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(54) **POWERED ARTIFICIAL KNEE WITH AGONIST-ANTAGONIST ACTUATION**

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(63) Continuation-in-part of application No. 12/608,627, filed on Oct. 29, 2009, said application No. 12/608,627 is a continuation of application No. 11/642,993, filed on Dec. 19, 2006, now abandoned, which is a continuation-in-part of application No. 11/395,448, filed on Mar. 31, 2006, which is a continuation-in-part of application No. 11/495,140, filed on Jul. 29, 2006, which is a continuation-in-part of application No. 11/600,291, filed on Nov. 15, 2006, which is a continuation-in-part of application No. 11/499,853, filed on Aug. 4, 2006, now Pat. No. 7,313,463, which is a continuation-in-part of application No. 11/395,448, filed on Mar. 31, 2006, Continuation-in-part of application No. 11/395,448, filed on Mar. 31, 2006, Continuation-in-part of application No. 11/495,140, filed on Jul. 29, 2006, which is a continuation-in-part of application No. 11/395,448, filed on Mar. 31, 2006, Continuation-in-part of application No. 11/600,291, filed on Nov. 15,

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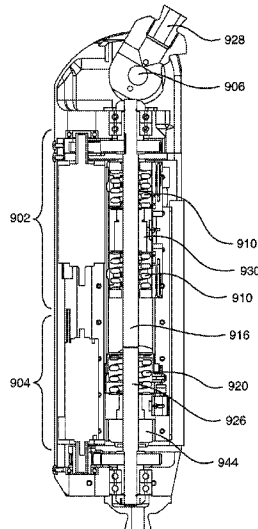
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(52) **U.S. Cl.** **623/39**

(57) **ABSTRACT**

A knee prosthesis comprises an agonist-antagonist arrangement of two series-elastic actuators in parallel, including a knee joint, flexion and extension actuators connected to the joint in parallel with a leg member, and a controller for independently energizing the actuators to control the movement of the knee joint and leg. The flexion actuator comprises the series combination of a flexion motor and a flexion elastic element and the extension actuator comprises the series combination of an extension motor and an extension elastic element. Sensors provide feedback to the controller. The flexion actuator and the extension actuator may be unidirectional, with the flexion and extension elastic elements being series springs. The extension actuator may alternatively be bidirectional, with the extension elastic element being a set of pre-compressed series springs. Alternatively, the flexion elastic element may be a non-linear softening spring and the extension elastic element may be a non-linear hardening spring.



