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(71) Demandeur/Applicant:
REHABILITATION INSTITUTE OF CHICAGO, US

(72) Inventeurs/Inventors:
KUIKEN, TODD, US;
LIPSEY, JAMES H., US;
TOMMASO, LENZI, US;
CEMPINI, MARCO, IT

(74) Agent: BRUNET & CO. LTD.

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(54) Title: POWERED AND PASSIVE ASSISTIVE DEVICE AND RELATED METHODS

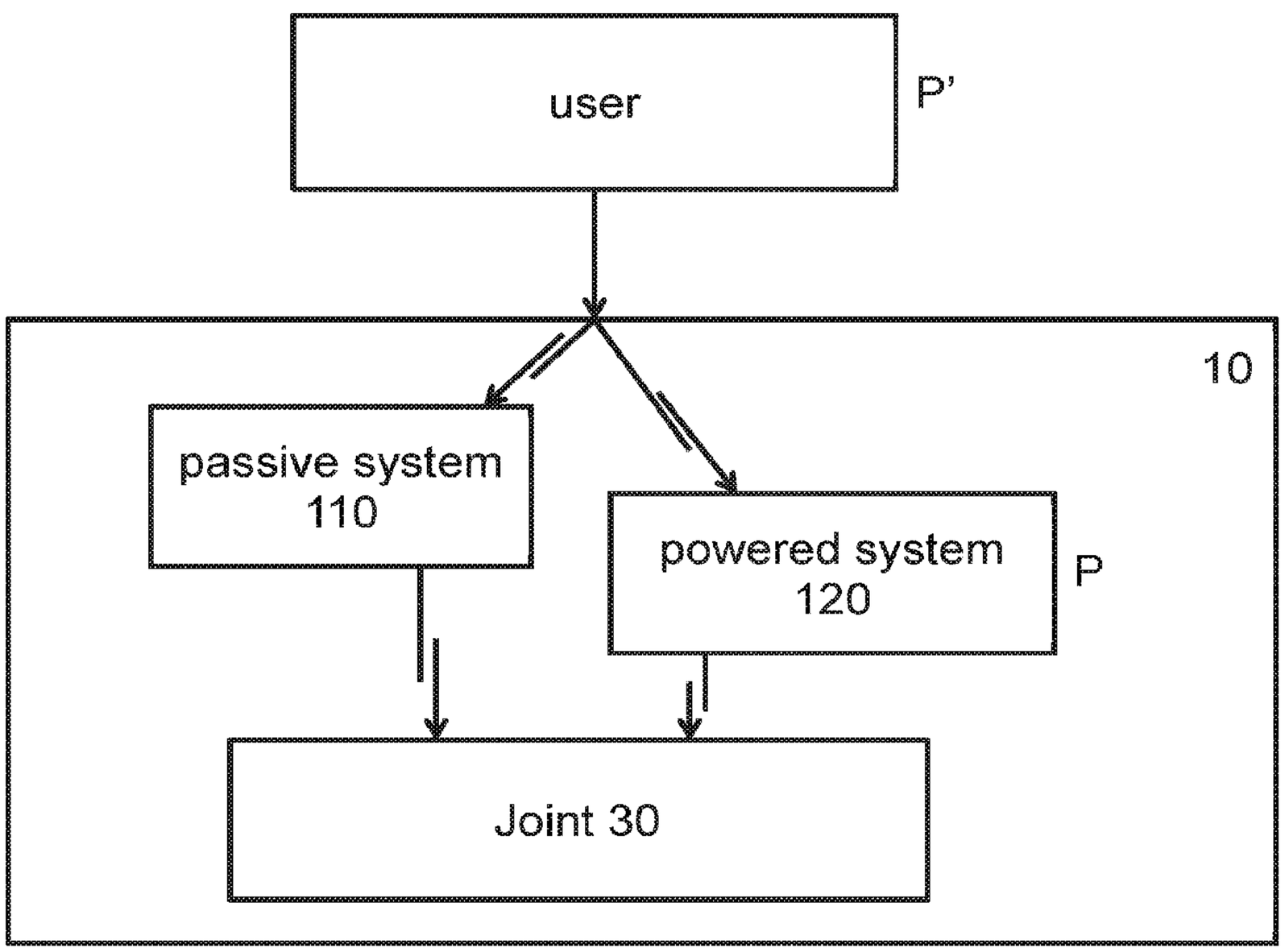

FIG. 1

(57) Abrégé/Abstract:
Systems and methods for assistive devices for replacing or augmenting the limb of an individual, such devices comprising a joint and a powered system; the powered system having a first configuration in which the powered system rotates the joint by applying power to the joint, and a second configuration that allows for rotation of the joint without actuation of the powered system.

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(71) **Applicant**: **REHABILITATION INSTITUTE OF CHICAGO** [US/US]; 345 E. Superior Street, Chicago, Illinois 60611 (US).

(72) **Inventors**: **KUIKEN, Todd**; 1220 Forest Ave., Oak Park, Illinois 60302 (US). **LIPSEY, James H.**; 811 N. Taylor Ave., Oak Park, Illinois 60302 (US). **TOMMASO, Lenzi**; 345 E. Superior Street, Chicago, Illinois 60611 (US). **CEMPINI, Marco**; via Tommaso Gherardi del Testa, 46.56030 Terricciola (Pisa) (IT).

(74) **Agent**: **KAPPERS, Robert F.**; McAndrews, Held & Malloy, Ltd., 500 W. Madison, 34th Floor, Chicago, Illinois 60661 (US).

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[Continued on next page]

(54) **Title**: POWERED AND PASSIVE ASSISTIVE DEVICE AND RELATED METHODS

(57) **Abstract**: Systems and methods for assistive devices for replacing or augmenting the limb of an individual, such devices comprising a joint and a powered system; the powered system having a first configuration in which the powered system rotates the joint by applying power to the joint, and a second configuration that allows for rotation of the joint without actuation of the powered system.

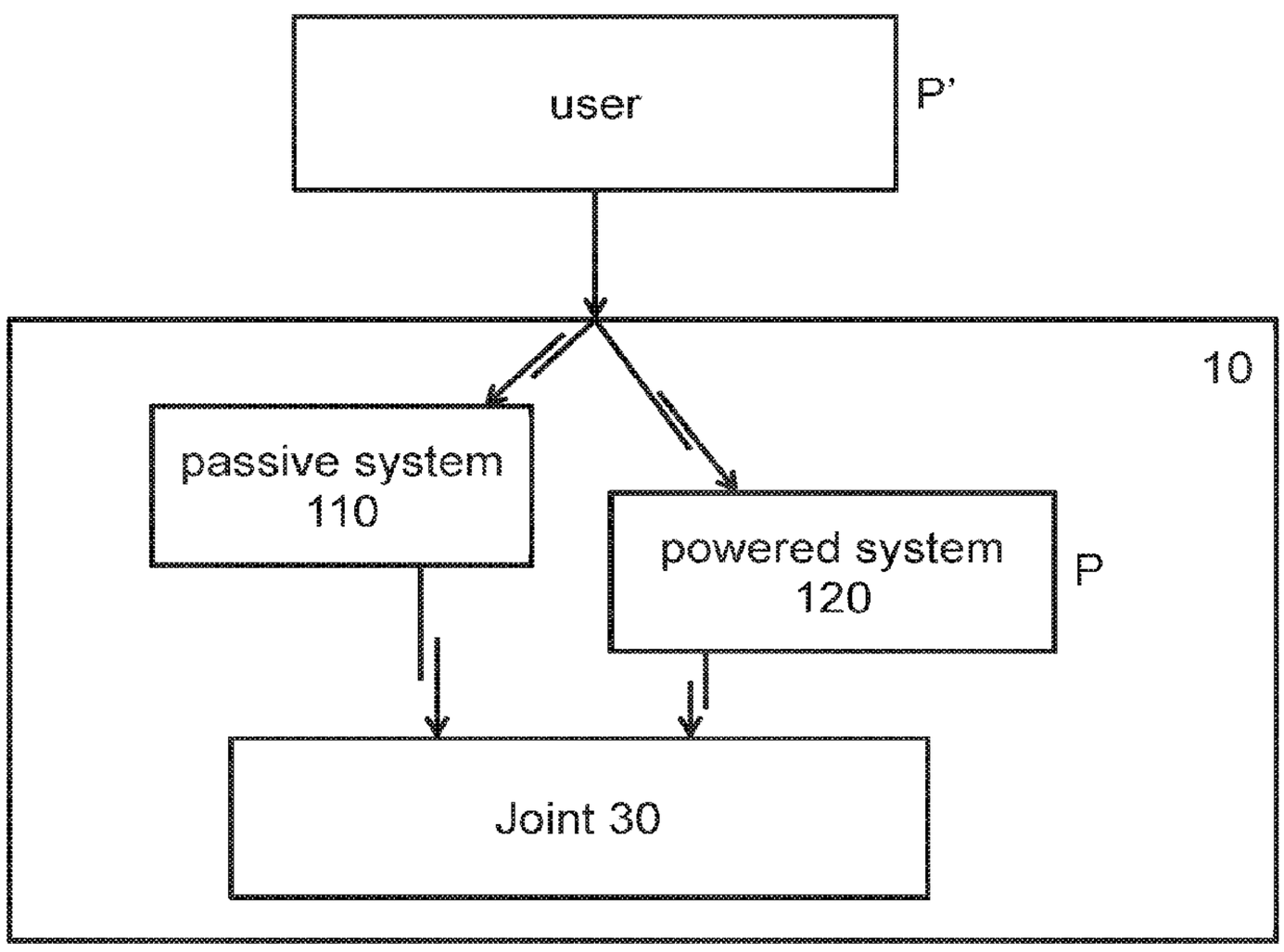

FIG. 1

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POWERED AND PASSIVE ASSISTIVE DEVICE AND RELATED METHODS

RELATED APPLICATIONS

[0001] This application claims benefit to U.S. Provisional Patent Application 62/088,849 filed on December 8, 2014, which is incorporated by reference.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] The invention was made with government support under contract H133E130020 awarded by the National Institute on Disability and Rehabilitation Research of the U.S. Department of Education. The government has certain rights in the invention.

[MICROFICHE/COPYRIGHT REFERENCE]

[0003] [Not Applicable]

FIELD OF THE INVENTION

[0004] The application relates generally to the field of assistive devices, and particularly to assistive devices such as lower limb prostheses, orthoses, or exoskeletons.

BACKGROUND OF THE INVENTION

[0005] An above-knee amputation is a highly debilitating condition. Transfemoral amputees exert as much as twice the energy of their counterparts with fully intact lower limbs when walking on level ground. Tasks such as climbing stairs or standing up from a seated position are exceedingly more difficult for transfemoral amputees.

[0006] Passive prosthetic knees provide some support for walking. Some passive prosthetic knees incorporate microprocessor devices to intelligently control the compliance of the knee. A passive prosthetic knee does not provide additional power to the knee beyond the power provided by its user. A user of a passive prosthetic knee must compensate to adapt to the lost knee power during walking and while performing other tasks. For instance, a user of a passive prosthetic knee may lead with his or her sound limb when climbing curbs or stairs. As another example, users of passive prosthetic knees will “side step” up or down ramps.

Some users of passive prosthetic knees do not have the strength to perform these tasks by compensating for the lack of power from the knee. In particular, elderly transfemoral amputees generally do not have the strength to use a passive prosthetic knee. As a result, many elderly transfemoral amputees, particularly those without family support, live in nursing homes rather than their own homes.

[0007] A powered prosthetic knee can provide a user with lost functionality by providing power similar to power provided by a biological knee. One commercially available powered prosthetic knee is the Power Knee by Össur (Reykjavik, Iceland), which uses a motor to provide the power. A powered prosthetic knee can give more functionality to its user. However, in the prior art, the added functionality comes at the cost of a prosthetic knee with greater weight. For example, the Power Knee weighs 3.19 kg (7.1 lbs), more than twice that of most passive prosthetic knees. The extra weight in a powered prosthetic knee is in the motor, transmission, and battery needed to provide sufficient power over a reasonable period of time. The user must carry this extra weight when walking, climbing stairs, or performing other tasks.

[0008] To date, powered prostheses have not improved the efficiency of gait. We believe this is due to the extra weight of powered prostheses in the prior art, including weight from the motor, transmission, and battery. Powered lower limb prostheses improve a user's ability to climb stairs, but most people do not climb stairs during much of the day. The ability to climb stairs and perform other tasks that require a powered prosthetic knee is important to accomplish many activities of daily living, but such tasks make up a relatively small portion of a user's daily mobility needs.

BRIEF SUMMARY OF THE INVENTION

[0009] In an embodiment, an assistive device is disclosed for replacing or augmenting the limb of an individual. The assistive device may comprise a joint and an actuator linkage. The actuator linkage may have a link portion that is movable to a first position coaxial to the joint or to a second position at a distance from the joint, and the actuator linkage may apply a torque to the joint when the link portion is positioned at the second position.

[0010] In one aspect, the actuator linkage applies the torque to the joint through the link portion.

[0011] In one aspect, the assistive device further comprises an adjustable linkage. The adjustable linkage may extend from the joint to a predetermined end position. The link portion may be movable along the adjustable linkage between the first position and the second position.

[0012] In one aspect, the actuator linkage may comprise a linear actuator. In one aspect, the joint may be flexible without actuation of the linear actuator when the link portion is in the first position. The joint may be extendable without actuation of the linear actuator when the link portion is in the first position. The joint may be flexible and extendable without actuation of the linear actuator when the link portion is in the first position.

[0013] In one aspect, the second position of the link position is a predetermined position.

[0014] In one aspect, the link portion is movable to a plurality of positions between the first position and the second position.

[0015] In one aspect, the assistive device may comprise a motor for actuating the linear actuator, the linear actuator being positioned so that the actuating axis of the linear actuator is parallel to the axis of the motor.

[0016] In one aspect, the actuator linkage may further comprise a crank member having a first end attached to the linear actuator and a second end being the link portion.

[0017] In one aspect, an outer face of the motor is in contact with a portion of the assistive device to dissipate heat generated by the motor.

[0018] In another embodiment, an assistive device for replacing or augmenting the limb of an individual may comprise a joint and a powered system. The powered system may have a first configuration in which the powered system rotates the joint by applying power to the joint, and a second configuration that allows for rotation of the joint without actuation of the powered system. The powered system may comprise a motor. The powered system may further comprise a linear actuator. An outer face of the motor may be in contact with a portion of the assistive device to dissipate heat generated by the motor.

[0019] The assistive device may be a prosthesis, such as an upper-limb prosthesis, a lower-limb prosthesis, or an ankle prosthesis. The assistive device may be an orthosis, such as an upper-limb orthosis or a lower limb orthosis, such as a knee orthosis.

[0020] In an embodiment, a method for operating an assistive device for replacing or augmenting the limb of an individual comprises receiving a first set of information indicating that the assistive device will operate in a powered task in a first gait cycle; engaging a powered system to provide power to a joint of the assistive device; providing power to the joint when the assistive device is operating in the powered task; receiving a second set of information indicating that the assistive device will operate in a passive task in a second gait cycle; and disengaging the powered system in response to the second set of information.

[0021] In an aspect, the step of engaging a powered system to provide power to a joint of the assistive device comprises moving a link portion of an actuator linkage from a first position coaxial to the joint to a second position at a distance from the joint.

[0022] In an aspect, the step of providing power to the joint when the assistive device is operating in the powered task comprises actuating a linear actuator.

[0023] In an aspect, the step of disengaging the powered system in response to the second set of information comprises moving a link portion of an actuator linkage from a second position at a distance from the joint to a first position coaxial to the joint.

[0024] In an embodiment, an assistive device is disclosed for replacing or augmenting the limb of an individual. The assistive device may comprise a joint and a powered system; the powered system having a first configuration in which the powered system rotates the joint by applying power to the joint; and a second configuration that allows for rotation of the joint without actuation of the powered system.

[0025] In an aspect, the powered system is in the first configuration when the assistive device is performing a powered task and the powered system is in the second configuration when the assistive device is performing a passive task.

[0026] In an aspect, the assistive device comprises a damper for the joint.

[0027] In an aspect, the actuator linkage has a link portion that is movable to a first position coaxial to the joint or to a second position at a distance from the joint. The actuator linkage may apply power to the joint when the link portion is positioned at the second position.

[0028] In an aspect, the assistive device may further comprise an adjustable linkage extending from the joint to a predetermined end position; the link portion being movable along the adjustable linkage between the first position and the second position.

[0029] In an aspect, the actuator linkage of the assistive device may comprise a linear actuator and a motor. The linear actuator may be positioned so that the actuating axis of the linear actuator is parallel to the actuating axis of the motor.

[0030] The actuator linkage may further comprise a connecting rod with a first end connected to the linear actuator and a second end being the link portion.

[0031] In an aspect, a motor of the assistive device may have an outer face that is in contact with a portion of the assistive device to dissipate heat generated by the motor.

[0032] In an aspect, the link portion of the actuator linkage is further movable to one of a plurality of positions between the first position and the second position.

[0033] Other aspects of embodiments of the invention are disclosed in the following specification, including the claims and figures.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0034] FIG. 1 displays a diagram of one embodiment of the assistive device.

[0035] FIG. 2 displays a diagram of one embodiment of a motor train for use in the assistive device.

[0036] FIG. 3 displays a side view of one embodiment of the assistive device.

[0037] FIG. 4 displays another side view of one embodiment of the assistive device.

[0038] FIG. 5 displays a perspective view of one embodiment of the assistive device.

[0039] FIG. 6 displays a section view of one embodiment of the assistive device.

[0040] FIG. 7 displays a perspective view of one embodiment of a clutch for use in the assistive device.

[0041] FIG. 8 displays a diagram of one embodiment of a controller for use in the assistive device.

[0042] FIG. 9 displays a diagram of one possible transition from passive mode to powered mode of the assistive device.

[0043] FIG. 10A displays a labeled representation of sensors on one embodiment of a lower leg portion.

[0044] FIG. 10B displays a labeled representation of sensors on one embodiment of a foot.

[0045] FIGS. 11A, **11B**, and **11C** each displays a side view of a schematic representation of embodiments of an assistive device with respect to certain motor and linkage configurations.

[0046] FIGS. 12A, **12B**, and **12C** each displays a side view of a schematic representation of embodiments of an assistive device in different positions of flexion.

[0047] FIG. 13 displays a partial-sectioned view of an embodiment of an assistive device, displaying an internal motor arrangement and transmission.

[0048] FIGS. 14A, **14B**, and **14C** each display, at various knee angles, a partial-sectioned view of an embodiment of an assistive device in a powered mode.

[0049] FIG. 15 displays an embodiment of an assistive device being acted upon by a pre-tensioning mechanism and the resulting slider-crank offset.

[0050] FIGS. 16A, **16B**, and **16C** each display, at various knee angles, a partial-sectioned view of an embodiment of an assistive device in a passive mode.

[0051] FIGS. 17A, **17B**, and **17C** each display a side view of an embodiment of an assistive device, indicating a transition between a powered mode and a passive move of the assistive device.

[0052] FIGS. 18A and **18B** display plots of transmission ratio in various embodiments of an assistive device.

[0053] FIG. 19A displays a side view of an embodiment of an assistive device employing an offset slider crank configuration. **FIG. 19B** displays a frontal view of an embodiment of an assistive device employing an offset slider crank configuration. **FIG. 19C** displays a kinematic representation of an embodiment of an assistive device employing an offset slider crank configuration.

[0054] FIG. 20A displays a side view of an embodiment of an assistive device employing an offset slider crank configuration at zero degrees. **FIG. 20B** displays a side view of an embodiment of an assistive device employing an offset slider crank configuration at 45 degrees. **FIG. 20C** displays a side view of an embodiment of an assistive device employing an offset slider crank configuration at ninety degrees.

[0055] FIGS. 21A, **21B**, **21C**, and **21D** each display a side view of an embodiment of an assistive device with varying positions of a motor and liner actuator.

[0056] FIG. 22A displays a side view of an embodiment of an assistive device employing a prismatic joint configuration at zero degrees. **FIG. 22B** displays a side view of an embodiment of an assistive device employing a prismatic joint configuration at 45 degrees. **FIG. 22C** displays a side view of an embodiment of an assistive device employing a prismatic joint configuration at 90 degrees.

[0057] FIGS. 23A and **23B** each display a side view of an embodiment of a switching mechanism. **FIGS. 23C** and **24D** each display a top view of an embodiment of a switching mechanism.

[0058] FIG. 24A displays a side view of an embodiment of an assistive device employing a revolute joint configuration at zero degrees. **FIG. 24B** displays a side view of an embodiment of an assistive device employing a revolute joint configuration at 45 degrees. **FIG. 24C** displays a side view of an embodiment of an assistive device employing a revolute joint configuration at ninety degrees.

[0059] FIGS. 25A and **25B** each displays a side view of an embodiment of a movable pin joint for an assistive device.

[0060] FIGS. 26A and **26B** each displays a side view of an embodiment of a pawl ratchet switching mechanism for an assistive device.

[0061] FIGS. 27A-D each display a side view of an embodiment of an assistive device employing a singularity configuration.

[0062] FIG. 28 displays a side view of an embodiment of an orthosis.

DETAILED DESCRIPTION OF THE INVENTION

[0063] In one embodiment, the assistive device comprises a lightweight, lower-limb prosthesis.

[0064] In one embodiment, the assistive device operates in a first configuration, known as a powered mode, and in a second configuration, known as a passive mode. The assistive device operates in a powered mode when it operates a powered task and in a passive mode when it operates a passive task. In the powered mode, the assistive device provides additional power to one or more of its joints. In the passive mode, the assistive device does not provide additional power to one or more of its joints. The transition between powered mode and passive mode is used herein to refer to a change in the configuration of the assistive device in order to transition between operating a powered task and a passive task. A mode may have mechanical aspects, so that the mechanical configuration of the assistive device differs between the powered mode and the passive mode.

[0065] A powered task is a task that requires additional power to a joint of the assistive device beyond the power a user provides. Examples of powered tasks may include sit-to-stand transfers, stair climbing, ramp ascent or descent, hill ascent or descent, curb ascent or descent, running, repositioning, and kneel-to-stand transfers. Tasks in which the assistive device operates to react to unexpected events that could be dangerous for the user, such as tripping, scuffing, or collapsing during walking or static support of the user's body weight, are also considered powered tasks.

[0066] A passive task is a task that does not require additional power to a joint of the assistive device beyond the power a user provides. One example of a passive task is level ground walking, except where a user wishes to walk more quickly than he or she can using body power alone, in which case walking becomes an active task.

[0067] The assistive device may switch between a powered task and a passive task, for instance, in response to information collected using sensors coupled to the assistive device. One method of switching between a powered task and a passive task in response to information collected from such sensors is disclosed in pending U.S. Patent Application No. 13/925,668 to A. Young and L. Hargrove, Ambulation Controller for Assistive Device, filed June 24, 2013 (herein known as "the Young/Hargrove application"), which is incorporated

by reference. Another method of switching between a powered task and a passive task is to have the user switch by pressing a button on a remote that is in operative communication with the assistive device. Other methods that may be used to control the assistive devices described herein are described in pending U.S. Patent Application No. 14/853,577 to T. Lenzi et al., Stance Controller and Related Methods, filed September 14, 2015, which is incorporated by reference, and pending U.S. Patent Application No. 14/839,309 to T. Lenzi et al., Minimum Jerk Swing Control Assistive Device, filed August 28, 2015, which is incorporated by reference.

[0068] One embodiment of the assistive device is shown in **FIG 1**. The assistive device **10** may comprise a passive system **110** and a powered system **120**, as shown in **FIG. 1**. The passive system **110** and the powered system **120** may operate in parallel. In one embodiment, the passive system **110** may be employed for passive tasks and the powered system **120** may be employed for powered tasks. A portion of the passive system **110** may be employed for powered tasks and a portion of the powered system **120** may be employed for passive tasks. Certain elements of the assistive device **10** may be common to both the passive system **110** and the powered system **120**. Path flows of power from the user, through assistive device **10**, to a joint, such as joint **30**, may be engaged or disengaged, for instance by a clutch, as indicated by the broken arrows in **FIG. 1**.

[0069] As shown in the embodiment of **FIG. 1**, the user of the assistive device may provide power **P'** to joint **30** and the powered system **120** may provide power **P** to joint **30**. Power **P** may be, for example, a torque applied to joint **30**. The power **P** may complement the power **P'**.

[0070] FIG. 2 displays one embodiment of a motor train for use in an assistive device. As illustrated in **FIG. 2**, the powered system **120** comprises a motor train to transmit power to joint **30**. The powered system **120** may comprise a motor 80m and a transmission **80t**. When the motor **80m** actuates, the powered system **120** produces power **P**. When the transmission **80t** actuates, the powered system **120** provides power **P** to joint **30**. Transmission **80t** may be engaged or disengaged by clutch 20 to joint 30. As shown in **FIG. 2**, clutch **20** is located between transmission **80t** and joint **30**. Alternately, clutch **20** could be located between motor **80m** and transmission **80t**, or at another suitable location. In one

embodiment, the assistive device **10** is configured so that the transmission **80t** actuates to provide power **P** to joint **30** only when the assistive device **10** is operating in a powered task.

[0071] FIGS. 3-7 display one embodiment of assistive device **10**, wherein assistive device **10** is a lower limb prosthesis. As illustrated in **FIG. 3**, assistive device **10** may comprise a knee joint **30**. Knee joint **30** may further comprise damper **40**. Assistive device **10** may also further comprise a passive system **110** having an upper leg portion **15** and a lower leg portion **45**. Upper leg portion **15** may comprise a fastener 16 for attachment to socket **60**. The user dons assistive device **10** by wearing socket **60** over her residual lower limb. Lower leg portion **45** may comprise a pylon. In one embodiment, knee joint **30** is provided by the Modular Knee Joint 3R95 from by Ottobock (Duderstadt, Germany). Damper **40** provides resistance during movement of assistive device **10**. It should be understood that other damper embodiments are possible. For example, damper **40** may be hydraulic. In another embodiment, damper **40** may be mechanical, such as the damper provided in the Total Knee from Össur (Reykjavik, Iceland). In yet another embodiment, damper **40** may be pneumatic. Damper **40** may further comprise a spring that biases knee joint **30** to extension.

[0072] Assistive device **10** further comprises a powered system **120**. In one embodiment, shown in **FIGS. 3-7**, the powered system **120** comprises a motor train and a linkage that may be used to provide power to the knee joint **30**. As shown in **FIGS. 4** and **5**, the motor train may comprise a motor **80m**, transmission **80t**, and battery **80b**. Battery **80b** (further illustrated in **FIG. 5**) may provide power to motor **80m**. Transmission **80t** comprises linear actuator **85**. As illustrated in **FIG. 3**, linear actuator **85** is positioned within a member **83**. In one embodiment, illustrated in **FIG. 6**, member **83** comprises a housing having ball bearings **78** as well as shaft **76**, which provides an opening through member **83**. Linear actuator **85** is drivable through shaft **76**, along ball bearings **78**, and may be may be driven by motor **80m**. As illustrated by **FIG. 3**, the linkage of powered system **120** comprises links **82** and **81**, wherein link **82** is coupled to link **81** and link **81** is further coupled to upper portion **15** of passive system **110**. Motor **80m** may form part of link **82**. The powered system **120** further comprises a clutch **20**, which is coupled to member **83**. Clutch **20** is engagable to lower leg portion **45**. In one embodiment, clutch **20** comprises a clamp and linear actuator **85** comprises a ball screw.

