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Santos-Munne et al.

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(54) **WALKING AND BALANCE EXERCISE DEVICE**

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A61H 1/00 (2006.01)

(52) **U.S. Cl.** **601/5**; 602/16

(58) **Field of Classification Search** 601/5; 2/465; 600/587; 5/86.1; 602/5, 19, 32, 16
See application file for complete search history.

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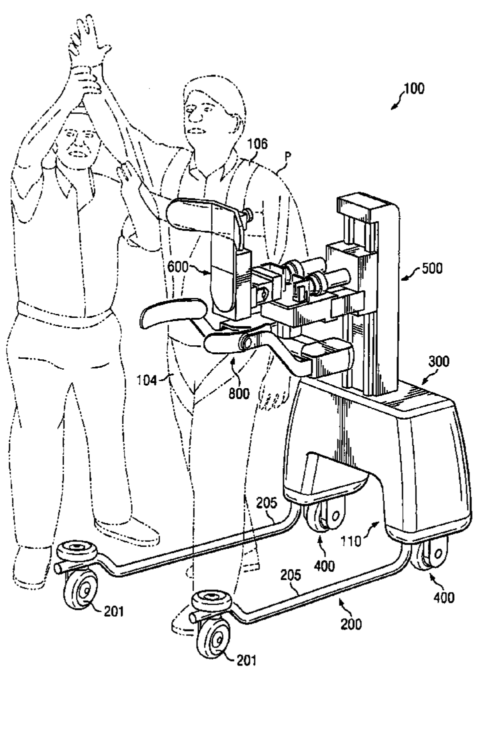
Primary Examiner—Michael A. Brown
(74) *Attorney, Agent, or Firm*—Drinker Biddle & Reath LLP

(57) **ABSTRACT**

A pelvic support unit is coupled to a base by a powered vertical force actuator mechanism. A torso support unit, which is affixed to the patient independently of the pelvic support unit, is connected to the base by one or more powered articulations which are actuable around respective axes of motion. Sensors sense the linear and angular displacement of the pelvic support unit and the torso support unit. A control unit is coupled to these sensors and, responsive to signals from them, selectively control the displacement actuator and articulation(s). Wheel modules are independently powered to both rotate and steer, and, responsive to the control unit, are capable of rolling the exercise device in a direction of travel intended by the patient.

26 Claims, 18 Drawing Sheets



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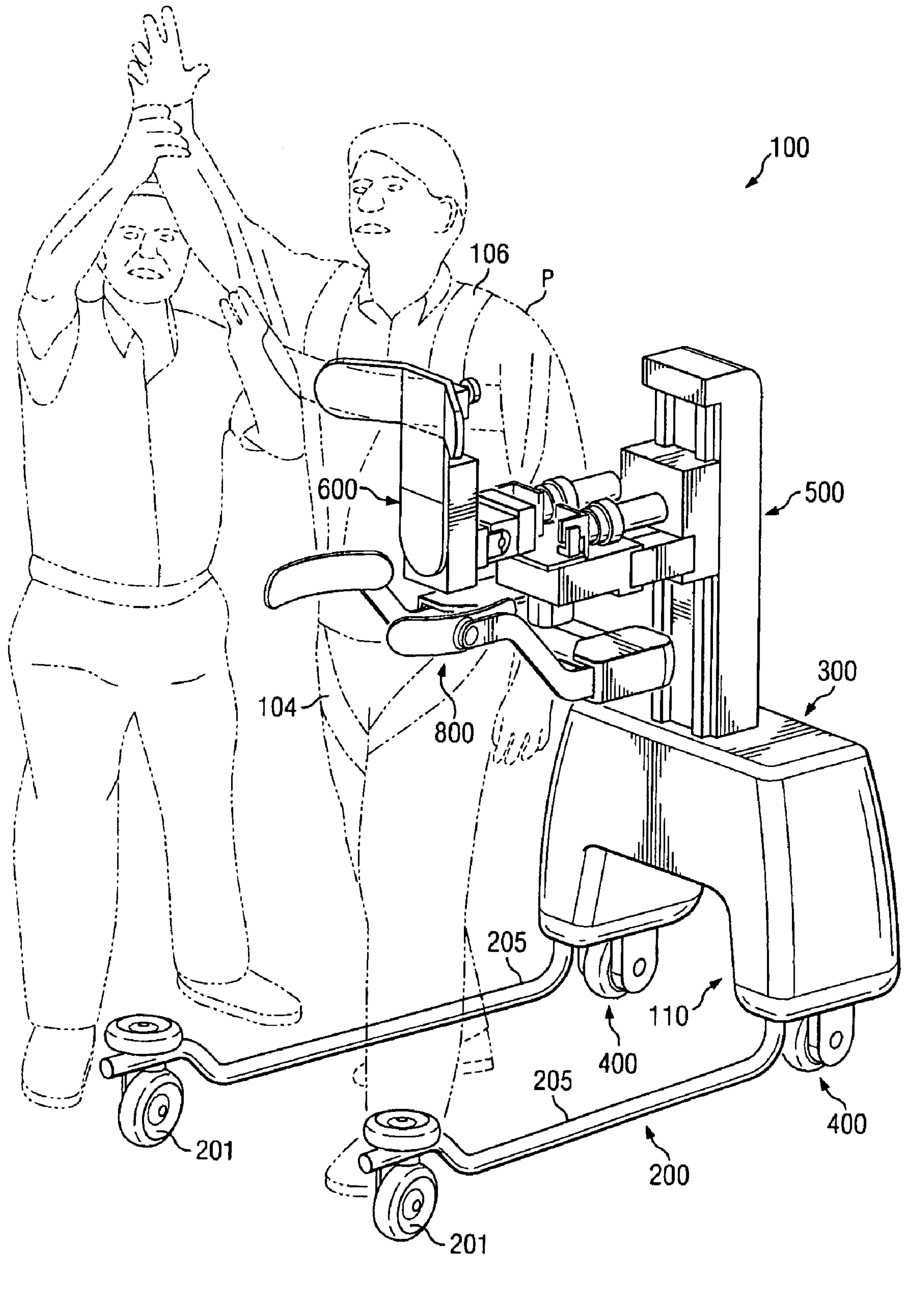


FIG. 1

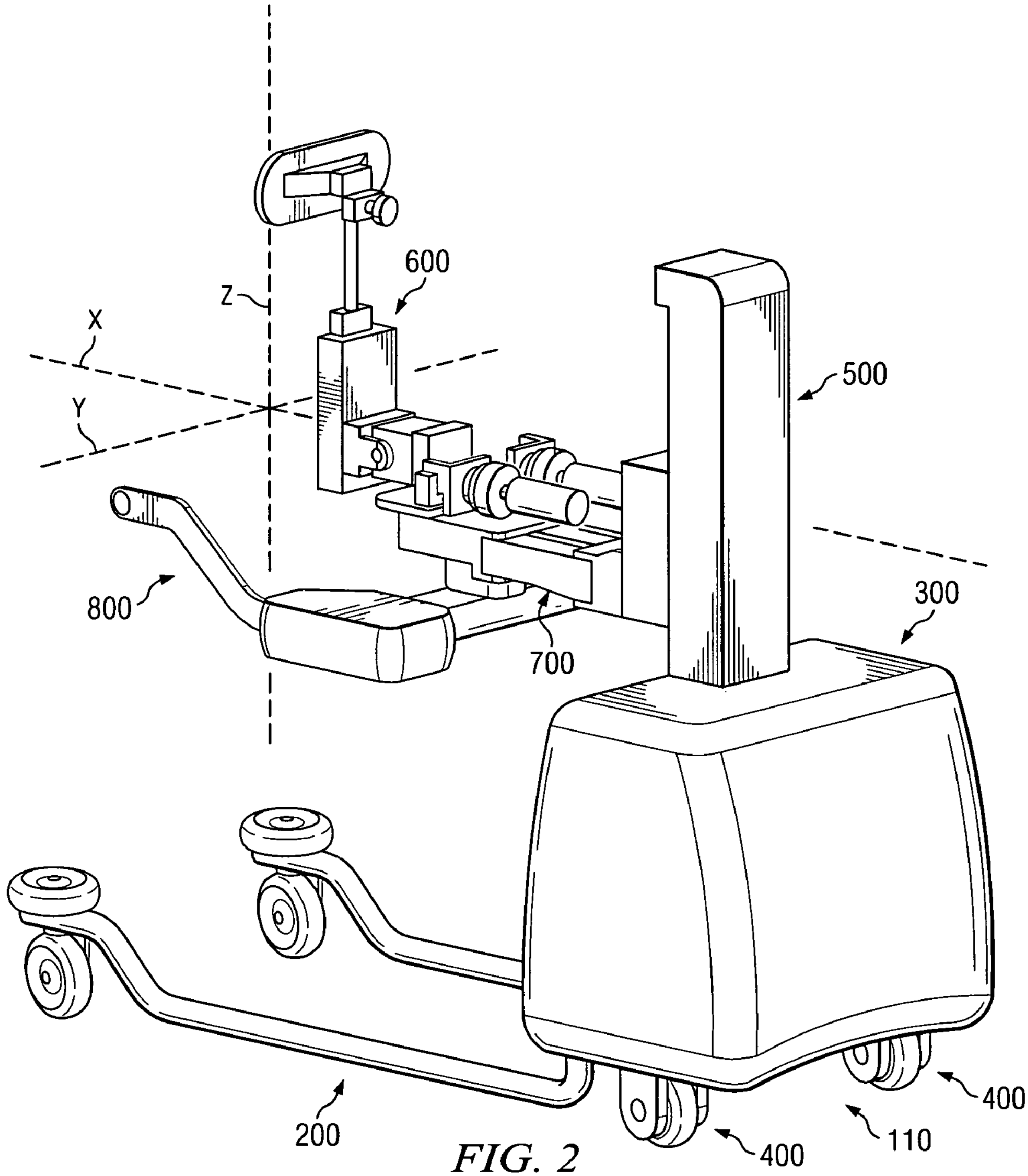


FIG. 2

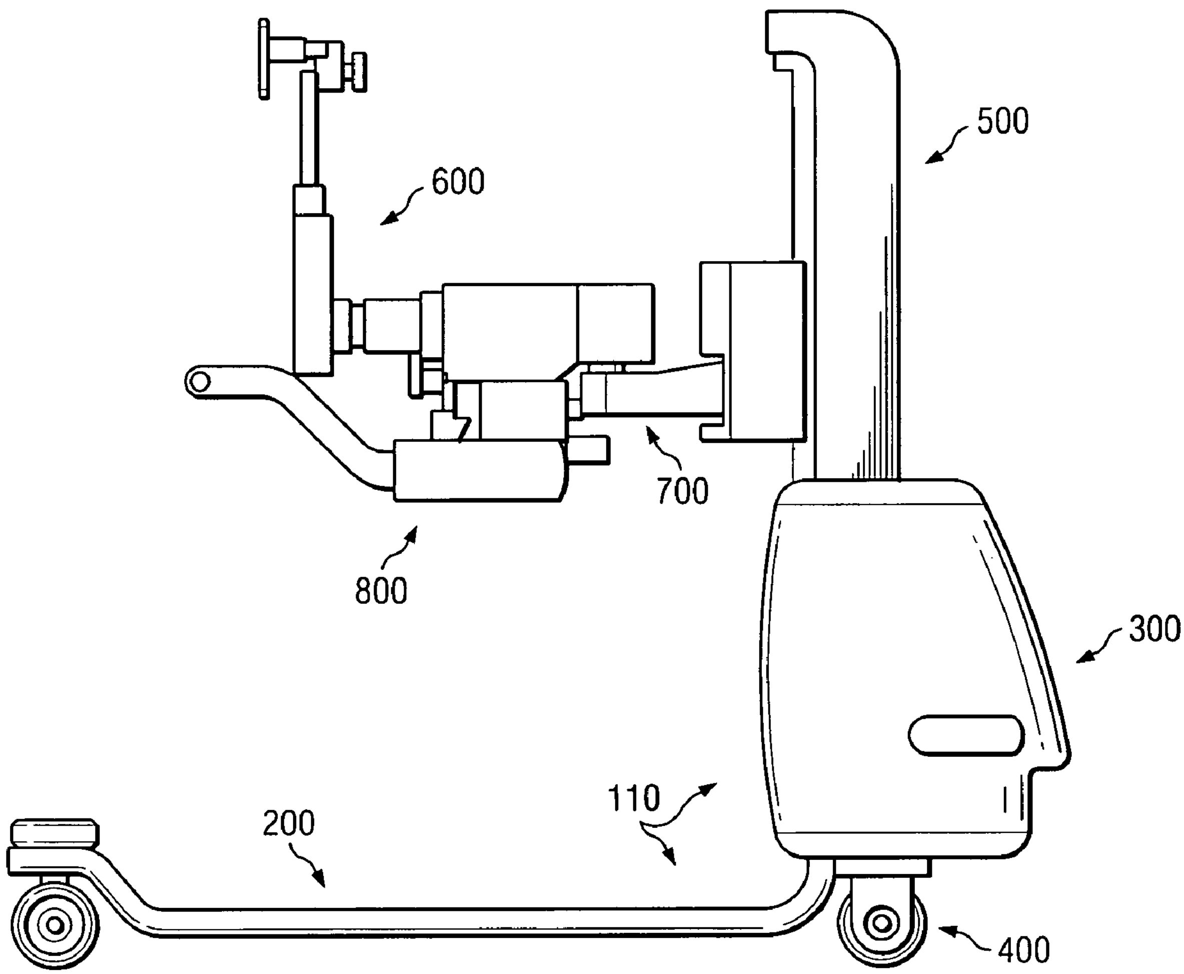
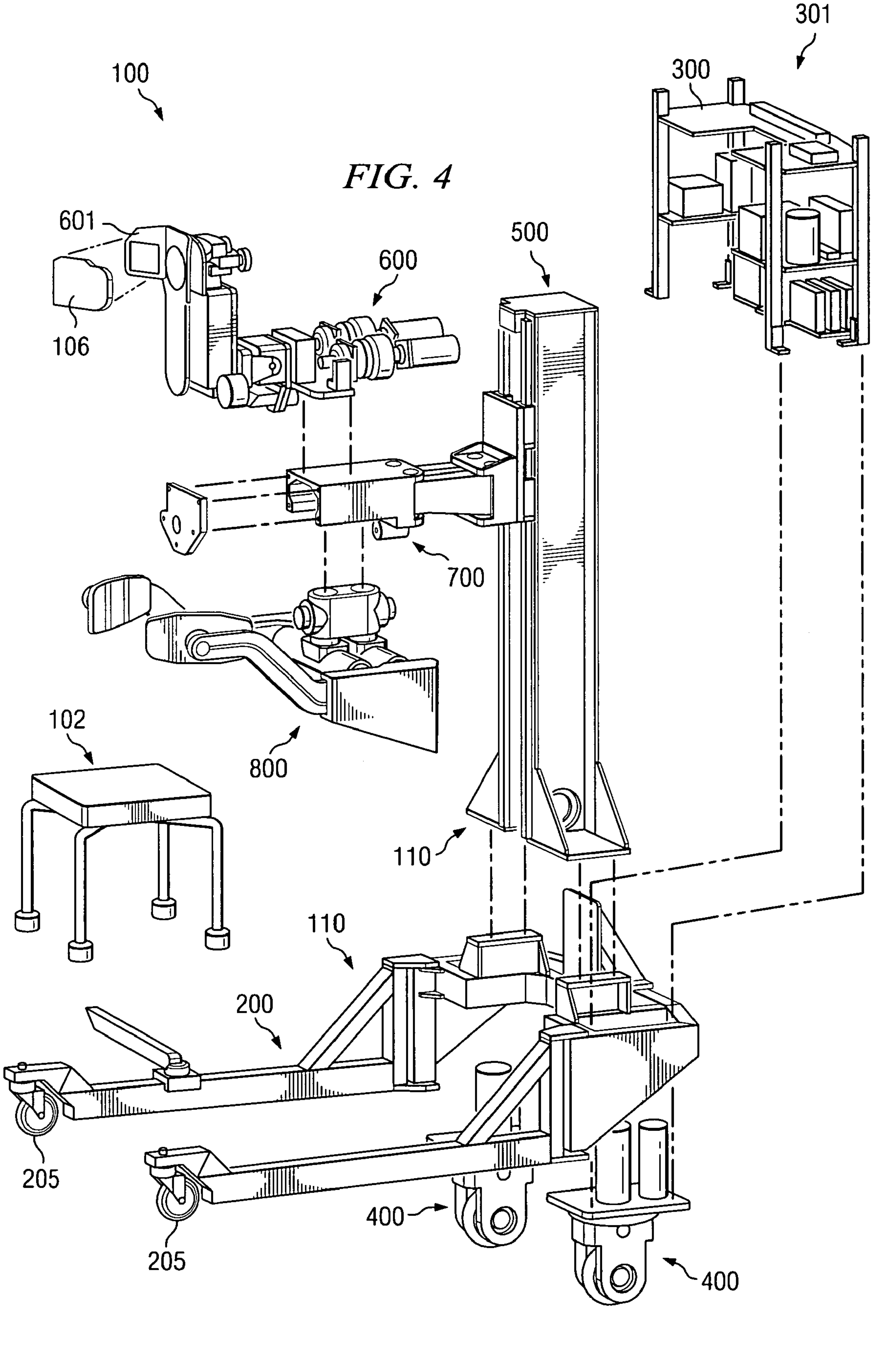


