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MIT-Skywalker: A Novel Gait Neurorehabilitation Robot for Stroke and Cerebral Palsy

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Abstract

The MIT-Skywalker is a novel robotic device developed for the rehabilitation or habilitation of gait and balance after a neurological injury. It represents an embodiment of the concept exhibited by passive walkers for rehabilitation training. Its novelty extends beyond the passive walker quintessence to the unparalleled versatility among lower extremity devices. For example, it affords the potential to implement a novel training approach built upon our working model of movement primitives based on submovements, oscillations, and mechanical impedances. This translates into three distinct training modes: discrete, rhythmic, and balance. The system offers freedom of motion that forces self-directed movement for each of the three modes. This paper will present the technical details of the robotic system as well as a feasibility study done with one adult with stroke and two adults with cerebral palsy. Results of the one-month feasibility study demonstrated that the device is safe and suggested the potential advantages of the three modular training modes that can be added or subtracted to tailor therapy to a particular patient's need. Each participant demonstrated improvement in common clinical and kinematic measurements that must be confirmed in larger randomized control clinical trials.

Index Terms

Rehabilitation Robotics; Gait; Walking; Stroke; Cerebral Palsy

I. Introduction

INJURIES to the central nervous system (CNS) such as stroke, cerebral palsy (CP), traumatic brain injury (TBI) and spinal cord injury (SCI) may result in major loss of motor control. Of these injuries, stroke is the most common, resulting in 795,000 new injuries every year in the United States alone and it is approximated that 77-80% of those will lead to motor function impairment [1][2]. Estimates show that 6.4 million stroke survivors reside in the United States [3]. CP is defined as injuries to the brain that occur prenatal or before two years of age that result in a movement abnormality. The prevalence is estimated at only 2-3 cases per 1000 births, but this number is expected to grow with the increase of survival rate among preterm babies. The United Cerebral Palsy Research and Educational Foundation estimates that 764,000 CP survivors reside in the United States [4].

Pharmacological interventions may offer future potential for neuro-protection and restoration, but presently the only way to ameliorate and reduce the consequences of a CNS injury is physical therapy delivered by clinicians and potentially augmented by robotic tools [5].

A. Rehabilitation Robotics for Stroke

For the upper extremity, robot-assisted therapy is a recommended treatment for stroke according to the American Heart Association, showing benefits that significantly outweigh risks [6]. As an example, the MIT-Manus, a robotic tool for upper extremity training, has been tested extensively in both the sub-acute and chronic phases of stroke and has shown significant motor control improvements that have long lasting effects [7][8][9]. The same cannot be said for lower extremity robotics.

In the same review that recommends upper extremity robotic therapy, the American Heart Association sees lower extremity (LE) robots as being “in their infancy” [6]. There are a multitude of devices for lower extremity including many treadmill-based devices [10][11][12]. Robotic devices can be classified into two types: exoskeletons [13][14][15] and end-effector robots [16][17][18][19]. Both of these forms have shown promise in small pilot studies [20][21][22][23] with the end-effector robots showing greater potential [24], and exoskeletons showing inferior results to manual gait therapy as practiced in the US in both sub-acute and chronic stroke populations [25][26]. This leaves the scientific community in the US to continue to question the efficacy of current robotic gait therapies.

These robotic systems were designed to replicate body-weight supported treadmill therapy (BWSTT), a method hypothesized to be the gold standard in gait neurorehabili-tation. It involves 2 or 3 therapists driving the patient's legs while shifting the patient's weight support. This purported gold standard was tested and contrary to its clinical proponents, disproved in the LEAPS trial, a 2011 Randomized Control Trial with over 400 stroke patients. The trial illuminated two tenets of rehabilitation: 1) a state-of-the-art locomotion program hinging on BWSTT is likely not the best form of gait rehabilitation therapy for stroke patients and 2) therapy can be equally effective if delivered during the chronic phase of stroke. The trial divided the enrolled participants into three groups. One group received the BWSTT locomotion program during the sub-acute phase of stroke (<6 months post-stroke), a second group received the BWSTT locomotion program during the chronic phase (>6 months post-stroke), and a third received a home-based “placebo” rehabilitation program in the sub-acute phase, focusing on “kitchen-and-sink” exercise that included stretching, strengthening, and balance, delivered in equal therapy time but never by practicing actual walking [27]. Overall, results demonstrated that 52% of all participants increased walking ability, but no significant differences were found between the groups in any of the primary outcomes including walking speed, balance, and quality of life [28]. This result begs significant soul-searching among researchers leading them back to the drawing board in order to develop a new approach to lower extremity neurorehabilitation [29].

II. Back to the Starting Gate: The MIT-Skywalker

The MIT-Skywalker is distinct from any of the existing rehabilitation robotic devices for gait. We previously have reported the overall concept [30][31] and the vision system [32]. Here we describe in detail the machine design, control algorithms and the safety and feasibility test with neurologically impaired individuals. In this section, we focus on our working model of a therapeutical approach for both upper and lower extremity therapy published in our prior work [30] and on the rehabilitation design assumptions which are uniquely realized by this system. Table I summarizes the evidence-based design assumptions and the novelty of the MIT-Skywalker system to accomplish them.

A. Evidence-Based Design Assumptions

A prior study of upper extremity stroke rehabilitation has shown that passively moving a paretic limb improves joint stability but does not alter the impairment of that limb, thereby having minimum impact on the neurorehabilitation [33]. Therefore, we assert that effective therapy must engage and force patients to attempt to perform all required movements. The hardware of the two major classes of gait rehabilitation robots (exoskeletons and foot plate robots) define a trajectory for the joint or end effector. This inherently violates the first design principle of self-directed movement. Every step differs slightly in length, profile, and timing, something that cannot be replicated in systems that impose trajectories. The MIT-Skywalker does not over-define the motion, assigning the patient complete control over the swing phase and trajectory. Further, the training algorithms (explained in III) rely on human-in-the-loop control via patient movements that removes the consistent timing constraint of the other rehabilitation robots.

Our second design principle embodies our working model of movement primitives that asserts the fundamental theory of movement, walking included, is within reach and allows us to propose a competent model of human walking. By “competent model” we mean that it may only be a first approximation of a fundamental theory, but it is good enough to improve the design of robots and regimens for LE therapy. The full theory of motor primitives is succinctly outlined by Hogan and Sternad [34]. To accommodate real-life walking with all its variations, we propose a modeling approach that decomposes walking into the dynamic primitives, specifically submovements, oscillations, and mechanical impedances.

In their summary of the theory of motor primitives, Hogan and Sternad define a rhythmic movement as a pseudo-periodic movement and a discrete movement as one with a definitive start and stop posture [34]. In a functional MRI study, Schaal et al. demonstrated that a discrete wrist movement recruited more regions of the brain than did the same movement performed rhythmically [35]. Additionally, it has been shown that motor learning of discrete tasks has a positive transfer to rhythmic tasks but not vice-versa [36]. The MIT-Skywalker is the first and so far the only robotic gait system to facilitate rhythmic, discrete, and balance training. In the discrete mode, patients are able to work on self-directed, visually-guided, discrete steps to targets projected onto a treadmill track (more detail in III).