[0073] The assistive device **10** is configured to actuate the powered system **120** when assistive device **10** operates in a powered task. In one embodiment, actuation of the powered system **120** comprises engagement of clutch **20** to lower leg portion **45**. Clutch **20** may be configured to engage or disengage only when damper **40** bears the full load supported by assistive device **10**. Sensors may allow assistive device **10** to measure the load supported by assistive device **10**. In one embodiment, sensors may be positioned on the lower leg portion **45** and transmission **80t**. In one embodiment, sensors **70L** on lower leg portion **45** (illustrated at **FIG. 10a**) comprise strain gauges or Force Sensitive Resistor sensors, and sensors **70** on transmission **80t** (illustrated in **FIG. 3**) comprise load cells. In another embodiment, sensors **70F** may be placed under foot **90** (illustrated in **FIGS. 5-6** and **10b**). In one embodiment, sensors allow assistive device **10** to measure when the damper **40** is bearing the entire load supported by assistive device **10**. In other embodiments, sensors allow assistive device **10** to measure when the damper **40** is bearing less than the full load supported by assistive device **10**. In these embodiments, the clutch **20** may engage or disengage when damper **40** bears less than the full load supported by assistive device **10**. Controller **150** (discussed below) uses information from sensors, for example sensors **70**, to determine the appropriate time at which to engage or disengage clutch **20**. In another embodiment, a determination of when to engage or disengage clutch **20** may be provided manually. For example, assistive device **10** may be in operative communication with a button which, when pressed by the user, causes the clutch **20** to engage or disengage.

[0074] When clutch **20** is disengaged from the lower leg portion **45**, assistive device **10** relies on passive system **110**. The power **P'** from the user's movement is transmitted through damper **40** so that the user may engage in level ground walking or another passive task.

[0075] When clutch **20** is engaged, the powered system **120** may provide additional power **P** to assist the user in performing a powered task. Linear actuator **85** is actuated by motor **80m**, which in one embodiment is a direct current motor. Actuation of the linkage comprising link **81**, link **82**, member **83**, linear actuator **85**, and clutch **20** causes flexion and extension of knee joint **30**. In one embodiment, linear actuator **85** may comprise a ball screw. In one embodiment, linear actuator **85** may have a proximal end **85p** and a distal end **85d**, illustrated in **FIG. 6**. As linear actuator **85** is actuated by motor **80m**, linear actuator **85** translates through member **83**, which drives links **82** and **81** to apply a force that causes flexion or

extension of knee joint **30**. In one embodiment, when the linear actuator **85** is actuated by motor **80m** so as to flex knee joint **30** (illustrated in **FIG. 4**), the linear actuator is driven through shaft **76** along ball bearings **78** so that member **83** moves along linear actuator **85** towards linear actuator distal end **85d**. When the ball screw of linear actuator **85** is actuated by motor 80m so as to drive the linkage to extend knee joint **30** (illustrated in **FIGS. 3** and **6**), the linear actuator **85** is driven through shaft **76** along ball bearings **78** so that member **83** moves along linear actuator **85** towards linear actuator proximal end **85p**. In one embodiment, ball bearings **78** naturally hold linear actuator **85** in place, and prevent linear actuator **77** from sliding through shaft **76**, when motor **80m** is not activated.

[0076] The engagement/disengagement of clutch **20** has a low energy requirement because use of the powered system **120** is not needed during level ground walking. Because powered system **120** is relatively rarely employed by assistive device **10**, the power required to employ powered system **120** each day is relatively low.

[0077] The transition between powered mode of assistive device **10** and passive mode of assistive device **10** is needed to switch between a passive task and an active task, for instance, in a transition between level-ground walking and stair ascent. Because the number of transitions needed to support a typical day of use is relatively low, clutch **20** undergoes limited engagement cycles and experiences low wear. As a result, the dimensions of the clutch **20** can be reduced. In one embodiment, clutch **20** is made of metal and weighs no more than 250 grams.

[0078] FIG. 7 illustrates one embodiment of clutch **20**. Clutch **20** is comprised of a collar **21**, rings **22**, screw **23**, motor **24**, and clutch transmission **25**. In one embodiment, collar **21** is a high-friction clamping collar made of aluminum. In one embodiment, rings **22** are low-friction and made of plastic. In one embodiment, screw **23** is a set screw. In one embodiment, motor **24** is a DC motor. In one embodiment, clutch transmission **25** comprises a worm gear and a pinion gear. Motor **24** regulates the position of the screw **23** through clutch transmission **25**. In turn, the position of screw **23** determines the effective diameter of collar **21**. Adjustment of the angular position of motor **24**, regulates the effective diameter of collar **21**. When the diameter of collar **21** is greater than the diameter of lower leg portion **45**, clutch **20** is disengaged from assistive device **10** and only rings **22** are in contact with the

lower leg portion **45**. Clutch **20**, therefore, can slide up and down on lower leg portion **45**. When the effective diameter of collar **21** is smaller than the nominal diameter of lower leg portion **45**, such that collar **21** compresses lower leg portion **45**, axial forces from friction between collar **21** and lower leg portion **45** hold clutch **20** in place, therefore engaging clutch **20**. Clutch **20** may be connected to member **83** by a bolt arrangement or other appropriate connecting mechanisms.

[0079] The design specifications for battery **80b** limit mobility of assistive device **10** to about **100** powered tasks, including sit-to-stand transfers, stair climbing, ramp ascent or descent, hill ascent or descent, curb ascent or descent, and kneel-to-stand transfers. It should be understood that battery technology continues to improve, and future batteries may provide additional power without requiring additional weight. In one embodiment, the design specifications for battery **80b** are such that the average user may climb up to 10 flights of stairs, or an equivalent combination of stairs, ramps and sit-to-stands (a sit-to-stand is comparable to taking one step on a flight of stairs). As the number of transitions needed to support a typical day of use is low, a small motor **80m**, transmission **80t**, and battery **80b** may be used due to a small number of engagement cycles and low wear. For example, motor **80m** may have a mass of 175g, a peak torque of 1 Nm, a peak speed of 17000rpm, a nominal voltage of 48V, and a nominal power of 120W. Transmission **80t**, for example, may weigh 400g. Exemplary dimensions of ball screw **77** of transmission 80t are a 3mm lead and a 10mm diameter. Battery **80b**, for example, may have a voltage of 48V and a weight of 100g.

[0080] *Controlling the motor.* Assistive device **10** may comprise controller **150**. Controller **150** includes logic that drives motor train **80**, which may include motor **80m**, transmission **80t**, and battery **80b**. **FIG. 8** displays a representation of controller **150**. In one embodiment, controller **150** is connected to motor train **80**. Controller **150** may comprise an off-the-shelf component, such as the Overo® Air Computer-On-Module (GUM3503A) offered by GumStix Inc. (Redwood City, CA) or a custom built component. Controller **150** comprises microprocessor **160**, such as the Texas Instruments OMAP 3503 Applications Processor with processor speed of 600 MHz, or another appropriate microprocessor. Microprocessor **160** may comprise non-volatile memory **190** and RAM memory **195**.

[0081] Controller **150** is programmed with logic to actuate motor train **80** when assistive device **10** is performing a powered task. In one embodiment, controller **150** may be a myoelectric controller that receives EMG information from the user that controller **150** uses to control assistive device **10**. In another embodiment, controller **150** may use information from a set of sensors coupled to the assistive device **10**, such as sensors **70** (illustrated in **FIG. 3**), in order to determine the appropriate task to perform.

[0082] In one embodiment clutch **20** could be manually actuated by the user, for example through a lever. In another embodiment, clutch **20** may be controlled by a computing device, such as a smart phone or a smart watch. In another embodiment, clutch **20** may be controlled by controller **150** in response to the detection of the user's intention to change ambulation mode (e.g., from walking to stair climbing), as shown for example in the Young/Hargrove application. Clutch **20** may be electrically connected to controller **150**. Clutch **20** may have its own actuating mechanism, which may be a motor, solenoid, or other actuator. Communication between controller **150** and clutch **20** could be wired or wireless.

[0083] Clutch **20** may preferably be designed so that it is a low power device, thus saving additional weight to the overall assistive device **10**. Trading weight for power may result in a clutch that engages and disengages more slowly (for instance, during a period of 200-300 ms) than a more powerful (and therefore heavier) clutch that would engage the lower leg portion **45** substantially more quickly. The engagement and disengagement of the clutch **20** may be performed at any point during the execution of a gait cycle in level-ground walking. This is possible because the passive system **110** of assistive device **10** allows completion of the gait cycle in level ground walking without requiring the motor 80m to be engaged and active. In other words, clutch **20** can be engaged and disengaged during the execution of the level-ground gait cycle without altering the movement of the knee joint **30**. While the clutch **20** is engaging or disengaging, motor **80m** may compensate for friction, viscosity, and inertia of transmission **80t** so that the powered system **120** is providing a minimal amount of power, but still is not providing power to knee joint **30**.

[0084] When transitioning from a powered task to a passive task (for example, from stair climbing to level-ground walking), the first gait cycle in level-ground walking can start with clutch **20** engaged but powered system **120** not providing power to knee joint **30**. Clutch **20**

may engage throughout the first step during the gait cycle. Motor **80m** and transmission **80t** are connected but are not providing power to knee joint **30**. The passive system **110** is supporting the user's entire load and providing the required power for the user to walk. Because the engagement process is relatively slow, clutch **20** may rely on a smaller actuation system.

[0085] Assistive device **10** may follow the control scheme illustrated in **FIG. 9**. When assistive device **10** is in powered mode, clutch **20** is engaged and motor **80m** provides power to knee joint **30** as required by the specific task (e.g., stair climbing, sit-to-stand). When assistive device **10** is in passive mode, clutch **20** is disengaged and the motor is not providing power to knee joint **30**. Additionally, assistive device **10** may have a transition mode, in which clutch **20** is engaging or disengaging but motor **80m** is not providing power to knee joint **30**. Assistive device **10** may be in transition mode at any point in the level-ground gait cycle.

[0086] Motor encoder **87** provides one or more feedback signals that track its position. Signals from motor encoder **87** are sent to controller **150**, which uses the information in the signals to determine the position of knee joint **30**. In one embodiment, the position of knee joint **30** is determined using kinematics of the linkage (for example, links **81** and **82**) of the assistive device **10**. For instance, knowing the position of motor encoder **87** and member **83** allows controller **150** to compute the position of knee joint **30**. In other embodiments, sensors may be applied on knee joint **30** to determine its position, which may be an acceptable alternative even though additional sensors would increase the weight of assistive device **10**.

[0087] One example of a transition from a passive mode to a powered mode, during a transition from walking to climbing stairs, is shown in **FIG. 9**. In this example, the user starts by walking on assistive device **10** and assistive device **10** is in walking mode (passive mode **951**). Clutch **20** is disengaged (block **931**) as the user is walking in this passive mode. While walking, the user nears a set of stairs. In the swing phase, prior to stepping on the first stair, a change in mode is detected. This detection is represented by **M** in **FIG. 9**. The change in mode may be detected as described in the Young/Hargrove application. Alternately, other means may be used to detect a change in the mode, such as receiving a

signal from the push of a button coupled to assistive device **10** during a manual change in mode. Upon detection, clutch **20** begins to engage (block **932**). Motor **80m**, which was off during the earlier portion of the swing phase (block **941**), begins to provide a small amount of power (block **942**) to compensate for friction, viscosity, and inertia of transmission **80t**. The net power provided by motor **80m** in block **942** to the knee joint **30**, however, is still about zero. Clutch **20** becomes fully engaged (block **933**), which is represented in **FIG. 9** as occurring before the end of swing phase but which may occur any time up to the start of stance phase of the stair climbing task (powered mode **952**). On the start of the next gait cycle, assistive device **10** begins to operate in the stair climbing task (which, as shown in **FIG. 9**, begins with a stance phase). **Motor 80m** fully engages (block **943**) and assistive device **10** transitions from passive mode (block **951**) to powered mode (block **952**). The additional power **P** provided by the powered system helps the user climb the stairs.

[0088] In another embodiment, the powered system **120** may be physically detachable and/or re-attachable from passive system **110** or otherwise from the assistive device. In such configuration, the powered system **120** could be configured to be used on passive assistive devices already available in the marketplace. Such a feature would allow a patient to select a passive assistive device of his or her preference from different commercial providers, and then attach it to a powered system **120** for improved performance over the passive assistive device alone.

[0089] *Benefits.* Some benefits of the systems and methods described herein are apparent to one of ordinary skill in the art. A lightweight assistive device augments mobility but is not so heavy as to be a burden during operational use, such as walking or performing other tasks. The assistive device provides power for certain tasks that require power. In one embodiment, the assistive device does not provide power to the knee joint during level ground walking. In one embodiment, the assistive device provides power to the knee joint when performing a powered task such as sit-to-stand transfers, stair climbing, ramp ascent or descent, hill ascent or descent, curb ascent or descent, running, repositioning, and kneel-to-stand transfers. Because the assistive device provides power to the joint only during these or other similar powered tasks, the assistive device uses a lighter motor, battery, and/or transmission. The assistive device is therefore light enough to be tolerable for walking, while providing the functionality necessary to accomplish more demanding mobility needs.

[0090] The powered tasks are generally short in duration, compared to the thousands of level ground steps taken each day. Because of the short duration of powered tasks, and the option to limit the user to a reasonable maximum duration of powered tasks, assistive device 10 may include a much smaller motor because it is acceptable to overload motors for short periods of time. For instance, a user of the assistive device described herein may climb one to two consecutive flights of stairs at a time, and ten flights of stairs per day. Additionally, the infrequency of use of the motor will provide time for it to cool down between uses.

[0091] This system will also require much less onboard energy due to the relatively low number of powered tasks that people need to perform to navigate compared to the frequency of level ground walking over the course of a day. This means a smaller battery can be used to power the assistive device. A smaller battery coupled with a smaller motor allows for significant weight savings.

[0092] The motor and transmission are generally only used during the powered tasks, which are shorter in duration and limited in the number of iterations taken each day, compared to level ground steps and other passive tasks. Therefore, the motor and transmission will wear less than if they were used for level ground steps and other passive tasks. As a result, a smaller motor and transmission can be used, and significant weight savings can be realized. At the same time, the maintenance of the assistive device may be reduced, lowering the overall cost of the device.

[0093] Another embodiment of an assistive device is shown in **FIG. 11**. The assistive device **1000** comprises an upper part **1010** and a lower part **1020.** The upper part **1010** and the lower part **1020** are connected through a knee joint **1030**. In an embodiment, the knee joint **1030** may be a hinge joint. The lower part **1020** may be connected to a pylon **2000**, such to extend the total length of the lower part **1020** in order to connect the knee joint **1030** to a foot component **3000**. The motion of the knee joint **1030** around its axis may be achieved through a passive system **1100** and an active system **1200**. The passive system **1100** and the active system **1200** may connect the lower part **1020** to the upper part **1010**. In one embodiment, the passive system **1100** comprises a resistance element **1500**. In various embodiments, the resistance element **1500** may be a friction element, a damper, a pneumatic device, or a hydraulic device. The resistance element **1500** applies resistance to slow the extension or

flexion of the knee joint **1030**. The resistance element **1500** may provide a constant resistance, a velocity dependent resistance, or another position dependent resistance. The resistance element **1500** may further comprise a biased spring in parallel to help the knee joint **1030** return to full extension after being flexed.

[0094] FIGS. 11A, **11B**, and **11C** each display a side view of a schematic representation of an embodiment of an assistive device. The figures display certain exemplary offset slider crank embodiments and possible arrangements of a motor for an assistive device. As shown in **FIGS. 11A**, **11B**, and **11C**, the motor **1310** may be placed in different locations in different embodiments of the assistive device. In one embodiment, as shown in **FIG. 11B**, the shaft of the motor **1310** can be directly attached to the screw **1320**. In other embodiments, such as the embodiment shown in **FIG. 11C**, the shaft of the motor **1310** may drive the screw **1330** through a transmission **1340**, which may be a synchronous transmission mechanism with mating rotating elements. In one embodiment, the transmission **1340** may be a synchronous transmission mechanism, for instance one comprising a belt **1370**, a pulley **1350**, and a pulley **1360**. The nut **1330** may be driven up and down along the screw **1320** by rotation of the motor **1310**.

[0095] The slider **1220** may connect to the linear guidance **1260** through linear bearings, which in various embodiments may be recirculating ball bearings or plastic bushings, that allow the slider **1220** to slide freely up and down along the guidance **1260** (as shown in one embodiment in **FIG. 13**) without rotating with respect to said lower part **1020**. Therefore, in one embodiment, the screw nut **1330** allows with its movement the motor **1310** to drive the slider **1220**. Therefore, the linear actuator **1300** drives the active mechanism **1200**. In various embodiments, the linear actuator may be pneumatic or hydraulic, although such systems (which may also require generators, compressors, and/or fluids) may add additional weight to the overall assistive device. In yet other embodiments, the linear actuator may be a piezoelectric actuator or a moving coil.

[0096] The assistive device **1000** may use sensors and a battery system similar to those already described for its control and operation. In one embodiment, the active system **1200** comprises a four-bar linkage in an offset inverted slider-crank configuration. A linear actuator **1300** is connected to the motor **1310**, either directly as shown in **FIG. 11B** or by a

by a transmission **1340** as shown in **FIG. 11C**. The linear actuator **1300** is coupled to a connecting rod **1210**, which transmits the motion from the linear actuator **1300** to the crank **1230**, which may be rigidly affixed to the upper part **1010.** The connecting rod **1210** attach to the crank **1230** with a rotational joint **1240**. In an embodiment, the linear actuator comprises a screw **1320** and a nut **1330**. The screw **1320** may be a ball screw, lead screw, roller screw, or other appropriate screw. A linear guidance **1260** and a slider **1220** may support the linear motion of the linear actuator **1300**. The linear guidance **1260** may be rigidly attached to the lower part **1020**, and the slider may be rigidly attached to the nut **1330**, so that as so that the linear guidance **1260** provides linear support to the nut **1330** as it travels along the length of the screw **1320**. The connecting rod **1210** also may attach to a slider **1220** with a rotational joint **1250**.

[0097] FIG. 13 shows a partial sectioned view of an embodiment of the assistive device **1000**. **FIG. 13** shows the internal motor arrangement and the belt-tensioning mechanism of the transmission **1340**. The linear actuator **1300** comprises a transmission **1340**. In an embodiment, the transmission **1340** may be a synchronous transmission mechanism. For example, the transmission **1340** shown in **FIG. 13** comprises two parallel-axes rotating elements synchronously mating, such that the motor **1310** and the screw **1320** have parallel axes. The transmission **1340** shown in **FIG. 13** comprises a pulley **1350**, a pulley **1360,** and a belt **1370**. The pulley **1350** is coaxial to the motor **1310** and the pulley **1360** is coaxial to the screw **1320**. In an embodiment, the motor **1310** is located within the lower part **1020**, for instance within the frame of the lower part **1020**. In order to best dissipate heat from the motor **1310** into the frame of the lower part **1020**, the frame of the lower part **1020** may be dimensioned so that the inside face of the frame of the lower part **1020** touches or is in contact with (such as in planar contact with) an outer face of the motor **1310**. As the motor **1310** operates, the heat creates is dissipated through the surface of the lower part **1020**.

[0098] The motor **1310** may be substantially aligned with the direction of the pylon **2000**. Locating the motor **1310** in this way can minimize the weight asymmetry of the assistive device **1000** with respect to the sagittal plane and to the knee-foot direction. Other advantages include protecting the motor **1310** from external agents, dampening of the noise from the fast-spinning stages of the linear actuator **1300**, and realization of a compact and rugged arrangement of the components, particularly keeping the motor **1310** and the screw

1320 parallel and within the same longitudinal encumbrance (shown, for instance, in **FIG. 14**). Batteries for the motor **1310** may be variously positioned. For instance, the batteries may be positioned in pairs, around the active component **1200**, or in other appropriate positions.

[0099] The assistive device **1000** may further include a mounting frame **1040** which connects the linear guidance **1260** to the lower part **1020**. The frame **1040** may be mounted at different distances away from the lower part **1020** and may be mounted, for instance, using setscrews and/or slotted holes and bolts, as shown in **FIG 15.** Changing the set distance of the linear guidance **1260** from the lower part **1020** changes the inter-axes distance between the pulley **1350** and the pulley **1360**, and provides an initial tension into the belt **1370**.

[00100] **FIGS. 12A**, **12B**, and **12C** each displays a side view of a schematic representation of embodiments of an assistive device at 0, 45, and 90 degrees of flexion when the assistive device is in a powered mode. The knee angle is defined by the crank angle plus an angular offset depending upon the particular realization of the upper part **1010**. The assistive device 1000 may be designed so that when the knee angle is at about 107 degrees, the nut **1330** is in a singularity with respect to the connecting rod **1210**, to assist in the transition from sit to stand. Having the nut **1330** in singularity with the connecting rod **1210** provides a little play for the nut to move along the rod **1210** without requiring actuation by the motor **1310**. Regardless of the particular configuration, the transformation between the angle of rotation of the motor **1310** and the angle of the crank **1230** depends upon the transmission of the linear actuator **1300**, the offset **e** of the mechanism, the length **a** of the crank **1230** and the length **b** of the rod **1210**. These values can be set by design to optimize the range of motion and torque/speed capability of the mechanism, for specific device applications. The particular inclination of the axis of the linear guidance **1260** with respect to the direction of the pylon **2000** does not affect the overall transmission of the active system **1200**, and thus can be freely adjusted in order to meet other design criteria (such as shape size and arrangement of the components, structural requirements, aesthetical requirements, and other appropriate design criteria). In particular, in various embodiments, the linear actuator **1300** can be located in different positions. For example, the linear actuator **1300** can be located outside and in front of the lower part **1020**, outside and behind the lower part **1020**, or inside the lower part **1020**, such as inside the pylon **2000**.

[00101] The total transmission ratio (TR) is the product of two components: the TR of the linear actuator itself (how many millimeters of nut displacement correspond to 1 degree of motor rotation) and the TR of the kinematic chain (geometry- and position-dependent). The first one, itself, is given by the product of the TR of the pulley stage (revolution of driven pulley for 1 revolution of driving pulley) and the screw TR (millimeters of the lead). Table 1 below summarizes total transmission ratio (crank rotations/motor rotations), with the screw and the pulley for the design, and some variations over the geometry. These affect the shape of the TR-angle curve, which is shown in FIG. 18A, while a pulley TR of 42/18 and a screw TR of 2 mm / 360 degrees only act as a uniform multiplication factor.

Knee angle	Total TR	Plot numbering (FIG. 18A)	Offset of the mechanism **e**	Length of the crank **a**	Length of the rod **b**
0 deg	275	1810	32.5 mm	45 mm	100 mm
30 deg	330				
60 deg	296				
90 deg	137				
108 deg	0				
0 deg	245	1820	15 mm	45 mm	100 mm
30 deg	330				
60 deg	326				
90 deg	186				
108 deg	50				
0 deg	169	1830	32.5 mm	25 mm	100 mm
30 deg	183				
60 deg	149				
90 deg	59				
108 deg	-13				
0 deg	264	1840	32.5 mm	45 mm	50 mm
30 deg	330				
60 deg	307				
90 deg	107				
108 deg	-100				
(any)	0	(null)	32.5 mm	0 mm	100 mm

Table A

[00102] FIG. **18A** displays a series of graphs plotting knee angle (x-axis) and total TR (y-axis). Negative TR means that (theoretically) the nut **1330** must be driven in the opposite direction, to continue angle extension. In the assistive device **1000**, the point of zero-TR relates to the operation of the mechanical end stops.

[00103] Other locations for the linear actuator may be possible in alternative embodiments of the design for different applications. For example, the linear actuator **1300** may be located outside, in the front or in the back, with the motor **1310** pointing downward or upward, or with other spatial orientation depending upon the geometry of the synchronous transmission mechanism **1340**. As shown in **FIG. 15**, the distance between the vertical axis of the knee joint **1030** and the axis parallel to the linear guidance **1260** passing through the rotational joint **1250** defines the offset **e** of the assistive device **1000**. Additionally, setting the distance between the linear guidance **1260** and the lower part **1020** allows setting of the mechanism offset **e**, which can be matched with the transmission **1340** by choosing a belt **1370** of proper length.

[00104] In an embodiment, the dimensions may be adjusted such that **e** ranges in between 28.5 mm and 35 mm. More precisely, in an embodiment, the distance between the main vertical axis of the structure 1020 and the screw axis is 8 millimeters greater than the distance **e**. Alternately, the distance **e** may be characterized as 28.5 mm plus the gap between the lower part **1020** and the frame **1040** (see **FIG. 5**). This regulation is primarily for providing pretension to the belt **1370**, as the correspondent variations in the TR curve are minimal. **FIG. 18B** displays plots of knee angle (x-axis) and transmission ration (y-axis) for exemplary values of **e** = 38 (plot **1850**), 35 (plot **1860**), 32.5 (plot **1870**), 30 (plot **1880**) and 28.5 mm (plot **1890**).

[00105] As shown in **FIG. 13**, the active component **1200** is positioned posterior to the pylon **2000**, similar to the position of the gastrocnemius muscles relative to the shin of the human leg. In this position, and in other suitable positions, the active component **1200** and the rest of the assistive device **1000** may be covered, with a housing or other covering, such as a cosmetic covering. A covering may be made of one or more of a foam material, silicone, latex, rubber, vinyl, or other material known in the art. It may be rigid or flexible.

[00106] **FIGS. 14A**, **14B**, and **14C** display a side view of the assistive device **1000** at various stages of operation in powered mode. In **FIG. 14A**, the nut **1330** begins at a position near to the distal end of the screw **1320**. When the motor **1310** is turned on, its rotation causes the pulley **1350** to rotate, which pulls the belt **1370** so that it rotates around the pulley **1360**. The pulley **1360** is mechanically coupled to the screw **1320**, and so rotation of the

pulley **1360** causes rotation of the screw **1320**, which pulls the nut **1330** towards the proximal end of the screw **1320**. Pulling of the nut **1330** in this proximal direction creates a pushing force on the connecting rod **1210**, which transfers the pushing force to the crank **1230** through the rotational joint **1240**. The rotational joint **1240** has a threaded interior that attaches to the screw **1420** and prevents the force from the connecting rod **1210** from pushing the rotational joint **1240** proximally up the screw **1420**. Instead, the force from the connecting rod **1210** pushes on the rotational joint **1240**, which transfers the force to the crank **1230.** The crank **1230** is rigidly affixed to the knee joint **1030**, and so the force between the nut **1330** and the crank **1230** creates a torque that acts on the knee joint **1030**, causing it to extend. **FIG. 14B** displays a side view of the assistive device **1000** with the knee joint bent at about a 45 degree angle. By comparing the position of the nut **1330** in **FIG. 14A** with the position of the nut **1330** in **FIG. 14B**, the reader can see how the change in position of the nut **1330** on the screw **1320** results in an extension of the knee joint **1030**. As the nut **1330** continues moves proximally along the screw **1320**, the knee joint **1030** more fully extends, as shown in **FIG. 14C**. The reader may compare the position of the nut **1330** in **FIGS. 14A**, **14B**, and **14C** to see how the change in attachment position of the nut **1330** on the screw **1320** causes extension of the knee joint **1030**. Similarly, operating the motor **1310** in the reverse direction causes the screw **1320** to rotate in the opposite direction, which pulls the nut **1330** towards the distal end of the screw **1320**, which creates a tension in the connecting rod **1210**, the rotational joint **1240**, and the crank **1230** that causes the knee joint **1030** to flex. The reader can see the change in the assistive device **1000** as the knee flexes by comparing **FIG. 14C** with **FIG. 14B**, and by comparing **FIG. 14B** with **FIG. 14A**.

[00107] For the assistive device **1000** to operate in passive mode, the motor **1310** and the linear actuator **1300** may be decoupled from a mechanism in the assistive device **1000** that assists in the rotation of the knee joint **1030**. This can be done in several ways, including but not limited to disengaging the connection between the motor shaft **1310** and the screw **1320**; disengaging the connection between the nut **1330** and the slider element **1220**; disengaging the connection between the crank **1230** and the upper body **1010**; or disengaging the connection between the sliding guidance **1260** and the lower part **1020**. Decoupling the motor and/or linear actuator **1300** enables the knee joint **1030** to rotate independently of the

rotation of the motor **1310** or actuation of the linear actuator **1300**, so that a patient can walk (and so bend the knee joint **1030**) without the use of the motor.

