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MIT-Skywalker: A Novel Environment for Neural Gait Rehabilitation*

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***Abstract*— A novel concept of rehabilitation is proposed for the recovery of walking post-stroke made possible by a novel piece of robotic hardware, the MIT Skywalker-γ prototype. Rather than prescribing motion for the patient similar to most current rehabilitation robots, we built an environment to foster self-directed movement. The concept is based upon our working model on dynamic motor primitives, prior rehabilitation results and a survey of common gait pathologies associated with stroke. Skywalker-γ was carefully developed to provide an environment in which three motor primitives can be trained in isolation or in combination to further insights into both rehabilitation and human motor control.**

I. INTRODUCTION

Each year, 795,000 Americans will suffer a stroke and it is estimated that 6.4 million stroke survivors reside the US [1]. The prevalence of stroke increases with age and thus, as the average age in the US will increase in the next 20 years due to the baby boomer generation, so will the number of stroke victims and stroke survivors. It is estimated that 80% of people suffering a stroke will experience motor deficits [2]. Though there has been a thrust towards developing pharmaceutical interventions for neuro-protection and neuro-recovery, to date only one drug has demonstrated protectant capacity following an ischemic stroke and none promotes neuro-recovery [3]. Rehabilitation is the only method at this time that has been shown to yield lasting impact to promote neuro-plasticity and promote movement recovery following stroke [4]. Upper extremity motor control is fairly well understood and has been translated nicely into robotic systems that now hold the highest recommendation by the American Heart Association and the American Stroke Association as well as the Veterans Administration. However, the same cannot be said for the lower extremity or for walking therapy [5].

A. Locomotion Rehabilitation Therapy

Different leading methods of gait rehabilitation have been explored over the years. In the 1990s, the *neurophysiological treatment concepts* of Karel Bobath dominated internationally [6]. At the same time, a new paradigm (*task-specific repetitive concepts*) began to emerge, which applied to stroke, suggested that those who wish to walk must walk. And thus, body weight supported treadmill therapy (BWSTT) was born. Patients are suspended in a body weight support harness over a treadmill while two therapists take their positions, one sitting adjacent to the paretic leg in order to provide movement assistance, and the other standing behind the patient to support trunk movement. In a landmark study, Hesse et. al showed that treadmill training with partial body weight support compared favorably to the Bobath method in improving both gait ability and walking velocity [7]. BWSTT became the benchmark of gait rehabilitation. A review of 21 randomized controlled trials (RCTs) showed that both gait speed and walking distance improved after gait-oriented training [8]. Increased brain activity has been observed during BWSTT in fNIRS [9] and after BWSTT in fMRI scans of stroke patients making ankle pointing movements, suggesting that the intervention has a neurophysiological effect in stroke [10].

The next logical question asked whether BWSTT is the best way to rehabilitate stroke patients to walk. The answer to this question is rather unclear. Meta-analysis indicated that there were no statistically significant differences between BWSTT and other interventions for walking rehabilitation in multiple studies [11]. The confusion regarding the advantages of BWSTT lies in the small size and differences in protocol between all of these studies, most of which assess less than 30 patients. In order to provide a definite answer to this question, a well controlled, large randomized controlled trial (RCT) sponsored by NIH and known as the Locomotor Experience Applied Post-Stroke (LEAPS) trial was conducted with 408 patients across the country at multiple facilities. This study was done specifically to compare the effects of a state-of-the-art locomotion program that included BWSTT to those of a sham home-based exercise program. Note that the sham home program was not expected to affect the primary outcome which was gait speed [12]. Surprisingly and contrary to the study proponents expectation, at one year after stroke, there were no significant differences in improvement between either of the groups [13]. The strong negative result of the LEAPS study requires introspection and presents an opportunity to reassess the next generation of locomotion rehabilitation interventions.

B. Locomotion Robots

At the end of the 1990s, a time when studies were suggesting the efficacy of BWSTT, engineers sought to develop robotic methods to replace the laborious and repetitive tasks of therapists during BWSTT. The two major classes of these robots were exoskeletons and end-effector foot plates.

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Exoskeletons include LOPES[14], ALEX[15], the AutoAmbulator and Lokomat[16]. One of the first and perhaps the most commercially successful locomotion robot to date is the Lokomat. The Lokomat uses actuators at the hip and knee to move the patient through a neurologically healthy kinematic path while walking with body weight support. Pilot studies implied its potential [17][18]; however, more recent studies showed mixed results with two RCT that compared a Lokomat training group to a conventional gait training group concluded that the conventional group experienced significantly greater gains in walking speed and distance that were still evident at a 3-month follow up examination [19][20].

