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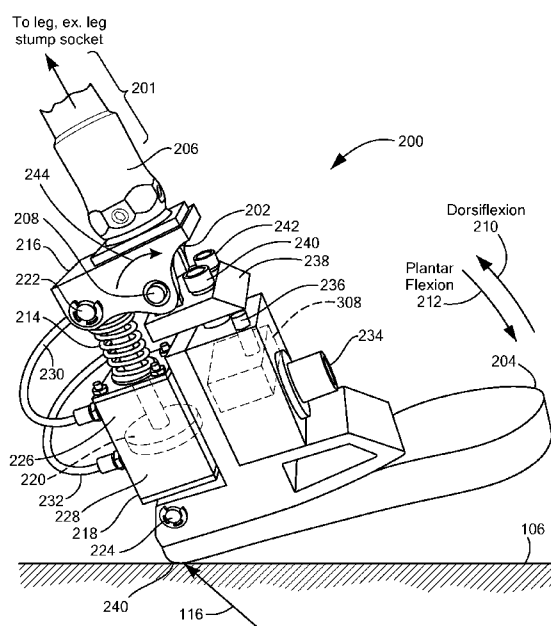


FIG. 2

(57) Abstract: A passive and slope adaptable prosthetic foot automatically adapts to terrain slope, without requiring motors or batteries, and provides a biomimetic range of motion, without dampers and their inherent energy losses. The foot incorporates a passive, mechanically-activated cutoff valve that responds to a ground reaction force, rather than active electronics or a microprocessor, in an hydraulic circuit that automatically locks and unlocks a prosthetic ankle at appropriate points of a human gait cycle. A damping coefficient of the hydraulic circuit, and a spring constant of a spring, permits the foot to achieve foot flat before locking, and stores sufficient energy during each stance phase to automatically self-reset during a following swing phase.

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Passive and Slope Adaptable Prosthetic Foot Ankle

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/540,647, filed August 3, 2017, titled “Passive and Slope Adaptable Prosthetic Foot,” the entire contents of which are hereby incorporated by reference herein, for all purposes.

BACKGROUND

TECHNICAL FIELD

[0002] The present invention relates to prosthetic ankles and, more particularly, to prosthetic ankles that automatically and passively, i.e., purely mechanically, adapt to slope of terrain.

RELATED ART

[0003] In the United States, approximately 378,000 individuals have undergone amputation [Ref. 1]. Commercially available passive prosthetic foot-ankle systems generate effective foot-ankle function by relying on spring flexion or rotational movement about one static equilibrium point. These prostheses are suitable for walking on level ground, but problems often arise when users attempt to walk on uneven or sloped terrain [Ref. 2]. Able-bodied persons are able make necessary ankle alignment (angle) adjustments for safe, stable ambulation on uneven or sloped terrain, but amputees often have to adjust their gait patterns to compensate for deficiencies of their prostheses, often by relying heavily on their non-affected limbs, increasing energy expenditure and limb socket discomfort [Ref. 3]. Failure to adapt to terrain slope can lead to increased peak loading in limb sockets and tissue damage on residual limbs [Ref. 4].

[0004] Some prosthetic feet automatically adjust to terrain slope. Currently available prostheses that allow for ankle motion and adjustment to uneven terrain can be divided into two primary categories: microprocessor-controlled and passive hydraulic damped devices. Microprocessor-controlled prosthetic feet include Ossur’s Proprio Foot [Ref. 5] and Endolite’s Elan

foot [Ref. 6]. These actively operated devices are capable of controlling dorsiflexion and plantar flexion of the prosthesis. However, these devices do not independently adapt to each step. Instead, the microprocessor requires data collected over several footsteps before it can adjust to a new terrain slope. Thus, these devices cannot fully adjust to a relatively large change in slope in a single step. Therefore, such prostheses are unsuitable for uneven terrain. Additionally, these prostheses are not passive, consequently they are large and heavy, and they require batteries.

[0005] Marketing literature for a recently-released Meridium prosthetic foot by Ottobock claims the prosthesis adjusts “immediately to the user’s walking conditions, whether on slopes, stairs or varying terrain” [Ref. 7]. However, this claim has not yet been investigated in the literature.

[0006] Passively hydraulically damped prosthetic feet include the Echelon foot by Endolite [Ref. 8] and the MotionFoot by Motion Control Inc. [Ref. 9]. These feet incorporate hydraulic components to passively control rates of dorsiflexion and plantar flexion. However, dampers in these prostheses dissipate energy from the system, which may increase metabolic cost to users. Additionally, dampers often have physical stops at their ends of the ranges of motion (sometimes permitting as little as 3 degrees of motion from a neutral angle) of the prosthesis, consequently causing the ankle to rotate about a fixed equilibrium point [Ref. 10]. As a result, these feet are not slope adaptable.

[0007] It would be desirable for a prosthesis to set an equilibrium point independently for each step, based on current slope of a surface encountered, much like the Mauch ankle does [Refs. 11, 15]. See US Pat. No. 2,843,853, the entire contents of which are hereby incorporated by reference herein for all purposes. Designed by Hans Mauch in the late 1950s, this prosthetic ankle was designed to improve quality of life for individuals living with amputations by providing slope adaptability. The Mauch ankle utilizes a ball that rolls in a track to close a port in a hydraulic circuit, thereby effectively locking the ankle when the shank reaches vertical. However, the Mauch ankle suffers from leakage problems and needs frequent maintenance [Refs. 10, 11]. An improved version of the Mauch ankle by Hansen, et al. (see, for example, US Pat. Publ. No. 2014/0088730, the entire contents of which are hereby incorporated by reference herein for all purposes) solves the leaking problems by replacing a rotary hydraulic damper with a linear hydraulic damper and by incorporating a cantilevered footplate offsets energy loss from the dampeners during rollover. However, this improved ankle requires an electronic tilt sensor to activate a cutoff valve to lock the ankle, making the device an actively operated prosthesis rather than a passive prosthesis [Ref. 12].

[0008] A prosthetic ankle should store sufficient energy during each stance phase to reset during the next swing phase, and a prosthetic ankle should not lock before it achieves foot flat. However, the prior art provides no guidance for selecting springs or hydraulic components with characteristics, such as spring constants or damping coefficients, to meet these needs. Furthermore, the prior art provides insufficient guidance regarding timing of activating the lock in a prosthetic ankle.

SUMMARY OF EMBODIMENTS

[0009] An embodiment of the present invention provides a passive prosthetic ankle. The passive prosthetic ankle mechanically couples a leg of a user to a foot. In use, the leg, foot and ankle are subject to a ground reaction force. The ground reaction force acts on the foot. Magnitude of the ground reaction force varies as a result of a gait of the user.

[0010] The prosthetic ankle includes a prosthetic talocrural joint. The prosthetic talocrural joint is configured to pivotally couple the leg to the foot to permit dorsiflexion and plantar flexion. A spring is mechanically coupled to the leg and the foot. Pivoting of the prosthetic talocrural joint deflects the spring.

[0011] An hydraulic cylinder defines a volume. A piston is linearly reciprocable within the hydraulic cylinder volume. The piston hydraulically divides the hydraulic cylinder volume into a first chamber having a first chamber volume and a second chamber having a second chamber volume. The hydraulic cylinder and the piston are mechanically coupled to the leg and to the foot. Pivoting of the prosthetic talocrural joint moves the piston within the hydraulic cylinder to alter the first chamber volume and the second chamber volume. An hydraulic fluid is disposed in the first chamber and in the second chamber.

[0012] A check valve is hydraulically coupled between the first chamber and the second chamber. The check valve permits flow of the hydraulic fluid through the check valve only during plantar flexion of the prosthetic talocrural joint.

[0013] A normally-open cutoff valve is hydraulically coupled in parallel with the check valve. When the cutoff valve is open, the cutoff valve permits flow of the hydraulic fluid through the cutoff valve during both dorsiflexion and plantar flexion of the prosthetic talocrural joint. The cutoff valve is configured to passively close in response to the ground reaction force.

[0014] The passive prosthetic ankle is characterized in that the spring has a spring constant of at least about 4,352 N/m.

[0015] The passive prosthetic ankle is further characterized in that the spring, the hydraulic cylinder, the piston, the hydraulic fluid, the check valve and the cutoff valve, along with associated plumbing, collectively form an hydraulic circuit having a damping coefficient no greater than about 1,391 kg/s.

[0016] In some embodiments, there is no check valve in series with the cutoff valve.

[0017] In some embodiments, there is no variable restrictor of the hydraulic fluid in series with the cutoff valve.

[0018] In some embodiments, there is no variable restrictor of the hydraulic fluid in series with the check valve.

[0019] In some embodiments, there is no variable restrictor of the hydraulic fluid in series with either the cutoff valve or the check valve.

[0020] Optionally, in combination with any other requirement, the cutoff valve is configured to close within about 0.086 seconds of foot flat of the gait of the user.

[0021] Optionally, in combination with any other requirement, the spring and the hydraulic circuit are configured, i.e., the spring constant and the damping coefficient are selected, to return the prosthetic talocrural joint to a neutral angle within a single swing phase of a human gait.

[0022] Optionally, in combination with any other requirement, the spring has a spring constant of at least about 5,000 N/m, or at least about 10,000 N/m or at least about 20,000 N/m.

[0023] Optionally, in combination with any other requirement, the spring is configured to urge the prosthetic talocrural joint to return to an equilibrium point.

[0024] Optionally, in combination with any other requirement, the spring is configured to urge the prosthetic talocrural joint to pivot in dorsiflexion.

[0025] Optionally, in combination with any other requirement, the prosthetic talocrural joint is capable of plantar flexion of at least about 32°.

[0026] Optionally, in combination with any other requirement, the prosthetic ankle also includes a resilient foot plate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] The invention will be more fully understood by referring to the following Detailed Description of Specific Embodiments in conjunction with the Drawings, of which:

[0028] Fig. 1 is a schematic diagram illustrating heel strike, foot flat and toe off sub-phases of a stance phase of an able-bodied human gait, including x and y components of a ground reaction force acting on the foot, as known in the prior art.

[0029] Fig. 2 is a perspective view of a passive and slope adaptable prosthetic foot, according to an embodiment of the present invention.

[0030] Fig. 3 is a schematic diagram of a hydraulic circuit within the passive and slope adaptable prosthetic foot of Fig. 1, according to an embodiment of the present invention.

[0031] Fig. 4 is a graph over time of the x and y components of the ground reaction force of Fig. 1, as known in the prior art.

[0032] Fig. 5 illustrates the passive and slope adaptable prosthetic foot of Fig. 2 and the hydraulic circuit of Fig. 3 at heel strike, according to an embodiment of the present invention.

[0033] Fig. 6 illustrates the passive and slope adaptable prosthetic foot of Fig. 2 and the hydraulic circuit of Fig. 3 once the foot is flat on the ground, according to an embodiment of the present invention.

[0034] Fig. 7 illustrates the passive and slope adaptable prosthetic foot of Fig. 2 and the hydraulic circuit of Fig. 3 as the ankle bends prior to toe off, according to an embodiment of the present invention.

[0035] Fig. 8 illustrates the passive and slope adaptable prosthetic foot of Fig. 2 and the hydraulic circuit of Fig. 3 after toe off, according to an embodiment of the present invention.

[0036] Fig. 9 schematically illustrates forces acting on a prosthetic ankle and resulting moments, as calculated according to an embodiment of the present invention.

[0037] Fig. 10 is a graph plotting the ground reaction force acting on a foot over time, including an analysis of time between heel strike and foot flat, according to an embodiment of the present invention.

[0038] Fig. 11 is a schematic illustration of a spring-damper model of the passive and slope adaptable prosthetic foot of Figs. 2, 3 and 5-8, according to an embodiment of the present invention.

