

Gait Rehabilitation Apparatus

Field of the Invention

The invention concerns a rehabilitation apparatus for assisting with remobilisation of a patient, including component parts thereof, and a method of gait rehabilitation concerning use of said apparatus.

Background of the Invention

Neurological impairments after injury, such as a stroke, can result in hemiparesis or partial paralysis which can deprive patients of the ability to perform activities of daily living (ADL) like walking. Stroke survivors typically show significantly reduced gait speed, shortened step length and loss of balance in their gait patterns and often experience falls. However, it has been proven that repetitive and persistent stimulation of defective parts of the brain can restore and reorganize motor functions caused by neurological disorders. Thus, there is a strong need for therapeutic interventions to do this. By reducing biomechanical inefficiency and improving unstable walking patterns independent walking and ADL could be re-achieved.

Satisfactory rehabilitation outcomes are strongly associated with a high degree of goal oriented motivation and tasks. Thus, appropriate sensory inputs through proper instruction, explanation, feedback and participation are essential to promote learning skills for the neurologically challenged. Although non-ambulatory hemiparetic patients are able to improve their walking ability through conventional rehabilitation processes these processes require excessive work by therapists in assisting walking, setting the paretic limb and controlling trunk movements. Moreover, as therapists often have to support the body-weight of the patient, the quality of the gait rehabilitation is limited due to the physical exhaustion of the therapist. Therefore the availability, duration, and frequency of training sessions are often limited. Moreover, improved walking performance of a patient is not quantified using conventional rehabilitation apparatus which means training programs have to rely on a therapists' qualitative judgment. Consequently, trial-and-error approaches are typically used.

Robotic assisted gait rehabilitation apparatus have begun to attract attention as an alternative to conventional gait rehabilitation since they facilitate or replace the physical training effort of the therapists and allow more intensive and repetitive motions. They also

increase training motivation by providing objectives and quantifiable measures of performance or by using interactive biofeedback. Treadmill based apparatus are the most prevalent robotic rehabilitation apparatus. However, this type of system provides only forward movement along a pre-determined path. This constrains a patient to a fixed platform and a pre-determined gait pattern which is not natural and so it leads to less satisfactory functional outcomes. Additionally, the lack of cycle-to-cycle variation in the kinematics and sensorimotor feedback may cause habituation to sensory input, and reduce sensory responses to weight-bearing locomotion and ultimately impair motor learning. In addition, the over-head harness body weight support (BWS) system allows only unrestricted movement in the vertical direction and restricts pelvic rotation, pelvic lateral movement - which may be useful for balancing - and hinders the generation of desired gait patterns.

The pelvis allows force transfers from the lower extremities to the trunk, contributing to the forward progression of the body and to trunk vertical support. The pelvis also moves laterally shifting body weight to each limb to maintain balance. These motions are important for energy efficient walking. It has been claimed that the fixation of the pelvis severely affects gait dynamics by shortening step width and reducing coronal trunk rotation, and by lengthening step length and sagittal trunk rotation. Therefore, fixation of the pelvis should be avoided if any natural gait is to be achieved during gait rehabilitation. Additionally, there still lies ambiguity in the assumption that walking on a treadmill can represent an actual gait over-ground in terms of body mass shifting, body mass acceleration and sensorimotor feedback such as proprioceptive input. Walking on a treadmill provides significantly greater cadence, smaller stride length and stride time as well as a reduction in the majority of joint angles, moments, power and pelvic rotation excursion compared with over-ground walking. Most of all, over-ground walking is considered as the most natural gait pattern with actual foot contact with the ground, so an over-ground walking rehabilitation apparatus is desired for increasing gait performance as well as having natural gait patterns.

Statements of the Invention

According to a first aspect of the invention there is provided a rehabilitation apparatus for assisting with remobilisation of a user comprising a ground-engaging frame adapted for omni-directional movement and attached thereto at least one upstanding member for supporting:

i) a variable body weight off-loading device whereby a user's body weight can be selectively off-loader by a chosen amount and, operably coupled thereto, ii) a pelvic support brace wherein said brace has associated therewith a control device comprising a force/torque sensor whereby the motion of the user can be monitored and at least one defined period of the gait cycle or when the motion deviates from an expected pattern said body weight off-loader is activated to take a pre-selected amount of body weight thereby supporting a user during the gait cycle or motion deviations.

