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Compliant bimanual rehabilitation device and method of use thereof

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(54) **COMPLIANT BIMANUAL REHABILITATION DEVICE AND METHOD OF USE THEREOF**

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A61H 1/00 (2006.01)

(52) **U.S. Cl.**
CPC ***A61H 1/0274*** (2013.01); ***A61H 1/00*** (2013.01)

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USPC 601/5, 23, 24, 33
See application file for complete search history.

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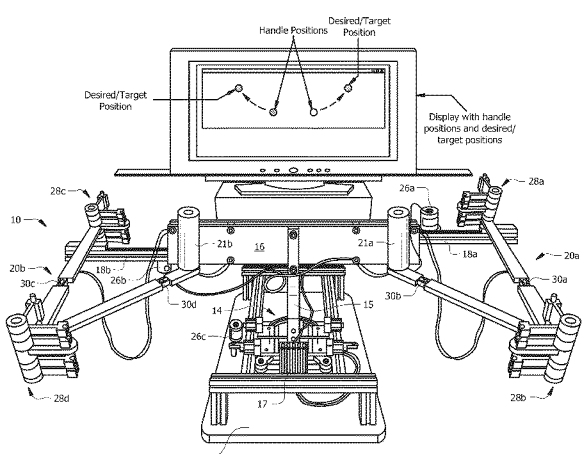
(57) **ABSTRACT**

A compliant bimanual rehabilitation system. The device allows for the user or operator's hands to be coupled with a variety of coupling stiffnesses and in a variety of symmetry modes, leading to enhanced rehabilitation of the impaired arm. Structurally, the device includes a carrier assembly slidably coupled to a base along a y-axis, an upper assembly rotatably coupled to the carrier assembly along a z-axis, handle slides slidably coupled to the upper assembly along an x-axis, compliant handle assemblies coupled to the handle slides, and handles coupled to the compliant handle assemblies. Encoders and load cells can also be positioned accordingly to monitor the position of the components and force applied to the device. Spring stacks can be coupled to the compliant handle assemblies to adjust coupling stiffnesses. The handles are indirectly linked to each other to facilitate rehabilitation of the paretic arm using the sound arm.

17 Claims, 14 Drawing Sheets



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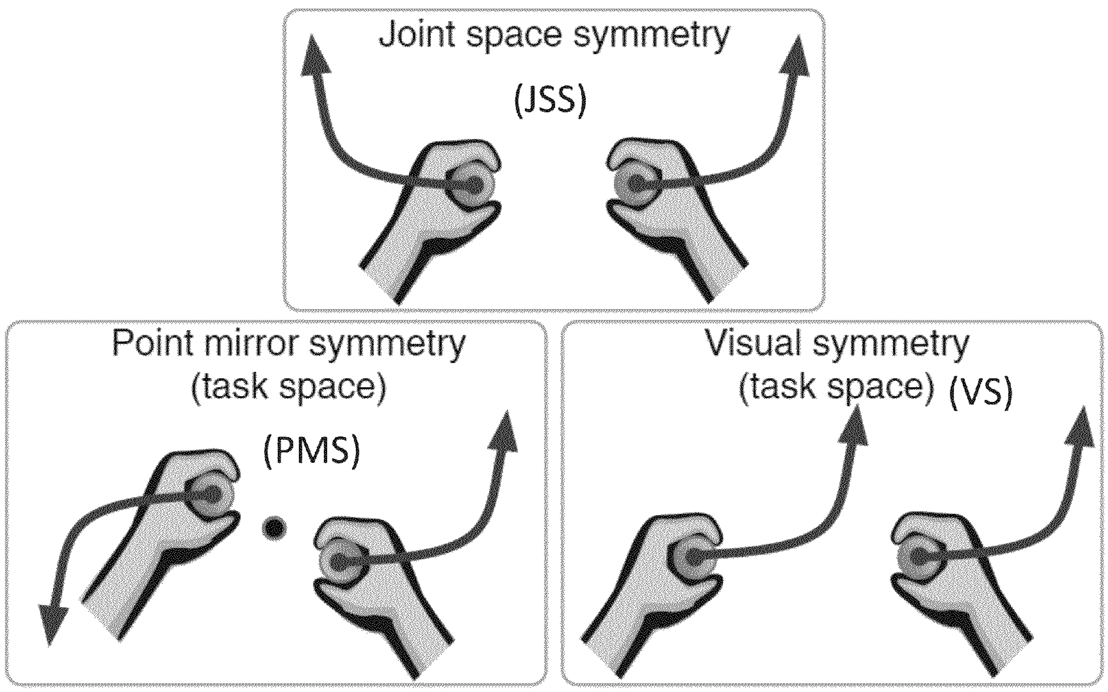
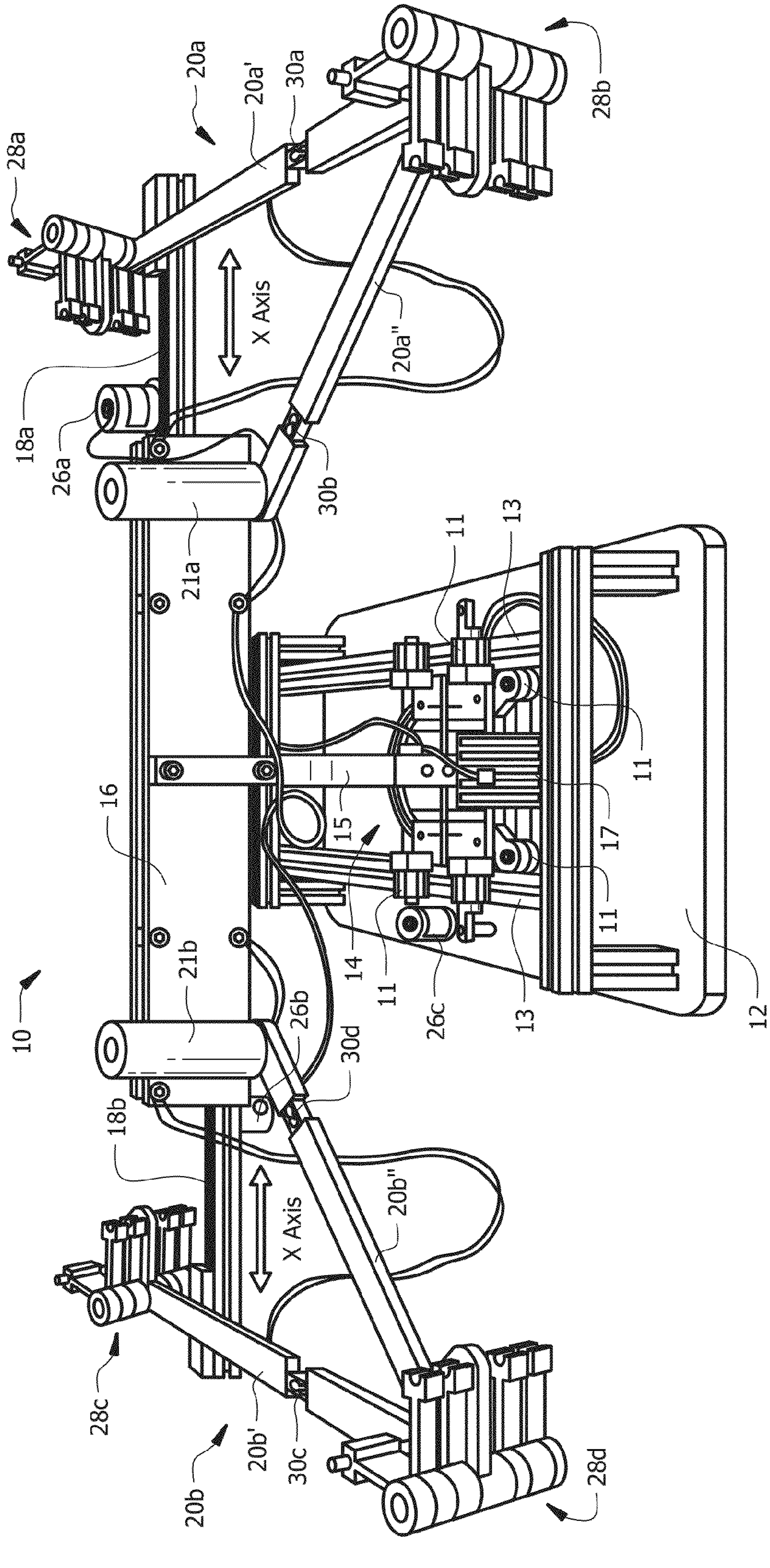


FIG. 1 (prior art)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13
14
15
16
17
18a
18b
20a
20a'
20a''
20b
20b'
20b''
21a
21b
26a
26b
26c
28a
28b
28c
28d
30a
30b
30c
30d
X Axis
X Axis

FIG. 2

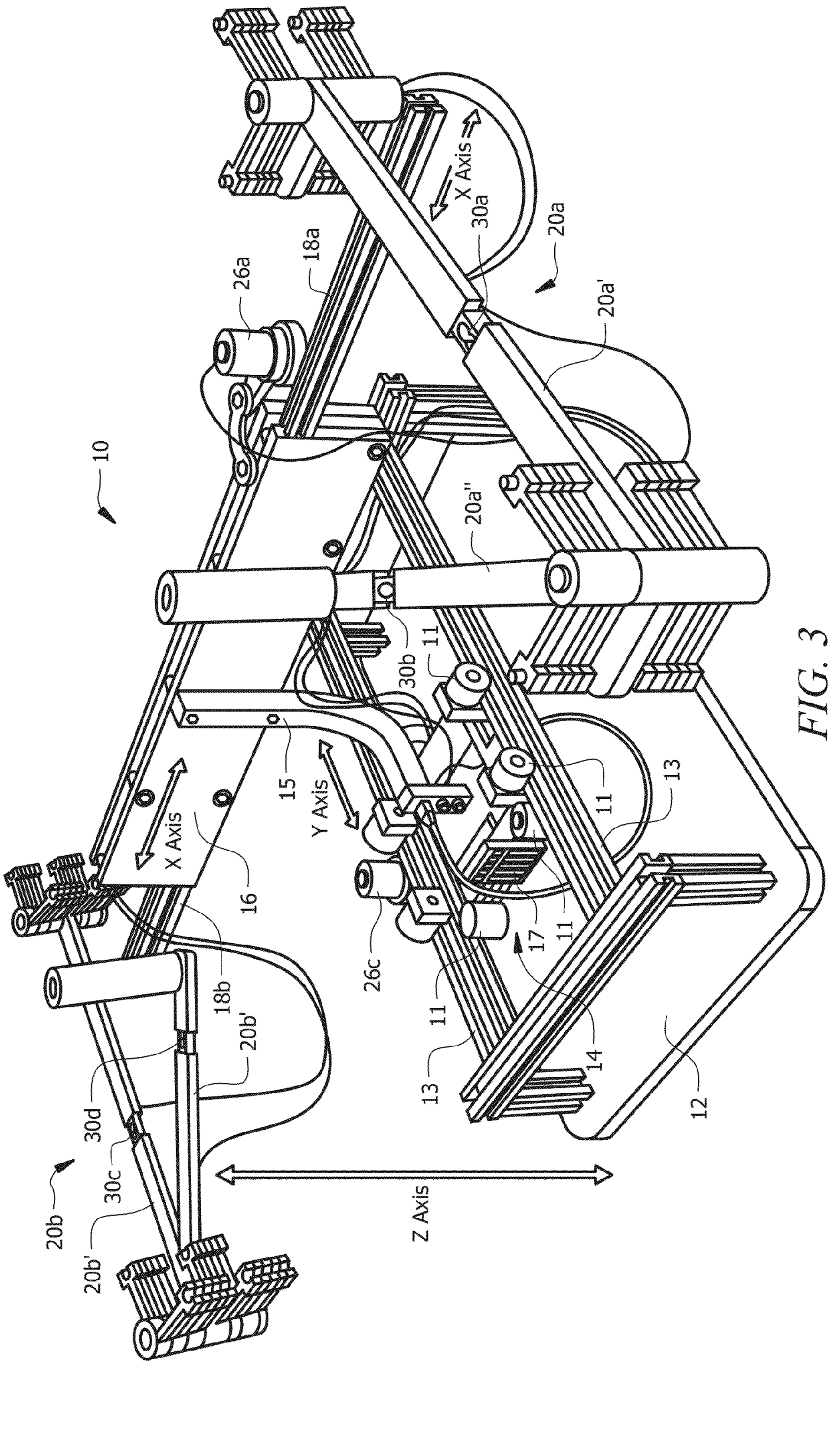

10
26a
18a
30a
X Axis
20a
20a'
20a''
30b
11
11
13
11
15
Y Axis
X Axis
16
17
11
26c
14
11
11
13
12
18b
20b'
30d
30c
20b
20b'
Z Axis