[0039] Fig. 12 is a bar chart plotting test data from an embodiment of the passive and slope adaptable prosthetic foot of Figs. 2, 3 and 5-8.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

[0040] Embodiments of the present invention provide passive and slope adaptable prosthetic feet. These prostheses improve quality of life for individuals using prosthetic feet by automatically adapting to terrain slope, without requiring motors or batteries. These embodiments provide biomimetic ranges of motion, without dampers and their inherent energy losses. Embodiments of the present invention incorporate passive, mechanically activated cutoff valves, rather than active electronic or microprocessor controlled valves, in hydraulic circuits that automatically lock and unlock prosthetic ankles at appropriate points of a gait cycle. Furthermore, these embodiments permit users to achieve foot flat before locking, and they store sufficient energy during each stance phase to automatically self-reset during a following swing phase.

Gait Biomechanics and Vocabulary

[0041] The terms force, vector, moment and torque have their respective common meanings from physics. A force, such as a ground reaction force, has a magnitude and a direction. Thus, a force can be represented by a vector. A moment is an expression involving a product of a distance and a physical quantity, and in this way a moment accounts for how the physical quantity is located or arranged. For example, a moment of force acting on an object, often called torque, is the product of the force and the distance from a reference point.

[0042] A spring is an elastic object that stores mechanical energy. Examples of springs include compression springs, extension springs and torsion springs. Resilient materials, such as resilient foam, can be used as springs, thus the term “spring,” as used herein, includes such materials.

[0043] A flexure is a flexible element, or combination of elements, engineered to be compliant in one or more specific degrees of freedom.

[0044] As used herein, “pivotally coupled” means mechanically coupled so as to provide rotational or approximately rotational motion in at least one dimension. The motion need not be purely rotational. The motion may, for example, include some parasitic motion, such as translation.

[0045] As used herein, “active” means externally powered, such as by a battery, as opposed to “passive,” which means unpowered, except possibly directly by a human user and/or by a spring that stores or accumulates energy from mechanical operation of a prosthesis driven by the human

user during a portion of a gait cycle and that releases some of the stored energy during a portion of the gait cycle.

[0046] As used herein, “posterior” means behind, relative to the normal direction of forward walking of a human being, and “anterior” means in front of, relative to the normal direction of forward walking of a human being.

[0047] As used herein, “plantar flexion” means movement of a foot in which the foot or toes flex downward toward the sole of the foot or the ground. In contrast, “dorsiflexion” means flexion of the foot in an upward direction. In a human foot, plantar flexion and dorsiflexion involve pivoting the foot about an ankle joint. Similarly, in a prosthetic foot, plantar flexion and dorsiflexion involve pivoting the prosthetic foot about a prosthetic ankle joint. However, some prostheses have resilient foot plates, in which case the foot plates can experience (perhaps a limited amount of) dorsiflexion and rebound with plantar flexion, without the prosthetic foot necessarily pivoting about the prosthetic ankle joint, for example if the prosthetic ankle joint is locked.

[0048] As used herein, a “keel” is a device in a stored-energy foot prosthesis that bends the foot upward when weight is applied to the toe.

[0049] A brief summary of terms related to human gait biomechanics used herein is provided, with respect to Fig. 1. A human gait cycle of each leg 100 is divided into two primary phases: a swing phase and a stance phase. During the swing phase, the foot moves through the air, without contacting the ground. During the stance phase 102, schematically illustrated in Fig. 1, the foot 104 is in contact with the ground 106 and goes through three sub-phases 108, 110 and 112.

[0050] The first sub-phase is heel strike 108, at which time the heel 114 first comes into contact with the ground 106. A ground reaction force (GRF) 116 acts at the heel 114. The ground reaction force 116 consists of two components: a horizontal ground reaction force component (GRF_x) and a vertical ground reaction force component (GRF_y). During heel strike 108, the horizontal ground reaction force component (GRF_x) acts from the front of the foot 104 toward the back of the foot 104 to decelerate the foot 104.

[0051] The second sub-phase of the stance phase 102 is foot flat 110. At the beginning of foot flat 110, the foot undergoes plantar flexion 118 until the foot 104 is completely flat on the ground 106. Once the foot 104 is flat on the ground 106, the shank 120 rotates 122 towards the front of the foot 104, resulting in dorsiflexion 124. Throughout the stance phase 102, a center of pressure 126 on the foot 104 moves from the heel 114 towards the toe 128, thus shifting the location of the

ground reaction force 116. Additionally, the horizontal ground reaction force component (GRF_x) becomes approximately zero when the shank 120 of the leg 100 is vertical. As the shank 120 continues to rotate 122 forward, the direction of the horizontal ground reaction force component (GRF_x) changes to forward, acting to propel the knee 130 forward over the foot 104.

[0052] The third sub-phase of the stance phase 102 is terminal stance, where the foot 104 again plantar flexes 132 and the heel 114 lifts off the ground 106, such that only the toes 128 remain in contact with the ground 106. At the end of terminal stance, the toes 128 break contact with the ground in an event called toe-off 112. After toe off 112, the foot 104 is completely off the ground and swings forward in the air (not shown), moving on to the next cycle.

Passive and Slope Adaptable Prosthetic Foot

[0053] Fig. 2 is a perspective view of a passive and slope adaptable prosthetic foot 200, according to an embodiment of the present invention. The passive and slope adaptable prosthetic foot 200 includes a passive prosthetic ankle 202 for mechanically coupling a leg 201 to a foot plate 204. The leg 201 may include a pylon 206, which may be coupled via a stump socket and/or other prosthetic components (not shown) to a user. In use, the ground reaction force 116 acts on the passive and slope adaptable prosthetic foot 200, while magnitude and direction of the ground reaction force 116 varies as a result of a gait of the user.

[0054] The prosthetic ankle 202 includes a prosthetic talocrural joint 208 configured to pivotally couple the leg 201 to the foot plate 204. The prosthetic talocrural joint 208 may include a pin made of steel or another suitable material. Thus, the prosthetic ankle 202 can pivot, relative to the foot plate 204, about the pin (prosthetic talocrural joint) 208, resulting in dorsiflexion 210 or plantar flexion 212, as indicated by respective arrows. In some embodiments, the prosthetic talocrural joint 208 may be implemented with a living hinge, cross-flexure joint or other flexure bearing. In some embodiments, the prosthetic talocrural joint 208 may be implemented with a ball and socket or any other suitable compliant joint that provides a pivotal coupling.

[0055] A spring 214 is mechanically coupled to the leg 201, via the passive prosthetic ankle 202, and to the foot plate 204, such that pivoting of the prosthetic talocrural joint 208 deflects the spring 214. In the embodiment of Fig. 1, an upper end of the spring 214 is mechanically coupled to an upper portion 216 of the prosthetic ankle 202, and a lower end of the spring 214 is mechanically coupled, via a hydraulic cylinder 218, to the foot plate 204, such that pivoting the prosthetic talocrural joint 208 in a direction that results in plantar flexion 212 also compresses the spring 214.

The hydraulic cylinder 218 and a piston 220 (shown in phantom) disposed within the hydraulic cylinder 218 are mechanically coupled to the leg 201 and to the foot plate 204, such as via respective pivot pins 222 and 224.

[0056] Fig. 3 is a schematic diagram of a hydraulic circuit 300 within the passive and slope adaptable prosthetic foot 200. The hydraulic cylinder 218 defines a volume, and the piston 220 linearly reciprocates within the hydraulic cylinder volume. The piston 220 hydraulically divides the hydraulic cylinder 218 into a first chamber 226, above the piston 220, and a second chamber 228, below the piston 220. As the prosthetic talocrural joint 208 (Fig. 2) pivots, the piston 220 moves within the hydraulic cylinder 218 to alter the relative volumes of the first chamber 226 and the second chamber 228. In some embodiments, as the piston 220 moves within the hydraulic cylinder 218, the sum of the volumes of the first and second chambers 226 and 228 remains constant.

[0057] A hydraulic fluid 302 is disposed in the first chamber 226 and in the second chamber 228. Hydraulic lines 230 and 232 are hydraulically coupled to the first and second chambers 226 and 228, respectively. Thus, as the piston 220 moves, hydraulic fluid 302 is expelled through one of the hydraulic lines 230 or 232 from one of the first and second chambers 226 or 228, and hydraulic fluid 300 is taken up by the other of the first and second chambers 228 or 226 through the other one of the hydraulic lines 232 or 230. In some embodiments, the amount of the hydraulic fluid 302 expelled through one of the hydraulic lines 230 or 232 from one of the first and second chambers 226 or 228 equals the amount of the hydraulic fluid 300 taken up by the other of the first and second chambers 228 or 226 through the other one of the hydraulic lines 232 or 230. However, if the amounts of the hydraulic fluid expelled and taken up are unequal, the hydraulic circuit 300 may include a hydraulic fluid accumulator 234.

[0058] A check valve 304 is hydraulically coupled between the first chamber 226 and the second chamber 228 to permit the hydraulic fluid 302 to flow through the check valve 304 only in a direction indicated by an arrow 306, therefore only during pivoting of the prosthetic talocrural joint 208 that results in plantar flexion 212 (Fig. 2). A spring-return, push-button operated, normally-open cutoff valve 308 (also shown in phantom in Fig. 2) is also hydraulically coupled between the first chamber 226 and the second chamber 228, i.e., in parallel with the check valve 304. When open, the cutoff valve 308 permits the hydraulic fluid 302 to flow in both directions 316, therefore during both plantar flexion 212 and during dorsiflexion 210. However, when closed, the cutoff valve 308 does not permit any hydraulic fluid 302 to flow through the cutoff valve 308.

[0059] During pivoting of the prosthetic talocrural joint 208 that results in plantar flexion 212 (Fig. 2), the piston 220 moves within the hydraulic cylinder 218 in a direction indicated by an arrow 310 (Fig. 3), and the hydraulic fluid 302 flows through hydraulic circuit 300 in a direction indicated by an arrow 312. The prosthetic talocrural joint 208 can always pivot to provide plantar flexion 212, because the check valve 304 permits the hydraulic fluid 302 to flow through the check valve 304 in the direction of the arrow 306, regardless of the state of the cutoff valve 308.

[0060] However, during dorsiflexion 210 (Fig. 2), the piston 220 moves, or is at least urged, within the hydraulic cylinder 218 opposite the direction of the arrow 310 (Fig. 3), and the hydraulic fluid 302 flows, or at least exerts a pressure, through the hydraulic circuit 300 in a direction indicated by an arrow 314.

[0061] The cutoff valve 308 is configured to passively close in response to the ground reaction force 116 (Fig. 1) and to open in response to absence of the ground reaction force 116. In some embodiments, the cutoff valve 308 is configured to close within about 0.086 seconds of foot flat of the gait of the user.

[0062] It should be noted that no ground reaction force 116 is exerted during the swing phase. The ground reaction force is exerted only during the stance phase 102 (Fig. 1). Thus, the cutoff valve 308 is open during the swing phase and closed during at least a portion of the stance phase 102. When the cutoff valve 308 is open, the hydraulic fluid 302 may flow through the cutoff valve 308 in either direction, as indicated by a two-headed arrow 316, thereby permitting the prosthetic talocrural joint 208 to pivot in either direction, thereby permitting both easy dorsiflexion 210 and easy plantar flexion 212. However, when the cutoff valve 308 is closed, the hydraulic fluid 302 may flow only through the check valve 304, thus only in the direction indicated by the arrow 306, thereby permitting the prosthetic talocrural joint 208 to pivot in only one direction, thereby permitting only easy plantar flexion 212. If the foot plate 204 (Fig. 2) is resilient, the foot plate 204 may experience some dorsiflexion 210, even if the cutoff valve 308 is closed.

