

June 17, 1969

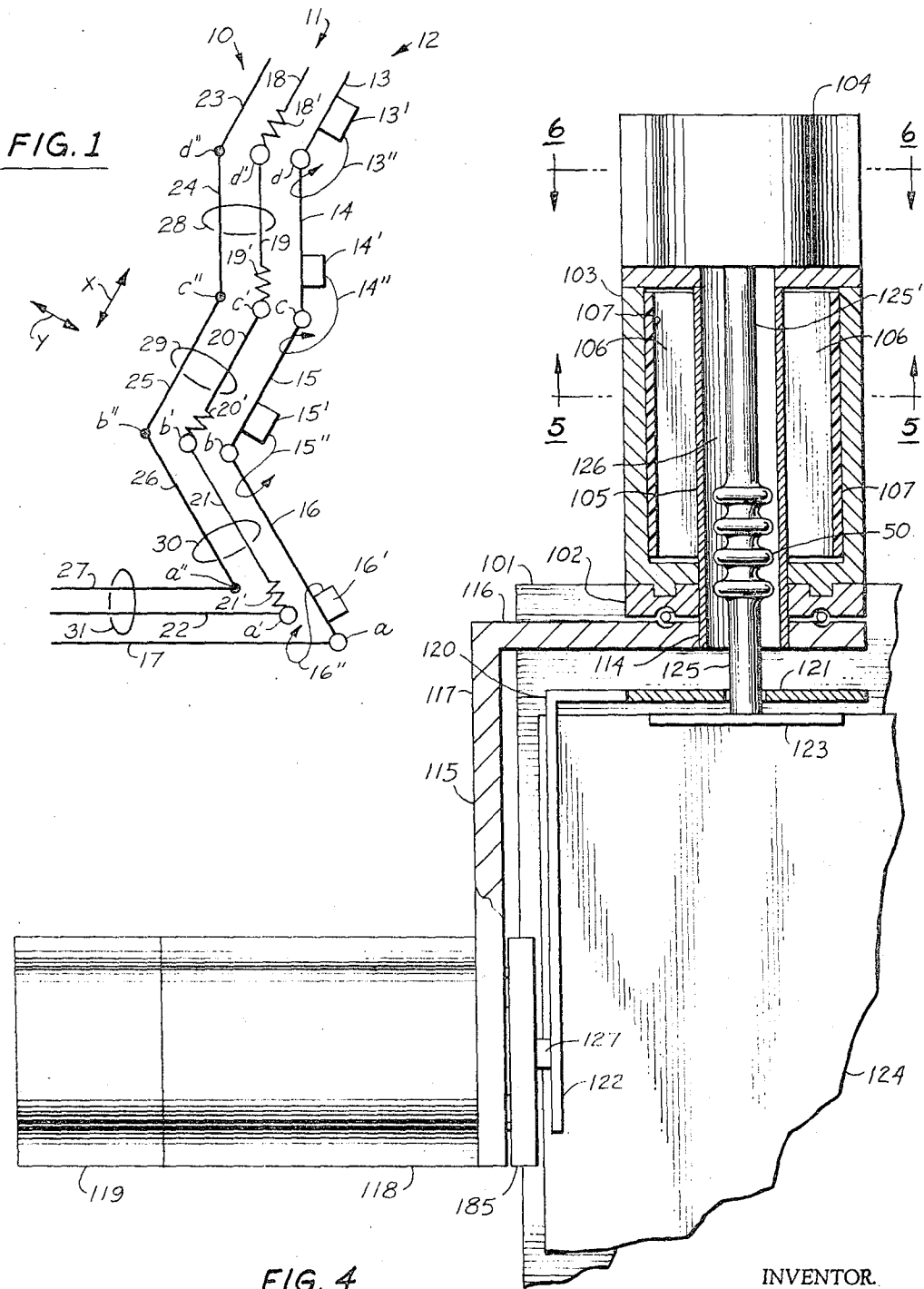
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3,449,769

