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An Arm for a Leg: Adapting a Robotic Arm for Gait Rehabilitation

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Abstract— **The purpose of this study was to adapt a multipurpose robotic arm for gait rehabilitation. An advantage of this approach is versatility: a robotic arm can be attached to almost any point on the body to assist with lower- and upper-extremity rehabilitation. This may be more cost-effective than purchasing and training rehabilitation staff to use several specialized rehabilitation robots. Robotic arms also have a more human-like morphology, which may make them less intimidating or alien to patients. In this study a mechanical interface was developed that allows a fast, secure, and safe attachment between a robotic arm and a human limb. The effectiveness of this interface was assessed by having two healthy subjects walk on a treadmill with and without a robotic arm attached to their legs. The robot's ability to follow the subjects' swinging legs was evaluated at slow and fast walking speeds. Two different control schemes were evaluated: one using the standard manufacturer-provided control algorithm, and another using a custom algorithm that actively compensated for robot-human interaction forces. The results showed that both robot control schemes performed well for slow walking. There were negligible differences between subjects' gait kinematics with and without the robot. During fast walking with the robot, similar results were obtained for one subject; however, the second subject demonstrated noticeable gait modifications. Together, these results show the feasibility of adapting a multipurpose robotic arm for gait rehabilitation.**

I. INTRODUCTION

Restoration of walking ability is an important goal of rehabilitation following neurological disorders such as stroke or spinal cord injury. Conventional gait training programs are often labor intensive. For example, in body-weight-supported treadmill training, physical therapists provide manual assistance to move a patient's leg and/or pelvis in a desired trajectory, which can demand high therapist effort.

There is a growing interest in using robots to automate gait training and relieve the physical burdens placed upon therapists. Consequentially, there has been a proliferation of robotic devices for gait rehabilitation applications. These robots are able to alter gait by pushing and/or pulling on a person, and have met with varying degrees of success in terms of rehabilitation outcomes [1-6]. Most gait rehabilitation robots are highly specialized devices that perform singular functions. Although many of these robots are quite sophisticated, as with any device, they have limitations. Some designs may be intimidating to patients (e.g. a large exoskeleton or several wires and push-rods); others may require long and involved patient setups.

Instead of adding to the current stock of customized gait rehabilitation robots, an alternative approach may be fruitful. Specifically, adapting a commercially available robotic arm for gait rehabilitation may provide advantages over traditional approaches. A robotic arm could perform many functions, e.g. it could be attached to any point on the body for lower- and/or upper-body rehabilitation. For universities and clinics this may be more cost-effective than purchasing several specialized robots. Robotic arms also have a human-like morphology, which may make the robot less alien to patients (e.g. by resembling a therapist holding onto a patient's leg). Finally, using an off-the-shelf robotic arm would allow researchers to focus on improving robot control algorithms for greater success in gait rehabilitation.

Using a multipurpose robotic arm for gait rehabilitation holds promise, but several challenges must be overcome. First, there must be a way to attach the robot arm to a human limb, preferably one that takes a minimum amount of time. Second, there should also be a mechanism to automatically and instantaneously detach the robotic arm if a patient stumbles. Finally, the robotic arm should be transparent, i.e. it should be able to follow a moving subject and not interfere with their nominal gait.

This paper first presents a mechanical interface that allows for a safe connection between a robotic arm and a human limb. Next, the ability of a robotic arm to follow the leg of healthy subjects walking on a treadmill is evaluated, and the potential for gait rehabilitation assessed.

II. ROBOT-HUMAN INTERFACE

A. Mechanism Overview

A mechanism was developed that allows a robotic arm to be attached to the human body in a quick and safe manner. The mechanism consisted of two parts: one that attached to the robot and another to the human body. The *robot attachment* included a ball joint to increase mobility and a rare-earth magnet for attachment/detachment. The *human attachment* consisted of a limb brace with a receptacle for the robot attachment. Both attachments, which coupled a Whole-Arm Manipulandum (WAM, Barrett Technology, Inc., Newton MA, USA) to a human leg, are shown in Figure 1.