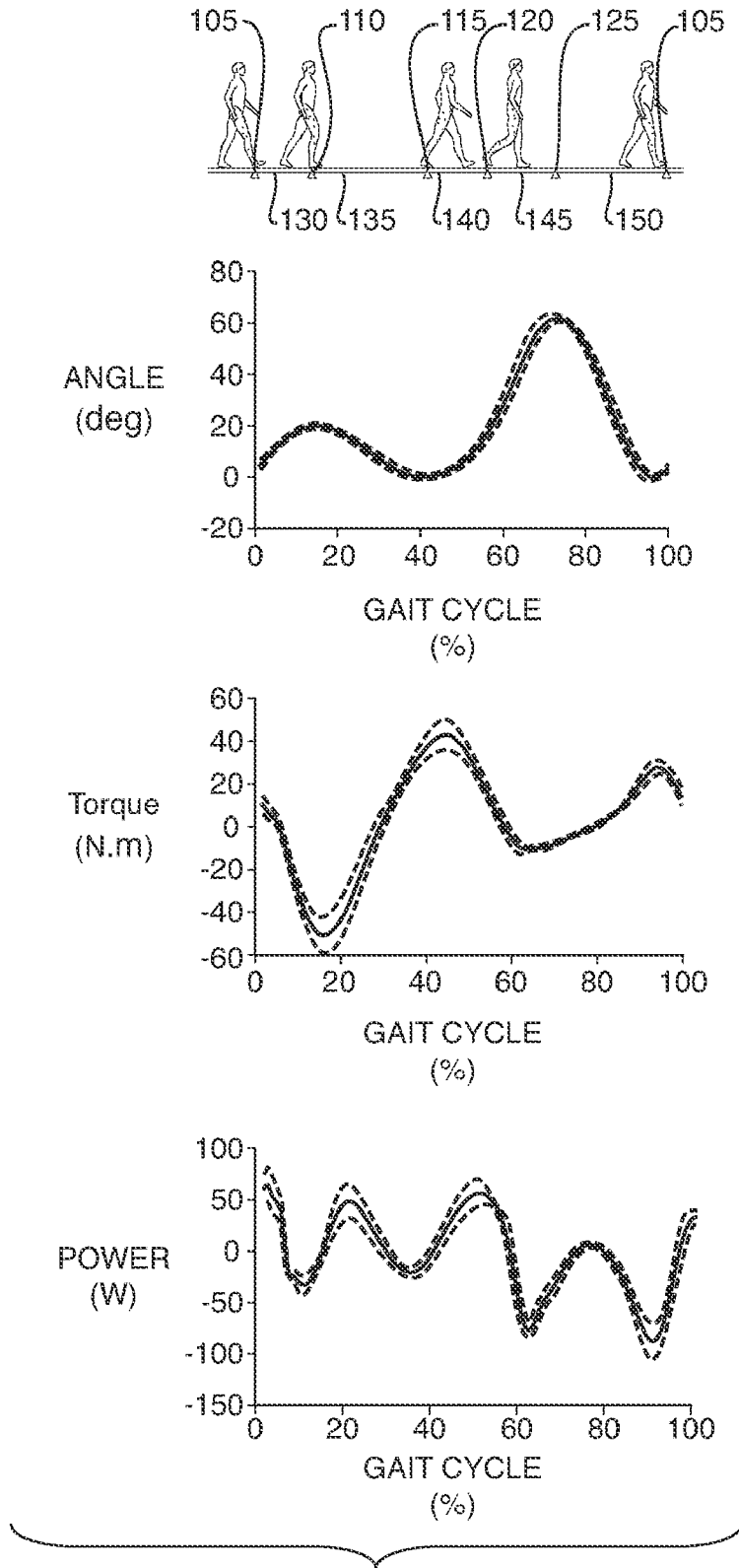


FIG. 1A

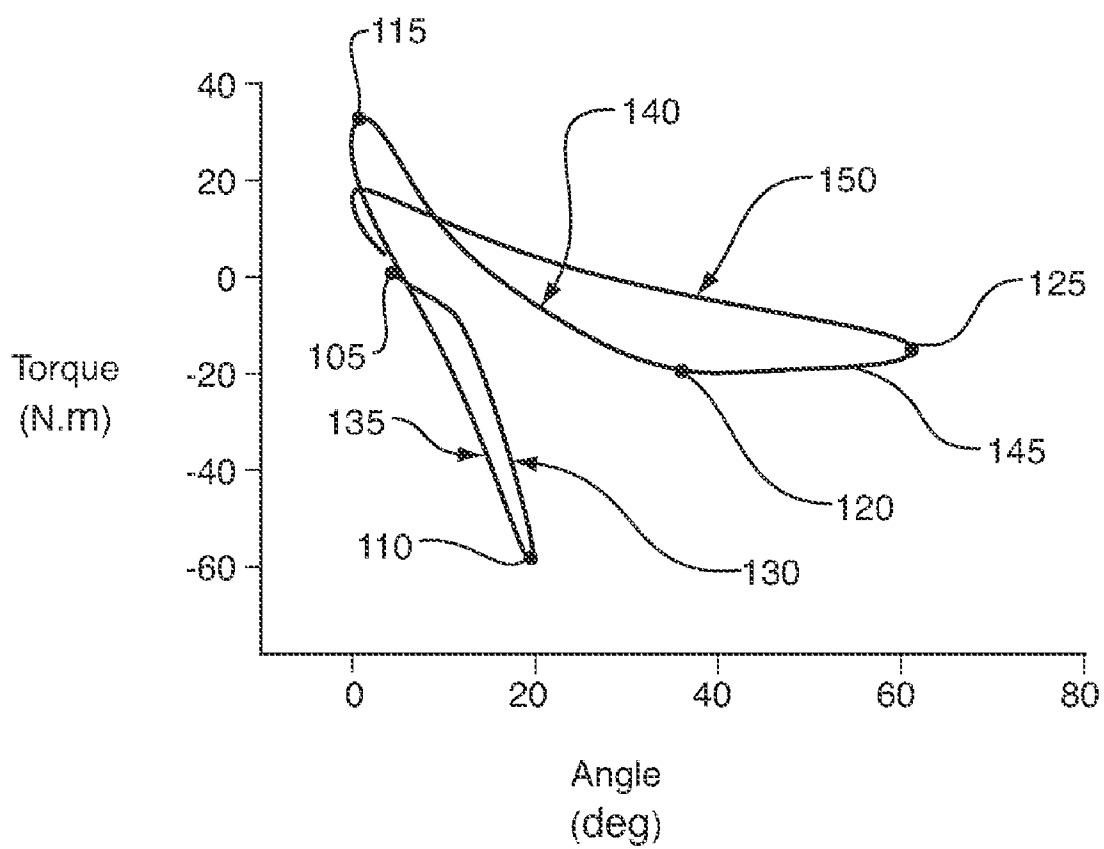