[00108] Alternatively, the decoupling of the motor and transmission from the knee joint may be achieved by selectively introducing an additional joint into the kinematic linkage between the motor **1310** and the knee joint **1030**. As described above, this kinematic linkage includes the knee joint **1030**, the crank **1230**, the rotational joint **1240**, the connecting rod **1210**, the rotational joint **1250**, and the slider **1220**. Introducing an additional joint adds an extra degree of freedom in between the rotation of the motor **1310** and the rotation of the knee joint **1030**. The rotation of the knee joint **1030** may be decoupled from the displacement of the nut **1330**, and therefore from the movement of the linear actuator **1300** and the motor **1310**. The additional joint may be coupled to a clutch, which can selectively engage or disengage the additional joint in order to transition the assistive device **1000** from powered mode to passive mode.

[00109] **FIG. 17A**, **17B**, and **17C** each display a side view of an embodiment of the assistive device **1000** showing the assistive device **1000** transitioning from an powered mode (in **FIG. 17A**) to a passive mode (in **FIG. 17C**). In **FIG. 17A**, the rotational joint bar **1240** is positioned at the far end of a slot in the crank **1230**. The rotational joint **1240** may be threaded and attached to the screw **1420**. When the motor **1410** rotates the screw **1420**, the rotational joint **1240** is moved along the length of the screw **1420**. The sequence of **FIGS. 17A**, **17B**, and **17C** show the motor **1410** actuating to move the rotational joint **1240** from an end position (shown in **FIG. 17A**) to an intermediate position (shown in **FIG. 17B**) to a position that is coaxial to the knee joint (shown in **FIG. 17C**). The rotational joint **1240** may be positioned in other intermediate positions between the end position and the coaxial position. As the rotational joint **1240** moves towards the coaxial position, the moment arm **a** of the connecting rod **1210** acting on the knee joint **1030** reduces, until the rotational joint **1240** becomes coaxial with the knee joint **1030**. When the rotational joint **1240** is coaxial with the knee joint **1030**, the moment arm **a** has a length equal to 0, the active system becomes singular, and the patient is able to rotate the knee joint **1030** without a change in the position of the actuator **1300** and without requiring active motion or a torque from the linear actuator **1300**.

[00110] **FIGS. 16A**, **16B**, and **16C** each display a side view of the assistive device **1000** at various stages of operation in passive mode. **FIG. 16C** displays the assistive device **1000** in an upright position, as if the patient were standing on it. **FIG. 16B** displays the assistive device **1000** after the patient has taken a step forward with his or her sound leg, bringing the other leg (the assistive device **1000**) into a swing phase and showing the assistive device **1000** swinging backwards. **FIG. 16A** shows the assistive device **1000** in a fully flexed position, which because it is so fully flexed would be rarely achieved by the patient during walking, and is shown here to help illustrate the general operation of the assistive device **1000** in a passive mode.

[00111] As shown in the **FIGS. 16A**, **16B**, and **16C**, the knee joint **1030** flexes but the active component (including the motor **1310**, the transmission **1340**, the linear actuator **1300**, the nut **1330**, the connecting rod **1210**, the rotational joint **1240**, and the screw **1420**) are not in active movement. Although they rotate around the knee joint 1030 as the knee joint 1030 bends, they do not actuate and do not change position with respect to the position of the knee joint **1030** or the passive component **1100**. The motion of the assistive device **1000** while in passive mode results from the energy the patient provides while operating the assistive device **1000** in a passive task. There are no other additional degrees of motion sliding, spinning or pivoting while the assistive device **1000** is passive, except for the rotation of the knee joint **1030** and the operation of the passive system **1100**, such as the damper **1500**. Limiting the duration of movement of the active components extends their life, increases battery life, reduces noise, allows for a lighter assistive device, and has other benefits.

[00112] The transition between the powered mode of the assistive device **1000** and the passive mode of assistive device **1000** may be provided by another small active system **1400**. In an embodiment, the active system **1400** may comprise a small electrical motor **1410** driving a screw **1420**, which drives the rotational joint **1240** along a slot **1430** (which may or may not be on a straight line) connecting the original position (at a distance a from the knee joint **1030**) with the position of the knee joint **1030**. The motor **1410** is activated only occasionally, during the transition between tasks, rather than continuously during the motion. Therefore, the motor **1410** can be driven at its maximum performances (for shorter transition time) without negative consequences on the thermal heating, electrical consumption, or mechanical life. Additionally, this allows the motor **1410** to be easily controlled at constant

voltage, and switched off when the absorbed current overcomes a threshold that indicates the rotational joint **1240** has reached a mechanical stop in the slot of the crank **1230**. This feature allows for control of the motor **1410** without the need for precise or resolute sensors, or additional control layers. In other embodiments, the screw **1420** and/or the motor **1410** may be replaced with or augmented by pneumatic, hydraulic, piezoelectric, or moving coil systems.

[00113] A minimal position sensor on the active system **1400** may be used to set the desired attachment position of the rotational joint **1240** along the screw **1420** and/or slot **1430**, thus enabling the possibility to control the length **a** of the active mechanism **1200**. This feature provides for an effectively tunable variable transmission. The additional advantage is the possibility to tune the contribution of the active mechanism, by lowering its torque transmission ratio with respect to the fully active configuration, but conversely increasing its speed ratio, basically without affecting the performances of the motor **1310**. This feature is advantageous as it allows to meet requirements for mildly-power and varying-speed tasks (e.g. raising a slope, fast walking). The assistive device **1000** may be controlled using a microcontroller which receives information from sensors coupled to the assistive device **1000**, such as encoders, load cells, IMUs, and the like which, for instance, help determine the position of the knee joint **1030**. The microcontroller may output a needed amount of current to a first current driver, used to control the motor **1310**, and a second current driver, used to control the motor **1410**. Each current driver and motor combination may employ a closed feedback loop. One skilled in the art will recognize that there are many other ways to configure the electronics to control the assistive device.

[00114] In an embodiment, a method for operating the assistive device **1000** is described as follows. The controller of the assistive device **1000** receives a first set of information from sensors coupled to the assistive device **1000**. The first set of information indicates that the assistive device **1000** will operate in a powered task, such as climbing stairs. The motor **1410** moves the rotational joint **1240** to the appropriate location along the screw **1420**, for instance, the position furthest from the knee **1030**, and the motor **1310** begins to actuate. Actuation of the motor **1310** causes the nut **1330** to travel away from the knee joint **1030**, drawing the lower part including the pylon **2000** up and causing the knee **1030** to flex in preparation for climbing a stair. The assistive device continues to operate to provide the

necessary flexion and extension to assist the user up the staircase. At the top of the stairs, the controller receives a second set of information from the sensors coupled to the assistive device **1000**. The second set of information indicates that the assistive device will transition to a passive task, such as level ground walking. The motor **1410** moves the rotational joint **1240** inwardly towards the knee **1030** until the rotational joint **1240** is coaxial to the knee 1030. The motor **1310** and the linear actuator **1300** stop actuating. The user is able to walk along level ground, with the damper **1500** providing the appropriate passive resistance, and without requiring actuation of the active components such as the motor **1310**, the linear actuator **1300**, the rod **1210**, and the rotational joint **1240**. Similar methods may be employed to transition the assistive device between other powered tasks and passive tasks.

[00115] Various other embodiments of assistive devices that employ principles similar to those described above are displayed in **FIGS. 19-27**. Starting with **FIG.19**, an assistive device **2100** comprises a knee joint **2102** that has both passive and active components, and a pylon **2104** that connects the knee joint **2102** to the foot component **2106**. In one embodiment the active component of the knee joint **2102** is actuated through a four-bar linkage in an offset slider crank configuration. In this configuration, the knee angle is defined by the crank angle plus an angular offset that can be set by design to optimize the range of motion and torque/speed capability of the offset slider crank mechanism for specific device applications. A connecting link **2110** transmits the movement between the slider **2112** (which in one embodiment may be screw **2126**), which is located in parallel to the pylon, and the crank **2114**. The connecting link **2110** attaches to the crank **2114** with a rotational joint **2116**. The connecting link **2110** also attaches to a slider **2112** with a rotational joint **2118**. The distance between the location of rotating knee joint **2120** and rotational joint **2118** in the x axis defines the offset of the mechanism. The slider **2112** is connected to a linear actuator, which in one embodiment comprises a DC motor **2124**, a screw **2126** (which in various embodiments may be a ball screw, lead screw, or roller screw) and a screw nut **2128**. The shaft of motor **2124** is attached to the screw **2126**, so that one rotation of the motor shaft equals one rotation of the screw. The nut **2128** is driven up/down on the screw **2126** by rotation of the motor shaft. The nut **2128** is connected to the rotational joint **2118** with a supporting link **2130**. The supporting link **2130** connects to the pylon **2104** through linear bearings, which in various embodiments may be ball bearings or plastic bearings, that allow

the supporting link **2130** to slide freely up-down on the pylon **2104** (as shown in one embodiment in **FIGS. 20A, 20B**, and **20C**) without rotating with respect to said pylon **2104**. Therefore, in one embodiment, the supporting link **2130** allows the slider to move and also allows the motor **2124** to drive the slider **2112**.

[00116] In various embodiments, the linear actuator can be located in different positions (**FIG. 21**). For example, it can be located outside the pylon in the front, outside the pylon in the back, or inside the pylon. Other locations for the linear actuator may be possible in alternative embodiments of the design for different applications.

[00117] For the assistive device **2100** to operate in passive mode, the motor **2124** and the powered linear transmission **2132** may be decoupled from knee rotation. This enables the knee joint to rotate independently of the motor **2124** and transmission **2132**. The decoupling of the motor and transmission from the knee joint can be achieved in one embodiment by selectively introducing an additional joint to the kinematic chain (which in the embodiment previously described comprises three rotational joints **2120**, **2116**, **2118**; the slider **2112;** and links **2114** and **2110**) for the powered mode operation. This additional joint adds an extra degree of freedom in between the motor rotation and the knee joint rotation, which allows decoupling the rotation of the knee joint **2102** from the displacement of the nut **2128**, and therefore from the rotation of the transmission and the motor **2124**.

[00118] The additional joint can be added at several locations in the kinematic chain comprising the offset slider-crank. In various embodiments, the additional joint may be a prismatic joint or a revolute joint, or other suitable joint.

[00119] In one embodiment (**FIG.22**), a prismatic joint is added by disconnecting the nut **2128** from the supporting link **2130** so that the position of rotating joint **2118** becomes independent of the position of nut **2128**. In this kinematic configuration, when the knee joint **2102** rotates, the connecting link **2110** causes the supporting link **2130** to slide along the pylon **2104** without causing the nut **2128** to move, and therefore without requiring rotation of the motor **2124**.

[00120] In one embodiment (**FIG.23**), the nut **2128** is selectively disconnected from the supporting link **2130** using an asymmetric mechanism that uses a fixed mechanical end-stop **2140** on one side and a movable end-stop **2142** on the other. This switching mechanism

allows movement of the nut **2128** with respect to the supporting link **2130** to be locked as needed to transition between active and passive modes. The fixed mechanical end-stop **2140** prevents the nut **2128** from moving upward with respect to the supporting link **2130**. Guides **2125** prevent rotation of the nut **2128** with respect to the supporting link **2130** as a result of rotation of screw **2126.** The action of the fixed mechanical end-stop **2140** depends on the relative position of the motor shaft **2125** and the knee joint **2102**. For any knee joint position, there is a motor shaft position that causes the nut to contact the fixed mechanical end-stop **2142** on the supporting link **2130**. Therefore, the motor **2124,** which moves the knee joint **2102** in powered mode, can also lock knee joint movement in one direction without the intervention of any other mechanism.

[00121] Locking the knee joint **2102** in the opposite direction (i.e., nut moving downward) requires a movable linkage to constrain the added prismatic joint. In one embodiment (**FIG.23,** side view), the movable linkage can be composed of one or two links **2142** that rotate or displace in the horizontal plane until their moving ends enter into a slot **2141**, which may be machined into the supporting link **2130**. The slot **2141** provides support for the vertical interaction forces between the nut **2128** and the supporting linkage **2130** as required to lock the additional prismatic joint, and to set the knee joint **2102** in powered mode.

[00122] In another embodiment (**FIG.24**), transitions between passive and powered modes may be achieved by adding a revolute joint in between the crank link **2146** and the knee link **2148**, concentric to the rotating knee joint **2150**. This additional degree of freedom allows the knee joint **2102** to rotate independently with respect to the crank link **2146**. As a consequence, the knee joint **2102** also moves independently with respect to all the linkages of the slider-crank mechanism, and no movement is transmitted to the nut **2128**, the screw **2126,** or the motor **2124**.

[00123] Switching between the passive and powered mode requires selective locking/unlocking of the additional revolute joint. In one embodiment, this is can be achieved by using a fixed (immobile) mechanical end-stop **2150** built as part of the knee joint **2102**, and a moveable pin **2154**. The mechanical end-stop **2150** and the movable pin **2154** lock the rotation of the crank link **2146** with respect to the knee link **2148**. Thus they can selectively introduce or remove an additional degree of freedom in the kinematic chain.

[00124] In another embodiment, the additional revolute joint may be locked by using a pawl-ratchet mechanism (**FIG. 26**). The ratchet **2156** is fixed to the crank link **2146**. The pawl **2158** is attached to, and rotates with respect to pylon **2104** through a revolute joint. As it rotates, the pawl **2158** contacts the ratchet **2156**, which locks it in position.

[00125] In yet another embodiment, an additional degree of freedom can be selectively introduced or removed from the kinematic chain by using a singularity (**FIG. 27**). In this embodiment the crank link **2146** and the knee link **2148** are connected through an additional revolute joint **2160**. The revolute joint **2160** is located half-way in between the knee joint **2150** and the revolute joint **2116** that attaches the crank link **2146** to the connecting link **2110**, such that the distance from revolute joint **2150** to revolute joint **2160** equals the distance from revolute joint **2160** and revolute joint **2118**.

[00126] When revolute joint **2160** is locked, the assistive device is in powered mode (the knee kinematics is an offset slider crank mechanism). When revolute joint **2160** is unlocked, the crank link **2146** can rotate with respect to revolute joint **2160** and fold on the knee link **2148** so that rotating joint **2150** and revolute joint **2116** align. The rotation of the crank link **2146** can be generated by the motor **2124** moving the nut **2128** and the connecting link **2110**. The folding of the crank link **2146** and the consequent alignment of revolute joint **2116** on rotating joint **2150** causes a degeneration of the kinematic chain (singularity). Due to this kinematic degeneration, the knee link **2148** can rotate without causing the displacement of the connecting link **2110**. Therefore, in this "folded" configuration, the knee joint **2102** can rotate independently with respect to the motor **2124**. In this embodiment, not only the motor **2124** and transmission but also the crank link **2146**, the slider **2112**, and the connecting link **2110** do not move in the passive mode.

[00127] In another embodiment, an assistive device may comprise an orthosis. For example, the orthosis **1500** may be a hybrid powered orthosis for motion assistance. In one embodiment, shown in **FIG. 28**, the orthosis **1500** may have components similar to the assistive device **1000** shown in **FIG. 3**. The orthosis **1500** may be arranged in parallel to a patient's lower limb, with upper and lower parts **1510** and **1520** interacting one with the user's thigh and the other with the shank (to which anatomical segment where to attach the most cumbersome part **1520** can be chosen basing on the specific addressed user), and with

the axis of the joint **1550** substantially aligned with the user's knee joint. Braces **1530** and **1540** may connect the orthosis **1500** to the patient's limb. In such configuration, using the same principles described above, the orthosis **1500** may be used an active power source for motion assistance, or as a passive orthosis. Additionally, in other embodiments, the system may be employed on an exoskeleton, resulting in an exoskeleton with smaller motors and batteries than those employed in always active powered exoskeletons. Conversely, when in passive mode the system will behave as a passive orthosis for enhanced stability. It should be understood that the orthosis **1500** shown in **FIG. 28** is only one of many different types of orthoses that may utilize the basic principles described herein. Additionally, as a generalization, the same principles may be used by one of ordinary skill in the art to develop other wearable powered orthoses, for assistance orthoses at different anatomical joints like the hip joint (with a brace at the trunk and another brace at the thigh, the joint of the orthosis aligned with the hip flexion/extension axis), the ankle joint (with a brace at the shank and another brace at the foot, the joint of the orthosis aligned with the ankle dorsi/plantar flexion axis), or an upper-limb joint, such as the elbow joint.

[00128] Although the described embodiments of the assistive device and their advantages have been described in detail, a person of ordinary skill in the art would understand that various changes, substitutions, and alterations can be made without departing from the spirit and scope of the claimed subject matter as defined by the appended claims.

CLAIMS:

What is claimed is:

1. An assistive device for replacing or augmenting the limb of an individual, comprising a joint and a powered system;

the powered system having:

a first configuration in which the powered system rotates the joint by applying power to the joint; and

a second configuration that allows for rotation of the joint without actuation of the powered system.

2. The assistive device of claim 1, wherein the powered system is in the first configuration when the assistive device is performing a powered task and the powered system is in the second configuration when the assistive device is performing a passive task.

3. The assistive device of claim 1, further comprising a damper for the joint.

4. The assistive device of claim 1,

wherein the powered system comprises an actuator linkage;

the actuator linkage having a link portion that is movable to a first position coaxial to the joint or to a second position at a distance from the joint;

the actuator linkage applying power to the joint when the link portion is positioned at the second position.

5. The assistive device of claim 4, further comprising an adjustable linkage extending from the joint to a predetermined end position; the link portion being movable along the adjustable linkage between the first position and the second position.

6. The assistive device of claim 4, wherein the actuator linkage comprises a linear actuator and a motor.

7. The assistive device of claim 6, wherein the linear actuator is positioned so that the actuating axis of the linear actuator is parallel to the actuating axis of the motor.

8. The assistive device of claim 6, wherein the actuator linkage further comprises a connecting rod with a first end connected to the linear actuator and a second end being the link portion.

9. The assistive device of claim 6, wherein an outer face of the motor is in contact with a portion of the assistive device to dissipate heat generated by the motor.

10. The assistive device of claim 6, where the link portion further movable to one of a plurality of positions between the first position and the second position.

11. The assistive device of claims 1, 2, 3, 4, or 5, wherein the powered system comprises a linear actuator comprising an actuator screw.

12. The assistive device of claims 1, 2, 3, 4, or 5, wherein the powered system comprises a motor having an outer face in contact with a portion of the assistive device.

13. The assistive device of claims 1, 2, 3, 4, or 5, wherein the assistive device is a prosthesis.

14. The assistive device of claims 1, 2, 3, 4, or 5, wherein the assistive device is an orthosis.

15. The assistive device of claims 1, 2, 3, 4, or 5, wherein the assistive device is an upper limb orthosis.

16. The assistive device of claims 1, 2, 3, 4, or 5, wherein the assistive device is a lower limb orthosis.

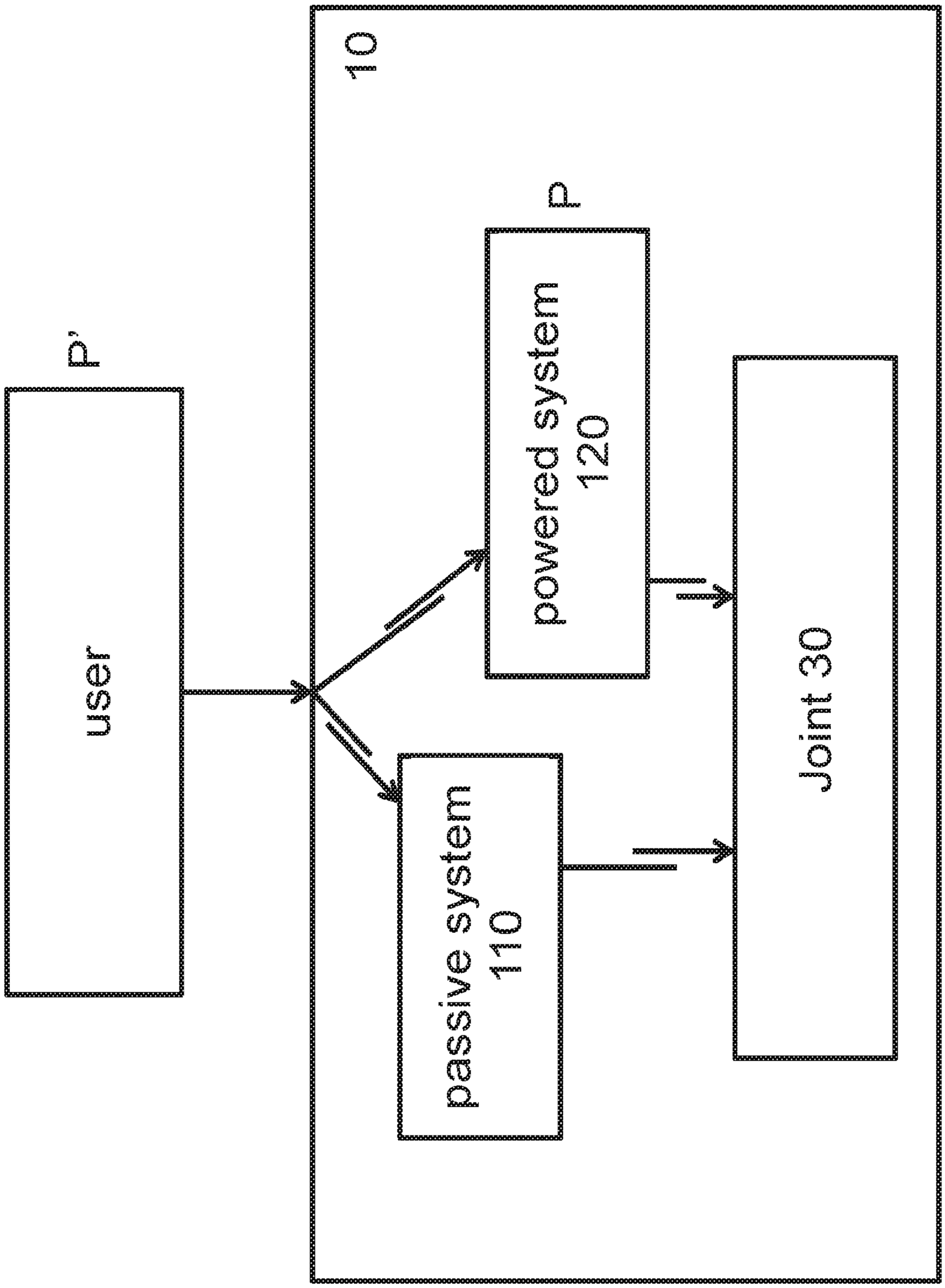

FIG. 1

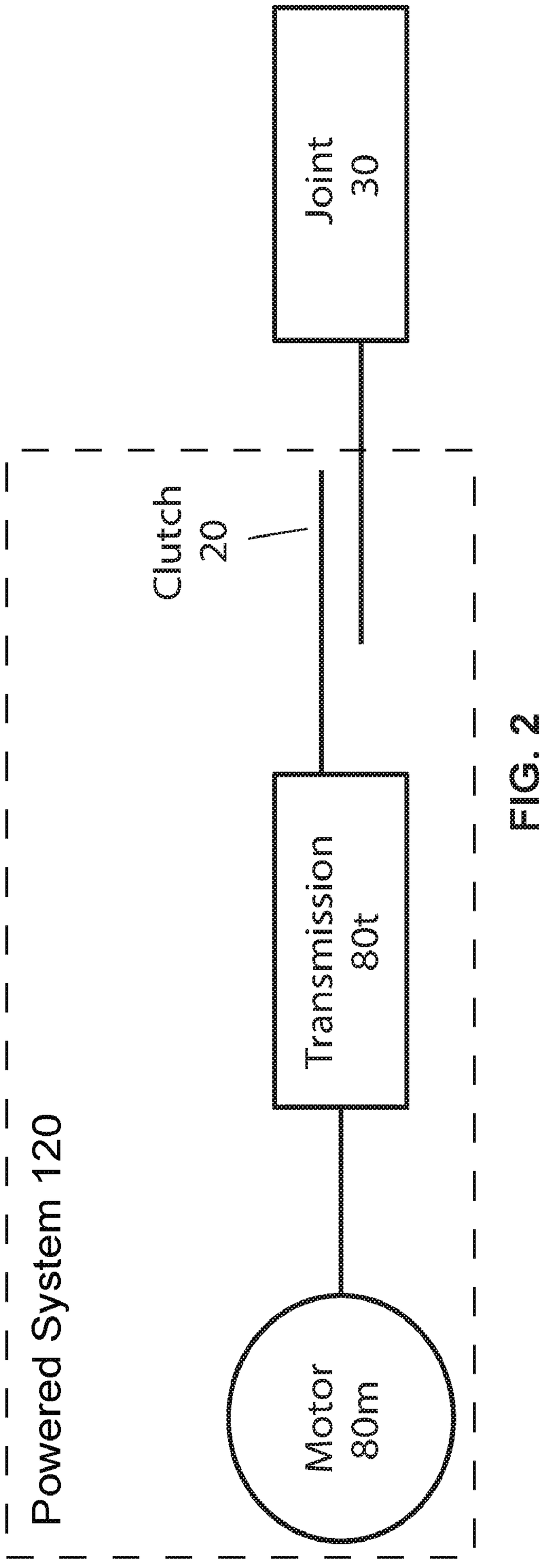
Joint
30
Clutch
20
Powered System 120
Transmission
80t
Motor
80m