FIG. 3

FIG. 4



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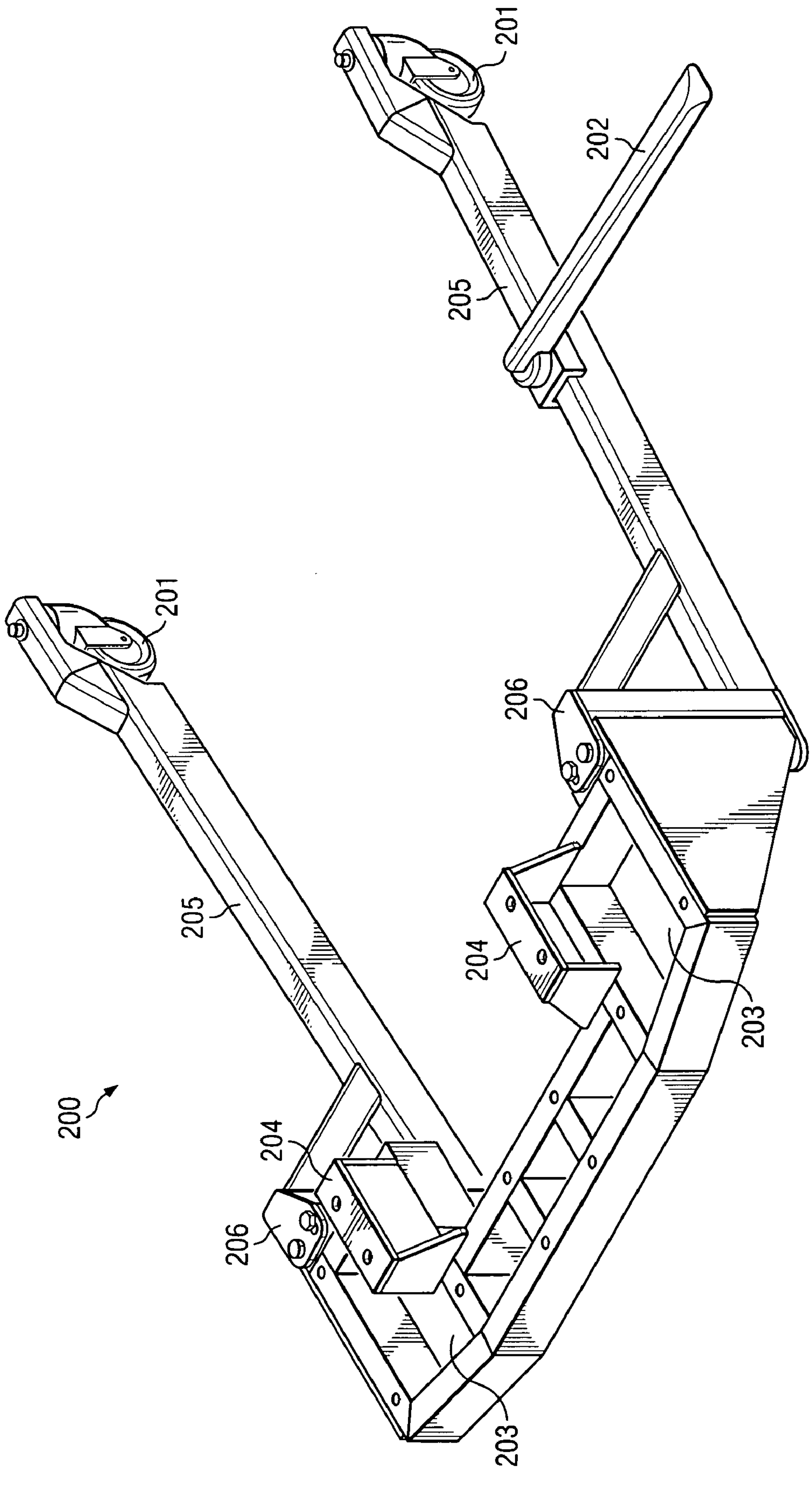

FIG. 5

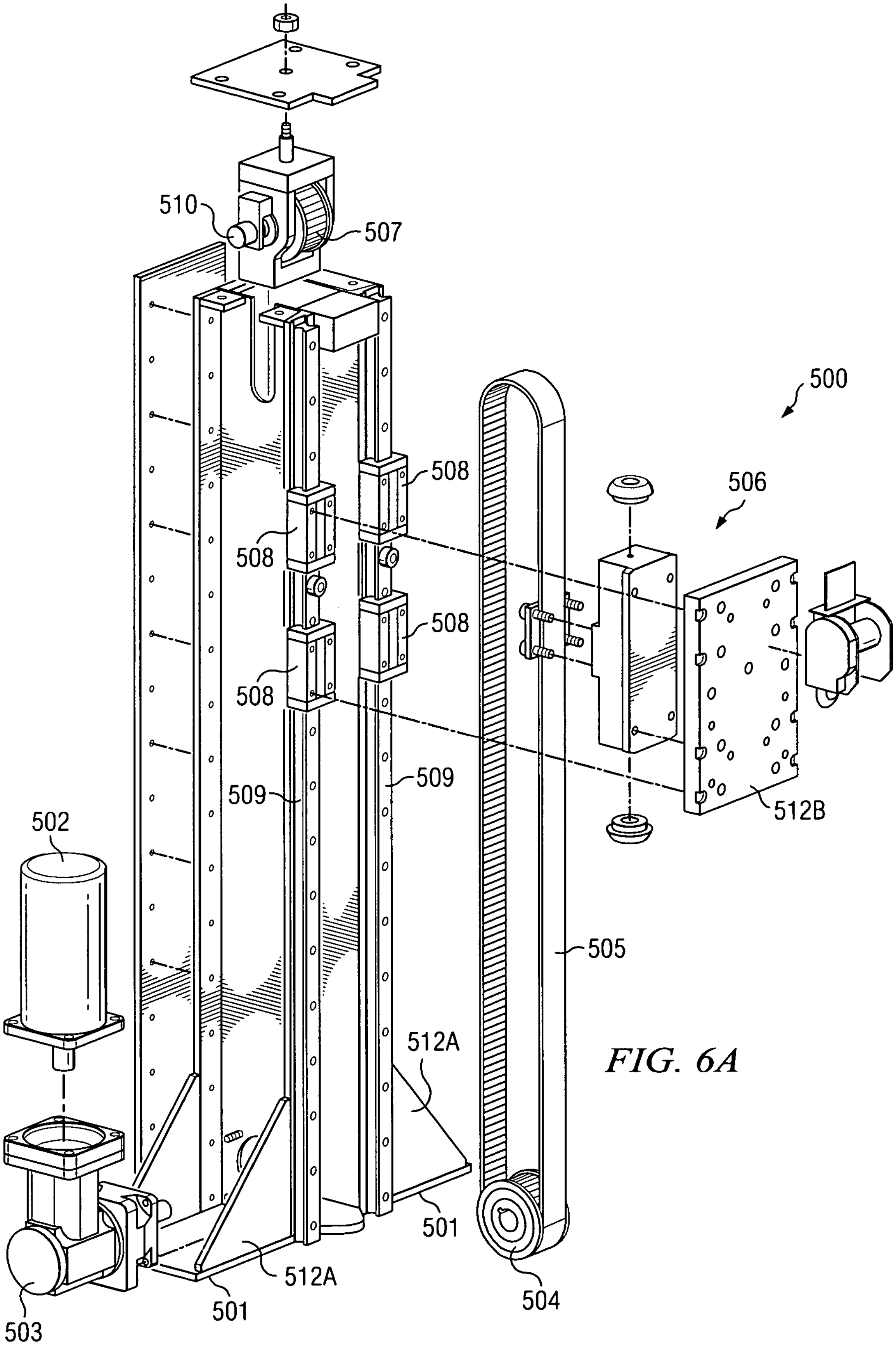
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FIG. 6A