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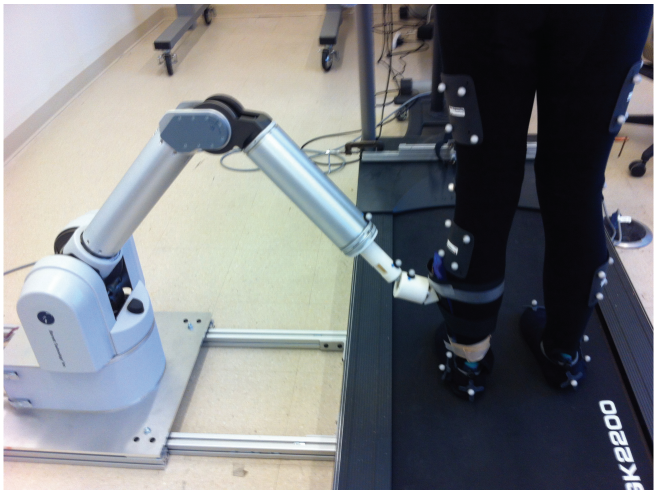
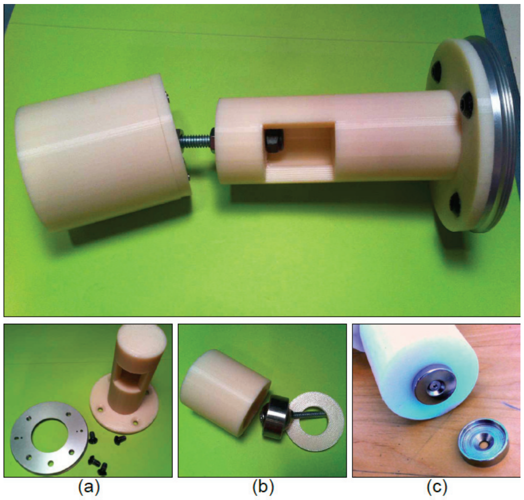


Figure 1.Robot attached to the lower leg.

B. Robot Attachment

A one-piece plastic base cylinder was made with a 3D printer (U-Print SE Plus, Stratasys, Eden Prairie, MN, USA) and attached to the WAM tool plate (Figure 2A). A second plastic cylinder that housed a ball joint was attached to the base cylinder with a screw (Figure 2B). The ball joint was added because the four degree-of-freedom WAM could not follow the leg of a person walking on a treadmill without reaching a range-of-motion limit. Although a powered "wrist" could be added, using a ball joint was a simpler and sufficient solution. The ball joint had a zinc-plated steel housing with a nickel-plated steel ball and oil-impregnated bronze insert; the maximum swivel angle was 42° (Part 4786T7; McMaster-Carr, Princeton, NJ USA).



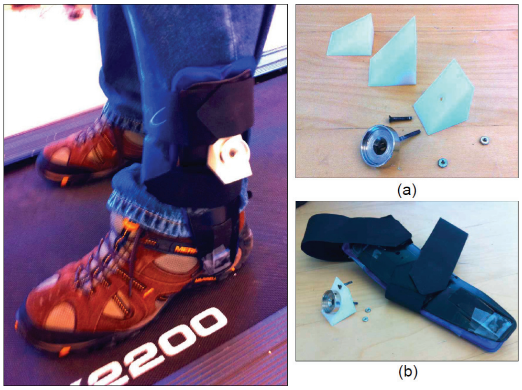
(a) (b) (c)

Figure 2. Robot attachment with details of mechanism pieces: (a) plastic base cylinder, (b) ball joint and socket, (c) rare-earth magnet.

A rare-earth magnet was attached to the end of the plastic cylinder to connect the robot to the human (Figure 2C). Trial-and-error was used to select a magnet strong enough to stay attached during normal activities, but would also detach if the robot and/or subject behaved abnormally. A neodymium ring magnet (RX033CS-S; K&J Magnetic Inc.) was used with an axial pulling force of 20.51 lbs (single magnet vs. steel plate).