FIG. 2

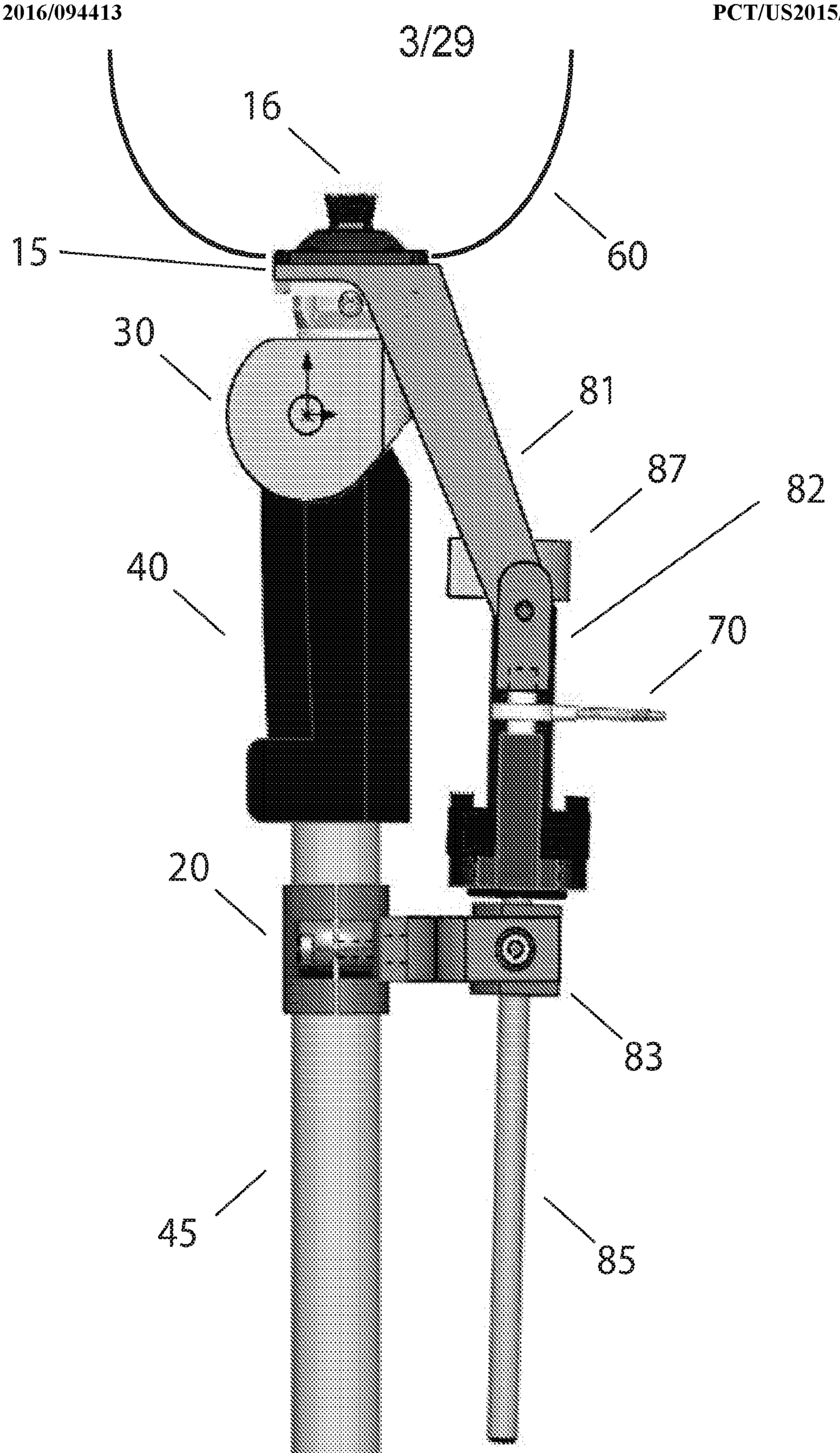

FIG. 3

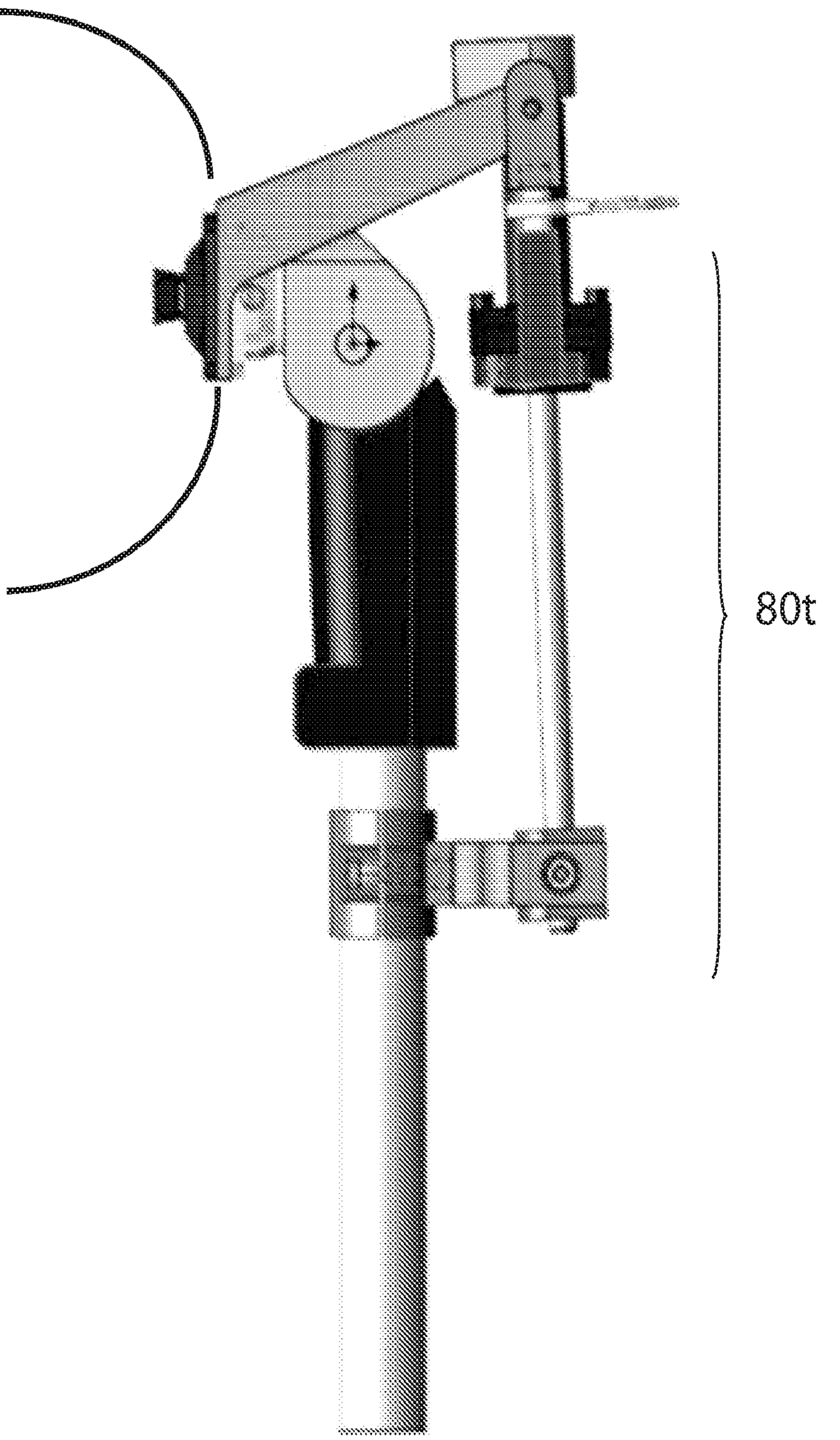

FIG. 4

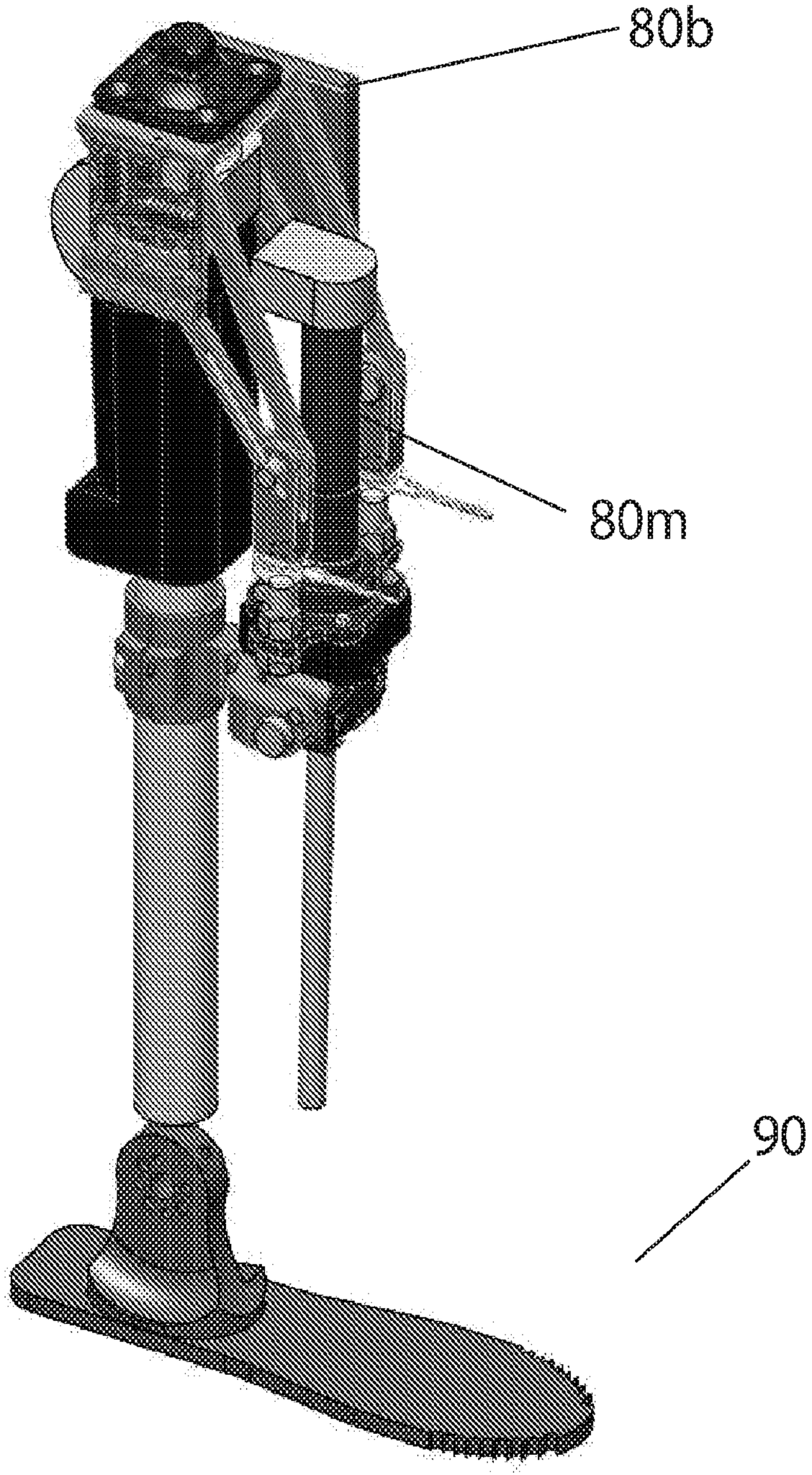

FIG. 5

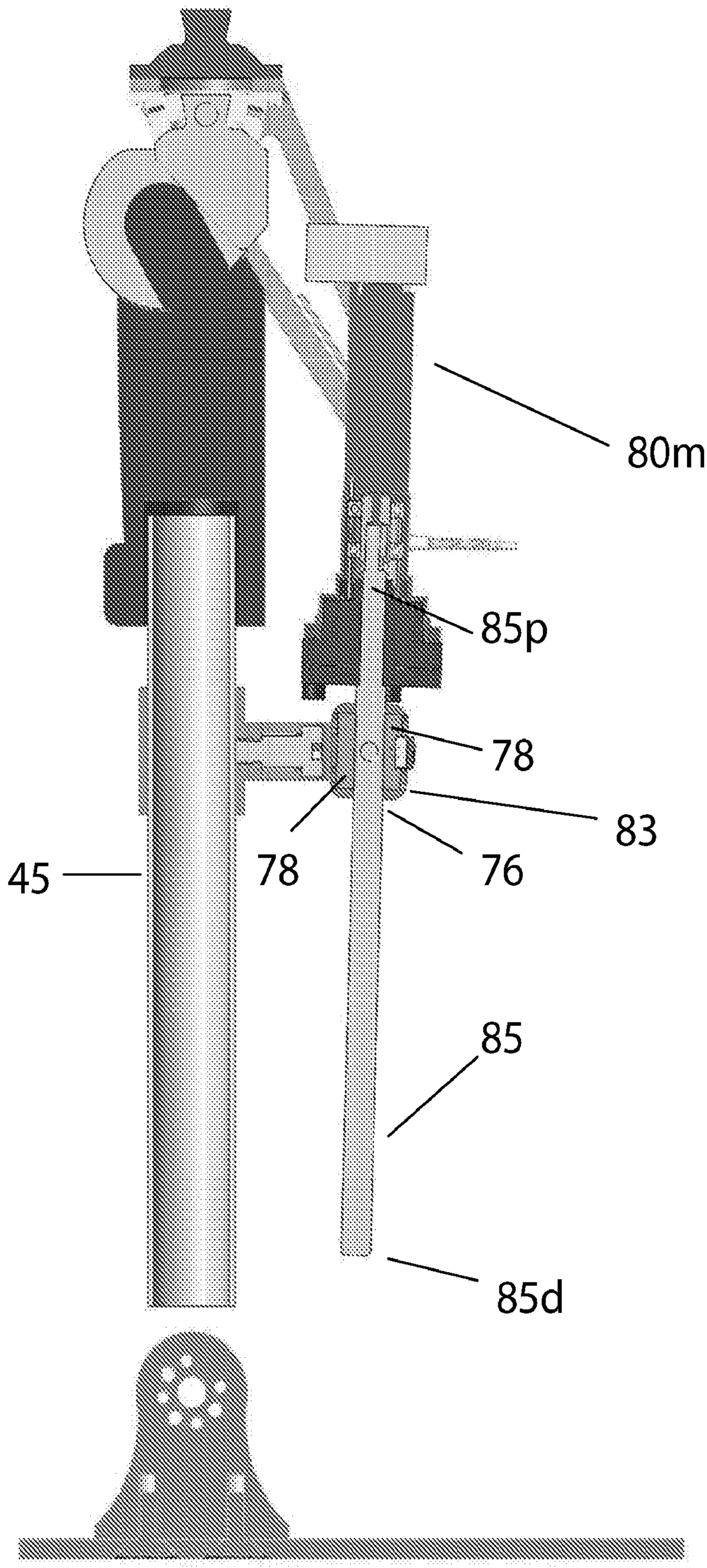

FIG. 6

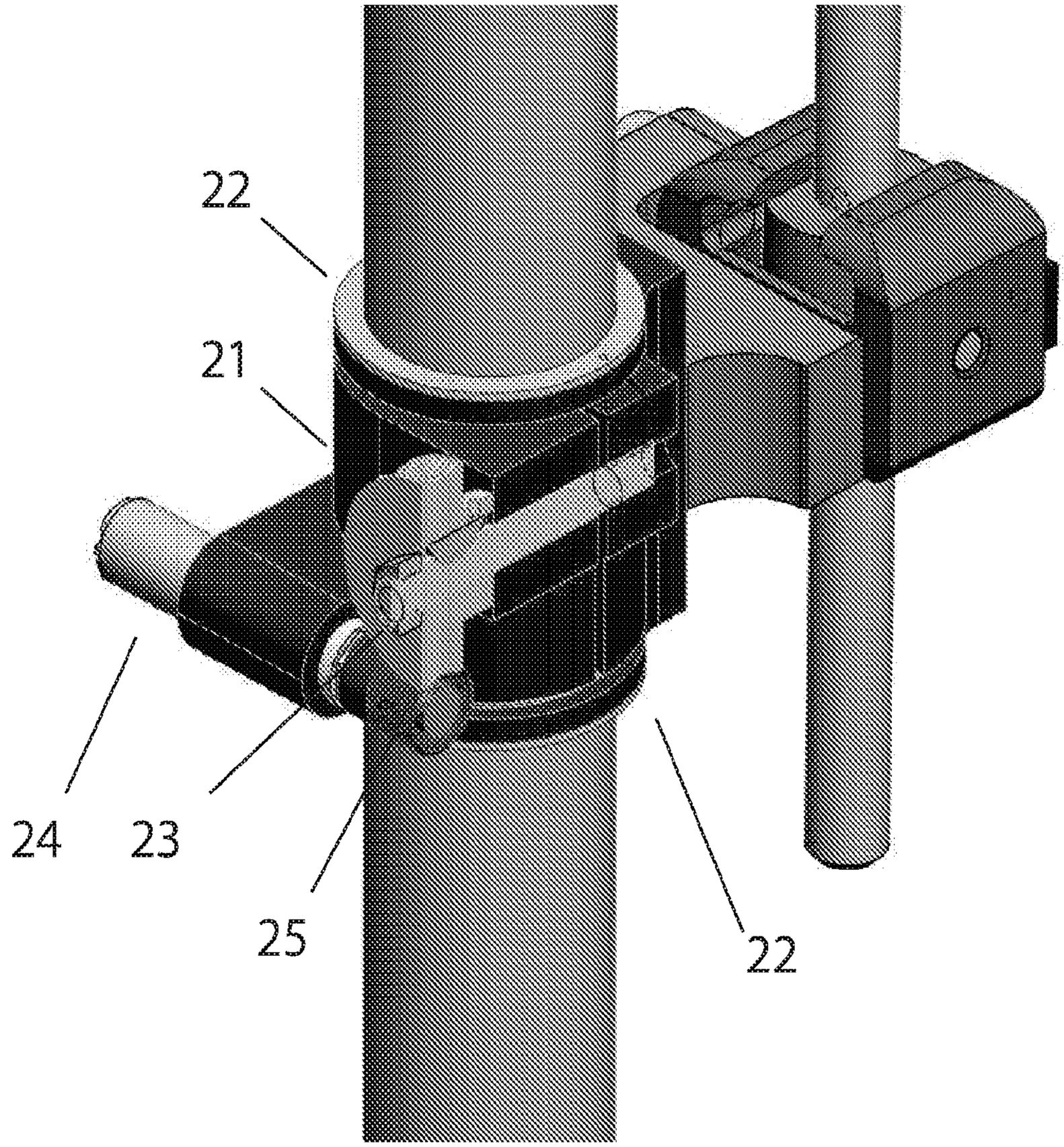

FIG. 7

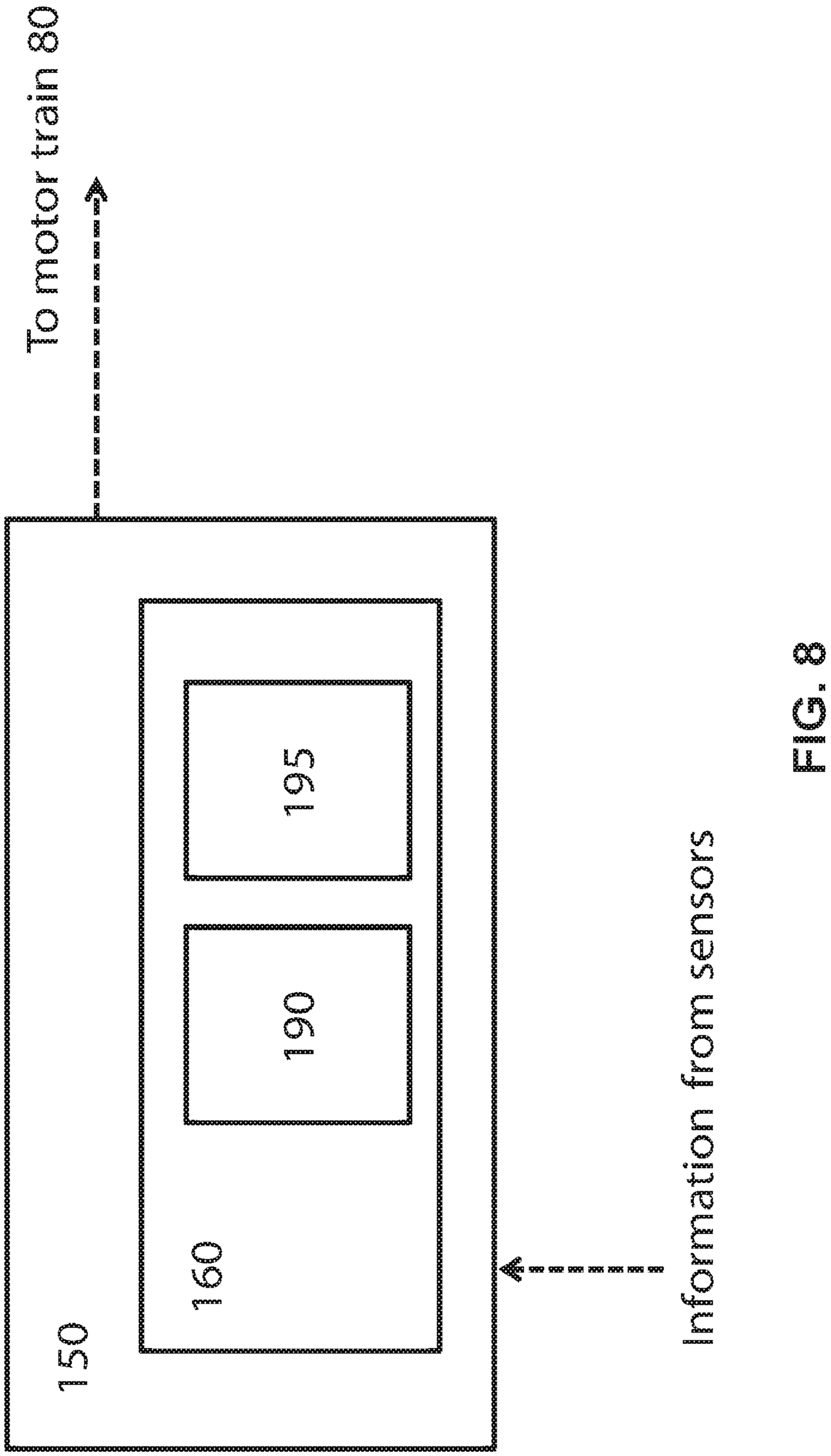

FIG. 8

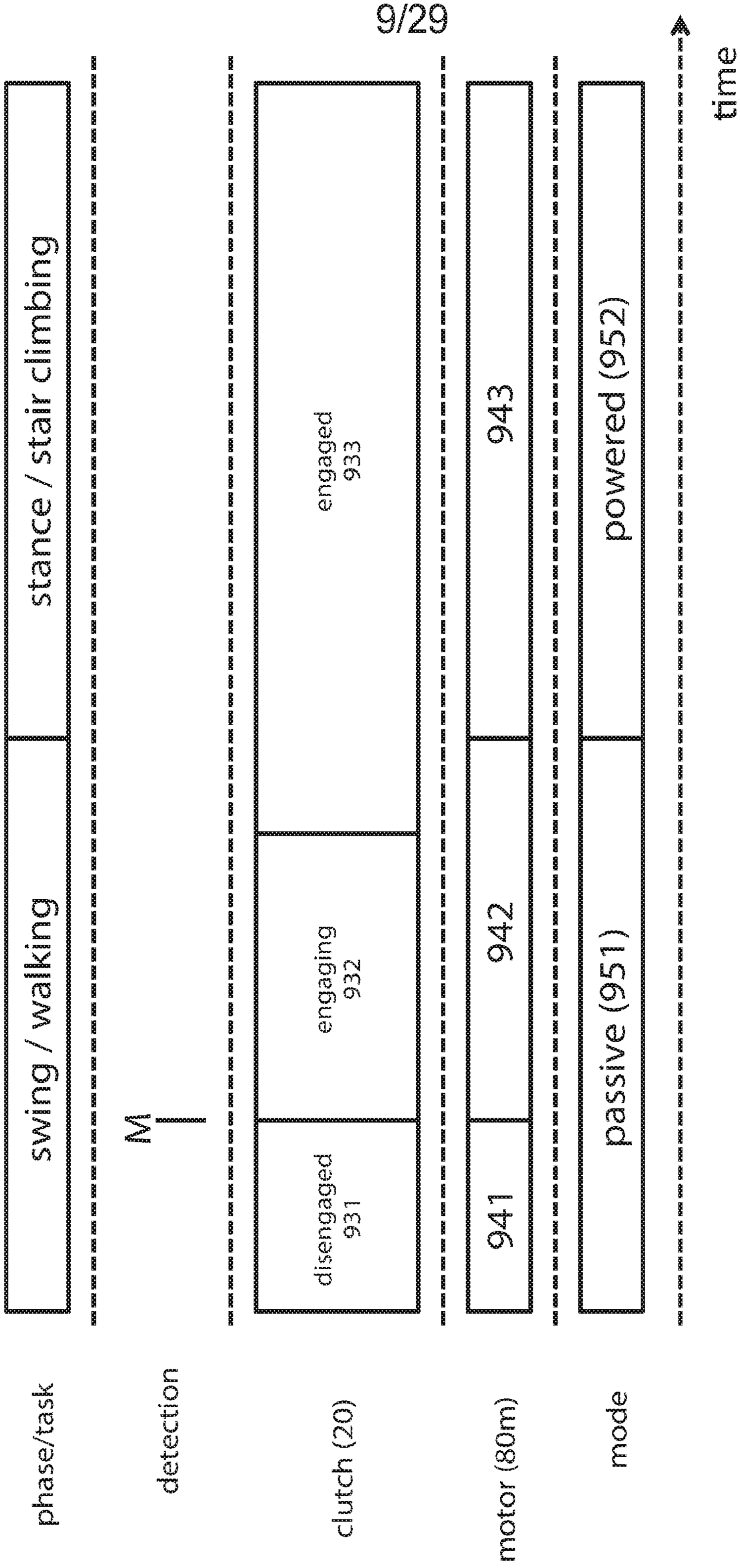
time
stance / stair climbing
swing / walking
M
disengaged
931
engaging
932
engaged
933
941
942
943
passive (951)
powered (952)
phase/task
detection
clutch (20)
motor (80m)
mode