This apparatus allows unrestricted pelvic motion during rehabilitation and selective off-loading of a user's body weight during use which provides the requisite stability to encourage confidence and progress during rehabilitation. Moreover, the apparatus allows a user to move in any direction under the users' own control to avoid the inhibition of sensorimotor input.

In a preferred embodiment of the invention said control device comprises a recording means whereby use of the apparatus by a user is recorded for subsequent inspection and/or downloading. Yet preferably said force/torque sensor of said control device has multiple degrees of freedom, ideally three or more ideally six degrees of freedom. More ideally still, said control device comprises virtual mass and damper parameters which act as low pass filters whereby 'high frequency' noise generated by vibration and shock are filtered. Preferably said parameters operate according to the following expression:

$$G(s) = \frac{V(s)}{F(s)} = \frac{1}{Ms + B}$$

where M is the mass, and B is the damping parameter. The time response of the system for a step input is (2).

$$v(t) = \frac{F}{B}(1 - e^{-t/\tau}) \quad (2)$$

where τ is the time constant defined by $\tau = M/B$. A linear 3 DoFs mass-damper model for the over-ground device system is defined in (3).

$$\begin{bmatrix} M_x & 0 & 0 \\ 0 & M_y & 0 \\ 0 & 0 & J_z \end{bmatrix} \begin{bmatrix} \dot{V}_x \\ \dot{V}_y \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} B_x & 0 & 0 \\ 0 & B_y & 0 \\ 0 & 0 & B_z \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ \omega \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix} \quad (3)$$

where $M_{x,y}$ and $B_{x,y}$ are mass and damper and J_z is moment of inertia and B_z is damping in vertical axis.

More preferably still said control device also comprises an electromyograph (EMG) and/or an inertial measurement unit (IMU) sensor based biofeedback system.

In yet a further preferred embodiment of the invention said pelvic support brace is in the form of a harness, ideally, comprising a rear and two side engaging members against which a user can be supported. More ideally still, said members are adapted for snugly, but comfortably, engaging about the pelvic region of a user. Ideally said members are adjustable, typically, though not exclusively, manually adjustable. Yet more preferably, said pelvic support brace is adapted for vertical movement, and so can be moved up or down with respect to said upstanding member, whereby the position of said brace can be adjusted to accommodate users of different heights.

In yet a further preferred embodiment of the invention said body weight off-loading device moves the trunk and/or pelvis in a vertical plane. Thus, preferably, said body weight off-loading device comprises a load-bearing support adapted ideally for movement in a vertical plane, typically with respect to the upstanding position of a user. Ideally, the body weight off-loading device is variably powered to provide a variable amount of support for a user during different parts of a gait cycle. Thus, in use, in a part of the gait cycle where a user experiences difficulties, the body weight off-loading device is powered to provide support for a user and in those parts of the gait cycle where help is not needed, power to the body weight off-loading device is diminished. In one embodiment of the invention said body weight off-loading device comprises a slidable bar adapted for vertical movement and to which said brace is attached and further which can be made to move up or down by variable amounts whereby the body weight of different height users can be selectively off-loaded.

In yet a further preferred embodiment of the invention said apparatus is provided with a trunk engaging support or brace which is mounted for pivotal movement, additionally and ideally said trunk engaging brace is mounted for bending in the anterior-posterior plane.

In yet a further preferred embodiment of the invention said ground-engaging frame is provided with at least one active split offset castor (ASOC) unit comprising two coaxial wheels. Ideally, a pair of such units is provided at the rear of said frame. More ideally still said frame is rectilinear and comprises two parallel side members and at least one, ideally rearward, connecting cross-member. In this arrangement one of said ASOC units is provided at the rear of each side member and either a steering wheel or a trailer wheel is provided at the front of each side member.

According to a second aspect of the invention there is provided a control device for use in an apparatus according to the invention comprising any one or more of the afore described features.

- 5 According to a third aspect of the invention there is provided a method of gait rehabilitation comprising use of said apparatus of the invention.

Ideally, said use involves positioning a user in said brace, preferably setting said control device such that the mass and damper parameters of the forward-backward and/or lateral
10 movement are within a desirable range. Then allowing said user to move in said apparatus.

For the purpose of illustration only, and without limiting the nature of the invention, said mass and damper parameters may be set in the following ranges: Mass is between 8-12Kg including all 1Kg intervals there between and Damper is between 80-140Ns/m including all
15 1Ns/m intervals there between.