End-effector foot plate robots include Lokohelp, Gait Trainer I[21], Haptic Walker[22] and the G-EO system[23]. For years, there were only small patient trials using the end effector type robots[24][25]; however, in 2007, the DEGAS (DEutsche GAngtrainerStudie) study showed that a group receiving locomotor training with the Gait Trainer I along with physiotherapy improved significantly more in walking speed, among other clinical scales, over the group receiving only physiotherapy [26]. Coupling physiotherapy with training on the G-EO system, the newest machine developed by Hesse's group, has been shown to result in a significantly larger improvement in walking velocity and stair climbing ability compared to a group receiving only physiotherapy [27]. It is important to note that all studies used physiotherapy in combination with the robots for the robot groups. None have compared the robot directly to physiotherapy.

Other robotic systems developed for locomotion rehabilitation include balance machines such as CAREN[28] which employs a moveable platform and the MIT Anklebot, which actuates the ankle in two degrees of freedom. The initial studies with the Anklebot in seated posture during pointing movement has led to the surprising result of increasing walking speed by at least as much as occurred from usual physiotherapy for hemiparetic stroke patients [29][30].

II. THEORIES AND EVIDENCE

The LEAPS study, lack of consistent benefits from exoskeleton rehabilitation devices, and the equality of training the ankle in seated position tells us that there is still much to learn about locomotion rehabilitation post stroke. We looked to neuroscience, the successes and failures of rehabilitation thus far and specifically at common gait pathologies to design a novel approach to locomotion rehabilitation. Our method was to employ motor learning and control as the basis to design an environment that promotes locomotion and to let the design of the machine follow this environment.

A. Hebbian Plasticity In Rehabilitation

The physiological mechanism underlying the potential of rehabilitation is neural plasticity [31] commonly expressed by the Hebbian axiom "neurons that fire together, wire together". Our goal is to promote neural plasticity by linking supra-spinal movement intention with afferent feedback from a successful motion completion. We do not expect significant changes without the patients attention and intention to move [32]. The success of upper extremity rehabilitation lies in the ability for the patients CNS to influence the trajectory and onset of motion. One potential setback of exoskeleton and footplate machines is the existence of a motion profile that the machine must be driven through. Our first design parameter was, therefore, to create an environment in which the body's movement can be expressed freely without attachments restricting movement to pre-defined kinematics.

B. Movement Primitives

Hogan and Sternad outlined our working model of dynamic primitives, asserting that sensorimotor control may be able to be broken down into three primitives: submovements, oscillations, and mechanical impedances [33]. When relearning to walk, severe stroke patients resemble infants, using discrete steps (steps with a clear starting and stopping point), a motion that is similar to discrete upper extremity reaching movements, which has been hypothesized to be composed of a superposition of elemental primitives known as submovements [34]. This contrasts with healthy walking which could be described as a rhythmic motion (pseudo-periodic oscillations). It would be easy to postulate that these two types of movement come from the same neural circuitry; yet, brain scans show the distinct brain mapping of these two modes of human motion [35]. Consequently, it seems logical that the rehabilitation environment should support both discrete and rhythmic movements.

While rhythmic and discrete movement might characterize free movement, walking includes collision with the floor and mechanical impedance constitutes the third and last purported primitive of motion. Thus an ideal environment would provide an opportunity to control impedance and safely practice balance, both statically (while standing) and dynamically (while walking).

III. IMPAIRMENTS AND PATHOLOGIES

The effect of every stroke is different with a unique lesion size and location, thereby affecting motor control in a unique way. Table I shows a few examples of pathological gait due to stroke [36][37][38]. An optimal rehabilitation environment will be able to address all these pathologies, thereby providing an opportunity to address the underlying impairment.

TABLE I

CONTROL IMPAIRMENTS AND GAIT PATHOLOGIES

Control Impairments	Common Gait Pathologies
Spasticity	Drop Foot
Selective Control	Equinovarus
Primitive Locomotor Patterns	Genu Recurvatum
Inappropriate Phasing	Stiff Knee Gait
Proprioception	Asymmetric Gait
	Balance Problems
	Slow Gait Speed

IV. DESCRIPTION OF HARDWARE

The MIT Skywalker-γ prototype has five active degrees of freedom (DOF), each controlled precisely with a servomotor. Two of the drives are mirrored across the bisecting sagittal plane of the machine, resulting in three unique control systems (drives).