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

Filed June 27, 1966

Sheet 1 of 8



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Sheet 2 of 8

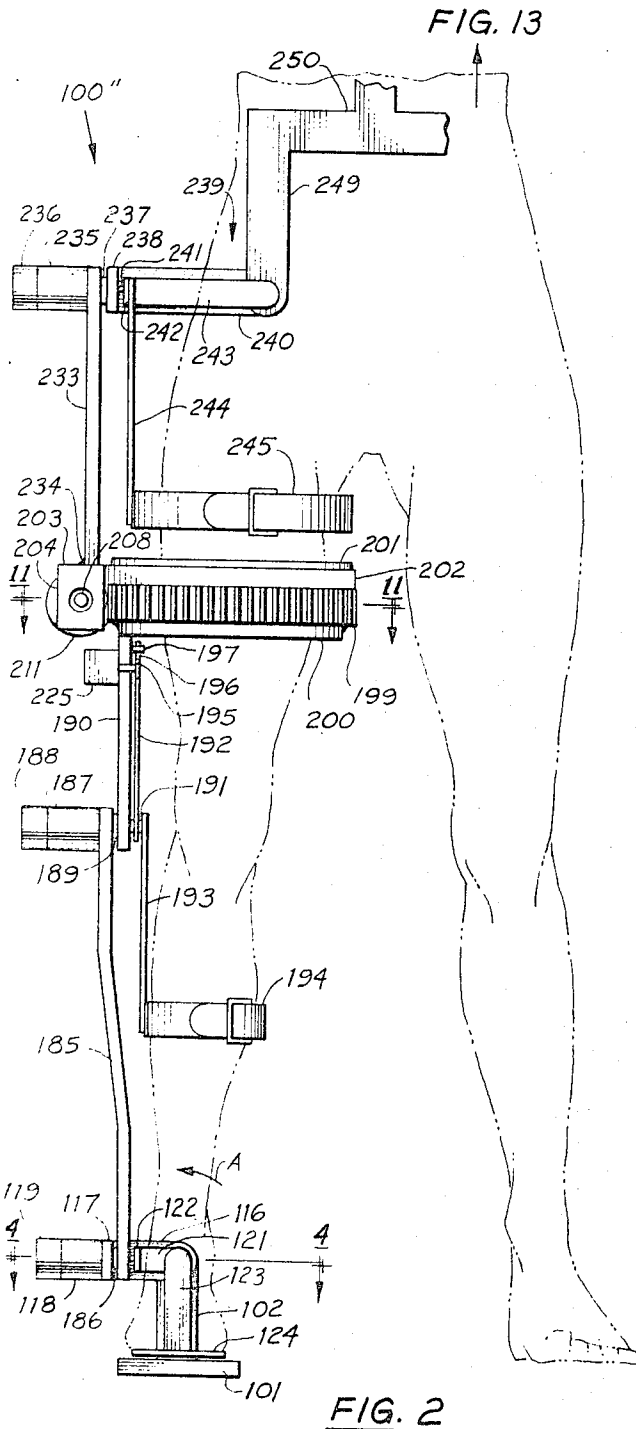


FIG. 2

