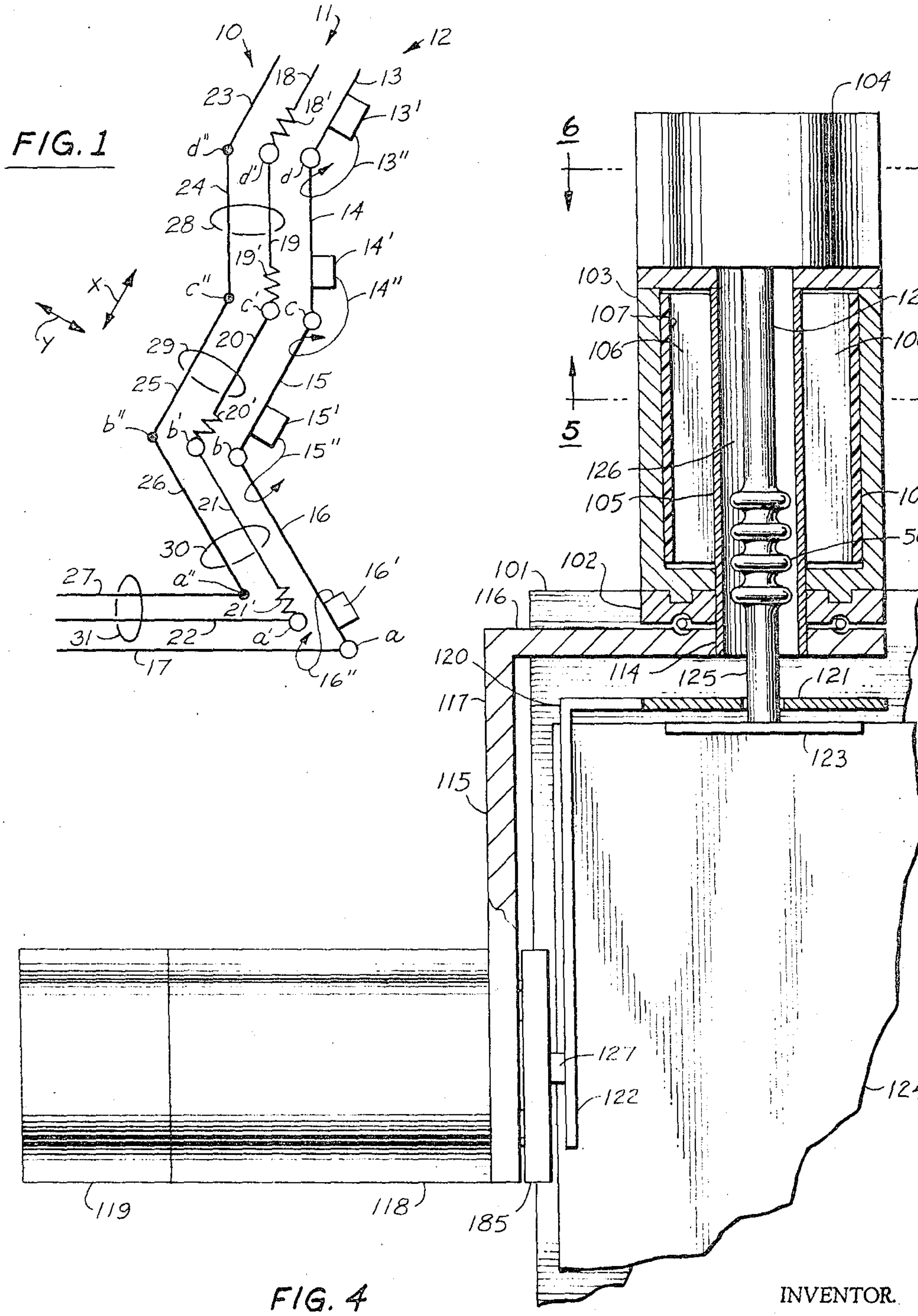

FIG. 1

FIG. 4

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June 17, 1969 N. J. MIZEN 3,449,769
POWERED EXOSKELETAL APPARATUS FOR AMPLIFYING HUMAN
STRENGTH IN RESPONSE TO NORMAL BODY MOVEMENTS
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FIG. 13