C. Human Attachment

The human attachment consisted of a standard air/gel ankle brace (Figure 3B; DeRoyal Industries, Powell, TN), a 3D-printed plastic plate, and a steel cup (Figure 3A). The plate was screwed on the brace, on which a cup was attached to receive the magnet. This plate was angled to be in line with the WAM to reduce the angle between the WAM and the ball-joint.



(a)

(b)

Figure 3. Human attachment with mounting datails: (a) socket for magnetic attachment and plastic plate for different mounting angles, (b) ankle brace.

III. EVALUATION OF ROBOT-HUMAN INTERFACE

A. Robot Control

For gait rehabilitation with a robotic arm it is not only important to have a suitable attachment mechanism, the robot should also be able to follow a patient without imposing unwanted forces, i.e. the robot should be transparent. The WAM uses low friction cable drives that allow the mass of the motors to be located away from the end-effector, keeping inertia (and friction) low. This makes the WAM relatively transparent; however, the degree of transparency for gait rehabilitation applications is unknown: would a person be able to walk "normally" with the WAM attached to their leg? To answer this question the WAM's transparency was evaluated under two gait conditions: 1) with the WAM's nominal operation mode, which controls the motor currents, and 2) with a control scheme that also actively compensates for robot-human interaction forces. In this study the former is called *standard control*, and the latter, *force control*.

Standard Control: In this control scheme the WAM controller commands a particular current to each motor to compensate for gravitational forces. When an external force is applied to one or more of the WAM linkages by a human, it turns the WAM motors and therefore the current within the motors changes, which generates torques that resist motion. However, when this occurs, the WAM controller immediately adjusts the motor currents to maintain the commanded currents. This way, to move the robot a human operator needs to only overcome relatively low inertial and frictional forces, and does not need to exert additional force to move the motors. The net effect of this control scheme is that the WAM will maintain a position in space, yet can be easily moved by application of external forces.

Force Control: The inclusion of a three-axis force and torque sensor on the WAM end-effector allows force control to be implemented. This was achieved by using the manufacturer-supplied Libbarrett C++ library to operate the WAM with a Jacobian transpose controller [7]. Given an external force F at the end-effector in Cartesian space and the Jacobian for a joint configuration, the robot joint torques τ are calculated as

$$\tau = J(q)^T kF$$

where $J(q)^T$ is the Jacobian transpose, q are the joint angles, and k is a proportional gain ($k = 1.6$). The torques are applied to the motors such that the end effector moves in the direction of the external force. This reduces robot-human interaction forces. The magnitude of τ is regulated by k; increasing k makes the robot follow the external force more aggressively. However, if the gain is too high instability may result.

B. Subjects

The ability of the WAM to follow the leg of two healthy subjects walking on a treadmill was evaluated. The subjects signed an informed consent document approved by the Northeastern University Institutional Review Board.

C. Experimental Setup

Subjects walked on a motorized treadmill (GK2200, Mobility Research, Tempe, AZ). Lower extremity motion was captured using an optical motion capture system (Oqus 300; Qualysis, Gothenburg, Sweden). Reflective markers were placed on both the legs and pelvis following the standard Visual 3D convention (C-Motion, Germantown, MD).

D. Protocol

There were three evaluation conditions: 1) no robot, 2) robot with *standard control,* 3) robot with added *force control*. Each condition was performed for one minute at 1 and 2 mph. The faster speed was close to the subjects' preferred walking speed; the slower speed was chosen because patients often walk at a slower speed. The WAM was attached to a point midway between the left lateral malleolus and left lateral femoral epicondyle, i.e. mid-shank (Figure 1).