In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprises", or variations such as "comprises" or "comprising" is used in an inclusive sense
20 i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

All references, including any patent or patent application, cited in this specification are hereby incorporated by reference. No admission is made that any reference constitutes
25 prior art. Further, no admission is made that any of the prior art constitutes part of the common general knowledge in the art.

Preferred features of each aspect of the invention may be as described in connection with any of the other aspects.

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Other features of the present invention will become apparent from the following examples. Generally speaking, the invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including the accompanying claims and drawings). Thus, features, integers, characteristics, compounds or chemical moieties
35 described in conjunction with a particular aspect, embodiment or example of the invention

are to be understood to be applicable to any other aspect, embodiment or example described herein, unless incompatible therewith.

Moreover, unless stated otherwise, any feature disclosed herein may be replaced by an alternative feature serving the same or a similar purpose.

Throughout the description and claims of this specification, the singular encompasses the plural unless the context otherwise requires. In particular, where the indefinite article is used, the specification is to be understood as contemplating plurality as well as singularity, unless the context requires otherwise.

An embodiment of the present invention will now be described by way of example only with reference to the following wherein:

Figure 1 shows a perspective view of a rehabilitation apparatus in accordance with the invention;

Figure 2 shows in diagrammatic form the omni-directional nature of the frame of the apparatus;

Figure 3 shows a perspective view of an active Body Weight Support System of the apparatus of the invention;

Figure 4 shows a perspective view of a Mass-damper Admittance Control System;

Figure 5 shows a perspective view of the pelvic support system; and

Figure 6 shows (a) forward-backward movement as a function of gait (b) lateral movement as a function of gait and (c) rotational movement as a function of gait velocity. These velocities of CoM are shown with/without the apparatus of the invention.

General Design Description

The overall system has been developed and a prototype of the apparatus is shown in Fig.1. The system includes an omni-directional platform, a human-machine interface with anforce/torque (FT) sensor, and active BWS system, an EMG and IMU sensor based biofeedback system. With this system, a patient can move in any direction without being constrained in one plane of movement, and the body weight can be supported by the active

BWS system so that a therapist can facilitate the gait rehabilitation more effectively and practically with less physical effort. The specific description follows below.

Referring firstly to figure 1, there is shown an apparatus in accordance with the invention. It comprises a ground-engaging frame (1) of a rectilinear construction having a pair of parallel side members (2) connected together by a pair of cross-members (3). The cross-members are positioned rearward of the midline and so the front of the frame provides an enclosure in which a user's feet can be positioned. Attached, centrally to the cross-members is an upstanding square-sectioned frame (4) which houses a conventional lifting apparatus which may take any preferred form such as a conventional hydraulic lift for example. Those skilled in the art will appreciate that the invention is not to be limited by the nature of the lifting apparatus rather any lifting apparatus suitable for purpose may be selected to work the invention.

Attached to the lifting apparatus is a pelvic support brace (5). This is best understood by referring to figure 3 and figure 5. The pelvic brace is in the form of three pelvic engaging pads: a rear pad (6) and two side pads (7). Although not shown, these pads are adjustable to frictionally, but relatively comfortably, engage with the pelvic region of a user. Those skilled in the art will appreciate that the invention is not to be limited by the nature of the pelvic support brace rather any pelvic support brace suitable for purpose may be selected to work the invention. In use, the pelvic pads wrap around the users' waist especially in the region of the pelvis and greater trochanter femur, and they are designed to be adjustable according to a subject's anatomy. The pelvic pads are mounted on a pelvic brace (8) with spherical flange bearings (9), so that pelvic anterior-posterior tilt can be provided. The back of the pelvic brace is connected to swivel joint (10) covered by fiberglass. The property of the fiberglass is compliant yet stiff enough to support the truck movement of the anterior superior iliac spine. Thus, pelvic obliquity can be carried out. A trunk support brace (11) may be added and connected via a swivel joint (12). The swivel joint can provide lateral movement of the trunk support so that the trunk support can bend laterally. In addition, the trunk support brace is linked to the swivel joint with the fiberglass so that anterior-posterior trunk bending can be provided.

The pelvic support brace also comprises a FT sensor (13) which is located here to be near the Centre of Mass (CoM) of the body of a user whereby the force/torque (F/T) of the user's body can be accurately transferred to the FT sensor.