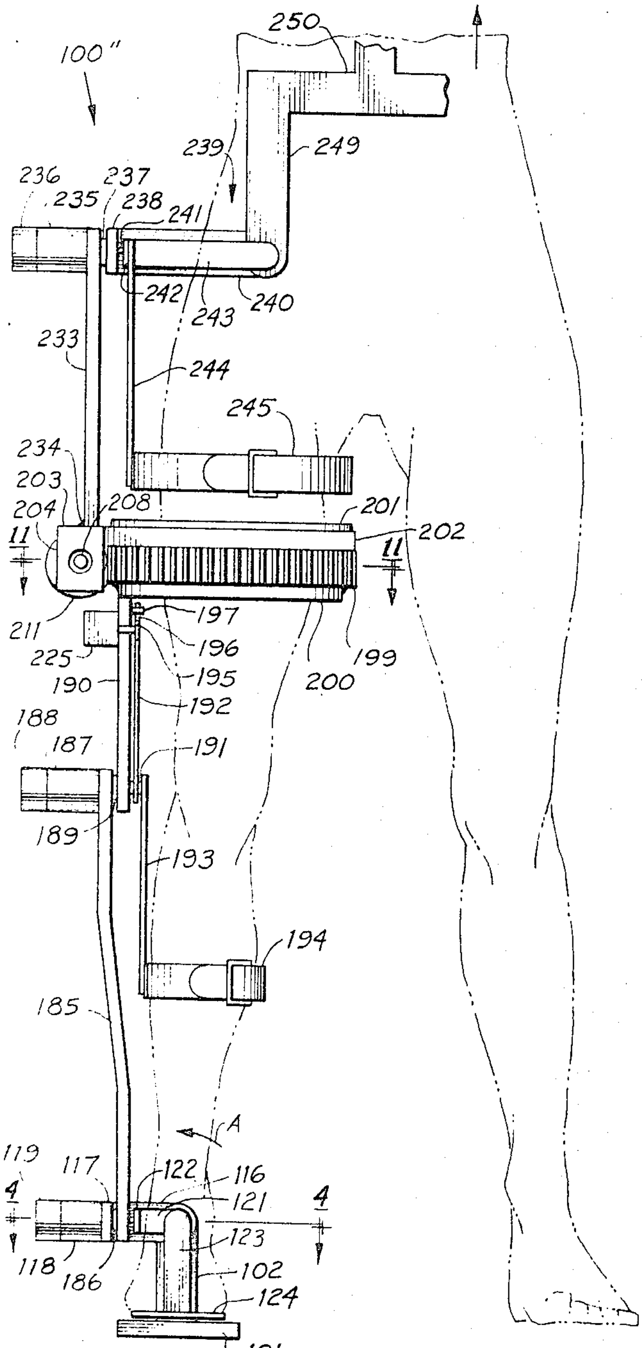

FIG. 2

FIG. 14

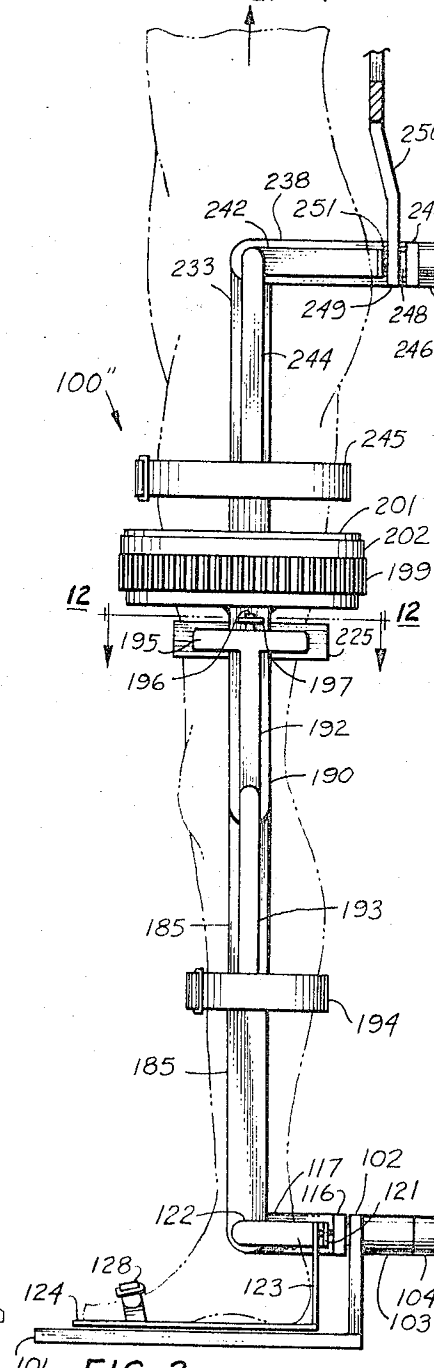

FIG. 3

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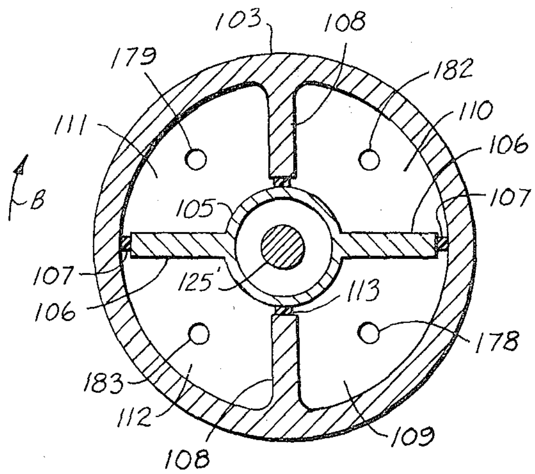
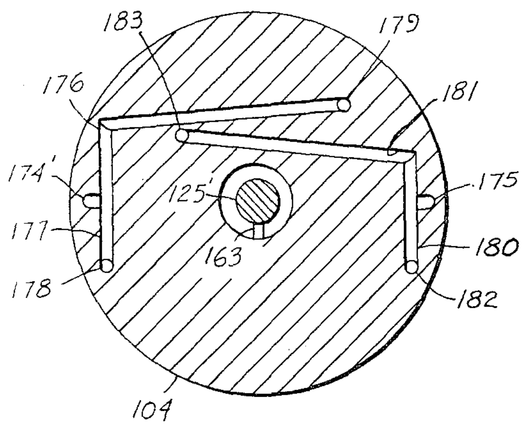


FIG. 5

FIG. 9



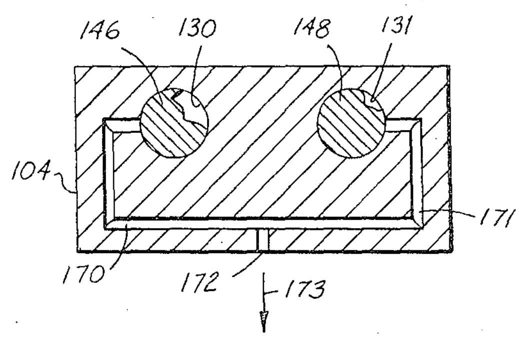


FIG. 10

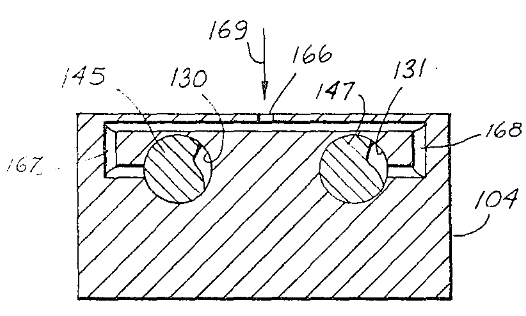


FIG. 7

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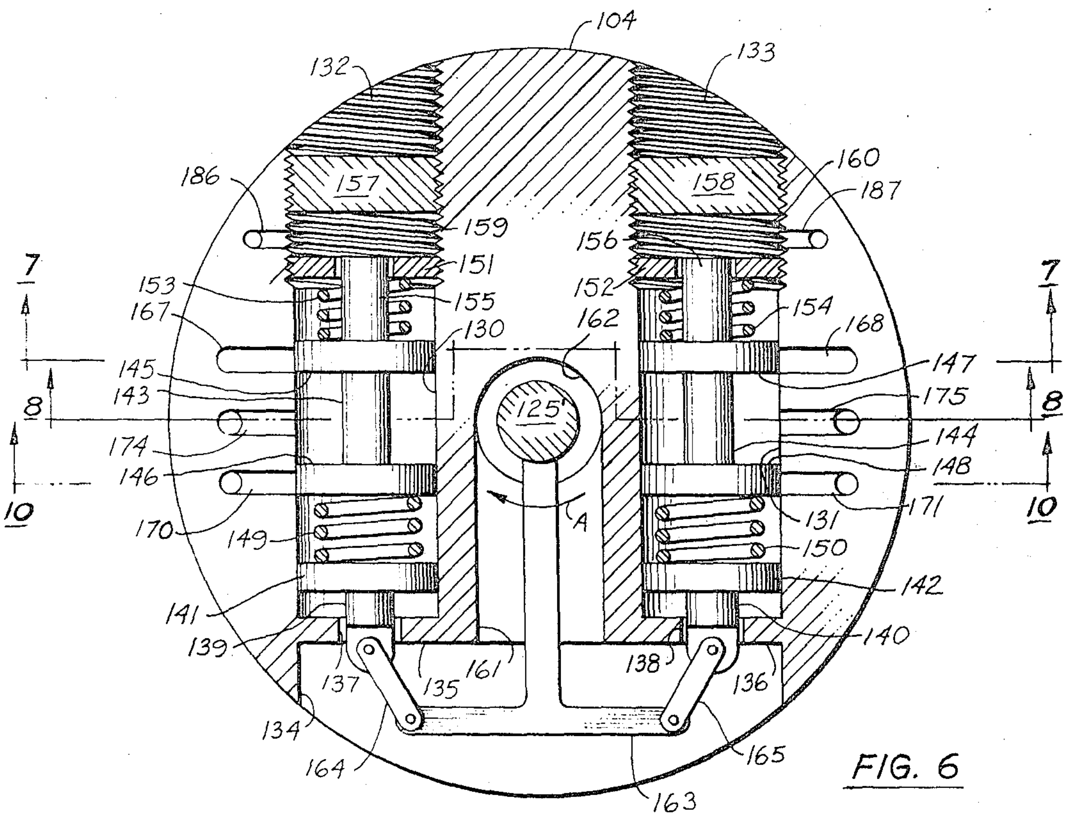

FIG. 6

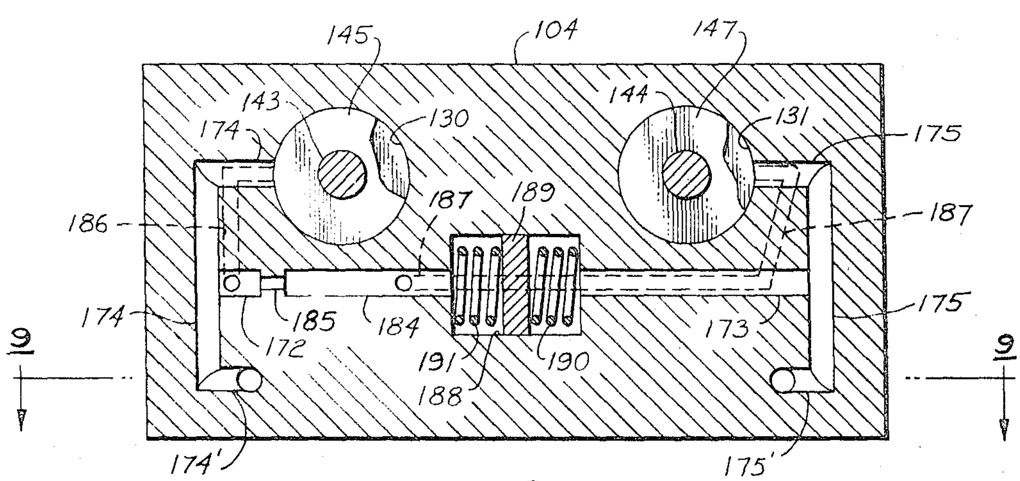

FIG. 8

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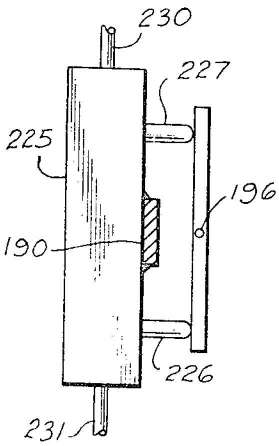