E. Data Reduction and Analysis

The motion of the left ankle was used to characterize the influence of the robot on subjects' gait and assess transparency. To account for potential drifting of the subject on the treadmill, the anterior-poster and medial-lateral left ankle (lateral malleolus marker) positions were referenced to the left hip (iliac crest marker). The approximate time of heel-strike was identified as local minimums in the vertical displacement of the heel (heel marker). Using the heel-strike event, the ankle kinematics were segmented into individual gait cycles. Linear interpolation was used to determine the ankle position at integer percentages of the gait cycle (0-100%). For each of the experimental conditions, the cycles were averaged and 95% confidence intervals (across cycles) calculated. The velocity of the ankle was calculated by differentiating the position data with respect to time using the central difference method, and this data was segmented and averaged in the same way as the position data. The velocity calculation used a smoothed version of the position data, smoothed with a Savitzky-Golay FIR filter (polynomial order of 4 and frame size of 21). The toe-off event was identified by finding local minimums in the toe marker anterior-posterior position data, which represent the time at which the foot transitions from moving backwards on the treadmill belt into swing. Swing time was calculated as the time between toe-off to the subsequent heel strike (of the same limb) and was expressed as a percentage of the gait cycle.

IV. RESULTS

The goal of the analysis was to evaluate the transparency of the WAM for gait rehabilitation. The ankle position and velocity are shown for Subject 1 in Figure 4. The no-robot (green line), robot with standard control (blue), and robot with force control (red) data are shown for the slow walking speed. The locomotor pattern of Subject 1 with the robot operating under both the standard and force control schemes was similar to their gait without the robot. The force control scheme provided a slightly better match during late-swing.

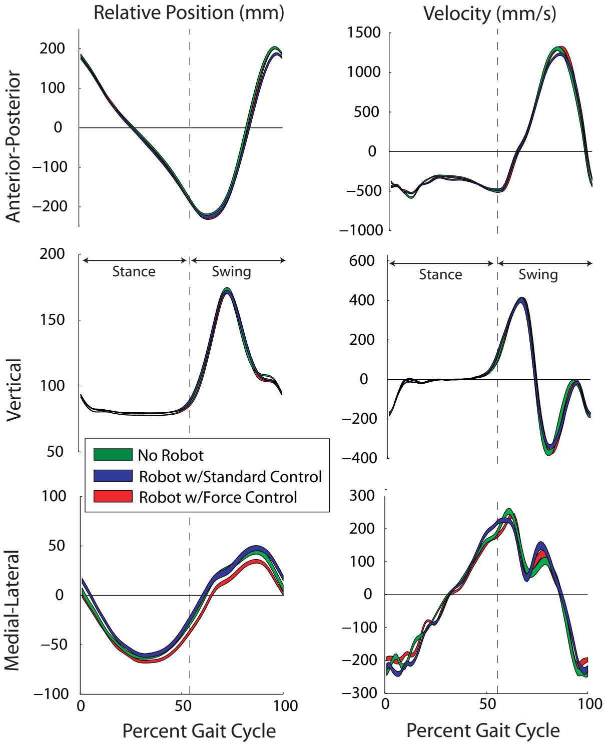


Figure 4. Kinematics of the left ankle under each of the experimental conditions. The anterior-posterior and medial-lateral ankle positions are relative to a point on the pelvis (iliac crest). Shading indicates the confidence interval (calculated across cycles).

For a different perspective, the average two-dimensional ankle kinematics for both subjects is shown in Figure 5 for the different robot control schemes and fast and slow walking. As shown in Figure 4, for Subject 1 there were only small differences between the no robot condition and those with the robot for slow walking; however, there were larger differences for fast walking (Figure 5; lower-left panel). In the latter case, the heel tended to lift off slightly earlier in the gait cycle with the robot, and as the leg swung through the leg appeared to drag, such that the ankle was behind its position without the robot. This is supported by the analysis of the average leg swing times, which became longer with the robot (Subject 1; fast walking condition; Figure 6).

For the other subject, Subject 2, there was good correspondence between the no-robot and with-robot conditions for *both* slow and fast walking (Figure 5). The only noticeable difference was a longer swing time for slow walking with the robot under standard control (Figure 6).