To stabilize any oscillations in the force/torque (F/T) signals provided by a user's body an admittance control system is used which consists of selectable virtual mass and damper parameters that provide natural and intuitive interaction between a user and the apparatus. The force and torque of the CoM of the body is translated through the pelvic support brace and is detected by the FT sensor. The detected force and torque are translated into velocities through the admittance control system. The mass-damper model of the admittance control system acts as a low pass filter so that the high frequency noise due to shock and vibration from the system can be reduced.

Thus a user standing within the ground-engaging frame is positioned within the pelvic support brace and once comfortable is ready to use the apparatus.

Once the control device is activated the Mass and Damper parameters are chosen (if they have not already been chosen) and the user is given a certain selected amount of lifted support provided by activation of the lifting apparatus. The F/T sensor monitors the use of the apparatus by the user and interacts with the lifting apparatus to control the amount of assisted support the apparatus offers a user during various stages of use of same. For example, in some circumstances the control device can be set to offer further lifting support during defined stages of the gait cycle which stages will be determined by the nature of the injury the apparatus is working to overcome. Additionally, or alternatively, said control device can be set to offer further lifting support when a user's gait deviates from a defined one or more parameters such as degree of lateral and/or rotational movement.

There is a strong need to support pelvic motion without being constrained in any direction of movement since a patient has to practice normal and realistic gait in a natural way to recover from motor defects. We have therefore used an omni-directional frame in our invention. This is best understood by referring to figure 2. The design we have used for this frame includes an active split offset castor (ASOC) unit (14) consisting of two coaxial conventional wheels. This system has a number of advantages such as use of a simple structure, high energy efficiency, and robust mobility on uneven terrain. Our testing of this design leads us to predict that over-ground walking with omni-directional mobility can result in natural locomotion in environments congested with static and/or dynamic obstacles and even narrow aisles. In our preferred apparatus we have used a pair of ASOC units, each one attached to the rear of each side members (2).

With the figure 2 design, 3 Degrees of Freedom of pelvic motion can be supported: forward-backward, side-to-side (lateral) and rotational movement. Consider a platform that is carried by active split offset castors units that move on a plane, the central point of the platform VCX, VCY, and its' angular velocity, Ω can be defined by the velocity of each wheel, V11, V12, V21, and V22 (Fig. 2). Therefore, the three Degrees of Freedom of the central point can be controlled by the velocity of each wheel. This system has a number of advantages which include use of simple structure, high energy efficiency, and robust mobility on uneven terrains.

Body Weight off-loading or Support (BWS) System

Biomechanical demands of a walking task can be controlled by modulating walking speed and supporting the load caused by body weight. Neurological damage to brain motor function can result in a patient suffering from the loss of BWS ability. Thus our integrated BWS system can play an important role in gait rehabilitation, particularly for individuals who have suffered a stroke or spinal cord injury. Therefore, offloading a certain percentage of body weight allows a neurologically challenged patient with weak muscles to practice gait training more efficiently. We have therefore designed an active BWS system that provides a selectively controllable amount of body support but still allows the pelvis and trunk to move vertically to perform a natural-like gait pattern. A users' body weight can be actively measured via the vertical axis of the FT sensor, and a constant offloading weight can be comfortably imposed by the lifting device and pelvic brace controlled via the control device during dynamic walking (Figure 3).

Human-machine interface

The interface between the apparatus and a user is a pelvic support harness combined with a FT sensor, ideally, we prefer to use a FT Sensor having six Degrees of Freedom. Given that the robotic rehabilitation apparatus always interacts with a user, the design has to take into account a user's gait characteristics. A user generally has physical contact with the pelvic harness system for support. A key requirement is that the interface should be able to adapt a users' intention for different levels of physical and mental functionality. It also should provide a natural feeling for a user and be easy for a user to learn and to use.

A user and the apparatus have direct physical interaction at the Centre of Mass (CoM) of the body which is the pelvis, the force and torque of the CoM can be assumed to represent the walking movement. These force and torque signals contain a user's intention as well as gait information of the user. However, using force signals directly to generate motion can

result in unstable motion due to fluctuation of the signals. We have therefore designed an admittance control method which uses virtual mass and damper parameters to provide a natural and intuitive interaction between user and apparatus [22]. As can be seen in the Figure 4, the force and torque of the CoM of the body is translated through the pelvic support harness and detected by the force/torque sensor (13). The detected force and torque are translated into velocities through the admittance control system. A mass-damper model acts as a low pass filter so that any high frequency noise due to shock and vibration from the system can be reduced. Use of a damping parameter returns output of the FT signal to equilibrium as quickly as possible without oscillating. Thus a user can interact with the system and have a different feel of the system by tuning these parameters.

