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# Design of a Gait Training device for control of pelvic obliquity

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*Abstract* - **This paper presents the design and testing of a novel device for the control of pelvic obliquity during gait. The device, called the Robotic Gait Rehabilitation (RGR) Trainer, consists of a single actuator system designed to target secondary gait deviations, such as hip-hiking, affecting the movement of the pelvis. Secondary gait deviations affecting the pelvis are generated in response to primary gait deviations (e.g. limited knee flexion during the swing phase) in stroke survivors and contribute to the overall asymmetrical gait pattern often observed in these patients. The proposed device generates a force field able to affect the obliquity of the pelvis (i.e. the rotation of the pelvis around the anteroposterior axis) by using an impedance controlled single linear actuator acting on a hip orthosis. Tests showed that the RGR Trainer is able to induce changes in pelvic obliquity trajectories (hip-hiking) in healthy subjects. These results suggest that the RGR Trainer is suitable to test the hypothesis that has motivated our efforts toward developing the system, namely that addressing both primary and secondary gait deviations during robotic-assisted gait training may help promote a physiologically-sound gait behavior more effectively than when only primary deviations are addressed.**

*Index Terms*—**Rehabilitation Robotics, Impedance Control**

## I. INTRODUCTION

GAIT rehabilitation is a field that has been gaining increased attention from the research community in the past few decades [1][2]. In fact, the increased life expectancy observed around the world has brought to light the importance of maintaining an acceptable quality of life at an affordable cost to individuals and national healthcare providers. In this perspective, independent gait, especially in elderly people, is of crucial importance [3]. Among the disabilities that can affect mobility, stroke-caused hemiplegia is certainly one of the most important. In the US alone, there are approximately 6.5 million stroke survivors and about 800,000 new cases every year [4]. A significant portion of stroke survivors experience impairments that affect their ability to move and to ambulate freely and a great part of them maintain impaired motor behavior after the rehabilitation therapy [5]. Hemiplegia leads to asymmetrical gait patterns in stroke survivors [6], due to primary gait deviations such as knee hyperextension during stance and stiff-legged gait (defined as limited knee flexion during swing). The primary gait deviations lead, over time, to the development of compensatory motor behaviors. These deviations often affect the control of the pelvis [2]. Hip hiking [2] – an exaggerated elevation of the pelvis on the hemiparetic side – is one of the most common compensatory motor behaviors and is a direct consequence of the need for compensating for the decreased knee flexion exhibited by many stroke survivors. Gait rehabilitation for stroke survivors is mainly focused on the improvement of the ambulatory functions of the patients, as a means for increasing their quality of life. In the past two decades, the idea of improving gait through the restoration of physiological walking patterns has gained increasing attention, and has led to the development of novel therapies such as weight supported treadmill-based therapy [7] and robotic therapy [8].

Many robotic devices for gait rehabilitation have been developed so far, such as the Lokomat [9], which is able to allow high intensity gait training and to effectively track the outcomes of the therapy. This FDA registered device is able to control the movements of the hip and knee joints, promoting patterns consistent with physiological movement. Nevertheless this device restricts translational and rotational movements of the pelvis. This configuration does not allow distinct approaches for addressing secondary gait deviations of the pelvis. The LOPES [10] overcomes this limitation by allowing translation of the pelvis, while constraining rotation. Another interesting system is the PAM/POGO [11] that allows full control of 3 translations and 2 rotations of the pelvis through pneumatic actuators. Authors report on applying a force field around pelvic obliquity of 200N-m/rad (3.5 N-m/deg) which is rather low in light of our findings presented here. This robotic device may be not ideal due to its complexity relative to similar devices and to the difficulty to synchronize the control of the actuation of such number of degrees of freedom (DoFs). From a clinical point of view, given the gait deviations affecting the pelvis, it is of interest to control at least some of the DoFs of the pelvis, such as pelvic obliquity (rotation about the anteroposterior axis that

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is mainly affected during hip-hiking). In this paper, we present a device, called Robotic Gait Rehabilitation (RGR) Trainer [12], specifically designed for the control of pelvic obliquity during gait training. The rationale for this device is to actively modify pelvic obliquity by applying forces on the pelvis itself to facilitate rotations around the anterioposterior axis while the remaining DoFs of the pelvis and the legs are left free. This machine could be used to operate on gait abnormalities affecting the pelvis such as hip-hiking. This approach is based on the hypothesis that by addressing both primary and secondary gait deviations one would maximize the outcomes of robotic-assisted gait training.

