

On the Control of the MIT-Skywalker

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Abstract—Walking impairments are a common sequela of neurological injury, severely affecting the quality of life of both adults and children. Gait therapy is the traditional approach to ameliorate the problem by re-training the nervous system and there have been some attempts to mechanize such approach. In this paper, we present a novel device to deliver gait therapy, which, in contrast to previous approaches, takes advantage of the concept of passive walkers and the natural dynamics of the lower extremity in order to deliver more “ecological” therapy. We also discuss the closed-loop control scheme, which enables safe and efficient operation of the device, and present the initial feasibility tests with unimpaired subjects.

I. INTRODUCTION

Every 40 seconds, someone in the United States has a stroke [1]. For every 1,000 children born in the US, 2.8 youngsters have cerebral palsy [2]. The impact of these and other neurological conditions on walking is significant and locomotor capacity is a critical factor in determining an individual’s degree of disability. Physical therapy is the standard of care to educate the individual on how to ameliorate or regain walking abilities. We introduced a paradigm shift in 1989 when we started the development of the MIT-Manus [3]. The goal was to provide robotic tools to facilitate and increase the productivity of clinicians while optimizing the potential for patients to recover.

Yet, to employ mechanical devices to deliver therapy is not a new idea with the most common device now used in gait therapy being the treadmill. Treadmill training offers task-oriented repetitive movements that can improve strength, aerobic capacity, and movement coordination [4]. Body weight support treadmill training (BWSTT) has been shown to improve gait function in patients with locomotor disorders [5], [6]. Weight-supported treadmill training for hemiparetic patients has been shown to improve balance, lower-limb motor recovery, walking speed, endurance, and other important gait characteristics, such as symmetry and stride length [6]; currently, there is a large NIH sponsored randomized clinical trial (RCT) study (www.leaps.usc.edu; Principal Investigator: Pamela Duncan).

However, BWSTT requires a therapist to monitor and manipulate the pelvis in addition to one or two therapists needed to propel the leg(s) forward. Robotic devices were built in an attempt to automate the therapy process further.

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While several robotic devices already exist (e.g., to manipulate the ankle, MIT’s Anklebot; to provide smart body weight support, KineAssist, Zero-G; to manipulate the pelvis, UC Irvine’s Pam and Pogo, MIT-Pelvis robot; to manipulate the foot, Gait Trainer I, Haptic Walker, G.E.O; to manipulate the knee and hip, Lokomat, Lopes, Motorika/Healthsouth Autoambulator), presently only two devices have been used extensively during therapy on more than 20 patients with published clinical outcomes, namely the Gait Trainer I and the Lokomat. Gait Trainer I is an end-effector based robot with quick set-up time, incorporating both an adjustable Body Weight Support (BWS) and sliding foot plates that are secured to the patient’s feet [7]. While it minimizes the number of therapists to only one needed to manipulate the knee, the planar sliding motion reproduces the kinematic but it does not reproduce heel-strike. The Gait Trainer I was tested in a large multi-site RCT, DEGAS study, with positive results. The Lokomat system is an exoskeletal device. It includes a treadmill, an active BWS (newest generation), and a robotic orthosis with four degrees of freedom, actuating left and right knee and hip joints [8]. This device attempts to replicate the kinematics of an unimpaired subject, but it does not incorporate any means to promote weight shifting from one leg to the other and also forces the ankle to be always in a dorsiflexed position. Although there were some positive pilot results using the Lokomat [9], recent studies found that Lokomat training had no advantage compared to conventional therapy [10], [11]. Because of the much higher intensity of training in the Lokomat group, we interpreted this result as an indication that the kinematic experience might not be affording the proper neurological stimulus. More recently ETH Zurich initiated pilot testing on an improved version of their software that affords a more interactive experience [12].

We have recently completed the alpha-prototype of the MIT-Skywalker. This novel rehabilitation robot is unique and distinct from other existing rehabilitation robotic devices for gait. It delivers safe and efficacious gait therapy inspired by the concept of passive walkers [13]. The MIT-Skywalker creates the required ground clearance for swing while exploiting gravity to assist during leg propulsion. Preliminary tests with a mannequin and unimpaired subjects, demonstrated its ability to allow gait therapy without restricting the movement to a rigid kinematic profile, providing ecological heel-strike and hip-extension and maximizing patient participation during therapy. Since the working principle is based on the dynamics of the leg, it doesn’t require any mechanism attached on the patient’s leg and, therefore, minimizes significantly the time for do-on and -off.