FIG. 9

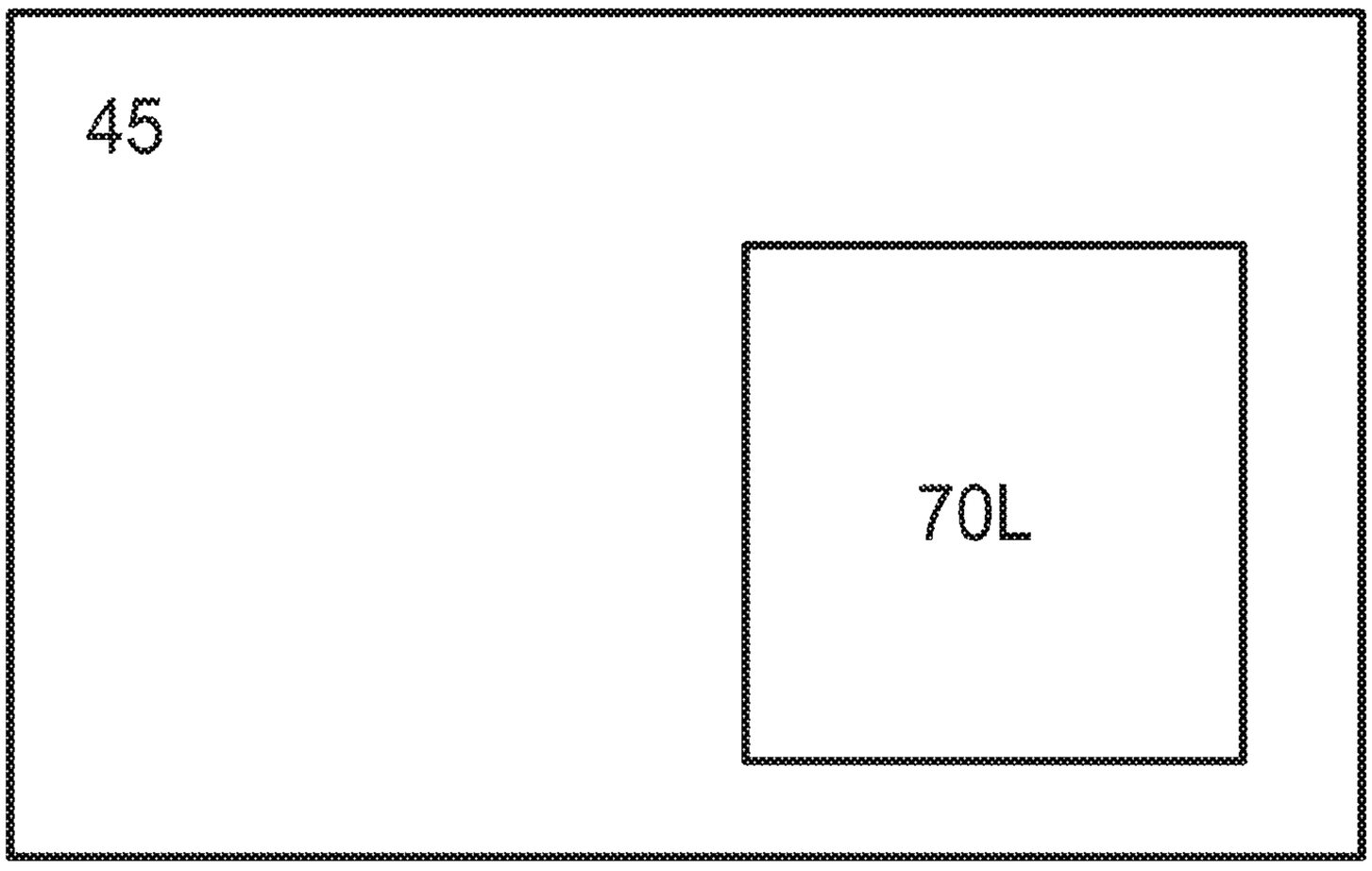

FIG. 10A

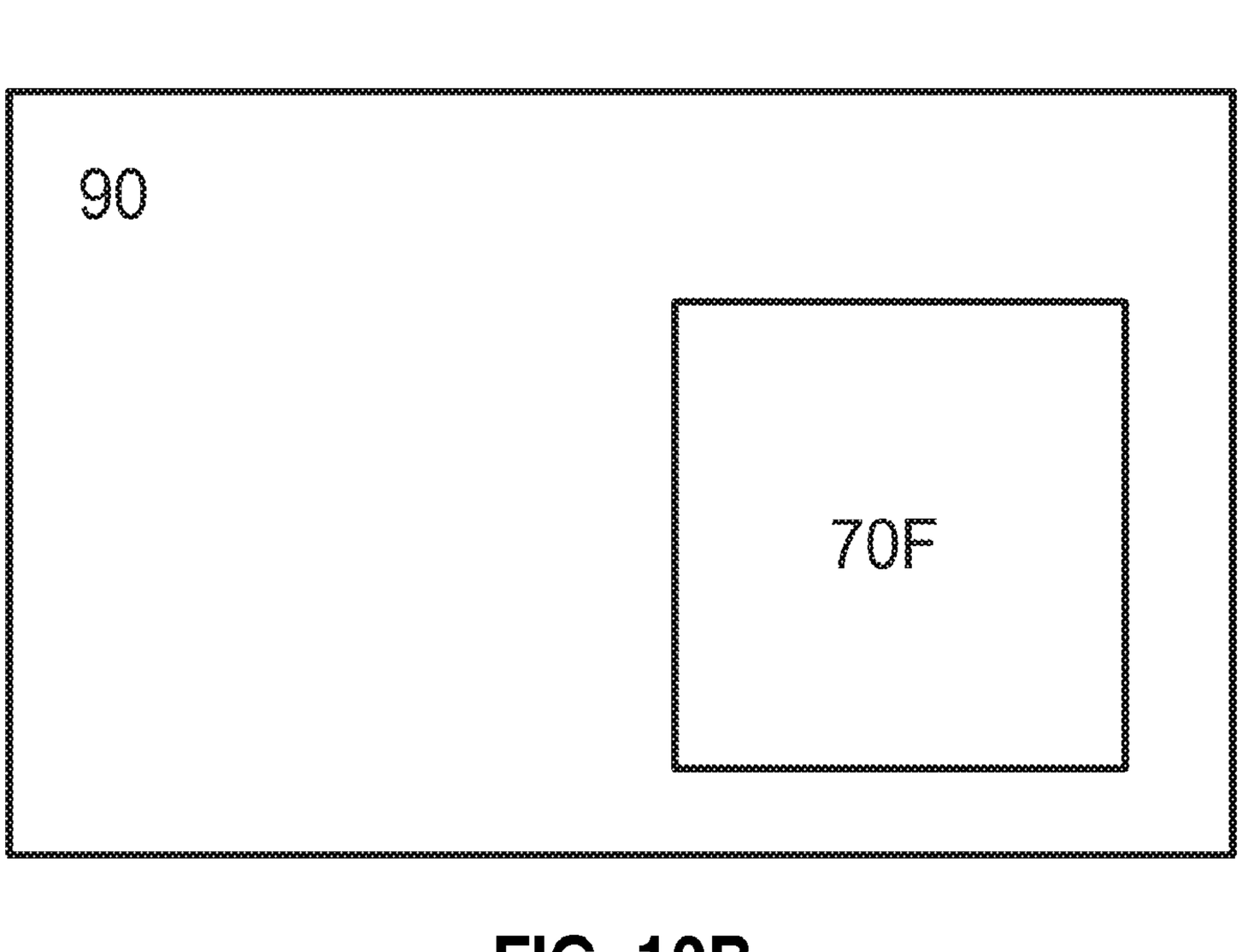

FIG. 10B

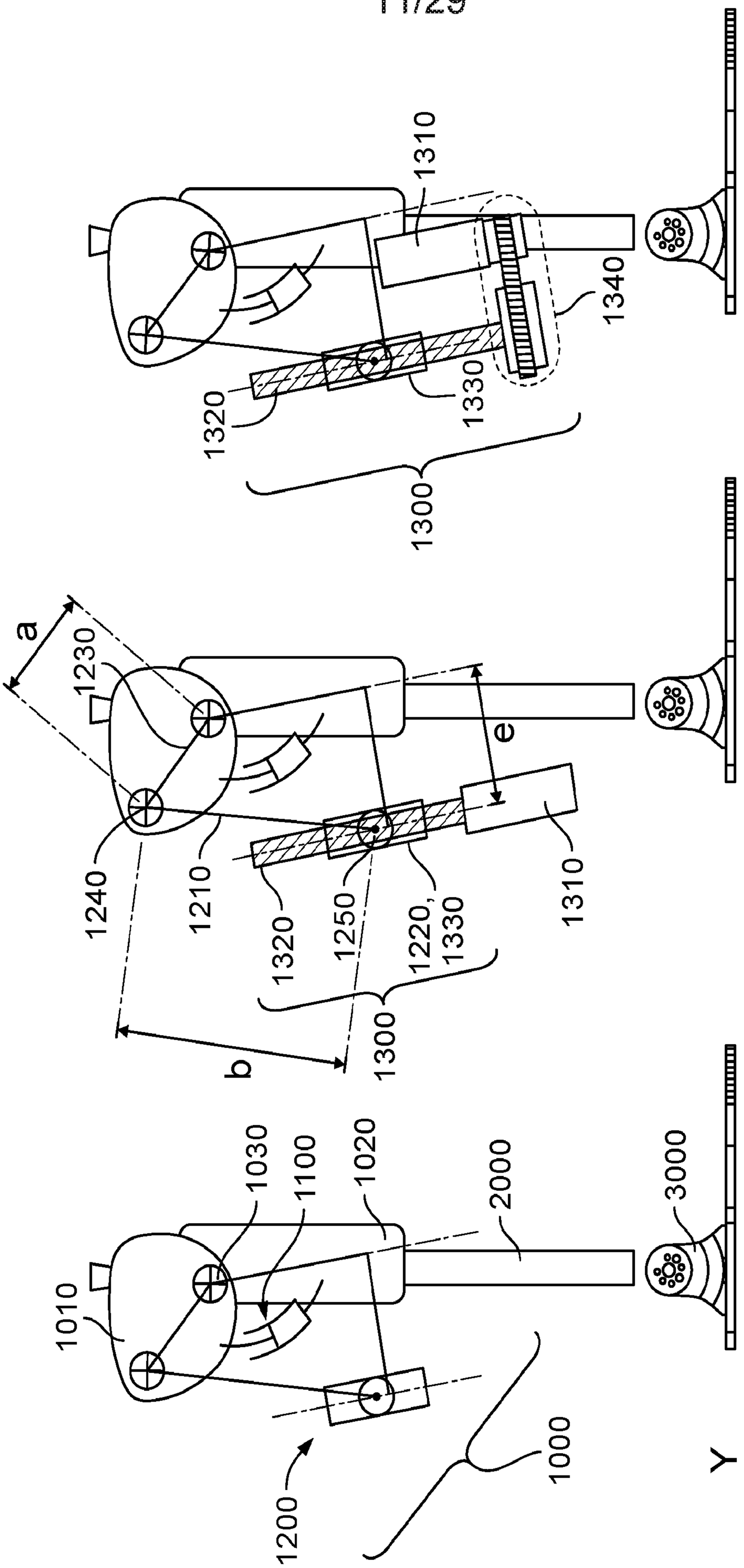

FIG. 11C

FIG. 11B

FIG. 11A

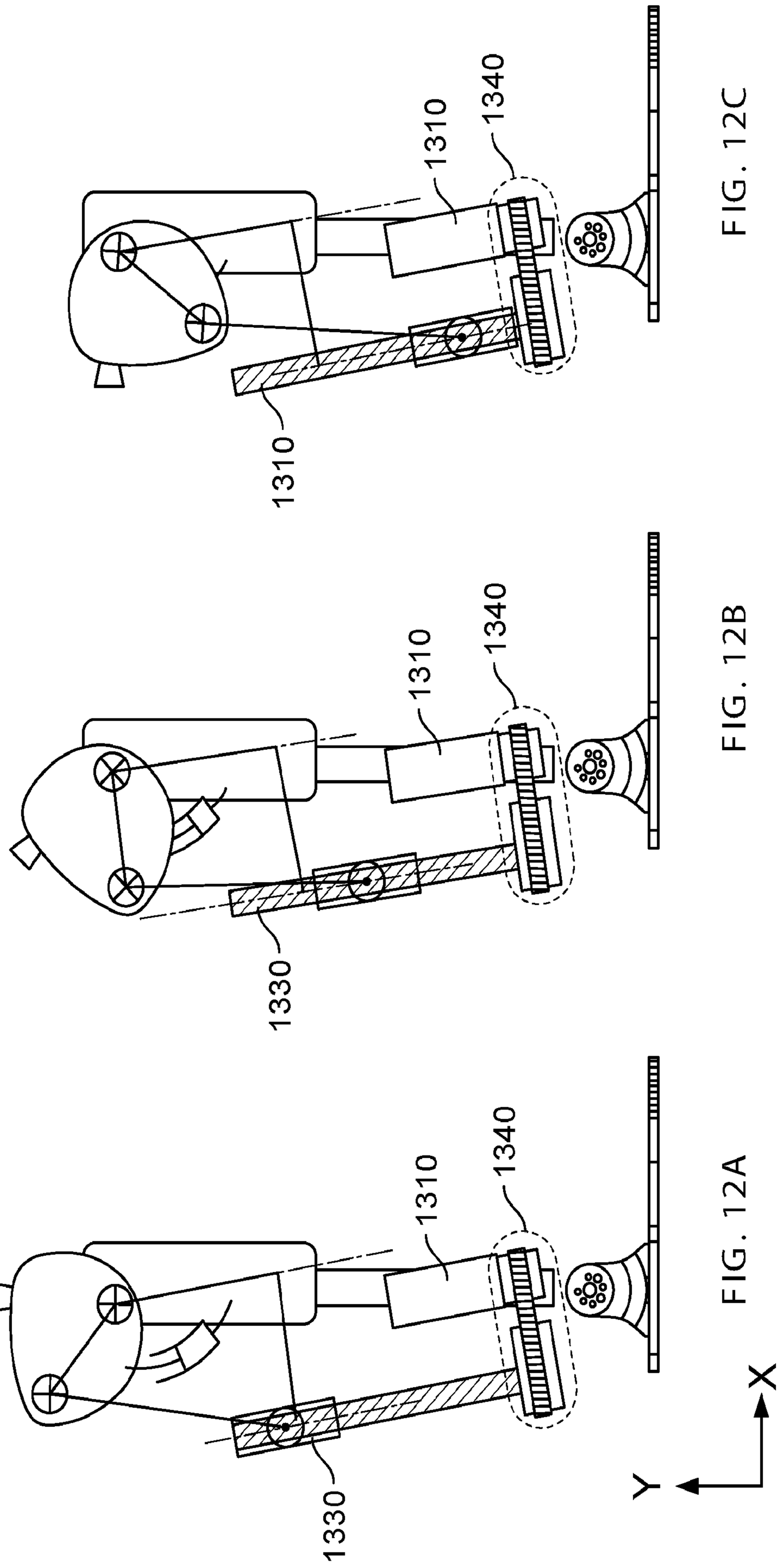

FIG. 12C

FIG. 12B

FIG. 12A

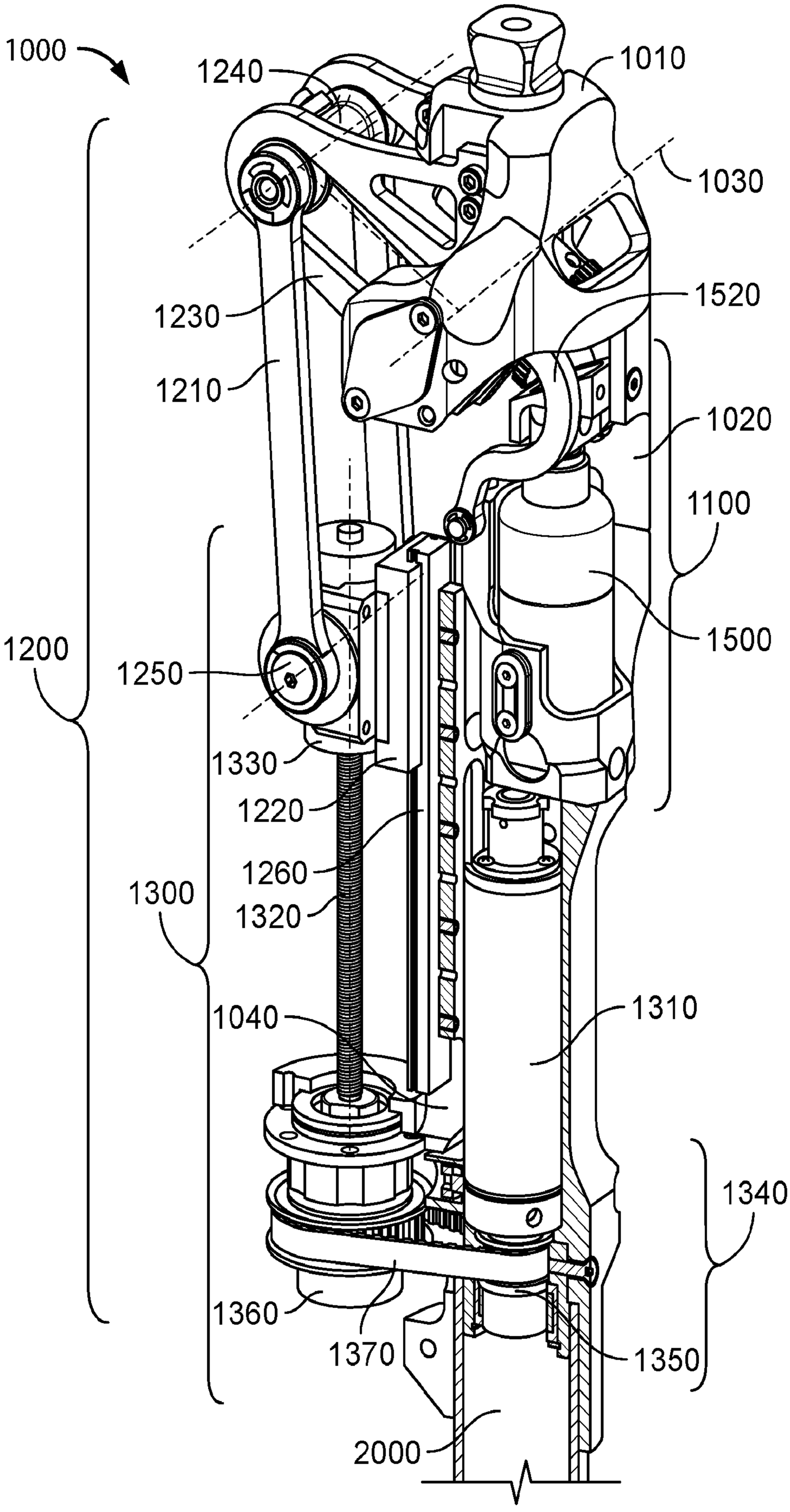
1000
1240
1010
1030
1230
1520
1210
1020
1100
1200
1250
1500
1330
1220
1260
1300
1320
1040
1310
1340
1360
1370
1350
2000