FIG. 1B

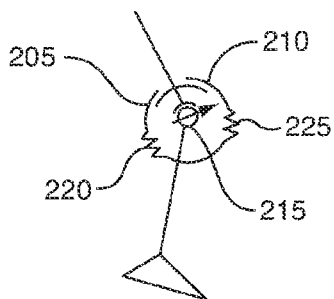


FIG. 2A

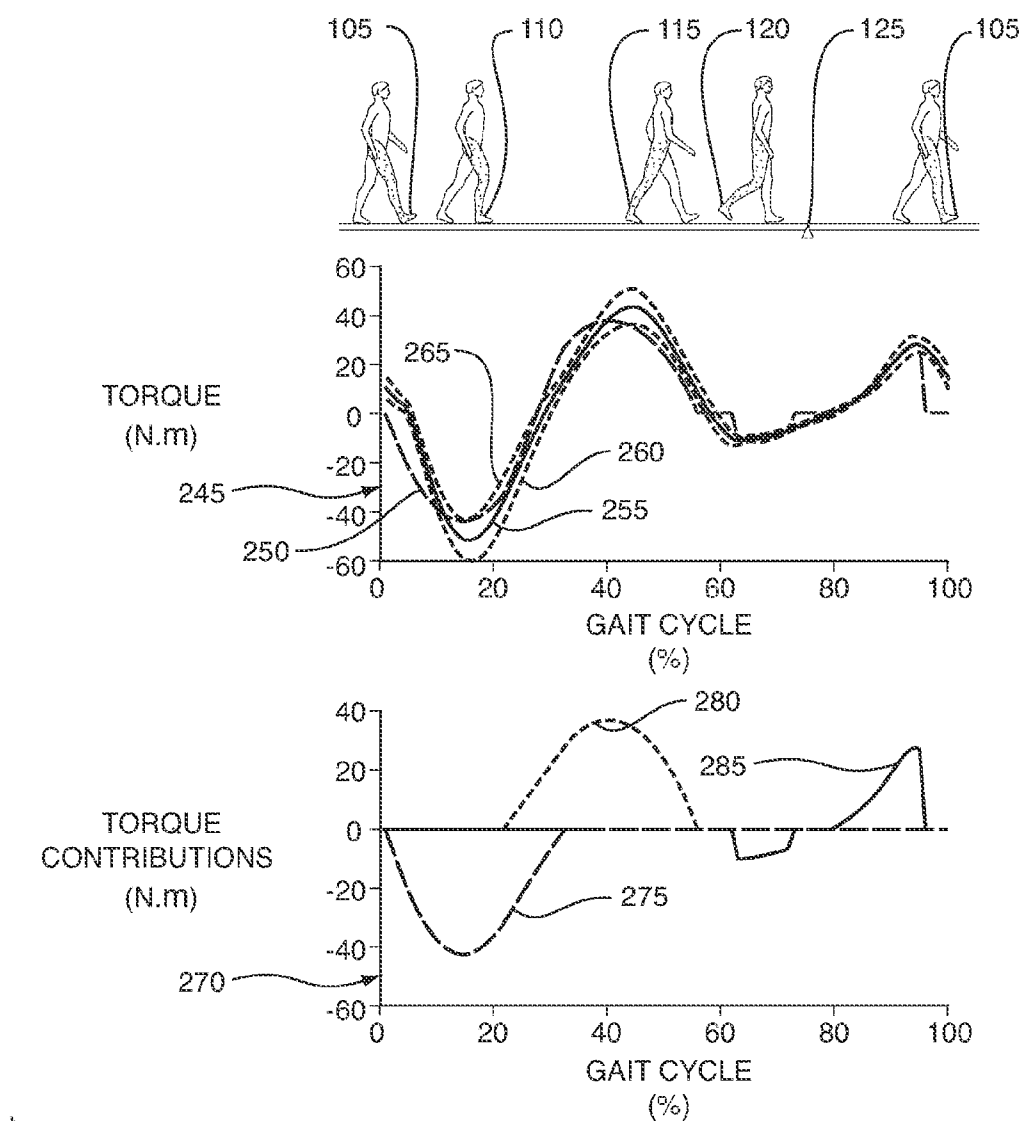


FIG. 2B

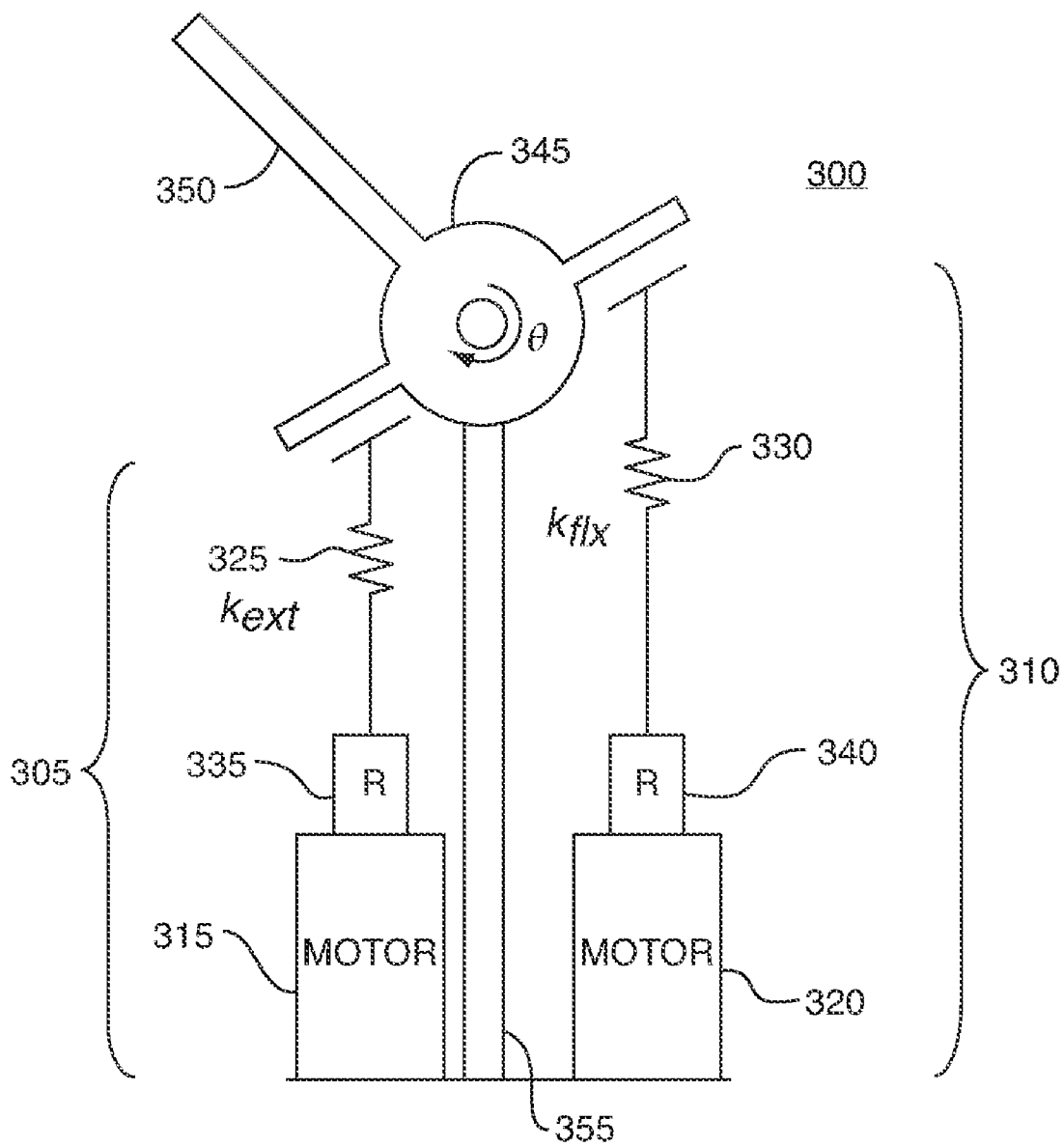