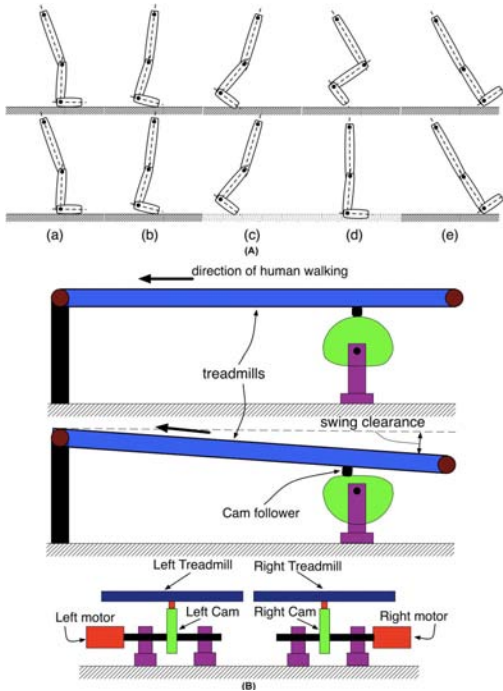


Fig. 1. (A) Gait phases for walking on a flat surface (top row) and a surface that drops between toe-off (c) and heel strike (e) (bottom row). (B) Side and front views of the cam systems actuating the two treadmills.

II. DESCRIPTION AND CONTROL OF THE MIT-SKYWALKER

A. Hardware Concept

In conventional gait physiotherapy, the therapist pushes or slides the patient's swing leg forward, either on the ground or on a treadmill. In clinic-tested robot-assisted gait therapy, the leg is propelled by either the robot orthosis acting on the patient's leg (Lokomat) or foot plates attached on the patient's foot (in Gait Trainer I). Instead of lifting the patient's leg manually or mechanically, we achieve forward propulsion in the MIT-Skywalker by lowering the walking surface. This provides both swing clearance and takes advantage of dynamics and gravity to propel the leg forward while allowing proper neural inputs for hip extension and ecological heel strike. Figure 1 illustrates those phases.

Our alpha-prototype was built in order to accommodate patients in the range of the 99th percentile adult male and the 1st percentile adult female. Moreover, the MIT-Skywalker must provide a stable walking surface that is parallel to the ground, allows adequate clearance for the patient's leg to swing without knee flexion, and also allows return to the horizontal plane in time for the heel strike of the next stride, as shown in Fig. 1A. The walking surface for each leg is a treadmill, which stays horizontal during the stance phase and may be lowered to provide swing clearance to the impaired leg. The alpha-prototype includes a split treadmill system and a cam to lower the tracks. The cam system lowers each treadmill to a constant angle as depicted in Fig. 1B. We opted to lower the treadmill to a fixed angle for design simplicity as it will afford employing cheaper motors in a

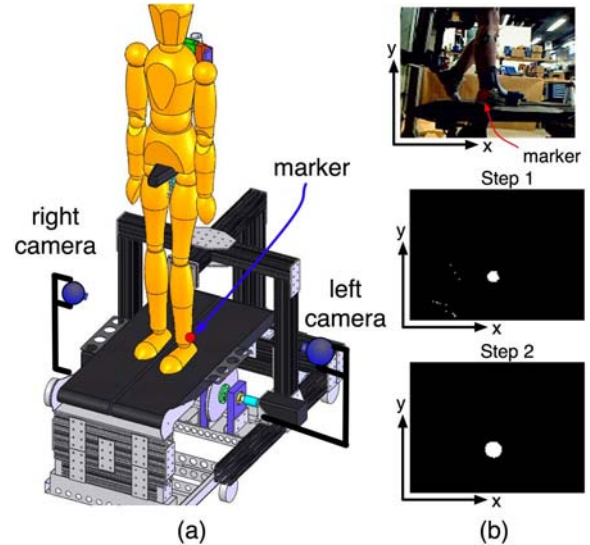


Fig. 2. a) The MIT-Skywalker platform equipped with two cameras on the sides to monitor the position of the red markers placed on the user's heels. b) Top: The captured frame from the right camera where the red marker is shown. Step 1 & 2: Successive steps of the image processing used to detect the marker position on the camera frame. White image regions correspond to the selected pixels belonging to the sets R and S respectively.

home version. In addition, the alpha-prototype includes a body-weight support system since many patients are not able to support their weight on the impaired leg(s) or they may need assistance maintaining balance. This system provides enough support to unload up to 100% of the patient's weight and keep the patient safe from falls, yet not interfere with the required ranges of leg motion. While kinematically-based devices employ overhead full-body harnesses, we designed a system to afford fast don-on and -off. It consists of a simple chest harness providing stabilization for the upper body and a saddle/bicycle-like seat for body-weight support [14]. The seat is mounted on a system of 4 springs of different stiffness values selected to position the pressure points on the subject's buttock and 2 rotation joints that allow both vertical motion (max. displ. 1 in) and roll and pitch rotation (max. rot. 5 deg).