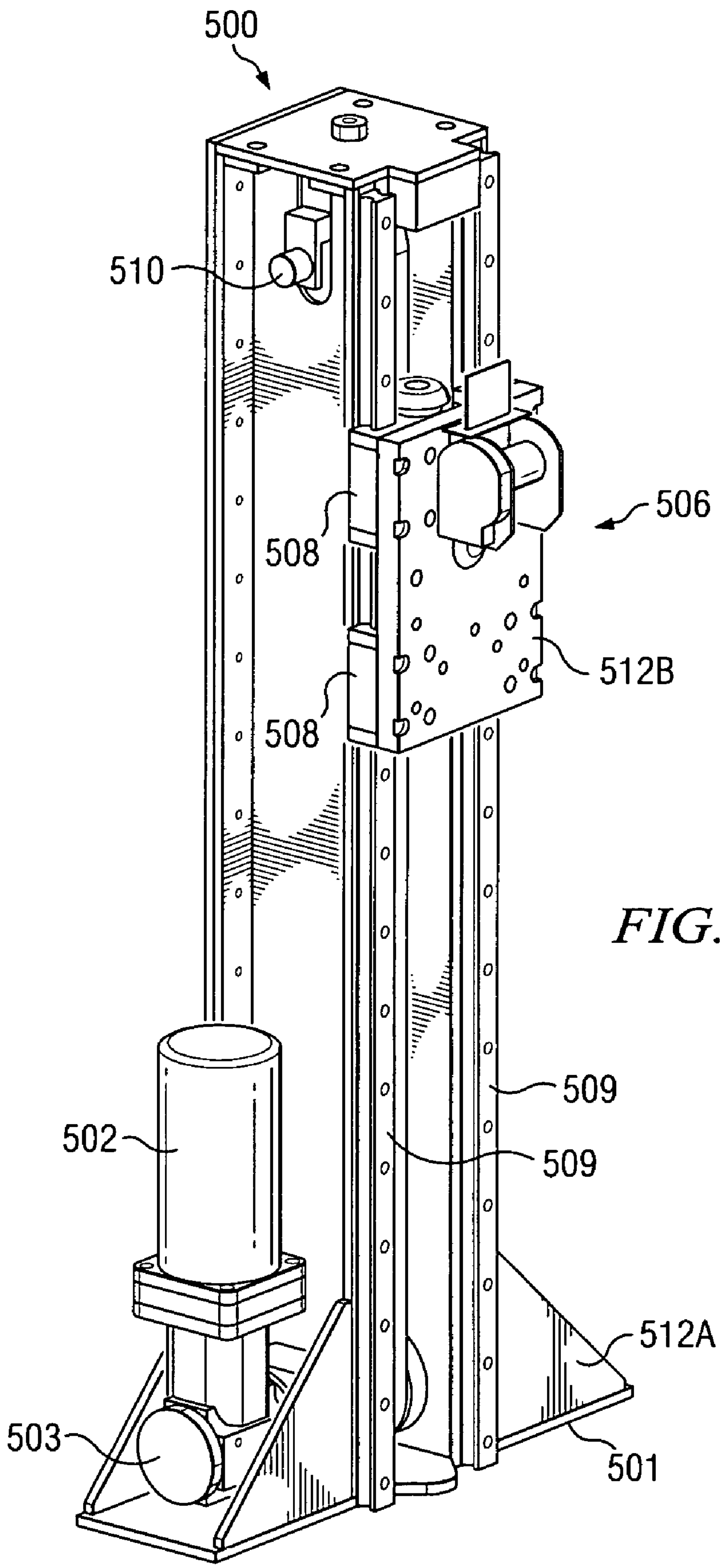

FIG. 6B

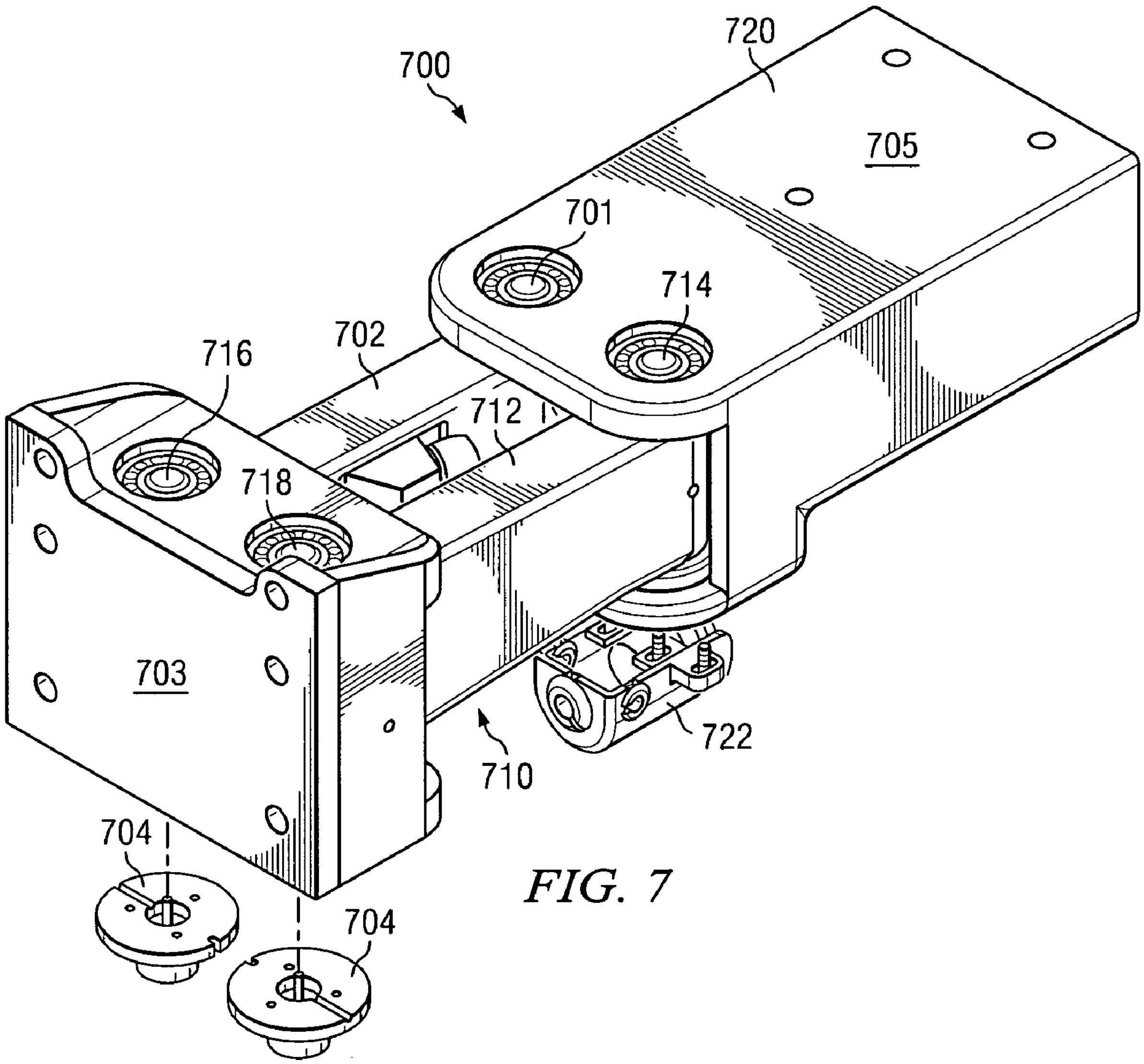

FIG. 7

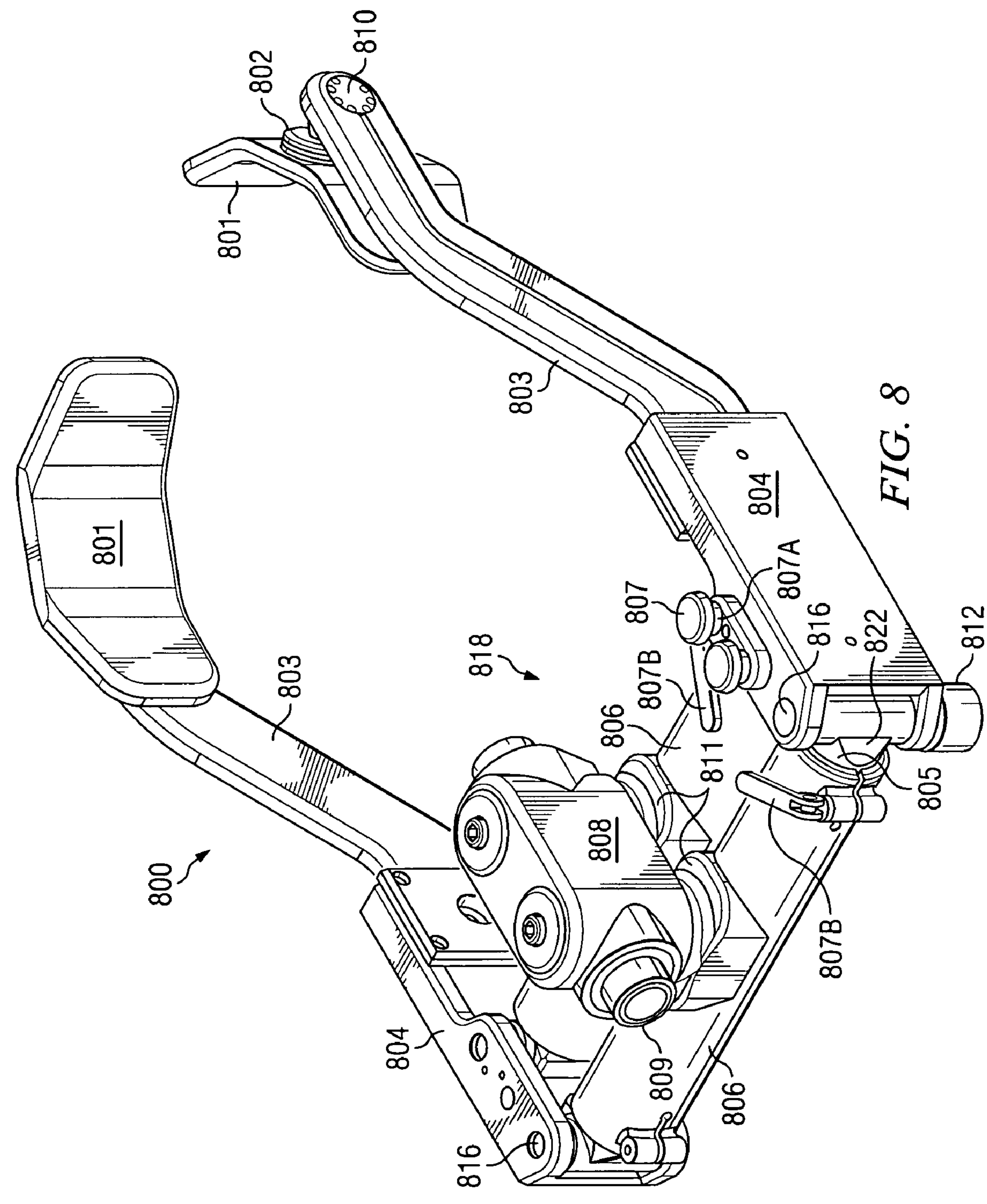
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FIG. 8

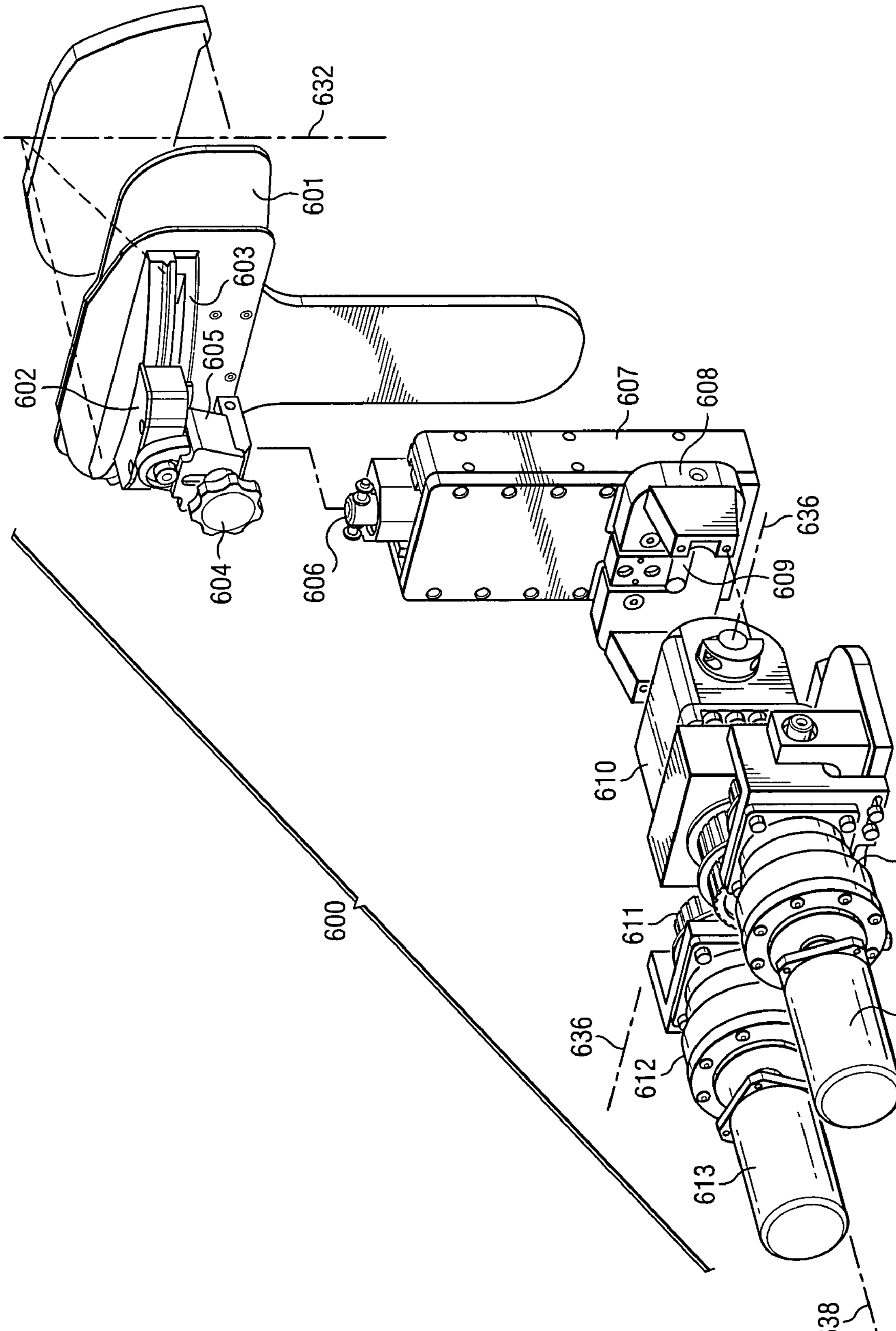
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FIG. 9