In this paper, we provide a description of the device and of its control mechanisms. Then, results obtained testing the device on healthy subjects are presented and discussed. These tests were focused on characterizing the device itself and its ability to modify pelvic obliquity during gait training.

## II. MATERIALS AND METHODS

### A. Overall Design of the RGR Training Machine

The system consists of two components (Figure 1):

- A stationary frame that supports the actuation system (a servo-tube linear electromagnetic actuator fixed on the left side of the frame) and a linear potentiometer for calculation of pelvic obliquity (on the right side); the system was configured to actuate the left side of the body.
- A brace system for the pelvis and the leg that is attached to the stationary frame. This part acts as an exoskeleton whose main use is to reliably transfer the force applied by the actuator at the pelvis (through a spherical joint) to the rest of the lower limb.

The braces are completely adjustable in order to allow a natural walking behavior from the subject. This system has been designed to be used while the patient is walking on a standard treadmill. Measurement instrumentation, such as a load cell for evaluating interaction forces during actuator's activity, and potentiometers for pelvis and knee position feedback have also been included in the design of the system. These sensors are either used in the control scheme of the device or for evaluation of the training and functioning outcomes afterwards. The position feedback from the actuator and the linear potentiometer are used to calculate the angular position of the brace in the frontal plane thus the obliquity of the pelvis of the subject. The obliquity angle $\theta$ of the brace is computed using the two linear position signals (the one from the actuator and the one from the potentiometer on the other side).

The subjects have a free range of motion of 14 cm for the pelvis in the vertical direction, and the actuator is gravity compensated in order to minimize interaction forces between the subject and the system. The movement in the horizontal plane is left free in order to allow subjects to walk with their natural gait pattern.

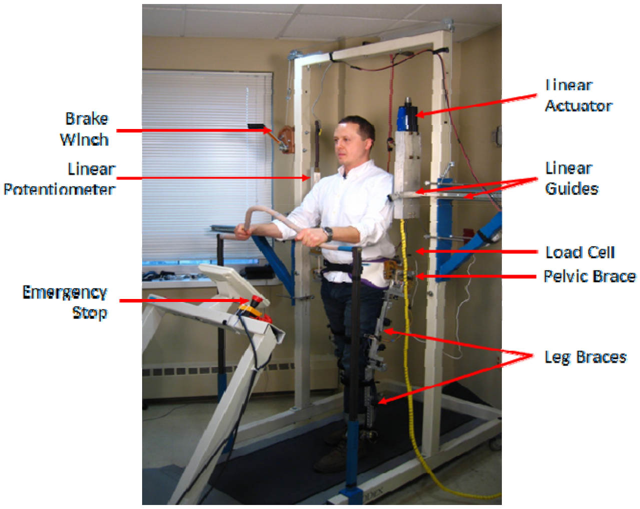

Figure 1. The RGR device with the main components highlighted

### B. Control System

The force field production is controlled by means of an impedance controller consisting of an inner force feedback loop and an outer position feedback loop. The design is based on that of the controller originally proposed by Hogan [13]. The force command $F_{act}$ sent to the actuator is calculated as in equation (1) in the linear motion case:

$$F_{act} = (G+1)[K_c(x_0 - x) + B_c(\dot{x}_0 - \dot{x})] - (G)F_{ext} \quad (1)$$

where $x$ is the actual position of the endpoint, $x_0$ is the current position in the reference trajectory, the gains $K_c$ and $B_c$ represent the virtual spring stiffness and virtual damping at the actuator's endpoint, $G$ is the proportional loop gain and $F_{ext}$ is the force measured by the load cell at the endpoint of the actuator. The gain $G$ was tuned experimentally during bench testing and $G = 0.7$ has been used in human subject tests. The value for $K_c$ represents the proportional gain and is chosen according to the desired strength of the force-field that drives the subject to the desired trajectory. The value for $B_c$ is determined from equation (2) as proposed by Lawrence [14] such that a damping ratio $\zeta$ of 0.3 is achieved.

$$B_c = 2\zeta\sqrt{m_{act} * K_c} \quad (2)$$

where $m_{act}$ represents the mass of the actuator. Our implementation of the control law described by equation (1) is for rotational motion, with gain $K_c$ specified in terms of N-m/deg. A detailed description of the device and the control system as well as its characterization have been previously presented by Pietrusinski et al [12].