FIG. 3

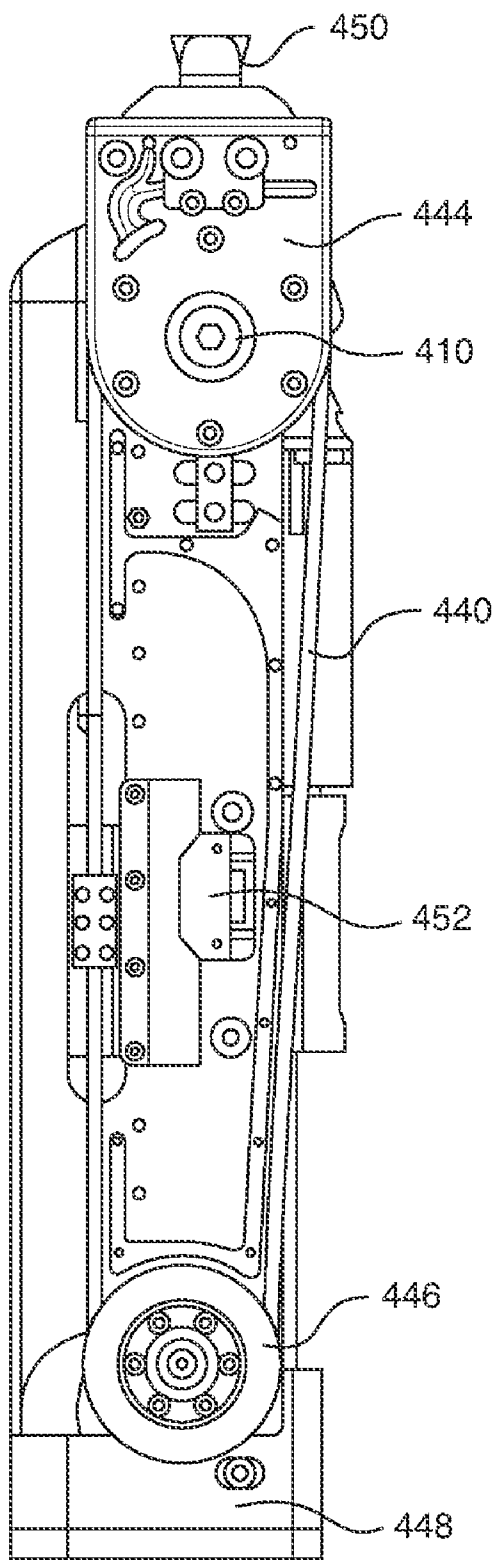


FIG. 4A