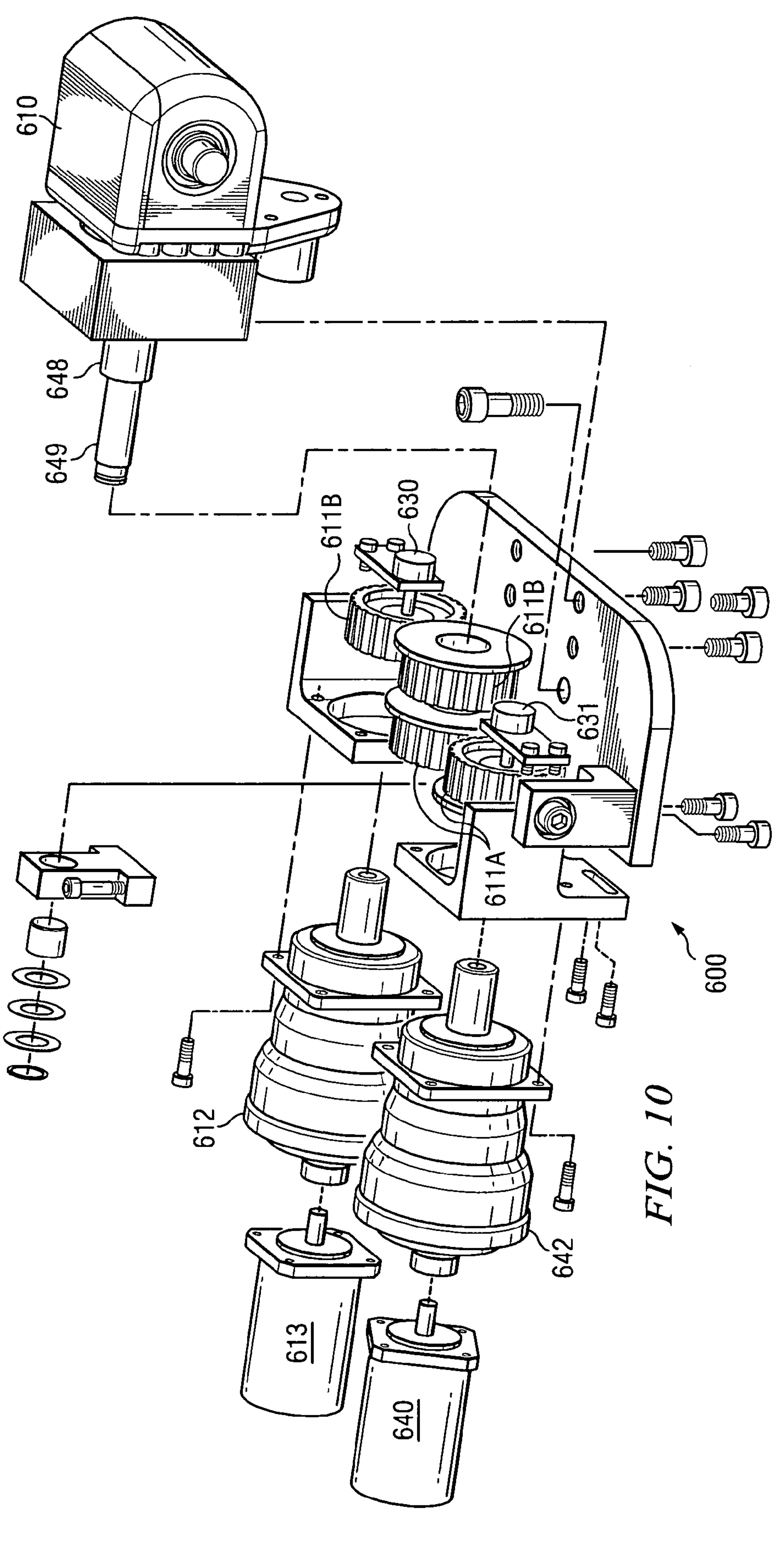

FIG. 10

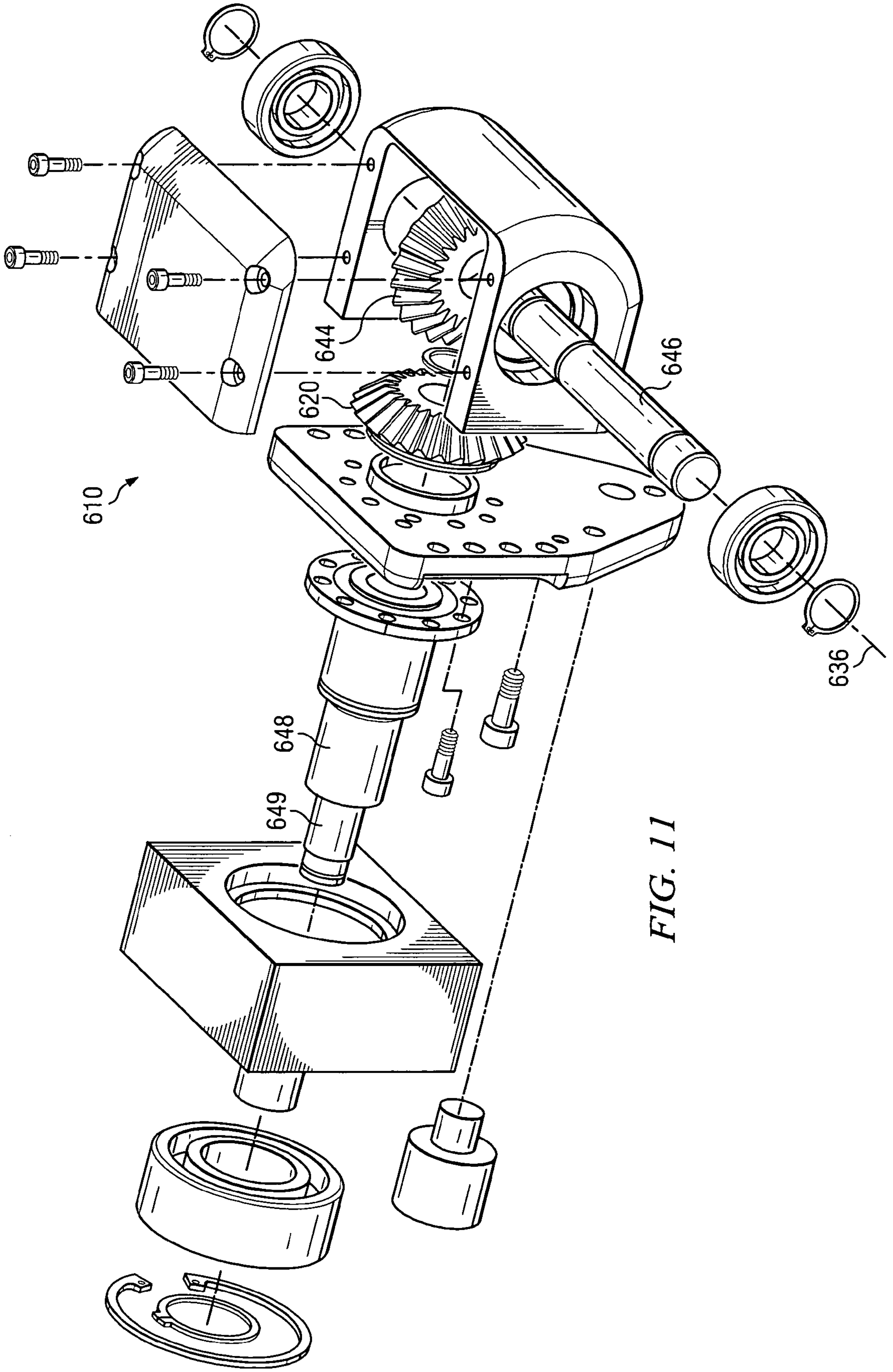

FIG. 11

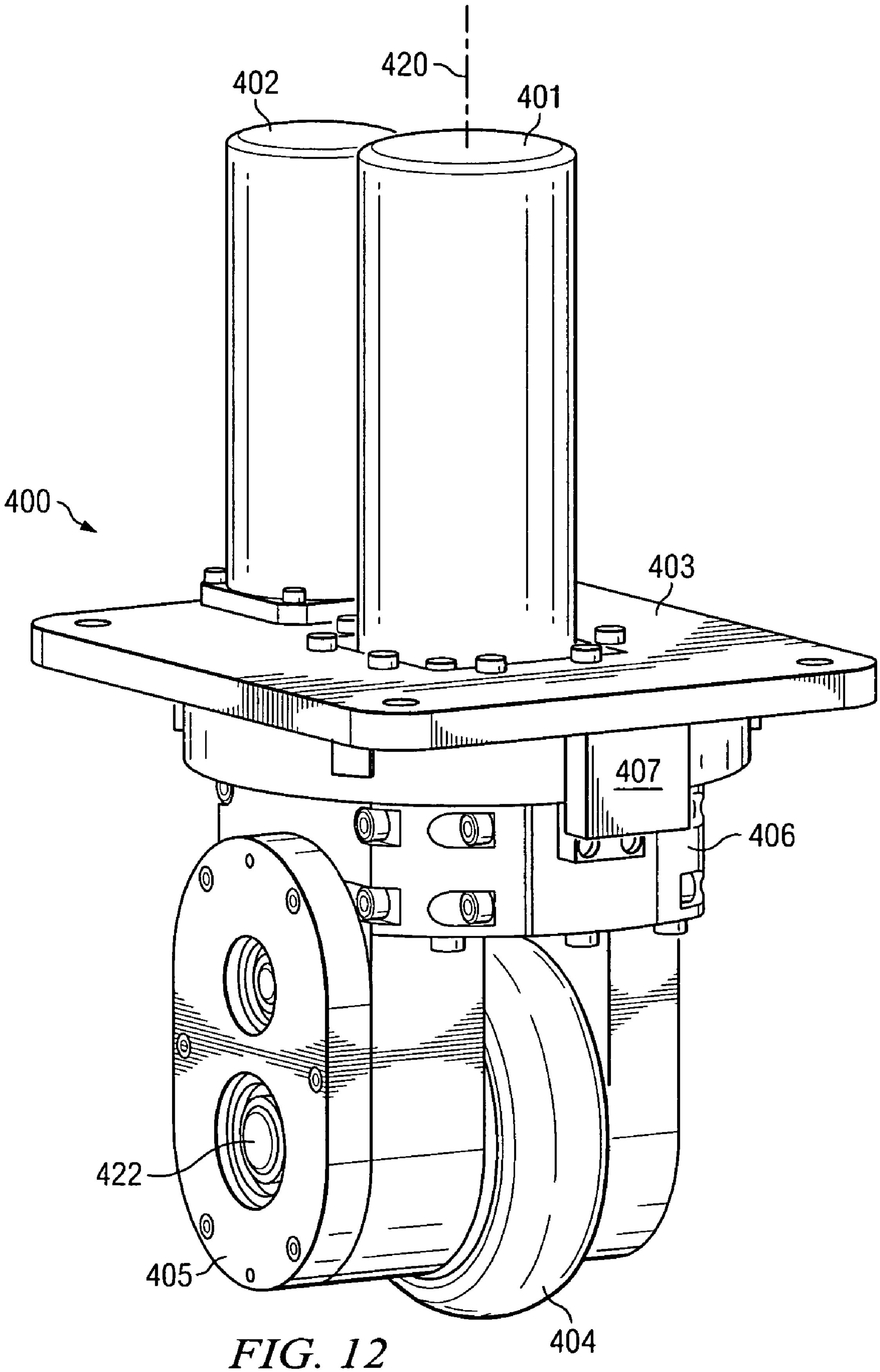

FIG. 12

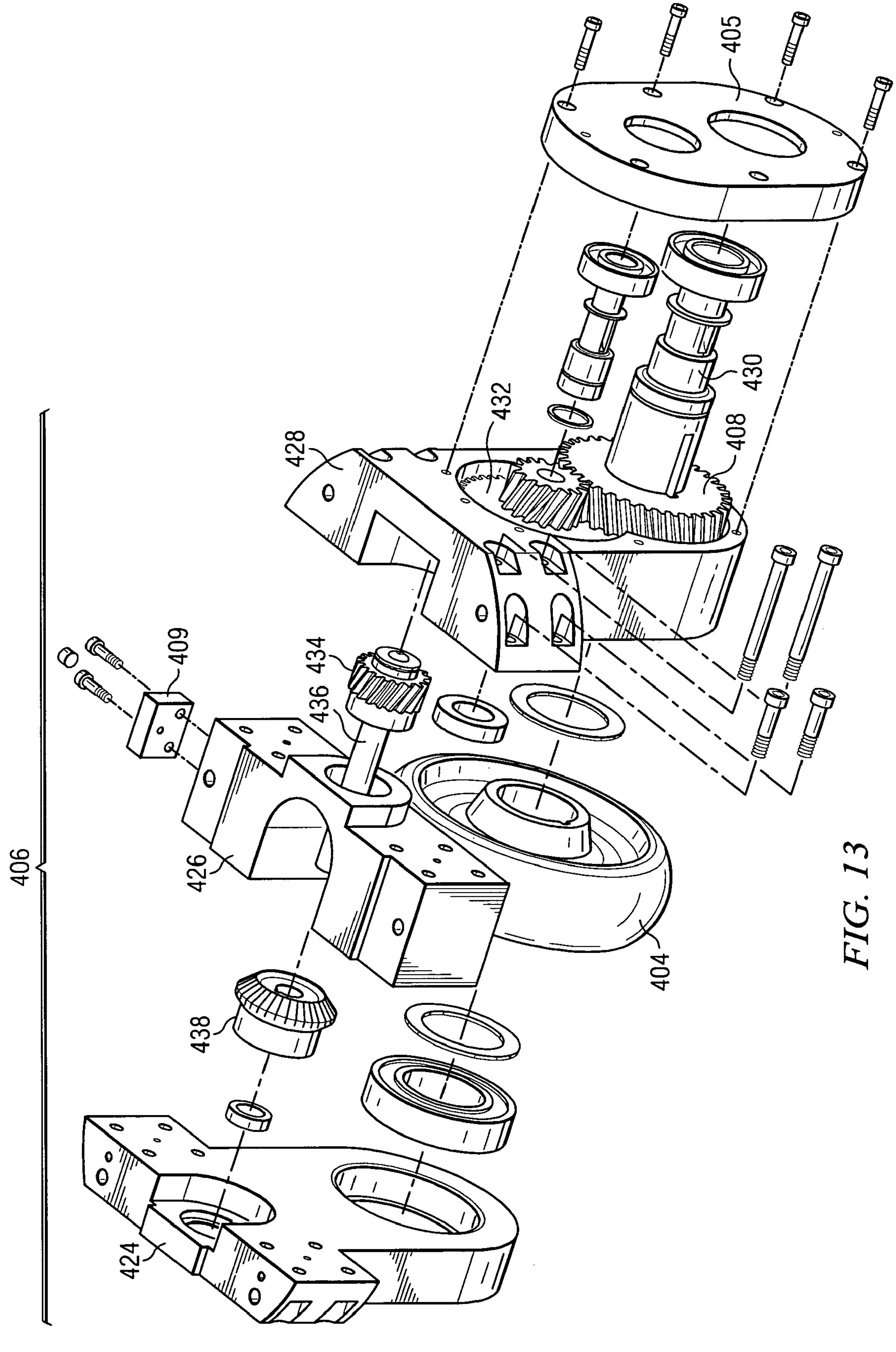

FIG. 13

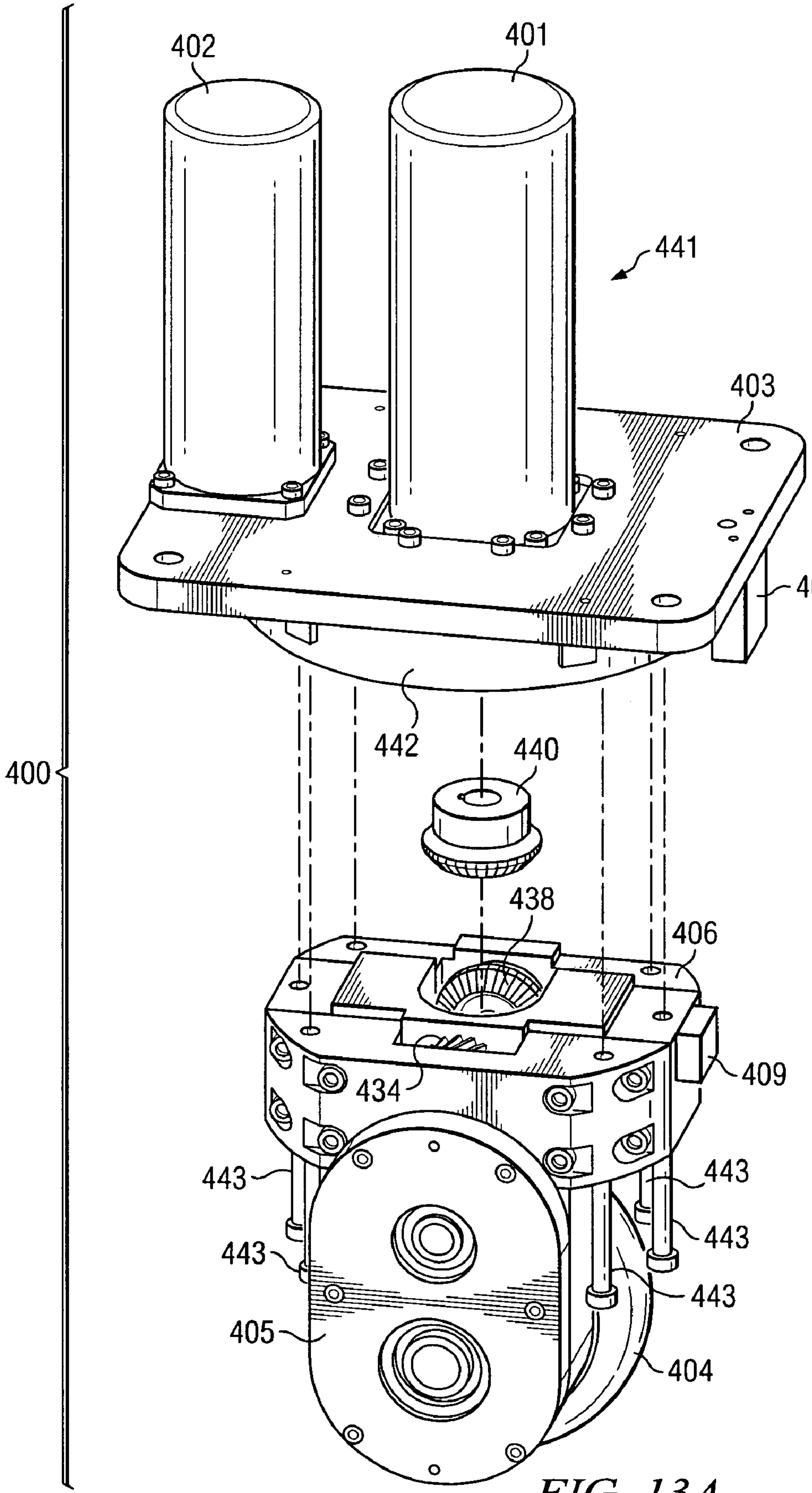
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FIG. 13A

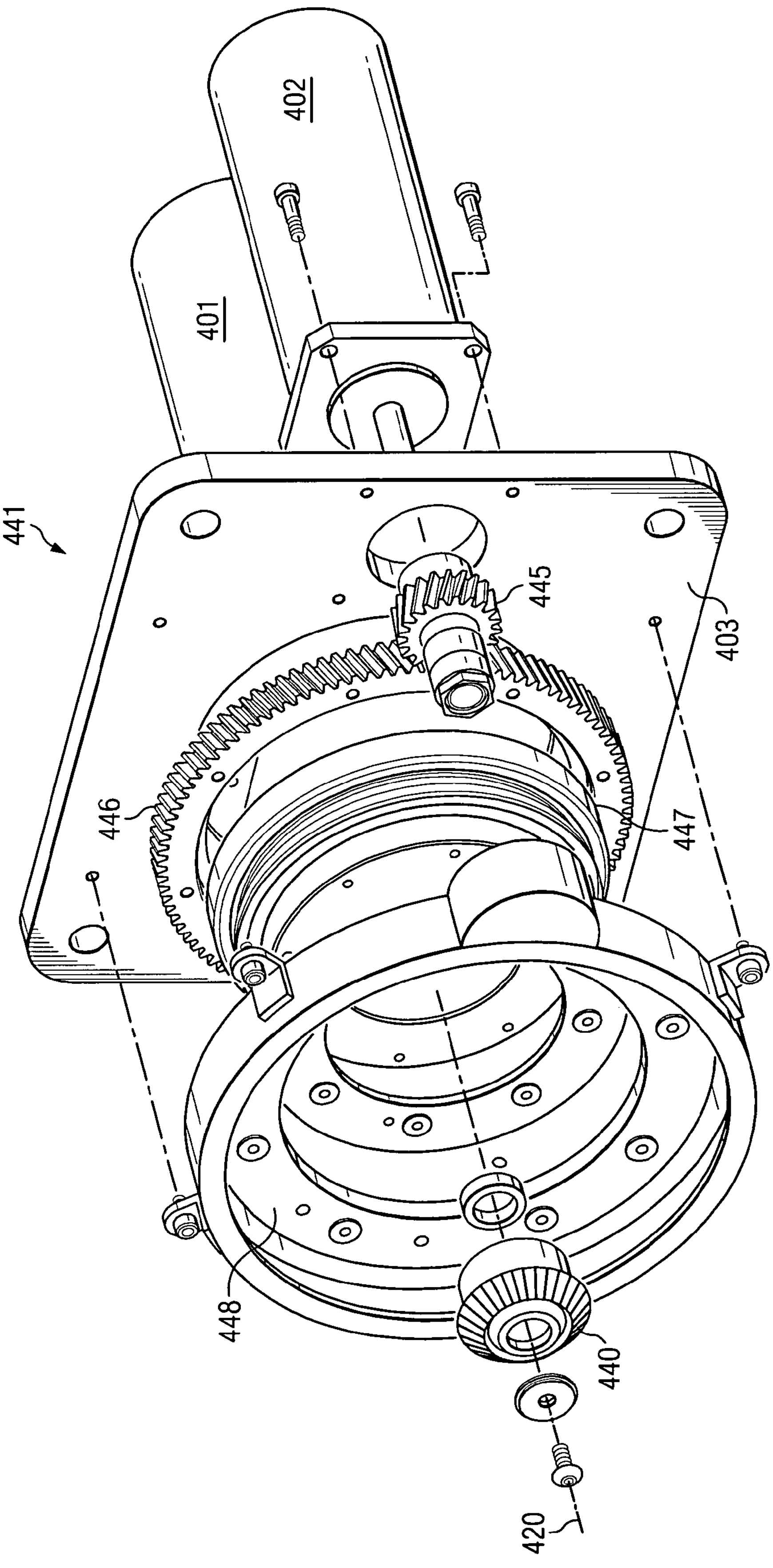
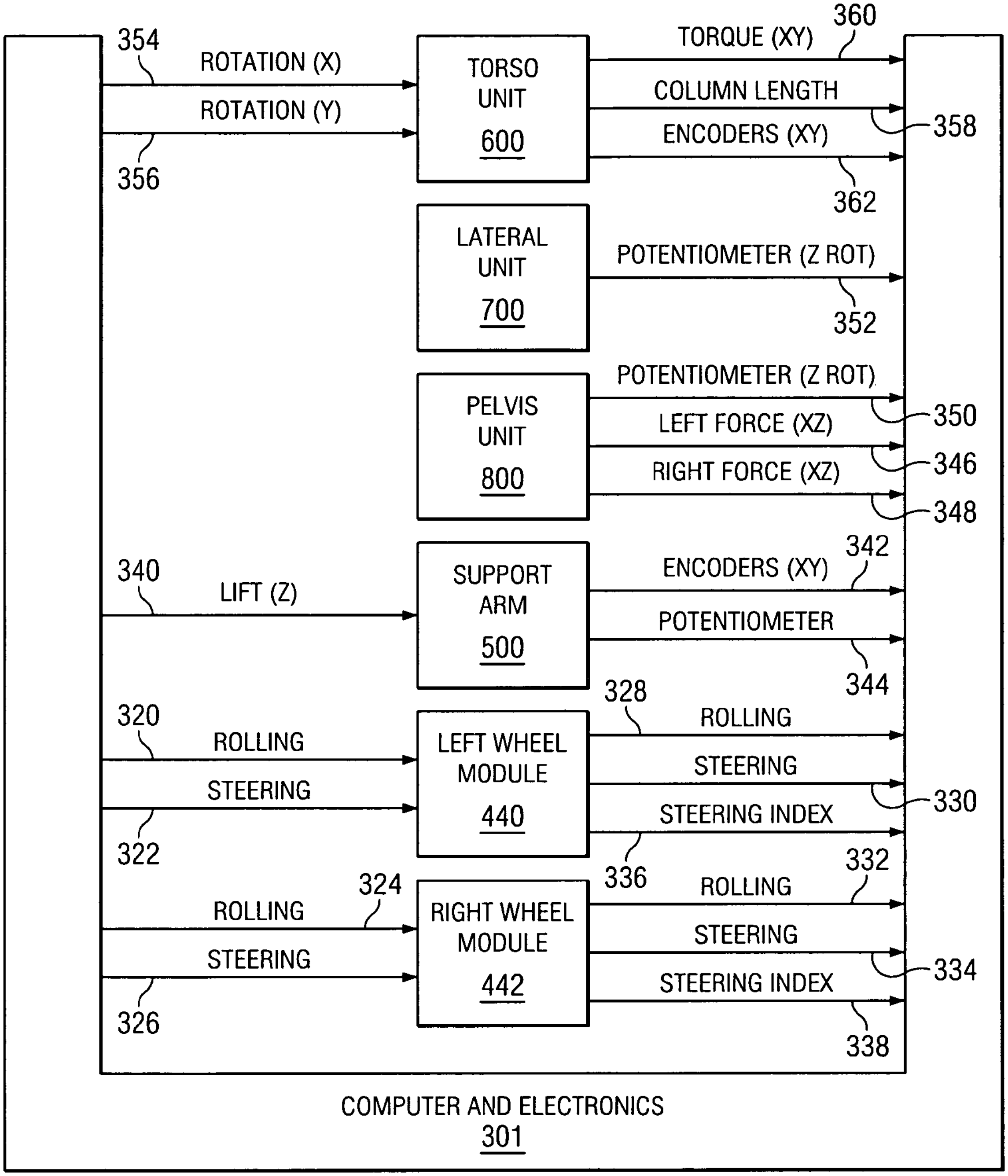


FIG. 13B



354
ROTATION (X)
ROTATION (Y)
356
TORSO UNIT 600
TORQUE (XY)
360
COLUMN LENGTH
358
ENCODERS (XY)
362
LATERAL UNIT 700
POTENTIOMETER (Z ROT)
352
PELVIS UNIT 800
POTENTIOMETER (Z ROT)
350
LEFT FORCE (XZ)
346
RIGHT FORCE (XZ)
348
340
LIFT (Z)
SUPPORT ARM 500
ENCODERS (XY)
342
POTENTIOMETER
344