It is undeniable that upright walking requires active balance mechanisms that often rely on modulating mechanical impedances. Impaired balance is a consequence of most neurological injuries such as stroke and cerebral palsy [37][38]. Balance training has been shown to reduce postural asymmetry associated with hemiparesis and was a part of the home-based protocol in the LEAPS study which resulted in similar walking benefits as compared to the BWSTT locomotion groups [39][27]. The MIT-Skywalker can perturb patients in the frontal and sagittal plane to disturb and train balance.

Our final design principle imposes the need to accommodate a vast spectrum of pathological gaits and impairment levels as defined in [40]. MIT-Skywalker is uniquely capable of doing this, affording at least three independent training modes (rhythmic, discrete, and balance training) that can be added or subtracted depending on the patient's needs as showcased in the feasibility study presented in section IV.

B. A New Take on Rhythmic Training

Healthy walking can be described as pseudo-periodic motion. This first method of training seeks to restore the rhythmicity of walking. Whether a patient has a drop foot condition or a stiff leg, the ground offers a challenge during swing phase often surmounted by the patient developing a compensatory motion such as circumduction or vaulting of the hip. These strategies ultimately add challenge and disturb the rhythmic pattern of gait.

To solve this problem, we employed TRIZ in the design of the MIT-Skywalker. TRIZ is a Russian acronym which translates to, “The Theory of Inventive Problem Solving,” developed by Genrich Altshuller beginning in 1946 [41]. Altshuller recognized that one of the roadblocks to successful inventions was that many problems stem from contradictions between two or more components or desired traits. He defined “inventing” as identifying and eliminating the contradictions. For gait neurorehabilitation, the contradiction encountered was that while a walking surface is necessary for gait, this surface inhibits the leg during the swing phase and requires clearing the surface and propelling the leg forward.

An applicable TRIZ principle is “Do it in Reverse” [41]. During conventional over-ground physiotherapy, BWSTT, exoskeleton therapy or foot platform therapy, the swing leg advances forward by physical manipulation. Instead of lifting the patient's leg manually or mechanically, we lower the walking surface which both provides swing clearance and takes advantage of pendular dynamics to propel the leg forward. Inspiration for this idea came from the concept of “passive-walkers” [42].

The MIT-Skywalker transfers this dynamic concept to rehabilitation and human gait, creating the required ground clearance for swing and exploiting gravity to assist during swing by dropping the floor away at toe-off (fig. 2). By removing the ground constraint, the rhythmic training mode allows the patient to “feel the rhythm of walking once again” as it was described by a stroke victim during the rhythmic training program. Preliminary tests with a mannequin and unimpaired subjects demonstrated the MIT-Skywalker ability to allow gait therapy without restricting the movement to a rigid, repetitive kinematic profile [31]. It maximizes the amount of weight bearing steps with ecological heel strike. It also promotes active patient participation during therapy while having a compact design that can be implemented in a variety of settings. Contrary to existing devices, it will not specify a rigid kinematic profile that must be followed and it will address the need of allowing proper neural inputs provided by hip extension and ecological heel strike.

III. MIT-Skywalker Design

Figure 1 shows a full view of the mechanical system of the MIT-Skywalker system. Here we detail the hardware design and characterization.

A. Mechanical System

The MIT-Skywalker contains 5 active degrees-of-freedom (drives). Each drive is actuated with a brushless servomotor and driver from Kollmorgen (Danaher Business Systems, Radford,VA) with 2 motors actuating the split treadmill, 2 motors actuating the sagittal plane rotation, and 1 motor actuating the frontal plane rotation. In what follows, we will describe these drives in this particular order.

The MIT-Skywalker relies on two custom-made treadmills that operate independently of one another. Each belt is of a standard 20-inch belt width and 60-inch roller-to-roller distance. Belt motion is dictated by a 0.67kW AKM43E motor (13.4Nm peak intermittent, 4.24Nm continuous @ 1,500 RPM with an AKD-P00306 motor driver) that creates treadmill belt motion through a ribbed v-belt transmission similar to a standard treadmill. Standard treadmill motors are very large, heavy and often are rated at or above 2.2kW because they need to support speeds up to 12mph (5.36m/s). Training with the MIT-Skywalker is designed to support walking with a desired maximum speed of only 4mph (1.79m/s) and, thus, it can rely on a much smaller, less powerful motor. To quantify the force required to support continuous walking on a treadmill, a standard Sole F80 treadmill was studied by observing current (i) and voltage (V) at a range of speeds with a 75kg subject walking on the track. Working with the mechanical efficiency curve of the treadmill motor, we were able to estimate mechanical power (P_m) via equation (1) where η is the efficiency at a specific current. At 1.79m/s, we estimated P_m to be 0.64kW. The maximum continuous force (F) of a treadmill system at a velocity (v) of 1.79m/s was then simply calculated to be 356N by equation (2). To achieve this, a transmission ratio between the motor and the linear motion of the treadmill was chosen to be 102:1 rad/m. The maximum continuous speed of the motor with the chosen driver is 189 rad/s at 4.1Nm of torque and thus yields a maximum continuous treadmill speed of 1.85m/s with a force of 418N (notice here that at 189rad/s, the mechanical power available is above the rated value). This exceeds the design requirement with a healthy factor of safety and because the treadmills are in parallel, the obtainable RMS force is doubled. The design also offers peak force of 2,734N for intermittent lifting tasks (allowing patients to be raised up a sloped track without a problem). It should be mentioned that the track itself was custom made from light and strong okoume plywood with a thin Teflon coating to decrease friction. The frame of each treadmill is made of 6061-T6 aluminum. The combination of these light materials yields a 25.5kg treadmill that is approximately one-third of the weight of a standard treadmill without sacrificing structural integrity.

$$P_m = \eta i V \quad (1)$$

$$F = P_m / v \quad (2)$$

The treadmill track drops are accomplished with what we term the “sagittal plane drives”. Each drive consists of a 1.65kW AKM53H motor (27.7Nm peak intermittent, 10.5Nm continuous @ 1500 RPM with an AKD-P00606 motor driver) with a pressed and clamped helical pinion gear that interacts with a linear cam via a rigidly-attached helical rack gear (fig. 3). The helical gears were chosen to minimize the operational noise and to maximize the load rating of the gears per unit width. A cam-follower rigidly attached to the treadmill track follows the cam path of the linear cam, thus creating track motion. The tracks are hinged about the axis of the front treadmill roller such that actuation of the sagittal plane drive rotates the track about its front end. Figure 4 shows a more in-depth view of the linear cam paths. The three linear cam paths are joined by gentle fillets to ensure smooth movement of the cam-follower. The motor-to-track rotational transmission ratio (radian:radian) for A, B and C is 86.7:1; 206:1; and 53.2:1 respectively. Section A was designed to make full use of the motor power to be able to fully drop and raise the track within the healthy swing phase time (0.4s) [43]. The simulation shows a required RMS torque of 9.09Nm for full drops (11.6°) in 0.4 seconds while holding the full patient weight during stance. In addition to dropping the tracks, the sagittal plane drive must support all scenarios such as when a therapist needs to access the patient. The high gear ratio of section B was designed to ease the load on the motor during the horizontal position in case a therapist joins the patient on the machine. The high gear ratio divides the torque created by the weight of a patient plus therapist on the machine to a manageable level. We assume a maximum mass of 270kg on the machine at 0.76m from the front roller. This would create approximately 2000N/m of torque on the treadmill frame. The large transmission ratio of section B decreases the torque load on the motor to less than 10Nm, which is within the continuous capability of the motor. Section C was designed to create small upward movements of the track in order to assist toe-off propulsion.