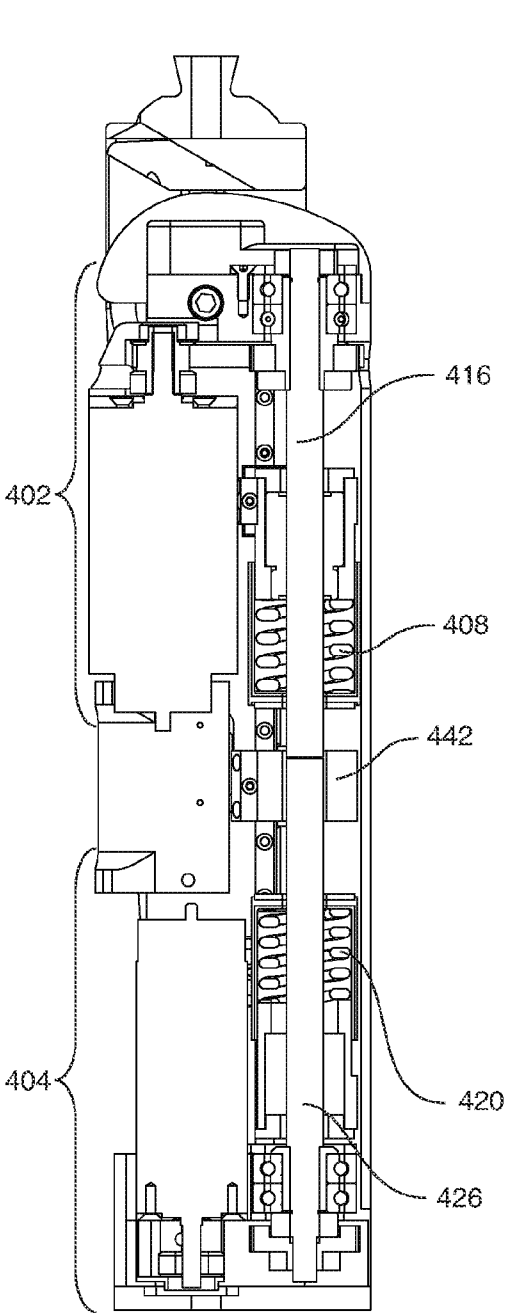


FIG. 4B

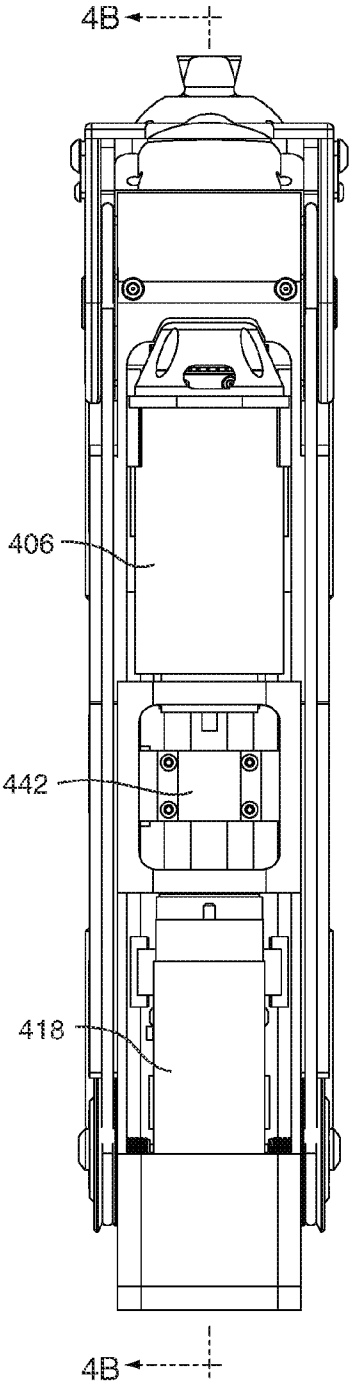