320
ROLLING
STEERING
322
LEFT WHEEL MODULE 440
328
ROLLING
STEERING
330
STEERING INDEX
336
324
ROLLING
STEERING
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RIGHT WHEEL MODULE 442
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ROLLING
STEERING
334
STEERING INDEX
338
COMPUTER AND ELECTRONICS
301

FIG. 14

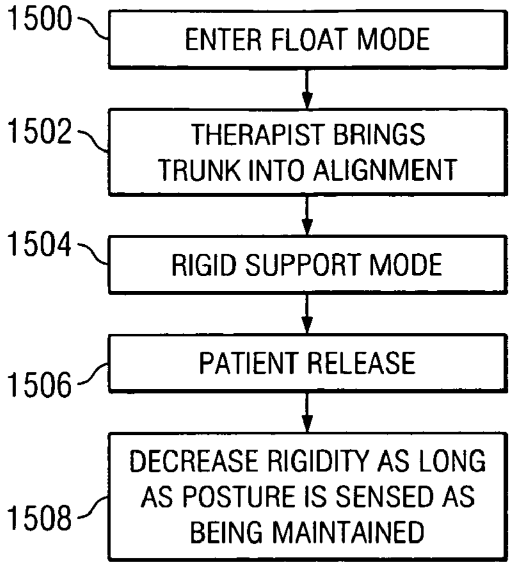

FIG. 15

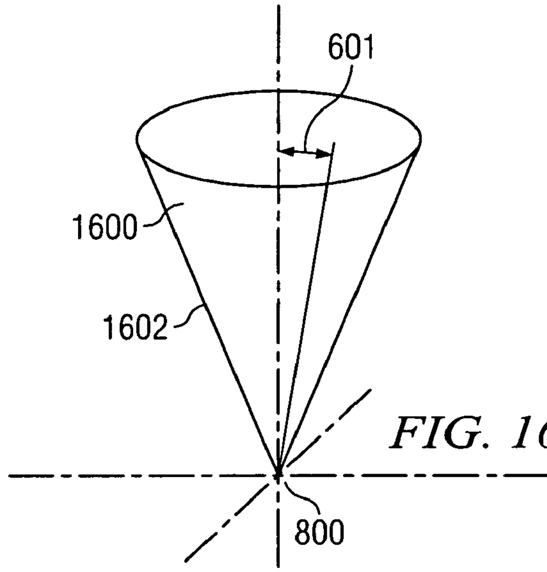

FIG. 16

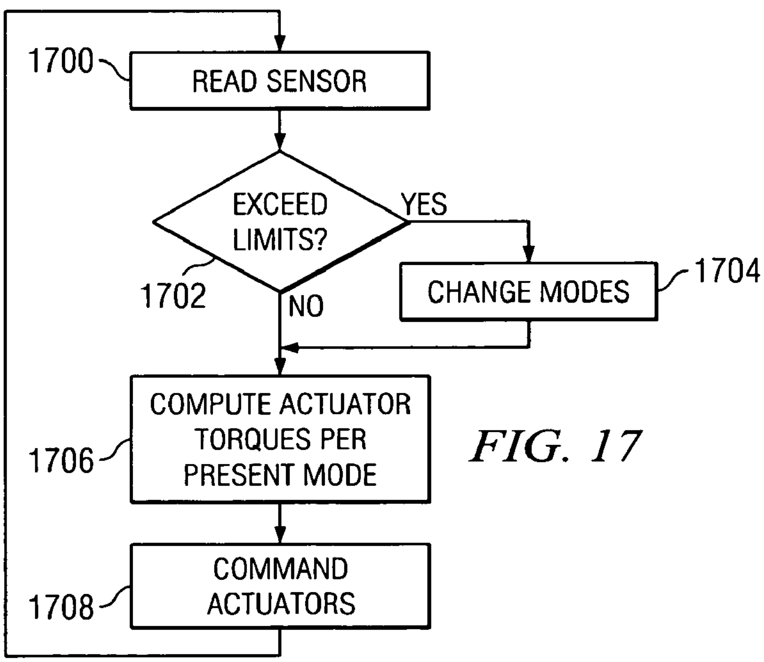

FIG. 17

WALKING AND BALANCE EXERCISE DEVICE

GOVERNMENT LICENSE RIGHTS

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms provided for by the terms of Contract No. 70NANB3H3003 awarded by the U.S. Department of Commerce.