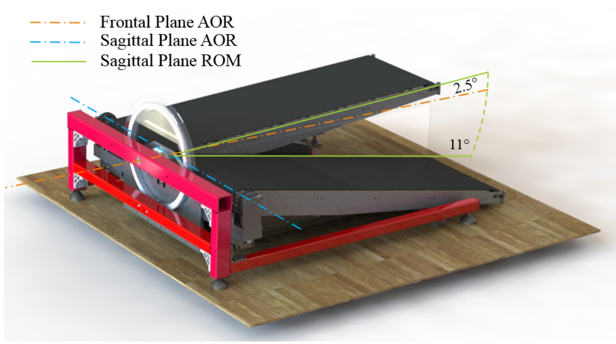


Fig. 1. Skywalker-γ axes of rotation (AOR) and sagittal plane range of motion (ROM)

A. Treadmill Drive

The treadmills used in Skywalker-γ use standard sized treadmill belts, but differ from a standard treadmill in their ability to be run independently in both position control mode and velocity control mode, making use of a full state feedback controller. Additionally, the treadmills were constructed from light weight materials.

B. Sagittal Plane Drive

Each treadmill can be actuated to rotate about the axis of the front treadmill roller (figure 1). The sagittal plane motion is capable of moving above the horizontal by 2.5° and can drop to 11° below the horizontal. The drop results in a distance of approximately 6 inches under the foot of a patient. A drop-and-rise profile can be done in less than a half of a second, fast enough to accommodate an unimpaired swing phase. Two motors drive nonlinear cam systems to independently create appropriate sagittal plane motion profiles.

C. Frontal Plane Drive

The final motor rotates the whole two track assembly in the frontal plane around an axis that runs through the middle of the two tracks, coincident with the horizontal walking surface (figure 1). The range of motion of the frontal plane DOF is -2.8° to 6° and it can move in a 0°-6°-0° profile in less than half of a second.

D. Body Weight Support

The body weight support used in this system relies on a bicycle seat, a lap belt and a loose fitting chest harness as seen in figure 2. The bicycle seat is mounted to a shaft that is able to rotate in the transverse plane, but is restrained in other rotational DOFs by cylindrical linear bearings. A spring and linear potentiometer allow for and record vertical deviation which can be used to infer the vertical vector of body weight support force. The whole system shown in figure 2 is attached to a mechanical jack that sets the height of the BWS, thereby determining the preload on the springs. The advantages of this design over an overhead harness is the ability for quicker donning, support that acts closer to the patient's center of mass (see figure 4) and specifically for the Skywalker system, it restrains lateral and forward motion to keep the patient centered on the machine.

Fig. 2. Skywalker-γ body weight support device

E. Vision System

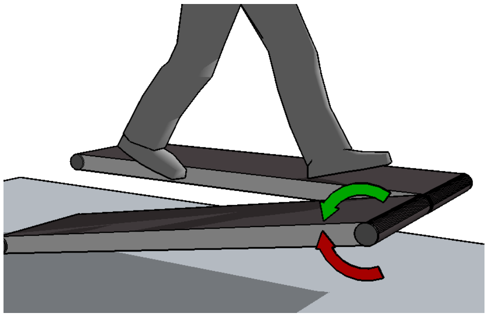
The Skywalker-γ system incorporates a custom vision system utilizing a high speed camera link camera (up to 340 fps) to provide real time estimates of the angle of the thigh and shin so as to determine the posture and position of the patient. The cameras are outfitted with a 720nm infrared transmitting filter which blocks visible light but allows an array of infrared emitters, attached to the patient, to reach the cameras sensor, making the camera system ideal for a clinic with changing backgrounds.

F. Controls

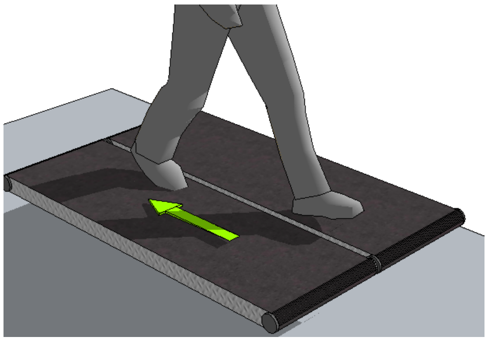
Low level control loops are closed inside of industrial motor drivers. A National Instruments PXI platform is utilized for high level control, vision data, and the treadmill position loop. The PXI controls are written in Labview.