[0063] In the embodiment of Fig. 2, the cutoff valve 308 is a normally-open valve that is activated, i.e., closed, via depressing a spring-returned push button 236. The push button 236 is depressed by an upper rocker 238 that freely slides vertically along two shoulder bolts 240 and 242. As the prosthetic ankle 202 pivots clockwise (as viewed in Fig. 2 and as indicated by an arrow 244) about the prosthetic talocrural joint 208, i.e., as the passive and slope adaptable prosthetic foot 200 dorsiflexes, the prosthetic ankle 202 depresses the upper rocker 238 which, in turn, depresses the

push button 236, activating (closing) the cutoff valve 308. Optionally, the upper rocker 238 may be omitted, and the prosthetic ankle 202, or a cam (not shown) on the prosthetic ankle 202, may depress the push button 236. Thus, the passive and slope adaptable prosthetic foot 200 is able to easily plantar flex 212 when the passive and slope adaptable prosthetic foot 200 experiences no ground reaction force 116, i.e., during the swing phase and, optionally, at the very beginning, such for up to about 0.086 seconds after, heel strike 108.

[0064] In the gait cycle, when a user strikes the heel 240 of the passive and slope adaptable prosthetic foot 200 against the ground 106, the push button 236 of the cutoff valve 308 is activated within about 0.086 seconds, closing the cutoff valve 308. Flow of the hydraulic fluid 302 is, therefore, shut off in the dorsiflexion 210 direction 314, as the foot plate 204 rolls over the ground 106. However, the check valve 304 enables plantar flexion 212, allowing the foot plate 204 to adjust automatically to the slope of the ground 140 (“find the ground”) after heel strike 108. Upon toe-off 112 (Fig. 1), the user’s weight shifts her weight to the other foot, releasing the push button 236 and opening the cutoff valve 308. The spring 214 restores the foot plate 204 to a resting position. That is, the passive and slope adaptable prosthetic foot 200 automatically dorsiflexes 210, as urged by the spring 214, and the hydraulic fluid 302 flows through the open cutoff valve 308 in the direction of arrow 314.

[0065] The spring 214 should have a spring constant of at least about 4,352 N/m to store sufficient energy during each stance phase to reset during the next swing phase. The spring 214, the hydraulic cylinder 218, the piston 220, the hydraulic fluid 302, the check valve 304 and the cutoff valve 308 collectively form an hydraulic circuit 300. The hydraulic circuit 300 should have a damping coefficient no greater than about 1,391 kg/s to enable the adaptable prosthetic foot 200 to prevent the ankle locking before the adaptable prosthetic foot 200 achieves foot flat. The spring 214 and the hydraulic circuit 300 are configured, i.e., the spring constant and the damping coefficient are selected, to return the prosthetic talocrural joint 208 to a neutral angle within a single swing phase of a human gait. Details about how these values can be calculated, and further details about the adaptable prosthetic foot 200, are provided below.

Analysis

[0066] To explore different ways of passively actuating the slope adaptability of the prosthetic foot 200, gait cycle data were analyzed to study the feasibility of using various measurable characteristics, such as ground reaction force 116, ankle moment, ankle flexion angle

and foot center of pressure 126. We used empirical data from Winter, which was collected from a 56.7kg able-bodied test subject [Ref. 13]. The data were normalized so that they could be applied to subjects of different body weights and sizes. After evaluating Winter's data [Ref. 13], the team determined that the ground reaction force 116 aligned well with the desired timing for activating and deactivating slope adaptability.

[0067] The ground reaction force 116 is split into its horizontal (GRF_y) and vertical (GRF_x) components (Fig. 1) over a gait cycle. The vertical component (GRF_y) is much larger in magnitude than the horizontal component (GRF_x) and is always positive i.e., pointing up. This makes the vertical component of the ground reaction force 116 a suitable candidate for activating the slope adaptability of the slope adaptable prosthetic foot 200. Fig. 4 is a graph 400 of the horizontal (GRF_y) 402 and vertical (GRF_x) 404 ground reaction force components over a single gait cycle. The plot of the vertical (GRF_x) component 404 shows two sharp peaks: one peak 406 right after heel strike, and one peak 408 just before toe off. These peaks 406 and 408 coincide well with the points in time when slope adaptability should be activated and deactivated, respectively.

[0068] Slope adaptability is critical to improving quality of life for individuals living with amputations, as it provides them additional lifestyle flexibility and opportunities, and decreases pressure and potential injury on their bodies. This led the team to develop the concept of utilizing the force from the user's weight through the shank 120 to activate the cutoff valve 308 in the hydraulic circuit 300, enabling slope adaptability in the foot. The team investigated different means to use the weight to activate the cutoff valve 308, including systems employing gears and magnets. Following a preliminary literature review and design analysis of these alternatives, the team determined that a spring-return, push-button style activation would provide a viable solution.

[0069] Figs. 5-8 are side views of the passive and slope adaptable prosthetic foot 200 at three respective sub-phases of a stance phase 102, and after toe off, including corresponding respective schematic diagrams of the hydraulic circuit 300 showing hydraulic fluid flow during the respective sub-phases and after toe off of a human gait cycle (Fig. 1), according to an embodiment of the present invention. As noted, the hydraulic circuit 300 includes a hydraulic cylinder 218 with a piston 220 and spring 214, a one-way valve (check valve) 304 and a cutoff valve 308 connected in parallel. The cutoff valve 308 can be activated and deactivated by an external input to either cut off or allow fluid flow. In this case, the cutoff valve is activated by the user's weight, specifically the ground reaction force 116, and resulting ankle reaction forces. The cutoff valve 308 is normally

open, meaning that if the switch is not depressed (not activated), the valve is open and fluid can flow through it.

[0070] When the heel 240 strikes the ground 106 (Fig. 5), the piston 220 is compressed by the weight of the user. Hydraulic fluid 302 flows through the check valve 304 as indicated by the arrow 306, and this allows the foot to plantar flex 212 to find the ground 106. During this time, the cutoff valve 308 is activated (shut off) by the ankle reaction force, meaning the hydraulic fluid 302 cannot flow from the top chamber 226 to the bottom chamber 228, thus preventing dorsiflexion.

[0071] Once the foot plate 204 is flat on the ground (Fig. 6), the shank attempts to rotate forward and dorsiflex, but the cutoff valve 308 remains activated (shut), as there is still a force acting on the cutoff valve 308 button. As a result, the ankle joint angle (θ) remains constant. Instead of ankle dorsiflexion, the footplate 204 starts to bend (Fig. 7) to allow the shank to move forward. This bending allows the footplate 204 to store energy, to aid in lifting the foot off the ground after toe off (Fig. 8).

[0072] At toe off (Fig. 8), the weight is lifted off the cutoff valve 308, allowing the cutoff valve 308 to open, thereby allowing the hydraulic fluid 302 to flow through the cutoff valve 308, as indicated by arrow 800. The spring 214 urges the piston 220 to extend, allowing dorsiflexion 210 to occur. The spring 214 releases its stored energy at this point, helping the foot to dorsiflex 210 and return to its neutral position in swing phase. Overall, the hydraulic circuit 300 allows the foot to adapt to varying slopes by varying the amount of piston 220 compression.

[0073] The objective of the pressure analysis was to determine the maximum pressures that occurs within the hydraulic circuit. This information is critical to identifying the appropriate components to construct the circuit, which ensures proper function and longevity of the system for the user.

[0074] Our analysis begins with the moments that occur around the center of the ankle. The human ankle's muscles, tendons and ligaments work together to create a moment to balance the moment generated by the ground reaction forces 116. Fig. 9 details the forces acting on the prosthetic ankle and the resulting moments [Ref. 2].

[0075] With this analysis and the ground reaction force 116, ankle angle and ankle location data evaluated previously, it is possible to calculate the moment the hydraulic cylinder 218 must generate to balance the moments generated by the spring 214 and the ground reaction forces 116. Equation 1 is the result of this moment analysis.

$$F_{Cylinder} = \frac{M_{spring} - M_{GRF_1x} - M_{GRF_1y}}{L_{Cylinder}} \quad (1)$$

Equation 2 gives the resulting pressure generated by this force

$$P_{Cylinder} = \frac{F_{Cylinder}}{A_{Cylinder}} \quad (2)$$

[0076] Knowing the pressure in the hydraulic cylinder 218 allows for calculation of the pressure inside the remainder of the hydraulic circuit 300. The cutoff valve 308 and the check valve 304 that control the flow of the hydraulic fluid 302 experience a pressure that depends on both the pressure in the hydraulic cylinder 218 and the geometry of the tubing that connects the valves 304 and 308 to the piston 220. Applying the principle of conservation of energy, it is possible to determine the pressure in the hydraulic piping, as given by Equation 3.

$$P_{Pipe} = P_{Cylinder} + \frac{pv^2_{piston}}{2} - \frac{pv^2_{pipe}}{2} - \frac{pfLV^2_{pipe}}{2D_{pipe}} \quad (3)$$

Completing the analysis described above generated values for the maximum allowable pressure in the hydraulic cylinder (792 psi) and 218 in the piping system (791 psi).

These results are the foundation of the initial hydraulic circuit 300 design.

[0077] The second primary element of the hydraulic circuit 300 design is the energy stored by the system and the energy required to reset the ankle during the swing phase. The addition of the hydraulic cylinder 218 to the prosthetic ankle adds damping and energy loss to the system. It is critical to design this system in a manner such that the damping of the hydraulic circuit 300 does not prevent the user activating the locking mechanism through the application of weight onto the ankle.

[0078] The key factors in the energy analysis are: time available between heel strike 108 and foot flat 110 to lock the ankle; time available during swing phase to reset the ankle, and the energy stored by the foot plate 204; maximum allowable damping coefficient that will allow the foot to lock and reset during the gait cycle; and minimum spring coefficient required to reset the ankle during swing phase.

[0079] The first step in the energy analysis is to determine the time available to allow the foot to “find the surface” between heel strike 108 and foot flat 110 and the time available to reset the ankle while the foot is in swing phase. These times establish the conditions that dictate the maximum allowable damping coefficient and the minimum requirement for the spring constant. If the damping coefficient is too high, the user’s weight is insufficient to achieve foot flat during the available time period. If the spring constant is too low, the ankle cannot reset in the early swing

phase for toe clearance and the ankle cannot prepare for the user's next step. An analysis of the experimental gait cycle data indicates that foot flat occurs approximately 0.086 seconds after heel strike, as indicated in the graph of Fig. 10.

[0080] Due to the previously discussed time analysis, the dynamics of the system may be tuned such that the foot achieves foot flat fast enough for a typical human gait cycle and returns to neutral during a standard swing phase. As a result of this design, it is possible to analyze the hydraulic ankle as a spring-damper system.

[0081] Much like the time analysis, there are two distinct scenarios in which the spring damper system can be analyzed. The first scenario is the heel strike to foot flat phase. In this scenario, the user applies a force to the system by transferring weight onto the foot. Fig. 11 schematically illustrates the ankle modeled as a spring damper system between heel strike and foot flat. Under these conditions, the spring-damper system can be modeled with Equation 4, where β is the damping coefficient, k is the spring constant and x is the distance travelled.

$$F(t) = \beta \dot{x} + kx \quad (4)$$

[0082] The second scenario occurs when the foot is in swing phase. During the swing phase, the user does not apply a force to the spring damper system. In this scenario, the spring-damper system can be modeled by Equation 5.

$$\beta \dot{x} + ks = 0 \quad (5)$$

[0083] The final element of the spring-damper system is to consider the range of motion the system experiences as the spring 214 compresses and the circuit locks (cutoff valve 308 closes). The geometry of the ankle design creates a moment arm (r) between the location of force application into the system and the linkage to the spring-damper system. In addition, experimental results compiled by Hansen, et al. indicate that an existing actively operated slope adaptable foot allows for 16 degrees of plantar flexion (angle θ) as the foot plate finds the ground after heel strike [Ref. 2]. This degree of plantar flexion, combined with the moment arm of the spring-damper system linkage, allows for the calculation of distance the spring compresses after heel strike.