FIG. 12

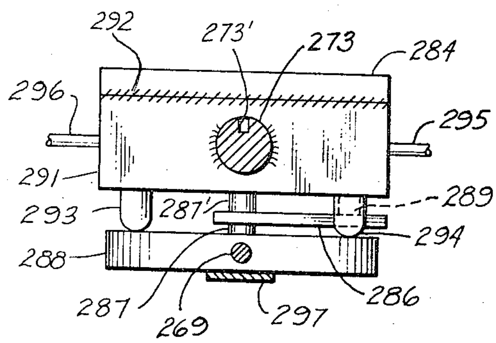

FIG. 16

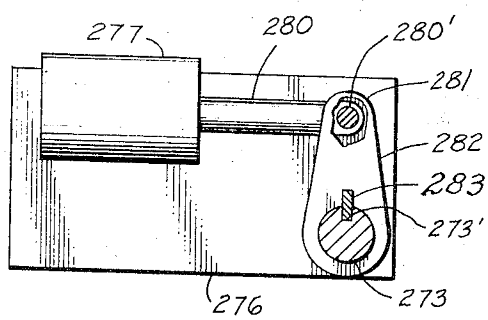

FIG. 15

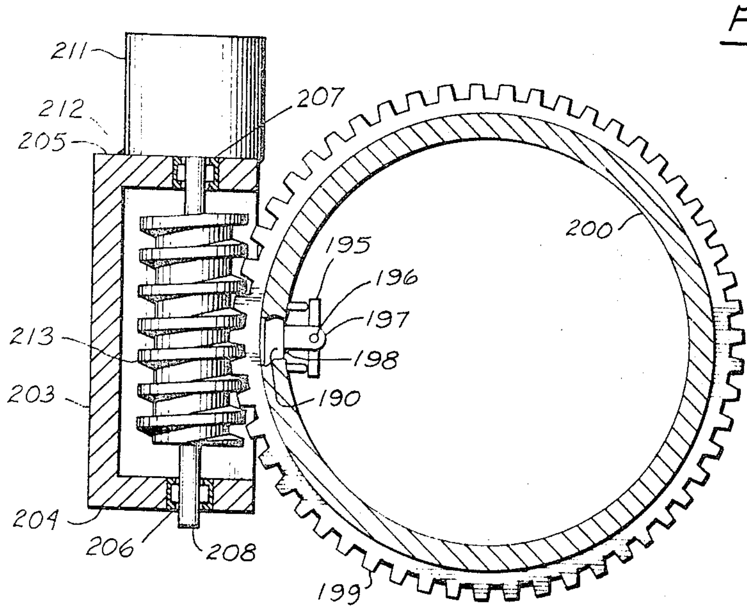

FIG. 11

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FIG. 17

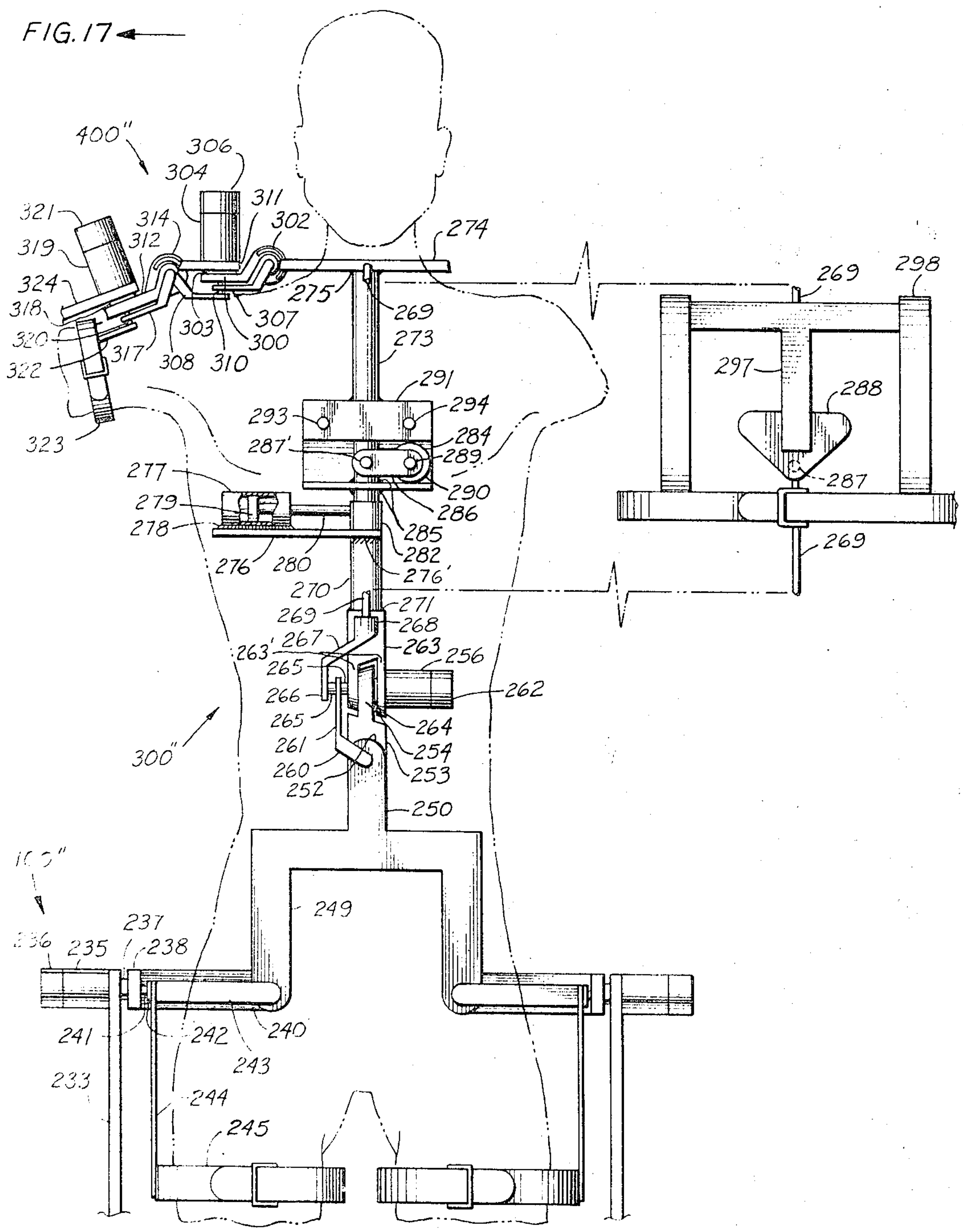

FIG. 13

FIG. 2

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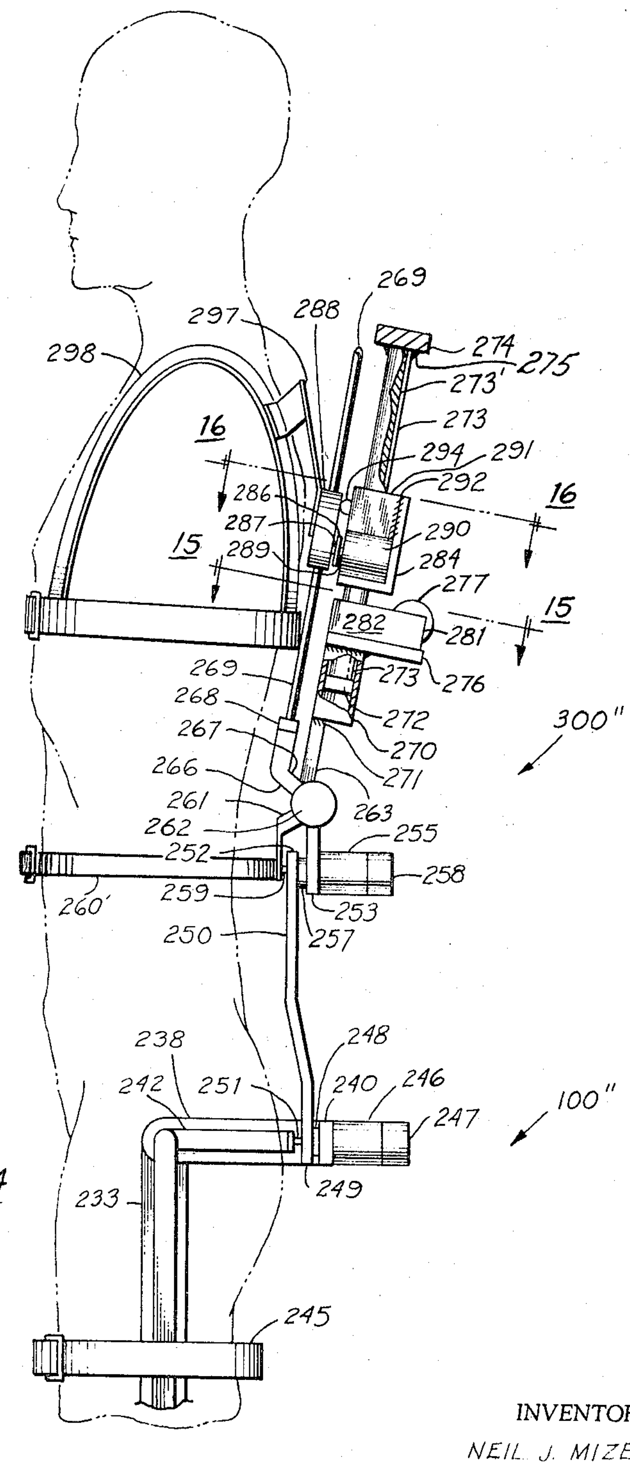