FIG. 3

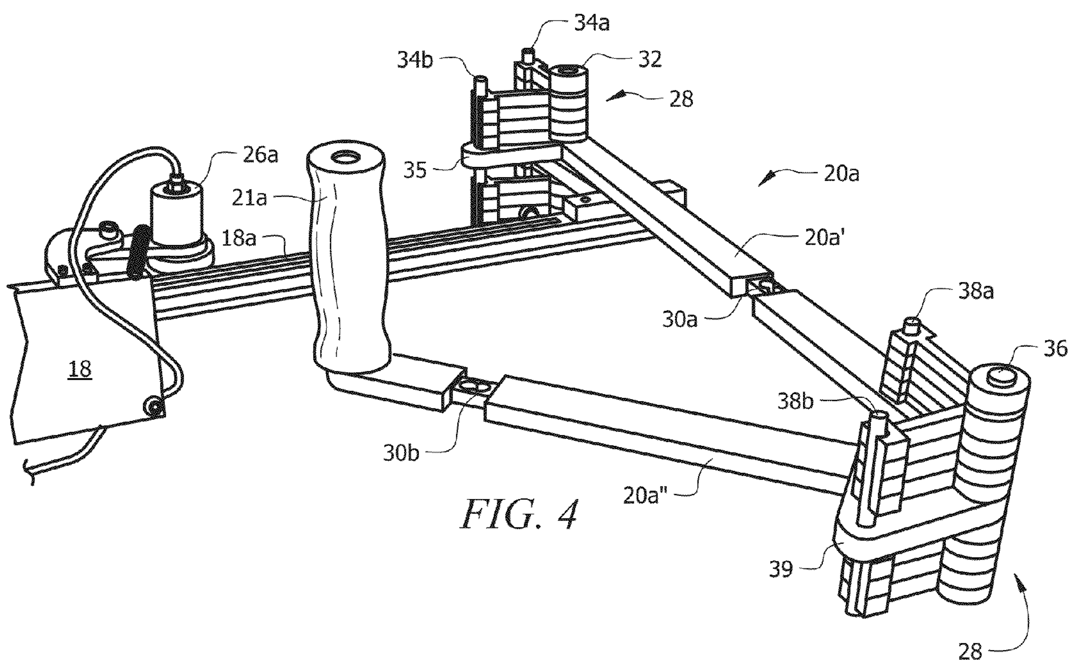

34a
34b
32
28
26a
35
20a
21a
18a
20a'
38a
30a
36
18
38b
30b
20a"
39
28

FIG. 4

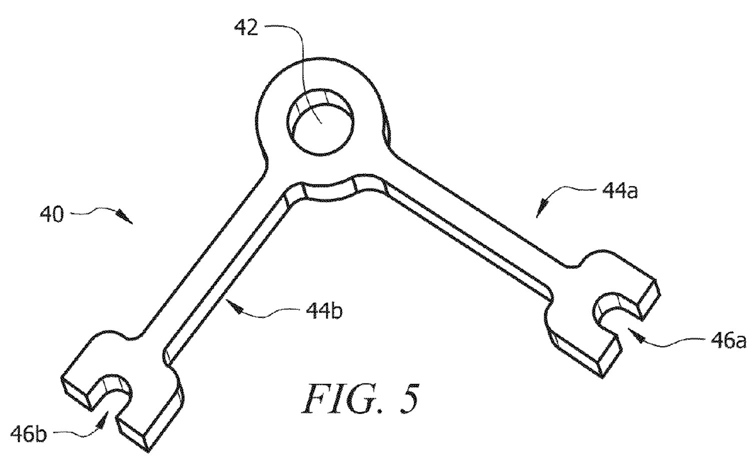

42
40
44a
44b
46a
46b

FIG. 5

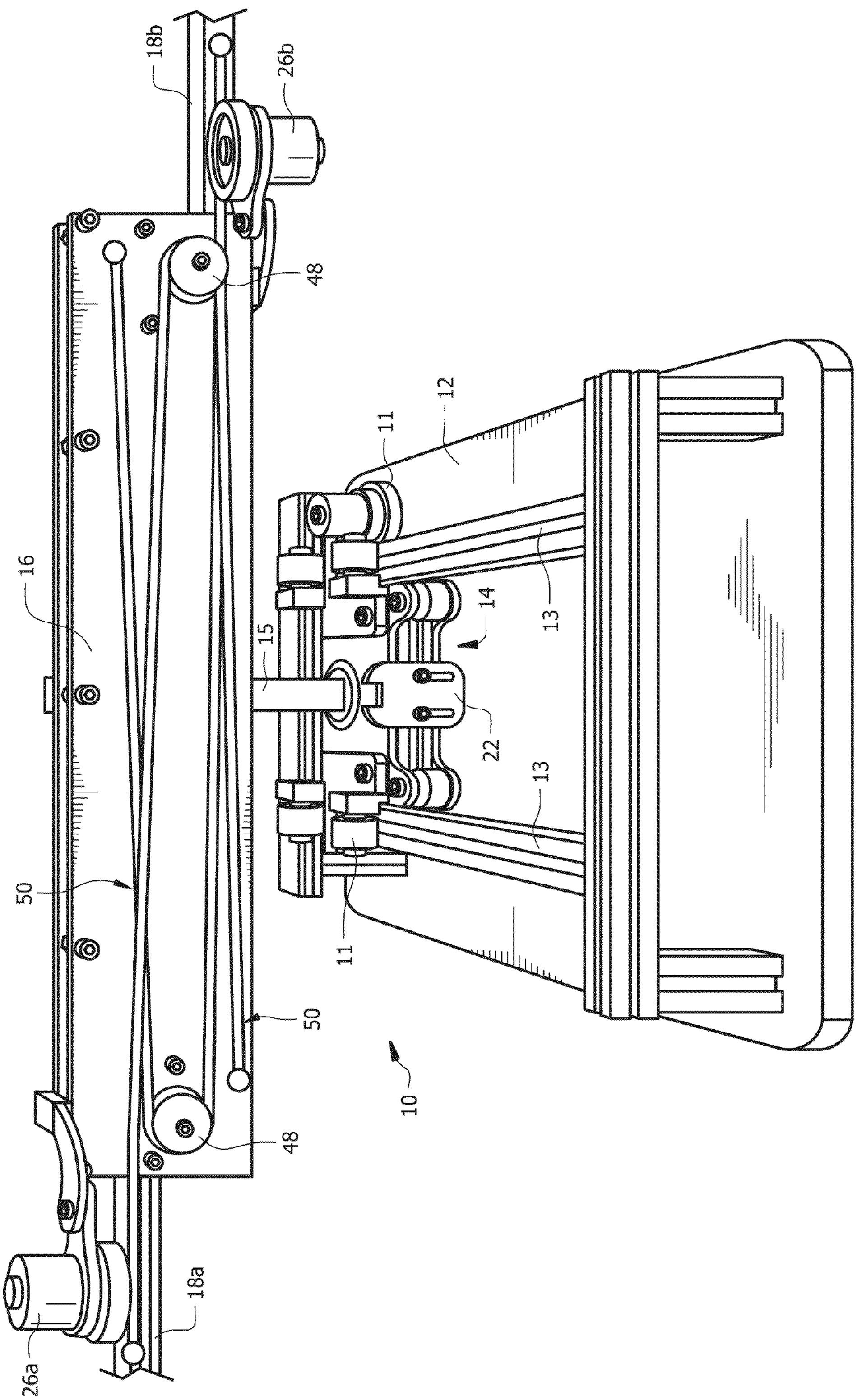


FIG. 6

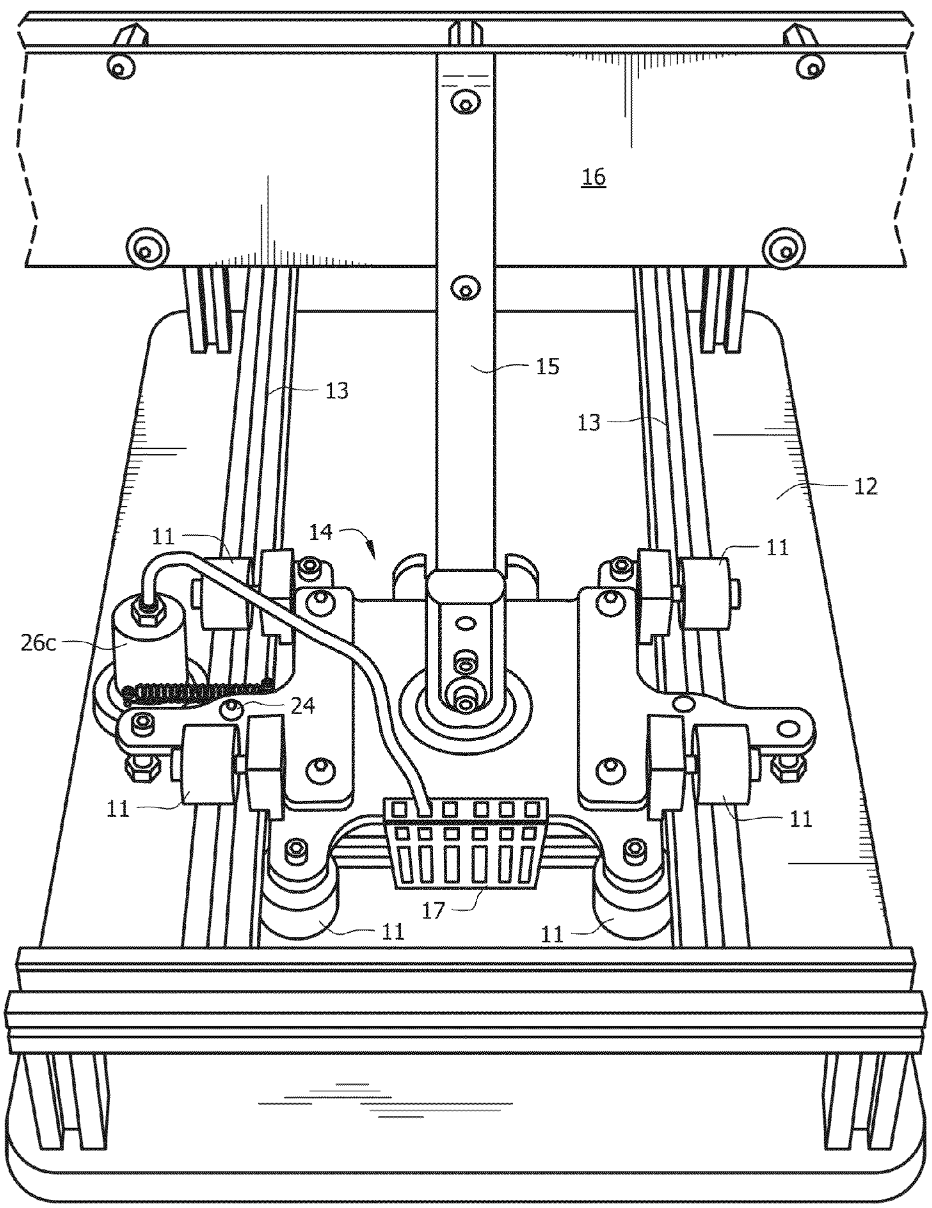


FIG. 7A

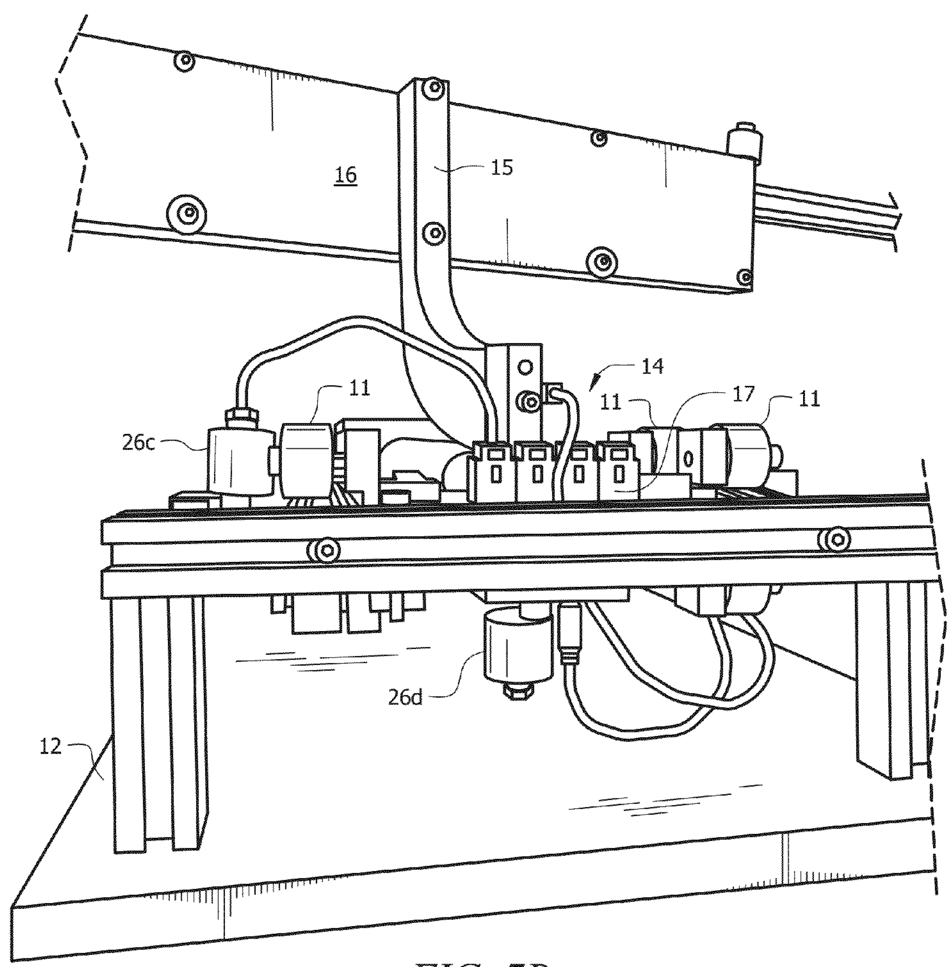


FIG. 7B

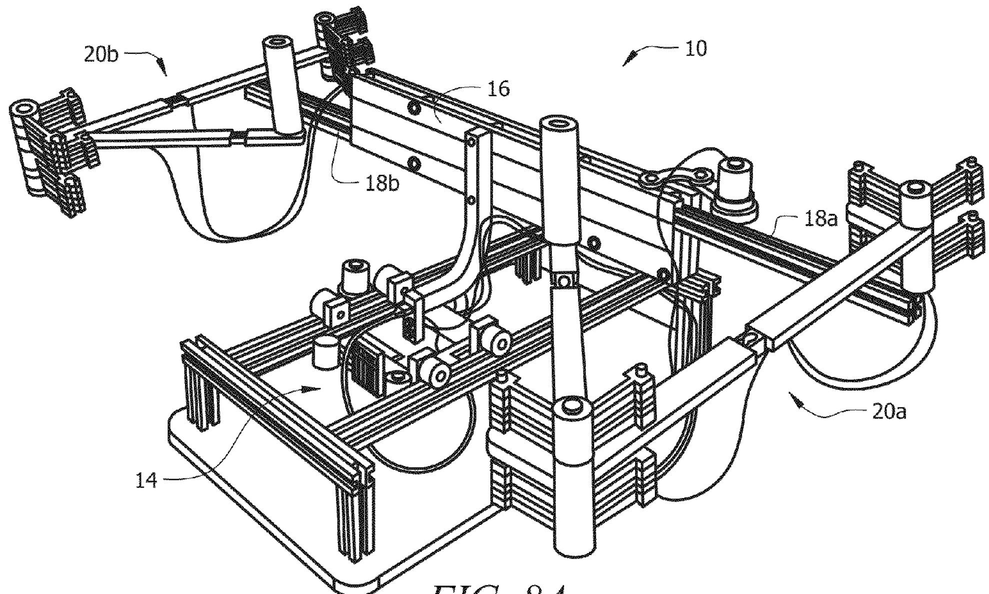


FIG. 8A

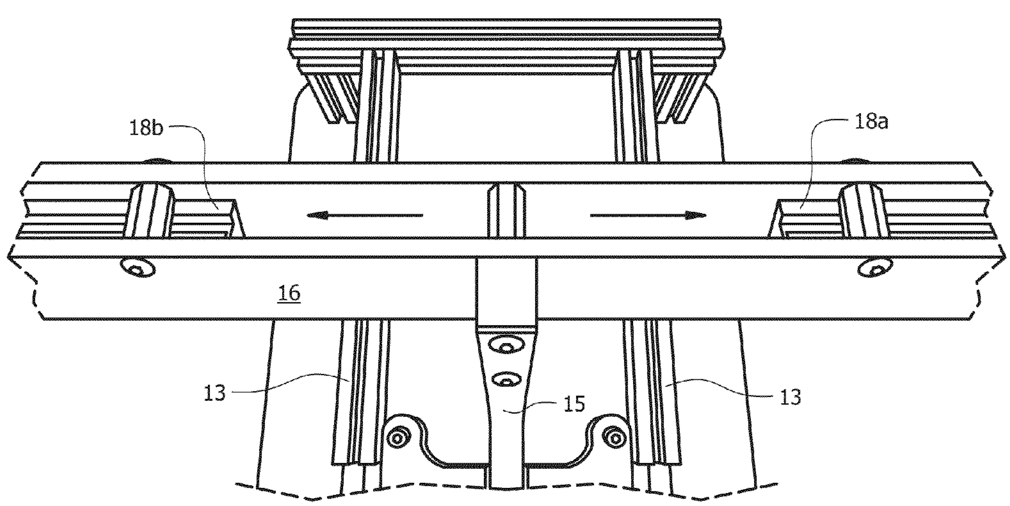


FIG. 8B