The “frontal plane drive” acts to rotate the full two treadmills and the sagittal plane drive assembly in the frontal plane around the axis coincident with the treadmill surface that bisects the machine. Simulations again defined the power requirements for the frontal plane drive by assessing the power required to move the full assembly to 6° and back to 0° in 0.5 seconds. The drive relies on a 0.55KW AKM51E motor (11.6Nm peak intermittent, 4.41Nm continuous torque @ 1,200 RPM with an AKD-P00306 motor driver) to rotate the whole two-track assembly in the frontal plane. The motor is connected to a 10:1 single stage planetary gear system. A straight cut pinion gear is pressed to the output shaft of the gear box and interacts with a large ring gear rigidly fastened to the steel frame to create frontal plane motion (seen in figure 1). The transmission ratio between the motor and frontal plane rotation is 90:1. To constrain the frontal plane motion, a large ball bearing supports the front of the assembly and a pair of cam followers sitting on the ground support a radial cam attached to the assembly in the rear (fig. 3).

The AKM53H and AKM51E motors are outfitted with mechanical brakes (each rated at 14.5Nm) that engage and hold the motor shaft when the motor is disengaged. This offers a convenient and power efficient mode when the sagittal or frontal plane motion is not required. Individual circuit breakers are implemented for each drive that can be used to select which motor is running and which is being restrained by the brakes.

In addition to the robotic system, an actuated custom body-weight support device was developed for the MIT-Skywalker. This system utilizes a bicycle seat mounted atop a 19.6N/mm compression spring to offload participant weight. A linear potentiometer is attached to the bicycle seat to record the spring deflection, thereby estimating the percentage of body weight being supported. As shown in figure 1, the body-weight support also includes a loose fitting chest harness used only to prevent falls. The advantage of using a bicycle seat for weight support is twofold. First, it offers a quick donning process that takes less than 30 seconds to ready a patient. Second, it locates the offsetting force just below the body's center of mass which affords modeling body motion as an inverted pendulum. Most of other body-weight support systems hinge overhead, well above the center of mass, creating pendular stability which removes the opportunity for the patient to practice balance and self-stabilization. A more detailed description of the body-weight support hardware can be found in prior work [30].

B. Machine Controls and Characterization

All three drives rely on a position loop that encloses a velocity loop, a particularly convenient and robust method of controls. The advantage of such a structure is highlighted in the treadmill drive controls (fig. 5). The velocity loop is enclosed within the firmware of a Kollmorgen AKD motor driver and the position loop is enclosed via custom software within a PXI real-time system (National Instruments Corporation, Austin, TX). This architecture allows the PXI control suite to switch easily between velocity and position control depending on whether or not the position loop is closed.

Each of the drives was characterized by dynamic system analysis or by step response comparisons between model and experimental testing. Table II lists the bandwidths of each drive (observed magnitude crossover frequency at -3dB). The sagittal plane was observed to be capable of dropping to 10° below horizontal and raising back up to horizontal in under 0.40 seconds, which shows the system is powerful enough to support a full drop in the time it takes for a healthy swing phase of gait. The frontal plane drive proved to be capable of rotating to 5° and back to horizontal in 0.45 seconds, a perturbation capable of disrupting healthy subject's gait.

C. Vision System

The MIT-Skywalker makes use of a high resolution and bandwidth vision system capable of analysis of hip angles, knee angles and estimated heel positions at 100Hz in real time. Two cameras (fig. 1) are located on either side of the patient, observing 2D motion of the legs in the sagittal plane by analyzing 4 infrared markers attached to the legs by custom ligatures. For the rhythmic and balance algorithms described in section III, heel positions were approximated by equation (3) using marker definitions seen in figure 6 (we also tested the system with low resolution cameras and obtained satisfactory results [44]). Even though we are using a body-weight support centered at midline, the body can slide and rotate freely. Notice there is no offset for the translation of the hips that leads to an absolute error in the x-position. However, since our goal is to determine when to lower the treadmill, which requires finding the timing of the minimum x-position, this method is satisfactory.

$$\begin{gathered}\theta_h=\tan^{-1}\left(\frac{x_2-x_1}{y_2-y_1}\right)\\ \theta_k=\theta_h-\tan^{-1}\left(\frac{x_4-x_3}{y_4-y_3}\right)\\ x=L_t\sin(\theta_h)+L_s\sin(\theta_h-\theta_k)\end{gathered} \quad (3)$$

To negate the effect of hip translation, the discrete program estimates the heel position using the absolute position of a shin marker in conjunction with the estimated shin angle as shown in figure 6 and equation (4). The discrete method, while more accurate, relies on the length measurements (L_m), which must be obtained every time the markers are attached. The rhythmic method uses the lengths of the thigh (L_t) and shin (L_s), measured once at baseline, making it more convenient.

$$\begin{gathered}\theta_1=\tan^{-1}\left(\frac{x_4-x_3}{y_4-y_3}\right)\\ x=x_3+L_m\sin(\theta_1)\end{gathered} \quad (4)$$

More information about the resolution and accuracy of the vision system can be found in [32].

IV. Training Algorithms Implementation

In this feasibility study the MIT-Skywalker was employed to deliver three distinct modes of training: rhythmic, discrete, and balance. Below, we describe in detail the programs created for use in the feasibility study presented in section V.

A. Rhythmic Training Mode

The timing of the track drops is determined by the vision system estimating the position of the heel on the track. When a minimum x-position is found (indicating the onset of patient-directed swing phase), a signal is sent to drop the track. This triggering approach proved quite reliable for all patients and healthy subjects when properly conditioned with boundaries and filters. For instance, to ignore tremor raw data was interpolated over 10 points to locate a minimum (delaying the drop time by 23-68ms). Drops were prevented from occurring unless the vision system identified 4 markers and at least 0.7 seconds elapsed between consecutive drops. More details on the algorithms can be found in [45].

In the interest of a quick but soft drop, the sagittal plane drive was programmed to drop 2.5° (approx. 3.3 cm below the horizontal plane at the mid frontal plane) and back to horizontal in 0.7 seconds. Acceleration of the initial drop (approx. $250^\circ/s^2$) was four times the deceleration at the end of the perturbation, resulting in a soft feel on heel strike. Among our impaired participants, swing time ranged from 0.47 to 0.63 seconds at training speeds between 0.11 and 0.98 m/s. The soft feel of the final track movement was deemed comfortable by all subjects even if the foot hit the track earlier prior to the track returning to horizontal position. While two additional more aggressive drop profiles were programmed, they were never employed as study subjects felt comfortable with the least aggressive drop. Our initial drop target of 0.4 seconds for swing was based on healthy gait at about 2 m/s.

When delivering the rhythmic program, three additional goals were implemented for some participants.