V. ENVIRONMENT DESIGN

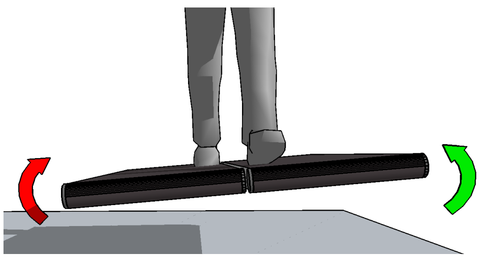
Designing an environment for rehabilitation requires the ability to remove constraints preventing the desired movement task while promoting lost function. As specified by the movement primitives, we propose three modes of training that may be used for independent training and then combined as subjects motor function improves.



(a) Rhythmic Training



(b) Discrete Training



(c) Balance Training

Fig. 3. Proposed Training Paradigms

A. Rhythmic Training

Healthy gait includes a significant component of rhythmic movement. It is this rhythmic mode of walking that is being targeted by most locomotion robots following suit of BWSTT. They embodied the concept of using external actuators to push the legs towards a predefined trajectory. The end goal is for patients to work towards this rhythmic gait; thus our environment must promote rhythmic walking but, in the interest of allowing the patient to influence the timing and path, we will do so without the use of a rigid trajectory imposed by the actuators. Rather, we will accomplish this by harnessing gravity.

Gravity alone has been shown to be sufficient to actuate bipedal locomotion as in the case of passive walkers operating on a slight downward slope [39]. The MIT Skywalker-α prototype demonstrated how to employ this concept to promote rehabilitation; however, instead of walking down a slope, the subjects walked on a split belt treadmill that dropped during the toe-off phase of gait, using gravity to propel the leg forward as a pendulum during the swing phase of walking [40].

Skywalker-γ enhances the rhythmic training by offering a larger track deflection during swing phase and can now be actuated above the horizontal to add assistance during toe-off. The track can be made to drop to any angle between $0°$ and $11°$, customizable to the patient's needs. The training concept is to drop the track fully to begin training for a severe patient (see figure 3(a)). As the patient becomes more proficient, the treadmill speed can be increased and the track can be dropped to a shallower depth to encourage the patient to recruit more independent control during the swing phase. Additionally, the BWS system can be lowered to decrease the amount of assistance. In this way, we can constantly challenge our patient to become involved in the training. We will make use of the vision system to control the timing of dropping and raising the track at terminal stance and heel strike respectively.

We expect that this paradigm of training can be used to treat patients with drop foot and stiff knee gait (characterized by low flexion), ridding the patient of the floor constraint that blocks swing phase. We also expect this type of training to be used to right an asymmetry problem by gradually changing the phasing of gait. Table II summarizes the modes of training with the various gait pathologies mentioned in table I.

B. Discrete Training

To train discrete type walking in which independent steps are taken with a defined start and stop point and non-null time interval between stop and start, the environment must respond to movements made by the patient, allowing that person to initiate the movement, determine the length of the stride, and the movement taken in the frontal plane during swing phase. This type of task corresponds to initiation of movement, navigating through obstacles, and stopping; it is currently being implemented during conventional therapy (see figure 3 of [12]) but never on a treadmill or robotic devices. We seek to enable this type of training by making use of our smooth servo controlled split belt treadmill.

C. Balance and Impedance Training

Training balance has been shown to improve asymmetry associated with hemiparetic gait [38]. Traditional BWSTT, exoskeletal robots and foot plate robots make use of a body weight support device that hangs from overhead, creating a fairly large radius from the body's center of mass (CM) (figure 4). This has the potential to create a pendulum effect which differs substantially from natural balance mechanisms. Locating the BWS near the center of mass will allow the body to tilt and sway in an unrestricted manner providing the proper environment for the human balance to be perturbed and practiced.