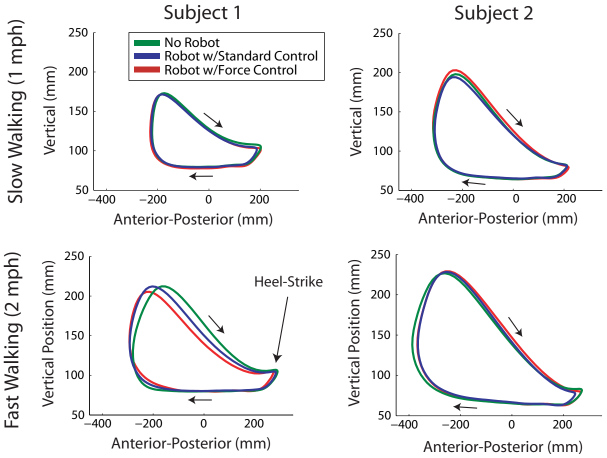


Figure 5. Average two-dimensional ankle kinematics for two subjects with and without the robot for fast and slow walking speeds.

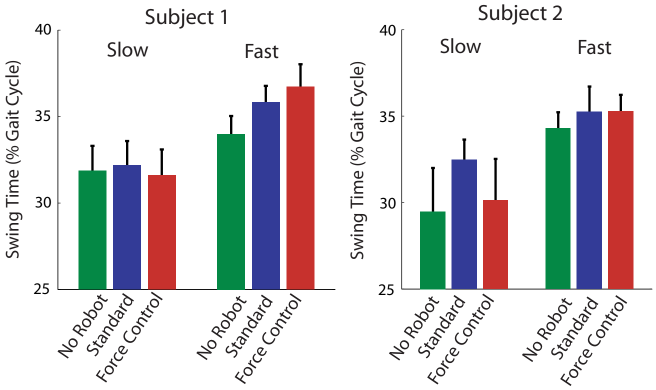


Figure 6. Average leg swing time for each of the experimental conditions. Error bars show one standard deviation across gait cycles.

V. DISCUSSION

The results show the feasibility of adapting a robotic arm for gait rehabilitation. A robot-human interface was developed, which allowed a firm mechanical connection between the robot and a human limb, yet also permitted freedom of movement for the human relative to the robot. A magnetic coupling allowed for fast attachment, as well as quick detachment in the event of an anomaly or malfunction in the robot or human controllers.

The WAM, a commercially available multipurpose robotic arm, was used as the robotic platform. The robot-human interface performed well. Once a subject was ready on the treadmill, it took only seconds for the experimenter to securely attach the robot to the subject's leg, and the robot remained attached throughout the trial. Although only a single attachment site was used on the leg, it would be straightforward to use the same attachment system on a different body location, such as the upper leg or pelvis.

The standard WAM controller allowed the robot to act in a transparent manner, such that it could follow a human's leg while walking on a treadmill. Transparency was acceptable for both test subjects during slow walking (1 mph). This is important because many patients tend to walk with a slower speed. When the walking speed was increased (2 mph) the effectiveness of the robot control algorithms became subject-dependent. In one subject the robot was able to keep up with the leg (Subject 2), but in another subject it appeared that the robot slightly dragged the leg (Subject 1).

It was expected that adding an additional layer of force-based compensation to the control scheme would improve the robot transparency. This is because the standard WAM controller does not compensate for friction and inertia. When the leg lifts from the treadmill and accelerates into swing, there will be an inertial force from the robot. Under force control, this force would be detected and the robot will try to move in the direction of the force, which should ultimately reduce the force felt by the subject. Contrary to this expectation, for Subject 1 during fast walking, the force-based control seemed to drag the leg more than the standard control scheme. At this time the cause of this effect is unclear; it was not due to higher leg velocities – the peak ankle velocity was similar for both subjects in fast walking.

Although these results are promising, they are based on a limited sample of healthy adults. Further experimentation is needed, particularly on patient populations. Also, the robotic interface was attached to only one leg. However, there is no reason to expect that the transparency would be significantly different if a robotic arm was attached to each leg. Nevertheless, a one-sided robotic interface would be suitable for some patient populations, such as those with chronic stroke, who primarily have unilateral deficits.

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