1) Speed enhancing programs—On top of the standard rhythmic protocol described above, the speed enhancing programs focused on raising participant's training speed up to a maximum of 1.79m/s. Section VIB details the speed training session as performed during the feasibility study.

2) Asymmetric speed programs—The asymmetric speed programs focused on altering the step-length asymmetry via speed distortion (asymmetric split-belt speeds). We employed different speeds at the split-treadmill with track speed separated by a percentage (k) to a nominal treadmill speed (n). k varied from 0.05 to 0.33 during training. Section VIC details the use of asymmetric speed training as performed during the feasibility study.

3) Vision distortion programs—A visual display presented in front of patients similar to figure 7 distorted the perceived length of each step while instructing participants to equalize the distorted steps to induce changes in step-length symmetry as seen in [46]. Section VIC details the use of vision distortion training as performed during the feasibility study.

B. Discrete Training Mode

In this mode of training, the treadmill tracks operate in position mode. A random target is projected onto the treadmill track from an overhead projector (fig. 8) that varies on leg side and distance from mid-stance. Difficulty is adjusted by making the maximum step length shorter (shorter steps were deemed harder by participants). The patient is instructed to land the heel on the target. Once the vision system recognizes that the patient's heel has landed, the algorithm compares the x-position of the heel with the x-position of the target to determine if the target was hit. If the difference of the two x-positions were within half the width of the target, the system assigned a point for success. The treadmill track gently moves the heel back to a neutral position underneath the body. A half second later, a new target is displayed. The number of successfully hit targets and the success rate is displayed at the front end of the treadmill. Study participants considered this simple game very engaging.

C. Balance Training

The MIT-Skywalker system is capable of imposing perturbations on both the frontal and sagittal planes. In this feasibility study, only frontal plane perturbations were used with a stereotyped sinusoidal profile ranging from (0° -2.5° 2.5° 0°) in 1.4 seconds. This is a fairly gentle profile for a healthy subject but challenging for our stroke and cerebral palsy participants. The initial rotational direction was presented randomly and perturbation timing was randomized between 2 and 4 seconds. For participants with a moderate impairment, the frontal plane perturbations were used in concert with the rhythmic program. For our most severely disabled participant, the frontal plane perturbations were used exclusively to develop balance during standing alone. We employed a video game in the form of a surfer (fig.7) to indicate the frontal plane rotation.

V. Safety and Feasibility Study

Safety and feasibility was studied in three patients with different levels of impairment during a month long trial. Here the goal was to confirm the purported safety of the device and study the feasibility of the three training modes. Subsequent steps involve a pilot study comparing outcome of the present protocol and usual care to determine the sample size of a future randomized clinical trial (RCT). Alternatively, in case of negative outcome, cease due to futility and research alternative training modes to shape future pilot and clinical trials rehabilitation programs.

A. Methods

1) Participants—Three volunteers with chronic neurological impairments participated in this safety and feasibility study (see table III). The MIT Committee on the Use of Humans as Experimental Subjects (COUHES) approved the study. All participants gave their informed consent prior to enrollment. Participant 2 (P2) was permitted to wear his ankle foot orthoses for all training sessions. His bilateral canes were excluded as much as his personal perception of safety allowed (subject used canes for over 50 years). Participant 3 (P3) removed her electrical stimulator for all training and evaluation sessions.

2) Training Programs—For all participants, the training program lasted one month (3-4 times per week). During this month, the participants did not receive any other form of therapy. Each session lasted 1 hour composed by 5 or 6 Skywalker training blocks of 5 minutes with 10 to 25% body weight support. One minute of rest was given between each training block. The remaining time included setup, consultation, or socialization. A single type of training was employed each day, but training type varied from session to session.

Participant 1 (P1) received a total of 16 sessions (9 rhythmic, 4 discrete and 3 balance). Because P1 volunteered for 4 days per week of training, we were able to extend training to additional protocols. Her 9 rhythmic sessions included 3 speed enhancing sessions and 6 symmetry altering programs, broken down into 4 asymmetric speed and 2 visual distortion programs.

Participant 2 received 12 one-hour sessions (4 rhythmic, 4 discrete and 4 balance). Two modifications were used in his training. He was used to relying on bilateral canes but the rhythmic session included track drops which made it uncomfortable to use them. A special handrail system was made to accommodate him during rhythmic training. The speed of the treadmills elicited anxiety and drastically increased spasticity. To compensate, single leg training sessions became the focus after the first two rhythmic training sessions (one track moving while the other was held stationary). His canes were permitted on all discrete programs. The balance program was used without the rhythmic drops and without the treadmill moving. He was able to release both canes while standing erect amidst frontal plane oscillations.

P3 received 12 sessions (4 rhythmic, 4 discrete and 4 balance). Two of her four rhythmic sessions were asymmetry correcting programs (1 speed and 1 vision as described above). *3*) *Real-time and clinical evaluations*

Before and after each session, participants were asked to walk for approximately 30 seconds to 1 minute at the same comfortable speed each participant selected on the first day of training while the MIT-Skywalker vision system recorded hip and knee kinematics. During training, kinematics and heart rate were also recorded.

Clinical Evaluations were performed by a physical therapist before and after the 1-month long study at least one day removed from therapy. Subjects underwent clinical evaluations that included a 6-minute walk test, self-selected and maximum walking velocity tests (measured as the average velocity of the middle 6 meters of a 10-meter walk test), the Berg balance scale, the Tardieu (joint spasticity) scale and sagittal plane kinematic analysis. During kinematic analysis, subjects were not only outfitted with thigh and shin sensors but also with toe and heel sensors to observe the foot position via a trakSTAR system (Ascension Technology Corp.). A video camera was set up to record the gross sagittal plane body positioning.

B. Results

After the month long study, we concluded that the system is both safe and capable of delivering all modes of training described in section IV. Rhythmic detections were reliable and flawless for all subjects (see section IV). That said, due to his anxiety, participant 2 had difficulty with the rhythmic paradigm, and we limited this form of training to his first two sessions. We then employed single leg rhythmic training sessions (one track moving while the other was held stationary). The discrete routine detection was also quite safe and reliable but it failed once to identify the correct position of the heel for this participant 2. The failure was due to tassels that hung from his bilateral canes crossing the path between the infrared markers and the cameras. At any time, 4 markers per leg must be identified. In case one or more markers are not identified, the controller stops the robot. This was quickly identified and fixed for the subsequent training sessions.

Here we will examine the clinical results as a series of case studies to highlight different aspects. Table IV details the results as recorded before and after the one month study.

1) Participant 1—We observed a 14% increase on the 6-minute walk test with an average heart rate (HR) increase of 8% during the test, a 30% increase in self-selected velocity, and a 10% increase in maximum walking velocity. She showed a slight increase in the Berg balance scale, being able to stand on one foot for more than 5 seconds. The Tardieu scale remained unchanged with spasticity being found in the right hip and knee using a V3 stretch. Kinematic analysis showed a statistically significant decrease (paired t-test $p<0.001$) in step-length asymmetry (data over 15 strides, initial right step length was 11% longer than left, final 2% longer).