For example, with F as the user input force in the respective directions (forward-backward, lateral and rotational movement) and V as the system response in the same direction, the transfer function of the system is defined in (1).

$$G(s) = \frac{V(s)}{F(s)} = \frac{1}{Ms + B} \quad (1)$$

where M is the mass, and B is the damping parameter. The time response of the system for a step input is (2).

$$v(t) = \frac{F}{B}(1 - e^{-t/\tau}) \quad (2)$$

where τ is the time constant defined by $\tau = M/B$.

A linear 3 DoFs mass-damper model for the over-ground apparatus system is defined in (3).

$$\begin{bmatrix} M_x & 0 & 0 \\ 0 & M_y & 0 \\ 0 & 0 & J_z \end{bmatrix} \begin{bmatrix} \dot{V}_x \\ \dot{V}_y \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} B_x & 0 & 0 \\ 0 & B_y & 0 \\ 0 & 0 & B_z \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ \omega \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix} \quad (3)$$

where $M_{x,y}$, and $B_{x,y}$ are mass and damper and J_z is moment of inertia and B_z is damping in vertical axis.

Functional electrical stimulation (FES)

Functional electrical stimulation (FES) is a method for activating sensory-motor systems by delivering stimulating current to the targeted nerves to induce muscle contraction. FES can help patients with drop foot to follow correct gait kinematics. FES training is not only portable and inexpensive; it provides sensorimotor integration through electromyography (EMG)-triggered activation. For patients who are unable to execute the precise coordinated movements of gait, FES can improve volitional activation, reduce spasticity and improve out-of-synergy coordination and reduce abnormal co-contraction. Evidence suggests that the combination of bodyweight supported treadmill training combined with FES produced

better gait coordination and function than training without FES. In using FES for gait rehabilitation, the key is to detect the gait phase accurately so that electrical signals can be applied at the correct time to produce proper gait pattern. We therefore attach EMG sensors (15) and inertial measurement (IMU) sensors (16) to an individual and use signals generated by the former sensors to decide the target for stimulation and the IMU sensors for accurate gait phase detection.

Gait Experiment

The efficient use of the system depends on choosing the most appropriate virtual mass and damper parameters of the admittance control, these parameters, which represent normal gait for each user, are user dependent and should be established for each user. In the following description the mass and damper parameter of the forward-backward and lateral movement were experimentally chosen as $M_{X,Y} = 10$ kg, and $B_{X,Y} = 120$ Ns/m among $M_{X,Y} = 8, 10, 12$ kg, and $B_{X,Y} = 80, 100, 120, 140$ Ns/m. The moment of inertia, J_z , and the damping B_z of rotational movement were selected as J_z with $3 \text{ kg}\cdot\text{m}^2$ and B_z with $30 \text{ N}\cdot\text{s}$. Because our goal was to investigate the alteration of kinematics of CoM when a user was walking with the apparatus the velocity profiles with and without the apparatus were observed during gait to test the feasibility of the apparatus.

Experiment without the Apparatus

For a reference of normal gait trajectory of CoM, 5 healthy young subjects (average age: 27.25 years, height: 172.25 cm, and weigh: 62.63 kg) participated in this study. All subjects were instructed to walk naturally with their preferred speed on a 10m distance walk way in a gait lab. 4 markers were attached on the landmarks of the pelvis; left and right anterior-superior iliac spine, and left and right posterior-superior iliac spine. 8 high speed optical cameras (Vicon, Oxford, UK) captured the 3D position of the reflective markers with a sampling rate of 100Hz. All subjects were instructed to walk more than 3 successful trials. The raw kinematic data was pre-processed through customized software (Nexus, Oxford, UK) provided by a Vicon motion capture system. The 3D marker information were low-pass filtered using a 4th order Butterworth filter with cutoff frequency of 6Hz and these pre-processed data were extracted into Matlab program to calculate positions of the CoM such as forward-backward, lateral, and rotational movements during gait. The velocities of CoM were obtained by differentiating the positions with respect to time.