FIG. 14

FIG. 3

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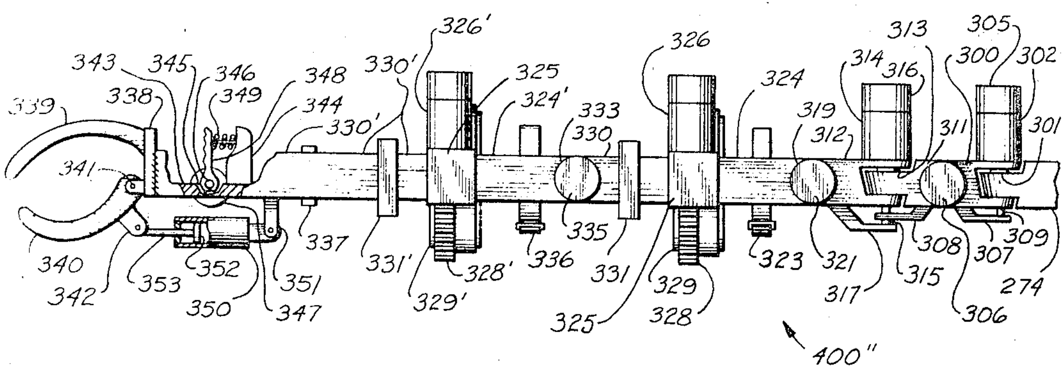

FIG. 18

FIG. 17

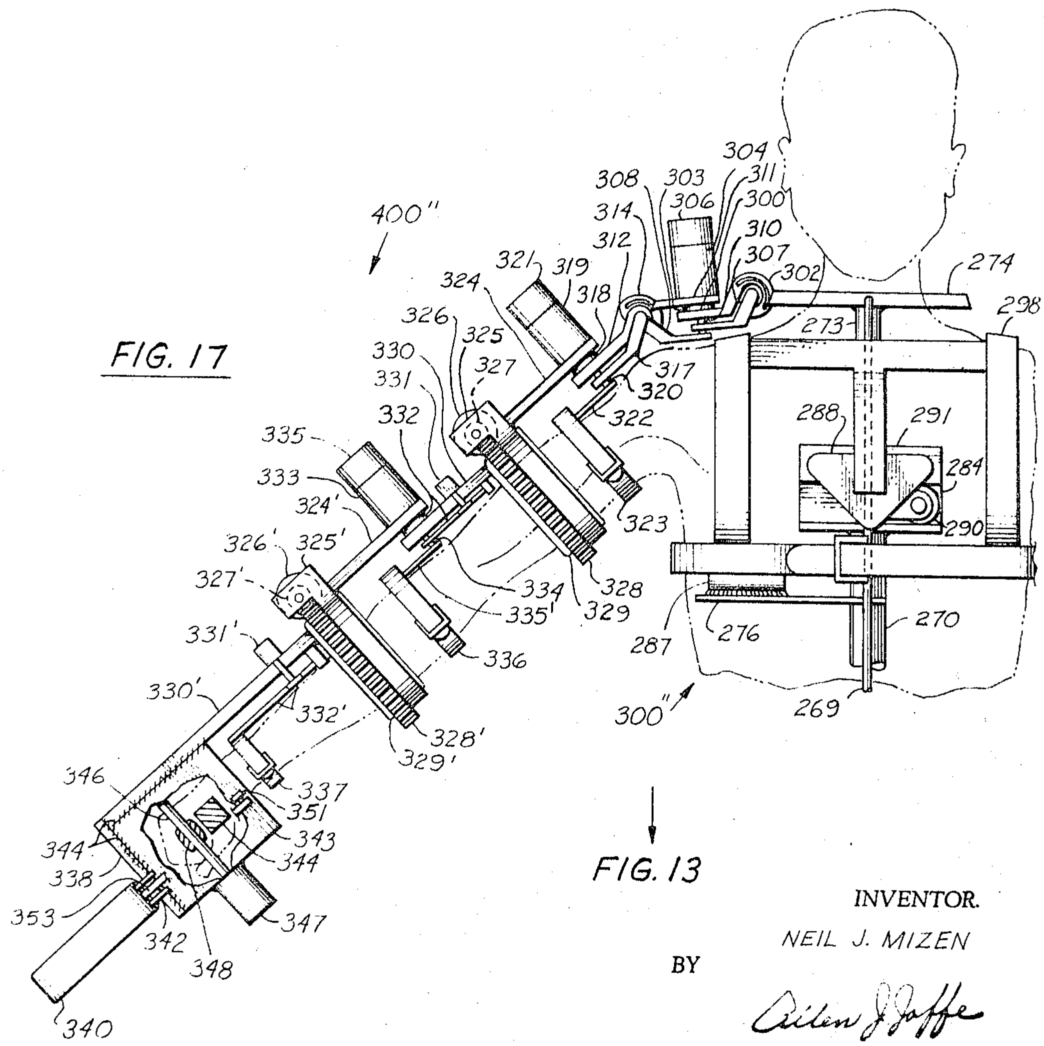

FIG. 13

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United States Patent Office

3,449,769

Patented June 17, 1969

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3,449,769

POWERED EXOSKELETAL APPARATUS FOR AMPLIFYING HUMAN STRENGTH IN RESPONSE TO NORMAL BODY MOVEMENTS

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Int. Cl. A61f *1/00;* A61h *1/02*

U.S. Cl. 3—1.2 10 Claims

ABSTRACT OF THE DISCLOSURE

A powered exoskeletal apparatus comprising articulated joints, compatible with those of man, each of which are powered by one or more servo-motors which respond to the output of a plurality of sensor assemblies strapped to the wearer. Follow-up mechanisms are provided to move the sensors in response to the powered movement of the articulated joints.

The present invention relates to a powered exoskeletal device that functions as a "Man Amplifier."

In the past, tasks requiring high force levels have been performed by machines utilizing man for control, but applying his physical capability in an unnatural way. This approach has resulted in a large number of special purpose tools and equipment. An alternative approach, and one that is the subject of the present invention is to devise an anthropomorphic device which extends man's physical capability while maintaining the advantages of his natural motion.

The invention contemplates a servo-powered exoskeletal structure adapted to be worn by a man, which structure is adapted to respond to man's normal movement and at the same time provide for the amplification of his power capabilities by several orders of magnitude.

Thus, as the wearer's effective muscular and skeletal strength can be amplified, his endurance is increased, allowing him to perform tasks normally requiring large amounts of physical exertion—while retaining most of man's flexibility and adaptability.

The tasks that the powered exoskeletal apparatus of the present invention can perform are those which involve lifting and moving objects which are too heavy for the unaided man. This would be especially advantageous in remote areas where heavy handling equipment cannot be readily installed. The apparatus can be used for such tasks as clearing away small trees, and obstacles, erection of shelters, positioning of equipment and supplies, laying of steel-mesh portable runways, loading or moving munitions and emergency rescue.

Basically, the powered exoskeletal device consists of a structrual exoskeleton with appropriate articulated joints, compatible with those of man. All external loads, as well as the weight of the structure itself, are borne by the structural skeleton. Each joint is powered by one or more servo-motors which provide the necessary torques and power boosts. These servos respond to the output of sensors linking man and machine, and cause the appropriate mechanism to follow the natural motion of its human counterpart.