2) Participant 2—We observed a 5% increase on the 6-minute walk test with an average HR increase of 4% during the test. P2 recorded no change on the self-selected velocity and a 7% increase in maximum walking velocity. His greatest change after training was reflected in the Berg Balance Scale in which he made a 270% improvement. There were 6 sub-categories for which Participant 2 scored 0 at admission but scored either 3 or 4 after training. These categories included: sitting to standing, standing unsupported, standing with eyes closed, standing with feet together, reaching forward and retrieving an object from the floor. Initially total scoring a 10, P2 scored a total of 37 at discharge. In other words, P2 moved from a high risk to a medium risk of falling. The Berg Balance Scale is made up of 14 tasks scored 0 to 4. A score from 0-20 indicates a high risk of falling, 21-40 indicates a medium fall risk, and greater than 40 assigns a low fall risk rating. The Tardieu scale remained unchanged, finding spasticity in both legs in response to a V3 stretch.

3) Participant 3—P3 recorded a 4% decrease in the 6 minutes with an average HR decrease of 2% HR during the test, a 6% decrease in self-selected velocity, a 6% gain in the Berg balance test being able to stand on one leg after training. The Tardieu scale initially found spasticity in the left hip, knee and ankle in response to a V3 stretch. Afterwards, no spasticity could be induced by the stretch. Sagittal plane kinematic analysis showed a more normal paretic foot trajectory. Initially, P3 showed toe-strike and after training, she had a normal heel strike.

VI. Discussion

The MIT-Skywalker system has evolved over time. The initial α-prototype demonstrated the passive-walker capability on a mannequin [31]. The β-prototype demonstrated the ability to test healthy subjects and was used to study interlimb coordination [47]. Finally the γ-prototype was developed to support patients with severe to moderate gait impairments due to stroke or cerebral palsy. Improvements made in the γ-prototype include a patient-ready body-weight support system, a more capable control system described in this paper as well as a more robust structure encasing the treadmill tracks.

This study marks the first time the MIT-Skywalker system has been tested with persons with neurological impairments due to stroke or cerebral palsy. Here we documented the safety and feasibility of the three different training routines and show their promise for the rehabilitation therapy of various disabilities (stroke and cerebral palsy) at three impairment levels. Participant 1 had a mild disability due to cerebral palsy. Participant 2 had a major walking disability due to cerebral palsy and Participant 3 had an average stereotypical gait pattern seen after stroke. MIT-Skywalker showed its versatility to accommodate each. Further, each participant was able to make gains in one or more of the tested parameters even though the injury onset was greater than 5 years in the past. Ultimately, our training approach must be validated and benchmarked against usual care in future randomized clinical trials.

A. Discrete Program for all Levels of Walking

The MIT-Skywalker is the first rehabilitation robot to introduce discrete training. Discrete training success rates varied by subject. P1 was initially able to hit 93% of targets and eventually was able to reach 100%. P2's first session recorded a success rate of 18% and his last session recorded 86%. P3 increased her accuracy from 64% to 76%. The programs were progressively made more difficult by shortening the maximum target distance which was deemed more difficult by subjects, perhaps because it might require more motor control.

A non-structured non-validated post-training interview with each subject so as to understand and gain feedback from their experience suggested that, unanimously, the discrete training was considered the most challenging both mentally and physically. While we cannot isolate the effects of any of the three programs used in this study, we can hypothesize that the discrete program allowed participants to repeatedly practice heel strike, something that plagued each one of them.

From a safety standpoint, the discrete program was 100% safe and reliable aside from the one error due to cane tassels (discussed earlier). Based on our feasibility test, we would recommend training first with the discrete program and progressing to rhythmic and balance as patients get comfortable.

B. Speed Training

Participant 1 was the only subject that significantly improved over-ground walking speed. She was also the only subject who had dedicated speed training with the rhythmic training paradigm (3 sessions). On the first day of training, P1 walked on the Skywalker with rhythmic drops and speed was increased to a comfortable walking speed, which she selected to be 0.45m/s. Prior to every block during speed training, P1 was asked whether we could raise the speed. If yes, we would raise speed by approximately 0.05m/s. Otherwise, she would train at the previously attained speed. This speed was used during a 5-minute block. This procedure was repeated for all blocks over the three sessions. We were able to increase her average training speed to 0.98 m/s on the Skywalker. Bilateral 0.7s track drops were used during most speed training. When her confidence and proficiency peaked, track drops were removed. This was the only time drops were removed during her rhythmic or balance training. By the last day of speed training, she was capable of walking on the Skywalker at 0.98m/s without drops. She stated that she would be running with any further increase in speed.

C. Symmetry Training

Symmetry can be trained with the MIT-Skywalker system. Participant 1 showed an improvement in step length symmetry and was the subject who was exposed to the highest number of symmetry training sessions. Within her month of training, Participant 1 completed 6 sessions of symmetry training within her rhythmic sessions. Four of these were speed symmetry distortions and two were based on visual feedback distortions.

Three of the speed asymmetry sessions used small alterations in speeds ($.05<k<.07$) from nominal (n) such that the left speed was n(1+k) and the right was n(1-k). P1 was naive to the change and could not identify what was being done. One symmetry session resembled the experiments done by Reisman et al. [48], using $k=.33$ (moving one treadmill twice the speed of the other) as shown in figure 9. Similar to Reisman et al., in all cases we were able to induce immediate changes in step-length symmetry using asymmetric track speeds; however, the effect was opposite to the effect observed by Reisman[48]. On the MIT-Skywalker the step length of the foot on the fast treadmill became longer during training, yet resulted in a smaller step after training (fig. 9). In Reisman's study, the step on the slow treadmill became longer during training and resulted in a smaller step after training. Future studies are needed to clarify the reasons for this apparent reversal during training. In both studies, the augmentation principle holds (meaning that training with augmented asymmetry diminishes or reverses the asymmetry immediately following training).

Implicit visual distortion programs similar to [49] were used to test the effects on symmetry. P1 was asked to equalize two bars that represented each side's step length. Distortion was introduced to make the longer step length seem even longer, resulting in a conscious shortening step on the longer side. We also tested the reverse program that made the long step seem shorter, inducing P1 to exaggerate her initial asymmetry. While there was a large effect during training, neither program yielded statistically significant changes in symmetry after training.

P3 received one session of speed asymmetry and one of visual distortion. Intra-session changes in gait asymmetry were consistent with above results.

D. Balance Training

Gentle frontal plane perturbations were used in combination with the rhythmic drops for Participants 1 and 3, and in isolation with Participant 2. One must take the results with the appropriate caveats in this case study, but we can speculate that the drastic change in the Berg balance scale for P2 was due to the work done on the balance training days, as all other training sessions were done using balance aids such as his bilateral canes or a railing system. At the beginning of balance training, P2 was reluctant to give up his canes. He could not recall a time in his life that he had been standing without use of his canes or holding onto the walls to maintain balance. After his second training session, he was able to release the canes while standing completely erect, being swayed right and left by the gentle waves.

E. Walking Therapy for Adults with Cerebral Palsy

The case studies highlighted the potential for changes in adults with cerebral palsy. It demonstrated significant changes in severe and mild cases. For example, Participant 1 entered the study with a self-selected over-ground walking speed of 0.89 m/s and at completion selected 1.17 m/s. Matching age and gender, normal self-selected velocity is 1.40 m/s [50].

