KineAssist: A Robotic Overground Gait and Balance Training Device
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Abstract — **The KineAssist is a robotic device for gait and balance training. A user-needs analysis led us to focus on increasing the level of challenge to a patient's ability to maintain balance during gait training, and also on maintaining direct involvement of a physical therapist (rather than attempting robotic replacement.) The KineAssist provides partial body weight support and postural torques on the torso; allows many axes of motion of the trunk as well as of the pelvis; leaves the patient's legs accessible to a physical therapist during walking; servo-follows a patient's walking motions overground in forward, rotation, and sidestepping directions; and catches a patient who begins to fall. Design and development of the KineAssist proceeded more rapidly in the context of a small company than would have been possible in most research contexts. A prototype KineAssist has been constructed, and has received FDA approval and IRB clearance for initial human studies. We describe the KineAssist's motivation, design, and use.**

I. INTRODUCTION

The job of a physical therapist is a demanding one. Clinicians use their own bodies to lift, move, and provide "safety nets" for patients who may be three times larger than the clinician. The intensity and duration of physical therapy sessions is often limited due to simple exhaustion of the clinician. Safety concerns prevent the clinician from challenging the patient as much as they could to enhance learning since falls or other injuries are not acceptable.

In identifying opportunities for robotics, our approach was to discover user needs through observations and interviews in physical therapy settings, determine key tasks where needs are the greatest, and assess the kinematics required to support these tasks with a robotic device.

We performed observations in a broad range of physical therapy settings in the Chicago area. These sites were chosen to encompass the range of patients, tasks, and environments where physical therapy is delivered. We observed inpatient, outpatient, and home settings. We visited both hospital-based and private clinics. We observed therapeutic tasks with both orthopedic and neurological diagnoses. Diagnostic categories included joint replacement, lumbar diagnosis, traumatic brain injury, spinal cord injury, cerebral vascular accidents (stroke), burns, pediatrics, and Parkinson's disease.

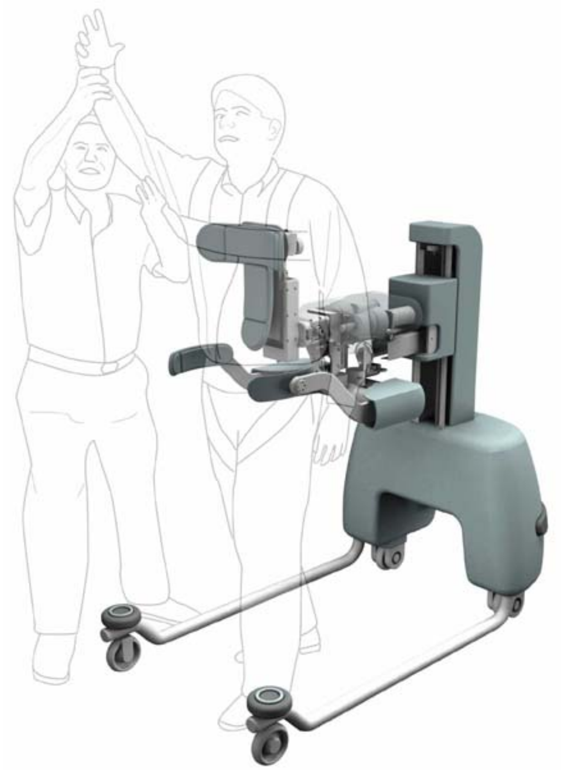

Fig. 1. Artist's rendition of the KineAssist in use. A physical therapist works with a patient on balance exercises.

The entire project team participated in the research observations. Our mix of backgrounds – from physical therapy to cognitive psychology to engineering to industrial design – was useful in generating a rich range of perspectives around what we saw and allowing us to have a shared understanding of the physical therapy world.

We identified that the area of greatest need that we could address with techniques from human-interactive robotics, was to make it possible to practice over-ground walking in combination with balance, while maintaining close

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Contact information, affiliations, videos and more information may be found at www.chicagopt.com

KineAssist is a registered trademark. A US patent application has been filed on the KineAssist.

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interaction between patient and clinician.