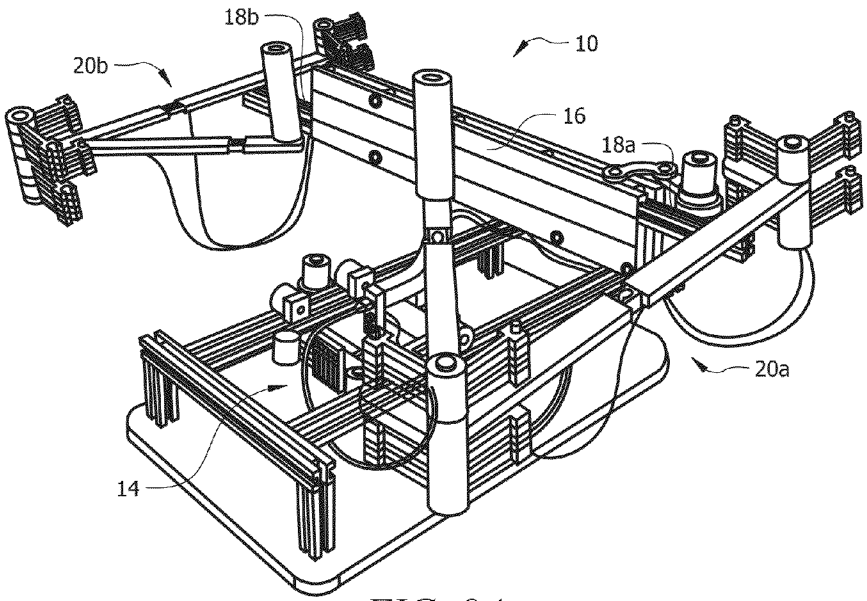


FIG. 9A

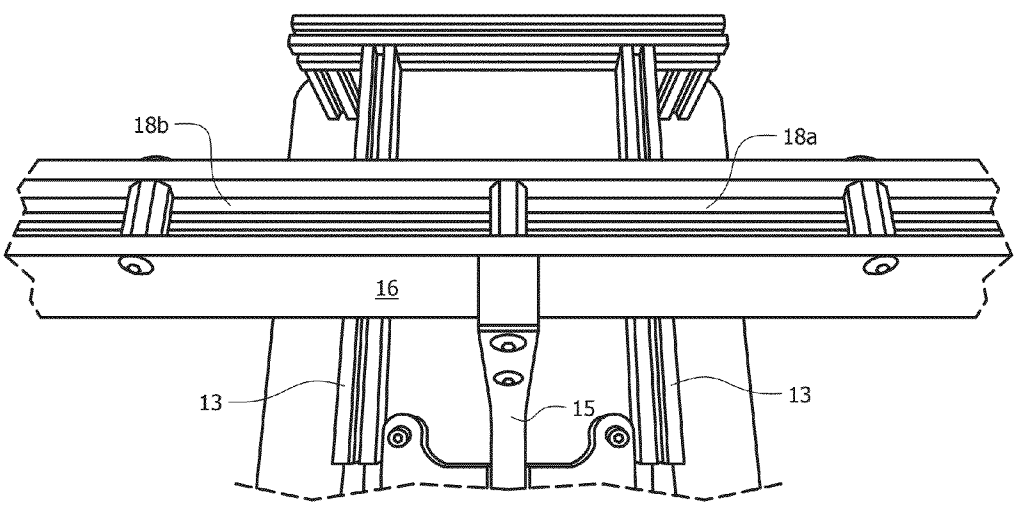


FIG. 9B

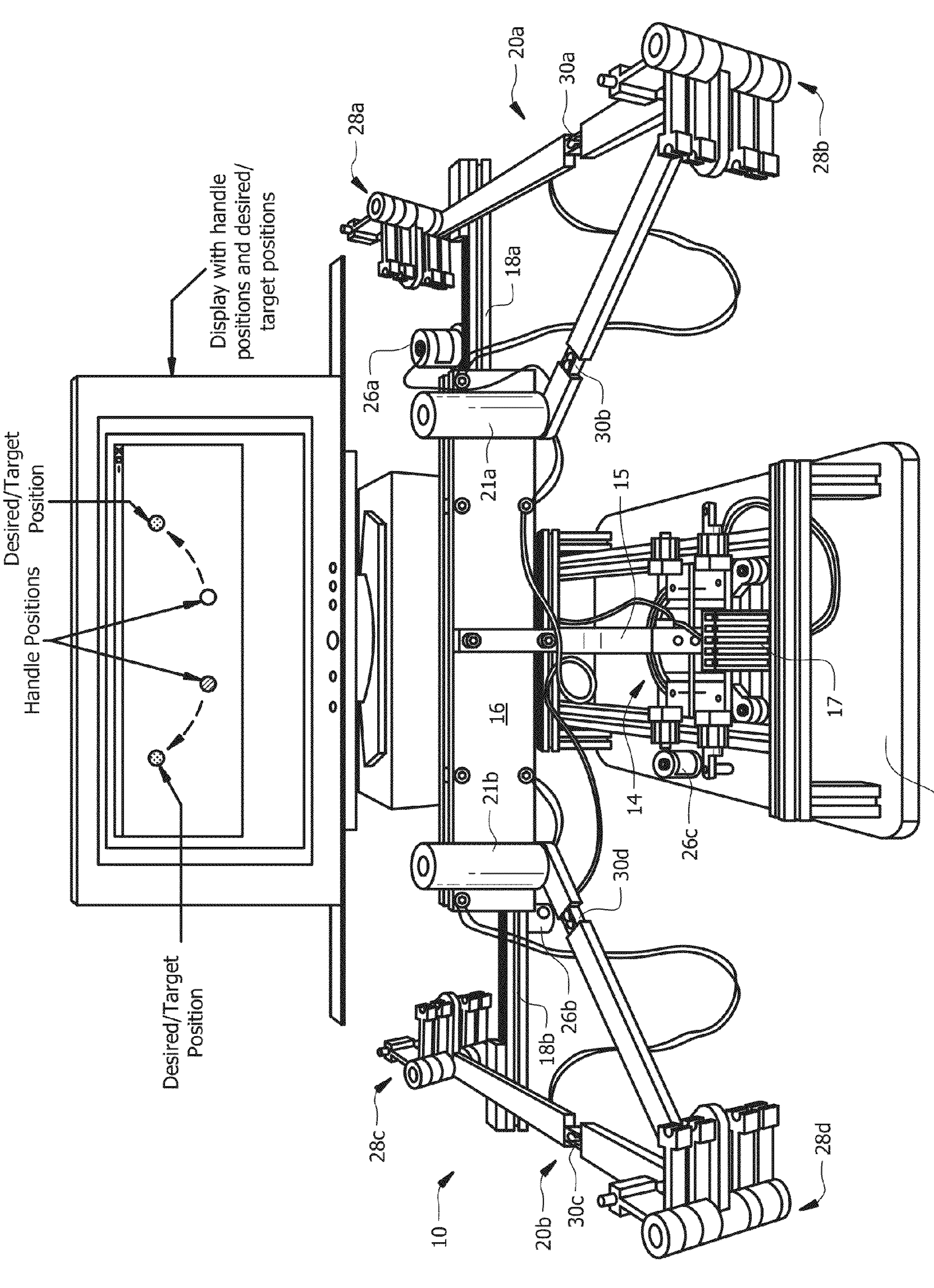

Display with handle positions and desired/ target positions
Desired/Target Position
Handle Positions
Desired/Target Position
10
12
14
15
16
17
18a
18b
20a
20b
21a
21b
26a
26b
26c
28a
28b
28c
28d
30a
30b
30c
30d

FIG. 10

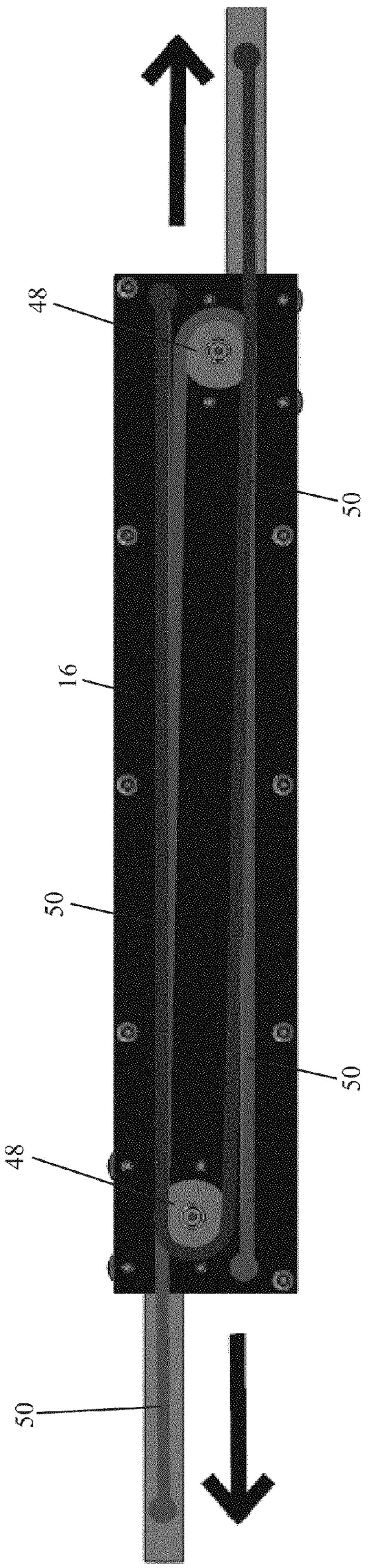


FIG. 11A

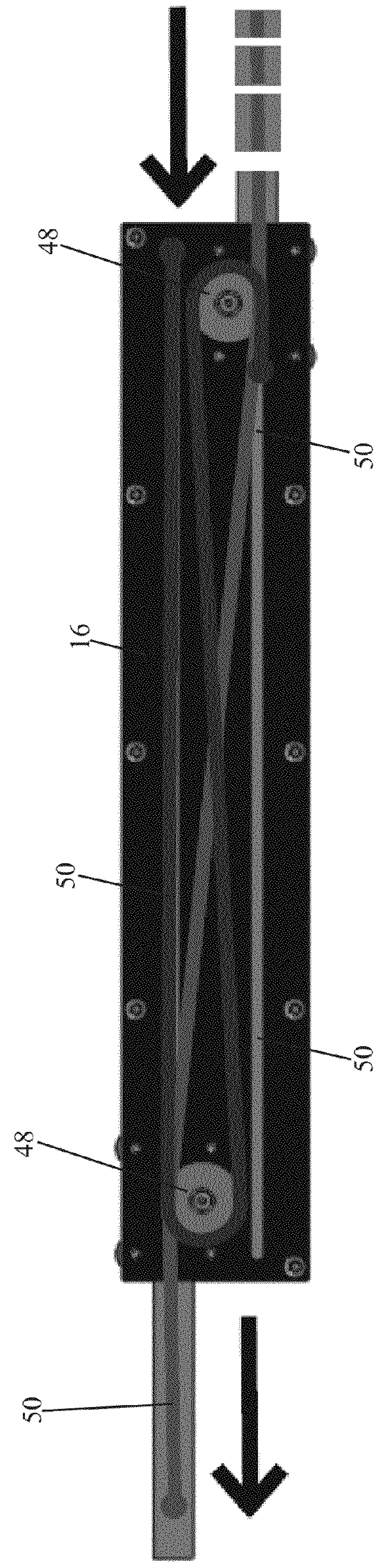
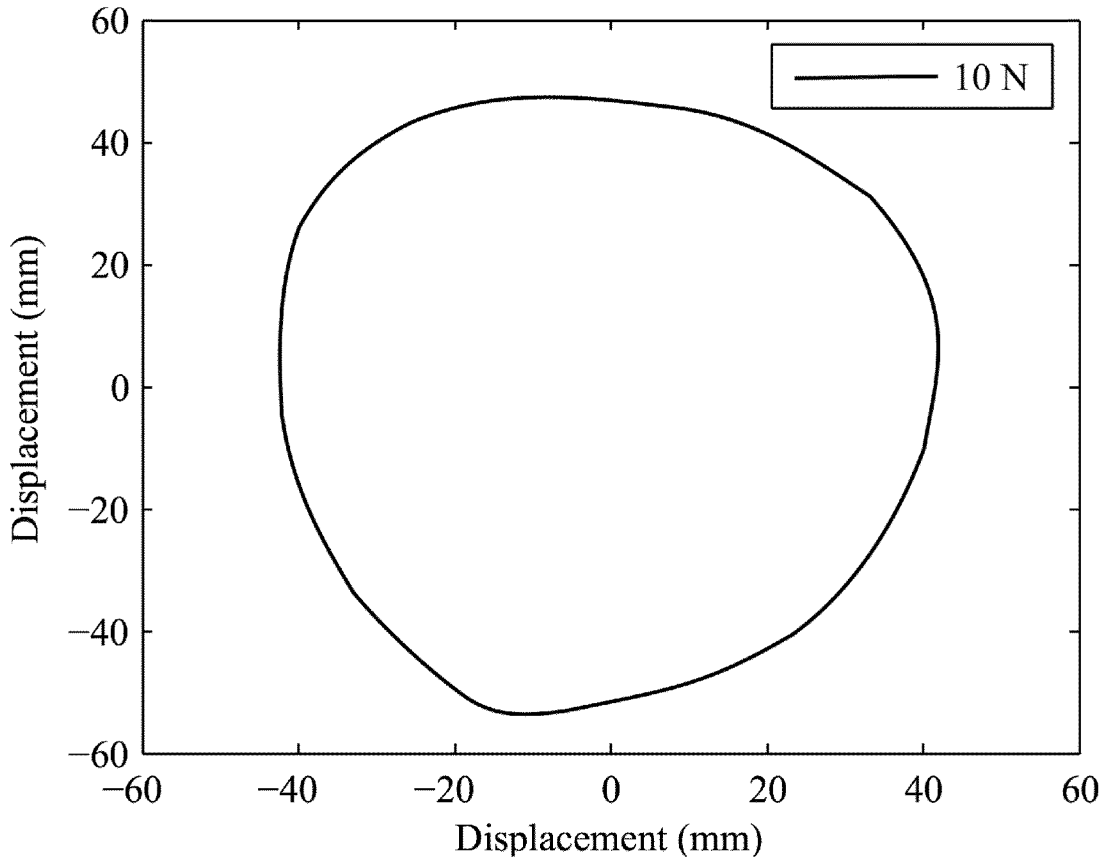