Due to reimbursement policies in the US, therapy for CP subjects takes place before the age of 18. In fact, we could not find a single study for gait rehabilitation therapy of adults with cerebral palsy. Here, we show that this type of therapy can also benefit adults and we hope it will spur others to consider this neglected population.

VII. Conclusion

In this paper we present the description of the hardware and findings from the safety and feasibility study of the MIT-Skywalker involving persons with impairment due to stroke or cerebral palsy. Initial results were very promising and we will be commencing a larger set of clinical studies shortly.

Acknowledgments

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Biographies

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Hermano Igo Krebs (F′14) joined MIT's Mechanical Engineering Department in 1997 where he is a Principal Research Scientist and Lecturer – Newman Laboratory for Biomechanics and Human Rehabilitation. He also holds an affiliate position as an Adjunct Professor at University of Maryland School of Medicine, Department of Neurology, and as a Visiting Professor at Fujita Health University, Department of Physical Medicine and Rehabilitation, at University of Newcastle, Institute of Neuroscience, and at Osaka University, Department of Mechanical Engineering He is one of the founders and Chairman of the Board of Directors of Interactive Motion Technologies, a Massachusetts-based company commercializing robot technology for rehabilitation. He is a Fellow of the IEEE. Dr. Krebs was nominated by two of IEEE societies: IEEE-EMBS (Engineering in Medicine & Biology Society) and IEEE-RAS (Robotics and Automation Society) to this distinguished engineering status *"for contributions to rehabilitation robotics and the understanding of neuro-rehabilitation."* Dr. Krebs has published and presented extensively on rehabilitation robotics. His work goes beyond Stroke and has been extended to Cerebral Palsy for which he received "*The 2009 Isabelle and Leonard H. Goldenson Technology and Rehabilitation Award*," from the Cerebral Palsy International Research Foundation (CPIRF). In 2015, he received the IEEE-INABA Technical Award for Innovation leading to Production "*for contributions to medical technology innovation and translation into commercial applications for Rehabilitation Robotics."* His goal is to revolutionize the way rehabilitation medicine is practiced today by applying robotics and information technology to assist, enhance, and quantify rehabilitation.

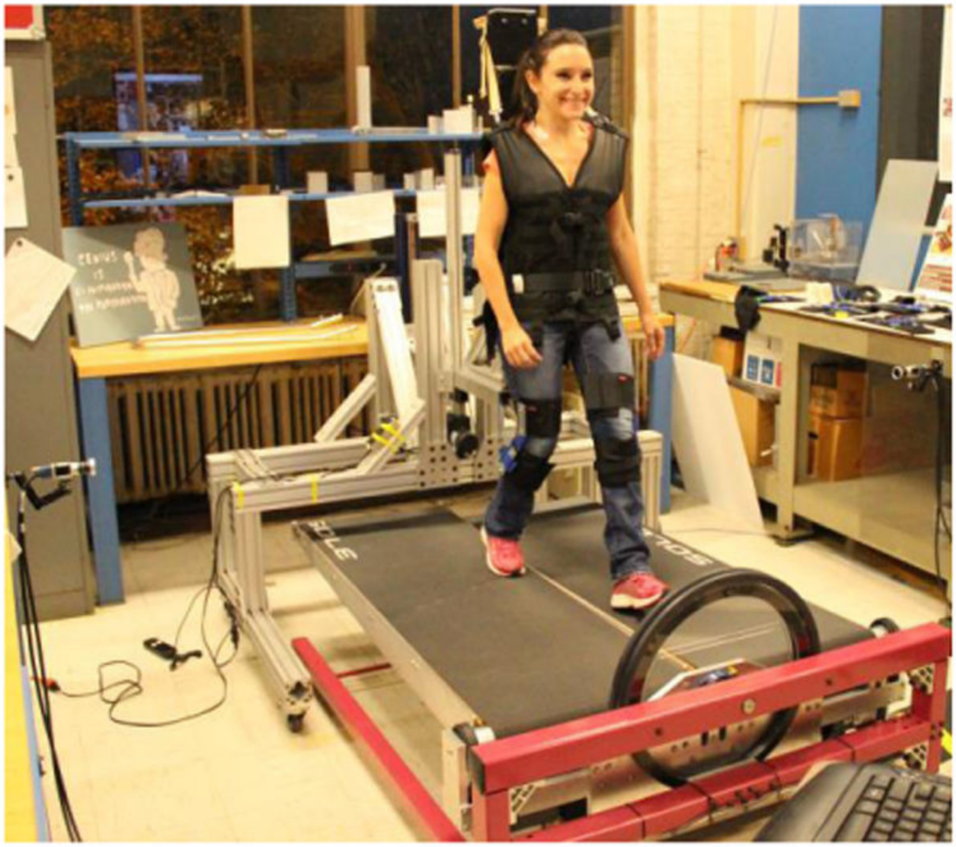

Fig. 1.

A study participant with impairments due to Cerebral Palsy trains on the MIT-Skywalker. Subject is looking at a monitor that displays the training goals in a form of video-games.

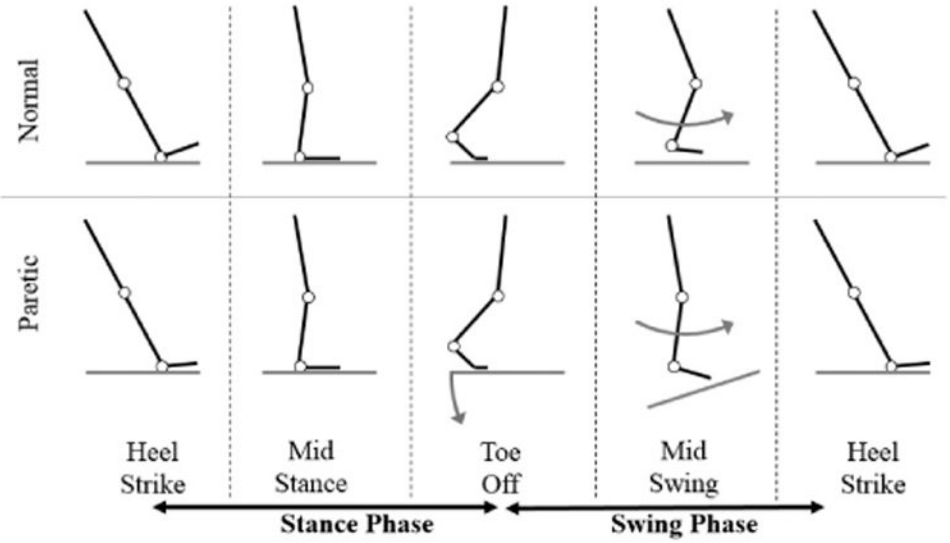

Fig. 2.

The MIT-Skywalker concept of assistance. Top row shows healthy gait: the leg supports the trunk while it moves backward relative to the trunk during the stance phase; at toe-off the support is shifted, the ankle completes a propulsive plantarflexion movement, and initiates a dorsiflexion movement to clear the ground initiating the swing phase. The walking surface is necessary during the stance phase, but it inhibits the leg during the swing phase and requires clearing the surface and propelling the leg forward. In the MIT-Skywalker, the split treadmill moves the patient's foot to the toe-off position. Once the vision acquisition system recognizes the heel x-position has reached a minimum (patient-initiated swing phase), the track is dropped, allowing the foot to swing forward freely for another step partially assisted by gravity (pendulum) and by patient's effort.