[0084] Given these known dimensions and the previously discussed time value associated with system activation, it is possible to solve for the damping coefficient and the spring constant by solving the above equations as a system of equations. Doing so yields a minimum spring constant value of about 4,352 N/m and a maximum damping coefficient of about 1,391 kg/s. These values

establish the design requirements that should be fulfilled by the design of the hydraulic circuit, spring 214 selection and hydraulic fluid 302 selection.

[0085] The next step in the energy analysis considers the footplate 204 as a cantilever beam in bending that stores and returns energy in the same manner as a spring. The analysis centers on a comparison between a traditional prosthetic ankle and one with a hydraulic circuit that allows for a greater angular deflection by allowing the foot to plantar flex until it locates the ground and then locks to prevent dorsiflexion.

[0086] A traditional prosthetic ankle maintains a 90-degree angle through the gait cycle, and data from Hansen, et al. indicates that the footplate deflects approximately 32 degrees during the gait cycle [Ref. 2]. This deflection was calculated by assuming a beam in bending.

[0087] This analysis indicates that a standard prosthetic ankle with a typical foot plate material stores approximately 45 J during the gait cycle. Equation 6 describes the energy stored in the foot plate 204 as part of a traditional fixed ankle system.

$$E = \frac{1}{2} k \alpha^2 \quad (6)$$

The addition of a hydraulic circuit 300 allows for an additional 16 degrees of bending due to the increased plantar flexion as the foot finds the ground following heel strike, which equates to greater energy storage. The new angle through which the beam bends is the original angle, α , plus the additional angle allowed by the hydraulic system, α_{piston} , as shown in Equation 7.

$$E = \frac{1}{2} k (\alpha + \alpha_{piston})^2 \quad (7)$$

This additional 16 degrees of plantar flexion allows the foot plate to store an additional 34 J of energy. This additional stored energy can be returned to the user during the gait cycle, indicating that this hydraulic system not only provides slope adaptability, but also improved energy storage and return.

Prototype

[0088] A prototype was built as a system of discrete components including piping, fittings and the valves. A cutoff valve manufactured by Clippard with a push button activation system that met design specifications was identified. By locating the push button valve underneath the shank, the user's weight directly activates the cutoff valve 308 in the hydraulic circuit 300.

[0089] To verify the feasibility of using a push button valve to activate a hydraulic circuit, an enlarged version of the circuit was built and affixed to prosthetic foot prototype designed by John Skelton, sent to us by Hansen, et al.

[0090] The system uses a check valve 304 and push button cutoff valve 308 to control the piston 220, and thus the movement of foot relative to the shank. The check valve 304 allows for one-way flow, or plantar flexion 212. The cutoff valve 308, in its normal (open) state, allows for flow in both directions in the hydraulic circuit 300, enabling dorsiflexion 210 and plantar flexion 212. However, when the button 236 is pushed, the cutoff valve 308 closes, preventing flow in either direction. In an embodiment, the push button cutoff valve 308 is located underneath the shank, and activated by the user's weight.

[0091] In the human gait cycle, when the human user strikes his heel against the ground, the push button cutoff valve 308 is activated. Flow is shut off in the dorsiflexion 210 direction, ensuring the ankle is stiff as the foot rolls over across the ground 106. However, the check valve 306 enables plantar flexion 212, allowing the foot to adjust to the slope of the ground 106 as it rolls over.

[0092] Upon toe-off 112, the user's weight is shifted to the other foot, releasing the push button cutoff valve 308. With the aid of a spring (not visible) under the upper rocker 238, the foot is restored to a neutral (resting) position (angle).

[0093] The prototype demonstrated feasibility of the hydraulic circuit 300 in controlling the movement of the foot and shank. Next, the team worked on the integration of this circuit with the rest of the foot in a compact, secure manner. Three potential solutions were investigated: a rotary hydraulic system, a manifold design and a smaller scale pipe and valve system. Ultimately, the team selected the manifold design due to the relative ease of manufacturing and its ability to withstand the high pressures in the system (over 800 psi).

[0094] The design of the hydraulic circuit 300 is based upon the pressure and energy evaluation above. The spring previously used by Hansen, et al. in an actively operated hydraulic ankle was selected as it provided significant stiffness at 25,000 N/m, although springs with other suitable stiffnesses, such as at least about 5,000 N/m, 10,000 N/m or 20,000 N/m, may be used. This spring also met the energy and pressure requirements discussed previously. Maintaining consistency between the Hansen, et al. components was deemed useful as it provides a means to compare the active and passive models.

[0095] The hydraulic fluid 302 should be selected, based upon the maximum allowed damping coefficient for the system. The Hagen-Poiseuille equation describes the relationship between the change in pressure and the dynamic viscosity of a fluid (Equation 8):

$$\Delta P = \frac{8\mu LA_{piston}v}{\pi r^4} \quad (8)$$

It is possible to solve for the force acting on the hydraulic piston 220 based on the piston's area, and rearranging Equation 8 provides the following relationships (Equations 9, 10, 11) exerted on the piston 220 by the hydraulic fluid 302 and the dynamic viscosity of the hydraulic fluid 302:

$$F = \Delta P A_{piston} \quad (9)$$

$$F = \beta v \quad (10)$$

Where

$$\beta = \frac{\mu LA_{piston}^2 v}{\pi r^4} \quad (11)$$

[0096] Selecting mineral oil with a viscosity of 0.00618 Pa·s yields a damping coefficient of about 415 kg/s, which meets the previously determined requirement that the damping coefficient be below 1,391 kg/s. Hansen, et al. also uses mineral oil. Consistency between hydraulic fluids allow for comparison between models and prototypes.

[0097] To show that the hydraulic cylinder 218 creates a damping system for the piston 220, the team needed to prove that there is laminar flow in the piston cylinder 218. The damping mainly occurs in the cylinder 218 containing the piston 220. The team disregarded other parts of the hydraulic circuit 300, including the interior pipes of a manifold (not visible) and tubing 230 and 232 connecting the piston cylinder 218 to the manifold.

[0098] Next, the team calculated the Reynolds number to determine if the flow is laminar or turbulent, see Equation 12. The density and absolute viscosity of the mineral oil are known. The inside diameter of the cylinder 218 used in the prototype is 0.025 meters. The velocity is determined based on data from Winter [Ref. 13] on the speed of the piston 220, relative to the cylinder 218, during the gait cycle. Using these values, the Reynolds number was determined to be 623 (dimensionless number), which is less than 2,000, classifying the flow in the piston as laminar.

$$Re = \frac{\rho * V * d}{\mu} = 623 \quad (12)$$

[0099] To test our assumption that the piston 220 acts as a hydraulic damper, the team determined if the flow is fully developed in the cylinder 218. Upon testing, it was determined, the

flow is not fully developed, because the cylinder 218 is far shorter than the minimum entrance length for fully developed laminar flow, as shown in Equation 13.

$$Le = 0.06 * Re * d = 0.9345 \text{ m} \quad (13)$$

Because the flow is not fully developed, the damping experienced by the real system is higher than calculated. We believe our model is, never the less, still useful as a first order approximation of the hydraulic system, and we selected mineral oil as the hydraulic fluid 302 because it provides a conservative damping coefficient for the system. The mineral oil provides a damping coefficient that is significantly less than the maximum constraint previously calculated (415 kg/s to meet a maximum constraint of 1,391 kg/s).

[0100] The manifold was machined from aluminum, and a Clippard switch-activated valve was placed into the manifold to create the cutoff valve 308. The one-way check valve 306 was constructed of a pin with a neoprene ball of 4.7625 mm (3/16-inch) diameter. This rubber ball is seated above a restriction in the pipe diameter. When hydraulic fluid 302 flows up through the pipe, the ball is lifted away from the diameter restriction, allowing the hydraulic fluid 302 to flow. Hydraulic fluid 302 attempting to flow the other way is blocked by the ball as the ball rests against the diameter restriction and obstructs flow.

[0101] Another prototype utilized a footplate, piston and shank attachment piece from John Skelton's model. The keel was redesigned and split into a rocker piece and an upper keel, housing the manifold in between. Both pieces were machined out of aluminum using a water jet and mill. A cutout was created in the rocker to reduce its weight. The manifold was affixed to the rocker using bolts through the back of the rocker and through the footplate. Part of the accumulator piece from Skelton's model was affixed to the front of the manifold.

[0102] The switch-activated cutoff valve 308 allows the user to apply weight to the ankle and prevent the hydraulic cylinder from extending. This cutoff valve 308 is normally opened, meaning that if the spring-retained push button 236 is not depressed, the cutoff valve 308 is open and hydraulic fluid 302 can flow through the cutoff valve 308. When the user applies weight to the ankle at heel strike, this force is transferred through the pylon and pyramid to the ankle through the upper rocker 238. This upper rocker 238 rests on a spring (not visible) and slides vertically on two shoulder bolts 240 and 242 that constrain the upper rocker's motion. When the user applies weight to the ankle, the upper rocker 238 moves downward on the shoulder bolts 240 and 242 and depresses the spring-retained push button 236, thereby closing the cutoff valve 308. Closing this

cutoff valve 308 prevents dorsiflexion 210, but allows the ankle to plantar flex 212 due to the one-way check valve 306. This plantar flexion 212 allows the footplate 204 to find the walking surface 106.

[0103] The system was filled with hydraulic fluid upon completing fabrication. Air was bled from the system through an iterative process. The system was checked for leaks and left over night to allow for slow leaks to become apparent. Once leaks were resolved, the team conducted proof of concept testing.

Proof of concept testing

[0104] The two primary objectives of the prosthetic foot were passive operation and slope adaptability. By achieving these two objectives, the current state of the art foot could be improved upon using this type of hydraulic circuit 300, with the above-described spring constant and damping coefficient, to improve the quality of life for individuals living with amputations. Due to the design and construction of the foot, the device is passive. To test the slope adaptability, the team considered testing several variables, including incline, walking speed, load and surface type. After discussions with partners, it was determined that incline was the only critical variable to proving the concept.

[0105] The team tested devices on three inclines: 16 degrees uphill, 16 degrees downhill, and level ground. Sixteen degrees was identified as the testing angle because that is the estimated improvement the hydraulic ankle could expect to achieve over a standard prosthesis, as presented in the energy calculations above. To conduct effective testing, the team worked with Hansen, et al. and reviewed Skelton's thesis to develop a methodology that would remove variation in angles recorded when the foot first achieves heel strike.

[0106] The trials on each incline were completed ten times. Upon heel strike, the team measured the angle between the shank and the footplate with a digital angle finder. After plantar flexion, the team again measured the angle between the shank and the footplate. The difference in these two values provided the plantar flexion angle. Fig. 12 presents data collected through the testing, including the averages and 95% confidence intervals, where sample size $n = 10$.

[0107] These data show that the prosthesis achieved an average of 17.7 degrees, 15.9 degrees and 16.3 degrees for uphill, downhill and level ground inclines, respectively. The team believes this proves the hydraulic circuit concept, and our parameter values, in that each foot can reach approximately 16 degrees on each incline. This means the hydraulically operated foot can achieve on average 16 degrees more plantar flexion than the standard prosthetic foot. This provides

significantly increased slope adaptability, which will therefore increase flexibility and expand lifestyle opportunities for individuals living with prosthetics.

