trial was about 30 seconds. Walking task was conducted within the device with the following settings: (i) leg and device fully gravity balanced, referred to as "full-balanced" condition, (ii) device only is gravity balanced, referred to as "device balanced" condition.

Fig. 5 shows the plots of the hip joint angle versus the knee joint angle during an entire gait cycle for a representative healthy subject and a patient performing walking [19]. It is clear from these plots that for the "full balanced" condition, the range of motion at both hip and knee joints is larger than with "device balanced" condition. For the stroke patient, this increase in range of motion is nearly 50%. This increased range of motion was expected according to our simulation results in Fig. 1.

A chronic stroke survivor, 56 year old male, with right hemiparesis volunteered for training with the GBO to determine long-term training effects. Formal evaluations of kinematics and kinetics were performed during both over-
ground and treadmill walking, mid-way through the 15 training sessions, and after the final training session. The over-ground walking evaluation was also repeated four weeks following the last training session.

Gravity assistance began at 100% and was gradually reduced over sessions to 0%. Each training session consisted of four blocks, 10 minutes each, of treadmill walking, each followed by five minutes of rest, or longer if requested. The subject began training at his preferred treadmill walking speed of 1.5 mph, increased to 1.7 mph by mid-training and 1.9 mph by the final evaluation.

The swing kinematics data over the 15 days showed that improvements measured during over ground gait were as follows: Knee flexion excursion during swing improved from the initial evaluation significantly as did the hip flexion. In addition, the hip was slightly more extended at terminal stance during over ground walking compared to the first evaluation. The ankle was less planar flexed at heel strike, indicating improvement in ankle dorsiflexion. These were encouraging findings that indicated continued improvement after training.

B. Active Leg Exoskeleton (ALEX)

Tests with the active leg exoskeleton were performed with six healthy adult subjects. This was done to evaluate whether the device could be used to induce short-term adaptations of the walking pattern, even of healthy subjects.

The top panel in Figure 6 provides an example of the patient’s knee-hip trajectories obtained from the initial walking evaluation (left) and from the last training session (session 15; right) using the GBO with device-only balancing. The patient’s knee excursion during the swing phase showed impressive increases over the training sessions although he still maintained the double-loop pattern, indicating an early knee extension followed by additional knee flexion prior to heel strike. The bottom panel in Fig. 6 illustrates changes of hip-knee coordination in the fully-balanced condition (100% assistance) between sessions 1 and 3. Note that, in contrast to device-only balancing (top panel), the patient was able to perform a single loop pattern of hip-knee coordination when the leg was fully gravity balanced that was more like the normal pattern. Moreover, within three sessions of practice, the pattern became more normal looking during the first half of the cycle following toe-off.

The swing kinematics data over the 15 days showed that the range of motion gradually increased, accompanied by a decrease of applied hip torque in the initial period of the swing. Following the 15 training sessions with the GBO, improvements measured during over ground gait were as follows: Knee flexion excursion during swing improved from the initial evaluation significantly as did the hip flexion. In addition, the hip was slightly more extended at terminal stance during over ground walking compared to the first evaluation. The ankle was less planar flexed at heel strike, indicating improvement in ankle dorsiflexion. These were encouraging findings that indicated continued improvement after training.

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For the experimental subjects, both the compliance of the virtual walls and assisting force were kept constant. What changed was the width of the virtual walls, i.e., the degree of constraint on the foot path. The constraint was maximal for the first block of training trials. The foot path was less constrained for blocks 2 and 3. The constraint was further relaxed for training block 4. Evaluation of the subjects’ walking performance on the treadmill was obtained with the motors of ALEX turned off at three time points: (1) prior to the initial block of training (pre-test), (2) prior to block 3 of training (mid-test), and (3) after block 4 of training (post-test). All of these data collections were performed with the template and current foot trajectory displayed to the subject. In addition, following the post-test, video feedback was turned off and the subject’s performance was recorded to test for evidence of foot path adaptation.

Results of one experimental subject’s performance during the four evaluation sessions are illustrated in Figure 7, where the thin solid line is the subject’s average foot path and the heavy dashed line is the prescribed foot path. The actual foot path deviated substantially from the required trajectory at the initial evaluation but was shaped to approximate the required trajectory even by the mid-training evaluation. That the trained pattern was maintained reasonably well in this subject following training, after the feedback was turned off completely, is remarkable.

The control subjects’ performance remained relatively constant throughout, while the experimental group showed a consistent reduction in the deviation from the required trajectory during training that was partially maintained even after removal of visual feedback, similar to the subject in Fig. 7. This result is striking given that walking patterns are highly ingrained through many years of practice. Of course, interpretation of this result requires caution given that treadmill walking differs significantly from over ground locomotion and is not well-practiced.

C. Swing-Assist Un-motorized Exoskeleton (SUE)

SUE was used to collect data on a single healthy subject, who walked on a treadmill at different speeds. In order to evaluate the effectiveness of the device, we computed the human applied joint torque from the swing data in two ways: (i) via a mathematical model, (ii) via force-torque sensors on the exoskeleton. If the device was working as intended, one would expect to see that the torques required in case (ii) are less than that those required in case (i) during swing. Representative torque plots at treadmill speeds of 2 mph, for which the exoskeleton was designed, are shown in Fig.8.

From these plots, we observe that a smaller hip joint torque was used by the subject with SUE, while the knee joint torque was smaller in magnitude during the first half of the cycle. These results are remarkable considering that only four design parameters were optimized in the design with simplistic model of walking on a treadmill [21].

IV. CONCLUSIONS

This paper described the design principles, training paradigms, and preliminary human subject results for three novel lower extremity exoskeletons intended for gait assistance and training of motor-impaired patients, such as after stroke or spinal cord injury. Gravity Balancing Orthosis (GBO) is an un-motorized exoskeleton that can alter the gravity at the joints of a swinging leg during walking. Experiments on healthy and stroke subjects confirmed that GBO extends the range of motion of a swinging leg, thereby, proposing reduced gravity to be an important learning paradigm for gait training of stroke patients. A 6-week gait training of a chronic stroke patient with GBO, while the gravity assistance was progressively reduced from 100% to 0%, showed significant improvements in gait and walking speed of the patient.

ALEX is a motorized exoskeleton that provides a flexible environment to maximize human-motor learning. Its control architecture prescribes a tunnel around a desired foot trajectory and laws that bring the foot close to the template trajectory. Tests on healthy subjects showed that humans could be trained to walk in a significantly altered gait on a treadmill, within 45 minutes. We believe that this result has deep implications in motor training of impaired patients. SUE is an exoskeleton that provides propulsive forces to a user during swing through clever designs of the exoskeleton spring parameters.

We believe that devices like GBO and ALEX can make a substantial difference in future gait training of patients suffering from stroke, while exoskeletons such as SUE and ALEX can impact training of spinal cord injury patients.

REFERENCES