FIG. 13

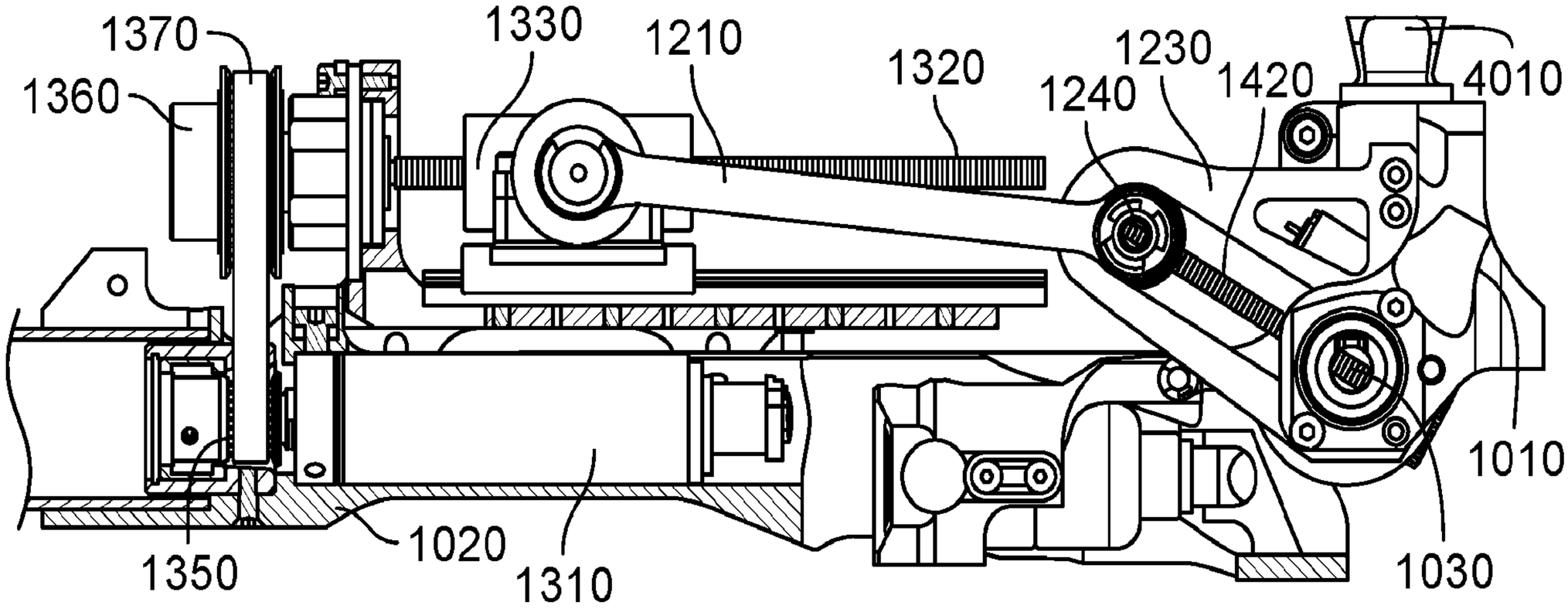

FIG. 14A

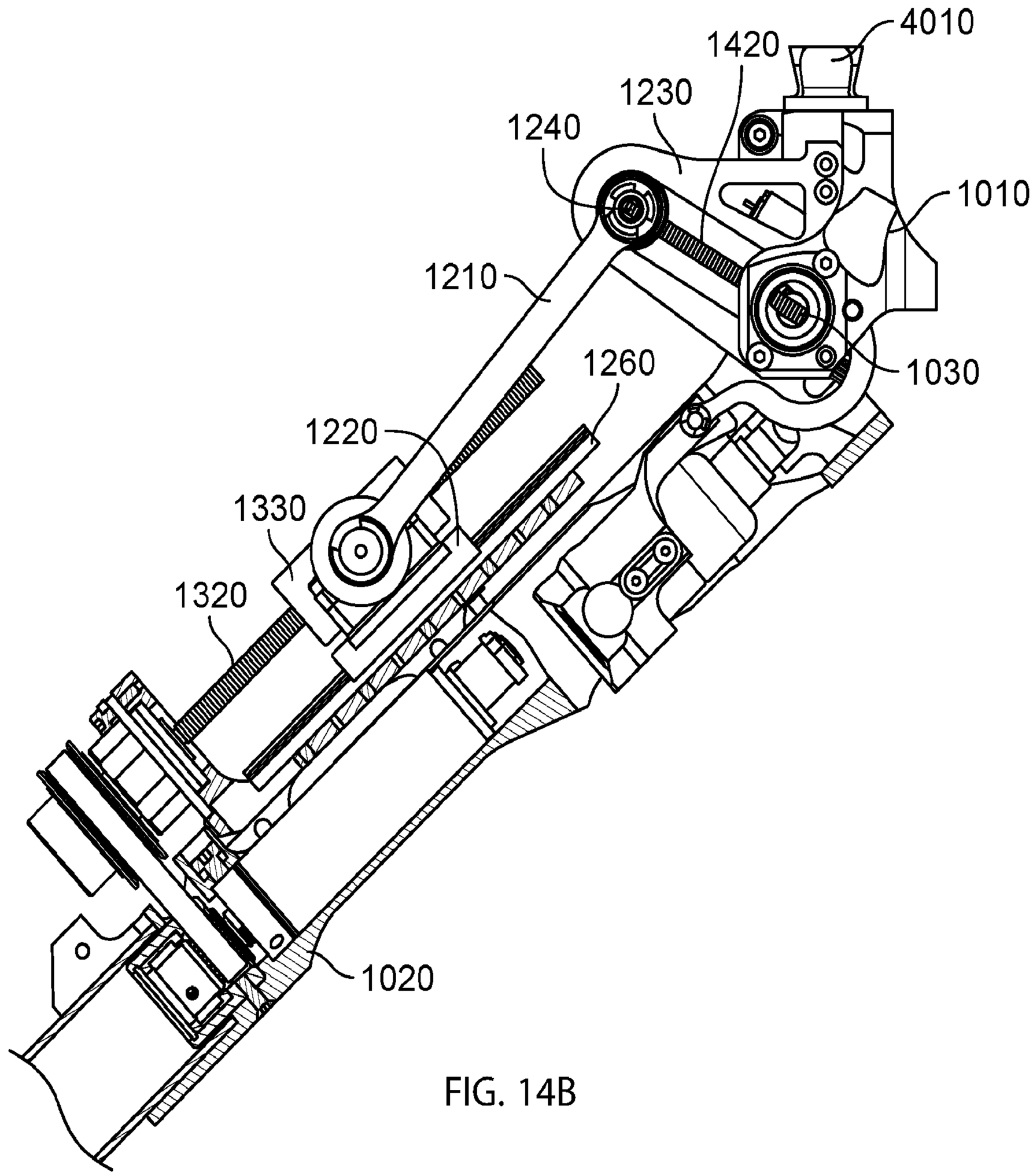

FIG. 14B

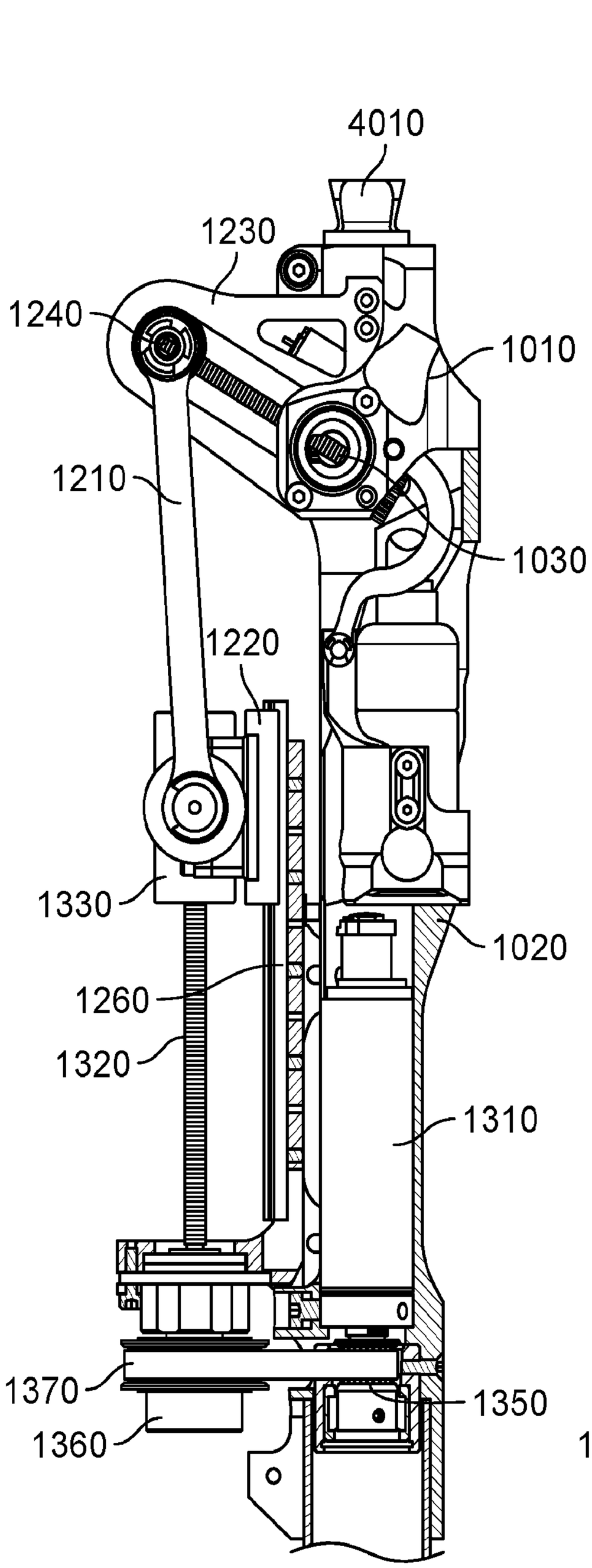

FIG. 14C

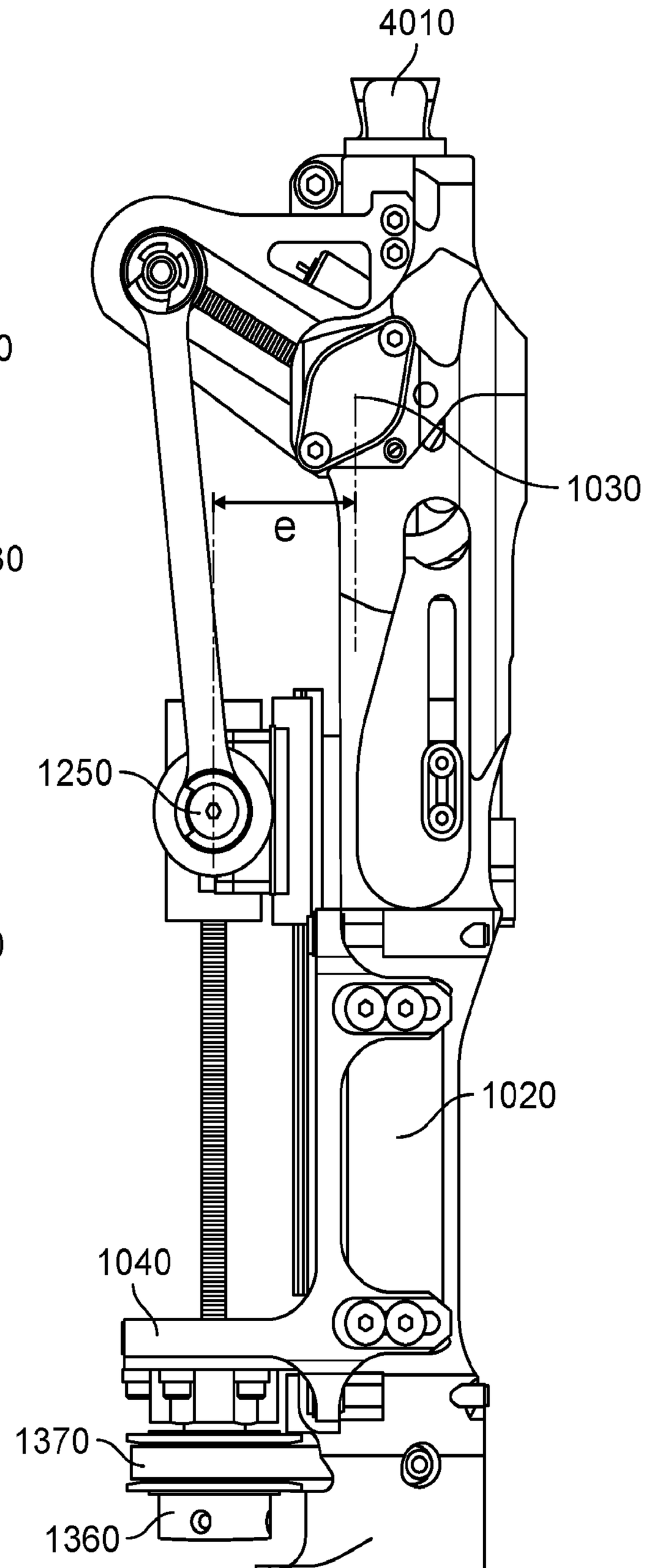

FIG. 15

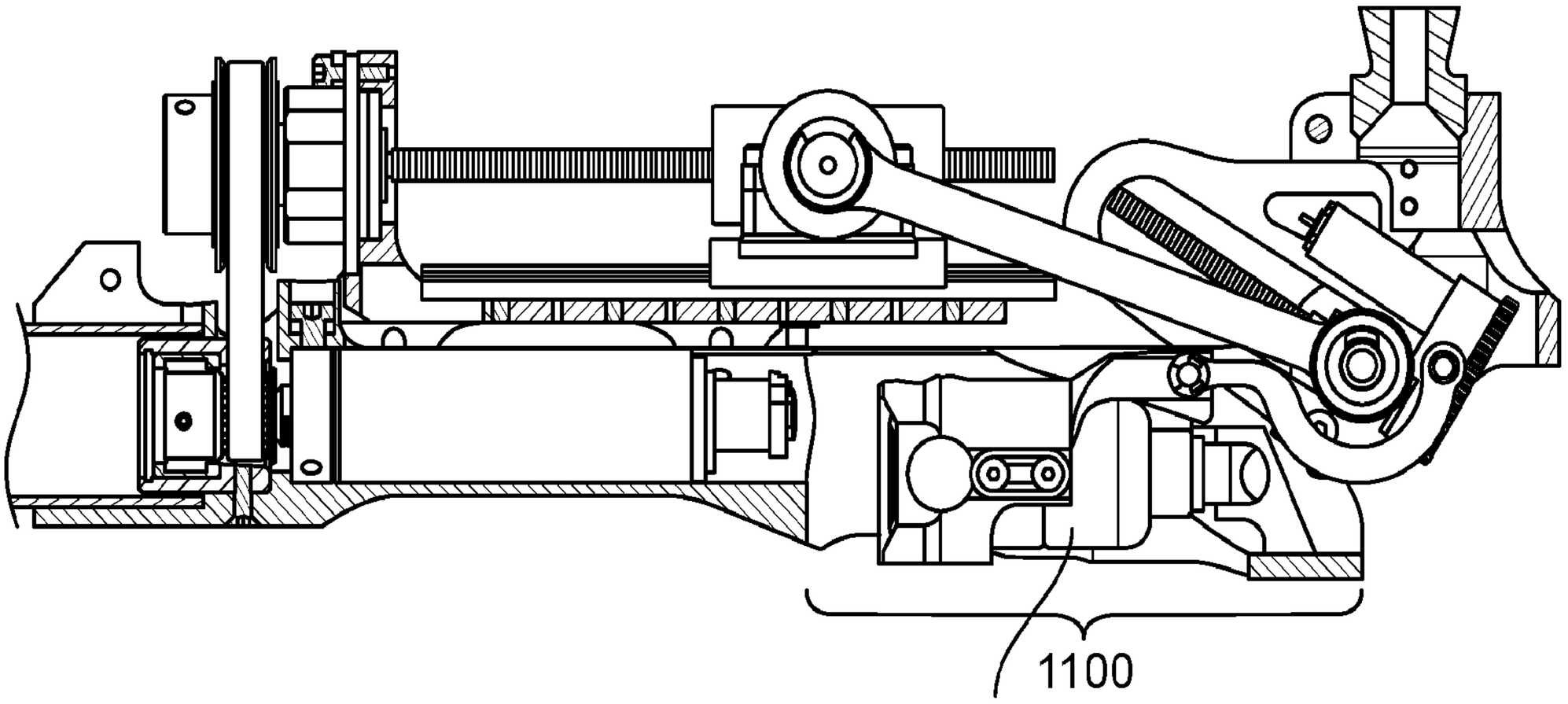

FIG. 16A

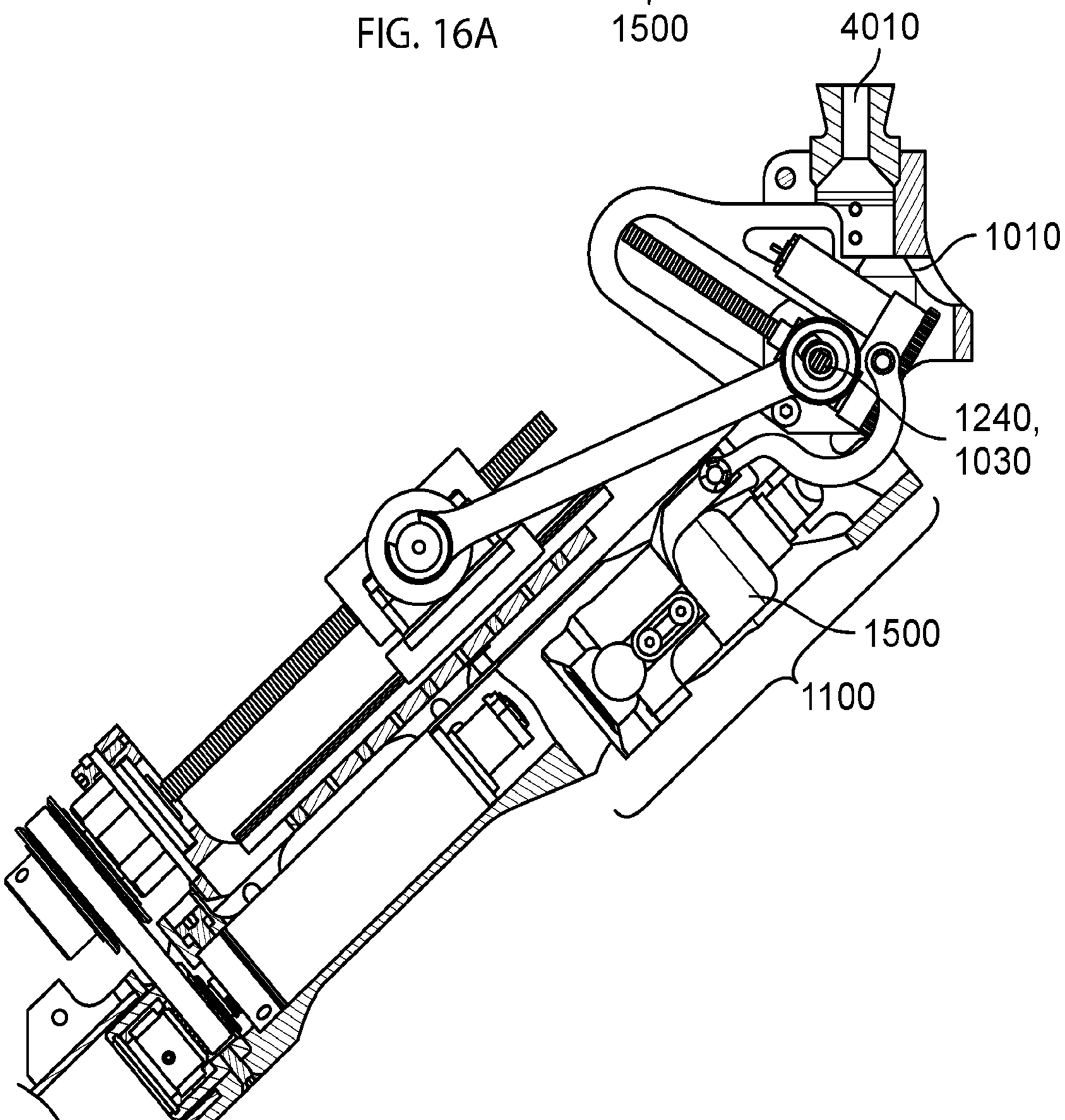

FIG. 16B

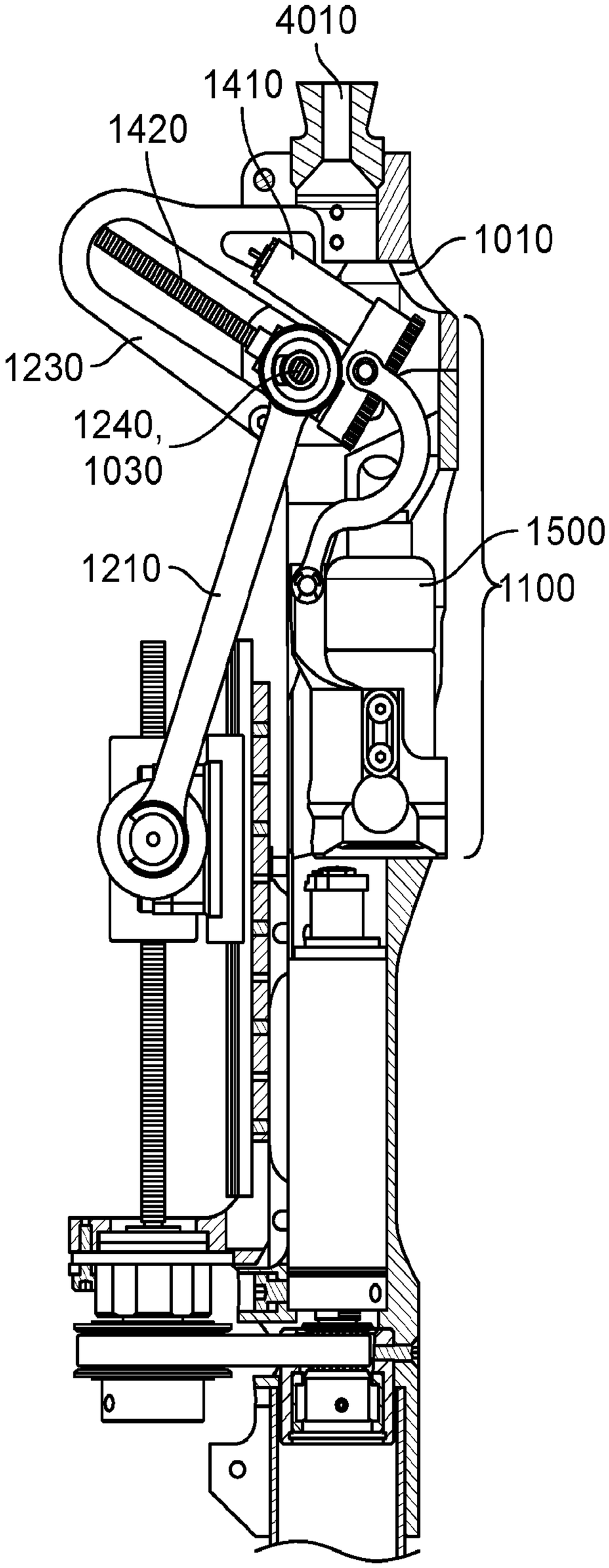

FIG. 16C

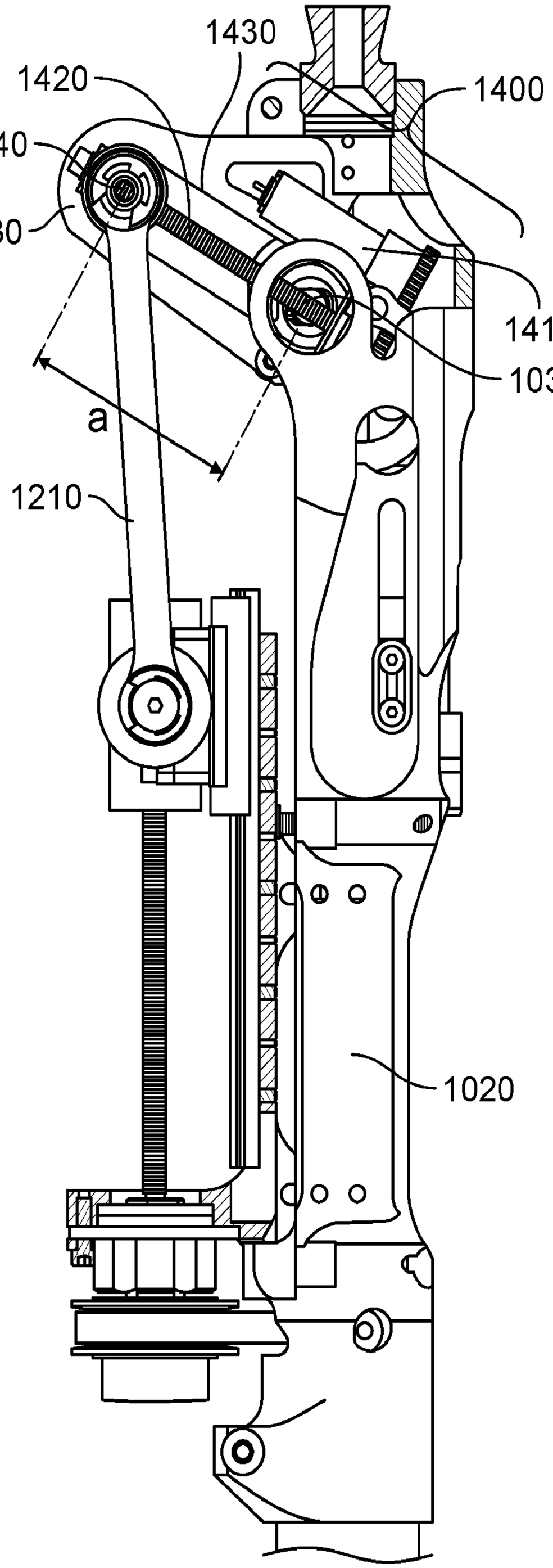

FIG. 17A

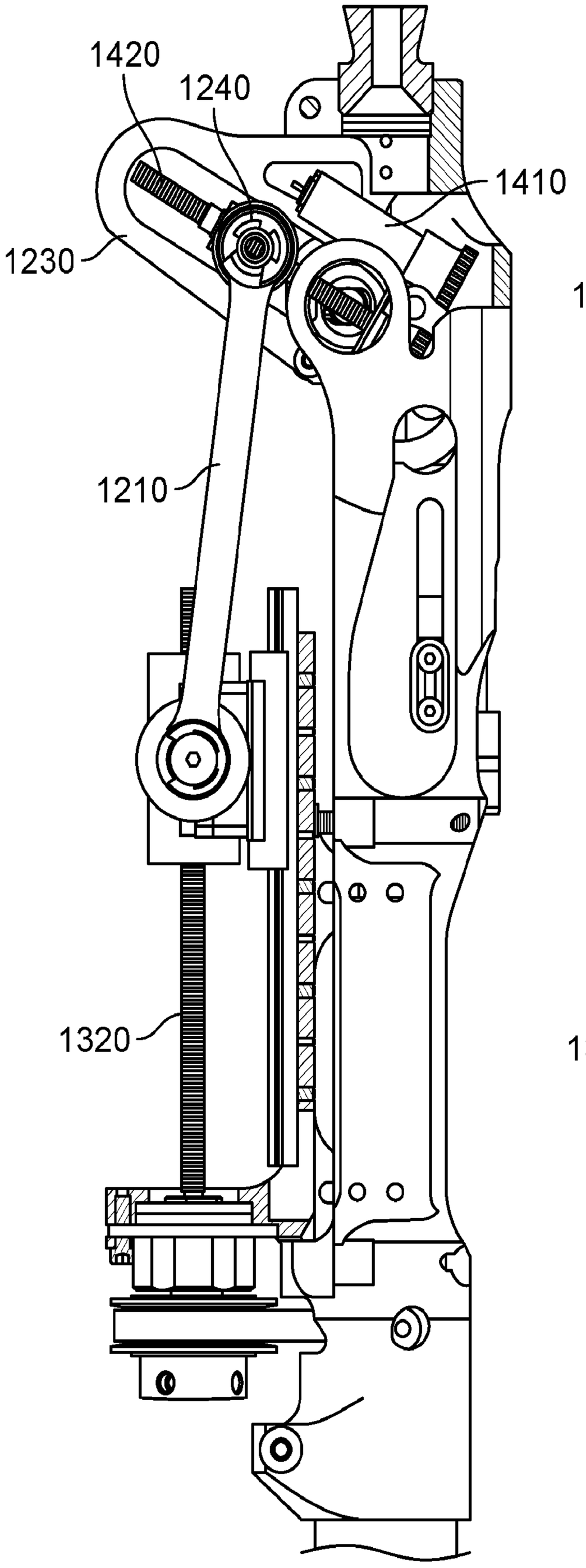

FIG. 17B

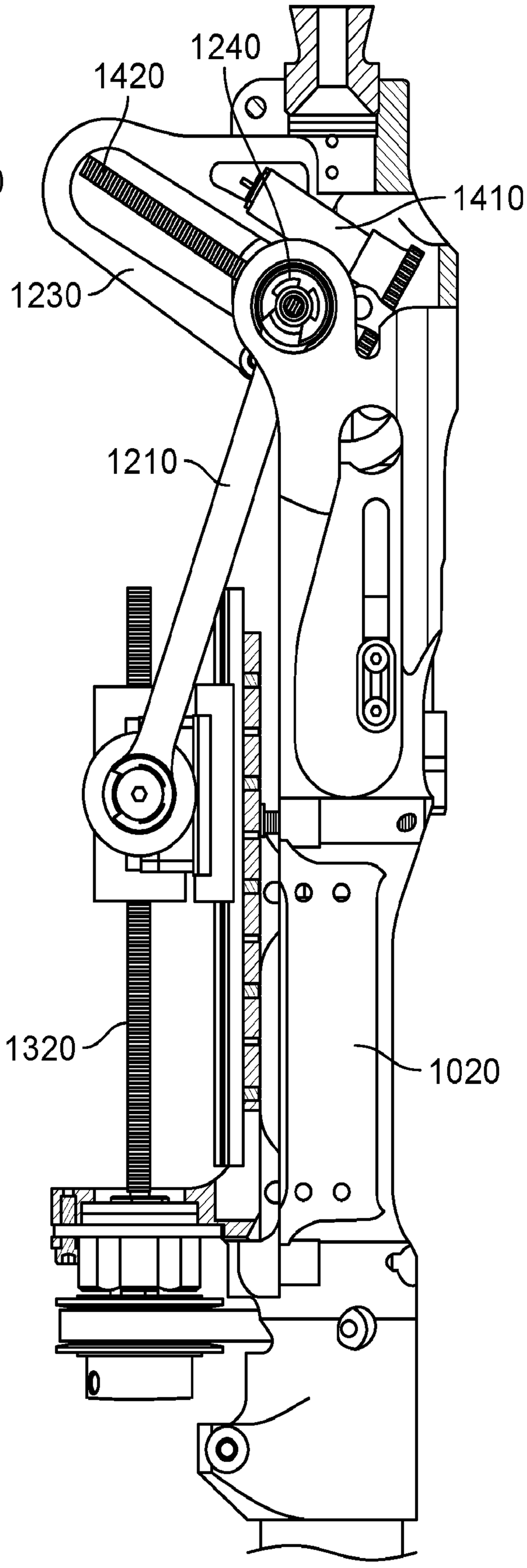

FIG. 17C

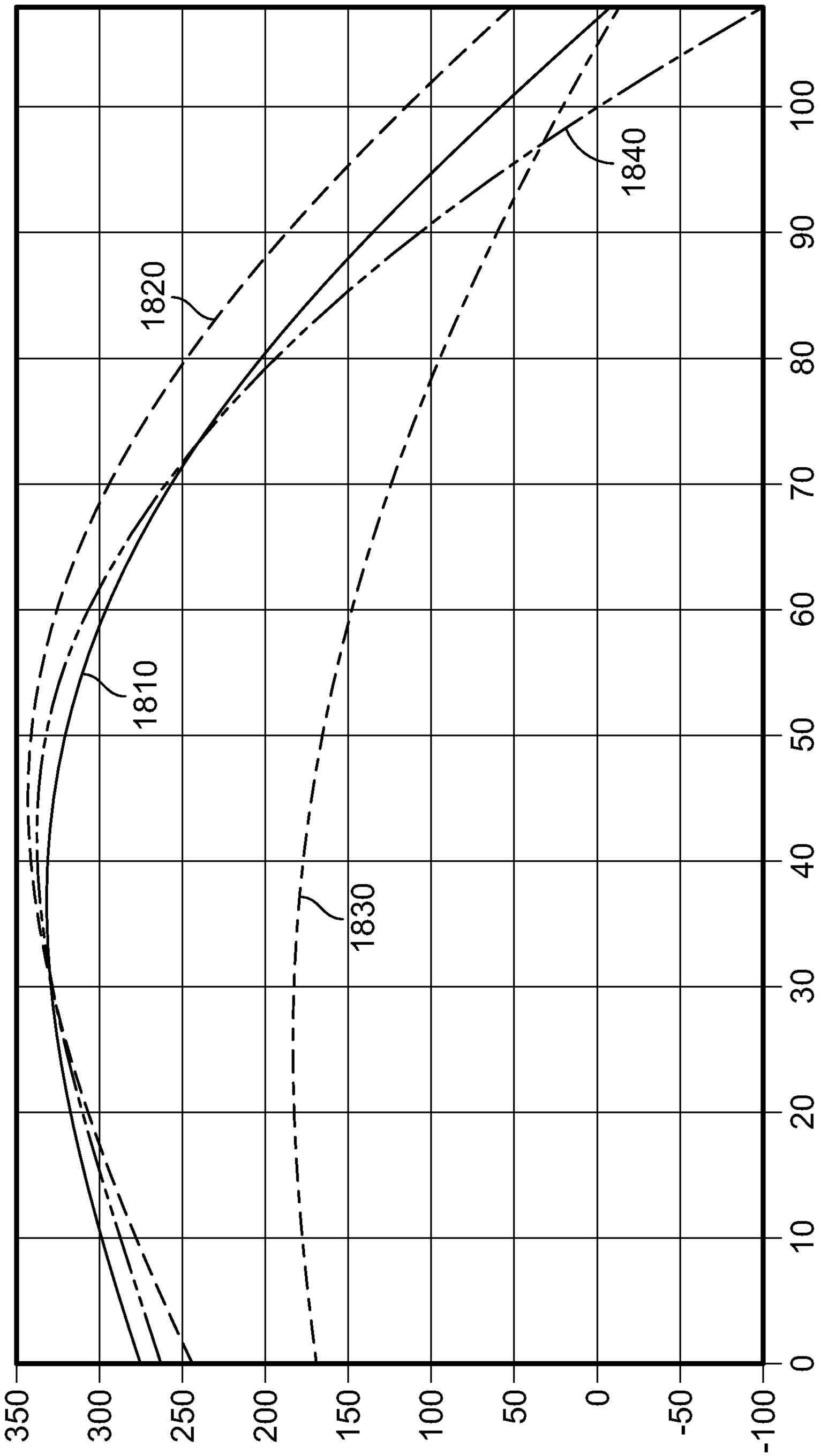
1820
1840
1810
1830
Total TR [1]
350
300
250
200
150
100
50
0
-50
-100
Knee angle [deg]
0
10
20
30
40
50
60
70
80
90
100

FIG. 18A

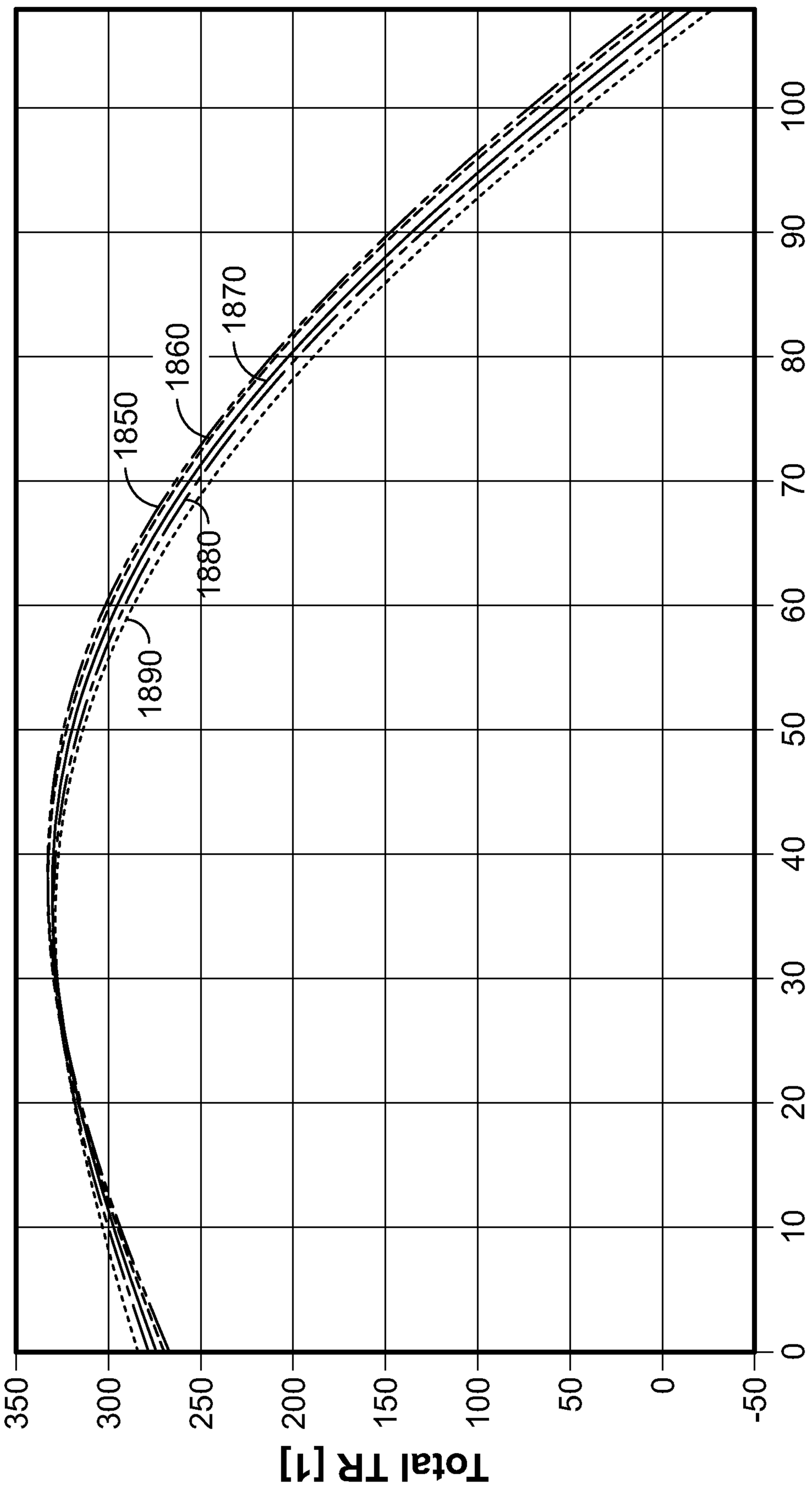
1850
1860
1870
1880
1890
Knee angle [deg]
Total TR [1]
0
10
20
30
40
50
60
70
80
90
100
350
300
250
200
150
100
50
0
-50

FIG. 18B

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RECTIFIED (RULE 91) - ISA/US