[0108] The team confirmed this data by conducting a strategic evaluation of the hydraulic foot at four critical locations in the gait cycle: heel strike, foot flat, toe off and swing phase. During this strategic evaluation, the team measured the angles between the shank and footplate, similar to above. The team also measured the time it took to reset the ankle after toe off, during swing phase. As mentioned previously, this timing is critical because if the ankle does not reset prior to heel strike, the user does not gain the full benefit of the hydraulic foot. In measuring this time, the team found that the ankle reset nearly immediately after the load was removed, therefore proving that the foot would have ample time to reset prior to heel strike.

[0109] The foot may be manufactured primarily from aluminum. However, aluminum may be too heavy. Other materials, such as composites, may be used to construct all or parts of the passive and slope adaptable prosthetic foot 200.

[0110] A shock absorber or a rotary hydraulic system may be used in place of the piston 220 and cylinder 218.

[0111] This passive hydraulic circuit 300 makes it possible for individuals using prostheses to adapt to varying slopes and changing terrain in one step. Current prosthetic feet available on the market that are slope adaptable are actively operated, making them heavy, expensive and impractical. Available prosthetic feet that are passively operated do not have the functionality required to quickly adapt to changing slopes. This hydraulic circuit 300, and our parameters, provides the functionality required to operate the foot passively and provide the slope adaptation capabilities. This provides individuals using the prosthetic foot with increased mobility and stability, therefore improving their quality of life.

[0112] Hydraulically operated prosthetic systems can be passively activated and the increased energy storage due to the hydraulic circuit operation.

[0113] This work proves that passively operated hydraulic systems can be used within a prosthetic foot. Using the individual's body weight and resulting ground reaction forces, the circuit can be passively activated to engage the system. The locking mechanism activated by the weight allows the user to safely complete a roll-over of the foot before unlocking at toe-off. The spring mechanism that supplements the hydraulic circuit provides the force required to pull the foot back into position prior to the following heel strike.

[0114] Additionally, this work proves that more energy can be stored in the footplate, such that the energy consumed by the hydraulic system does not exceed the energy stored in the footplate. This finding is valuable because it shows that users may be able to use this prosthetic foot regularly, therefore enjoying the improved stability and functionality, without adding the burden of additional energy required per step.

[0115] This circuit may be used in other hydraulically operated prosthetic feet. These feet may provide users with increased mobility and stability at a low cost of energy dissipation. Overall, this prosthetic foot has the capability of improving quality of life for individuals using prosthetics.

Citations

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[0128] [Ref. 13] Winter, David A. *Biomechanics and Motor Control of Human Movement*. 1st ed. New York, N.Y. [etc.]: Wiley, 2009.

[0129] [Ref. 14] Modified from graphic provided by A. H. Hansen.

[0130] [Ref. 15] Mauch, Hans A. “The Development of Artificial Limbs for Lower Limbs.” *Bulletin of Prosthetics Research* (1974): pp. 158-16.

[0131] While the invention is described through the above-described exemplary embodiments, modifications to, and variations of, the illustrated embodiments may be made without departing from the inventive concepts disclosed herein. For example, although specific parameter values, such as dimensions and materials, may be recited in relation to disclosed embodiments, within the scope of the invention, the values of all parameters may vary over wide ranges to suit different applications. Unless otherwise indicated in context, or would be understood by one of ordinary skill in the art, terms such as “about” mean within $\pm 20\%$.

[0132] As used herein, including in the claims, the term “and/or,” used in connection with a list of items, means one or more of the items in the list, i.e., at least one of the items in the list, but not necessarily all the items in the list. As used herein, including in the claims, the term “or,” used in connection with a list of items, means one or more of the items in the list, i.e., at least one of the items in the list, but not necessarily all the items in the list. “Or” does not mean “exclusive or.”

[0133] Disclosed aspects, or portions thereof, may be combined in ways not listed above and/or not explicitly claimed. In addition, embodiments disclosed herein may be suitably practiced,

absent any element that is not specifically disclosed herein. Accordingly, the invention should not be viewed as being limited to the disclosed embodiments.

CLAIMS

What is claimed is:

1. A passive prosthetic ankle for mechanically coupling a leg (201) of a human user to a foot that, in use, are subject to a ground reaction force (116) that acts on the foot and whose magnitude varies as a result of a gait of the human user, the prosthetic ankle including:

a prosthetic talocrural joint (208) configured to pivotally couple the leg (201) to the foot to permit dorsiflexion (210) and plantar flexion (212);

a spring (214) mechanically coupled to the leg (201) and the foot, such that pivoting of the prosthetic talocrural joint (208) deflects the spring (214);

an hydraulic cylinder (218) defining a volume;

a piston (220) linearly reciprocable within the hydraulic cylinder (218) volume and hydraulically dividing the hydraulic cylinder (218) volume into a first chamber (226) having a first chamber volume and a second chamber (228) having a second chamber volume;

wherein the hydraulic cylinder (218) and the piston (220) are mechanically coupled to the leg (201) and to the foot, such that pivoting of the prosthetic talocrural joint (208) moves the piston (220) within the hydraulic cylinder (218) to alter the first chamber (226) volume and the second chamber (228) volume;

an hydraulic fluid (302) disposed in the first chamber (226) and in the second chamber (228);

a check valve (304) hydraulically coupled between the first chamber (226) and the second chamber (228) to permit flow of the hydraulic fluid (302) through the check valve (304) only during plantar flexion (212) of the prosthetic talocrural joint (208); and

a normally-open cutoff valve (308) hydraulically coupled in parallel with the check valve (304) to permit, when the cutoff valve (308) is open, flow of the hydraulic fluid (302) through the cutoff valve (308) during both dorsiflexion (210) and plantar flexion (212) of the prosthetic talocrural joint (208) and configured to passively close in response to the ground reaction force (116);

characterized in that:

the spring (214) has a spring constant of at least about 4,352 N/m; and

the spring (214), the hydraulic cylinder (218), the piston (220), the hydraulic fluid (302), the check valve (306) and the cutoff valve (308) collectively form an hydraulic circuit (300) having a damping coefficient no greater than about 1,391 kg/s.

2. A prosthetic ankle according to claim 1, wherein the cutoff valve is configured to close within about 0.086 seconds of foot flat of the gait of the user.
3. A prosthetic ankle according to any previous claim, wherein the spring and the hydraulic circuit are configured to return the prosthetic talocrural joint to a neutral angle within a single swing phase of a human gait.
4. A prosthetic ankle according to any previous claim, wherein the spring is configured to urge the prosthetic talocrural joint to return to an equilibrium point.
5. A prosthetic ankle according to any previous claim, wherein the spring has a spring constant of at least about 5,000 N/m.
6. A prosthetic ankle according to any previous claim, wherein the spring has a spring constant of at least about 10,000 N/m.
7. A prosthetic ankle according to any previous claim, wherein the spring has a spring constant of at least about 20,000 N/m.
8. A prosthetic ankle according to any previous claim, wherein the spring is configured to urge the prosthetic talocrural joint to pivot in dorsiflexion.
9. A prosthetic ankle according to any previous claim, wherein the prosthetic talocrural joint is capable of plantar flexion of at least about 32°.
10. A prosthetic ankle according to any previous claim, further comprising a resilient foot plate.

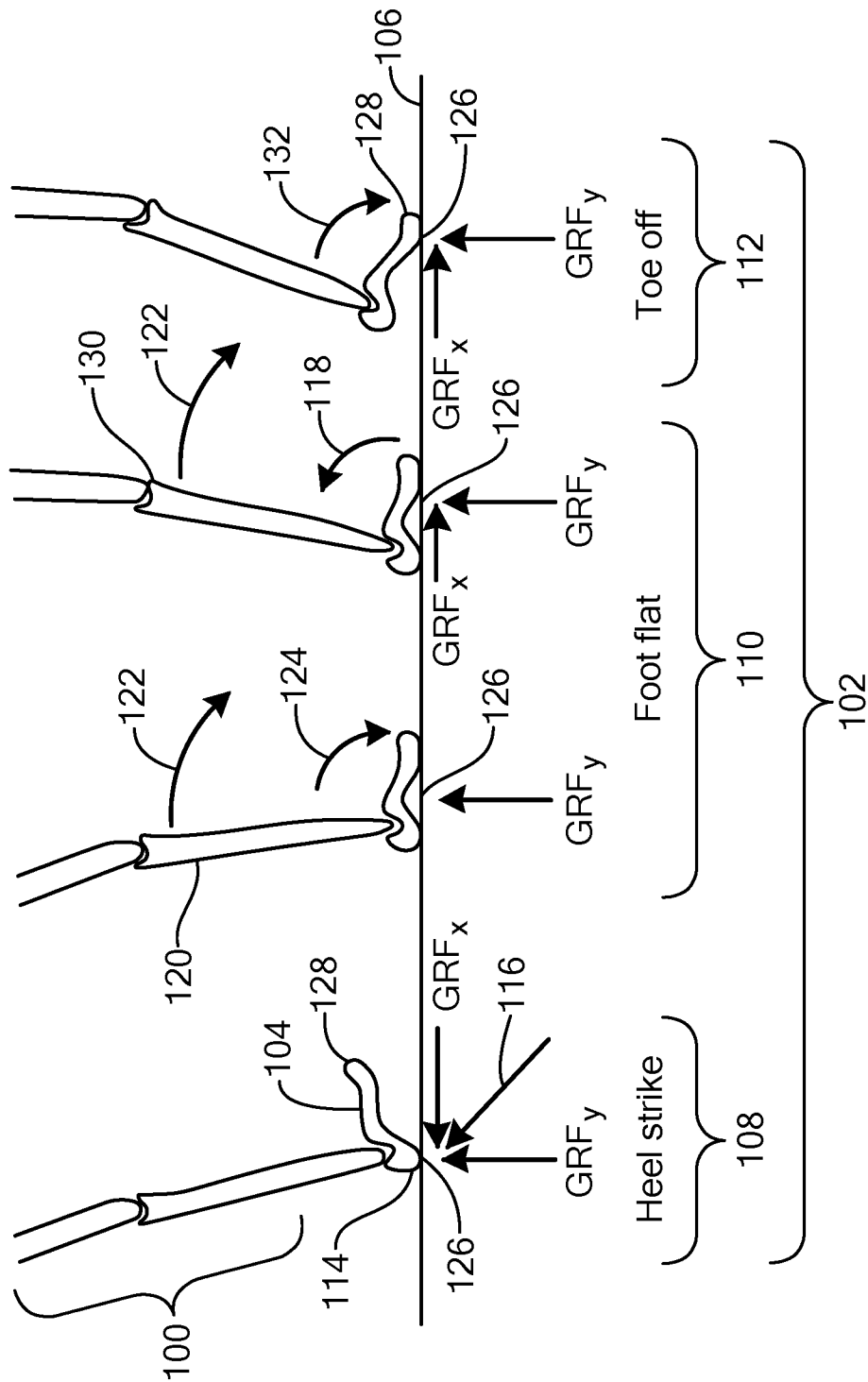


FIG. 1
(Prior Art)