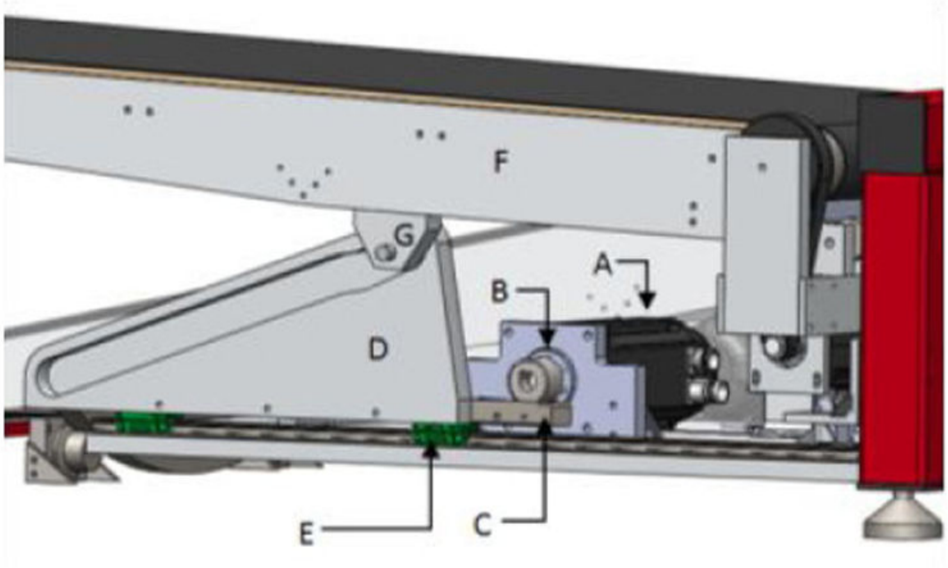

Fig. 3.

Sagittal Plane actuator and transmission. A. Brushless servo motor. B. Pinion gear. C. Rack Gear. D. Linear Cam. E. Linear Bearing. F. Treadmill Track. G. Cam follower mount.

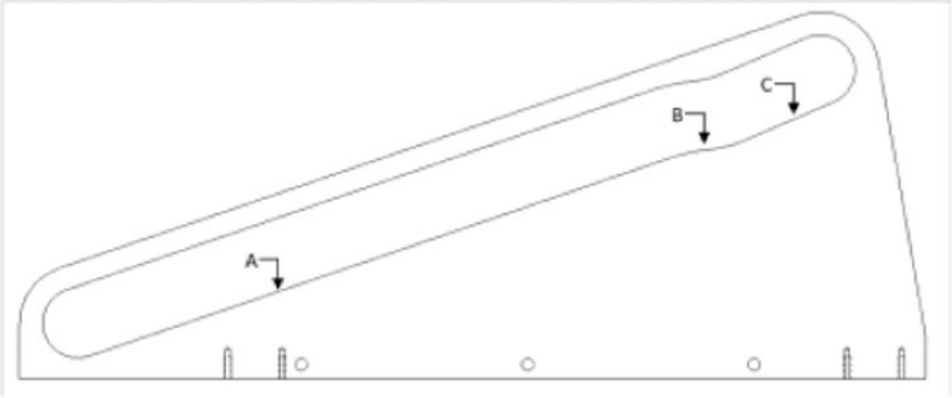

Fig. 4.

Tri-zone linear cam path. A: Track drop path B: Horizontal resting position C: Track raise path.

Fig. 5.

Treadmill motion control loop.

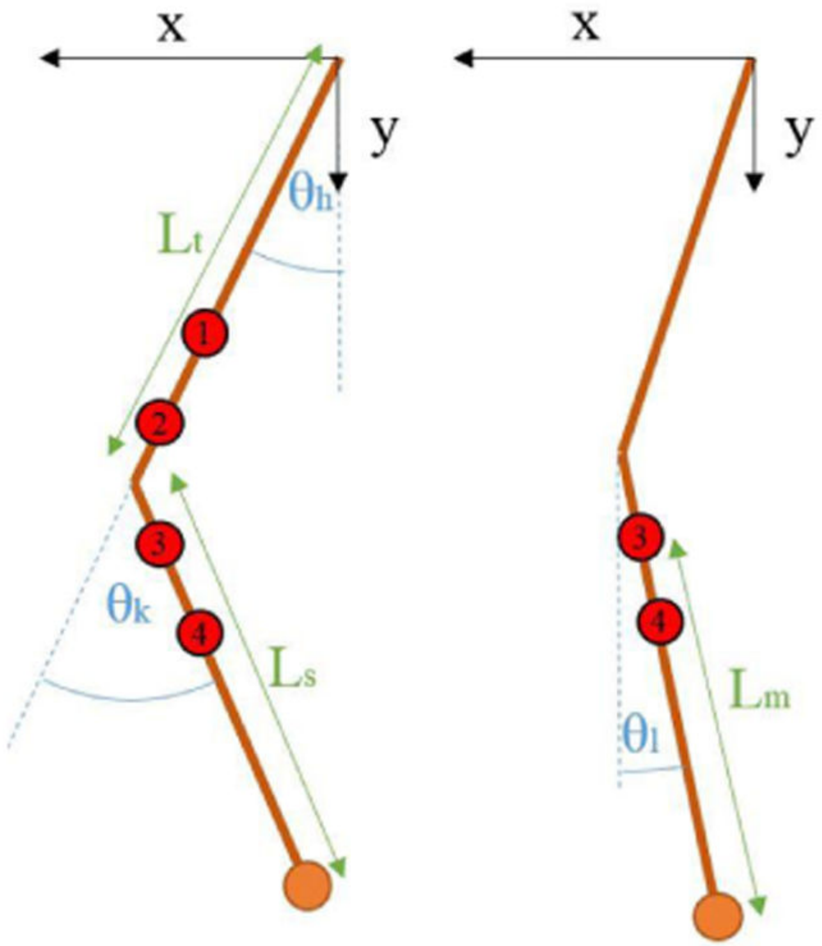

Fig. 6.

Schematics for the heel x-position estimation. Left: Analysis for rhythmic and balance programs. Right: Analysis for discrete program.