Addressing the problem of upper body control and balance is more important to the clinicians we interviewed than controlling motion of the legs. Clinicians are able to, and want to, control the motion of the legs manually. They are stressed by the requirements of safety and support in balance, and of trying to help the patient develop upper body competency while simultaneously addressing leg motion.

Also, while robotic assistance for leg motion has been addressed by several other groups, there has been minimal attention to balance.

Practicing gait in functional over-ground contexts, as opposed to treadmills, is widely considered desirable. Perhaps most importantly, clinicians wish to challenge patients at or beyond the patient's level of comfort, without risk of falls that could injure the clinician or the patient.

II. FOCUS ON LOCOMOTION

Locomotor ability is an important factor in determining the degree of physical disability after stroke (Perry, Garrett, Gronley, & Mulroy, 1995a). The impact of stroke on walking is significant, with only 37% of stroke survivors able to walk after the first week post-stroke (Jorgensen et al., 1995a; Jorgensen et al., 1995b). Even among those who achieve independent ambulation, significant residual deficits persist in balance and gait speed with a 73% incidence of falls among individuals with mild to moderate impairment 6 months post-stroke (Forster & Young, 1995; Keenan, Perry, & Jordan, 1984).

As a result of impairments, a majority of stroke patients have significant functional limitations during recovery, including the inability to walk. Common sensorimotor deficits following stroke that prevent ambulation include the inability to bear load through the limb or to generate propulsive forces, to move limbs swiftly through an appropriately timed trajectory, and to control lateral stability (Lehmann et al., 1987; Olney and Richards, 1996; Rogers et al., 1993). Most patients do not walk with a normal locomotor gait pattern. Instead they employ compensatory strategies to continue forward propulsion with a stable base of support and to address environmental barriers and physical perturbations. Externally based compensatory strategies include use of devices such as walkers or ankle orthotics, or the physical assistance of another person. Internally based compensatory strategies include reduced gait velocity, increased stance and double support time, knee hyperextension in stance, and hip circumduction during swing phase. Although the majority of stroke survivors will achieve some level of ambulation, there continues to be a strong need for therapeutic interventions that can reduce the long-term need for physical assistance and result in a biomechanically efficient and stable locomotor gait pattern that does not do damage over time.

Decreased speed of locomotion is one of the major characteristics that occur as a result of poststroke hemiparesis (Perry, 1969; Wagenaar & Beek, 1992; Brandstater, de Bruin, Gowland & Clark, 1983). Walking speed is an effective indicator of the degree of abnormality in gait quality, overall functional status, and clinical progress in people with hemiparesis (Dettmann, Linder & Sepic, 1987; Knutsson & Richards, 1979). Furthermore, gait speed has been found to correlate with ability to balance on either one or both lower extremities, degree of lower-extremity force recovery, Barthel Index score, degree of ambulatory independence, cadence of gait, and rating of overall gait appearance (Bohannon & Walsh 1992; Bohannon & Andrews,1990; Roth, Merbitz, Mroczek, et al., 1997).

Locomotor function post-stroke is thus a very important goal in rehabilitation. Improved locomotor function can result in greater quality of life and reduction in the risk of falls.

III. SAFETY AND CHALLENGE.

There is a need to provide safety in ways that do not diminish challenge. Safety is a paramount concern in physical therapy.

Safety concerns limit the amount of challenge a clinician can introduce in a therapeutic setting. It is well known that challenge enhances learning. For example, if a patient starts to fall over and recovers his balance, he has learned more than if he never has the chance to fall over. However, safety concerns over an injury from an actual fall tend to limit challenge opportunities like this. The clinician is prevented from practicing with the patient alone in functional environments. Sessions are confined to parallel bars or unrealistic harnessing systems that are mounted over treadmills. In current practice, functional practice is not an option due to the need for multiple people to assist in case safety is compromised. Realistic challenge has not been well integrated into clinical practice because of the limitations imposed by safety.

Clinicians try to get patients into more realistic, functional environments as quickly as they can. Patients who don't move out of the parallel bars at the appropriate stage in their rehabilitation may use the bars as a psychological crutch, preventing the development of skills and confidence in a real world setting.