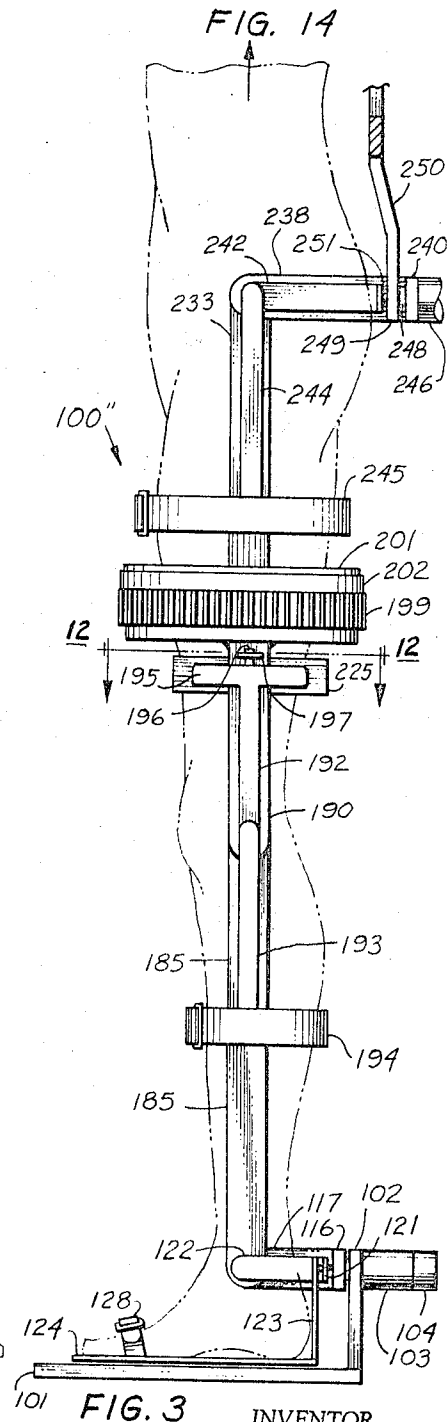


FIG. 3

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Filed June 27, 1966

Sheet 3 of 8

FIG. 9

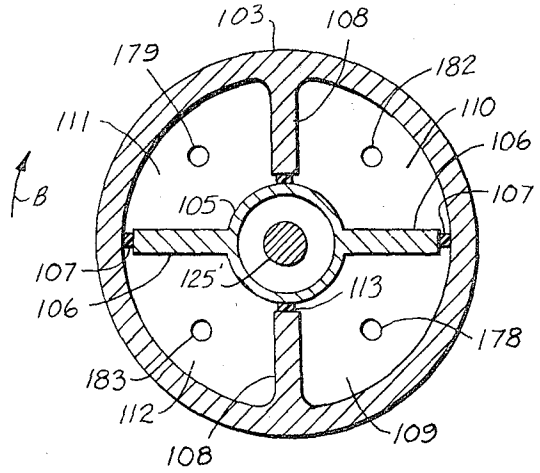
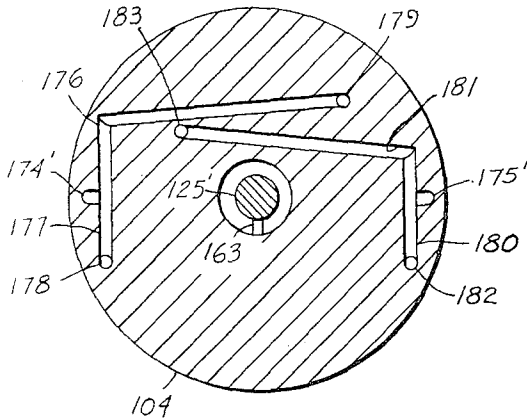