For a fuller understanding of the present invention, reference may be had to the following detailed description of the same and the accompanying drawings wherein:

FIGURE 1 is a schematic view illustrating the principles of the sensor and load supporting structure interaction,

FIGURE 2 is a front elevational view of the right leg assembly,

2

FIGURE 3 is a side elevational view of the leg assembly, viewed from the left of FIGURE 2,

FIGURE 4 is a section taken along line **4—4** of FIGURE 2,

FIGURE 5 is a section taken along line **5—5** of FIGURE 4,

FIGURE 6 is a section taken along line **6—6** of FIGURE 4,

FIGURE 7 is a section taken along line **7—7** of FIGURE 6,

FIGURE 8 is a section taken along line **8—8** of FIGURE 6,

FIGURE 9 is a section taken along line **9—9** of FIGURE 8,

FIGURE 10 is a section taken along line **10–10** of FIGURE 6,

FIGURE 11 is a section taken along line **11—11** of FIGURE 2,

FIGURE 12 is a section taken along line **12—12** of FIGURE 3,

FIGURE 13 is a front elevation of the spine assembly and is a continuation of FIGURE 2,

FIGURE 14 is a side elevation of the spine assembly and is a continuation of FIGURE 3,

FIGURE 15 is a section taken along line **15—15** of FIGURE 14,

FIGURE 16 is a section taken along line **16—16** of FIGURE 14,

FIGURE 17 is a front elevation of the shoulder, arm and hand assembly and is a continuation of FIGURE 13, and,

FIGURE 18 is a top plan view of the shoulder, arm and hand assembly.

The powered exoskeleton according to the present invention consists of a two-layed structure. An inner layer or sensor harness is adapted to be worn by a human and is adapted to sense the positions of various moving parts of said human wearer. An outer or load supporting structure similar to said sensor harness is adapted to respond to the sensed position of the various moving parts of said sensor harness; and is further adapted with the aid of a powered unit cooperating therewith, to move said sensor harness and an external load in a particular intended direction. Naturally, because of the powered unit, the external load can be many orders of magnitude greater than that which could be carried ordinarily by a man; thousands of pounds, for example.

Referring now to the drawings, and more particularly to FIGURE 1, there is shown in schematic form a two-dimensional, four-joined powered exoskeleton. This figure is designed to illustrate in an idealized manner the concept of the present invention, which involves a separate three-layered structure including an inner body structure **10**, an intermediate sensor structure **11** and an outer load supporting structure **12**.

The outer layer **12** represents the load supporting structure of the exoskeleton, hereinafter called the load structure, and comprises a plurality of rigid links **13, 14, 15, 16,** and **17** rotatably interconnected by a plurality of pinned joints *a, b, c,* and *d.* A motor **13'** is attached to link **13** and adapted to drive link **14**, the association being depicted by the curved line **13''**. In like manner, motors **14', 15',** and **16'** are provided to drive links **15, 16,** and **17**, respectively, and the drive associations are depicted by the curved lines **14'', 15'',** and **16''**, respectively.

The middle layer **11**, hereinafter termed the sensor hardness or sensor structure comprises a plurality of rigid links **18, 19, 20, 21,** and **22**, rotatably interconnected by a plurality of pinned joints *a', b', c',* and *d'*. As can be seen, the sensor hardness **11** matches the load structure **12** link for link, their axes of rotation *a–a', b–b', c–c',* *d–d'*, being coincident. Each of the sensor hardness links are designed to have some freedom to rotate with respect to the load structure links. This compliance is illustrated schematically at sections **18'**, **19'**, **20'**, and **21'**, such compliance being essential for proper operation of the exoskeleton as will become apparent hereinbelow.

The inner layer **10** represents the body structure of the human wearer and comprises a plurality of body sections **23**, **24**, **25**, **26**, and **27**; the joinders *a''*, *b''*, *c''*, and *d''* of which representing the various body joints as the elbow or knee, for example. The wearer layer sections are attached severally to their respective sensor harness links by means of belts **28**, **29**, **30** and **31**. As represented schematically, a certain amount of freedom of motion in the X and Y direction of the wearer is permitted with respect to the sensor harness.

The operation of the three-layered structure of FIGURE 1 will now be discussed. Assuming that the wearer moves his body section **24** with respect to body section **23**, this movement is transferred by belt **28** to link **19** of the sensor harness **11** causing the rotation thereof about pin *d'*. This rotation is permitted without any resistance of the load structure **12** because of the compliance mentioned earlier. Such rotation hereinafter called the error signal is sensed by the controller for motor **13'** thereby actuating motor **13'** to drive load structure link **14** against an external load. In this manner, movement of the wearer causes movement of the load supporting structure. Of course, as will become apparent as a discussion of the present invention proceeds, suitable feedback forces are developed to make the wearer conscious of the forces exerted as well as to prevent overshoot and injury to the wearer.

With an understanding of the basic concept of the exoskeleton, a discussion of the actual structure will now proceed.

Referring now to FIGURES 2 and 3, the leg assembly is indicated generally at **100''**. Only the right leg is shown since the left leg is similar. The whole leg assembly, in fact the whole exoskeletal apparatus is supported on a pair of flat, horizontal foot or load supporting base plates **101** (only one of which is shown). Suitably rigidly attached to foot plate **101** and projecting upwardly at right angles from the rear end thereof, is a vertical ankle plate **102**. Fixedly attached to plate **102** adjacent the upper end thereof and arranged on its rear side is a hydraulic motor housing **103**. A servo valve unit **104** is fixedly mounted on the rear end of motor housing **103**.

As shown in FIGURE 4, rotatably mounted in and extending through housing **103** and ankle plate **102** is a hollow, tubular cylindrical shaft **105** having suitably attached thereto a pair of radial vanes **106**. Suitable seals **107** are provided between the vanes **106** and the interior of housing **103**. As shown in FIGURE 5 an additional pair of radial vanes **108** are rigidly fixed to housing **103**. The vanes **106** and **108** divide the interior of housing **103** into four hydraulic chambers **109**, **110**, **111**, and **112**. Suitable sealing means **113** are provided between vanes **108** and tubular shaft **105**.

Exteriorly of housing **103**, tubular shaft **105** is fixedly attached as by welds to the wall of a through bore **114**, of a load supporting angle plate **115**, which has two legs **116** and **117** disposed at right angles. Leg **116** is arranged immediately in front of ankle plate **102** and leg **117** extends fore and aft laterally outwardly of foot plate **101**. A second hydraulic motor **118** and servo valve unit **119** are suitably attached on the laterally outer side of leg **117** of angle plate **115**. This motor-valve unit **118**, **119** is identical to motor-valve units **103**, **104** and therefore no separate description thereof is deemed necessary. Adjacent angle plate **115** is a sensor angle plate **120** having two legs **121** and **122** disposed at right angles. As is the case with all of the sensor structure to follow, sensor angle plate **120** is similar to its cordesponding load supporting angle plate **115**, only of smaller size. In closely spaced relation to leg **121** of sensor angle plate **120** is a vertical sensor ankle plate **123** having at the base thereof fixedly attached thereto a sensor foot plate **124**. Foot plate **124** is in closely spaced superimposed relation to foot plate **101**.

As shown in FIGURE 5, a cylindrical sensor shaft **125** is rigidly fixed to sensor plate **123** and extends through an opening in sensor angle plate **120** and is attached to a bellows coupling **50**. The other end of bellows **50** is attached to a sensor shaft extension **125'** which extends through tubular shaft **105** into servo valve housing **104** for the actuation thereof, as will become apparent hereinbelow. Sufficient clearance **126** is provided between sensor shaft **125'** and tubular shaft **105** such that limited lateral movement of the former wil lnot be prevented by contact with the latter. Coupling bellows **50** is of conventional design which allows bending and linear motion of shaft **125** with respect to **125'**, but will positively transmit torsion or rotation of one to the other. As is conventional, shaft **125'** is supported for rotary movement in bearings (not shown) arranged in an end of valve housing **104**. An identical sensor shaft **127** is attached to leg **122** of sensor angle plate **120**.

It can now be seen that members **101**, **102**, **116**, and **117** including motor **103** and **118** represent the load supporting exoskeletal foot and ankle subassembly whereas the members **124**, **123**, **121**, **122**, sensor shafts **125**, **125'** and **127** and the servo valves within housings **104** and **119** define the sensor foot and ankle subassembly. Suitable straps **128** may be attached to plate **124** to secure a man's foot thereto. In addition, suitable resilient means such as springs (not shown) can be located between members **101** and **124** to cushion and support sensor plate **124**.

Referring now to FIGURES 6–10, the cylindrical servo valve housing **104** on one side contains two bore recesses **130** and **131** having threaded open ends **132** and **133**, respectively. An enlarged recess **134** on the opposite side of housing **104** defines end walls **135** and **136** for bores **130** and **131**, respectively, which end walls contain drilled central openings **137** and **138** for the reception of stems **139** and **140** of spring abutment members **141** and **142**. Slidably and sealingly mounted in bores **130** and **131** severally are piston valve members **143** and **144**, respectively.