IV. FUNCTIONAL LOCOMOTOR RECOVERY

Recent findings from basic science provide preliminary evidence that functional locomotor recovery is possible after stroke or spinal cord injury when intense and accurate afferent input is provided in a task-specific and repetitive manner. Treadmill training is an example of a therapeutic modality that is derived from studies of adult cats with a low thoracic spinal transection who recovered the ability to step on a moving treadmill belt after they were trained on the treadmill and provided with truncal support, stimulation to recover extensor activity, and assistance in paw placement

(Barbeau & Rossignol, 1987; de Leon et al., 1998; Lovely, et al., 1986). Investigators have found that the spinal locomotor pools, which include a central pattern generator for automatic, alternating flexor and extensor leg muscle activity, are highly responsive to phasic segmental sensory inputs associated with walking and demonstrate evidence of learning during step training (Edgerton et al.,1997a; Edgerton et al., 1997b). Repetitive practice of the task was essential to the learning. Barbeau and colleagues were the first investigators to translate this paradigm to human application for re-training walking after spinal cord injury and stroke (Barbeau et al., 1987; Finch et al., 1991; Visintin & Barbeau, 1989; Visintin & Barbeau, 1994). In their initial work, Barbeau et al. (Barbeau et al., 1987) suspended the patient over a treadmill using an overhead lift for body-weight support and clinician-provided assistance to the legs.

Task-specific training appears to be critical to the success of a locomotor training intervention post-stroke (Richards et al., 1993). Treadmill training is a method of locomotor training that closely simulates the sensory elements specific to walking such as load on the lower extremities, upright trunk posture, proper lower limb kinematics, and normal walking speeds to generate effective lower limb stepping (Edgerton et al., 1997; Behrman & Harkema, 2000). Within the past 10 years, there have been 12 studies that have specifically investigated the effects of treadmill training with or without body weight support (BWS) on post-stroke locomotor recovery. Treadmill training (with or without BWS) appears to be more effective than conventional therapy alone in locomotor recovery after stroke (Richards et al., 1993; Hesse et al., 1995a; Hesse et al., 1995b; Laufer et al., 2001; Pohl, 2002; Sullivan et al., 2002). While there is building evidence that this therapeutic modality may be beneficial in improving locomotor ability after stroke, there is little agreement or systematic study of the optimal training parameters to maximize functional outcomes (Dobkin, 1999).

Seven studies have specifically examined the effectiveness of treadmill training with individuals post-stroke (Hesse et al., 1995a; Hesse at al., 1995b; Sullivan et al., 2002; Kosak et al., 2000; Nilssson et al., 2001; Teixeira et al., 2001; Visintin et al., 1998). In all of these studies, BWSTT was effective in improving gait-related outcomes. In two separate case study series using single subject design, Hesse and colleagues (Hesse et al., 1995a; Hesse et al., 1995b) found BWSTT to be more effective in improving overground walking speed than conventional physical therapy.

Recently, Pohl et al, (2002) investigated the effects of speed training during treadmill walking in persons with slow gait post-stroke. In this study, the investigators demonstrated that, after a 4-week training period, a speed training group had significantly greater overground walking speeds compared with those who were trained on a treadmill at customary speeds and those who were trained conventionally overground.

V. ADVANCED TOOLS FOR GAIT TRAINING

A number of rehabilitation machines have been introduced recently, based on treadmills or robotics. A survey of the available treadmill or robotic devices includes the following: (1) Colombo and colleagues have designed a robotically driven gait orthosis (DGO) that operates by computer interface with a standard treadmill. This device is now commercially available under the name Lokomat (2) MIT-MANUS is an ongoing project in MIT's Newman Lab. The goal of the project is to develop, implement and test a robotic system for physical therapy and neurological rehabilitation. (3) the "Assisted Rehabilitation and Measurement (ARM) Guide", built at the Rehabilitation Institute of Chicago, is a trombone-like device designed to guide reaching movements across the workspace, and to measure multi-axis force generation and range of motion of the arm, (4) Drs. Burger and Lum at VA Palo Alto Health Care System have developed a robotic system (MIME) that assists or resists elbow and shoulder movements in three-dimensional space. (5) The AutoAmbulator is a treadmill-based device that features an overhead harness system to support body weight, mechanically powered braces to move the patient's legs and numerous sensors to track vital signs, movement, and contact speed. The AutoAmbulator's creation was funded by HealthSouth and it has received FDA approval.