FIG. 5

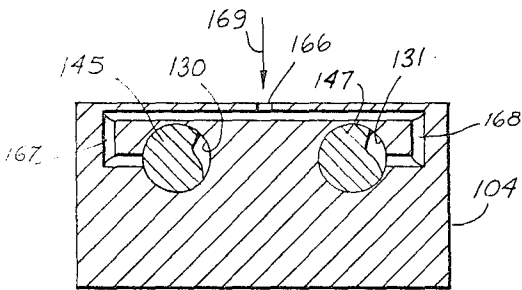


FIG. 7

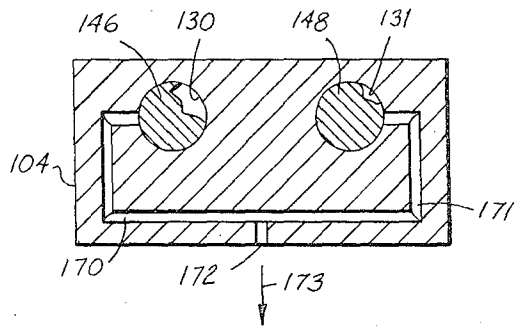


FIG. 10

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Filed June 27, 1966

Sheet 4 of 8

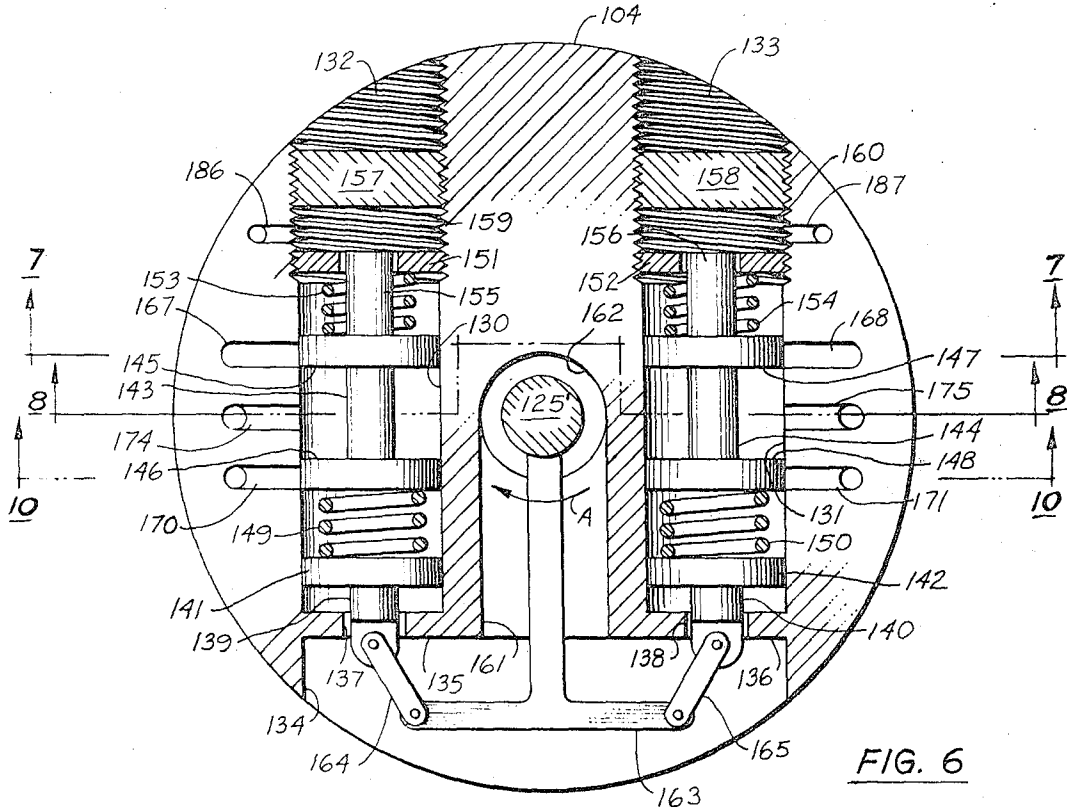


FIG. 6

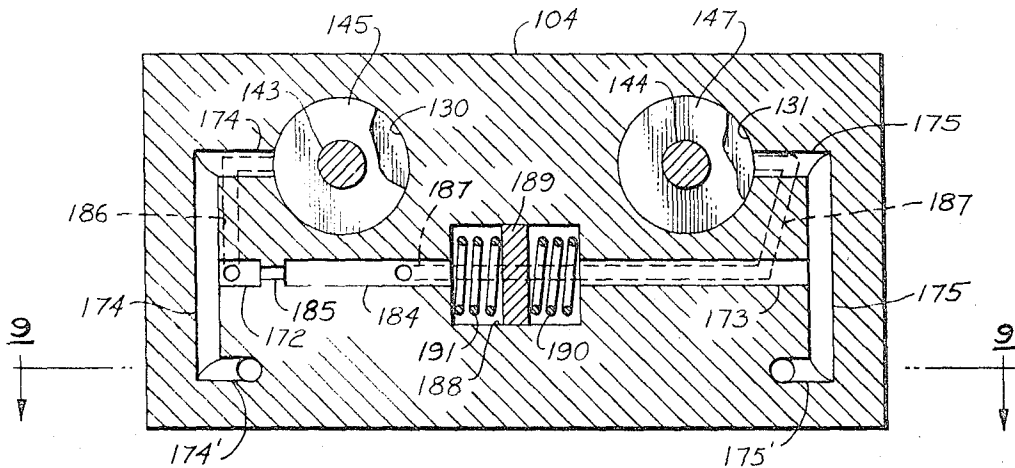


FIG. 8

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3,449,769

Filed June 27, 1966