Gait Experiment with the Apparatus

A subject aged 29 years, height of 171.5 cm, and weight of 72 kg participated in this experiment. The subject was asked to wear the harness and was securely attached to the apparatus of the invention. The subject walked on the 10 m walkway with a preferred gait speed. The mass and damper parameters had been selected as aforementioned. The detected force and torque of the CoM were translated into velocities through the admittance control model. The forward-backward, lateral, and rotational velocities obtained from admittance control were analyzed in this study.

Results

The velocities from 19 strides without apparatus, and 3 strides with the apparatus were analyzed and shown in Figure 6. The results of the forward-backward velocity without the apparatus are presented in Figure 6(a). The forward-backward velocity without the apparatus was 1.2 m/s at the initial contact (IC) and reduced to 0.9 m/s at the loading response (LR) phase. It was increased again during mid-stance (MSt) to terminal stance (TSt) when the opposite limb was moving forward. In sequence, the velocity was decreased during double support phase. Therefore, the velocity of forward movement showed a W shape during gait showing the mean velocity around 1.0 m/s. The apparatus did not alter the velocity profile of CoM but the mean velocity was relatively reduced to around 0.5 m/s. The results of the lateral velocity are presented in Figure 6(b). The lateral velocity was -0.15 m/s at the IC and increased to 0.15 m/s at the TSt phase. It was decreased again during swing phase. There was no meaningful change in lateral velocity profiles between with and without the apparatus showing that the apparatus can support forward-backward and lateral movements during the gait. Finally, rotational movement also could be achieved with the apparatus as can be seen in the Figure 6(c). The excursion of rotational velocity profile had no meaningful changes compared with the profile without the apparatus.

Discussion

This study has developed and testified a novel robotic over-ground gait rehabilitation apparatus.

The omni-directional mobility overcomes one of the major limitations of a treadmill based rehabilitation apparatus where movement is constrained in a forward direction. Using this omni-directional mobility, a user can spontaneously move in any direction and any configuration. Specifically, the apparatus can support forward-backward and lateral movement as well as rotational movement during walking. Stroke survivors tend to overuse or exaggerate pelvic movements to compensate the abnormal gait pattern and avoid falling

down during the swing phase of the gait cycle. Previous studies have proven that stroke survivors have increased anterior pelvic tilt, dropped contra-lateral pelvic in coronal plane and retracted side of pelvic in transversal plane [23]. In addition, Karen and his colleagues claimed that the pelvic lateral displacement was significantly increased for the stroke survivors to maintain deteriorated balance ability during walking [24]. Abnormal pelvic movements have triggered a strong need to support or to constrain the pelvic motion by putting the pelvic movement into the normal range of motion of gait.

In other words, the rehabilitation apparatus should be able to support the lateral movement but at the same time constrain pelvic motions in case the lateral displacement is highly exaggerated. The degree of support can be made through the information detected by the FT sensor embedded on the pelvis. In addition, the users can actively interact with this system so that the apparatus can be under the users' own control.

In this study we experimentally investigated proper virtual mass and damper parameters of the admittance control system to evaluate the performance of the developed apparatus. Although the forward-backward gait velocity was relatively reduce with the developed apparatus, the other velocity profiles (with and without the developed apparatus) showed no meaningful changes confirming the feasibility of the apparatus. However, when both the mass and damping were relatively high ($M = 12$ kg and $B = 140$ Ns/m), the apparatus was too heavy to carry and the mean gait velocity was significantly reduced (0.3 m/s). On the contrary, for models with small mass (8 kg) and damping (80 Ns/m), the motion was extremely oscillatory because the response was too sensitive. However, with 10kg mass and 120 Ns/m damping the system showed optimized movements for a normal gait.

The pelvic support body weight unloading system was mounted in this apparatus to provide comfortable off-loading and natural up-down movement in gait rehabilitation. This off-loading system can support the pelvic up-down movement, so that 4 Degrees of Freedom of pelvic motions can be supported by this apparatus.

In summary, the system has the following advantages over existing systems:

Natural and realistic over-ground gait training can be achieved through the omni-directional mobile platform.

Avoiding pelvic restriction gives additional degrees of freedom which makes the gait natural, but leads to a mechanically more complex design. The walker simplifies the

mechanical design for pelvic motion support by including omni-directional mobility, BWS support system and pelvic motion support harness (PMSH).

With the omni-directional platform and pelvic motion support brace the unrestricted pelvic lateral and rotational movements can be accomplished.

- 5 The force/torque sensor and admittance based interface provide an intuitive human-machine interaction control and enables more freedom in effective control methodology design.