A pair of piston lands **145** and **146** are provided for valve member **143** and a pair of lands **147** and **148** are provided for valve member **144**. Intermediate corresponding abutment members **141**, **142** and lands **146**, **148** severally are compression springs **149**, **150**, respectively. An additional pair of abutment members **151**, **152** severally are threaded into ends **132**, **133**, respectively, and provide support and adjustment for compression springs **153**, **154**. Valves **143**, **144** contain stems **155**, **156**, respectively, slidably passing through openings in said abutment members **151**, **152**. A pair of closure members **157**, **158** severally are threaded into ends **132**, **133**, respectively, defining with spring abutments **151**, **152** a pair of feedback chambers **159**, **160**.

A slot **161** communicates with recess **134**. Sensor shaft **125'** is mounted in a through bore **162** that communicates with slot **161**. Rigidly attached to shaft **125'** is the leg of a T-shaped linkage member **163**. A pair of links **164**, **165** severally are pinned at the ends thereof to linkage member **163** and stems **139**, **140**, respectively. As is apparent, member **163** and links **164** and **165** transmit rotary motion of sensor shaft **125'** into linear motions of abutment members **141**, **142** and through springs **149**, **150** to valves **143**, **144**.

As shown in FIGURE 7 a supply conduit **166**, adapted to communicate with a source of high pressure fluid (not shown), branches off into two passages **167** and **168** which communicate respectively with bores **130** and **131**. The direction of flow is indicated by arrow **169**.

Branch passages **170** and **171** communicate respectively with bores **130** and **131** and join into a common exhaust or return conduit **172**, shown in FIGURE 10. Conduit **172** is adapted to be connected to a low pressure return line (not shown). The exhaust flow is indicated by arrow **173**.

A pair of common passages **174** and **175** communicate respectively with bores **130** and **131** at points intermediate passages **167** and **170**, and **171**, respectively. As shown in FIGURE 8 passages **174** and **175** extend downwardly through housing **104** and communicate centrally thereof, with transverse branches **172** and **173**, respectively. Passages **174** and **175** end in short transverse passages **174′** and **175′**, respectively. As seen in FIGURE 9 passage **174′** divides into two transverse branch passages **176** and **177**, the longitudinal end portions **178** and **179** of which communicate respectively with chambers **109** and **111** (see FIGURE 5) of motor housing **103** when valve housing **104** is suitably mounted thereon as by bolts (not shown). Similarly, passage **175′** divides into two transverse branch passages **180** and **181**, the longitudinal end portions **182** and **183** of which communicate respectively with chambers **106** and **108** of motor housing **103**.

Branch **172** communicates with a passage **184** via a restriction **185**. A feedback conduit **186** communicates passage **172** with feedback chamber **159**, as shown by the dashed lines in FIGURE 8. A second feedback conduit **187** communicates passage **184** with feedback chamber **160**. Passages **173** and **184** communicate with an enlarged piston chamber **188**, containing a piston **189** slidably and sealingly engaged therein. A pair of centering springs **190** and **191** are provided severally on opposite sides of piston **189** to center the same. Although shown schematically, it is obvious that piston **189** and piston chamber **188** must be removably related to housing **104** for ease in assembly.

The operation of the external load support and sensor foot assemblies, being typical of many of the other joints to be discussed later, now follows.

Assuming that a man whose foot is strapped to foot plate **124**, decides to lift the inner side part of his foot. His first movement will cause sensor shaft to rotate counterclockwise in the direction of arrow A in FIGURE 2 or clockwise in the direction of arrow A as viewed in FIG. 6. This causes valve **143** to move upwardly in FIGURE 6 uncovering pressure port **167** and valve **144** to move downwardly uncovering exhaust port **171**. Pressure fluid then flows from port **167** to common port **174** to branch **174′** to passages **176** and **177** to branches **179** and **178** to chambers **111** and **109**. At the same time fluid in chambers **110** and **112** is exhausted via lines **180** and **181** to **175′** to **175** to exhaust port **171** to exhaust conduit **172**. The high pressure fluid in chambers **109** and **111** reacting against vanes **108** causes motor housing **103** to rotate in the direction of arrow B in FIGURE 5. Rotation of housing **103** causes rotation of plate **102** and therewith plate **101** in the direction of arrow A in FIGURE 2. Thus motion of sensor plate **124** causes corresponding motion of load foot plate **101**. In addition, since servo valve housing **104** is carried by motor housing **103**, it rotates therewith causing the sensor plates **123** and **124** through shafts **125**, **125′** to be carried by the movement of load plate **101**. A feedback force is accomplished by high pressure fluid in line **186** acting against stem **155** to urge valve **143** in a direction opposite to that initiated by movement of shafts **125** and **125′**. In this manner, a counter force is exerted against the man's foot, making him aware of a portion of the resistance against which the load plate **101** is moving.

The restriction **185** is provided to allow the feedback forces to decay with time. Piston **189** separates the fluid in line **184** from that in line **173**.

The resilient connection afforded by springs **149** and **150** allows for a certain limited movement of the wearer before actuation of valves **143** and **144** is initiated and provides a means of acquiring force balance at each.

It is apparent that other movements of the wearer's foot will result in a similar sequence of events leading to corresponding movements of the load structure.

Referring back to FIGURES 1 and 2 for a further discussion of the leg assembly **100′**, a lower leg load supporting link **185** is connected to the tubular shaft **186** of motor **118** that is similar to tubular shaft **105** previously discussed. Link **185** extends upwardly along the laterally outer side of the wearer's leg and terminates in the vicinity of the wearer's knee joint, and thereat is attached to motor housing **187** which extends laterally outwardly therefrom. A servo valve housing **188** is attached to the outer end of motor housing **187**. A hollow tubular shaft **189** similar to tubular shaft **105** extends through link **185** and is fixedly attached to an upper leg load supporting link **190** which also extends along the outside of the wearer's leg. A sensor shaft **191**, similar to sensor shaft **125** of FIGURE 4, passes through an upper leg sensor link **192** and is rigidly attached to a lower leg sensor link **193**. Attached to the lower portion of link **193** is a belt **194** for attachment to the calf of the wearer.

Motor **187** and servo valve **188** are identical to motor **103** and servo valve **104** previously described; therefore, no further description thereof is necessary. Suffice to say, that rotation of lower leg sensor link **193** caused by flexure of the wearer's knee joint, will cause a corresponding movement of lower leg load link **185** and all the load supporting structure that is connected therewith, just as movement of sensor foot plate **124** caused movement of load foot plate **101**.

The upper end of upper leg sensor link **192** terminates in a transverse head **195**. Projecting upwardly centrally from and fixedly attached to head **195** is a cylindrical stem **196**, that is rotatably received in an opening in a hinge **197** (see FIGURE 11). Hinge **197** is secured to load supporting link **190** as by welds **198**. At its upper end, link **190** is rigidly secured to an annular gear **199** which is rigidly fixed about a cylindrical thigh band **200** having an upstanding annular flange **201** to provide an upwardly facing shoulder which supports an annular support member **202** rotatably surrounding band **200**. Extending laterally of said support member **202** as an integral part thereof is a yoke **203** having a pair of legs **204** and **205**, with bearings **206**, and **207**. Rotatably received in said bearings and supported thereby is a cylindrical shaft **208**, which is driven by a conventional continuous drive hydraulic motor **211**. Motor **211** is fixed to leg **205** as by welds **212**. A worm gear **213** secured to shaft **208** for rotation therewith is in meshing engagement with annular gear **199**.

As shown in FIGURE 12, a servo valve unit **225** is secured to load supporting link **190** for movement therewith. Valve unit **225** is identical to servo valve unit **104** of FIGURE 6 insofar as the coaction between the ports and piston lands is concerned; therefore, no detailed decription thereof is now necessary. Thus, stems **226** and **227** are similar to stems **139** and **140** of the valve unit shown in FIGURE 6. It is important to note, however, that external fluid lines are necessary with servo **225** in that motor **211** is physically removed therefrom. This is achieved by flexible conduits **230** and **231** adapted to communicate with, supply and return ports (not shown) of motor **211**.

In the operation of the structure just described, rotation of the wearer's upper leg will cause rotation of upper leg sensor head **195** in hinge **197** thereby actuating the two piston valves within housing **225** in opposite directions through stems **226** and **227**. This will cause motive fluid to be supplied to motor **211** to cause continuous rotation of shaft **208**. Worm **203** then rotates gear **199** which in turn rotates load supporting link **190** in the same direction as initiated by rotation of sensor link **195**. As is apparent, since servo unit **225** is rigidly fixed to the load supporting link **190**, movement of the former will move the latter and also sensor **195** through stems **226** and **227**, thereby permitting exoskeletal or load supporting structure movement to cause the sensor structure to follow throughout the entire range of movement thereof. In other words, as is the case with all of the servo units of the present invention, the load supporting layer in response to an error signal input from a sensor layer not only drives an external load, but, in addition carries with it the sensor layer in true follow-up fashion.