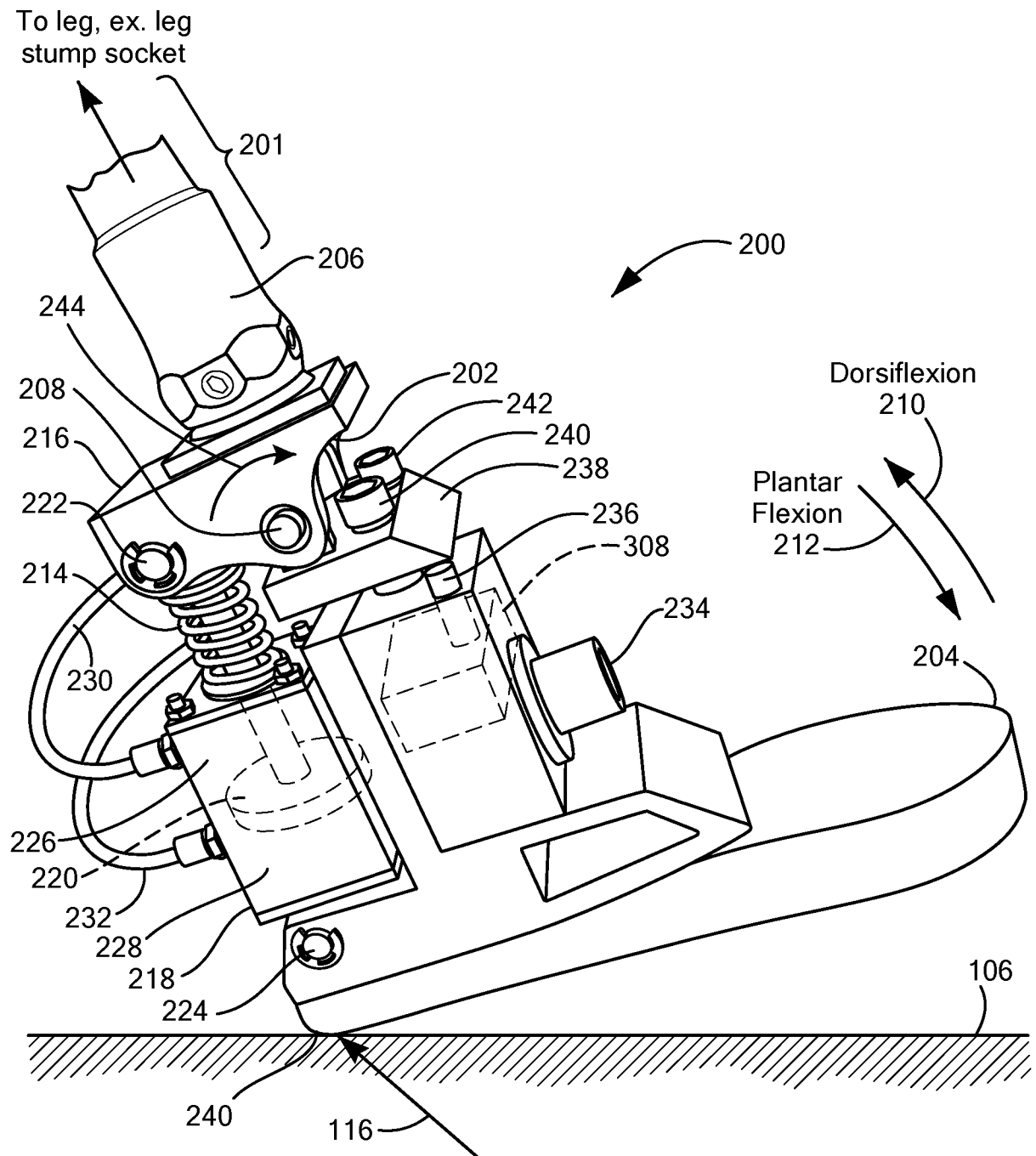
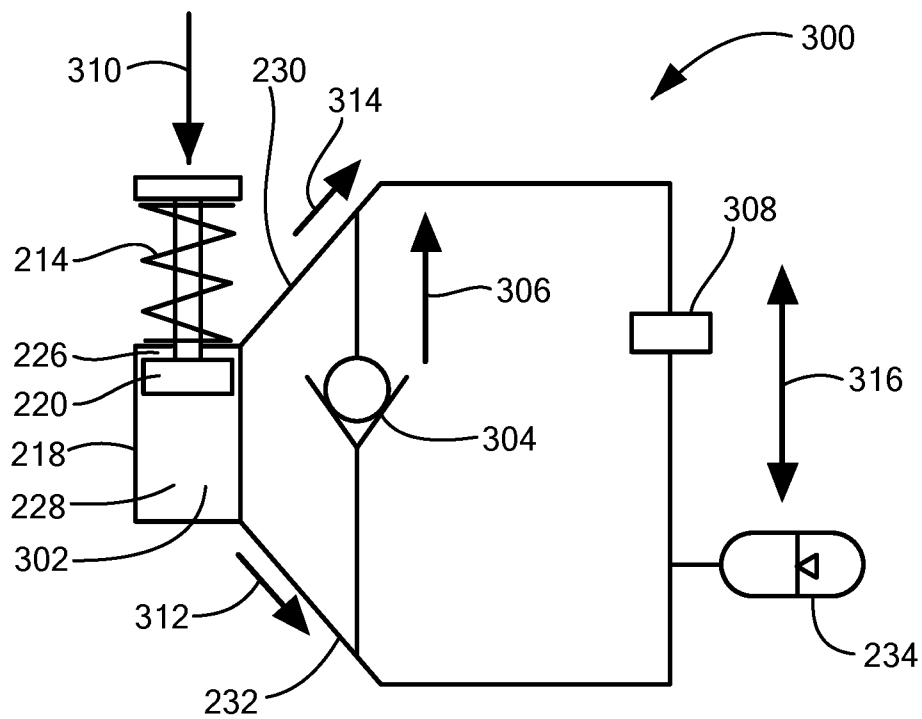
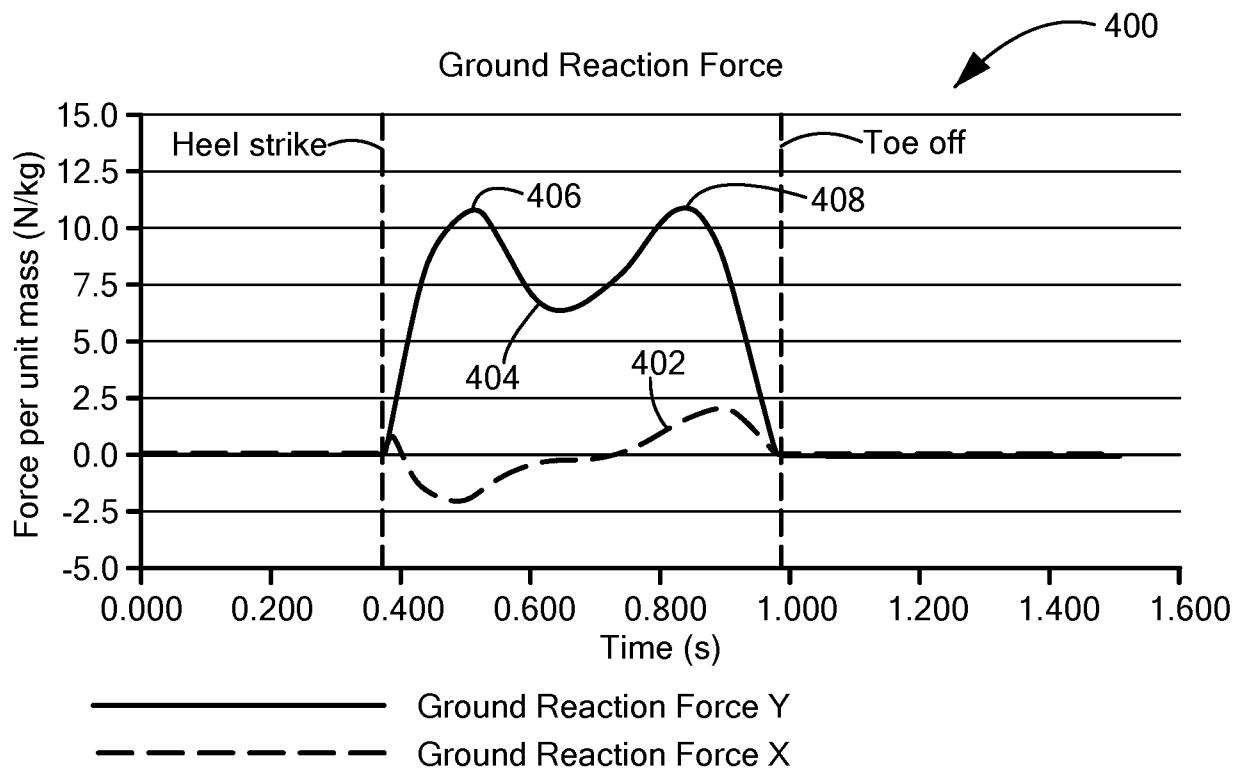


FIG. 2

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**FIG. 3****FIG. 4**

(Prior Art)