FIG. 11B



10 N
60
40
20
0
−20
−40
−60
Displacement (mm)
−60
−40
−20
0
20
40
60
Displacement (mm)

FIG. 12

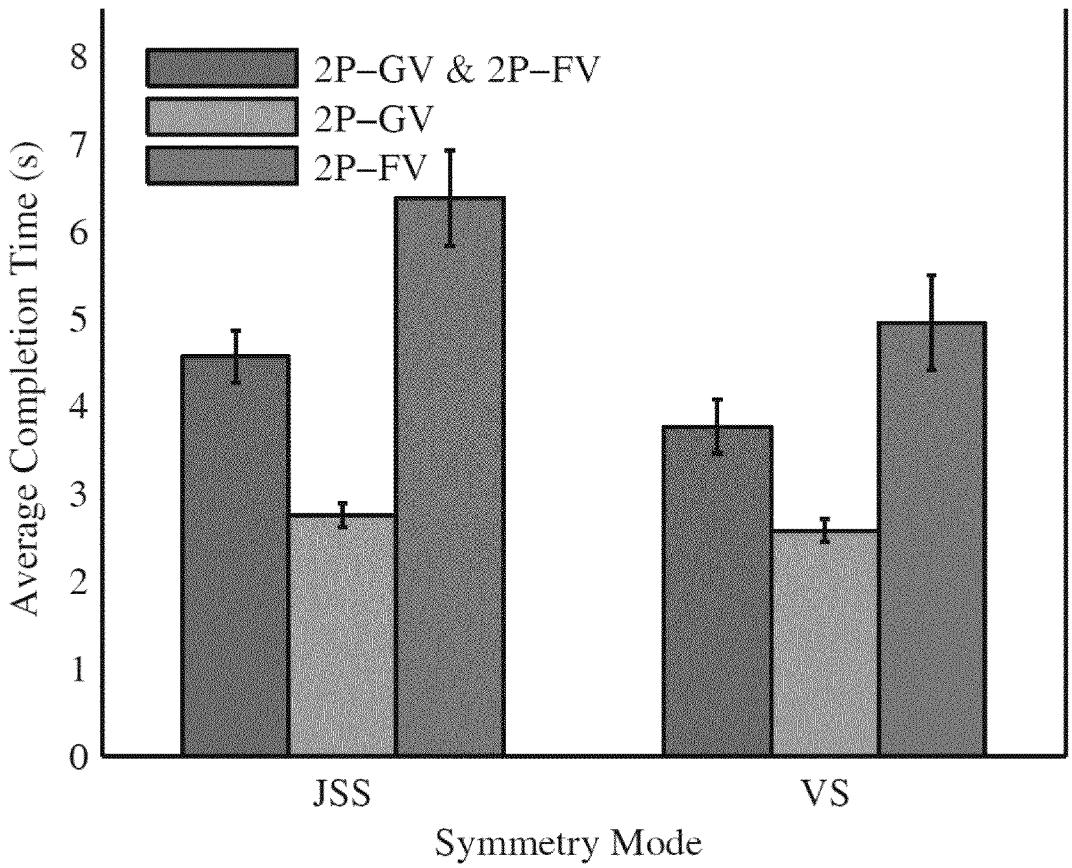

2P–GV & 2P–FV
2P–GV
2P–FV
Average Completion Time (s)
0
1
2
3
4
5
6
7
8
JSS
VS
Symmetry Mode

FIG. 13

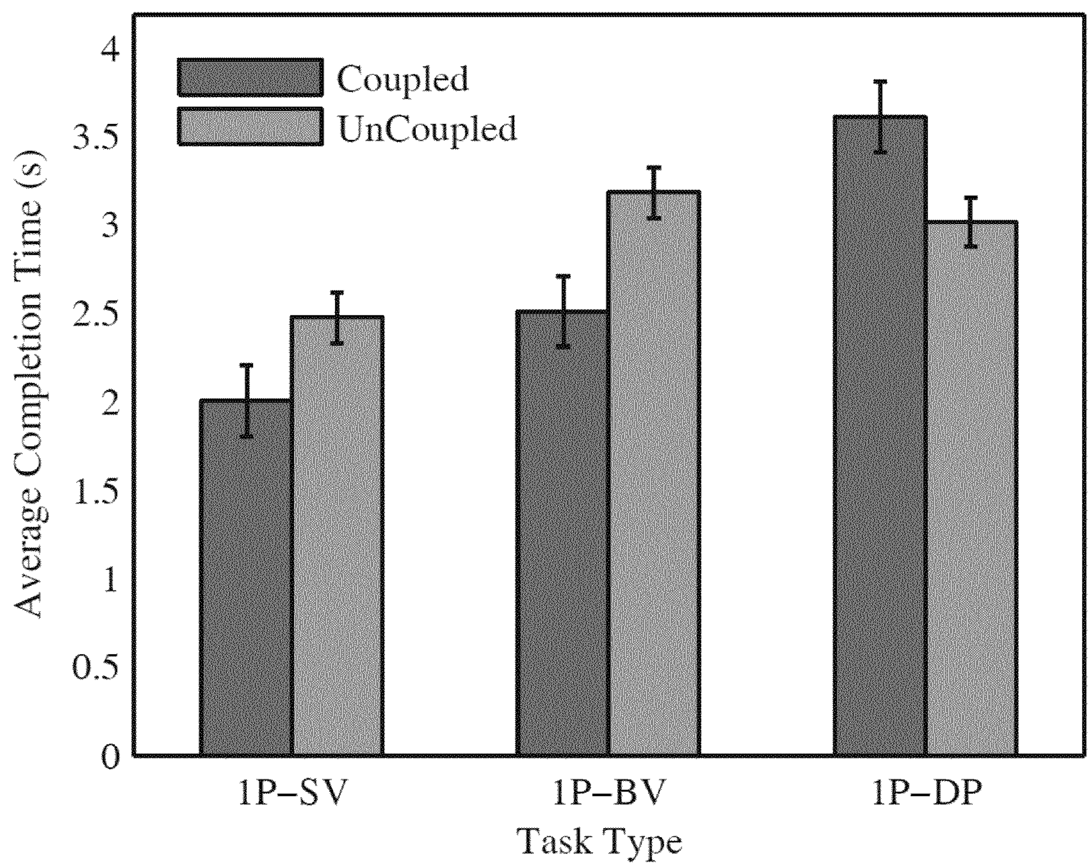

4
3.5
3
2.5
2
1.5
1
0.5
0
Average Completion Time (s)
Coupled
UnCoupled
1P−SV
1P−BV
1P−DP
Task Type

FIG. 14

COMPLIANT BIMANUAL REHABILITATION DEVICE AND METHOD OF USE THEREOF

CROSS-REFERENCE TO RELATED APPLICATIONS

This nonprovisional application is a continuation of and claims priority to U.S. Provisional Application No. 61/987,186, entitled "Compliant Bimanual Rehabilitation Device and Method of Use Thereof", filed May 1, 2014 by the same inventors, the entirety of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates, generally, to bimanual rehabilitation. More specifically, it relates to a device and method for bimanual rehabilitation for persons with hemiparesis.

2. Brief Description of the Prior Art

The goal of upper-limb rehabilitation following a stroke is to enable a person to use both hands in activities of daily living. Of the new rehabilitation methods proposed and tested in recent years, many show positive results [1] [2], but there is a need for a more effective method that clearly shows better results than traditional methods. A common thread among the successful studies is that the amount of time spent training the affected arm plays an important role in improving the functional ability of the affected arm. As it is difficult for therapists to devote as much time as is needed, researchers have looked to robotic techniques, bimanual techniques, and other techniques to supplement the rehabilitation.

Traditional and Robotic Rehabilitation Techniques

Conventional stroke rehabilitation therapies, such as the Bobath method [3] and proprioceptive neuromuscular facilitation [4] have been used for decades. However, these methods are time-consuming and require significant effort from physical therapists. Forced use [5] and the more recently developed Constraint-Induced Movement Therapy [6] bind the sound arm and force the individual to use only the paretic limb; however, this therapy is only viable for small to moderate impairment.

In recent years, robotic technologies have been used to provide rehabilitation to individuals, allowing access to rehabilitation for longer and more frequent periods of time. However, recent publications have noted that it is unclear whether robotic methods have the potential to produce greater benefits than conventional techniques when practiced for the same amount of time [1] [2].

To allow patients greater access to rehabilitative training, several methods have been developed to allow patients to rehabilitate at home [7] [8]. However, many of these home-based methods use a home computer with limited accessories that cannot provide assistance forces and can only operate over a small workspace. These methods are able to provide some benefit, but the rehabilitation effect is limited to individuals already having relatively high motor function.

Bimanual Rehabilitation

Bimanual rehabilitation allows individuals with hemiparesis to use their sound arm to help rehabilitate their impaired arm through simultaneous bimanual motions. Bimanual rehabilitation shows promise as a means of low cost home use rehabilitation. The key mechanism of rehabilitation is that the same neural signal is sent to both arms, which results in the same proprioceptive feedback from each limb since the arms are constrained to move together. Sending the same efferent signals to each limb results in similar afferent signals from the limbs, which helps re-train the motor pathways to the impaired side/limb [9] [10]. Several research groups have studied certain aspects of coupled and uncoupled bimanual rehabilitation [11] [12] [13] [14] [15], but few studies have examined what the ideal physical parameters for bimanual interaction should be.

The foregoing studies [11] [12] [13] [14] [15] either did not physically connect the hands or coupled the hands rigidly, and few studies have analyzed the effect of the coupling stiffness. An effective coupling stiffness is likely an intermediate stiffness, since a soft coupling would prevent severely impaired individuals from using this training method. With a completely rigid connection, the individual is likely to apply minimal force in their impaired hand since the healthy side would dictate all the motions [1] [16].

Further, it is not currently known which types of symmetry modes are most effective for bimanual rehabilitation. Mirror motions have been the most commonly used in bimanual rehabilitation studies to date. However, most daily tasks occur in a visual reference frame where the hands move in the same direction. Three common reference frames used in bimanual rehabilitation are Mirror or Joint Space Symmetry (JSS), Visual Symmetry (VS), and Point Mirror Symmetry (PMS) [17] [18](see FIG. **1**).

Preliminary studies of bimanual symmetric motions on healthy participants have shown that it is easier to follow and recreate motions in VS and JSS than in PMS [19] and that a coupling stiffness of 200 N/m or greater resulted in better path following and motion coupling. These studies were performed on a pair of PHANTOM OMNI force feedback devices.

Certain devices and methodologies for bimanual rehabilitation do exist in the art, though most use either a rigid physical coupling or a large robotic device to effect the coupling, since the best combination of bimanual symmetry modes and coupling stiffnesses is unknown. For example, U.S. Pat. No. 7,850,579 to Whitall et al. (also published as EP B1 and WO2001056662 A1) relates to a device for bilateral upper extremity training for patients with a paretic upper extremity, and more specifically, to a device providing bilateral upper extremity training that facilitates cortical remodeling. However, the bilateral arm trainer of Whitall et al. includes two separate handles on slides for each hand and the two motions are uncoupled except via the person's control, thus failing to provide physical coupling of the motions together in multiple symmetry modes.

U.S. Patent App. Pub. No. 2012/0029391 A1 to Sung et al. relates to a bilateral upper limbs motor recovery rehabilitation and evaluation system for patients with stroke. However, Sung et al. focuses on evaluating the amount of asymmetry an individual with stroke has. The system is designed to allow an individual to move bilaterally with both arms and measures the difference between the two arms and defines metrics to aid in evaluation. It does not include a semi-compliant physical connection or a method to switch between different symmetry modes.

U.S. Pat. No. 8,038,579 to Wei et al. relates to a system adapted to stroke patients for training and evaluating bilateral symmetric force output. However, the focus of Wei et al. is the force being mediated by a motor, which becomes costly and less user-intuitive for a home-user thereof.

Symmetric Motions for Bimanual Rehabilitation. Hernando Gonzalez Malabet, Rafael Alvarez Robles, and Kyle B. Reed. Oct. 18-22, 2010, Taipei, Taiwan relates to the development of bimanual rehabilitation for home-use. Although this publication is relevant to bimanual rehabilitation, it is more theoretical in nature and furthers an understanding of

how people couple motions, but does not discuss a device or method for coupling the hands.

Peter S. Lum, David J. Reinkensmeyer, Member, IEEE, and Steven L. Lehman, Associate Member, IEEE. Robotic assist devices for bimanual physical therapy: preliminary experiments. IEEE transactions on rehabilitation engineering, vol. 1, no. 3 sefizmber 1993 relates to the development of a device, operating under simple control laws, to assist a disabled hand, allowing performance of coordinated bimanual tasks. However, this publication is focused on bimanual wrist actuation and would not be conducive for whole arm movements.

Peter S. Lum, Steven L. Lehman, Associate Member, IEEE, and David J. Reinkensmeyer, Member, IEEE. The bimanual lifting rehabilitator: an adaptive machine for therapy of stroke patients. IEEE transactions on rehabilitation engineering, vol. 3, no. 2, June 1995 relates to the development of inexpensive bimanual lifting rehabilitators, each designed to retrain coordination in a specific activity of daily living, which could be used by physical and occupational therapists. This paper is focused on performing motions bimanually, but not on using one hand to assist the other during a reaching task. The "rehabilitator", rather than the person's healthy hand, assists the impaired hand, and the device enables only a limited type of rehabilitation.

Matic Trlepa, Matjaž Mihelj a Urška Puhb and Marko Muni. Rehabilitation Robot with Patient-Cooperative Control for Bimanual Training of Hemiparetic Subjects. Advanced Robotics: Volume 25, Issue 15, 2011 relates to the development and validation of a bimanual training system that stimulates the use of both arms of hemiparetic subjects. The adaptive assistance control adjusts the contribution of the unaffected arm, thus reducing the load on the paretic arm. This paper presents a bimanual rehabilitation method that couples the motions of both hands through an "adaptive assistance" paradigm that works by controlling how much force the sound arm can contribute to the overall motion using admittance control. The coupling in this system is effected by a rigid coupling to a robotic device, rather than a passive compliant coupling, and enables limited symmetry types.

Accordingly, what is needed is a more effective device and methodology for bimanual rehabilitation. However, in view of the art considered as a whole at the time the present invention was made, it was not obvious to those of ordinary skill in the field of this invention how the shortcomings of the prior art could be overcome.

While certain aspects of conventional technologies have been discussed to facilitate disclosure of the invention, Applicants in no way disclaim these technical aspects, and it is contemplated that the claimed invention may encompass one or more of the conventional technical aspects discussed herein.

The present invention may address one or more of the problems and deficiencies of the prior art discussed above. However, it is contemplated that the invention may prove useful in addressing other problems and deficiencies in a number of technical areas. Therefore, the claimed invention should not necessarily be construed as limited to addressing any of the particular problems or deficiencies discussed herein.

In this specification, where a document, act or item of knowledge is referred to or discussed, this reference or discussion is not an admission that the document, act or item of knowledge or any combination thereof was at the priority date, publicly available, known to the public, part of common general knowledge, or otherwise constitutes prior art under the applicable statutory provisions; or is known to be relevant to an attempt to solve any problem with which this specification is concerned.

BRIEF SUMMARY OF THE INVENTION

The long-standing but heretofore unfulfilled need for an upper limb rehabilitation system is now met by a new, useful, and nonobvious invention.

In an embodiment, the current invention is a rehabilitation system including a compliant bimanual rehabilitation device. The device comprises a base that defines the x-, y-, and z-axes of the device as a whole. A carrier assembly is slidably coupled to the base (e.g., via slide rails mounted on the top of the base) along the y-axis of the device. An upper assembly is rotationally coupled to the carrier assembly about the z-axis of the device. A handle slide is slidably coupled each end of the upper assembly along the x-axis of the device. A compliant handle assembly is coupled to each handle slide. A handle is fixedly coupled to each compliant handle assembly. Each handle permits a large range of arm movement. One of the handles is a guiding handle used by the user's sound arm, and the other handle is the following handle used by the user's paretic arm. The handles are indirectly linked to each other at an adjustable, predetermined coupling stiffness, such that when the device is in use, the user's paretic arm is linked to the user's sound arm. Thus, a movement of the guiding handle dictates a corresponding movement of the following handle according to a predetermined symmetry mode (e.g., JSS, VS, PMS).