Sheet 5 of 8

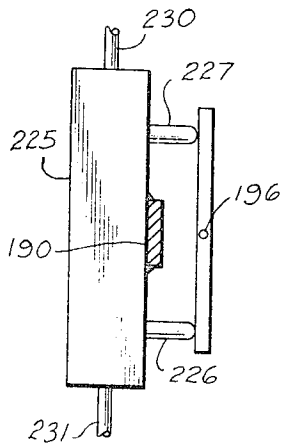


FIG. 12

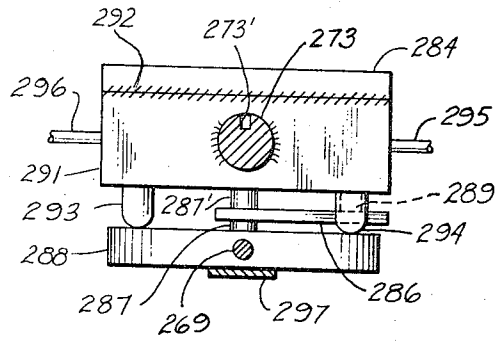


FIG. 16

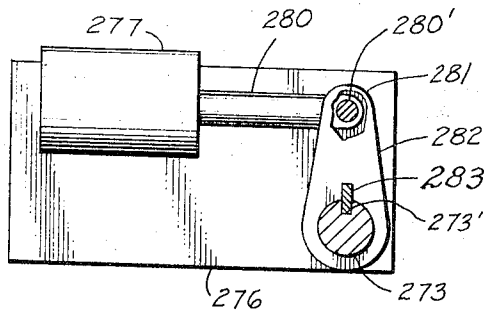


FIG. 15

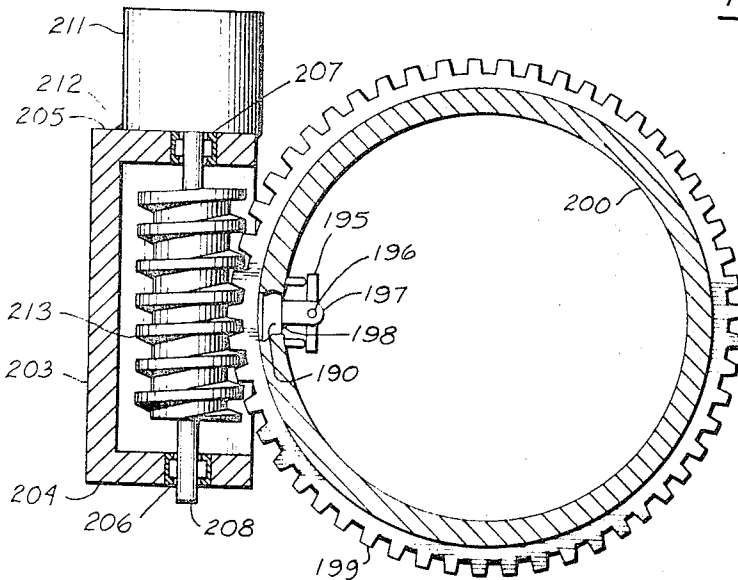


FIG. 11

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POWERED EXOSKELETAL APPARATUS FOR AMPLIFYING HUMAN
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Filed June 27, 1966