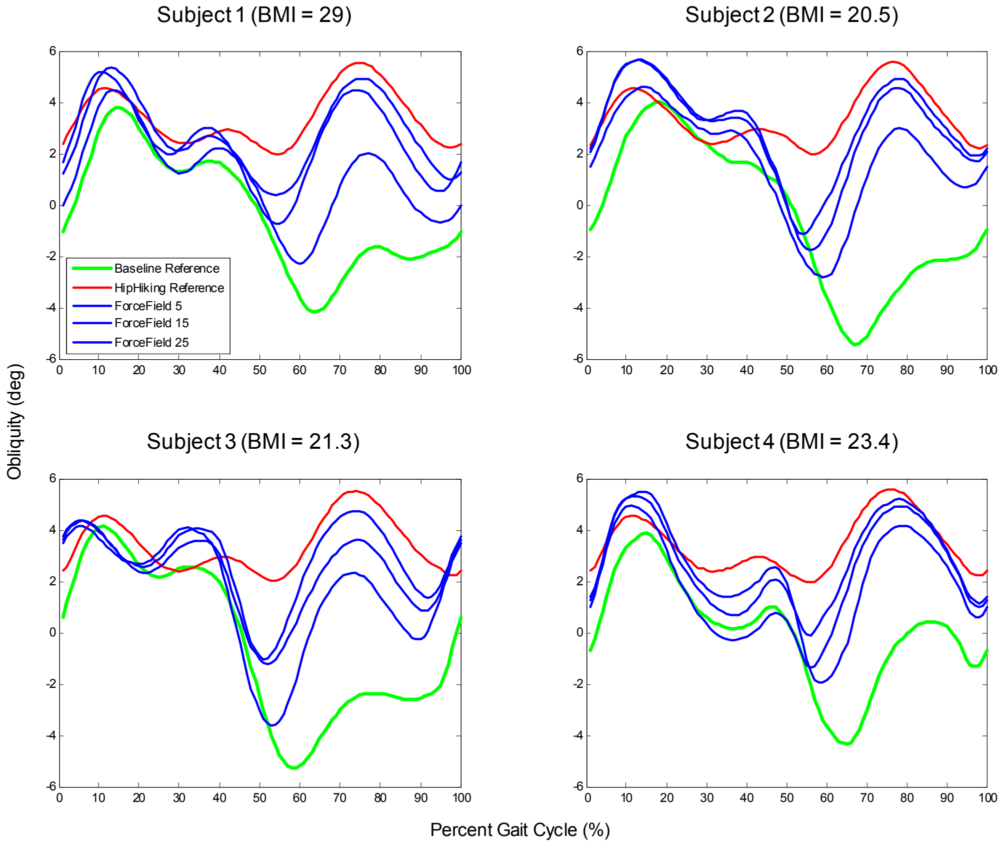

Figure 2. Results for the four healthy subjects during the induced hip-hiking tests. Green line represents their baseline obliquity trajectory during gait cycle, the red line represents the target hip-hiking trajectory and the three blue lines (solid, dashed and dash-dotted) represent the achieved trajectories at different level of force field. Force field control is active during left leg swing phase (50-100%)

In order to allow subjects to ambulate freely within the device it was necessary to allow the device to track the subjects' current position along their gait cycle. For this the Aoyagi synchronization algorithm with 8 lookup tables (position and velocity for hip and knee bilaterally) [11] was used for the estimation of the temporal position with respect of the subject's gait cycle using hip and knee angular positions and velocities. The controller drives the actuator in two different modalities:

- Zero force control, which is active during the stance phase and right leg swing, during which the RGR trainer is back-driven with limited interaction forces (lower than 8N). In this modality, the system is transparent and compensates for its weight.
- Force field control, which is active during left leg swing and applies forces in response to position error. In this modality, the system applies a force depending on the desired obliquity trajectory.