B. Closed-loop Control

The control of the cam system is key in providing the required swing clearance for the patient's leg and ecological hip-extension and heel-strike. Although we can probe the state of the device, we required feedback of the patient's leg in order to control the treadmill speed and cam system.

We experimented with a simple, camera-based motion tracking technique. It provides both flexibility and safety for the patient, requiring no sensors mounted on the patient's leg except for a small, easy-to-place marker. The marker is red-colored, has the shape of a circle with an approximate radius of 20mm, and is placed on the heel (sides of the calcaneus bone). Low-cost cameras (Logitech Webcam Pro 900, Logitech Inc.) are placed at each side of the device. The range of motion of the heel in the sagittal plane during normal walking (approx. 130 cm in the horizontal axis and 50 cm in the vertical axis), along with the angle of view of

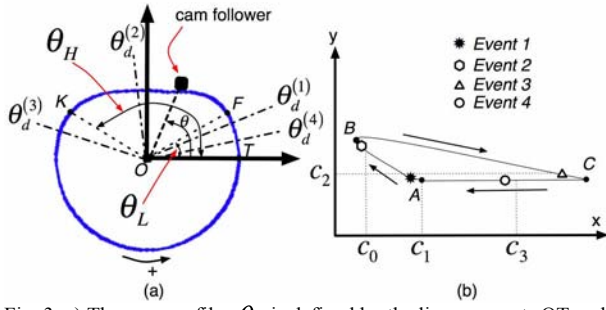


Fig. 3. a) The cam profile. θ_L is defined by the line segments OT and OF and is the angle that defines the starting point of the low dwell of the cam. θ_H is defined by the line segments OT and OK and is the angle that defines the final point of the low dwell of the cam. b) Path of the patient's heel on the image frame and events related to the heel coordinates. Path CA, AB and BC correspond to the stance, pre-swing and swing phases respectively.

the camera (approx. 60°), resulted in a camera positioning distance from the tracked marker of 110 cm. The camera provides high-resolution, colored images at the frequency of 30 Hz, which is adequate for the timing requirements of the control of the treadmill vertical motion during normal walking. The setup with the cameras and the markers is depicted in Fig. 2a.

1) *Marker Detection*: The image processing marker detection algorithm is based on the color and the size of the marker to be tracked (to differentiate from background movement in the clinic). Therefore, the pixels of the colored image that have high intensity in the red channel and low intensity in the green and blue channels of the colored image are initially detected¹ (Step 1 in Fig. 2b). Let R be the set of these red pixels. Then a subset S of R , $S \subseteq R$, is constructed by selecting the *red* pixels that have the most neighboring *red* pixels and we compare its radius to the marker (Step 2 in Fig. 2b). This step essentially filters the image containing the *red* pixels, so as to select only those belonging to the red marker. Finally, the position (c_x, c_y) of the marker on the image plane is given by:

$$c_x = \frac{\sum_{i=1}^n x_i}{n}, \quad c_y = \frac{\sum_{i=1}^n y_i}{n} \quad (1)$$

where x_i, y_i are the coordinates of each pixel i belonging to the set S and n the population of the set S . The image coordinate system is shown in Fig. 2b.

2) *Control phases*: In the following paragraphs, we describe the control architecture of the cam system while we report on the system monitoring and controlling only the patient's right leg; the architecture is equivalent for both legs.

a) *At the cam level*: Detecting the heel position in the sagittal plane can provide us with the information of the gait

phase and, therefore, accordingly decide about the control of the treadmill speed and vertical motion (cam system). More specifically, as noted before, the treadmill should remain parallel to the ground during the stance phase until the patient's foot is about to reach the toe-off phase. Then the treadmill should lower to allow the leg to swing forward and return to the horizontal plane in time for the heel strike. Let T be a point on the cam profile (chosen in a distance of α) degrees before the first follower point (fall-point F), encountered by rotating the cam counterclockwise as shown in Fig. 3a. Let K be the rise-point of the follower. Let θ_L be the angle defined by the line segments OT and OF, i.e. $\theta_L = \alpha > 0$, where O is the center of the cam. Accordingly, let θ_H be the angle defined by the line segments OT and OK. Let θ be the position of the cam at every time instance, defined in the range $[0, 2\pi)$, and formed by the line segment OT and the line segment connecting O with the point at which the cam touches the follower. In order to drive the cam appropriately, we first determine a subject-specific set of parameters for lowering or raising the treadmill according to the phase of gait the patient's leg is at; then, we should define four distinct control phases:

Phase 1: If the heel has left the ground and is moving with direction to the back, approaching the toe-off phase, i.e., moving along the AB path at Fig. 3b (terminal stance - pre-swing phase), the desired angle of the cam, θ_d , should be just before θ_L , i.e. $\theta_d^{(1)} = \theta_L - \varepsilon$, $\varepsilon \in \mathbb{R}^+$.