Referring again to FIGURES 2 and 3, a high load supporting link **233** extends upwardly laterally of the wearer's thigh and is rigidly fixed to suport member **202** by welds **234**. Its upper end is fixedly attached to motor housing **235** which extends laterally outwardly therefrom. Rigidly mounted on the outer end of housing **235** is a servo valve housing **236**. A tubular shaft **237** extends from the interior of the motor housing through an opening in link **233** and is fixedly attached to a leg **238** of a right angled load supporting hip link **239**. Hip link **239** has an additional leg **240** disposed at right angles to leg **238** and extending behind the wearer. A sensor shaft **241** extends from servo unit **236** through tubular shaft **237** through an opening in a leg **242** of a sensor hip link **243** and is rigidly attached to a sensor thigh link **244**. Servo unit **236**, motor **235**, tubular shaft **237** and sensor shaft **241** are identical to the corresponding elements shown in FIGURE 4; therefore, no further description thereof is necessary. A belt **245** is attached to the lower end of sensor link **244** and is adapted to be strapped about the wearer's thigh.

A hydraulic motor housing **246** is fixed to leg **240** of load supporting hip link **239** and extends rearwardly therefrom. Rigidly mounted on the outer end of motor **246** is a servo valve unit **247**. A tubular shaft **248** from the interior of motor housing **246** extends through an opening in member **240** and is fixedly attached to a leg **249** of a load supporting spine coupling link **250**. A sensor shaft **251** extends from servo unit **247** through tubular shaft **248** and is rigidly attached to a leg of sensor link **243** that is disposed at right angles to the leg **242** thereof. Servo unit **247**, motor **246**, tubular shaft **237** and sensor shaft **251** are identical to the corresponding elements shown in FIGURE 4; therefore, no further description thereof is necessary.

FIGURES 13 and 14 are continuations of FIGURES 2 and 3, respectively and illustrate the details of the spine assembly indicated generally at **300''**. As seen, spine coupling link **250** continues upwardly and terminates in a curved end **252**. A short load supporting link having two legs **253** and **254** disposed at right angles has fixedly attached to these legs severally hydraulic motor housings **255** and **256**, respectively. A tubular shaft **257** extending from the motor housing is rotatably received through an opening in leg **253** and is fixedly attached to link **250**. A servo valve unit **258** is fixedly mounted on the outer end of housing **255** and has extending therefrom a sensor shaft **259** which passes through tubular shaft **257**, an opening in link **250** and is rigidly attached to a short sensor link **260**. A belt **260'** straps link **260** to the waist of the wearer. Projecting upwardly from link **260** at an acute angle and integral therewith is a leg **261**.

A servo valve unit **262** is fixedly mounted on the outer end of motor housing **256**. A load supporting hinge link **263** has a bifurcated end defining two spaced legs **263'** which receive between them leg **254** of link **253**. A tubular shaft **264** extends from motor **256** through openings in members **254** and **263**; being fixed by welding or the like to member **254**. A sensor shaft **265** extends from servo unit **262**, through tubular shaft **264**, through openings in members **263** and **254** and **261** and rigidly fixed to a sensor link **266**. The servo valves **258, 262**, the motors **255, 256**, the tubular shafts **257, 264** and the sensor shafts **259, 265** are identical to the corresponding elements in FIGURE 4; therefore, no further description thereof is necessary.

The link **266** has a central angled portion **267** terminating in a short vertical end **268**. A cylindrical sensor spine shaft **269** is fixedly mounted on end **268** and extends upwardly therefrom. A hydraulic linear motor housing **270** is fixedly mounted on end **263** as by welds **271**. As shown in broken away section in FIGURE 14, housing **270** contains a piston **272** that is in slidable sealing engagement with the interior walls thereof. A piston shaft **273** extends from the piston **272** through the upper end wall of the housing and is fixed at its upper end to a load supporting shoulder plate **274**, as by welds **275** and has a slotted keyway **273'** extending the length thereof.

Fixed as by welds **276'** to the upper end of housing **270** is rectangular horizontal support plate **276**. A linear motor housing **277** is fixed to support plate **276** as by welds **278**. Slidably and sealingly mounted in housing **277** is a piston **279** having a shaft **280** extending therefrom through the housing. As shown in FIGURE 15, shaft **280** is pinned at **280'** to a bifurcated end **281** of a link **282**. Link **282** has a key **283** fitting into keyway **273'** of shaft **273**. As shown reciprocation of shaft **280** produces rotary movement of shaft **273**.

An L-shaped support member **284** is mounted on shaft **273** and is immovably fixed thereto as by welds **285**. A link **286** at one end is rotatably pinned at **287** through a bore **287'** therein to a triangular sensor plate **288** and fixedly attached at its other end to a sensor shaft **289** of a servo valve unit **290**. This valve unit is securely fastened to support member **284**. Sensor shaft **289** and servo unit **290** are identical to sensor shaft **125'** and servo **104** of FIGURE 6. Sensor plate **288** is freely mounted on shaft **269** for relative reciprocation and rotation. As can be seen, the arrangement is such that reciprocation of plate **288** produces rotation of sensor shaft **289** to thereby actuate servo unit **290**.

Appropriate external conduits (not shown) similar to passages **174'** and **175'** of FIGURE 8 are provided leading from servo unit **290** to motor **270** for supplying fluid to and exhausting fluid from opposite sides of piston **272** to cause upward or downward movement thereof.

A second servo valve unit **291** is also securely fastened to support member **284** as by welds **292**. This servo unit is identical to the servo unit **225** of FIGURE 12 and stems **293** and **294** are similarly provided for the actuation thereof. As shown in FIGURE 16 conduits **295** and **296** are provided for supplying fluid to and exhausting fluid from opposite sides of piston **279**. A bracket **297** attaches plate **288** to a flexible harness **298** that is adapted to be strapped about a wearer's shoulders and chest.

In opertaion, when a wearer bends forward his hip pivots and his spine extends. This body motion causes sensor link **266** to rotate thereby actuating servo unit **262** which, as previously described with regard to servo **104** of FIGURE 4, supplies fluid to motor **256** which produces corresponding rotation of load supporting link **263** and all the load supporting structure fixed thereto. At the same time, spine extension causes plate **288** to slide upwardly on shaft **269**; this causes rotation of sensor **289** thereby actuating servo unit **290** to supply fluid to motor piston **272** to produce corresponding upward movement of shaft **273** and all that structure fixed thereto.

The shoulder, arm and hand assembly is generally indicated at **400''** in FIGURES 17 and 18. Since both shoulders, arms, and hands are the same, only the right shoulder, arm and hand are shown. As shown, the arm, shoulder, and hand are straight out, that is, extending at right angles to the wearer's body. Inasmuch as the shoulder and arm assembly are basically comprised of structure such as motors, servo units, etc., previously described in detail, the discussion at this point will be necessarily brief. Thus, shoulder plate **274** is hinged for rotation about load supporting link **300** and fixed to tubular shaft **301** of motor **302**. Link **300** is fixed to motor housing **302** and to tubular shaft **303** of motor unit **304**. Servo valve units **305** and **306** are attached respectively to motor units **302** and **304**. Sensor links **307** and **308** are rotatably hinged with respect to one another; link **307** being fixed to sensor shaft **309** and link **308** being fixed to sensor shaft **310**. A load supporting link **311** is fixed at one end to motor **304** and at the other end thereof is hinged to a link **312** and fixed to a tubular shaft **313** of a motor **314**.

A sensor shaft **315** of a servo valve **316** passes through sensor link **308** and is fixed to a sensor link **317**. Link **312** is fixed at one end to motor **314** and at the other end thereof is fixed to a tubular shaft **318** of a motor housing **319**. Sensor link **317** at its other end is rotatable about a sensor shaft **320** of a servo unit **321**, which shaft is fixed to an upper arm sensor link **322**. A belt **323** is fixed to the end of sensor link **322** for attachment to a wearer's upper arm.

The various motors and servo valves, tubular shafts and sensor shafts, just described are similar to the motor servo valve tubular shaft and sensor shaft described in FIGURES 4 and 6, and, combined, function to simulate the shoulder joint of a wearer.

Link **324**, being fixed at one end to motor **319**, at its other end corresponds to link **233** in FIGURES 2 and 3. In fact, support member **325**, motor **326**, worm gear **327**, annular gear **328**, band **329**, link **330**, servo valve unit **331**, and T-shaped member **332** are identical to the corresponding structure in FIGURES 2 and 3; functioning similarly to produce rotation of load supporting link **330** in response to rotation of wearer's upper arm transmitted through sensor member **332**.