The transition of the actuated command between these two phases is smoothed by means of a sigmoid function in order to avoid abrupt force exertion from the actuator. The controller was implemented using LabVIEW Real-Time (National Instruments Inc). All data are sampled at 2 kHz, while the control loop operates at 500 Hz.

## III. TESTING

Testing with this device has been focused on investigating if the RGR trainer is able to modify pelvic obliquity during the swing phase. In order to do so, we developed a protocol on healthy subjects (4 males, ages 24-31, mean BMI 23.6). We decided to test the device's ability to modify pelvic obliquity by investigating its effectiveness in inducing hip-hiking in healthy subjects. In order to do so, the high back-drivability characteristic of the device was used to record "simulated" hip-hiking pelvic trajectories from 8 subjects. The subjects were strapped into the device and were asked to walk at their comfortable walking speed (around 3 km/h). After a familiarization period, the subjects were asked to simulate a hip-hiking behavior, by raising their pelvis during the swing phase of the gait cycle. A visual feedback based on the obliquity of the pelvis, together with a target obliquity trajectory marked by a 6 degree obliquity in excess to normative data (that is in line with values observed in hip-hiking stroke survivors [2]), was presented in order achieve the hip-hiking behavior. Pelvic obliquity trajectories were then recorded and a mean (over 100 steps) hip-hiking reference (Hip-Hiking Reference in Figure 2) trajectory was derived as the mean across subjects. The second part of testing investigated if the device was able to force the pelvic obliquity of 4 healthy subjects towards the target Hip-Hiking Reference trajectory. Three different levels of force-field strength (5, 15 and 25 N-m/deg in randomized order) were used. The levels of the force field were achieved through adjusting the proportional gain $K_c$. Subjects had a comfortable walking of approximately 3 km/h. For each force-field level, after a brief familiarization period, the system provided 100 steps of force-fields control (training)

## IV. RESULTS

The results reported in Figure 2 show that the RGR Trainer is able to guide pelvic obliquity towards a given trajectory (that in this case is the hip-hiking trajectory), with the peak obliquity angle that increases with the strength of the force field. In fact, visual inspection suggested that the peak obliquity during swing (that occurred around 75% of the gait cycle) had a tendency to increase in all subjects with force field levels of 15 and 25 N-m/deg, with the greater increase observed for subject 1 (top left plot) that is the one with the highest body mass index (BMI). A substantially smaller increase was instead visible for subjects 3 and 4 when observing the results for force field levels of 15 and 25 N-m/deg. This result suggests the existence of a subject-specific level of force field able to provide the necessary guidance (both in terms of active assistance and haptic feedback) for achieving the desired pelvic trajectory. This observation may be corroborated by the fact that the subject with the biggest difference in peak obliquity between the 15 and 25 N-m/deg force field levels is the one showing the second lowest BMI in the subject pool.

## V. CONCLUSIONS

This paper describes the design and testing results for the RGR Trainer device. This system, using one actuator acting on the rotation about the anterioposterior axis of the pelvis, generates sufficient force to induce gait patterns characterized by exaggerated pelvic obliquity in healthy subjects. The device intended use in clinical rehabilitation gait training on hip-hiking subjects although would be based on inducing pelvic drop during swing phase through a downward pushing force. A device like the one presented in this paper may represent an interesting solution in robotic training of gait disabilities, with a particular attention to abnormal motor patterns of the pelvis. In fact, compared to other devices for gait training [9] [10] [11], the single actuator-based design herein proposed allows a reliable control about the anterioposterior rotation of the pelvis while allowing physiologically natural motion in all the other DoFs of the pelvis. On the other hand in this system the control is only applied to one DoF of the pelvis. This device could although be used together with a device for the control of the knee to address secondary gait deviations such as hip-hiking in stroke survivors, under the hypothesis that acting on both primary and secondary gait deviations during the rehabilitative therapy may lead to improved outcomes in terms of regained gait ability, restoration of physiological walking patterns, and retention of motor gains.

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