Active mode - Kinematic configuration- **Offset Slider Crank**

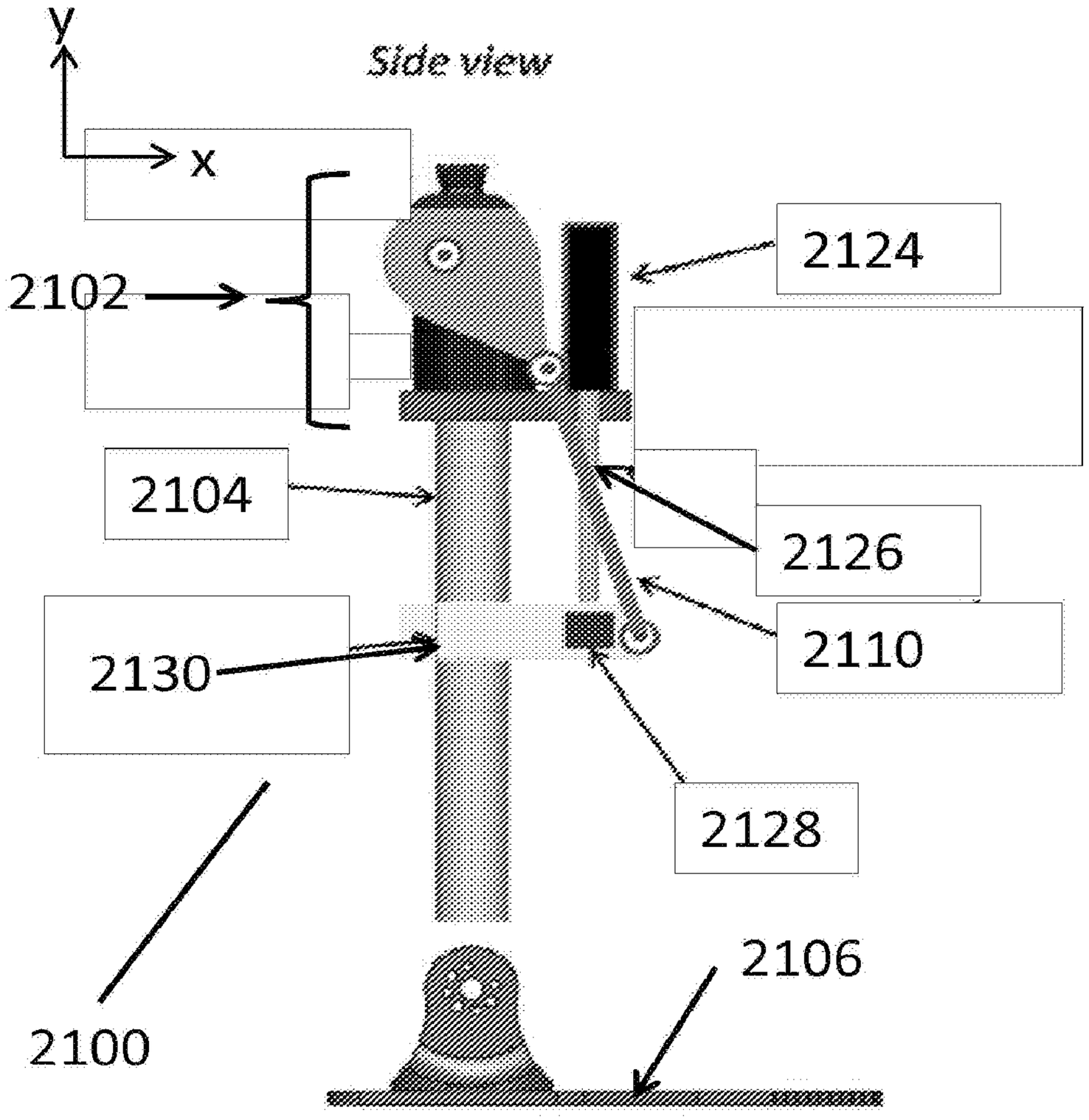

FIG. 19A

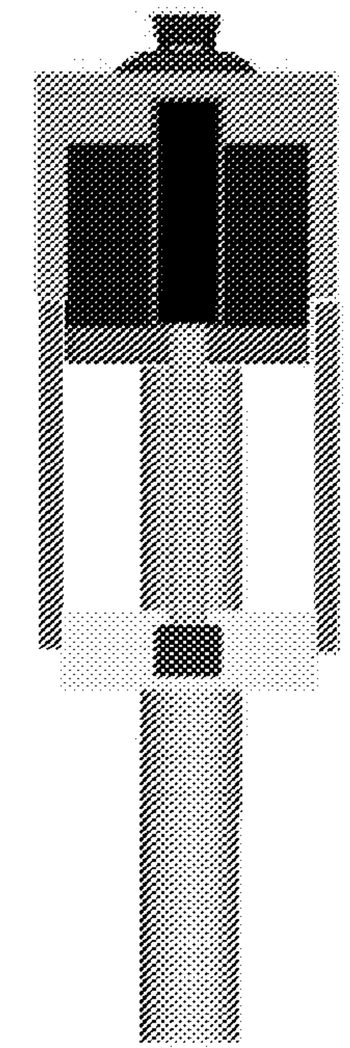

FIG. 19B

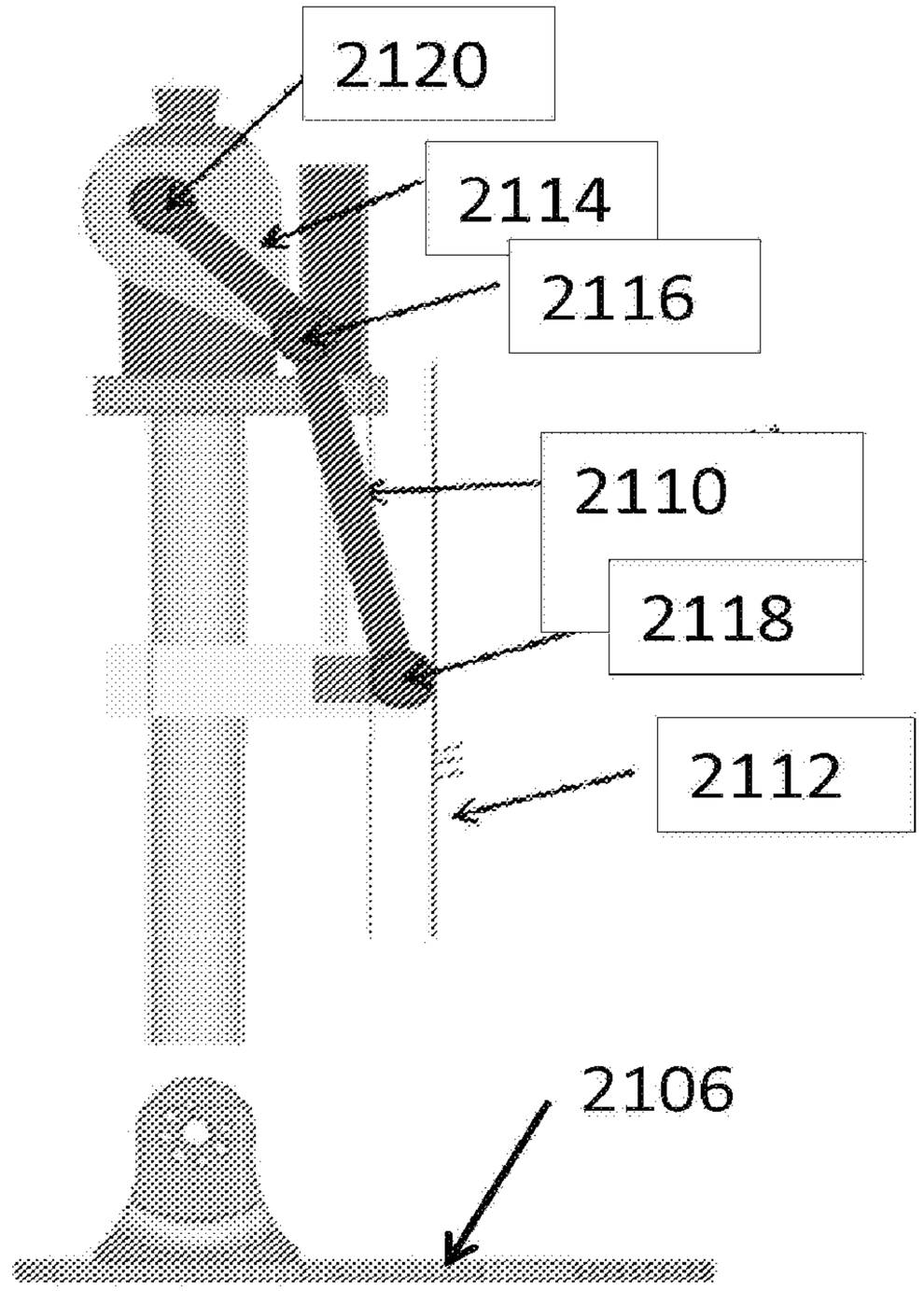

FIG. 19C

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RECTIFIED (RULE 91) - ISA/US