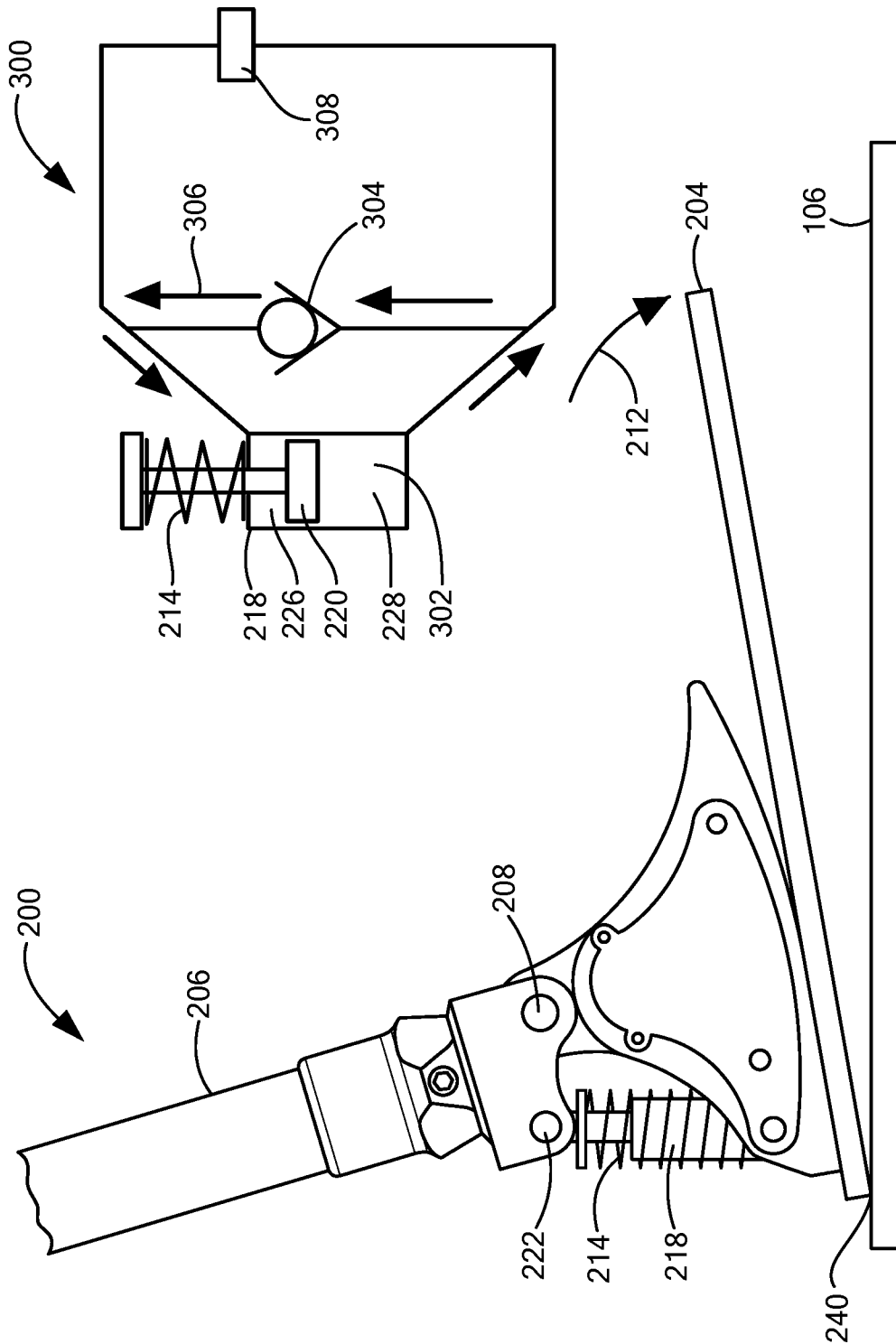


FIG. 5

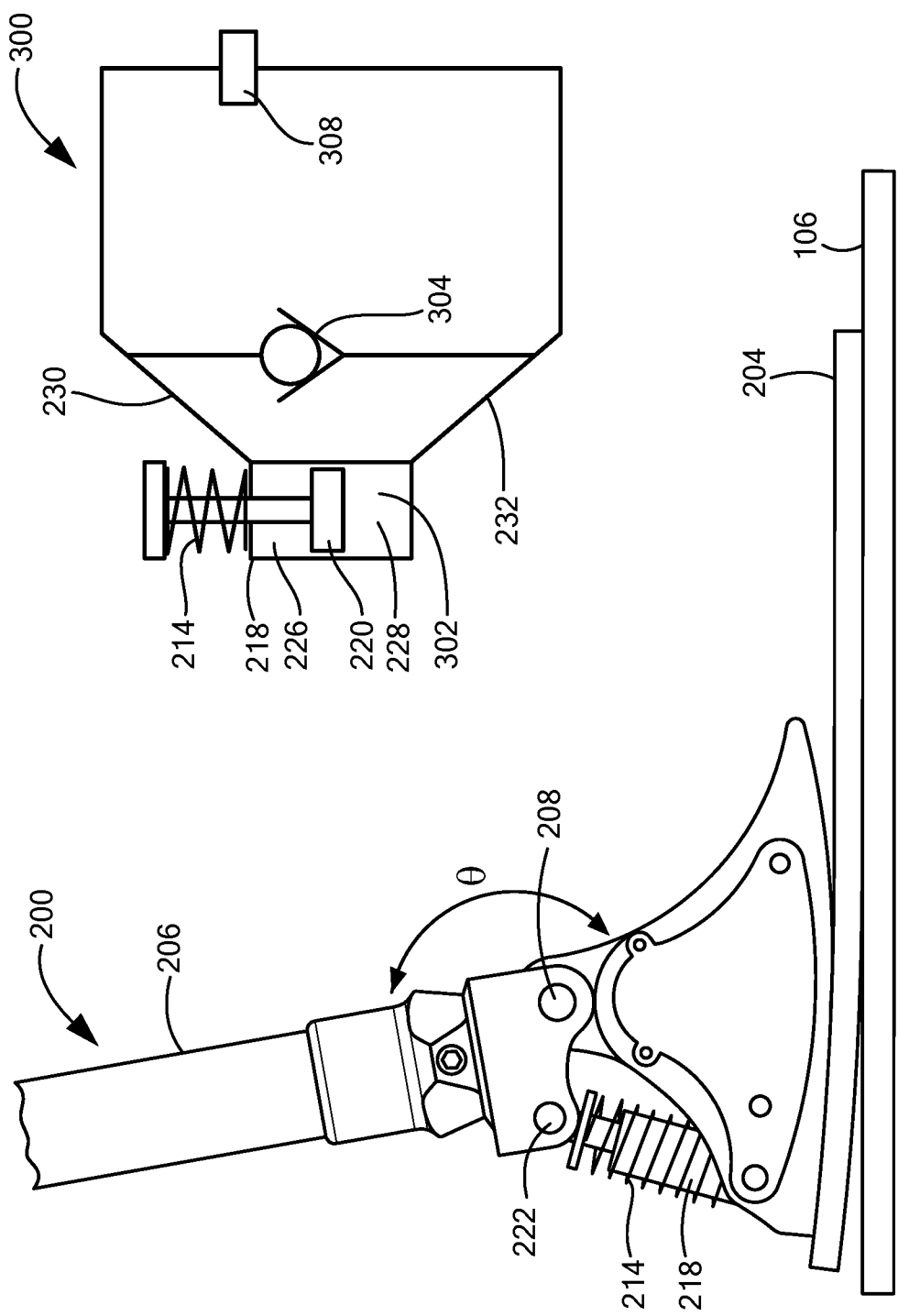


FIG. 6

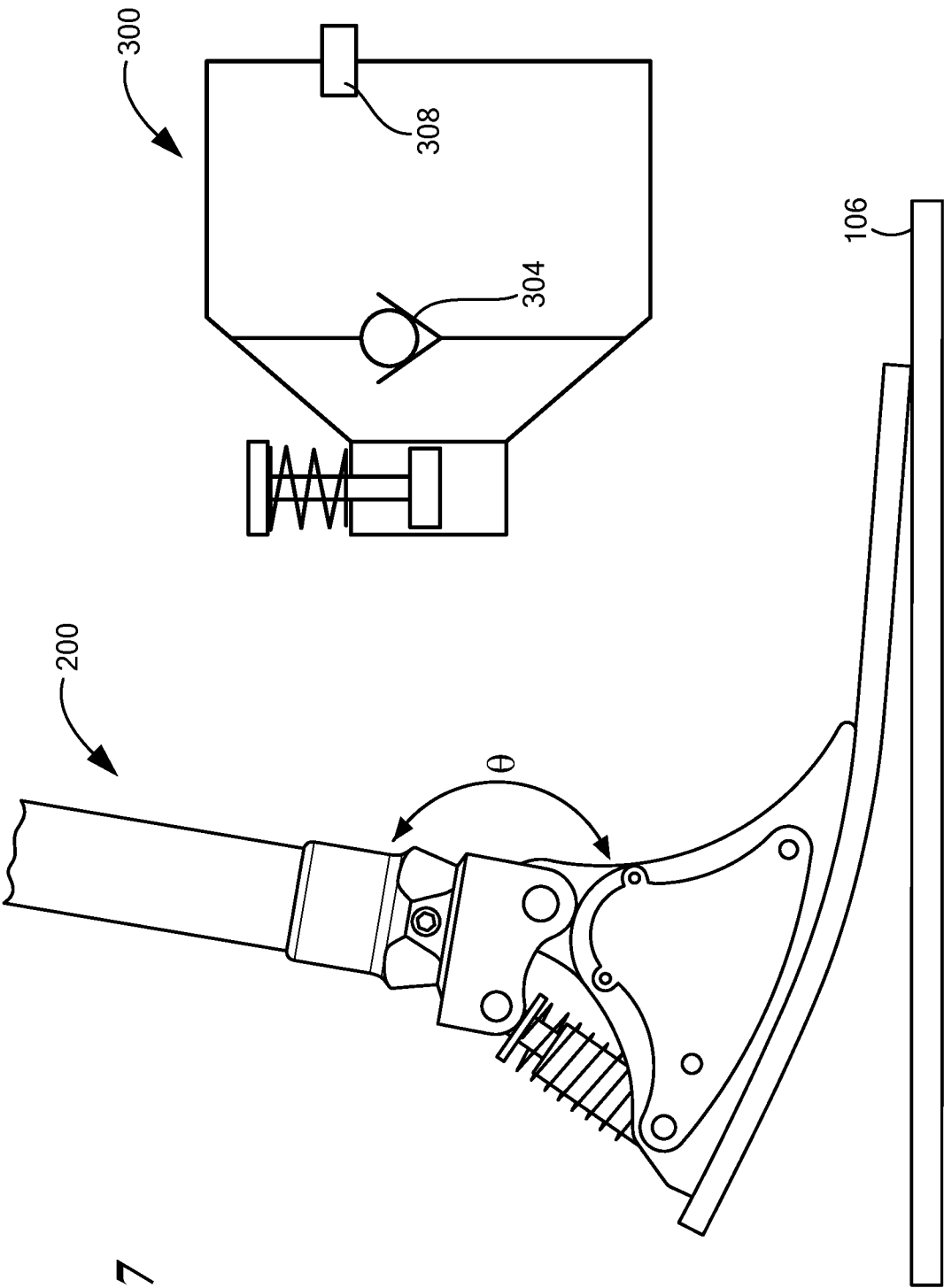


FIG. 7

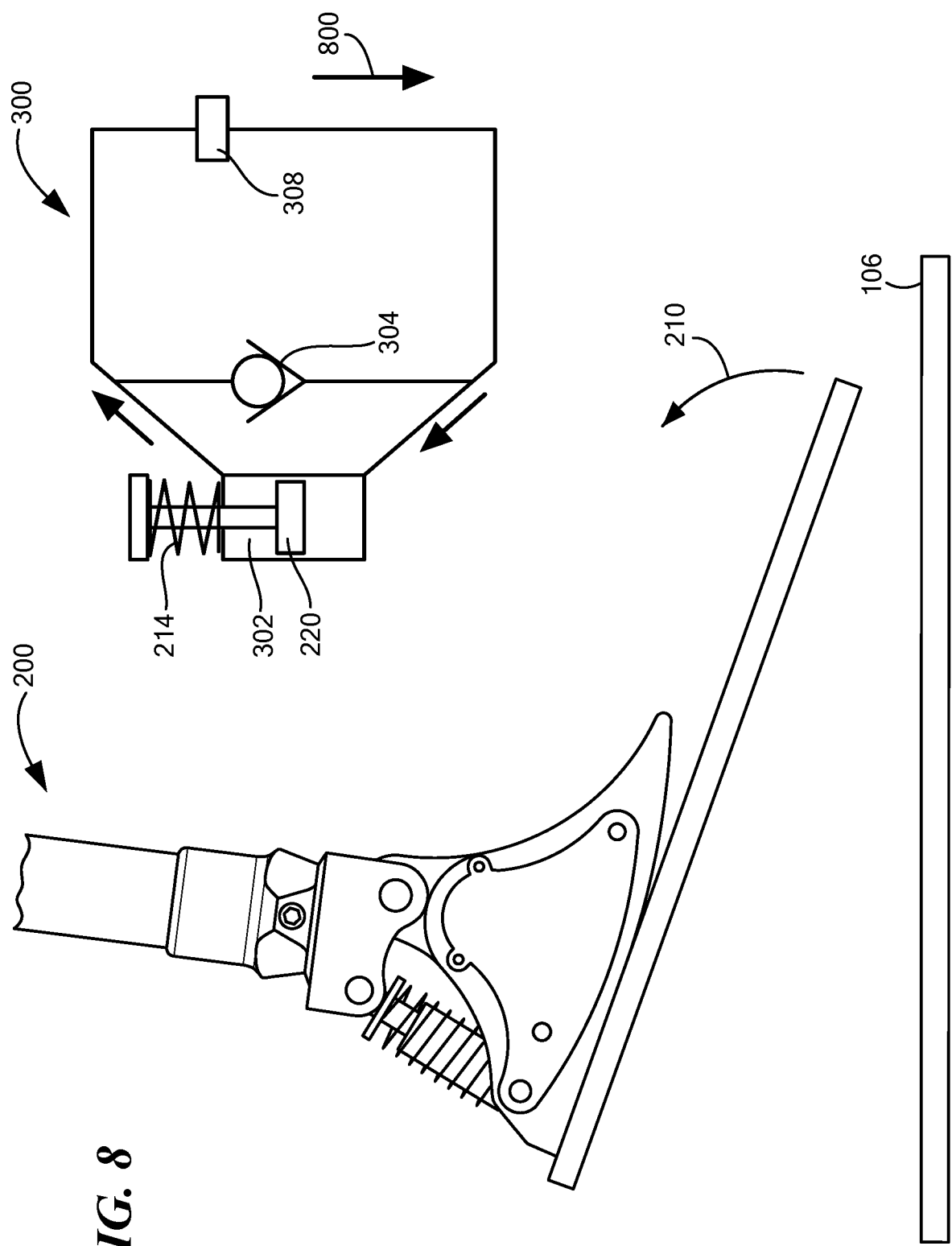


FIG. 8

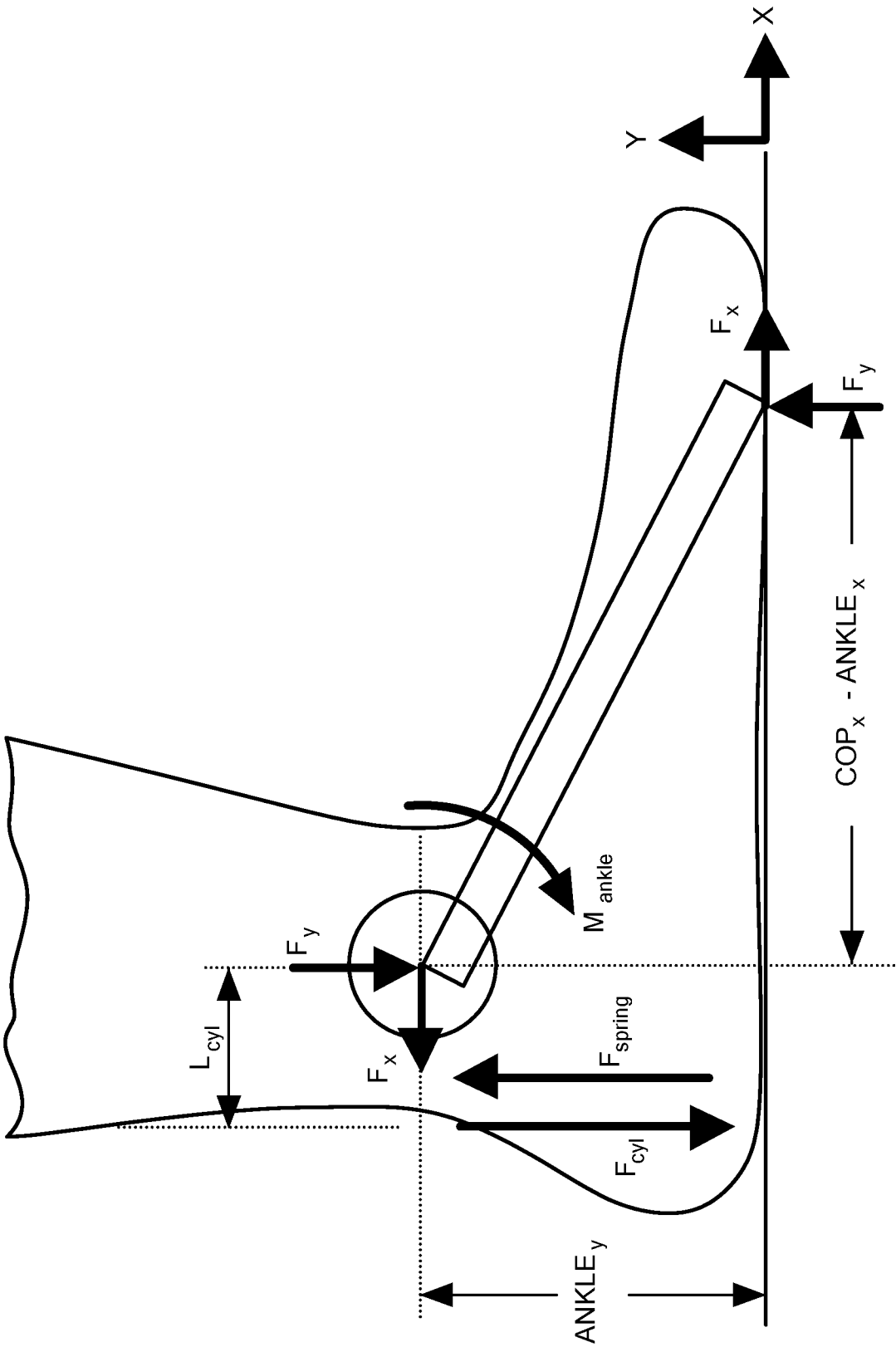
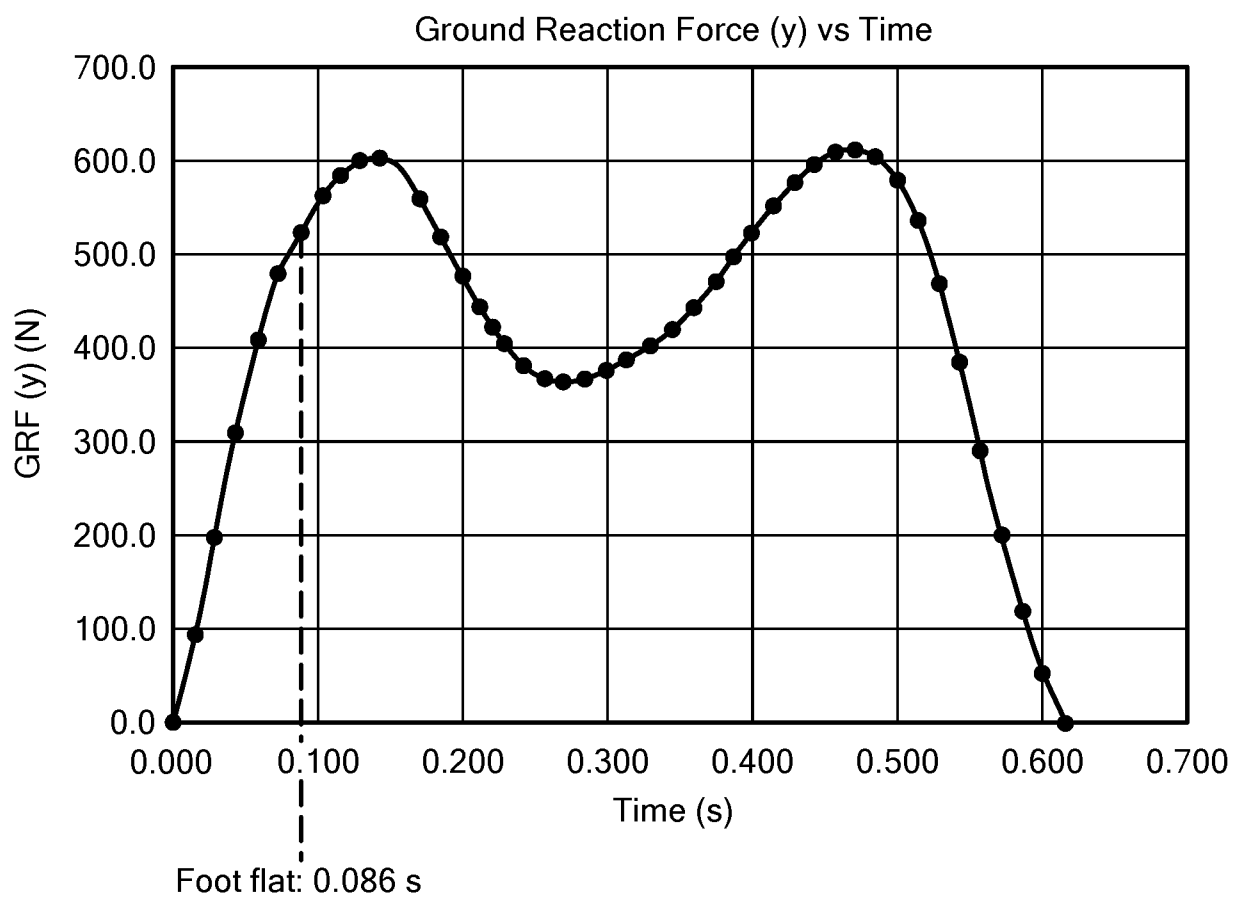
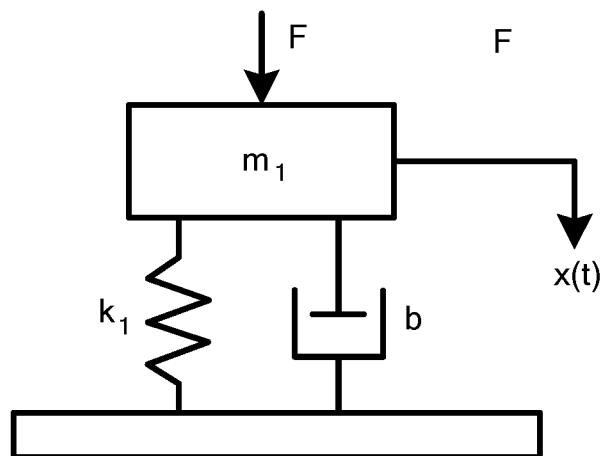
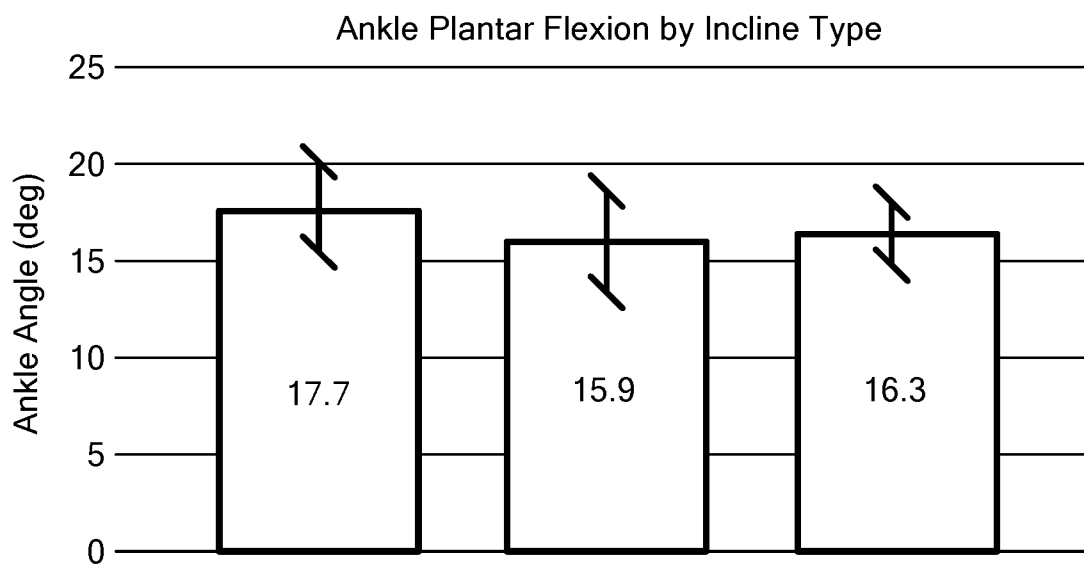


FIG. 9

***FIG. 10***

10/10

**FIG. 11****FIG. 12**

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/045219

A. CLASSIFICATION OF SUBJECT MATTER

INV. A61F2/66

ADD. A61F2/50 A61F2/74

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A61F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2017/156894 A1 (HANSEN ANDREW H [US] ET AL) 8 June 2017 (2017-06-08)	1-7,9,10
A	paragraph [0045] - paragraph [0057] claims 1-7; figures 1,7,8	8
A	----- WO 2011/117033 A1 (MOBBILI DINELLO [IT]) 29 September 2011 (2011-09-29) the whole document ----- -/--	1-10



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

18 October 2018

Date of mailing of the international search report

29/10/2018

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Lickel, Andreas

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2018/045219

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>ANDREW K LAPRE ET AL: "Simulation of a slope adapting ankle prosthesis provided by semi-active damping", ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY,EMBC, 2011 ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE, IEEE, 30 August 2011 (2011-08-30), pages 587-590, XP032318710, DOI: 10.1109/IEMBS.2011.6090110 ISBN: 978-1-4244-4121-1 the whole document</p> <p>-----</p>	1-10

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2018/045219

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2017156894	A1	08-06-2017	NONE

WO 2011117033	A1	29-09-2011	IT 1398912 B1 28-03-2013
		WO 2011117033 A1	29-09-2011