TECHNICAL FIELD OF THE INVENTION

The present invention relates in general to methods and apparatus for physical therapy, and in particular to a powered physical therapy device for assisting a patient in performing walking, balance and reaching tasks.

BACKGROUND OF THE INVENTION

Presently there are two approaches in which gait training is conducted: a fully manual approach and a device-assisted approach. In manual therapy the therapist uses a gait belt for the purposes of both preventing a patient from falling, and applying corrective forces during training. While this method is in common practice today, it suffers from the following problems: it is unsafe, awkward, frequently requires more than one therapist due to safety concerns (and hence expensive), difficult to sustain for a long time, and restricts sufficient access to the patient's legs.

Conventional devices used to assist therapists with gait training usually are variations of overhead body support systems (for example, LITEGAIT™ manufactured by Pro Med Products). These devices have not seen wide use because their uncomfortable harnesses and long setup times limit the duration of therapy sessions. In addition, their large, unwieldy frames restrict mobility of patients over the ground or floor and restrict device transport in a hospital setting.

Another conventional device, the LOKOMAT™ manufactured by Hocoma AG, is stationary, implements only one therapy approach (neurofacilitation) which involves repetitive movement of the legs within a specified kinematic pattern, and is primarily targeted to the spinal cord injury patient population. The trunk and pelvis is held stationary and the movements occur over a treadmill. Therefore, this device does not allow balance training, overground walking training or upper extremity practice during locomotion.

In view of these conventional devices, a need persists in the physical therapy field for a device which enhances safety, addresses balance in the context of gait training, allows practice with using the upper extremities, enhances patient mobility in a functional context of walking over ground, permits easy access by the therapist to the patient's legs, permits the physical therapist to challenge the patient in a safe manner, reduces setup time, and increases duration of therapy.

SUMMARY OF THE INVENTION

According to one aspect of the invention, a base of a physical therapy apparatus has coupled to it a pelvic support unit fittable to the patient and a torso support unit fittable to the patient. The pelvis support unit is coupled to the base through at least a first angular or translational articulation. The torso support unit is coupled to the base through a second articulation which is independent of the first articulation.

According to a further aspect of the invention, the physical therapy apparatus provided includes a frame which can travel

over the floor or ground and an upstanding support arm affixed to the frame. A pelvis support unit is fitted to the pelvic region of the patient and has a powered actuator which selectively applies a vertical force to the pelvis support unit relative to the base. In one of its modes of operation, the pelvis support unit applies a force in opposition to the force of gravity, relieving a therapist-selected portion of the patient's weight. The apparatus further includes a torso support unit which is fitted to the torso of the patient at a position above the pelvis of the patient. The torso support unit includes a powered articulation about at least one axis relative to the base which is independent of the powered vertical actuator associated with the pelvis support unit. Sensors are associated with the pelvis support unit and the torso support unit, or the structures supporting them, to sense the spatial position and orientation of these units relative to the base and, preferably, one or more of the forces and torques applied to these structures. A control unit is coupled to the sensors, to the powered vertical actuator and to the powered articulation to selectively move the pelvis support unit and the torso support unit relative to the base.

Preferably, the patient wears a torso harness affixed to the torso support unit and a pelvic harness affixed to the pelvis support unit. These harness elements are preferably separate from each other.

In one embodiment, the control unit is able to apply a selected amount of torque in a selected angular direction around the torso unit axis of articulation. This torque, for example, could be used to completely or partially resist a patient torso's excursion away from an appropriate posture.

In another aspect of the invention, the torso support system's powered articulation actuates around at least two axes of motion, such as tilt in a sagittal plane and tilt in a coronal plane. Sensors are provided to sense angular displacement, and/or torques, in both directions, and the control unit can actuate the powered articulation(s) to correct any excursion away from an appropriate posture, or on the other hand can intentionally challenge the patient in order to improve balance. The present invention presents a host of choices to the therapist in conducting physical therapy relative to walking, posture, standing, reaching, and other activities involving the position and movement of the torso and pelvis. By way of further example and not by limitation, the apparatus may be used or programmed to exaggerate the patient's deviation from correct posture in order to train the patient to fight the other way, to train for the correct rhythmic movements associated with a walking gait, to apply constant torque irrespective of patient posture, or to follow the lead of the patient but apply damping forces to make the patient's movements feel safe to the patient.

According to a further aspect of the invention, in one embodiment the base is movable across the floor or ground using at least two powered wheel modules or units, which are actuated to both roll and steer independently of each other. The control unit can actuate the powered wheels in order to conform the position and orientation of the physical therapy exercise device to a direction of travel in which the patient intends to go. This patient intent can be deduced from signals coming from sensors associated with the torso and/or pelvis support units, which can be chosen to be of the type which encode displacement, force/torque or both. Other means for moving the base relative to the ground or floor can be used.

According to yet another aspect of the invention, a physical therapy exercise apparatus is provided in which a pelvic support is coupled to a base by a powered vertical linear displacement mechanism. The physical therapist is therefore enabled to relieve some or all of the patient's weight using the control unit and force sensors. Nonetheless, the pelvic support unit is freely articulable around the vertical axis and other axes in order to permit the kind of pelvic motion which occurs during a walking gait. In a one embodiment, the pelvic support unit is also transversely articulable in order to permit a degree of side-to-side pelvic movement; in the illustrated embodiment this side-to-side articulated is accomplished by a lateral unit to which the pelvic support is joined. In one embodiment these articulations are effected by providing parallelogram linkages between the pelvic support unit and a lateral arm coupled to the base. Sensors are provided to sense the angular displacement of these pelvic unit articulations and/or forces or torques accompanying them, the signals resulting from which can be used by the control unit to take corrective action and/or change the direction of travel of the unit. A preferred embodiment of the invention enables the pelvic support unit to rotate around three axes of motion: Y (tilt or pitch), X (hike or roll), and Z (swivel or yaw). In a preferred embodiment at least motions around the X and Z axes are sensed. In alternative embodiments, one or more of these articulations may be actuated and controlled instead of being freely articulable or "floating".

In a preferred embodiment, the present invention provides a computer-controlled, servo-driven physical therapy aid designed to ensure a patient's safety during gait and balance training. The device has different features and modes of operation to assist the therapist in providing efficient gait and balance therapy to patients with a wide variety of disorders and levels of disability.

The device has several technical advantages over conventional apparatus and methods. First, a single therapist can conduct training without the assistance from other staff. Second, the device provides a responsive support system which permits natural body dynamics to occur during walking. This allows the patient to work on his or her balance as part of the exercise.

Third, the device permits the therapist to safely challenge the patient. Risk naturally occurs with balance. The patient can experience the onset of a fall and has to make necessary corrections in order to recover and continue walking. However, an unsuccessful recovery must not result in a potentially dangerous fall, and the present invention prevents this. Furthermore, because of the inherent safety of the apparatus the therapist can challenge the patient to a larger degree than would be possible in conventional practice.

Fourth, the present invention enhances efficiency in the delivery of therapeutic services. In order to make best use of the limited duration of a therapy session, it is important that setup time, such as harnessing the patient, be kept to a bare minimum. Otherwise there is a disincentive for the therapist to use the device. The present invention is designed to make transfer into the device, configuration of the device and harnessing the patient very brief.

Fifth, the overall design of the device enhances the therapist's access to the patient's legs. Therapists often like to grasp the patient's legs, feet, etc. to guide the patient. The therapist typically likes to sit beside the patient—on a stool or the like—as the patient is exercising. The present invention moves as much of the support device as is possible toward the rear of the patient and otherwise out of the way of the volume through which the therapist conventionally accesses the patient.

BRIEF DESCRIPTION OF THE DRAWINGS

Further aspects of the invention and their advantages can be discerned in the following detailed description, in which like characters denote like parts and in which:

FIG. **1** is an isometric view of a walking and balance exercise device according to the invention, with a patient and harness shown in phantom and hip pads and patient motion sensors removed for clarity;

FIG. **2** is an isometric view of the device shown in FIG. **1**, taken from another angle;

FIG. **3** is an elevational view of the device shown in FIGS. **1** and **2**;

FIG. **4** is an exploded view of an embodiment of the device similar to the embodiment shown in FIGS. **1-3**, with padding and covers removed in order to show further detail;

FIG. **5** is an isometric view of a frame unit which makes up a portion of the device shown in FIG. **4**;

FIGS. **6**A and **6**B are exploded and assembled isometric views, respectively, of a support arm forming a component of the device shown in FIG. **4**;

FIG. **7** is an isometric view of a lateral unit forming a structural component of the device shown in FIG. **4**;

FIG. **8** is an isometric view of a pelvis unit forming a structural component of the device shown in FIG. **4**;

FIG. **9** is an exploded isometric detail of a torso unit of the embodiment shown in FIG. **4**;

FIG. **10** is an exploded isometric detail of a portion of FIG. **9**, showing pulleys and other transmission components of the torso unit;

FIG. **11** is an exploded isometric detail of a portion of FIG. **10**, showing gearing and other transmission components of the torso unit;

FIG. **12** is an isometric view of an assembled motorized wheel module for use with the invention;

FIG. **13** is an exploded isometric view of a lower part of the motorized wheel module shown in FIG. **12**;

FIG. **13**A is a further exploded isometric view of the motorized wheel module shown in FIG. **12**, showing cooperation between drive motors and driven wheel housing;

FIG. **13**B is a further exploded isometric view of an upper part of the motorized wheel module shown in FIG. **12**;

FIG. **14** is a schematic diagram of a control system according to the invention;

FIG. **15** is a process diagram illustrating steps in trunk/pelvis stabilizer mode of operation of the invention;

FIG. **16** is a schematic diagram of a "cone of safety" established by one mode of operation of the invention; and

FIG. **17** a schematic and representative flow diagram of the "cone of safety" mode of operation.

DETAILED DESCRIPTION

According to one aspect of the invention, a gait and balance trainer is provided which includes a body harness, a responsive support system and wheels. A patient wears a pelvis harness and a torso harness which are connected to the responsive support system, whose motion with respect to the ground is controlled by at least two of the wheels. The responsive support system is designed to accommodate back and pelvis movement during walking by means of several active and passive degrees of freedom. The purpose of this is to allow natural walking patterns as well as to incorporate balance training into the exercise. The device according to the invention is capable of maintaining proper posture for weaker patients and can support a therapist-selected amount of their body weight.

In one use, the present invention allows a patient's natural walking body dynamics to occur unimpeded while providing a safety mechanism. The present invention can be used by the therapist in many ways to modify the patient's motion.

In the description below, the following coordinate system is used, as superimposed on FIG. **2**. The X axis is front-to-back and is normal to a coronal plane containing the Y and Z axes. The Y axis is lateral, transverse or side-to-side and is normal to a sagittal plane containing the X and Z axes. The Z axis is vertical and is normal to a transverse or horizontal plane containing the X and Y axes.

Referring first to FIGS. **1-4**, the relationship of the major components of the first illustrated embodiment of the invention, and their relationship to a patient and a patient's harness, will be described. In this illustrated embodiment, a device **100** according to the invention is comprised of a base **110**, which in turn includes a frame **200**, and a support arm or column **500** which is fixedly attached to and extends upwardly from the frame **200**. Device **100** further includes a lateral unit **700** which is supported by and is movably attached to the support arm **500**, a pelvis unit **800** attached to and supported by the lateral unit **700**, and a torso unit **600** that is also attached to and supported by the lateral unit **700**. While in the illustrated embodiment torso and pelvis units **600**, **800** are both supported by a single lateral unit **700**, in other embodiments they could be supported by separate cantilever structures projecting out form column or support arm **500**, and could also be supported by separate vertical support arms.

As will be below described, a preferred embodiment of the device **100** is capable of moving about on the floor or ground in concert with the travel of a patient P. In the illustrated embodiment, this locomotion is provided by two geared driving wheel modules **400** attached to and supporting the rear of frame **200**. The illustrated embodiment includes on-board sensor and control electronics **301**, and these can be housed in an electronic enclosure **300** mounted to the frame **200**. A separate stool **102** may be provided for the physical therapist.

In the illustrated embodiment the frame **200** may move over the ground or floor in any planar direction, including translation and rotation. These planar movements are made possible by selective actuation of the wheel modules **400**.

Support arm **500** applies a physical therapist-selected or -programmed amount of vertical lifting force to the patient P. The lateral unit **700** permits movement of the patient P from side to side. The pelvis unit **800** holds the patient securely through a pelvis harness **104**. Pelvis unit **800** applies lifting forces to the patient's pelvis, while at the same time allowing motions of the patient's pelvis consistent with walking and balance. The torso unit **600** holds the patient P's upper body securely while allowing motions of the upper body which are consistent with walking and balance. A torso harness **106** is used to affix the torso unit **700** to the patient P's upper body, and preferably is physically separate from pelvis harness **104**.

In one embodiment harnesses **104**, **106** are permanently attached to their respective pelvic and torso support systems **800**, **600**. Harnesses **104**, **106** may be formed in whole or part by various fabrics and may include various kinds of padding materials and/or inflatable sections as are known in the art.

Referring to FIG. **5**, in the illustrated embodiment the frame **200** includes wheels **201** which are rotatably affixed to the ends of respective outrigger arms **205**. Wheels **201** preferably are of the caster type, but may also be of other omni-directional type. While in other embodiments wheels **201** may be driving wheels that aid in moving the device **100** over the floor or other horizontal surface, in the illustrated embodiment the wheels **201** are "idler" wheels that conform to the lateral movement of the device **100** produced by rear driving wheel modules **400**. In alternative embodiments wheels **201** may be lockable into certain orientations, or may be fixed to move forward only. In certain alternative embodiments of the invention, such as a balance-only device or a device meant to be used in conjunction with a treadmill, wheels **201** may be locked or replaced with pads.