Phase 2: If initiation of the swing phase (toe-off) is desired, the desired angle of the cam should be between θ_L and θ_H in order to provide foot clearance, i.e., $\theta_d^{(2)} = \frac{\theta_L + \theta_H}{2}$. This angle is desired until heel-strike,

therefore as long as the heel is moving along the BC path shown in Fig. 3b (swing phase).

Phase 3: If the initiation of the stance phase is required (heel-strike), the angle of cam should be just after θ_H , i.e., $\theta_d^{(3)} = \theta_H + \delta$, $\delta \in \mathbb{R}^+$.

Phase 4: If the leg is moving with direction to the back, after heel strike and before heel-off, i.e., along the CA path at Fig. 3b (stance phase), the cam should rotate appropriately to be ready for the next swing phase; therefore a desired angle is defined as $\theta_d^{(4)}$, where $0 < \theta_d^{(4)} < \theta_d^{(1)}$.

From the cam specifications [15], it is $\theta_H - \theta_L = \frac{4\pi}{5}$.

According to this, we finally define the parameters above as $\varepsilon = \delta = \frac{\pi}{20}$ while $\alpha = \frac{\pi}{4}$. These values were chosen for

better performance and fast response of the treadmill positioning system with respect to events detected from the camera-based feedback system.

b) *At the image level*: The four phases at the cam level should be connected to corresponding phases or events at the image level, so that camera-based feedback will be used for the closed loop control of the treadmill positioning system. In Fig. 3b, the path of the marker on the image frame during

¹Typical threshold techniques are used, while the threshold values for each channel are chosen prior to the experiment. Contrast and brightness values for the camera sensors are appropriately adjusted to provide a more robust threshold value assignment, independent of the surrounding environment lighting conditions.¹

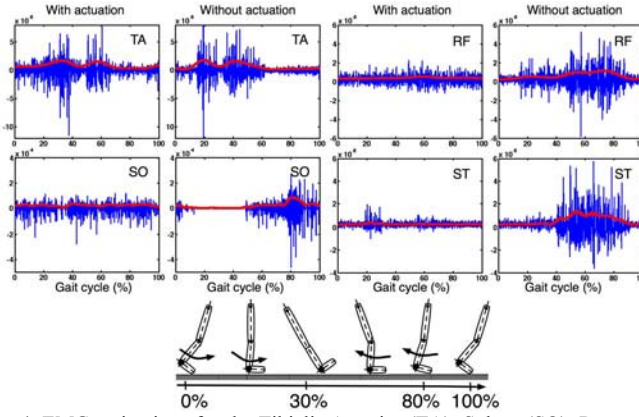


Fig. 4. EMG activations for the Tibialis Anterior (TA), Soleus (SO), Rectus Femoris (RF), and Semitendinosus (ST) for the actuated and non-actuated leg during one full gait cycle. Raw (blue thin line) and processed (red thick

the entire gait cycle is drawn. Using the previously mentioned events, we can define a closed-loop scheme in order to decide about the occurrence of the events that define the four phases for the cam control analyzed above. If (c_x, c_y) are the coordinates of the marker at the image frame, then we can define the events below as follows:

Event 1: Happens when $c_0 < c_x < c_1$ and $\dot{c}_y > 0$ where \dot{c}_y the time-derivative of c_y . It happens as soon as the leg is at the heel-off phase (terminal stance - pre-swing phase).

Event 2: Happens when $c_x \leq c_0$ and coincides with the toe-off and initiates the swing phase.

Event 3: Happens when $\dot{c}_x \geq \omega$ and $c_y \leq c_2$ and coincides with the heel-strike, terminating swing and initiating stance phase.

Event 4: Happens when $c_1 < c_x \leq c_3$ and $\dot{c}_x < 0$ and coincides with the mid-stance phase. \dot{c}_x is the time-derivative of c_x .