Link **330** is fixed to tubular shaft **332** of motor unit **333** that is fixed to link **324'**. A sensor shaft **334** from servo valve unit **335** passes through link **332** and is fixed to forearm sensor link **335'**. A belt **336** is fixed to link **335'** and is adapted to be strapped to a wearer's forearm.

The structure from **324'** to **332'** is similar to the like numeral elements except for the prime just described and functions to produce rotation of link **330'** in response to the wrist rotation of a wearer transmitted through sensor link **332'**. A belt **337** is attached to link **332'** and is adapted to be securely strapped to a wearer's wrist.

As shown in FIGURES 17 and 18, a jaw support plate **338** is welded along an edge to link **330'** and extends transversely thereof. A fixed jaw **339** is attached centrally of plate **338**. A movable jaw **340** opposite jaw **339** is rotatably pinned to plate **338** at **341**. A hinge **342** is fixed to jaw **340** adjacent **341**. An additional rectangular support plate **343** is welded at **344** to link **330'** and plate **338**. A pistol grip **344** is fixedly attached to plate **343** and extends transversely thereof. Plate **343** contains a transverse groove **345**. A sensor shaft **346** is mounted for rotation within bearings (not shown) in groove **345**, and extends into servo valve housing **347**. A trigger lever **348** is rigidly fixed to shaft **346**. A compression spring **349** is placed intermediate grip **344** and lever **348** for urging them apart. A linear hydraulic motor housing **350** is fixed to plate **343** at **351** and contains a piston **352** slidably and sealingly engaged with the interior walls thereof having a piston shaft **353** that is rotatably pinned to hinge **342**. As can be seen reciprocation of piston **352** produces rotation of jaw **340** about **341**.

Sensor shaft **346** is similar to sensor shaft **125'** of FIGURE 6; servo valve unit **347** is similar to servo valve unit **104** of FIGURE 6 and functions to control the supply and exhaust of fluid to opposite sides of piston **352**. It will be noted that spring **349** normally biases sensor shaft to a position whereat pressure fluid is supplied to piston **352** to move it to the right as viewed in FIGURE 18. Thus, normally jaw **340** is spaced away from jaw **339**.

A wearer's hand is adapted to wrap about pistol grip **344** with his fingers resting on lever **348**. Pressing on lever **348** against spring **349** will cause sensor shaft **346** to actuate servo valve **347** causing piston **352** to move to the left as viewed in FIGURE 18, thereby causing jaw **340** to close upon and grip an intended object. As with most of the other servos and motors, the external conduits are not shown.

Although not shown, an electric motor, pump and reservoir power source unit can be attached to the spine portion of the load supporting structure operating as a manifold to supply high pressure fluid to the supply ports of all the servo valve units and to receive low pressure exhaust fluid from the return ports of all the servo valve units. As an alternative, the power source for operation of the device may be remote.

While the exoskeletal device of the present invention has been described primarily as an external load supporting or carrying structure, it also may find particular application as a device useful in the rehabilitation of persons with particular muscle or nerve handicaps. Thus it is obvious that the powered unit could function as a means to control the movements of various parts of the body as an exercisor therefor. To this end the servo valve units with slight modification could be made to respond to an external command signal as well as a signal coming from the various sensor links. For example, the servo valves could be controlled by a computer following a prescribed program of various exercises or body movements.

A preferred manner of carrying out the principles of the present invention has been described; however, modifications will occur to those skilled in the art. Therefore, the present invention should be limited only by the scope of the appended claims.

What is claimed is:

1. A powered exoskeletal apparatus comprising;

(a) load supporting means,

(b) power means for moving said load supporting means,

(c) movable sensing means adapted to be attached to a human body,

(d) means for actuating said power means in response to movement of said sensing means to thereby move said load supporting means, and,

(e) follow-up means for moving said sensing means in response to the movement of said load supporting means.

2. The apparatus according to claim **1** wherein;

(f) said load supporting means comprises at least two external members interconnected for relative rotation, and,

(g) said sensing means comprises at least one inner member adjacent one of said external members.

3. The apparatus according to claim **2** wherein;

(h) said power means comprises a motor having a housing and a shaft extending therefrom for relative rotation relative thereto,

(i) said housing being immovably fixed to one of said external members and said shaft being immovably fixed to the other,

(j) said inner member being adjacent said external member that is fixed to said housing, and,

(k) said actuating means being carried by said motor housing.

4. The apparatus according to claim **3** wherein;

(l) said motor is a fluid motor, and,

(m) said actuating means is a servo valve unit.

5. The apparatus according to claim **1** wherein;

(f) said load supporting means comprises at least two external members,

(g) said power means comprises a motor having a housing and a shaft extending therefrom for rotation relative thereto,

(h) said housing being fixed to one of said external members,

(i) means interconnecting said shaft and the other of said external members for producing rotation of the other of said external members about an axis disposed at right angles to the rotational axis of said shaft,

(j) said sensing means comprises an inner member adjacent the other of said external members, and,

(k) said actuating means being carried by the other of said external members adjacent said sensing means.

6. The apparatus according to claim **1** wherein;

(f) said load supporting means comprises at least two external members interconnected for relative rotation and reciprocation,

(g) said power means comprises means to reciprocate one of said external members relative to the other of said external members,

(h) said sensing means being adjacent said one of said external members and adapted to be attached to the upper torso of the human body, and,

(i) said actuating means being carried by said one of said external members adjacent said sensing means.

7. A powered exoskeletal apparatus comprising;

(a) a group of indepenednt sensor subassemblies each adapted to be strapped to different parts of a human body,

(b) a continuous external load supporting member spaced outwardly of said sensor subassemblies,

(c) said load supporting member comprising a plurality of interconnected links having relative movements which simulate the moving parts of a human body,

(d) power means for producing relative movement of said interconnected links,

(e) means for actuating said power means, and,

(f) follow-up means for moving said sensor subassemblies in response to movement of said load supporting member.

8. The apparatus according to claim 7 wherein;

(g) said actuating means is responsive to movements of said sensor subassemblies.

9. The apparatus according to claim 7 wherein said sensor subassemblies comprise;

(g) a foot plate adapted to be strapped to the foot of a human body,

(h) an ankle plate connected to said foot plate,

(i) a pair of links rotatably interconnected for relative rotation about an axis that is substantially coincident with the axis of rotation of a human knee, one of said links adapted to be strapped to the calf area of a human body,

(j) a second pair of links rotatably interconnected for relative rotation about an axis that is parallel to the rotation axis of said first pair of links, one of said second pair of links adapted to be strapped to the thigh area of a human body,

(k) a third pair of links rotatably interconnected for relative rotation about an axis that is parallel to the rotation axis of said first pair of links, one of said third pair of links adapted to be strapped to the waist of a human body,

(l) a cylindrical shaft projecting from the other of said third pair of links,

(m) a bearing adapted to be attached to upper torso portion of a human body receiving said cylindrical shaft for reciprocation and rotation relative thereto,

(n) a fourth pair of links rotatably interconnected for relative rotation about a first axis,

(o) a fifth pair of links rotatably interconnected for relative rotation about a second axis,

(p) one of said fifth pair of links being rotatably interconnected with one of said fourth pair of links for relative rotation about a third axis that is perpendicular to said first and second axis,

(q) the other of said fifth pair of links adapted to be strapped to the upper arm portion of a human body, and,

(r) a sixth pair of links rotatably interconnected for rotation about an axis that is substantially coincident with the rotational axis of a human elbow, one of said sixth pair of links adapted to be strapped to the forearm of a human body.

10. In an exoskeletal apparatus for simulating the motion of the human shoulder, comprising;

(a) a first link,

(b) a second link rotatably connected to said first link for rotation relative thereto about a first axis,

(c) a third link rotatably connected to said second link for relative rotation about a second axis that is perpendicular to said first axis,

(d) a fourth link rotatably connected to said third link for relative rotation about a third axis that is perpendicular to said second axis,

(e) a fifth link rotatably connected to said fourth link for relative rotation about a fourth axis that is perpendicular to said third axis,

(f) a sixth link connected to said fifth link and movable relative thereto about a fifth axis that is perpendicular to said fourth axis,

(g) power means for moving said links,

(h) movable sensing means adapted to be attached to a human body,

(i) means for actuating said power means in response to movement of said sensing means to thereby move said links, and

(j) follow-up means for moving said sensing means in response to the movement of said links.

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