Frame **200** may include a stool attachment point or bar **202**, which is capable of pulling/pushing along the physical therapist's stool **102** shown in FIG. **4**. Attachment plates **204** receive support arm unit **500**. Attachment receptacles **203** receive respective wheel modules **400**. A rotatable and lockable mechanism **206** permits outrigger arms **205** to be spread apart from the illustrated parallel position to an angled-apart position, as might be useful as an aid for inserting a patient and/or a wheel chair. The ability to spread apart the outrigger arms **205** also allows the patient to perform balance exercises that require side stepping while maintaining the mobile base **110** in a fixed location.

Referring to FIG. **12**, each driving wheel module **400** includes a rolling wheel **404** which may be steered about a vertical axis **420**, and which is also driven in either a forward or reverse rolling direction. An attachment plate **403** is used to affix the wheel module **400** to a respective attachment receptacle, point or plate **203** on the frame **200**.

An assembly **406** rotates about axis **420**, carrying with it and thereby steering wheel **404**. A steering motor **402** controls the planar orientation of wheel **404** by moving the rotating assembly **406**. A drive motor **401** selectively imparts rotational force to the wheel **404**, which is illustrated in more detail in FIGS. **13** and **13**A. The action of steering motor **402** is communicated to the rolling axis **422** of the wheel **404** by gearing within a gear housing **405**, which is illustrated in more detail in FIGS. **13**A and **13**B.

Referring to FIGS. **13** and **13**A, the assembly **406** in the illustrated embodiment includes a left (according to the view in FIG. **13**) plate **424**, a top block **426** and a right plate **428**. A wheel rotating gear **408** is mounted on the axis of wheel **404** and imparts rotational force to the wheel **404** through a shaft **430**. Wheel gear **408** is driven by a gear stage **432**, which in turn is driven by a gear **434** on a shaft **436** parallel to the wheel axis. Coaxial with the gear **434** is a bevel gear **438** that communicates with vertically oriented gear **440** which is mounted on the shaft of motor **401**.

Referring to FIGS. **13**A and **13**B, the assembly **441** in the illustrated embodiment includes a fixedly mounted plate **403** and a rotating plate **448**. A rotating gear **445** is mounted on the shaft of steering motor **402** which imparts rotational force to plate **448** via rotating gear **446** which in turn is mounted on steering axis **420**. Rotating gear **446** rides on an outer race of a bearing **447** and is fastened to plate **448** via screws. Steering motion is imparted to the subassembly **406** via the fastened connection to rotating plate **448** using screws **443**.

In the illustrated embodiment, the rolling angular velocity and the steering angular velocity (around axis **420**) of wheel **404** are both measured by rotational encoders (not shown) built into respective motors **401** and **402**. These encoders are kinematically coupled to the rolling and steering wheel velocities of wheel **404** by the gear trains above described. The coding signals give incremental information only, which is sufficient to determine rolling velocity, but not completely sufficient for steering motion. To control the steering of device **100** it is necessary in this embodiment to determine the absolute steering orientation of wheel **404**. This is accomplished by a hall switch **407** on the upper housing **422** and a magnet **409** mounted on housing **406** (FIG. **13**A), which provides an indexing pulse to the electronics or control unit **301** (later described).

In FIG. **6**A, the support arm is shown in an exploded isometric view, While FIG. **6**B shows the support arm **500** in an assembled condition. A mounting flange **501**A as reinforced by gusset plates **512**, is used to mount the support arm **500** to the support arm receiving plates **204** of frame **200** (FIG. **5**). A motor **502** rotates a toothed pulley **504** via reduction gearing **503**. A vertically oriented, toothed endless drive belt **505** is mounted around the driving pulley **504** and a corresponding upper driven pulley **507**, mounted at or near the top of the support arm **500**. Motor **502** is actuated by signals from electronics module **301**.

A lateral unit carrier assembly **506** is affixed to an outer portion of the belt **505** so that it is vertically displaced upon the movement of belt **505**, either upward or downward. In this illustrated embodiment, the carrier assembly **506** is confined to a vertical axis of motion by four linear slide units **508**, which slide on a pair of vertically oriented, parallel slides **509**. The velocity and position of the lateral unit carrier **506** are sensed using an incremental encoder (not shown) incorporated into the belt driving motor **503**, in combination with a multi-turn potentiometer **510**, the latter of which is an absolute sensor.

The carrier **506** has a vertical face plate **512**B to which a vertical plate **703** of the lateral unit **700** is affixed (FIG. **7**). The lateral unit **700** allows free side-to-side motion of the patient P while the patient P is walking, balancing or reaching. A laterally translatable attachment **705** of the lateral unit **700** supports, in the illustrated embodiment, both the pelvis unit **800** and the torso unit **600**. The lateral unit **700** includes a parallelogram linkage **710** which includes lateral parallel bars **702** and **712** and bearing sets or pivots **701**, **714**, **716** and **718**.

In the illustrated embodiment the motion of the parallelogram linkage **710** is not actuated by any motor or other driver, but rather is passive and moves responsive to forces created by the patient P. While the parallelogram linkage **710** is not actuated, its angular position is nevertheless sensed by potentiometers **704**, which is used by control unit **301** to sense the lateral displacement of the patient. Attachment block **705** has an upper face **720** which carries the torso unit **600**, which is illustrated in FIGS. **9-11**. As shown in FIG. **1**, the torso unit **600** carries a torso harness **106** which is fitted to the patient P's upper torso. The torso harness **106** is attached to a torso harness plate **601**.

A first axis of motion allowed to patient P's torso is to rotate about a vertical axis. This rotation is allowed by a revolute slider **602**, which slides along and is captured by a convexly arcuate rail **603**. Optionally a locking screw **604** can be tightened to prevent rotation of the torso harness plate about an axis **650**, or therapist-adjustable stops (not shown) can be placed in rail **603** to prevent rotation of slider **602** beyond predetermined angular limits. A vertical axis of rotation **632** around which slider **602** and harness unit **601** articulates is selected to approximate an axis passing through patient P's vertical center of rotation. A potentiometer (not shown) mounted to slider **602** reads an angle of rotation around this vertical axis **632**.

The revolute slider **602** is attached to a bracket **605**. The bracket **605** attaches to a telescoping column **606**. Column **606** incorporates a length sensor (not shown) which in one embodiment can be a string potentiometer, an example of which is sold by Space Age Control Inc. of Palmdale, Calif. This length sensor measures the amount of column **606**'s extension.

The telescoping column **606** slides within a housing **607** which in turn is supported by a plate **608**. The plate **608** includes torque measuring apparatus, implemented in the illustrated embodiment by strain gauges (not shown) at location **609**. The strain gauges measure two axes of torque created by movement of the patient and communicated through sliding column **606**. These two axes of torque are about the X and Y axes. In the illustrated embodiment, the torque about a vertical or Z axis is not measured, although instrumentation easily could be provided for this measurement. The torque measuring apparatus is supported by an assembly **610** which is rotatable about two axes **636** and **638**. The assembly **610** is driven by pulleys **61** IA, which are turned by motors **613**, **640** via gear reduction units **612** and **642**.

FIG. **10** shows a portion of the torso unit **600** in more detail. Potentiometers **630** and **631** are attached to pulleys **611**A and **611**B in order to measure the rotational angles of the pulleys **611**A and **611**B and, because of the kinematic connection of the pulleys **611**A and **611**B to the telescoping column **606**, potentiometers **630** and **631** also serve to measure the angles of column **606**.

FIG. **11** is an exploded detail view of the assembly **610**. A bevel gear **644** is mounted on a transverse shaft **646**, which is coaxial with rotational axis **636** and permits/causes sliding column **606** to rotate in a sagittal plane. Driven bevel gear **644** is driven by a bevel gear **620** that is mounted to a shaft **649**. Shaft **649** communicates through pulley pair **61 1**A and reduction gearing **642** to motor **640**. Likewise shaft **648** connects to housing **610**, which is coaxial with rotational axis **638** and permits or causes the sliding column **606** to rotate in the coronal (frontal) plane. The shaft **649** communicates through pulley pair **611**B and reduction gearing **612** to motor **613**.

Thus, the torso harness **106** which attaches to patient P may freely move in the direction allowed by the telescoping column **606**, and may be actively controlled in two axes of rotation by the torso unit motors. The angle and torques associated with the torso harness **106** are measured and may be used by electronics **301** in assessing how the device **100** should be controlled.

In the illustrated embodiment, the lateral unit attachment block **705** also carries the pelvis unit **800**, which in the illustrated embodiment is attached to an underside of the attachment block **705** (FIG. **7**). A potentiometer **722** measures the rotation of the entire pelvis unit around a pelvis unit attachment shaft **809**. Referring to FIG. **8**, this pelvis unit attachment shaft **809** extends from a housing **808**. Housing **808**, together with parallel transverse rods **806** and elongate, substantially vertically oriented end plates **804**, constitute a parallelogram linkage **818** such that extended arms **803** will move in the same angular direction. Rods **806** articulate with end plates **804** at pivots **816** (two shown) and **807**(one shown).

The housing **808** includes bearings **811** that each have a substantially vertical axis of rotation, thereby permitting rods **806** to slide in parallel to each other and permit the articulation of parallelogram linkage **818**. The motion of the parallelogram linkage **818** translates extending arms **803** such that when one of the arms **803** moves forward, the other arm **803** moves backward. Each arm **803** attaches via a respective ball joint **802** to a respective pelvis cuff **801** which conforms to a respective side of the patient's pelvis, and also to pelvis harness **104** (FIG. **1**). The ball joint **802** allows three axes of rotation, and is instrumented by a respective force sensor **810** which projects through arm **803** and which senses force vectors on two axes.

The extending arms **803** attach, at their proximal ends, to the parallelogram linkage end plates **804**. The end plates **804** are adjustable relative to their separation distance from each other to accommodate patients of different pelvic widths. To accomplish this adjustment the end plates **804** can be telescoped into the ends **805** of the rods **806**, tubular shaped extensions **822** being provided for this purpose which extend from and pivot around pivots **816** and **807**. The end plates **804** can be swung open by removing pins **807**A and rotating about pivots **816** in order to allow a patient to be transferred into position by approaching the device **100** from the side.

A key property of the suspension system formed by lateral unit **700**, torso support **600** and pelvic support **800** is its accommodation to the patient, allowing the patient the freedom of motion required for gait and balance.

FIG. **14** illustrates one possible embodiment of a control system for use with the invention. Electronics **301**, which can incorporate a processor, memory, user interface and other elements of a controller or computer, are housed in an electronics enclosure **300** as shown in FIGS. **1-4**. The electronics **301** implement the control methods and algorithms of the invention. FIG. **14** shows the basic sensor signal and control paths from the sensors to the control unit or electronics **301**, and the control signals from the electronics **301** to each of the motors or other effectors employed by the invention. There are many ways to divide the control methods and algorithms between hardware electronics and software loaded on the computer, and the present invention is not limited to any particular hardware/software implementation.

The left wheel module **440** receives rolling and steering signals **320** and **322** from electronics **301**, which transmits similar but independent rolling and steering signals **324** and **326** to the right wheel module **442**. These driving signals may represent torque, velocity or position commands. The signals are ultimately transferred by motor amplifiers, in the illustrated embodiment housed within enclosure **300**, into currents. In a preferred embodiment all of the described motors are DC servomotors, which send communication signals back to their amplifiers (not shown). Since the close coupling between a motor and its amplifier is well-known, we will simply describe in shorthand fashion a signal, representing torque, velocity or position, as though it drives a motor directly. In the illustrated embodiment the steering and rolling signals **320-326** are velocity signals.

Signals from the wheel modules **440** and **442** include encoder counts generated by each motor, each of which represent the angle through which the motor has turned. These encoder count signals include rolling and steering signals **328**, **330** from left wheel module **440** and rolling and steering signals **332**, **334** from right wheel module **442**. For each module **440**, **442** there is a respective steering index signal **336**, **338**, which is used by the control unit **301** to establish an absolute steering orientation.

The support arm **500** receives a driving signal **340** to control the raising or lowering of the assembly **506**, and thus exert a body weight support function on the patient. Signals from the support arm **500** include an incremental encoder signal **342** from the motor **502**, and an absolute measure of displacement **344** generated by potentiometer **510**.

In the illustrated embodiment the pelvis unit **800** includes no actuators itself, but sends several signals to control unit **301**. These signals include the X and Z axis forces **346**, **348** measured at the patient's hips, as measured by force sensors **810**. The potentiometer **812** mounted on one of the pivots of the parallelogram linkage **818** measures the angle of parallelogram linkage **818** and generates signal **350** back to the control unit **301**. These signals can accompany other signals, such as signals encoding the entire rotation of the patient's pelvis unit about the X or sagittal axis from potentiometer **722** (FIG. **7**) or rotation of the hip pads **801** about the Y or transverse axis.

In the illustrated embodiment, there are no actuators in the lateral unit **700**, but unit **700** sends a signal **352** which encodes the lateral displacement along the Y axis allowed by lateral unit **600**, which represents the lateral motion of the pelvis unit **800** and torso unit **700**, and thus of the patient.

The torso unit **600** receives X and Y rotation signals **354**, **356** for its motors **613** (and potentiometer **631**), **640** (and potentiometer **630**) which rotate column **606** about X axis **638** and Y axis **636**, thus rotating the trunk of the patient or exerting a force to counter the patient-generated rotation of the his or her trunk. The control unit **301** receives several signals back from the torso unit **600**, including the length of telescoping column **606** (signal **358**), the torques about the X and Y axes **638**, **636** measured by strain gauges **609** (signal path **360**), the potentiometer signal measuring the rotational displacement of revolute slider **602**, and the encoder signals from motors **613**, **640** (signal path **362**).

In the illustrated embodiment, there are seven signals driving motors of the invention, and twenty-three signals communicated from various sensors to the control unit **301**. Other kinds of sensors could be used at these or other articulation points. Other aspects of the motion of the mechanical components herein described could be actuated, or those which are now actively actuated or motorized could be made passively movable, or could be locked to one or several positions. The precise number and kind of sensor inputs and driving outputs could vary considerably without departing from the invention.