In the above equations, the parameters $c_0, c_1, c_2, c_3, \omega$ are tuned appropriately for each subject during the system calibration phase. The events and their relation to the path of the patient's heel during walking are shown in Fig. 3b.

3) *Control architecture:* Having the desired cam position at each time instance, a position controller is implemented to drive the cam. The control law used is given by:

$$u = k_p(\theta_d^{(i)} - \theta) - k_D\dot{\theta} \quad (2)$$

where u is the control variable, i.e., the torque applied at the cam axis, $\theta_d^{(i)}$ the desired cam angle defined by the *Phase i* where $i = 1, 2, 3, 4$, $\dot{\theta}$ is the cam angular speed and k_p, k_D are positive gains. The gains were selected based on the dynamic modeling of the cam driving system and requirements for system performance in terms of rising time and overshoot. The details of this modeling are out of the scope of this and thus omitted.

III. ALPHA-PROTOTYPE CLOSED-LOOP CONTROL TESTING

A. Experimental Protocol

Four (4) healthy young subjects (three males, one female) tested the closed-loop control of the MIT-Skywalker by walking on the device both with and without the closed-loop cam actuation. Electromyographic (EMG) signals were acquired from muscles of both legs, while the knee joint angles were also measured during training (Myomonitor IV, Delsys, Boston, MA: EMG and goniometers). We simulated a normal subject walking on a treadmill (treadmill in horizontal position) and the stroke patient scenario with the cam system being actuated under one leg and not under the other leg. Muscle activity and motion patterns were compared for the two cases. We employed an ankle brace to simulate the prevention of drop-foot and allow the treadmill to provide the necessary swing clearance. The experimental protocol was approved by the MIT Committee on the Use of the Humans as Experimental Subjects (COUHES) and all subjects gave informed consent.

Surface EMG signals were acquired from four (4) muscles from each leg of the subjects using a wireless EMG system. The four muscles recorded were:

- The tibialis anterior (TA) which is mainly activated when the foot is dorsiflexed at heel strike.
- The soleus (SO) which is mainly responsible for forward propulsion and is activated during plantar flexion before toe-off.
- The rectus femoris (RF) whose highest activation occurs at heel strike while it exhibits a biphasic pattern.
- The semitendinosus (ST) which is mainly activated during stance phase and exhibits a triphasic pattern, consisting of three peaks at heel-strike, mid-stance and during the swing phase.

The knee angle is measured through goniometers placed at each knee. Knee angle measurements and surface EMG signals are recorded simultaneously in order to distinguish muscle activation and relate it to the phases of gait.

B. System Evaluation

The subjects were instructed to walk normally with their left leg and to relax their right leg allowing the device to provide the necessary clearance for the swing phase and the ecological heel strike. Raw and processed² EMG activation of the muscles of the right and left legs for Subject 1 is shown in Fig. 4. The tibialis anterior activates before and during heel-strike in order to control landing and foot slap with no significant differences between the cam actuated and non-actuated cases. The soleus and rectus femoris were activated before toe-off to provide the necessary leg propulsion at the non-actuated cam case (unimpaired gait); however, they showed no significant activity at the actuated cam case. This demonstrates that subjects did not actually intervene and maintained the right leg relaxed while gravity

² Processed signal is computed through full-wave rectification and low-pass filtering of the raw signal.

and foot clearance provided by the cam system facilitated the leg's swing phase. One must be cautious and not misinterpret the lack of EMG activity in the soleus. It is important to stress that we will not instruct our patients to relax, but we will adjust the treadmill speed to continuously challenge the patient and that will require voluntary contraction of these muscles. Finally, the semitendinosus was activated mainly during the stance phase as expected. Similar behavior was observed in the other 3 subjects.

IV. CONCLUSIONS AND DISCUSSION

As robot-assisted gait therapy is increasingly gaining acceptance at rehabilitation centers, the MIT-Skywalker may prove to be the most effective and low-cost gait rehabilitation device. The fast do-on and -off alongside its dynamic principles and ecological intervention may place this novel device apart from the existing rehabilitation devices. The camera-based closed loop control facilitates the safe and efficient control of the device, making it capable of providing an effective and interactive gait therapy program, based on the real-time information of the patient's leg motion. Finally, the system affords future integration with our Anklebot [16] and pelvis robot (Elvis-the-Pelvis [14]), thereby allowing entire lower body training. One has to apply the appropriate caveats to this manuscript: until we can collect clinical data with patients and evaluate who might benefit and what the potential outcomes are, we cannot evaluate the device's actual impact in the field. To that end, we will be deploying the MIT-Skywalker to the VA Baltimore shortly.

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