Each of the robotic devices described above was designed to simulate the role that a clinician could play in manipulating a limb during exercise. In each case, there is no manual involvement of the clinician. The devices are meant to replace a clinician rather than assist a clinician. Although the above devices relieve the work of the clinician, they also eliminate the skills and expertise that is developed with training and allows the clinician to fully engage in the motor learning process with the patient.

VI. DESCRIPTION OF THE KINEASSIST

The KineAssist has been developed as a response to the clinician's need to engage in intense, locomotor-specific, body-weight supported walking training while overground and while performing functional tasks. The prototype KineAssist meets this need. It is a microprocessor controlled, motor actuated device that assists clinicians in maintaining patient safety while the patient is performing walking, and balance exercises.

The KineAssist has a small footprint and programmable modes to address the needs of both low level inpatients with impaired mobility on a basic functional level, through more advanced outpatients with fall risk. The KineAssist has an omnidirectional mobile base, which uses cobot technology originally developed by Peshkin and Colgate for assistive devices in materials handling. It uses control methodology developed for haptic display. The mechanism provides forward and turning motion for the device in order to follow a walking person, and to turn around corners.

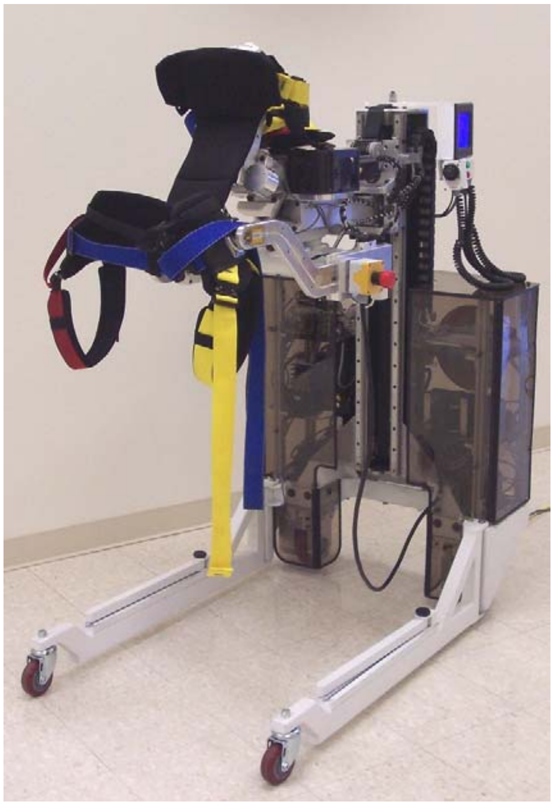

Fig. 2. KineAssist prototype

The legs of the mobile base are shown in Fig. 2 in their parallel configuration, which allows the KineAssist to pass through a standard door opening. The legs may also be angled outward 30 degrees to allow a patient more room for side-stepping. The motion of the mobile base is powered, and is highly response to the desires for motion of the patient, so that the patient does not have to pull the base. The patient's intent for motion is detected by a combination of passive sliders and integrated force sensors incorporated into the pelvic part of the patient support structure. Control algorithms move the base in response to the patient's forces and motions, so that the patient's walking and turning motions are unconstrained.

Pelvic and torso harnesses serve as the interface between the machine and the patient and provide the means of comfortably applying desired forces to the body as well as acting as a fall arrest device. The harnesses were custom designed; they are modified circus harnesses. Harnesses may seem commonplace but they can be a key factor in the success or failure of a rehabilitation device. Because body weight support protocols can apply large vertical forces, comfort is essential, and hard to achieve. Many harness systems impinge on the groin area and cause such pain that patients cannot withstand the duration of training intended.

Harness design also plays a major role in the time it takes to get a patient set up for a period of therapy. Twenty minutes is a typical set up time for other BWS systems. By a combination of good harness design and a system for harnessing while seated (rather than reclined), patients may be set up in the KineAssist in typically five minutes. In a one-hour session, a twenty minute setup time is a major deterrent to use. Our harnessing system is particularly critical because the intent of the KineAssist is to allow the clinician to challenge the patient to or beyond the patient's comfort zone. Falls are likely; the KineAssist must be able to slow and stop the patient without pain.