ACTIVE MODE – Offset Slider Crank movement

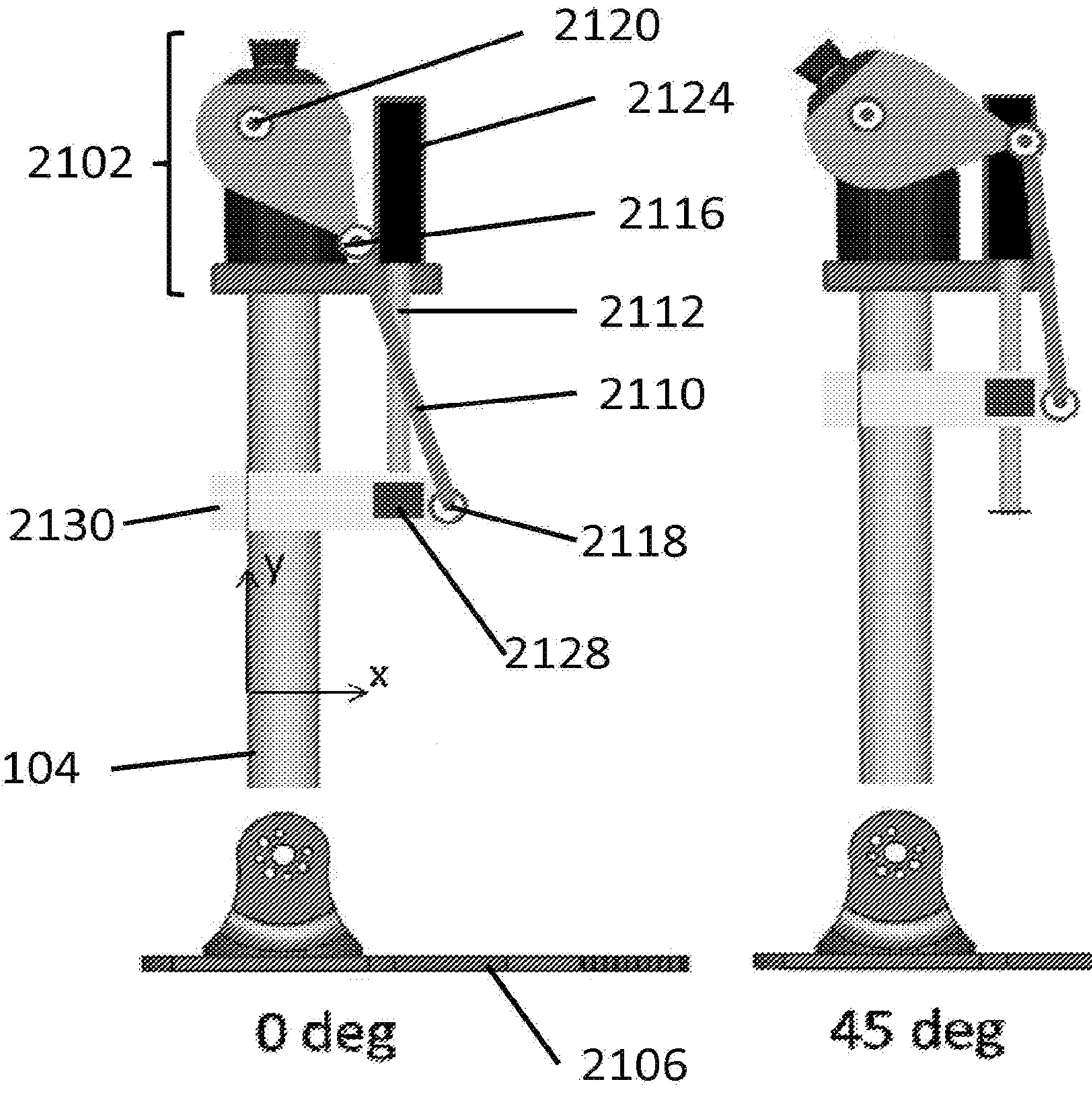


FIG. 20A

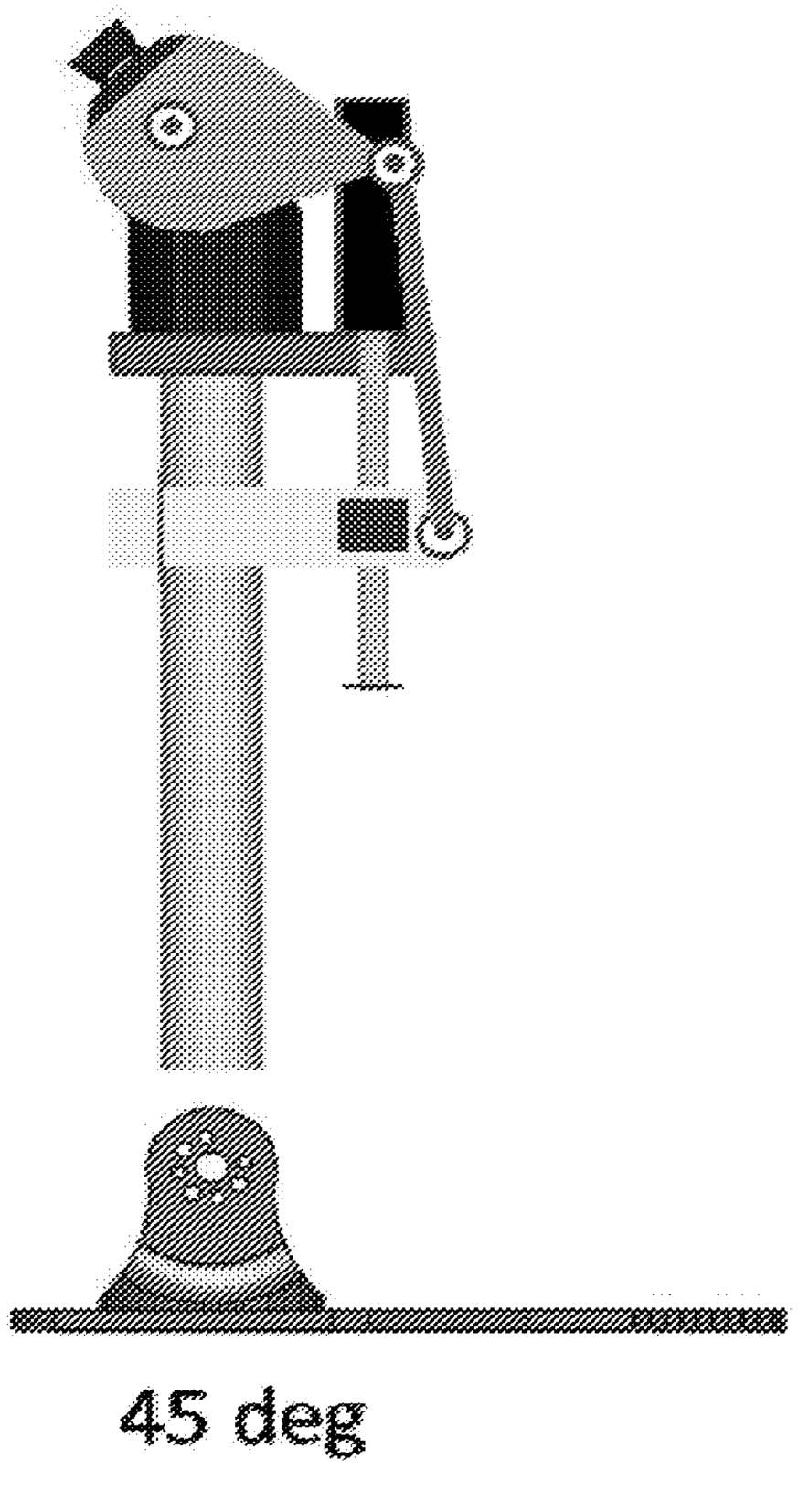


FIG. 20B

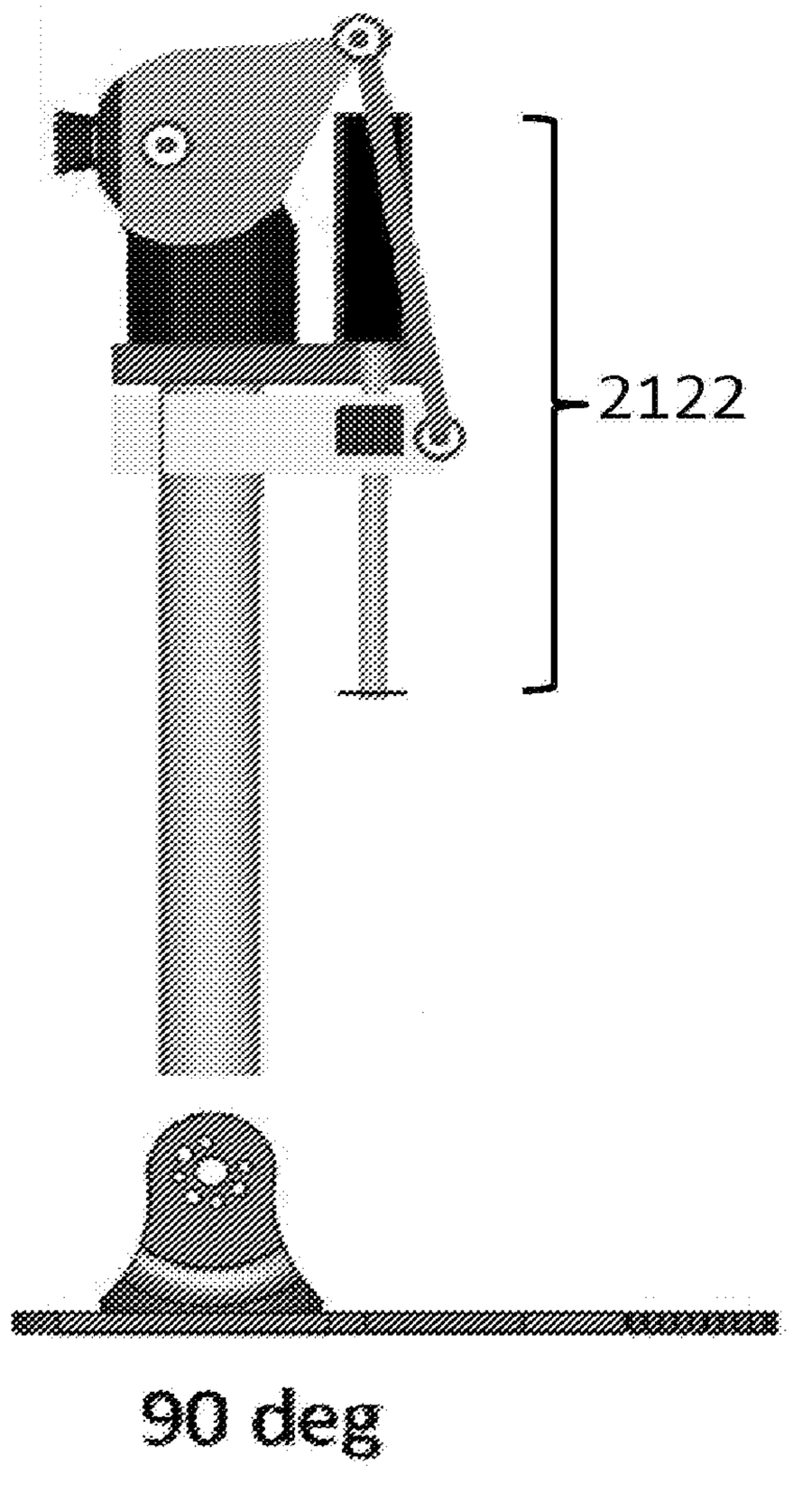


FIG. 20C

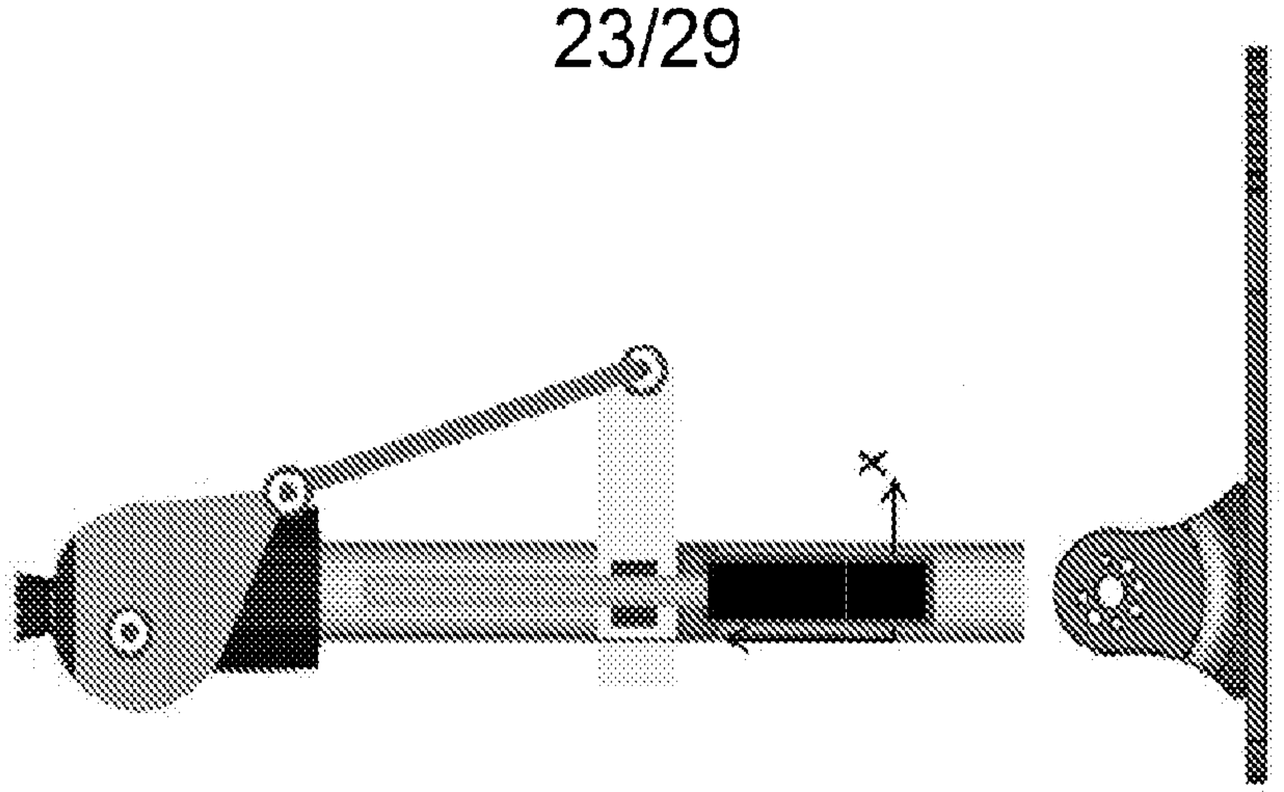


FIG. 21D

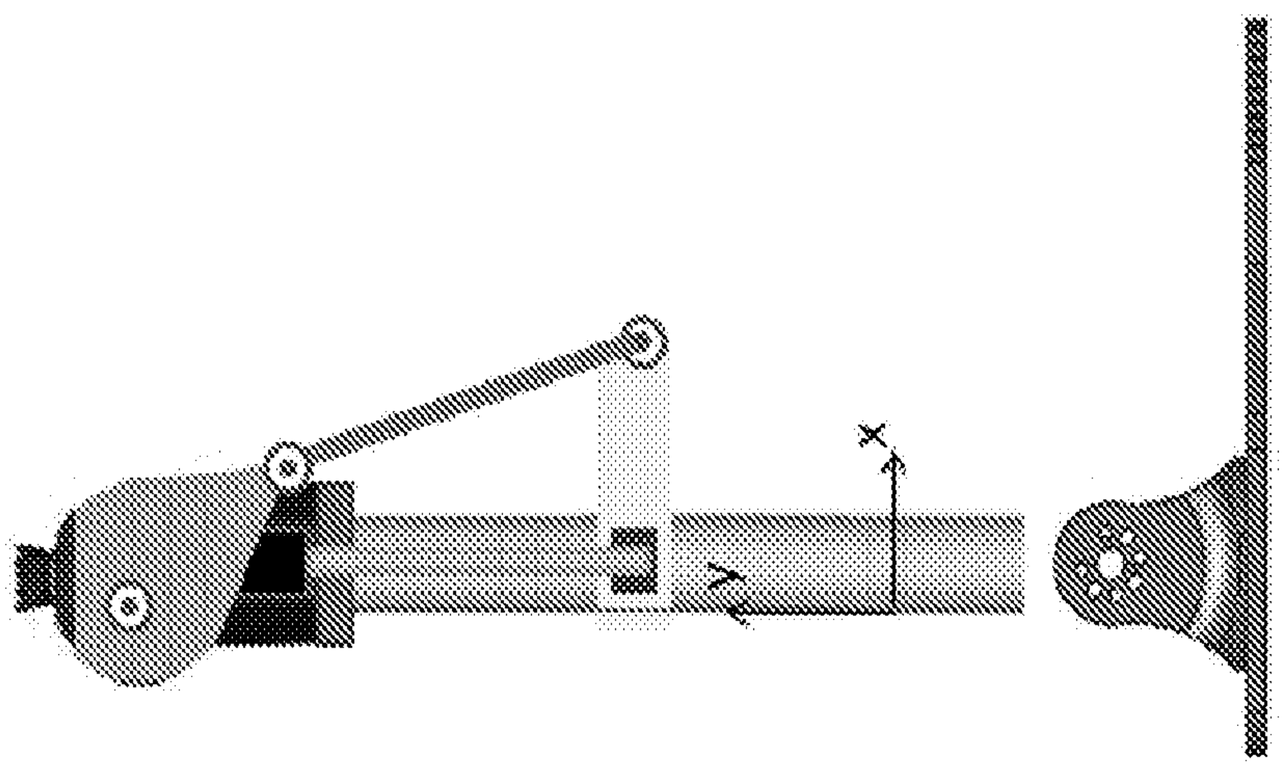


FIG. 21C

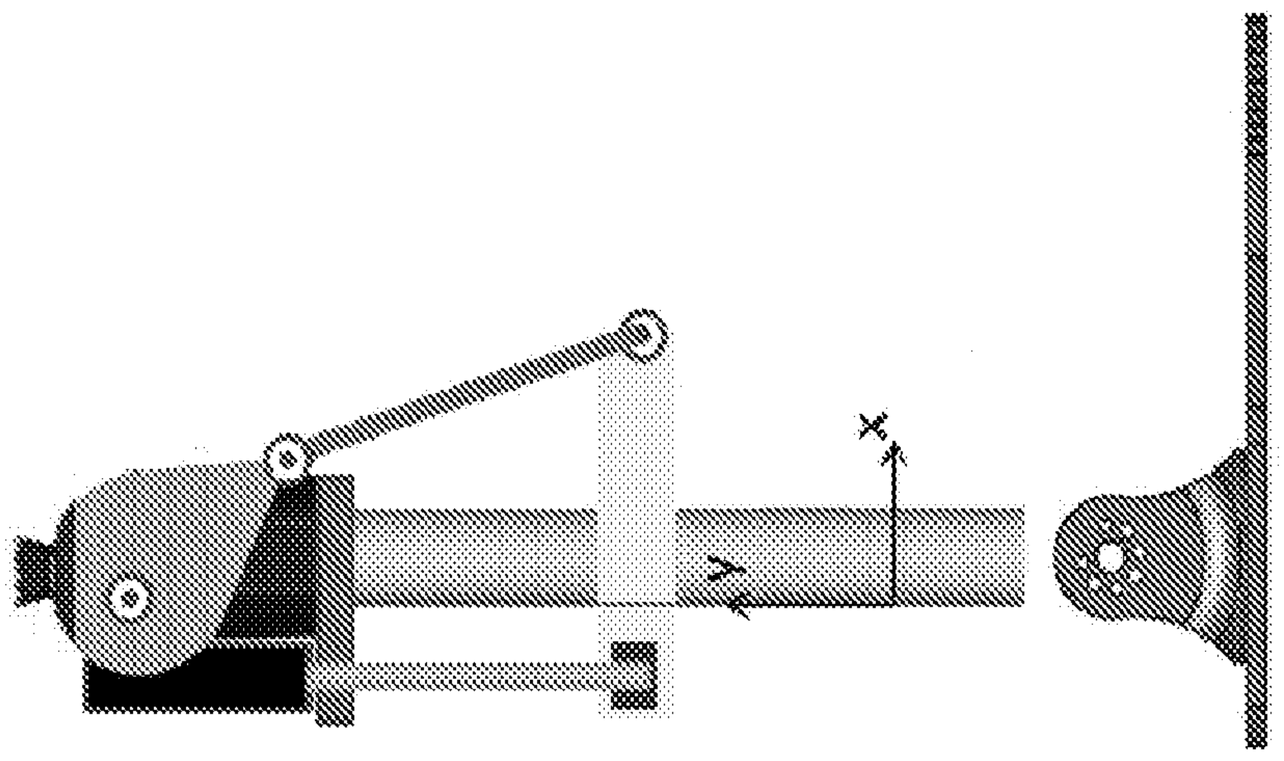


FIG. 21B

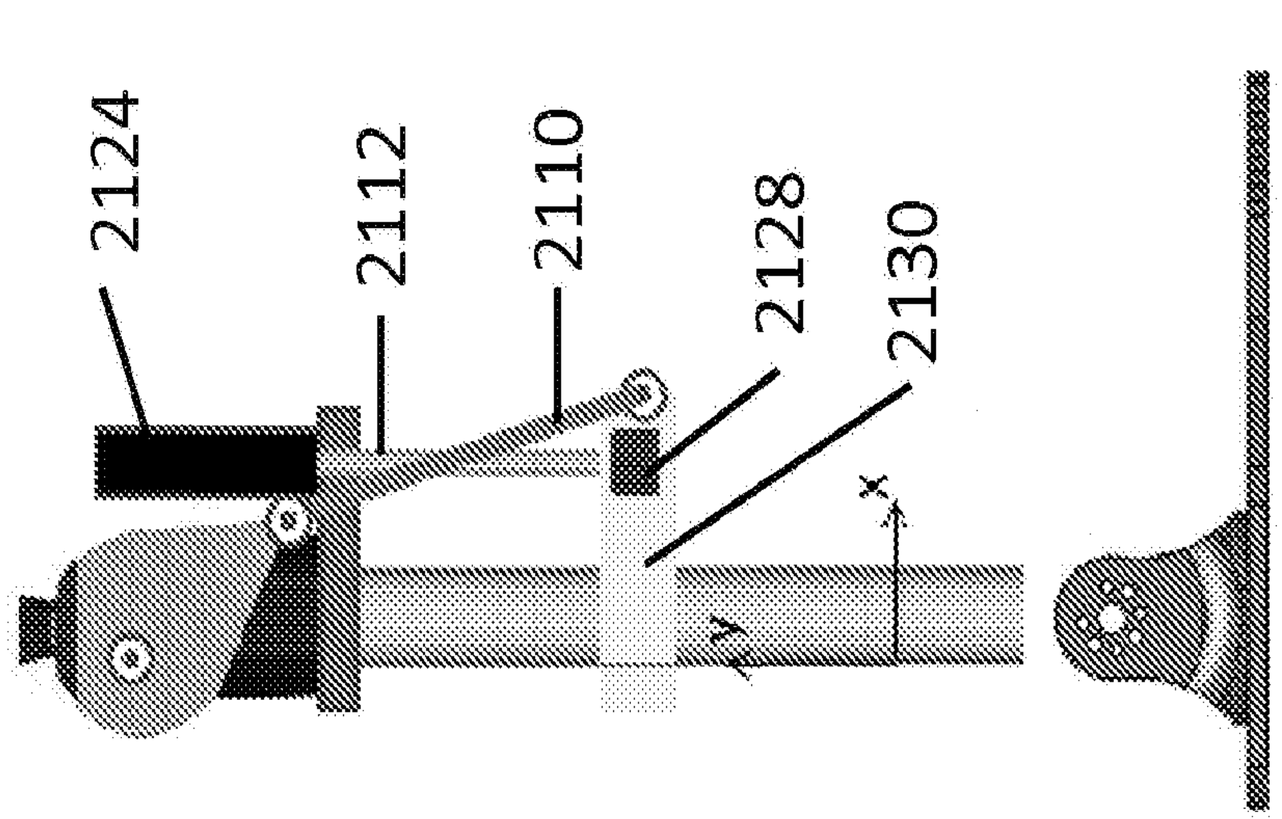
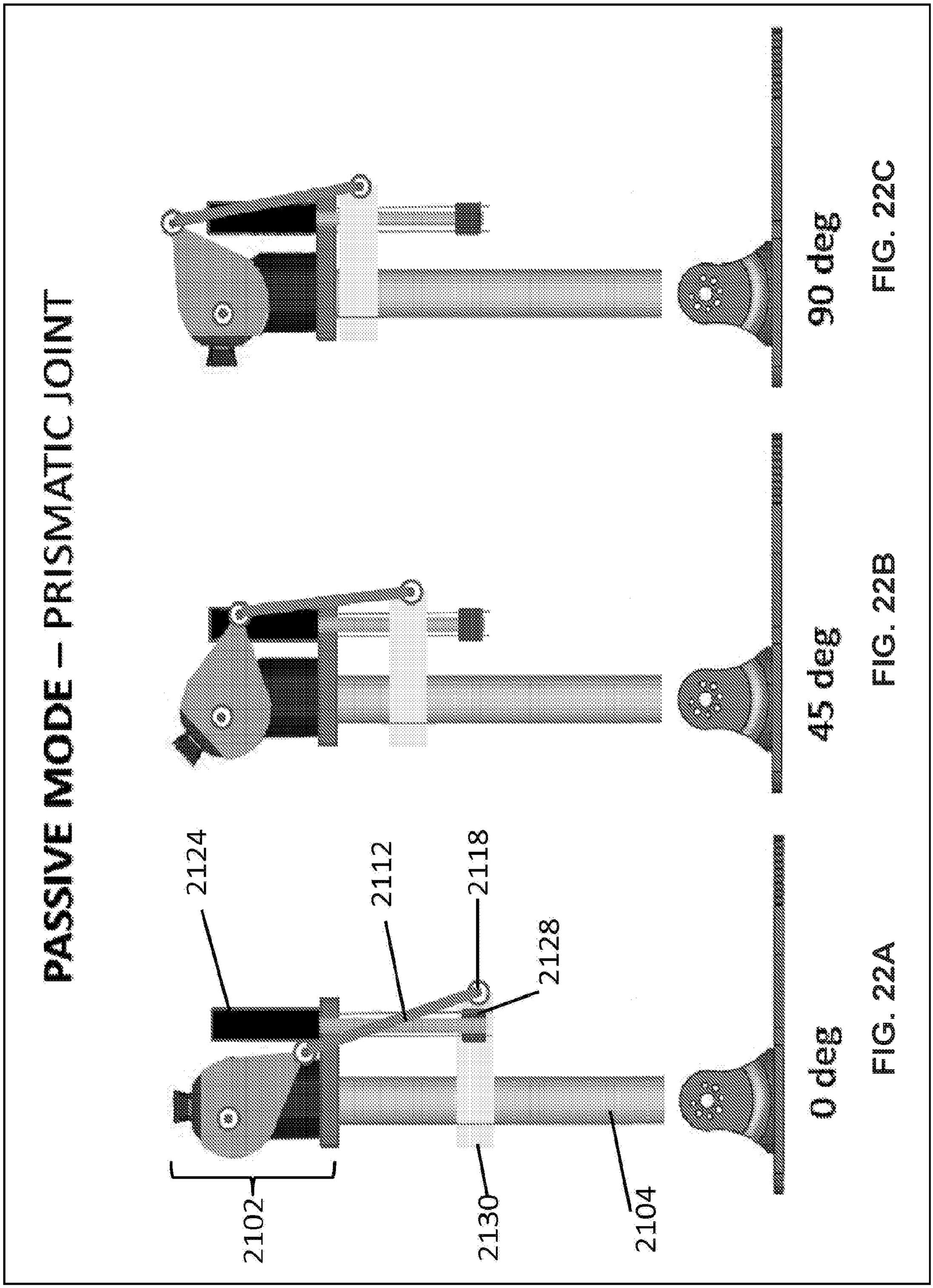


FIG. 21A


PASSIVE MODE – PRISMATIC JOINT
2124
2112
2118
2128
2102
2130
2104
0 deg
45 deg
90 deg
FIG. 22A
FIG. 22B
FIG. 22C

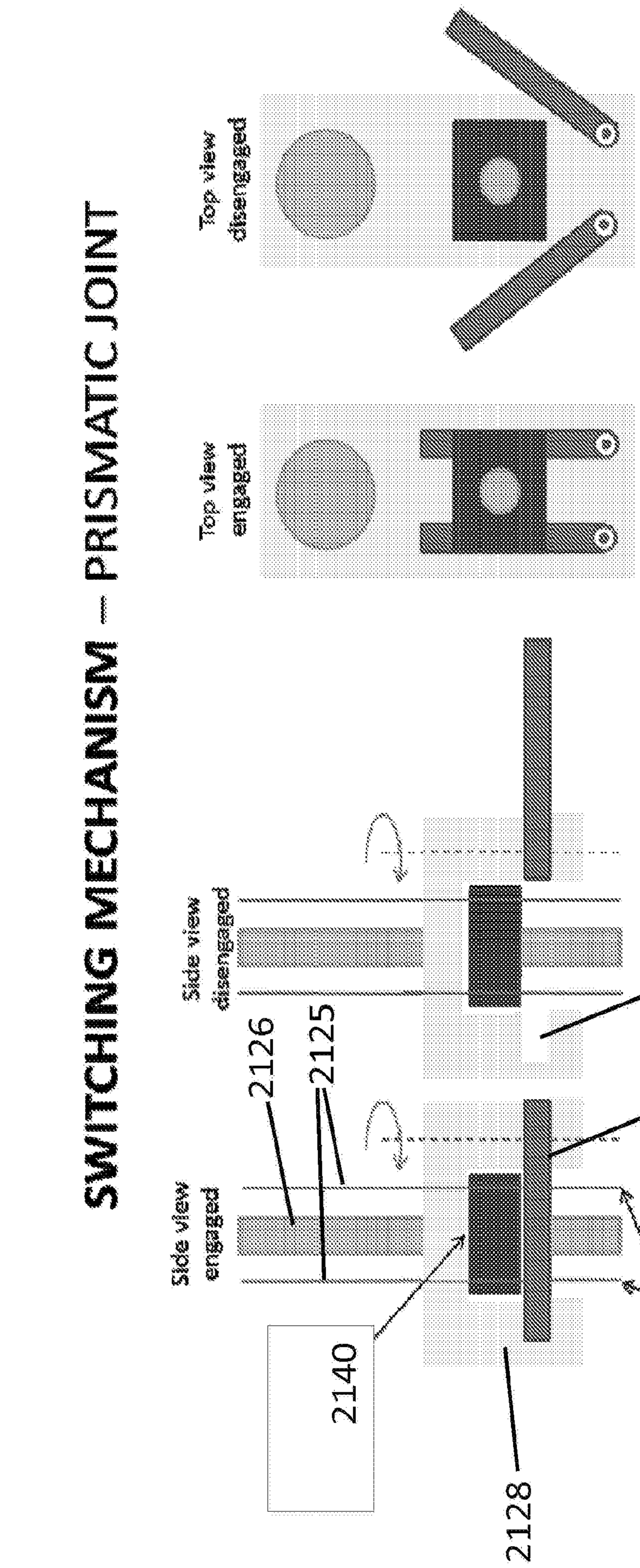


FIG. 23A

FIG. 23B

FIG. 23C

FIG. 23D

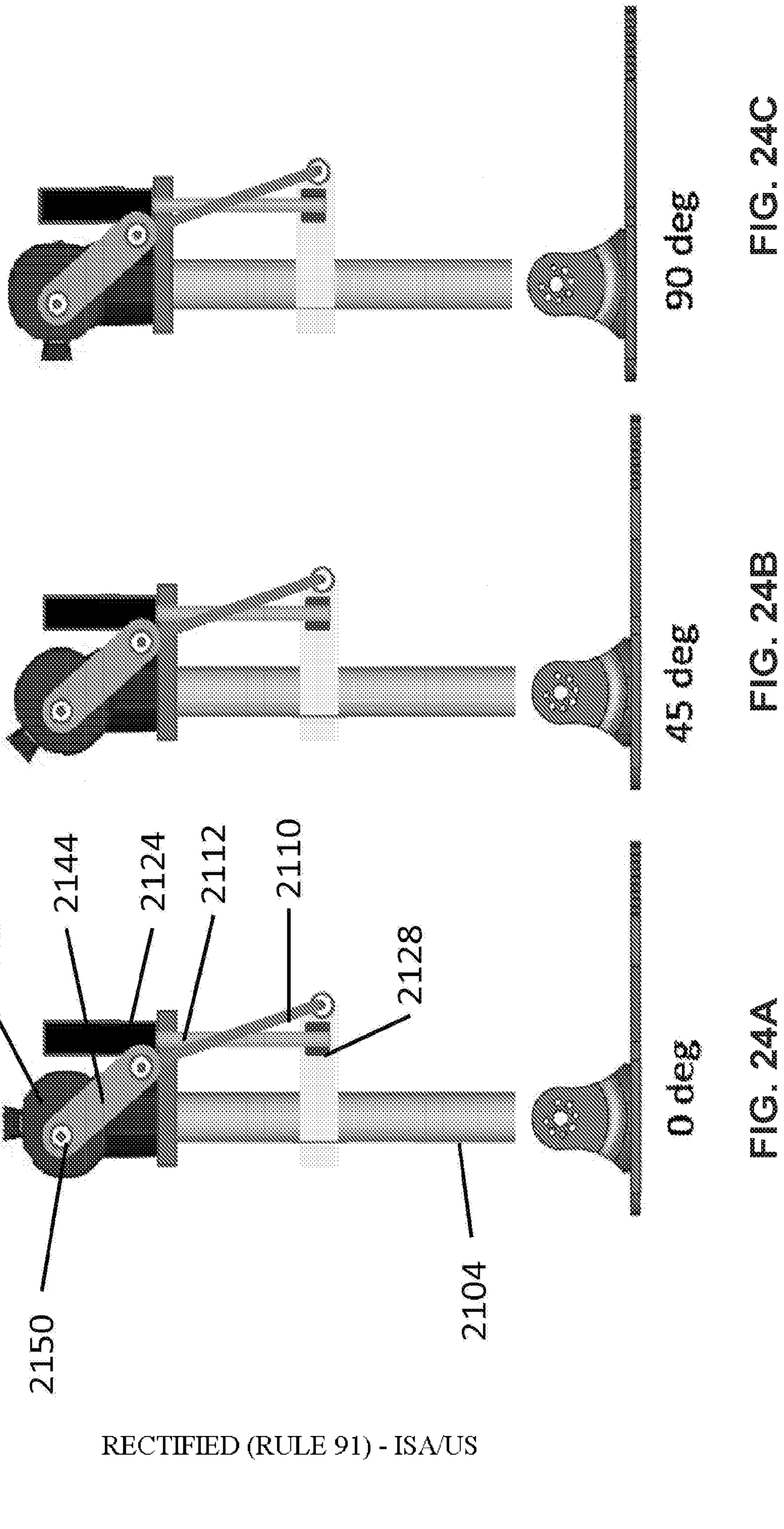


FIG. 24A FIG. 24B FIG. 24C

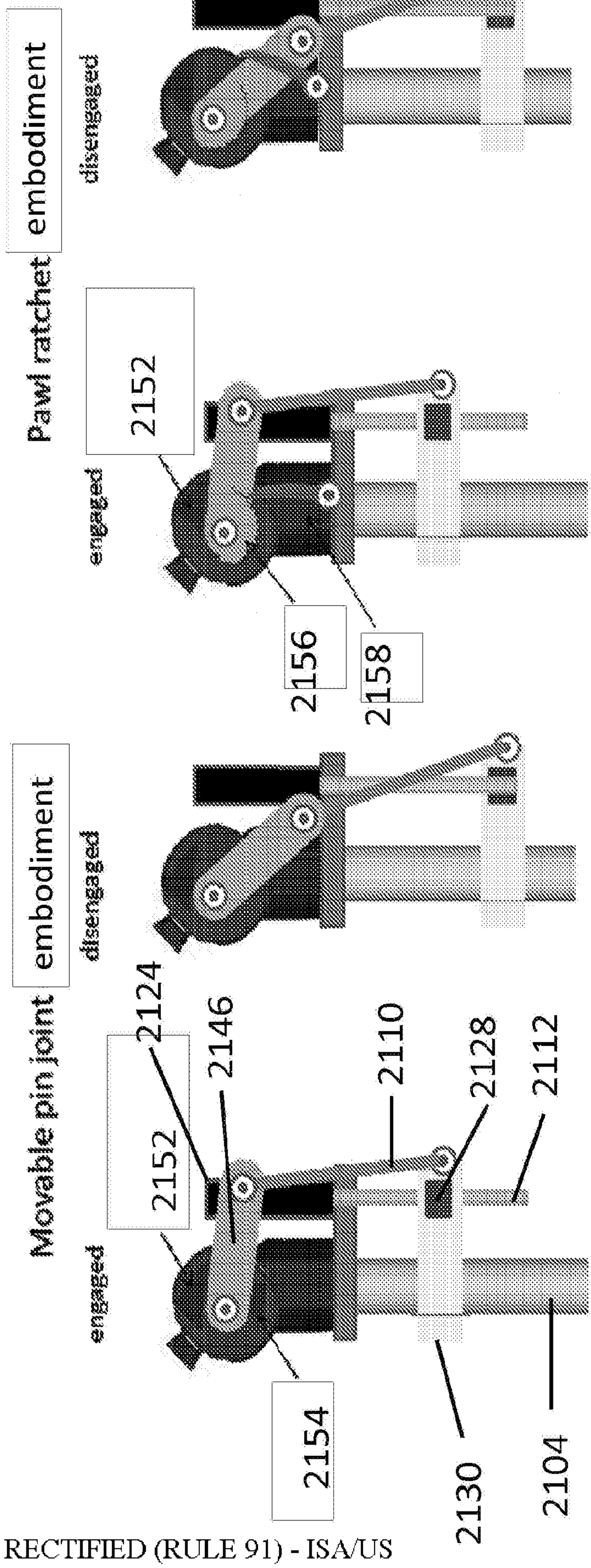


FIG. 25A

FIG. 25B

FIG. 26A

FIG. 26B

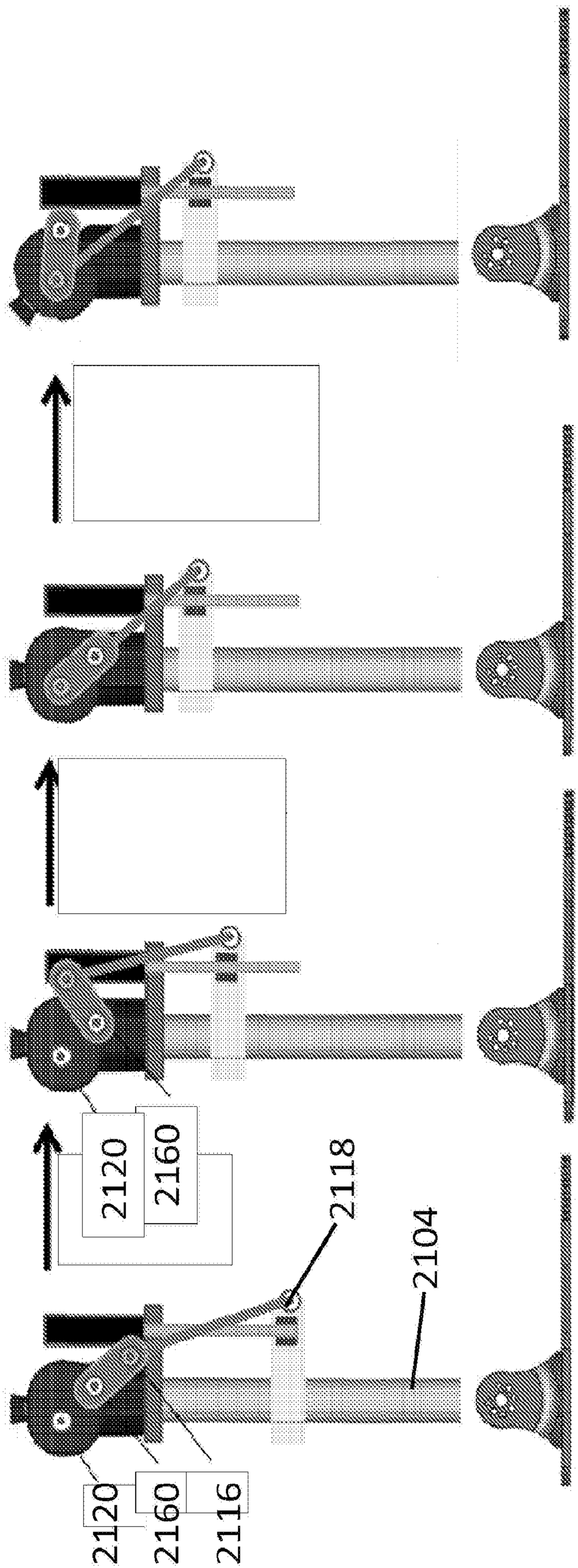


FIG. 27A

FIG. 27B

FIG. 27C

FIG. 27D

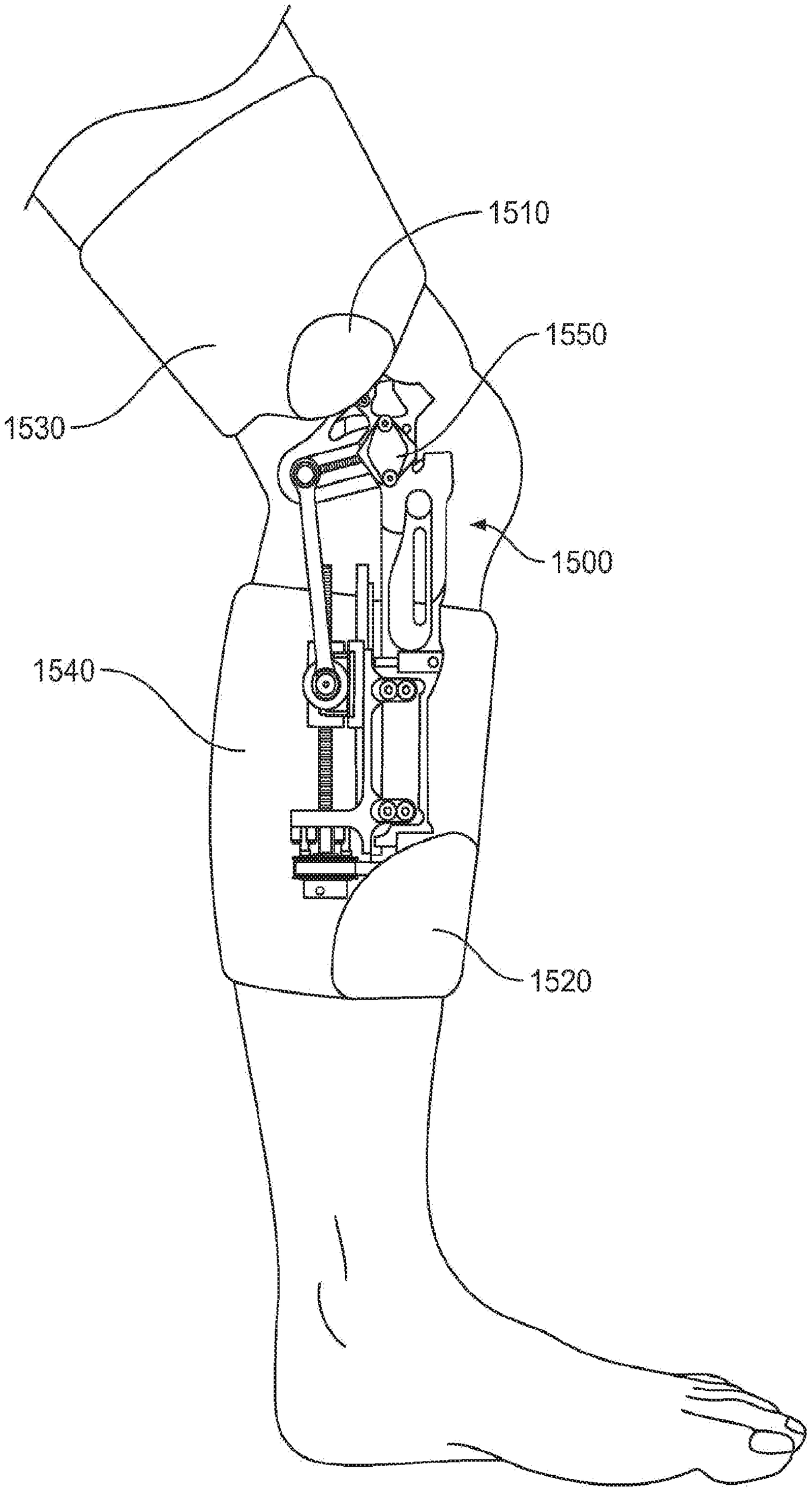


FIG. 28

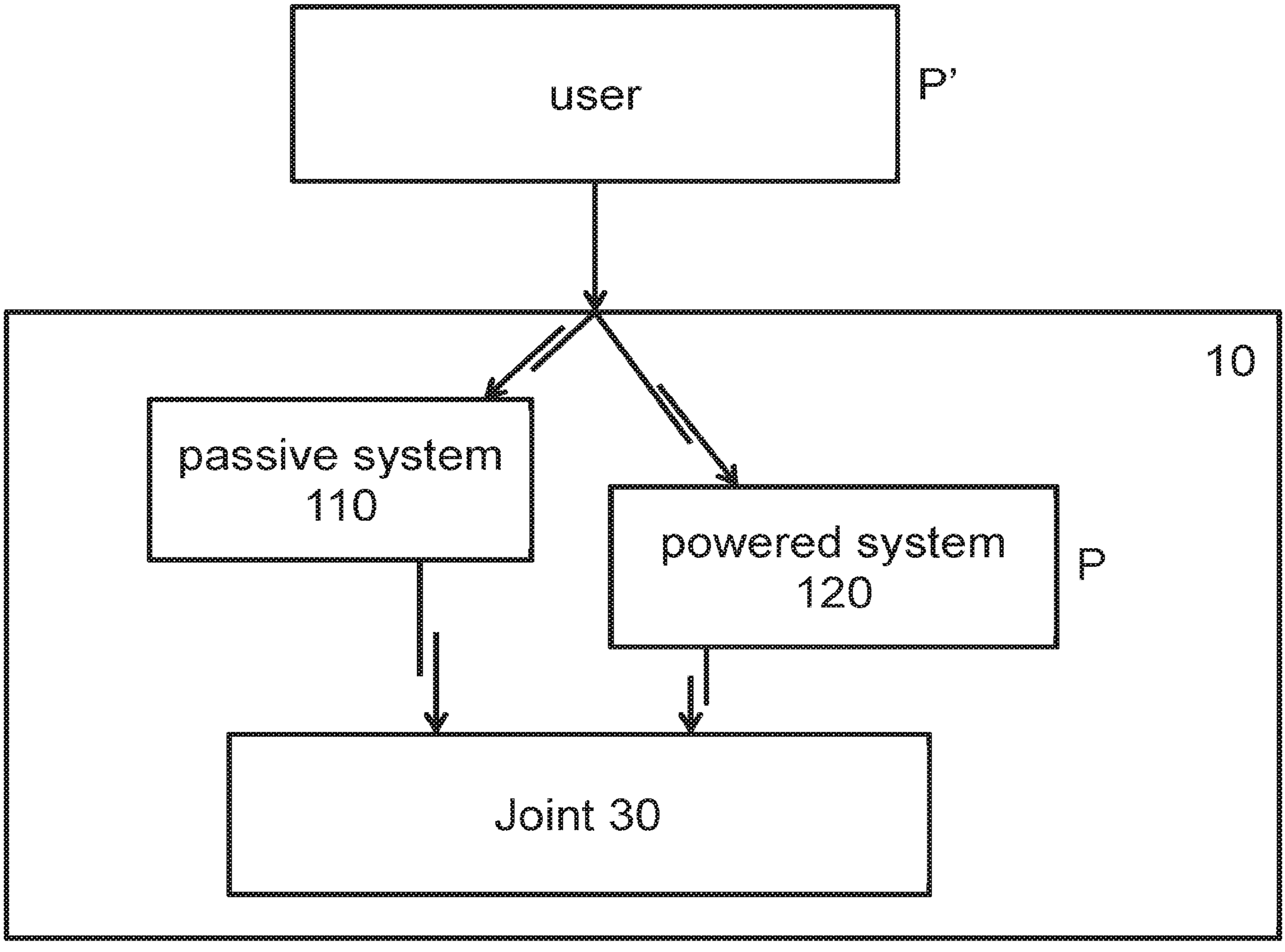


FIG. 1