The device may further include encoders in communication with one or more of the following: handle slides to determine a position of each handle slide along the x-axis, carrier assembly to determine a position of the carrier assembly along the y-axis, and upper assembly to determine a position of the upper assembly along the z-axis. In any case, each encoder would be in further communication with an electronic or computing device to transmit the position of the communicating structure to the electronic or computing device.

The device may further include load cells in communication with the compliant handle assemblies to determine an amount of force put on each compliant handle assembly by the user. The load cells would be in further communication with an electronic or computing device to transmit the amounts of force on the compliant handle assemblies to the electronic or computing device.

Each compliant handle assembly may be formed of a first component coupled to the handle slide and extending along the y-axis of the device and a second component coupled to the first component and extending inwardly from the first component. In this case, a load cell, as described, can be positioned along each component, resulting in at least four (4) load cells being disposed in the device.

The handles may be indirectly linked to each other via the handle slides being coupled to each other, which, in turn, couples the compliant handle assemblies together as well. In a further embodiment, the handle slides may be coupled to each other via a cable and pulley system. In this cable and pulley system, when the cable is looped around the pulleys an even number of times, the handles move in the same absolute direction; on the other hand, when the cable is loops around the pulleys an odd number of times, the handles mirror each other in movement.

The compliant bimanual rehabilitation device may further include a first locking mechanism for restricting movement of

the upper assembly in the z-axis and a second locking mechanism for restricting movement of the carrier assembly in the y-axis.

The rehabilitation system may further include a visual display communicatively coupled to the compliant bimanual rehabilitation device for indicating a current position of each handle, where the indicated positions move as the handles respectively move. Further, the visual display may also indicate a target position of each handle, whereby a goal of the user is to align the current positions with the target positions.

The compliant bimanual rehabilitation device may further include a spring system coupled to each compliant handle assembly to provide a bias against movement of the handles. The spring system can include one or more springs positioned at the joint between the handle slide and the compliant handle assembly and also positioned along each compliant handle assembly, resulting in at least four (4) sets of springs. If the compliant handle assemblies are formed of the components, as described above, then the springs disposed along each compliant handle assembly can be positioned between the components of each compliant handle assembly. The spring systems may be formed of spring stacks formed of a plurality of torsion springs stacked or abutting one another. Based on the needs of the user, the coupling stiffness can be adjusted by adding or removing torsion springs from the spring stacks. These torsion springs may each include a central portion that is coupled at the joints, along with two (2) forks having longitudinal extents that are angled (e.g., substantially perpendicular) relative to each other.

In a separate embodiment, the current invention is a rehabilitation device including a compliant bimanual rehabilitation device, comprising any one or more, or even all, of the foregoing characteristics or limitations.

These and other important objects, advantages, and features of the invention will become clear as this disclosure proceeds.

The invention accordingly comprises the features of construction, combination of elements, and arrangement of parts that will be exemplified in the disclosure set forth hereinafter and the scope of the invention will be indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the invention, reference should be made to the following detailed description, taken in connection with the accompanying drawings, in which:

FIG. **1** depicts common bimanual symmetry modes including Joint Space Symmetry (JSS) where the joint angles are mirrored, Visual Symmetry (VS) where the hands move through the same visual path, and Point Mirror Symmetry (PMS) where the hand motions are mirrored about a point in space.

FIG. **2** is a front perspective view of a compliant bimanual rehabilitation device according to an embodiment of the current invention.

FIG. **3** is a right corner perspective view of a compliant bimanual rehabilitation device according to an embodiment of the current invention.

FIG. **4** is a close-up perspective view of a compliant handle assembly (right compliant handle assembly in this figure) according to an embodiment of the current invention.

FIG. **5** depicts an exemplary spring that may be used in a compliant handle assembly according to an embodiment of the current invention.

FIG. **6** is a rear perspective view of a compliant bimanual rehabilitation device according to an embodiment of the current invention.

FIG. **7**A is a close-up view of a carrier assembly in a compliant bimanual rehabilitation device according to an embodiment of the current invention.

FIG. **7**B is a lower elevation view beneath the carrier assembly of FIG. **7**B, showing the lower encoder.

FIG. **8**A shows the compliant handle slide in an expanded position along the x-axis.

FIG. **8**B shows disposition of the compliant handle slides within the upper assembly when in the expanded position of FIG. **10**A.

FIG. **9**A shows the compliant handle slide in a contracted position along the x-axis.

FIG. **9**B shows disposition of the compliant handle slides within the upper assembly when in the contracted position of FIG. **11**A.

FIG. **10** depicts an embodiment of the compliant bimanual rehabilitation device (CBRD) implemented with an interaction game on a visual display. Handle positions are displayed as the middle/interior dots/circles on the visual display. Desired/target positions are displayed as the outer dots/circles on the visual display.

FIGS. **11**A-**11**B are diagrams of cable layouts as viewed from the rear of a compliant bimanual rehabilitation device according to an embodiment of the current invention. Cable runs are indicated by the horizontal lines, attached to the handle slides at their ends. FIG. **13**A corresponds to JSS and PMS. FIG. **13**B corresponds to VS. The right end of FIG. **13**B would be fully extended (not shown).

FIG. **12** depicts the compliant handle assembly stiffness ellipse.

FIG. **13** is a graphical illustration depicting results of average completion time analysis for Two Participant Study. When the guiding handle and desired position are visible (GV), the completion times are similar. When the guiding participant must move the follower's handle (FV), the task is completed faster in VS. Error bars represent 95% confidence interval.

FIG. **14** is a graphical illustration depicting results of average completion time analysis for Single Participant Study. For 1P-SV and 1P-BV, the average completion time was lower when the handles were coupled. Error bars represent 95% confidence interval.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In the following detailed description of the preferred embodiments, reference is made to the accompanying drawings, which form a part thereof, and within which are shown by way of illustration specific embodiments by which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the invention.

As used in this specification and the appended claims, the singular forms "a", "an", and "the" include plural referents unless the content clearly dictates otherwise. As used in this specification and the appended claims, the term "or" is generally employed in its sense including "and/or" unless the context clearly dictates otherwise.

Bimanual rehabilitation allows an individual to self-rehabilitate by guiding his paretic arm with his sound arm using an external physical coupling. This coupling allows the individual to move his impaired hand through motions he would not otherwise be able to make while still giving him complete control over the motion generated, something that a physical therapist or robot would not be able do. This method also allows for upper-limb rehabilitation devices that are signifi-

cantly lower in cost than robotic systems since much of the required force could be provided by the patient's healthy limb instead of the larger motors included on many current upper-limb rehabilitation robots. This would result in a lower cost and safer rehabilitation method that could be used at home, increasing access to rehabilitation. In an embodiment, the current invention is a device that allows the hands to be coupled in several common symmetry modes and with a selectable coupling stiffnesses. The device was tested with healthy subjects in tasks that mimic aspects of hemiparesis as well as standard bimanual tasks.

In an embodiment, the current invention is a compliant bimanual rehabilitation device ("CBRD") that physically couples two handles in any configuration, for example one or more of the symmetries shown in FIG. **1**, with an adjustable/selectable coupling stiffness.

The device can be seen in FIGS. **2-10** and is generally denoted as reference numeral **10**. Referring to FIG. **2**, the CBRD includes a guiding handle physically coupled to a following handle, wherein the guiding handle controls direction of movement of the following handle in a predetermined symmetry mode (e.g., joint space symmetry, point mirror symmetry, visual symmetry), and wherein the physical coupling of the guiding handle and the following handle has an adjustable, predetermined coupling stiffness. As can be seen in FIG. **10**, the CBRD can be communicatively coupled to a visual display for indicating a current left position of the left handle, a target left position of the left handle, a current right position of the right handle, and a target right position of the right handle.

Device **10** is divided into several sub-assemblies: the coupling system that connects the handle in a desired symmetry mode, formed of carrier assembly **14** and upper assembly **16**, and compliant handle assemblies **20***a*, **20***b* that allow the handles to be moved away from the correct symmetric positions but provide a spring force back towards the symmetric positions.

More specifically, CBRD device **10** includes base **12** that defines a top, a bottom, a left side, a right side, an x-axis, and a y-axis of CBRD device **10**. Carrier assembly **14** is mounted on top of base **12** and is slidably coupled to base **12** along slide rails **13**, where carrier assembly **14** is slidable along the y-axis of device **10**, for example via wheels or spools **11** (e.g., eight (8) wheels **11** can be seen, four (4) sliding along the top of slide rails **13** and four (4) sliding along the side (inside) of slide rails **13**) slidable along the inside of slide rails **13**. Upper assembly **16** is rotationally coupled to carrier assembly **14** via connector **15**, where the upper assembly **16** is rotational along the z-axis of device **10**.

Right handle slide **18***a* is slidably coupled to the right end of upper assembly **16**, where right handle slide **18***a* is slidably received within and along upper assembly **16**, such that right handle slide **18***a* is slidable along the x-axis of device **10**. This will become clearer as this specification continues. Right compliant handle assembly **20***a* is coupled to right handle slide **18***a* and extends proximally from right handle slide **18***a* substantially along the y-axis of device **10**, substantially perpendicular to the longitudinal axis of slide rails **13** (see right compliant handle assembly component **20***a*') and then inwardly toward base **12** (see right compliant handle assembly component **20***a*"). Right handle **21***a* is rigidly coupled to the free end of right compliant handle assembly **20***a* to permit a large range of right arm movement.

Spring stack **28***a* can be positioned at the connection point between right handle slide **18***a* and right compliant handle assembly **20***a*. Spring stack **28***b* can be positioned at the joint or connection point between right compliant handle assembly component **20***a*' and right compliant handle assembly component **20***a*". Spring stacks **28***a*, **28***b* will become clearer as this specification continues.

Left handle slide **18***b* is slidably coupled to the left end of upper assembly **16**, where left handle slide **18***b* is slidably received within and along upper assembly **16**, such that left handle slide **18***b* is slidable along the x-axis of device **10**. This will become clearer as this specification continues. Left compliant handle assembly **20***b* is coupled to left handle slide **18***b* and extends proximally from left handle slide **18***b* substantially along the y-axis of device **10**, substantially perpendicular to the longitudinal axis of slide rails **13** (see left compliant handle assembly component **20***b*') and then inwardly toward base **12** (see left compliant handle assembly component **20***b*"). Left handle **21***b* is rigidly coupled to the free end of left compliant handle assembly **20***b* to permit a large range of left arm movement.

Spring stack **28***c* can be positioned at the connection point between left handle slide **18***b* and left compliant handle assembly **20***b*. Spring stack **28***d* can be positioned at the joint or connection point between left compliant handle assembly component **20***b*' and left compliant handle assembly component **20***b*". Spring stacks **28***c*, **28***d* will become clearer as this specification continues.

Locking mechanism **22** (seen best in FIG. **6** as a locking plate) provides a configuration, when actuated, for the JSS and VS modes, which use movement along the x- and y-axes. Actuating locking mechanism **22** (or presence of locking plate **22**, as seen in FIG. **6**) restricts movement/rotation of upper assembly **16** in the z-axis. Thus, for the JSS and VS modes, right handle slide **18***a* and left handle slide **18***b* are capable of moving in the x-direction, along with movement of carrier assembly **14**, upper assembly **16**, right handle slide **18***a*, and left handle slide **18***b* in the y-direction, but no rotational movement of any structure in the z-direction since movement should only be in the x- and y-directions for these modes. If locking plate **22** is removed, rotation is permitted.

In turn, locking mechanism **24** provides a configuration, when actuated, for the PMS mode, which uses movement of upper assembly **16** along the z-axis. Actuating locking mechanism **24** restricts movement of upper assembly **16** in the y-axis. Thus, for the PMS mode, right handle slide **18***a* and left handle slide **18***b* are capable of moving in the x-direction, along with movement of carrier assembly **14**, upper assembly **16**, right handle slide **18***a*, and left handle slide **18***b* in the z-direction, but no linear movement of carrier assembly **14** or upper assembly **16** in the y-direction since movement should only be in the x- and z-directions for this mode.

Control of handle slides **18***a*, **18***b* can be achieved using knobs or pulleys **48** and cable(s) **50**, as can be seen in FIGS. **6**, **11**A, and **11**B. This will become clearer as this specification continues.

As can be seen most clearly in FIG. **4**, right encoder **26***a* is disposed in a fixed position on and in communication with right handle slide **18***a* in order to determine the position of right handle slide **18***a* (along the x-axis). Encoder **26***a* can be angular, linear, positional, or other suitable mechanism for determining the position of right handle slide **18***a* and converting that position to an analog or digital code potentially for transmission to an electronic or computing device.

Similarly, as can be seen most clearly in FIG. **6**, left encoder **26***b* is disposed in a fixed position on and in communication with left handle slide **18***b* in order to determine the position of left handle slide **18***b* (along the x-axis). Encoder **26***b* can be angular, linear, positional, or other suitable mechanism for determining the position of left handle slide

18*b* and converting that position to an analog or digital code potentially for transmission to an electronic or computing device.

Front encoder **26***c* is disposed in a fixed position on and in communication with carrier assembly **14** in order to determine the position of carrier assembly **14** (along the y-axis). Encoder **26***c* can be angular, linear, positional, or other suitable mechanism for determining the position of carrier assembly **14** and converting that position to an analog or digital code potentially for transmission to an electronic or computing device.

Optionally, as indicated in FIGS. **7**A-**7**B, lower encoder **26***d* can be fixedly positioned and in communication with upper assembly **16** in order to determine a position of upper assembly **16** in the z-axis. Encoder **26***d* can be angular, linear, positional, or other suitable mechanism for determining the position of upper assembly **16** and converting that position to an analog or digital code potentially for transmission to an electronic or computing device.

Optionally, to measure the force used by a user of device **10** on device **10** during rehabilitation, one or more load cells can be positioned right compliant handle assembly **18***a* and/or on left compliant handle assembly **18***b*. For example, load cell **30***a* can be positioned along an extent of right compliant handle assembly component **20***a*' of right compliant handle assembly **20***a*, and load cell **30***b* can be positioned along an extent of right compliant handle assembly component **20***a*" of right compliant handle assembly **20***a*.

Similarly, load cell **30***c* can be positioned along an extent of left compliant handle assembly component **20***b*' of left compliant handle assembly **20***b*, and load cell **30***d* can be positioned along an extent of right compliant handle assembly component **20***b*" of left compliant handle assembly **20***b*. Load cells **30***a*-**30***d* permit a therapist to monitor the amount of force placed upon said load cells **30***a*-**30***d* in order to track progression of a paretic limb. As such, load cells **30***a*-**30***d* may be electronically coupled to an electronic or computing device.

Device **10** may process the information/data received from encoders **26***a*-**26***c* and load cells **30***a*-**30***d* and communicate with the electronic or computing device via circuit board **17** or other suitable methodology.