The KineAssist is able to produce unweighting of the patient (partial body weight support training) up to 150 pounds of vertical force. The vertical column is powered to provide this force continuously, and at the same time to easily allow the vertical motions of the pelvis and torso which are a part of normal gait. The unweighting feature is rated to 150 pounds, but the KineAssist is designed for patients up to 350 pounds, and it can safely bring such a patient to a stop after only a few inches of fall. (The threshold distance for identifying and stopping a fall is selected by the clinician).

The KineAssist includes a trunk and pelvic mechanism, allowing bending motions both left-right, forward-backwards, rotations about a person's transverse axis, and hip rotations about the forward axis. The trunk and pelvis mechanism is designed to allow patient's natural walking body dynamics to occur unimpeded while providing safety.

Equally important to the mechanical structure of the KineAssist, is the control and software structure. Because the KineAssist is intended to allow significant challenges to the patient's balance, we have incorporated a Safety Zone, limiting the patient's upper body range of motion. It is a range of trunk excursions, defined by the clinician, in which the patient can move without any assistance or hindrance from the device. At the boundary of this range the trunk support implements a compliant constraint, adjustable in position and stiffness, which catches the patient when he or she loses balance.

Postural control may be used by the clinician to set the trunk and pelvic components independently of each other in order to maintain a person in a desired posture. The prescribed posture is then actively (under computer and motor control) maintained by applying bias forces to the patient's torso. In addition, the clinician may perturb the patient by, for example, pushing on the patient's shoulders or hips. However, even though the device does not actively perturb the patient, it will actively monitor/allow the patient motions necessary to recover from the perturbation while preventing them from falling outside of the Zone of Safety, if they were unable to recover from the perturbation. Finally a stabilization function defines how much support the device gives the patient at the trunk level. This can be adjusted by the depending on how much stability he/she feels the patient requires - from a somewhat rigid embrace to completely free.

We encourage the reader to visit www.chicagopt.com/info and download the video.

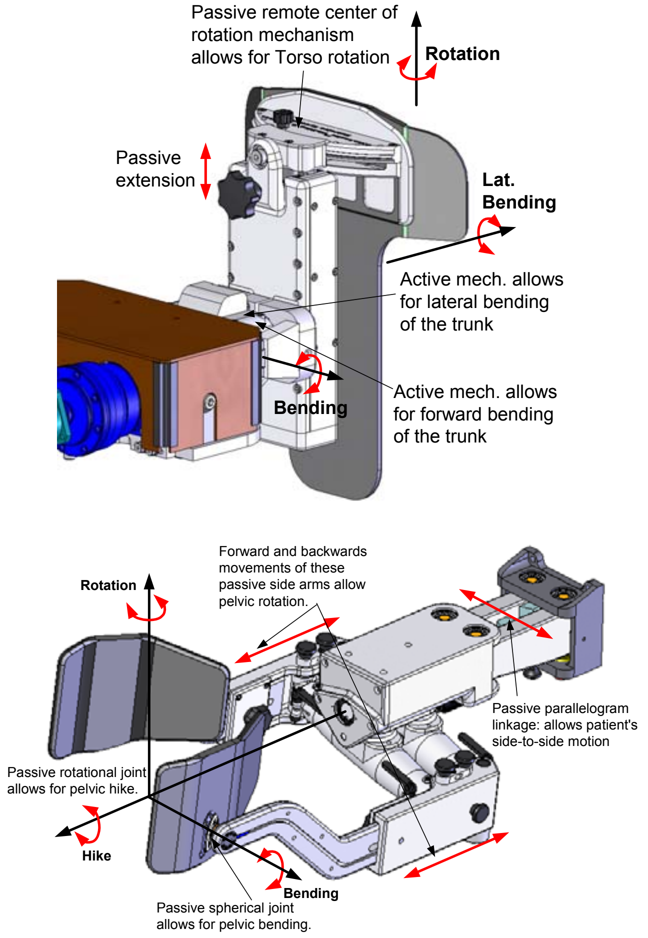

Fig. 3. (upper) Detail of trunk control mechanism. (lower) Detail of pelvis control mechanism.