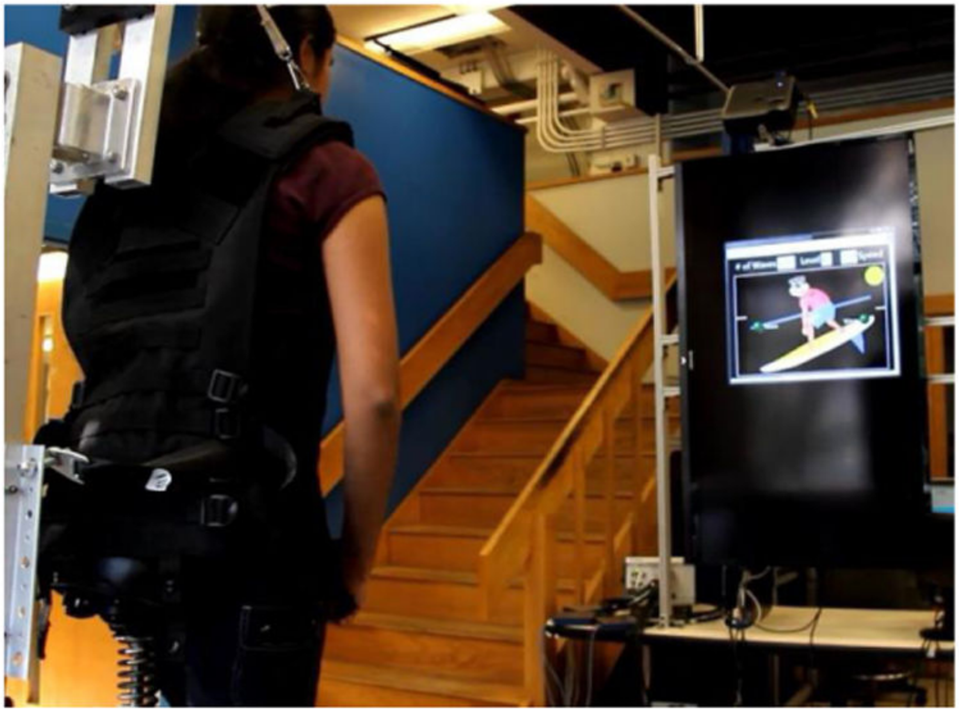

Fig. 7.

View from the MIT-Skywalker. A large screen is used to display games and real-time webcam video of the subject.

Fig. 8.

Discrete training mode stepping. A target is shown (white bar). The participant locates the target position with the heel. The success rate can be seen in front of the participant to keep her engaged in the training session.

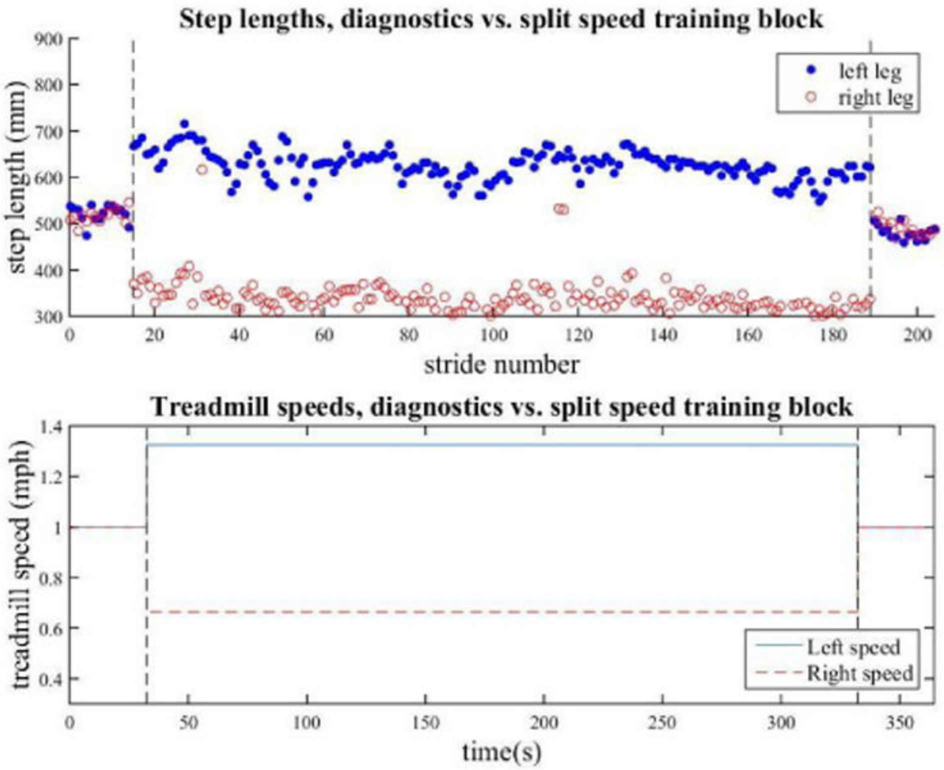

Fig. 9.

The bottom graph shows the speed in mph of each treadmill. Left of the vertical dotted line represents the step lengths recorded over a 30 second diagnostics session prior to training and right of the dotted line represents the post training diagnostic session. The middle section shows block 5/5 of the 11th training session of 16 (the sixth rhythmic session, R6). The top graph shows the step length of each step before, during and after training. For this day of training, P1's initial gait showed slight asymmetry to start with an average left step length 0.2% longer than the right. After training with a longer left step, the final diagnostic showed the left step length to be 2.8% shorter than the right, statistically significant via the paired t-test ($p < 0.05$).

Table I

MIT-Skywalker System Novelty

Design Assumption	Unique Capability
1 Effective rehabilitation therapy relies on engaging patients to induce self-directed movements i.e., passively moving patients is ineffective at inducing plasticity	Ensure self-directed movement: system is incapable of generating patient motion profiles
2 Rhythmic and Discrete movements are neurologically distinct	System is able to train both rhythmic and discrete neural circuits
3 Balance is important for walking and walking rehabilitation	System makes use of a custom body weight support system to safely perturb balance
4 CNS injuries yield a multitude of pathological gaits and severities	System is modular in speed and program variety to address common pathologies

Table II

Skywalker System Bandwidths

Drive	Bandwidth
Treadmill Velocity Loop	11.5 Hz
Treadmill Position Loop	4.1 Hz
Sagittal Plane Position Loop	6.2 Hz
Frontal Plane Position Loop	6.7 Hz

Table III

Participants at Initial Evaluation

	Participant 1	Participant 2	Participant 3
Age	24	56	58
Gender	Female	Male	Female
Classification	Triplegic Cerebral Palsy	Diplegic Cerebral Palsy	Hemiparetic Stroke
SSV[a]	0.89	0.50	0.24
MSV[b]	1.50	0.59	0.26
Device used	None	Bilateral canes and bilateral AFO[c]	Paretic-side tibialis anterior electrical stimulator

[a] SSV Self-selected over ground velocity at the 10m walk test

[b] MSV Maximum-selected over ground velocity at the 10m walk test

[c] AFO Ankle foot orthoses

Table IV

Clinical Evaluations Before and After 1 month Training

	Participant 1		**Participant 2**		**Participant 3**	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**
6mwt[a] (m)	*478*	546	200	209	213	204
Avg. HR during 6mwt (bpm)	*145*	157	126	131	93	91
SSV[b] (m/s)	*0.89*	1.17	0.50	0.50	0.24	0.22
MSV[c] (m/s)	*1.50*	1.65	0.59	0.63	0.26	0.26
Berg Balance Test (score/56)	54	55	10	37	52	55
Tardieu Scale (V3 spasticity joints)	Right Hip, Knee	Right Hip, Knee	Both Hips, Knees	Both Hips Knees	Left Hip, Knee, Ankle	None

[a] 6-minute walk test was performed at baseline and after the 1-month training period.

[b] Mean self-selected over ground velocity was estimated via the 10m walk test averaged over three attempts before and after training

[c] Mean maximum-selected over ground velocity was estimated via the 10m walk test averaged over three attempts before and after training