The amount of force needed for the user's sound and paretic limbs to move right compliant handle assembly **18***a* and left compliant handle assembly **18***b* using right handle **21***a* and left handle **21***b*, respectively, in the prescribed pattern (e.g., JSS, VS, PMS) can be adjusted via spring stacks **28**. Each spring stack **28** can be a singularly formed spring or formed of a plurality of springs, for example torsion spring **40** seen in FIG. **5**.

FIG. **4** specifically shows right handle slide **18***a* and right compliant handle assembly **20***a*, both of which having structures that are symmetrical with left handle slide **18***b* and left compliant handle assembly **20***b*. Thus, it should be understood that a description of more specific structures of right handle slide **18***a* and right compliant handle assembly **20***a* would be substantially similar and relevant to left handle slide **18***b* and left compliant handle assembly **20***b*.

Right compliant handle assembly component **20***a*' has a proximal end and a distal end, relative to a user of device **10**. On both its proximal end and its distal end, right compliant handle assembly component **20***a*' includes spring stack **28**. Spring stack **28** can be coupled to right compliant handle assembly component **20***a*' in any suitable way. For example, center post **32** and peripheral posts **34***a*, **34***b* can be positioned on the distal end of right compliant handle assembly component **20***a*' on distal base **35**. Similarly, center post **36** and peripheral posts **36***a*, **36***b* can be positioned on the proximal end of right compliant handle assembly component **20***a*' on proximal base **39**. Peripheral posts **34***a*, **38***a* can be positioned substantially in line with the longitudinal extent of right compliant handle assembly component **20***a*', and peripheral posts **34***b*, **38***b* can be positioned substantially normal to the longitudinal extent of right compliant handle assembly component **20***a*'.

As briefly noted previously, spring stack **28** may be formed of a plurality of springs, such as a plurality of torsion springs, one of which is indicated generally by reference numeral **40** in FIG. **5**, though any suitable torsion spring may be used. In this example, torsion spring **40** includes center aperture **42** and forks **44***a*, **44***b* with channels **46***a*, **46***b*, respectively, between the respective tines of forks **44***a*, **44***b*.

Center posts **32**, **36** are structured to be inserted through center aperture **42** of each torsion spring **40** (i.e., the inner diameter of center aperture **42** is larger than the outer diameter of center posts **34***a*, **34***b*). Center posts **32**, **36** and center aperture **42** can have any suitable corresponding shape or size.

Peripheral posts **34***a*, **34***b* are structured to be positioned within channels **46***a*, **46***b* of respective forks **44***a*, **44***b* of each torsion spring **40** (i.e., the inner length of channels **46***a*, **46***b* is larger than the outer diameter of peripheral posts **34***a*, **34***b*). Channels **46***a*, **46***b* and peripheral posts **34***a*, **34***b* can have any suitable shape or size. Similarly, peripheral posts **38***a*, **38***b* are structured to be positioned within channels **46***a*, **46***b* of respective forks **44***a*, **44***b* of each torsion spring **40** (i.e., the inner length of channels **46***a*, **46***b* is larger than the outer diameter of peripheral posts **38***a*, **38***b*). Channels **46***a*, **46***b* and peripheral posts **38***a*, **38***b* can have any suitable shape or size.

In certain embodiments, as seen in FIGS. **2**-**4**, spring stack **28** can be positioned both above and below distal base **35**. In this case, particularly if spring stack **28** is formed of a plurality of torsion springs **40**, any or all of center post **32** and peripheral posts **34***a*, **34***b* can be disposed through distal base **35**, such that torsion springs **40** can be secured above distal base **35** and below distal base **35**. Similarly, spring stack **28** can be positioned both above and below proximal base **39**. In this case, particularly if spring stack **28** is formed of a plurality of torsion springs **40**, any or all of center post **36** and peripheral posts **38***a*, **38***b* can be disposed through proximal base **39**, such that torsion springs **40** can be secured above proximal base **39** and below proximal base **39**. Torsion springs **40** can be secured using any suitable mechanism, such as a lock or stopper.

As can be seen in FIG. **4** in view of FIG. **5**, one of forks **44***a*, **44***b* of torsion spring **40** may be positioned substantially parallel to the longitudinal extent of right compliant handle assembly component **20***a*', and the other of forks **44***a*, **44***b* of torsion spring **40** may be positioned substantially normal to the longitudinal extent of right compliant handle assembly component **20***a*'.

As can be understood by one of ordinary skill in the art, the number of torsion springs **40** used can be altered, thus adjusting the amount of force needed to be expended by a user of device **10** in order to perform the rehabilitation program. It is also contemplated herein that spring stack **28** and torsion springs **40** are not needed at all in device **10**, as the amount of force needed in the rehabilitation program can be adjusted in a variety ways, such as with magnets, computerized adjustment, real-time or even automated adjustment, etc.

FIG. **6** is a rear view of upper assembly **16**, particularly depicting knobs or pulleys **48** and cable **50** that control handle slides **18***a*, **18***b* along the x-axis. As can be seen, cable **50***a* is

attached to right handle slide **18***a*, and cable **50***b* is attached to left handle slide **18***b*. A diagram of this mechanism can also be seen in FIGS. **11**A-**11**B. Altering the path of cable **50** changes the coupling of handle slides **18***a*, **18***b* to each other and thus controls how they may move relative to each other in the x-direction. If cable(s) **50** loops around pulleys **48** an odd number of times, the motions of handle slides **18***a*, **18***b* are mirrored to each other, for example as necessary for the JSS and PMS modes (see FIGS. **6** and **11**A). If cable(s) **50** loops around pulleys **48** an even number of times, handle slides **18***a*, **18***b* move in the same absolute direction, for example as required for the VS mode (see FIG. **11**B).

Referring back to the movement of right handle slide **16***a* and left handle slide **16***b* in the x-direction, FIGS. **8**A-**8**B show handle slides **18***a*, **18***b* in an expanded position, and FIGS. **9**A-**9**B show handle slides **18***a*, **18***b* in a contracted position. In particular, FIGS. **8**B & **9**B depict how handle slides **18***a*, **18***b* slide past one another (e.g., side by side, above and below, one within the other, etc.) within upper assembly **16**.

By physically coupling the sound and paretic limbs, an individual with hemiparesis would be able to move his impaired hand through motions he would not otherwise be able to make while still allowing him complete control over the motion generated. This method also allows for upper-limb rehabilitation devices that are significantly lower in cost than robotic systems since much of the required force could be provided by the patient's healthy limb instead of the larger motors included on many current upper-limb rehabilitation robots. This would result in a lower cost and safer rehabilitation method that could be used at home, increasing access to rehabilitation. The hands may be coupled in one of several symmetry modes, as seen in FIG. **1**, though other symmetry modes are contemplated by the current invention as well.

Example

Coupling System

The coupling system includes a four-jointed mechanism with three prismatic joints and one revolute joint. The first joint, hereafter referred to as the Y-axis joint, is prismatic and connects the base **12** to a captive carrier assembly **14** that supports the remainder of device **10**, allowing for motion towards or away from the human subject or participant for both JSS and VS modes. Bolt, lock, or other locking mechanism **24**, for example with a captive nut, is used to remove this degree of freedom for PMS. The second joint, in the center of carrier assembly **14**, is revolute and connects carrier assembly **14** to upper assembly **16** and allows the latter to rotate for PMS. This joint can be referred to as the Z-axis joint. Locking mechanism **22**, such as a locking plate, removes this degree of freedom for JSS and VS symmetry modes.

The motion of the Y-axis joint can be monitored by encoders **26***a*, **26***b* (e.g., optical) with an angular resolution of 0.25°. Encoders **26***a*, **26***b* contact right handle slide **18***a* and left handle slide **18***b*, respectively, with friction wheels of radius 2.38 mm, resulting in a linear resolution of 0.10 mm. Similarly, the Z-axis angle can be monitored by encoder **26***c* (e.g., optical) with a resolution of 0.25°.

The third and fourth joints described herein allow for lateral motion of handle slides **18***a*, **18***b* in JSS and VS and for radial motion in PMS. The motion of these X-axis joints can be monitored by encoders **26***a*, **26***b* with an angular resolution of 0.25°. Encoders **26***a*, **26***b* contact handle slides **18***a*, **18***b* with friction wheels of radius 2.38 mm, resulting in a linear resolution of 0.10 mm.

The motions of the third and fourth joints are coupled by cable runs (see FIGS. **6** & **11**A-**11**B) on the rear side of upper assembly **16**. As shown in FIGS. **11**A-**11**B, altering the path of cable **50** changes the coupling. If cable **50** loops around pulleys **48** an odd number of times, the motions of handle slides **18***a*, **18***b* are mirrored, as necessary for JSS and PMS (FIG. **11**A). If cable **50** loops around pulleys **48** an even number of times, handle slides **18***a*, **18***b* move in the same absolute direction, as necessary for VS (FIG. **11**B).

In JSS and VS, each handle has a workspace 330 mm deep and 431 mm wide, starting 124 mm from the centerline. In VS, the distance between the handles is 679 mm, so that the maximum extension for one handle is the minimum extension for the other. In PMS, the workspace is a disk with an inner radius of 124 mm and an outer radius of 555 mm. At full extension in JSS or PMS, the handles are 1110 mm apart.

The stiction in the joint formed of base **12** to carrier assembly **14** is approximately 4-20 N, though typically less than 10 N, dependent on the extension of handle slides **18***a*, **18***b* and the resultant torque applied to the joint. The resistance in the joint formed of carrier plate **14** and upper assembly **16** is negligible. The stiction in the joint formed of upper assembly **16** to handle slides **18***a*, **18***b* is approximately 10-15 N. The total mass of the carrier and all moving components is 6.9 kg. It is contemplated that stiction and weight can be further reduced as well.

Compliant Handle Assembly

Each handle **21***a*, **21***b* is connected to the coupling system by compliant handle assemblies **18***a*, **18***b*, respectively, that provides a restoring force towards the correct position or otherwise forces handle **21***a*, **21***b* towards the correct position, but allows handle **21***a*, **21***b* to deviate from this correct position. Each compliant handle assembly **18***a*, **18***b* includes three links (compliant handle assembly components **20***a*', **20***a*", **20***b*', **20***b*" are seen), connected by two pins (center posts **32**, **36**), and spring stacks **28***a*-**28***d*, formed of a stack of torsion springs **40** on each pin **32**, **36**. Springs **40** each include an L-shaped piece of acetal plastic, 51 mm per leg (see reference numeral **44***a*, **44***b*), with center aperture **42** for connecting center post **32**, **36** where the legs meet.

Torsion spring **40** was customized for device **10** and may optionally be used, as standard torsion springs are typically designed for larger deflections than used herein. To achieve the same stiffness, standard springs require more material, substantially increasing the size and weight. Torsion spring **30** also allows for more control over the stiffnesses implemented. The performance of torsion springs **40** was confirmed to be linear over the range used. It is, however, contemplated herein that any suitable spring(s) may be used with device **10**.

In each of compliant handle assemblies **20***a*, **20***b*, the second and third links make up the hypotenuse (see compliant handle assembly components **20***a*", **20***b*") and one leg (see compliant handle assembly components **20***a*', **20***b*'), respectively, of a 45°-45°-90° triangle, with handle **21***a*, **21***b* at the 90° corner. This results in the torques about center posts/pins **32**, **36** producing a symmetric stiffness ellipse at respective handles **21***a*, **21***b*, for small deflections, although large deflections will result in distorted stiffness ellipse. It is contemplated that the shape of the stiffness ellipse can be optimized accordingly.

Each of compliant handle assemblies **20***a*, **20***b* can be designed for a maximum deflection of 75 mm in any direction. For this deflection, the maximum width of each torsion spring **40** is 6 mm, hence a stack of torsion springs **40** with 6.4 mm thickness is used to achieve higher stiffnesses. Each spring **40** adds 110 N/m to the stiffness of the respective

connections between handles **21***a*, **21***b* and handle slides **18***a*, **18***b*; however, since both handles **21***a*, **21***b* are connected in this way, the overall coupling stiffness added by each set of springs **40** is 55 N/m, and the maximum combined deflection from correct coupled positions is 150 mm. The stiffness ellipse for one of handles **21***a*, **21***b* with two of springs **40** is shown in FIG. **12**.

The forces in the links are monitored by shear load cells **30***a*-**30***d*. From the load cell readings, the force on each of handles **21***a*, **21***b* can be calculated, and given a known joint stiffness, based on the number of springs **40** used, the joint deflection can be calculated, along with the position of handles **21***a*, **21***b*.

Display and Interaction Game

An individual/user/operator interacts with CBRD device **10** by grasping right handle **21***a* and left handle **21***b* and moving them to desired positions as displayed on a monitor/display screen, as seen in FIG. **10**. The motion along the x-axis is coupled by a cable system (formed of pulleys **48** and cables **50**) on the back of upper assembly **16**. Handles **21***a*, **12***b* are connected to handle slides **18***a*, **18***b* by compliant handle assemblies **20***a*, **20***b* with spring stacks **28** at the joints, where spring stacks **28** are formed of torsion springs **40**.

The workspace of the CBRD device can be visually represented on a display located above and slightly behind the device to allow users to interact with visually displayed targets. The displayed workspace was scaled down by a factor of 2.5:1, resulting in a visual workspace area that is about 132 mm tall and about 442 mm wide. For consistency, unless otherwise noted, all non-limiting dimensions given are for the physical workspace. Desired/Target positions of the right and left handles are presented in FIG. **10** as the outer circles/dots, which are about 40 mm (16 mm displayed) in diameter. As seen in FIG. **10**, the right and left handles are displayed as the inner circles, respectively, with both being about 40 mm in diameter, and the desired/target positions are indicated as the outer circles.

For the studies presented herein, the task that participants were asked to complete included matching the handle position(s) with the desired/target position(s). Each trial included a series of eighteen (18) segments, beginning with the display of randomly generated desired/target positions. The segment would end, and after a brief delay, the desired position would shift to a new position if the handle position was within about five (5) mm of the desired/target position or if about fifteen (15) seconds had elapsed since the desired/target position was first displayed.

The CBRD device allows for the study of the effect of coupling stiffness and symmetry on the efficacy of bimanual rehabilitation, as well as the performance of other bimanual tasks. This device could be used to fulfill the need for a low-cost home use rehabilitation device that is suitable for patients with varying degrees of impairment.

Study/Experiment

The study presented herein describes the design and preliminary analysis of a device that permits testing of the efficacy of different coupling stiffnesses and symmetry modes in bimanual rehabilitation.

To evaluate the effectiveness of the device at coupling hand motions, a series of studies were conducted. The eventual goal is stroke rehabilitation and in particular to quantify the performance of the device when one hand applies minimal input to the system: here, two people were used to mimic the lack of bimanual coordination that occurs in individuals with stroke. The guiding participant could see the handle and desired positions; the following participant was blindfolded and could only feel the motions. This is a harsher test since the two participants are completely uncoupled neurally whereas an individual with stroke can couple the motions, but cannot fully control one of the arms. Thus, the device was evaluated in both a dual and single participant study.

Two Participant Study

The purpose of this study was to quantify the performance of the device when one hand applies minimal input to the system. The guiding participant could see the handle and desired positions, while the following participant was blindfolded and could only feel the motions. Performance was compared under the following conditions

- Two Person-Guiding Visible (2P-GV): The guiding participant must place his handle in the target area
- Two Person-Following Visible (2P-FV): The guiding participant must place the follower's handle in the target area.