The active body weight support system can replace or facilitate the vertical motion of the truck while maintain the percentage of body-weight off-loading.

- 10 The quantification of gait performance using wearable motion capture system will help to conduct extensive neuroscience research on human sensory and motor functions.

This device has the potential to improve the mobility of the neurologically challenged by providing natural gait patterns and these findings call attention to the possible further studies on extensive human sensorimotor learning systems

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References

- [22] H. Y. Yu, M. Spenko, and S. Dubowsky, "An adaptive shared control system for an intelligent mobility aid for the elderly," *Autonomous Robots*, vol. 15, no. 1, pp. 53-66, Jul, 2003.

- [23] J. J. Salazar-Torres, B. C. McDowell, C. Kerr, and A. P. Cosgrove, "Pelvic kinematics and their relationship to gait type in hemiplegic cerebral palsy," *Gait Posture*, vol. 33, no. 4, pp. 620-4, Apr, 2011.

- 25 [24] K. J. Dodd, and M. E. Morris, "Lateral pelvic displacement during gait: abnormalities after stroke and changes during the first month of rehabilitation," *Arch Phys Med Rehabil*, vol. 84, no. 8, pp. 1200-5, Aug, 2003.

Claims

1. A rehabilitation apparatus for assisting with remobilisation of a user comprising a
 5 ground-engaging frame adapted for omni-directional movement and attached thereto at least one upstanding member for supporting:
 - i) a variable body weight off-loading device whereby a user's body weight can be selectively off-loaded by a chosen amount and, operably coupled thereto,
 - ii) a pelvic support brace wherein said brace has associated therewith a
 10 control device comprising a force/torque sensor whereby the motion of the user can be monitored and at least one defined period of the gait cycle or when the motion deviates from an expected pattern said body weight off-loader is activated to take a pre-selected amount of body weight thereby supporting a user during the gait cycle or motion deviations.
- 15 2. The rehabilitation apparatus according to claim 1 wherein said sensor has six degrees of freedom.
3. The rehabilitation apparatus according to claim 1 or 2 wherein said control device comprises mass and damper parameters that can be selectively controlled or set and so used as filters to determine the amount of force/torque accommodated by
 20 the apparatus.
4. The rehabilitation apparatus according to claim 3 wherein said mass (M) and damper (B) parameters are set within the following ranges, respectively:
 $M_{x,y} = 8-12 \text{ kg}$, and $B_{x,y} = 80-140 \text{ Ns/m}$.
5. The rehabilitation apparatus according to claim 4 wherein said mass and damper
 25 parameters are $M_{x,y} = 10 \text{ kg}$, and $B_{x,y} = 120 \text{ Ns/m}$.
6. The rehabilitation apparatus according to any one of claims 1-5 wherein said control device comprises a recorder whereby use of the apparatus by a user is recorded for subsequent inspection and/or downloading.
7. The rehabilitation apparatus according to any one of claims 1-6 wherein said
 30 control device comprises an electromyograph (EMG) and/or an inertial measurement unit (IMU) sensor based biofeedback system.
8. The rehabilitation apparatus according to any one of claims 1-6 wherein said pelvic support brace comprises a rear and two side engaging members against which a user can be supported:
- 35 9. The rehabilitation apparatus according to claim 8 wherein said members are adjustable.

10. The rehabilitation apparatus according to any one of claims 1-9 wherein said body weight off-loading device is adapted to move the trunk and/or pelvis of a user in a vertical plane.
- 5 11. The rehabilitation apparatus according to claim 9 wherein said body weight off-loading device comprises a vertical, slideable load-bearing support adapted for movement in a vertical plane.
12. The rehabilitation apparatus according to any one of claims 1-11 wherein said ground-engaging frame is provided with at least one active split offset castor (ASOC) unit comprising two coaxial wheels.
- 10 13. The rehabilitation apparatus according to claim 12 wherein said ground-engaging frame comprises a pair of said units.
14. The rehabilitation apparatus according to claims 12 or 13 wherein said frame is rectilinear and comprises two parallel side members and at least one rearward connecting cross-member wherein said ASOC unit is provided at the rear of each side member and either a steering wheel or a trailer wheel is provided at the front of each side member.
- 15 15. A control device for use in an apparatus according to any one of claims 1-14 wherein said control device has any of the features according to claims 1 and 3-7.
16. A method of gait rehabilitation comprising use of the apparatus according to claims 1-14.
- 20