Sheet 6 of 8

FIG. 17 ←

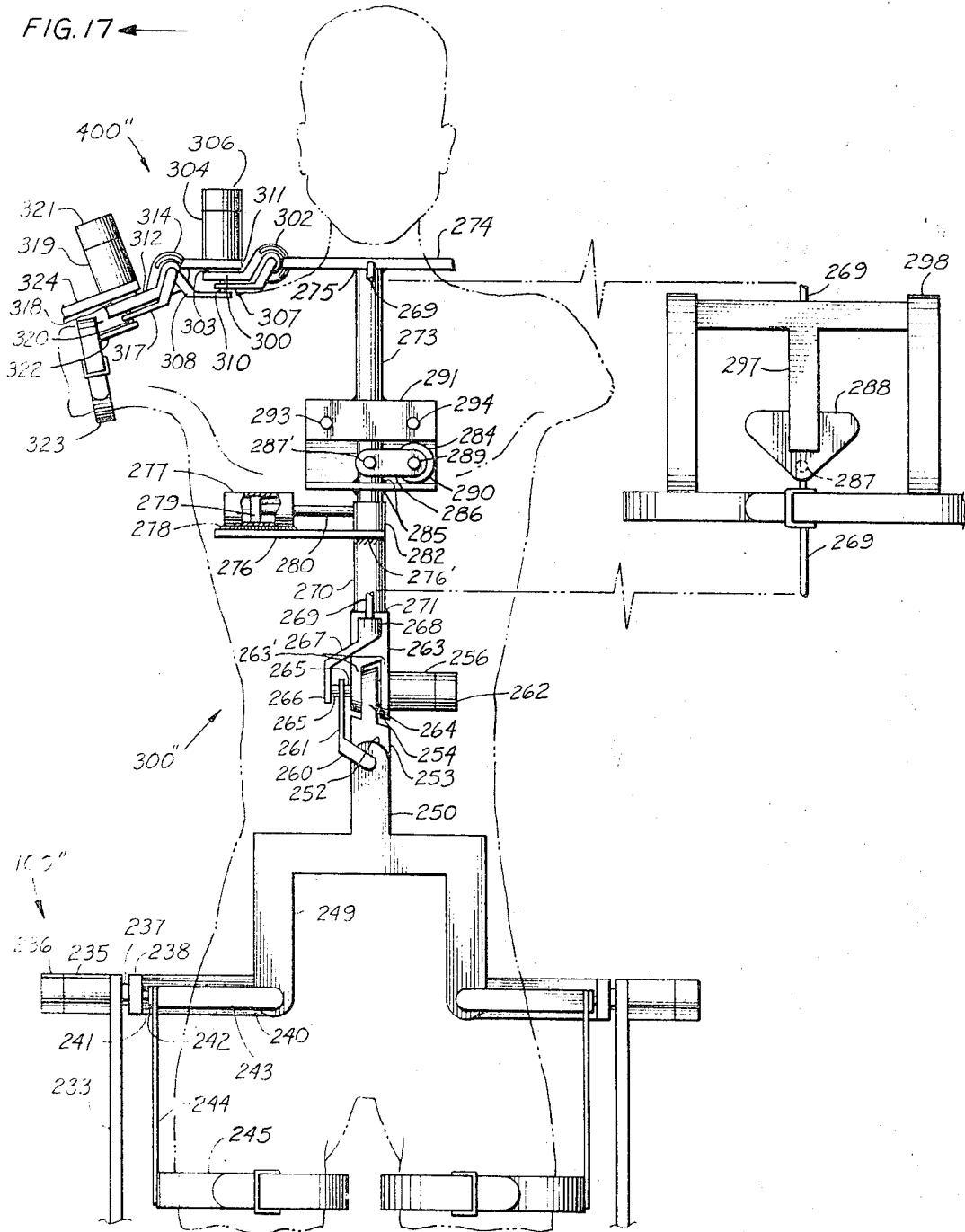


FIG. 13

FIG. 2

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Sheet 7 of 8

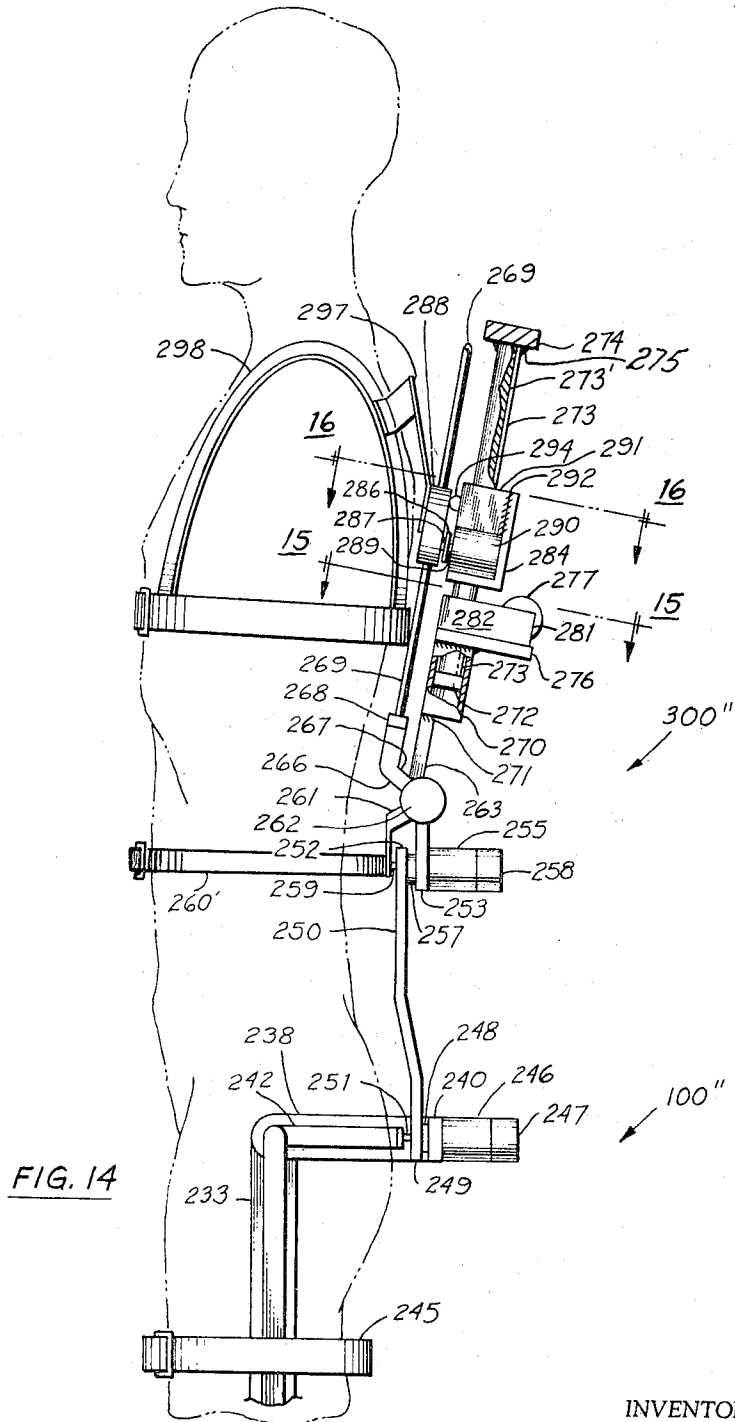


FIG. 3

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Sheet 8 of 8

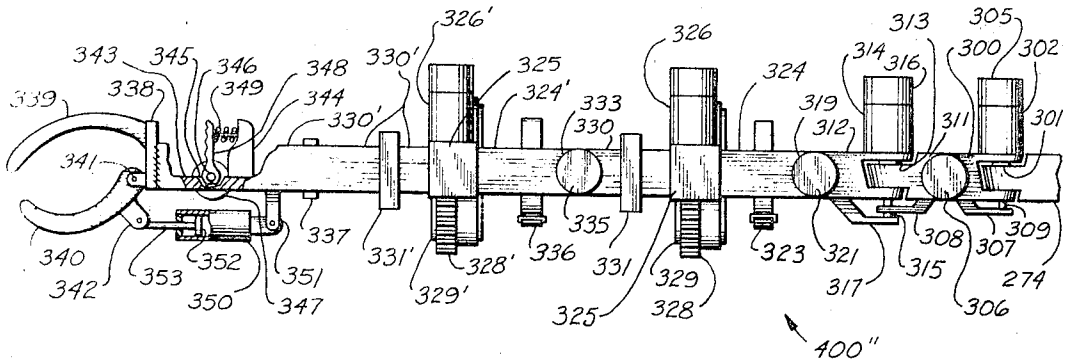


FIG. 18

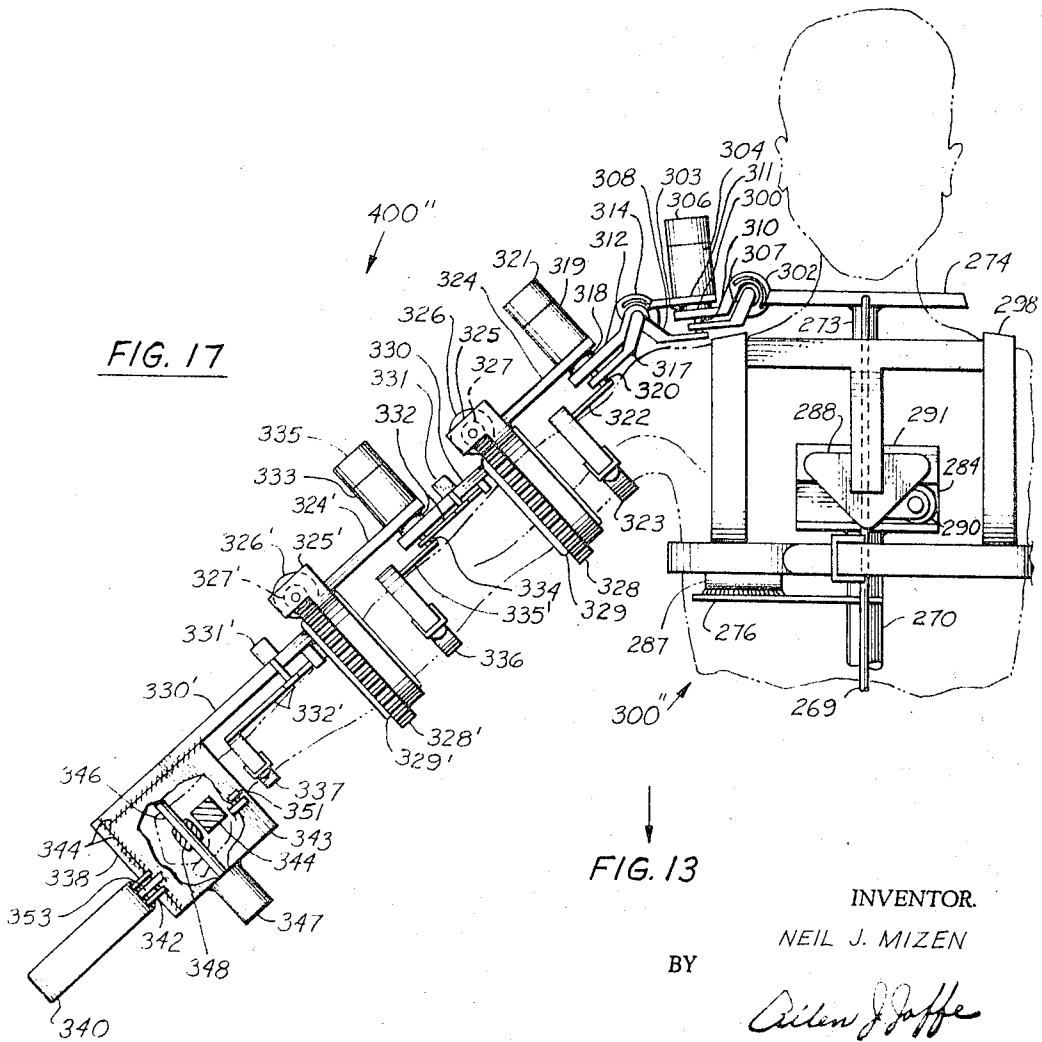


FIG. 17

FIG. 13

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**POWERED EXOSKELETAL APPARATUS FOR
AMPLIFYING HUMAN STRENGTH IN RE-
SPONSE 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 structural 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,

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-layered 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 joiners 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 corresponding 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 will not 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 counter-clockwise 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 sup-

porting 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 description 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 support 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 operation, 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 independent 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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