In the dual-participant study, two participants stood in front of the device and each grasped a handle. The participant on the right held the right handle and the participant on the left held the left handle, mimicking the way that it would be held by a person with a stroke during rehabilitation. For each trial, one participant was designated as the guiding participant and the other participant was considered the following participant. The desired positions and handle positions were only displayed to the guiding participant and the following participant was asked to close their eyes or use a blindfold. A curtain separated the participants so that the guiding participant could only see their side of the device and the computer screen. The purpose of the two participant study was to quantify the performance of the device when one hand applies minimal input to the system.

The participants were asked to complete two types of tasks in different coupling symmetry modes and with different coupling stiffnesses. The symmetry modes tested were JSS and VS; PMS was omitted because it has been shown to be more difficult to coordinate bimanual motions in [19] and to limit the total study time to 1 hour to reduce the possibility of participant fatigue. The coupling stiffnesses tested were 110 N/m and 380 N/m. The lower stiffness was selected to be between 50 N/m and 200 N/m since this was shown to be an area of transition in path perception accuracy [19]. The 380 N/m coupling stiffness was selected as the highest possible stiffness without reducing the compliant workspace area below the maximum diameter of 300 mm.

In one task, hereafter referred to as Two Person-Guiding Visible (2P-GV), only the guiding participant's desired and handle position were displayed, where the guiding participant must place his handle in the target area. For this task, the guiding participant was asked to match their handle position with the desired position as quickly as possible. In the other task, hereafter referred to as Two Person-Following Visible (2P-FV), the following participant's desired position and both handle positions were displayed, where the guiding participant must place the following participant's handle in the target area. For this task, the guiding participant was asked to match the following participant's handle position with the desired position.

Both participants completed all combinations of symmetry mode, stiffness and task type twice, once as the guide and once as the follower. The overall order of symmetry mode, stiffness, task and guiding participant was randomized for each pair of participants. However, to avoid confusion, and reduce delay time from switching configurations, the trials for each coupling stiffness were presented together. Similarly, for each coupling stiffness, all of the trials for one symmetry mode were presented before changing the symmetry mode, and for each symmetry mode, one guiding participant com-

pleted both tasks before the guiding participant was changed. Ten participants performed this study with IRB approval: eight were male, all were right handed, age 21-61 years old.

Single Participant Study

The purpose of this study was to analyze the effect of the CBRD on assisting a healthy participant in coordinating their hand motions. Performance was compared under the following conditions

One Person-Single Visible (1P-SV): Only one of the sets of handle and desired positions are shown.

One Person-Both Visible (1P-BV): Both sets of handle and desired positions are shown.

One Person-Distorted Positions (1P-DP): Both sets of handle and desired positions are shown, and the desired positions are distorted from their symmetric locations.

In this study, a single participant stood in front of the device and held both handles. The participants were asked to complete three types of tasks in different coupling symmetry modes and with the handles of the device in one of two coupling conditions: either physically coupled in the desired symmetry mode, or uncoupled where the handle positions are not physically coupled. The symmetry modes tested were the same as those tested in the two participant study. When the handles were coupled, a coupling stiffness of 380 N/m was used for consistency with the two participant study.

For the physically coupled trials, the device was locked in the desired symmetry mode. To uncouple the handles, neither the Y nor Z-axis joints were locked, allowing the handles to be positioned independently, anywhere in the device workspace, however, they were dynamically coupled by inertia and friction, and the handles would still twist by the same angle about the Z-axis. In the uncoupled trials, participants were instructed to couple their hand motions in the desired symmetry mode.

One task was identical to that of the two participant study. In this task, referred to as One Person-Single Visible (1P-SV), participants were asked to match one handle position to a desired position as quickly as possible, while moving both of their hands together in the desired symmetry mode. In another task, referred to as One Person-Both Visible (1P-BV), both left and right handle and desired positions were displayed in the current symmetry mode, and participants were asked to match both handle positions to the desired positions. The purpose of these tasks was to analyze the effect of the CBRD on assisting a healthy participant in coordinating their hand motions.

In the third task, referred to as One Person-Distorted Positions (1P-DP), both left and right handle and desired positions were displayed, but their positions from the zero position for the symmetry mode were distorted by a factor of 1:1.5, and participants were, again, asked to match both handle positions to the desired positions. The purpose of this task was to mimic the decreased perceptional ability of individuals with stroke and test the device's ability to transmit forces.

Participants completed all combinations of symmetry mode, coupling condition and task twice; 1P-SV was completed once with the left visible and once with the right visible, and similarly 1P-DP was completed once with the distortion on the left and once with the distortion on the right. The 1P-BV condition was simply completed twice under the same conditions.

The overall order of symmetry mode, coupling condition, task, and left or right display/distortion was randomized. However, to avoid confusion, and reduce delay time from switching configurations, the trials for each symmetry mode were presented together. Similarly, for each symmetry mode, all of the trials for one coupling condition were presented before changing the coupling condition. If the first trial that a participant would conduct in a new symmetry mode was uncoupled, and only one desired position displayed, i.e. they would have neither visual nor haptic indication of how to couple their hand motions, they were permitted to practice moving in the desired symmetry mode until they understood the correct way to couple their motions. Six participants performed this study with IRB approval, five were male, and all were right handed, age 21-25.

Analysis

To quantify performance during a trial, the average completion time and the average coupled position error were analyzed. The average completion time for a trial was determined by calculating the average segment time, from the display of a desired position or positions to the matching of the handle position(s) with the desired position(s), and averaging these segment times for each trial. The average coupled position error was the average, for a trial, of the distance between the right handle position and the projected symmetric position of the left handle at the end of each segment. The projected symmetric position of the left handle was determined by mirroring the position of the handle for JSS mode or adding 679 mm to the left handle position for VS mode.

For statistical analysis, an analysis of variance (ANOVA) was conducted to analyze the effects of symmetry mode, coupling stiffness or condition, task type and guiding side on the average completion time and average coupling position error. When the ANOVA yielded significant results, Tukey's honestly significant difference test was used. An alpha of 0.05 was used for all statistical tests.

Results—Two Participant Study

Since the two types of tasks in the dual-participant study are inherently different: moving a handle directly vs. moving a handle through the coupling of the device, the analysis was performed with both task types together, and for each task type individually.

For both tasks, an analysis of the average completion time showed statistically significant results between symmetry modes (F_1, 79=9.31, p=0.003), coupling stiffnesses (F_1, 79=4.69, p=0.03) and task types (F_1, 79=131.2, p<0.001). Post hoc analysis showed that the completion time was lower for VS mode, for the 110 N/m coupling stiffness, and for the 2P-GV task. The completion times for the symmetry modes and tasks are shown in FIG. **13**. The average completion time for 2P-GV was 2.7 s, and the average completion time for 2P-FV was 5.7 s.

For the 2P-GV task, analysis of the average completion time did not show statistically significant results between symmetry modes or coupling stiffnesses. For the 2P-FV task, analysis of the average completion time showed statistically significant results between symmetry modes (F_1, 39=9.45, p=0.004). Post hoc analysis showed that the average completion time was lower for VS than for JSS.

For both tasks, analysis of the average coupled position error showed statistically significant results between symmetry modes (F_1, 79=4.90, p=0.03) and coupling stiffnesses (F_1, 79=265.48, p<0.001). Post hoc analysis showed that the error was smaller for JSS than VS, 51 mm and 56 mm, respectively, and that the error was lower for the 380 N/m coupling stiffness than for the 110 N/m coupling stiffness.

For the 2P-GV task, analysis of the average coupled position error showed statistically significant results between coupling stiffnesses (F_1, 39=140.53, p<0.001). For the 2P-FV task, analysis of the coupled position error showed statistically significant results between coupling stiffnesses (F_1, 39=117.97, p<0.001). Post hoc analysis showed that the aver-

age error was lower for the 380 N/m coupling stiffness and was comparable to the average for both tasks.

Results—Single Participant Study

For the single participant study, the analysis was performed both with the data from the three tasks combined as well as for the data of the tasks individually. The coupled position error was only analyzed for the 1P-SV task because in the other tasks, the correct final position for both handles was displayed

For all three tasks and both coupling conditions, analysis of the average completion time showed statistically significant results between the task types (F_2, 143=40.17, p<0.001). Post hoc analysis showed that 1P-SV was completed faster than 1P-BV, which, in turn, was completed faster than 1P-DP. The average completion times for 1P-SV, 1P-BV, and 1P-DP were 2.2 s, 2.8 s, and 3.3 s, respectively.

For the 1P-SV task and both coupling conditions, analysis of the average completion time showed statistically significant results between coupling conditions (F_1, 47=40.17, p=0.003). Post hoc analysis showed that the task was completed faster with the handles coupled (FIG. **14**). In other words, coupling improves the completion times when the desired positions are in symmetric locations consistent with the coupling.

For the coupled 1P-SV task, analysis of the average completion time showed statistically significant results between symmetry modes (F_1, 23=7.14, p=0.05). Post hoc analysis showed that the task was completed faster in VS than in JSS. For the uncoupled 1P-SV task, analysis of the average completion time did not show statistically significant results. In other words, it was found that the time to place one handle in the desired position while uncoupled was comparable to matching both positions when the handles were coupled.

For the 1P-BV task and both coupling conditions, analysis of the average completion time showed statistically significant results between coupling conditions (F_1, 47=34.13, p=0.001). Post hoc analysis showed that the task was completed faster when the handles were coupled (FIG. **14**).

For the 1P-DP task and both coupling conditions, analysis of the average completion time showed statistically significant results between coupling conditions (F_1, 47=11.24, p=0.002). Post hoc analysis showed that the task was completed faster when the handles were uncoupled (FIG. **14**). Analysis of the completion time for the uncoupled 1P-DP task showed statistically significant differences between symmetry modes (F_1, 23=15.34, p=0.001). Post hoc analysis showed that the task was completed faster in JSS than in VS. Analysis of the completion time for the coupled 1P-DP task did not show statistically significant results.

For the 1P-SV task and both coupling conditions, analysis of the coupled position error showed statistically significant results between symmetry modes (F_1, 47=8.7, p=0.005) and coupling conditions (F_1, 47=32.2, p<0.001). Post hoc analysis showed that the error was smaller in JSS than in VS, and when the handles were coupled.

For the coupled 1P-SV task, analysis of the coupled position error showed statistically significant results between symmetry modes (F_1, 23=45.54, p<0.001). Post hoc analysis showed that the error was smaller for JSS than VS. For the uncoupled 1P-SV task, the error did not show statistically significant results between symmetry modes.

Discussion

The two participant study showed that both the 380 N/m coupling stiffness and VS mode results in faster completion times. The higher stiffness may improve completion time due to better haptic communication with the following participant, but may also be attributable to better control over the dynamic motion of the system. The fact that 2P-FV task is completed faster in VS than in JSS, as shown in FIG. **13**, makes sense because in JSS the guiding participant must account for the mirrored motion of the handle that he is attempting to move to the desired position, while in VS the following handle moves in the same direction as the handle that he is controlling directly. This indicates that for bimanual rehabilitation tasks in JSS mode, it may be beneficial to display the desired position of both handles so that an individual may focus on generating both motions together rather than on the motion of the healthy arm required to assist the impaired arm in the correct direction.

The two participant study also showed that the coupled position error is smaller for the 380 N/m coupling stiffness than for the 110 N/m coupling stiffness at approximately 30 mm and 75 mm, respectively, corresponding to forces applied of 11.4 N and 8.25 N, respectively, which is consistent with the friction in the coupling system. In other words, the 380 N/m coupling stiffness resulted in a smaller error between the handle positions (30 mm vs. 75 mm).

The coupled position error showed a difference between symmetry modes, indicating that there may be a difference in performance in coupling modes, although the difference is on the order of 10% of the coupled position error.

The 1P-SV task with the handles coupled showed that the average completion time was lower for VS than for JSS. This is consistent with the idea that many VS tasks, such as moving a large object, are done with the hands coupled together, and may be a more natural symmetry mode if only the desired position of one handle is displayed. However, preliminary studies [19] show that uncoupled non-harmonic motions should also be faster in VS than in JSS. The difference may be attributable to friction and inertial forces slowing the motions enough to mask the differences in completion time. Therefore, further coupled bimanual studies on a device with lower impedance should be conducted, and an effort should be made to reduce the impedance of the CBRD.

For the 1P-DP task, the average completion time was lower when the handles were uncoupled. This makes sense because when the handles are coupled for this task, the participant must fight against the device to move the handles to the distorted desired positions. The forces required to reach the desired positions ranged from about 0 N to about 45 N.

The single participant study also showed that for the 1P-SV and 1P-BV tasks, when the handles were coupled in the desired symmetry mode, the average completion time was lower, as shown in FIG. **14**. The figure also shows that the average completion time for 1P-SV uncoupled is comparable to 1P-BV coupled, demonstrating that coupling motions through the CBRD can reduce the difficulty of matching two visually displayed positions to that of matching only one. These results show that coupling the hand motions through the CBRD improves performance of a healthy subject at completing bimanual tasks, indicating that it should be implemented in bimanual rehabilitation studies to test its efficacy.

In conclusion, the results of the study show that the CBRD effectively couples the bimanual motions of healthy subjects in JSS and VS modes, and that a higher coupling stiffness results in better performance in two participant bimanual tasks simulating hemiparesis. This two participant study also showed that when only the desired position of the following participant was displayed, the trials were completed faster in VS than JSS, and that displaying both desired positions in a JSS bimanual rehabilitation task may be beneficial.

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All referenced publications are incorporated herein by reference in their entirety. Furthermore, where a definition or use of a term in a reference, which is incorporated by reference herein, is inconsistent or contrary to the definition of that term provided herein, the definition of that term provided herein applies and the definition of that term in the reference does not apply.

GLOSSARY OF CLAIM TERMS

Cable and pulley assembly: This term is used herein to refer to a mechanism by which one or more cables loops around one or more pulleys to change direction of the cable and transmit tension forces around the pulleys to apply a biased force against a load or structure.

Carrier assembly: This term is used herein to refer to a slidable structure to which the upper assembly is connected. In other words, the carrier assembly carries the upper assembly, handle slides, compliant handle assemblies, among other components of the overall rehabilitation device.

Compliant handle assembly: This term is used herein to refer to a set of structural components that function in unison, where the structural components are related to the movement of the connected handles under a particular stiffness and to rehabilitation of the user.

Connection joint: This term is used herein to refer to the point or area at which two structures meet and are coupled to each other.

Coupling stiffness: This term is used herein to refer to the bias or rigidity of a connection between two structures.

Current position: This term is used herein to refer to an indication of the virtual or digital location of a handle as seen on an electronic visual display, where the location corresponds to the actual physical location of the handle.

Encoder: This term is used herein to refer to a device that reads particular information and transmits that information to an electronic device in a readable format.

Following handle: This term is used herein to refer to the handle used by the user's paretic arm led by movement of the guiding handle used by the user's sound arm.

Fork: This term is used herein to refer to a component of an exemplary torsion spring used herein, where the component includes an elongate body with tines at the end that can surround or "grab" a post for stability of the torsion spring.

Guiding handle: This term is used herein to refer to the handle used by the user's sound arm to lead movement of the following handle used by the user's paretic arm.