The preferred embodiment of the present invention is useful in training a patient for balance as a part of walking, and also balance and reaching even when the patient is not moving forward. Among other inputs, the sensor system according to the invention preferably measures each of three signals: X at the hip force sensor **810**, Y from the potentiometers **704** on the lateral unit, and rotation about Z, taken from the hip force sensors **810** again. This permits the device **100** to measure any desired three dimensional direction in which the patient wants to move, and to translate these measurements into motion of the device in any planar direction.

For example, through the wheel modules **400** the device **100** can move directly sideways, can crab walk at an arbitrary angle to the X axis, and can turn device **100** around in place around the patient. This extraordinary degree of maneuverability is enabled by having four powered actuators (two rolling, two steering) in the two wheel modules **400**.

Modes of Operation

The device is capable of assisting the therapist with a variety of tasks commonly performed in the course of gait and balance training. These tasks correspond to modes of operation of the device, some of which can be explicitly selected via a user interface (not shown) of the control unit **301**, while others are invoked transparently based on sensory information. These modes include the following:

Over Ground Walker. The device moves, including both translation and rotation, in response to motion and forces of the patient. The various sensors described above are used to determine the motion or force of the patient, indicating a patient's intention to move or turn in a desired direction, and the wheel modules **400** are commanded in such a way as to allow the patient's motion in a desired direction. Alternatively, the motion of the device can be responsive to the commands of the therapist, through a keyboard, other graphical user interface, joystick or other input device—either locally or remotely.

Trunk/Pelvis re-aligner. The pelvis and trunk supports **800**, **600**, controlled by the therapist with aid of the above-described sensors, are used to supply the necessary forces and torques to bring the patient into postural alignment. A sequence of operation is illustrated in FIG. **15**. At step **1500**, the therapist enters the device into a float mode during which no forces are applied. Once that is established the therapist brings the patient's trunk into alignment at **1502**. Next, the device is made to enter into a rigid support mode at **1504** in which the trunk and pelvis are held in place. At **1506** the therapist releases the patient. At step **1508**, the control unit begins a gradual decrease in the stiffening forces that it is applying to the patient, which it will continue as long as it senses that the desired posture of the patient is being maintained within acceptable limits.

Trunk Perturber. In this mode, the device (automatically, according to a prerecorded exercise program loaded into the control unit **301**) or the therapist introduces forces intended to challenge the patient's ability to stay upright or in a certain posture. The device can accomplish this by moving the wheels **400** when the patient is stationary or by changing their velocity during walking. In addition, this can be accomplished by the trunk support mechanism by applying force bursts controlled by the therapist. Alternatively, the therapist can simply push or pull the patient at a variety of locations, knowing that the device will catch the patient if he or she cannot maintain balance.

Trunk/pelvis stabilizer. In this mode, the trunk and pelvis support mechanism apply restoring forces to maintain the upright orientation of the trunk. The stiffness of the support is adjustable by the therapist from fully rigid down to zero.

Trunk/pelvis catcher: cone of safety. The safety function of the trunk support **600** in conjunction with pelvis unit **800** is accomplished by enforcing a "cone of safety" for the patient which is a range of trunk and pelvis excursions. This is simplistically and schematically illustrated at **1600** in FIG. **16**. At a boundary **1602** of this range, the trunk support system **600** applies a constraint as communicated to it by the control unit **301**, which prevents a fall. The surface **1602** of the conical solid **1600** represents the range of allowable excursions. In FIG. **16**, a representative departure of the torso attachment point **601** from its optimum location on the Z axis is shown, which, in one embodiment, would not trigger a torso unit constraint, and in another embodiment would cause a constraint to be applied of less than complete stiffness.

While the "cone of safety" concept is described by way of example in terms of displacement away from the Z axis, the concept extends beyond this. The algorithm may include a monitoring of and response to a rate of angular movement as well as or in addition to displacement, and the deviation from expected norms in either speed or displacement could be measured from some reference other than a vertical axis. For example, the catching function, which results when the "cone" is violated, could be initiated at a torso angle which changes as a function of the over-ground speed. In another example, if the patient's feet (and thus the device) are moving over-ground to the left, the therapist might allow the patient reduced leeway to tip the torso left. Further, the torso information may be combined with sensor input from the pelvis unit to evaluate more completely the state of balance and support of the patient, and to invoke catching and limiting modes only when needed. It should be appreciated that the cone of safety is not necessarily a geometric construct but may be any computation upon the sensor readings.

The range of allowable excursions may be set by the therapist, or may be preset. In the representation of FIG. **16**, the "cone of safety" has a circular base but in actual practice the base may be elliptical or other more complex shape, as would be the case if the therapist set a range in the X direction to be more or less than a permissible range of excursion or velocity in the Y direction. Further, the shape need not be symmetrical.

Further, the "cone of safety" may not be hollow with a solid wall of constraint, but may instead gradually thicken toward its perimeter. That is, the torso support **600** may apply an amount of constraint which varies as a function of the degree of torso excursion, such that the patient feels little assistance in the vicinity of vertical trunk orientation, but experiences near-rigid trunk support farther away.

Vertical catcher. In this mode, the pelvis support **800** prevents the patient from falling down to the floor and catches the patient in a compliant manner. The rate of descent is controlled to a safe and comfortable level.

Body weight unloading. The device unloads a therapist-specified amount of the patient's weight in a compliant fashion to facilitate body weight-supported training.

Iso-kinetic walker. The device applies a therapist-adjustable amount of resistance in the direction of walking for strength training.

Sit-to-stand training. In this mode, the device facilitates sit-to-stand training by assuring that the patient cannot fall, and also by providing body weight support.

Transfer from sitting. Yet another mode of operation involves transferring the patient from a sitting position, e.g., in a wheelchair, into the device. This makes use of the lifting mechanism, which goes low enough to connect to a seated patient, and is strong enough to fully lift the patient. The arms **803** of the pelvis support unit **800** are capable of swinging out of the way (as by removing pins **807**A) so that the patient can be "transferred" laterally.

All of the aforementioned modes are implemented by a similar control framework, schematically illustrated in FIG. **17**. The various sensor readings are input at **1700** by the control computer **301**, and compared at **1702** to a limit function which implements the cone of safety. Depending on this comparison the control mode may be changed at **1704** to accomplish a catching or limiting function. Actuator torques are then computed at **1706** and commanded at **1708** to the various actuators.

While the present invention has been described in terms of a mobile apparatus, it also has application to stationary devices. For example, a device according to the invention could be used over a treadmill and in this instance would not need wheels.

In summary, patient-responsive physical therapy apparatus has been described which independently supports the pelvis and torso of the patient. The exercise device permits natural movements of the pelvis and torso occurring during a walking gait and provides support for a selected portion of the patient's weight. Among many other modes of operation, the device can be used to prevent torso excursions or velocities beyond a predetermined cone of safety, to challenge the balance of the patient, and to permit the patient to attempt to correct for a fall before intervening.

While various embodiments of the present invention has been described in the above description and illustrated in the appended drawings, the present invention is not limited thereto but only by the scope and spirit of the appended claims.

We claim:

1. A physical therapy walking exercise device, comprising:

a movable base;

at least two powered wheel modules mounted to the base and having independently actuable and powered steering and rolling actuators;

a patient support unit supported by the base and articulable about at least a vertical axis, at least one sensor associated with the patient support unit sensing the spatial position of the patient support unit relative to the base; and

a control unit coupled to said at least one sensor and the powered wheel modules, the control unit controlling the rotation and steering of the powered wheel modules responsive to signals from the patient support unit such that the device moves in a direction in conformance with a desired direction of travel of the patient.

2. The apparatus of claim **1**, wherein the base is mobile relative to the ground or floor.

3. The apparatus of claim **2**, wherein the base is operable to move relative to the ground or floor responsive to forces and motions exerted or made by the patient.

4. The apparatus of claim **1**, wherein the base is operable to translate across the ground or floor as well as to change direction across the ground or floor.

5. The apparatus of claim **1**, wherein the apparatus provides a body weight support function.

6. The apparatus of claim **1**, wherein the patient support unit includes a torso support unit having an actuator operable to apply a selected amount of torque.

7. The apparatus of claim **6**, wherein the torso support unit further includes at least one sensor for measuring said torque, and the control unit is coupled to the sensor for receiving a torque signal.

8. The apparatus of claim **6**, wherein the torso support includes a telescoping column coupling the torso support unit to the base.

9. The apparatus of claim **6**, wherein the patient support unit includes a pelvis support unit and the pelvis support unit articulates to allow motion transverse to the patient's direction of travel.

10. The apparatus of claim **9**, wherein the pelvis support unit allows rotation of the pelvis.

11. The apparatus of claim **10**, wherein the pelvis support unit further includes at least one sensor for measuring the rotation of the pelvis around at least one axis, the apparatus further including a control unit coupled to the sensor for receiving a signal encoding the rotation sensed by the sensor.

12. The apparatus of claim **10**, wherein the pelvis support unit further includes at least one sensor for measuring a torque around an axis of rotation, the control unit is coupled to said sensor for receiving a signal encoding the torque sensed by the sensor.

13. The apparatus of claim **6**, further comprising:

at least one sensor of the torso support unit for sensing a torque or angular displacement, the control unit coupled to the sensor for receiving a signal encoding the last said torque or angular displacement; and

at least one actuator of the torso support unit for applying a selected torque, the actuator coupled to the control unit for being actuated responsive to the signal, the control unit periodically monitoring said signal and comparing the encoded torque or angular displacement to a reference, the control unit actuating the actuator to exert a torque in opposition to the encoded torque or angular displacement in mitigation of the patient falling.

14. The apparatus of claim **1** further comprising:

the patient support unit including a pelvis support unit for fitting to the pelvis of a patient, the pelvis support unit coupled to the base and having a first actuator for selectively applying force to the pelvis support unit in a vertical direction relative to the base; and

a torso support unit for fitting to the torso of a patient at a position above the pelvis of the patient,

the torso support unit coupled to the base and having a powered articulation actuable about at least one axis relative to the base, the articulation being independent of the first actuator of the pelvis support unit;

sensors associated with the pelvis support unit and the torso support unit to sense the spatial position of the pelvis support unit and the torso support unit; and

the control unit being coupled to the sensors and to the first actuator of the pelvis support unit and the powered articulation of the torso support unit to selectively apply a force or torque to the pelvis support unit and the torso support unit.

15. The apparatus of claim **14**, wherein the first actuator of the pelvis support unit is also coupled to the torso support unit to selectively apply force to the torso support unit in a vertical direction relative to the base.

16. The apparatus of claim **14**, wherein the base includes an upstanding support arm, a lateral unit extending horizontally from the upstanding support arm and attached to the pelvis support unit, the first actuator coupling the lateral unit to the support arm so as to apply vertical force to the pelvis support unit and the lateral unit relative to the support arm.

17. The apparatus of claim **14**, wherein the first actuator of the pelvis Support unit is operable by the control unit to apply a selected amount of vertical force in opposition to the force of gravity.

18. The apparatus of claim **14**, wherein the powered articulation of the torso support unit is operable by the control unit to apply a selected amount of torque around an axis of articulation in a selected angular direction.

19. The apparatus of claim **14**, wherein the pelvis support unit includes a flexible pelvis harness affixable around the pelvis of the patient.

20. The apparatus of claim **14**, wherein the torso support unit includes a flexible torso harness affixable to an upper portion of the torso of a patient.

21. The apparatus of claim **20**, wherein the pelvis support unit includes a flexible pelvis harness separated from the torso harness, the pelvis harness affixable to the patient around the pelvis.

22. The apparatus of claim **1** further comprising:

the patient support unit including a pelvis support unit fittable to the pelvis of a patient for supporting a selected portion of the patient's weight in a vertical direction; and

a parallelogram linkage coupling the pelvis support unit to the base, the Parallelogram linkage permitting rotation of the patient's pelvis in a plane orthogonal to the vertical direction.

23. The apparatus of claim **22** further comprising:

a support arm upstanding from the base; and

a lateral unit displaceable in a vertical direction relative to the support arm,

the pelvis support unit being support by the lateral unit; and

a torso support unit fittable to the torso of a patient at a position above the pelvis support unit, the torso support unit supported by the lateral unit, wherein the parallelogram linkage permits movement of the pelvis support unit and the torso support unit in a transverse direction.

24. The apparatus of claim **22** further comprising:

at least one sensor for sensing a torque or angular displacement in the torso support unit, the control unit coupled to the sensor for receiving a signal encoding the last said torque or angular displacement; and

at least one actuator of the torso support unit for applying a selected torque, the actuator coupled to the control unit for being actuated responsive to the signal, the control unit periodically monitoring the signal and comparing the encoded torque or angular displacement to a reference, the control unit actuating the actuator to exert a torque in opposition to the encoded torque or angular displacement in mitigation of the patient falling.

25. A physical therapy walking exercise device, comprising:

a movable base;

at least two powered wheel modules mounted to the base and having independently actuable and powered steering and rolling actuators;

a patient support unit supported by the base and articulable about at least a vertical axis, the patient support unit including a torso support unit having an actuator operable to apply a selected amount of torque, and at least one sensor associated with the patient support unit sensing the spatial position of the patient support unit relative to the base; and

a control unit coupled to said at least one sensor and the powered wheel modules, the control unit controlling the rotation and steering of the powered wheel modules responsive to signals from the patient support unit such that the device moves in a direction in conformance with a desired direction of travel of the patient.

26. The apparatus of claim **25** further comprising:

the torso support unit being coupled to the base hand having a powered articulation actuable about at least one axis relative to the base, the articulation being independent of the first actuator of the pelvis support unit;

the patient support unit including a pelvis support unit for fitting to the pelvis of a patient, the pelvis support unit coupled to the base and having an actuator for selectively applying force to the pelvis support unit in a vertical direction relative to the base; and

sensors associated with the pelvis support unit and the torso support unit to sense the spatial position of the pelvis support unit and the torso support unit; and

the control unit being coupled to the sensors and to the actuator of the pelvis support unit and the powered articulation of the torso support unit to selectively apply a force or torque to the pelvis support unit and the torso support unit.

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