VII. COMPONENTS OF THE KINEASSIST

The KineAssist is composed of a mobile base and a smart brace:

Mobile base - The mobile base is a motor actuated platform. The wheels on the mechanism provide forward and turning motion for the device in order to follow a walking person and turning around corners. The motion of the mobile base is non-traditional in several senses. First, both lateral and forward-backward motions are required – to follow the patient in side-stepping, as well as in walking. Second, the motion of the mobile base is not programmed – it moves in response to the motion of the patient.

Smart brace - The smart brace is the mechanism that supports the person's trunk and pelvis and allows natural relative movements that occur in walking and balance exercises. It incorporates the following subcomponents:

Harness – The harness serves as the interface between the machine and the patient and provides the means of comfortably applying desired forces to the body as well as acting as a fall arrest device. The harness is permanently attached to the support mechanism, which properly positions the harness for securing the patient. Furthermore, structural elements of the device serve as anchor points for straps and buckles. In addition, the harness is designed in two pieces, upper level harness to secure the torso and the lower level harness to secure the pelvis. The two piece design further simplifies harness management issues that arise while the patient is being secured.

Trunk and Pelvis mechanism - allows the persons bending motions both left/right, forward/backwards, rotations about a person's transverse axis, and hip rotations about the forward axis. The trunk and pelvis mechanism is designed to allow patient's natural walking body dynamics to occur unimpeded while providing safety. The mechanism consists of two interconnected subcomponents: the trunk support, which comprises the upper part and the pelvis support on the bottom. The trunk support attaches to the patient at chest level via the harness and is used for postural alignment, trunk perturbations, trunk stabilization, and as a trunk safety catch mechanism. In addition, the trunk support may bare some of the load related to the body weight support mode of operation. The pelvis support mechanism is used as a stabilizer (similar to the trunk support), body weight support system and as a vertical fall prevention safety mechanism.

Support Arm - the support arm supports the patient's weight and allows for natural walking motions of the pelvis in the upward/downward and side-to-side directions. The trunk and pelvis mechanism is supported by the support arm which is mounted on the mobile base.

VIII. MODES OF OPERATION

Walking - mode allows the clinician to put a patient in the device and allow him to exercise by walking over-ground (i.e. in a hallway) or over a treadmill.

Challenge - allows the clinician to challenge the patient balance as he is walking by loosening or widening the prescribed zone of safety such that the patient can explore the limits of his/her stability while maintaining safety. For example, the clinician might place obstacles in the patients path so that the patient has to walk over them or around them.

Strength Training - mode the device applies resistance in the direction of walking for strength training specific muscle groups. This is achieved by adjusting the maximum speed the device can move.

Stabilization - mode the trunk and pelvis support mechanism applies forces to compliantly support the patient's upper body. The stiffness of the support is adjustable by the clinician from fully rigid down to zero. For example, in some situations the clinician might want to focus on the patients lower extremity by stabilizing the patient's upper body.

Postural control - the patient's trunk and pelvis is placed in a certain posture by the clinician and actively maintained by the device by applying clinician-adjustable bias forces.

As the patient proceeds to perform walking exercises the machine will maintain the patients prescribed posture while allowing his/her normal gait motions; much as a clinician would do today by holding a patient's upper body in a desired posture as they walk together.

Balance reaction task including lateral movement responses

Fig. 4. A still image from a 35 second silent movie showing the KineAssist in action. The movie may be found at www.chicagopt.com/info The movie shows (1) patient rising from sit to stand, assisted or freely allowed by the KineAssist. (2) patient walking, showing free hip and torso motions about several axes (3) physical therapist assisting with patient's legs during gait. Note that the clinician's chair is pulled along by the KineAssist. (4) patient's side stepping and torso motions to allow reaching and balance (5) patient tripping and falling and being caught by the KineAssist. (The patient in the movie is a healthy individual. Both the patient and the physical therapist are employees of Chicago PT LLC.)

<u>Body Weight Support</u> - the clinician is able to unload a desired amount of body weight off of the patient's legs by lifting him. The pelvis is rigidly held and the trunk is able to move within the zone of safety.

<u>Perturbation</u> - While the patient is performing either a static or dynamic activity the device allows for the clinician to throw the patient off balance by pushing the patient at different parts of the body.

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