Handle slide: This term is used herein to refer to a slidable structure that slides into and out of the upper assembly and to which the compliant handle assemblies are connected.

Indirectly linked: This term is used herein to refer to a connection between two structures without the structures actually being held together or directly attached to one another. In other words, the structures are connected to each other through other structures.

Load cell: This term is used herein to refer to a transducer that reads a user's force and transmits data regarding that force to an electronic device in a readable format.

Locking mechanism: This term is used herein to refer to any suitable structure (e.g., bolt, plate, etc.) that can be used to block or restrict movement of a structure in a particular direction.

Mirror: This term is used herein to refer to movement of two structures where the structures reflect each other. As such, the structures move in opposite directions in the x-axis and in the same direction in the y-axis.

Paretic arm: This term is used herein to refer to an arm characterized by any weakness of voluntary movement. The arm may be partially paralyzed, have reduced capability of voluntary movement, or otherwise be impaired.

Same absolute direction: This term is used herein to refer to movement of two structures in the same manner or course.

Sound arm: This term is used herein to refer to an arm characterized as being healthy or normal relative to a paretic arm.

Spring stack: This term is used herein to refer to an assembly of springs that abut one another to collectively form a unified spring system.

Spring system: This term is used herein to refer to an assembly or one or more mechanical structures, each having an inherent bias toward its normal position, such that it exerts a force toward its normal position when bent, compressed, or stretched.

Symmetry mode: This term is used herein to refer to a technique of upper limb rehabilitation where movement of the sound and paretic limbs correspond to one another, whether mirroring each other, moving in the same absolute direction, moving in opposite directions from each other, among other suitable patterns.

Target position: This term is used herein to refer to a virtual or digital indication of a desired location of a handle during rehabilitation, as seen on an electronic visual display.

Torsion spring: This term is used herein to refer to a spring that function by rotation, twisting, or other force. When twisted, torsion springs store mechanical energy and apply a force toward their normal positions. Thus, the more torsion springs that are used, the greater the force needed to maintain their twisted position.

The advantages set forth above, and those made apparent from the foregoing description, are efficiently attained. Since certain changes may be made in the above construction without departing from the scope of the invention, it is intended that all matters contained in the foregoing description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described, and all statements of the scope of the invention that, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. A rehabilitation system including a compliant bimanual rehabilitation device, comprising:

a base that defines a left side, a right side, a front side, a rear side, an x-axis, a y-axis, and a z-axis of said device, wherein said base has a top side and a bottom side;

a carrier assembly slidably coupled to said base, said carrier assembly being slidable along the y-axis of said device;

an upper assembly rotationally coupled to said carrier assembly, said upper assembly being rotational about the z-axis of said device, said upper assembly having a left end corresponding to said left side of said device and a right end corresponding to said right side of said device;

a left handle slide slidably coupled to said left end of said upper assembly, said left handle slide being slidable along the x-axis of said device;

a right handle slide slidably coupled to said right end of said upper assembly, said right handle slide being slidable along the x-axis of said device;

a left compliant handle assembly coupled to said left handle slide and extending from said left handle slide;

a right compliant handle assembly coupled to said right handle slide and extending from said right handle slide;

a left handle fixedly coupled to said left compliant handle assembly;

a right handle fixedly coupled to said right compliant handle assembly,

wherein one of said left handle and said right handle is a guiding handle and the other of said left handle and said right handle is a following handle,

wherein said left handle and said right handle are indirectly linked to each other at an adjustable, predetermined coupling stiffness, such that when said device is in use, a paretic arm of a user or operator of said device is linked to a sound arm of said user of said device, such that a movement of said guiding handle dictates a corresponding movement of said following handle according to a predetermined symmetry mode;

said left handle and said right handle indirectly linked to each other via said left handle slide and said right handle slide, said left handle slide and said right handle slide being coupled to each other, thus also coupling said left compliant handle assembly and said right compliant handle assembly to each other;

said left handle slide and said right handle slide being coupled to each other via a cable and pulley assembly including at least one cable and at least two pulleys;

wherein when said at least one cable is looped around said at least two pulleys an even number of times, said left handle and said right handle move in a same absolute direction, and

when said at least one cable is looped around said at least two pulleys an odd number of times, said left handle and said right handle mirror each other.

2. A rehabilitation system as in claim **1**, further comprising:

said carrier assembly being slidably coupled to said base via slide rails mounted on said top side of said base.

3. A rehabilitation system as in claim **1**, further comprising:

a left handle slide encoder in communication with said left handle slide in order to determine a position of said left handle slide along the x-axis of said device; and

a right handle slide encoder in communication with said right handle slide in order to determine a position of said right handle slide along the x-axis of said device,

wherein said left and right handle slide encoders are in further communication with an electronic device in order to transmit the positions of said left and right handle slides to said electronic device.

4. A rehabilitation system as in claim **3**, further comprising:

a carrier assembly encoder in communication with said carrier assembly in order to determine a position of said carrier assembly along the y-axis of said device,

wherein said carrier assembly encoder is in further communication with said electronic device in order to transmit the position of said carrier assembly to said electronic device.

5. A rehabilitation system as in claim **4**, further comprising:

an upper assembly encoder in communication with said upper assembly in order to determine a position of said upper assembly about the z-axis of said device,

wherein said upper assembly encoder is in further communication with said electronic device in order to transmit the position of said upper assembly to said electronic device.

6. A rehabilitation system as in claim **1**, further comprising:

a first load cell in communication with said left compliant handle assembly to determine an amount of force placed by said user on said left compliant handle assembly; and

a second load cell in communication with said right compliant handle assembly to determine an amount of force placed by said user on said right compliant handle assembly,

wherein said first and second load cells are in further communication with an electronic device in order to transmit the amounts of force on said left and right compliant handle assemblies to said electronic device.

7. A rehabilitation system as in claim **1**, further comprising:

said left compliant handle assembly including a first left compliant handle assembly component coupled to and extending from said left handle slide along the y-axis of said device, said left compliant handle assembly further including a second left compliant handle assembly component coupled to and extending inwardly from said first left compliant handle assembly component, and

said right compliant handle assembly including a first right compliant handle assembly component coupled to and extending from said right handle slide along the y-axis of said device, said right compliant handle assembly further including a second right compliant handle assembly component coupled to and extending inwardly from said first right compliant handle assembly component.

8. A rehabilitation system as in claim **7**, further comprising:

a first left load cell positioned along and in communication with said first left compliant handle assembly component to determine an amount of force placed by said user on said first left compliant handle assembly component;

a second left load cell positioned along and in communication with said second left compliant handle assembly component to determine an amount of force placed by said user on said second left compliant handle assembly component,

wherein said first and second left load cells are in further communication with an electronic device in order to transmit the amount of force on said left compliant handle assembly to said electronic device;

a first right load cell positioned along and in communication with said first right compliant handle assembly component to determine an amount of force placed by said user on said first right compliant handle assembly component; and

a second right load cell positioned along and in communication with said second right compliant handle assembly component to determine an amount of force placed by said user on said second right compliant handle assembly component,

wherein said first and second right load cells are in further communication with said electronic device in order to transmit the amount of force on said right compliant handle assembly to said electronic device.

9. A rehabilitation system as in claim **1**, further comprising:

a first spring system coupled to said left compliant handle assembly to provide a bias against movement of said left handle; and

a second spring system coupled to said right compliant handle assembly to provide a bias against movement of said right handle.

10. A rehabilitation system as in claim **9**, further comprising:

said first spring system including a first spring disposed at a connection joint between said left handle slide and said left compliant handle assembly, said first spring system further including a second spring disposed within said left compliant handle assembly, and

said second spring system including a third spring disposed at a connection joint between said right handle slide and said right compliant handle assembly, said second spring system further including a fourth spring disposed within said right compliant handle assembly.

11. A rehabilitation system as in claim **10**, further comprising:

said left compliant handle assembly including a first left compliant handle assembly component coupled to and extending from said left handle slide along the y-axis of said device, said left compliant handle assembly further including a second left compliant handle assembly component coupled to and extending inwardly from said first left compliant handle assembly component,

said second spring disposed at a connection joint between said first left compliant handle assembly component and said second left compliant handle assembly component,

said right compliant handle assembly including a first right compliant handle assembly component coupled to and extending from said right handle slide along the y-axis of said device, said right compliant handle assembly further including a second right compliant handle assembly component coupled to and extending inwardly from said first right compliant handle assembly component, and

said fourth spring disposed at a connection joint between said first right compliant handle assembly component and said second right compliant handle assembly component.

12. A rehabilitation system as in claim **9**, further comprising:

said first spring system being a first spring stack formed of a plurality of torsion springs stacked or abutting one another, and

said second spring system being a second spring stack formed of a plurality of torsion springs stacked or abutting one another,

whereby said predetermined coupling stiffness can be adjusted, based on said user, by adding or removing torsion springs from said first and second spring stacks.

13. A rehabilitation system as in claim **12**, further comprising:

said torsion springs each including a central portion and two (2) forks extending from said central portion, said two (2) forks having longitudinal extents that are angled relative to each other.

14. A rehabilitation system as in claim **1**, further comprising:

a first locking mechanism for restricting movement of said upper assembly about the z-axis of said device; and

a second locking mechanism for restricting movement of said carrier assembly in the y-axis of said device.

15. A rehabilitation system as in claim **1**, further comprising:

a visual display communicatively coupled to said device for indicating a current left position of said left handle and a current right position of said right handle, wherein said current left position and said current right position move as said left handle and said right handle respectively move.

16. A rehabilitation system as in claim 15, further comprising:

said visual display further indicating a target left position of said left handle and a target right position of said right handle, whereby a goal of said user is to align said current left position with said target left position and align said current right position with said target right position.

17. A rehabilitation system including a compliant bimanual rehabilitation device, comprising:

a base that defines a left side, a right side, a front side, a rear side, an x-axis, a y-axis, and a z-axis of said device, wherein said base has a top side and a bottom side;

a carrier assembly slidably coupled to said base via slide rails mounted on said top side of said base, said carrier assembly being slidable along the y-axis of said device;

a carrier assembly encoder in communication with said carrier assembly in order to determine a position of said carrier assembly along the y-axis of said device, wherein said carrier assembly encoder is in further communication with an electronic device in order to transmit the position of said carrier assembly to said electronic device;

an upper assembly rotationally coupled to said carrier assembly, said upper assembly being rotational about the z-axis of said device, said upper assembly having a left end corresponding to said left side of said device and a right end corresponding to said right side of said device;

an upper assembly encoder in communication with said upper assembly in order to determine a position of said upper assembly about the z-axis of said device, wherein said upper assembly encoder is in further communication with said electronic device in order to transmit the position of said upper assembly to said electronic device;

a left handle slide slidably coupled to said left end of said upper assembly, said left handle slide being slidable along the x-axis of said device;

a left handle slide encoder in communication with said left handle slide in order to determine a position of said left handle slide along the x-axis of said device, wherein said left slide encoder is in further communication with said electronic device in order to transmit the position of said left handle slide to said electronic device;

a right handle slide slidably coupled to said right end of said upper assembly, said right handle slide being slidable along the x-axis of said device;

a right handle slide encoder in communication with said right handle slide in order to determine a position of said right handle slide along the x-axis of said device, wherein said right handle slide encoder is in further communication with said electronic device in order to transmit the position of said right handle slide to said electronic device;

a left compliant handle assembly coupled to said left handle slide and extending from said left handle slide, said left compliant handle assembly including a first left compliant handle assembly component coupled to and extending from said left handle slide along the y-axis of said device, said left compliant handle assembly further including a second left compliant handle assembly component coupled to and extending inwardly from said first left compliant handle assembly component;

a first left load cell positioned along and in communication with said first left compliant handle assembly component to determine an amount of force placed by said user on said first left compliant handle assembly component;

a second left load cell positioned along and in communication with said second left compliant handle assembly component to determine an amount of force placed by said user on said second left compliant handle assembly component,

wherein said first and second left load cells are in further communication with said electronic device in order to transmit the amount of force on said left compliant handle assembly to said electronic device;

a right compliant handle assembly coupled to said right handle slide and extending from said right handle slide, said right compliant handle assembly including a first right compliant handle assembly component coupled to and extending from said right handle slide along the y-axis of said device,

said right compliant handle assembly further including a second right compliant handle assembly component coupled to and extending inwardly from said first right compliant handle assembly component;

a first right load cell positioned along and in communication with said first right compliant handle assembly component to determine an amount of force placed by said user on said first right compliant handle assembly component;

a second right load cell positioned along and in communication with said second right compliant handle assembly component to determine an amount of force placed by said user on said second right compliant handle assembly component;

wherein said first and second right load cells are in further communication with said electronic device in order to transmit the amount of force on said right compliant handle assembly to said electronic device;

a left handle fixedly coupled to said left compliant handle assembly;

a right handle fixedly coupled to said right compliant handle assembly,

wherein one of said left handle and said right handle is a guiding handle and the other of said left handle and said right handle is a following handle,

wherein said left handle and said right handle are indirectly linked to each other at an adjustable, predetermined coupling stiffness via said left handle slide and said right handle slide being coupled to each other, thus also coupling said left compliant handle assembly and said right compliant handle assembly to each other,

said left handle slide and said right handle slide being coupled to each other via a cable and pulley assembly including at least one cable and at least two pulleys, wherein

when said at least one cable is looped around said at least two pulleys an even number of times, said left handle and said right handle move in a same absolute direction, and

when said at least one cable is looped around said at least two pulleys an odd number of times, said left handle and said right handle mirror each other,

wherein when said device is in use, a paretic arm of a user or operator of said device is linked to a sound arm of said user of said device, such that a movement of said guiding handle dictates a corresponding movement of said following handle according to a predetermined symmetry mode;

a first locking mechanism for restricting movement of said upper assembly about the z-axis of said device:

a second locking mechanism for restricting movement of said carrier assembly in the y-axis of said device;

a first spring system coupled to said left compliant handle assembly to provide a bias against movement of said left handle,

said first spring system including a first spring stack disposed at a connection joint between said left handle slide and said left compliant handle assembly, said first spring system further including a second spring stack disposed at a connection joint between said first left compliant handle assembly component and said second left compliant handle assembly component,

said first and second spring stacks each formed of a plurality of torsion springs stacked on each other;

a second spring system coupled to said right compliant handle assembly to provide a bias against movement of said right handle,

said second spring system including a third spring stack disposed at a connection joint between said right handle slide and said right compliant handle assembly, said second spring system further including a fourth spring stack disposed at a connection joint between said first right compliant handle assembly component and said second right compliant handle assembly component,

said third and fourth spring stacks each formed of a plurality of torsion springs stacked on each other,

whereby said predetermined coupling stiffness can be adjusted, based on said user, by adding or removing torsion springs from said first and second spring stacks,

said torsion springs each including a central portion and two (2) forks extending from said central portion, said two (2) forks having longitudinal extents that are substantially perpendicular to each other; and

a visual display communicatively coupled to said device for indicating a current left position of said left handle and a current right position of said right handle, wherein said current left position and said current right position move as said left handle and said right handle respectively move,

said visual display further indicating a target left position of said left handle and a target right position of said right handle, whereby a goal of said user is to align said current left position with said target left position and align said current right position with said target right position.

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