The Skywalker-γ design's body weight support locates the offsetting force near the center of mass via the bicycle seat at the groin below the center of mass. The resulting inverted pendulum is unstable without external compensation, much like the free standing human. This, in combination with the loose vest, allows a person's balance to be perturbed while

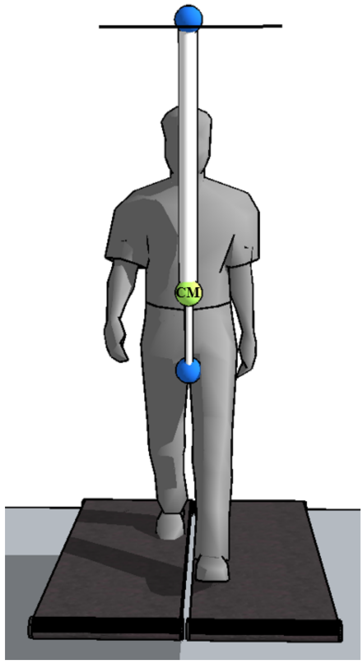


Fig. 4. Body weight support center of mass radii: overhead support vs crotch support

remaining safe. All three of Skywalker-γ's drives can be used to perturb a patient in a variety of ways–simulating an icey spot in the road, a change in grade, a tilted landscape (see figure 3(c)) or any combination of these that may occur while walking in the community–and those require modulation of the leg impedance during such interactions.

TABLE II
TRAINING MODES AND THE PATHOLOGIES TARGETED

Training Mode	Targeted Gait Pathology
Rhythmic	Drop Foot Stiff Knee Gait Asymmetric Gait
Discrete	Slow Gait Speed Genu Recurvatum
Balance	Balance Asymmetric Gait

VI. PRELIMINARY KINEMATIC DATA

Figure 5 depicts the kinematics of three test cases run on the Skywalker-γ. The blue and red plot compare the kinematics of a healthy subject with and without the body weight support while walking on the split-belt treadmill. The green plot represents the kinematics of an unactuated wooden mannequin being driven by the Skywalker-γ using the rhythmic training paradigm described above.

VII. CONCLUSIONS

While the number of locomotion rehabilitation robots is growing, efficacy remains unclear. Here we attempted to step back and learn from previous research studies, adopting at the same time the most recent theories of the underlying

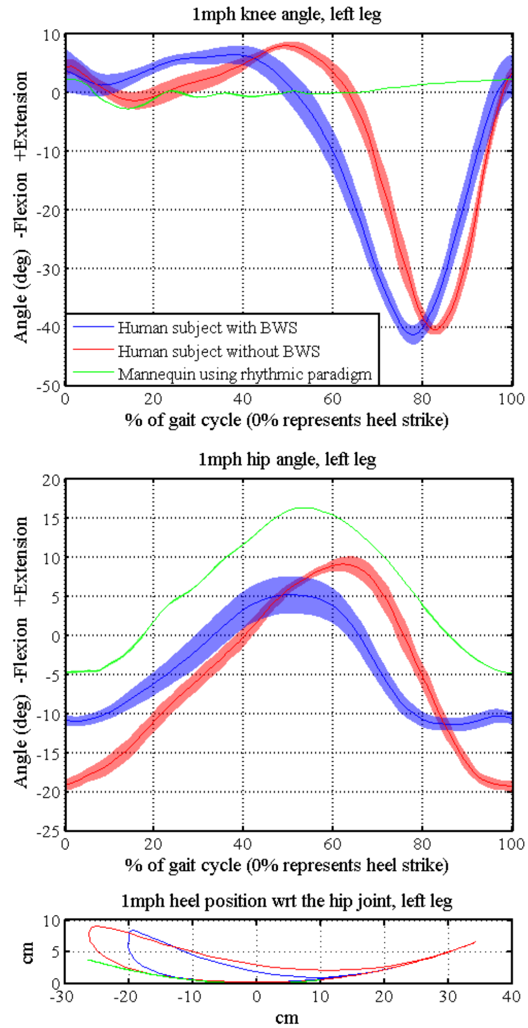


Fig. 5. Gait Kinematics: data from the real-time vision system collected and post-processed. Lines represent the mean trajectory and the shaded regions represent the standard deviation over 16 strides of the left leg. Note that the knee joint on the mannequin has significantly higher friction than the hip joint, resulting in low knee deflections during rhythmic training.

physiology and neuroscience. The work presented in this paper presents an embodiment and a new direction for rehabilitation that accounts for what we've learned. Our working model involves three dynamic primitives - discrete and rhythmic movement and mechanical impedances - and training under this model framework can now be implemented. As we complete the MIT Skywalker-γ prototype, the next step will involve a series of pilot experiments with stroke patients.

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