FIG. 4C

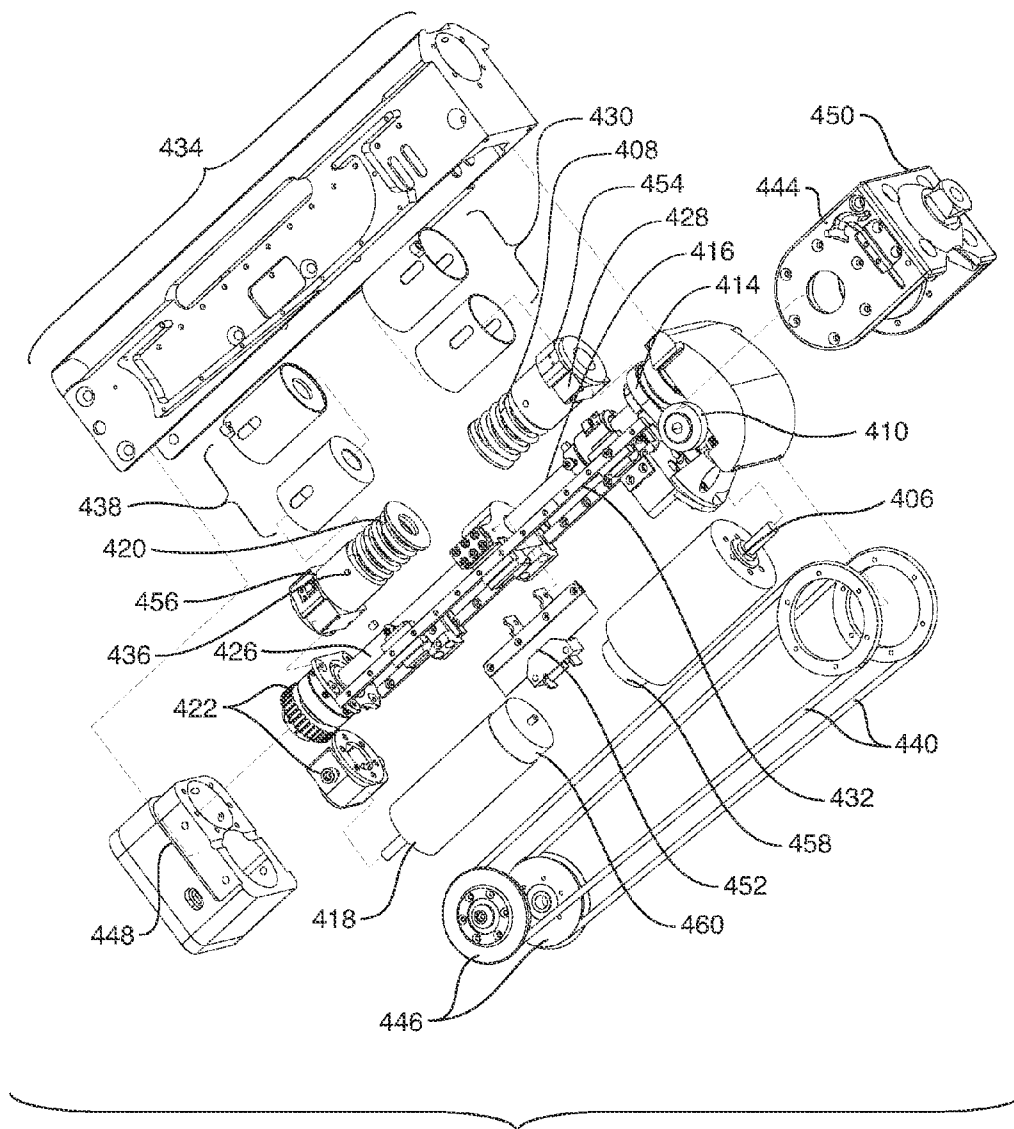


FIG. 5

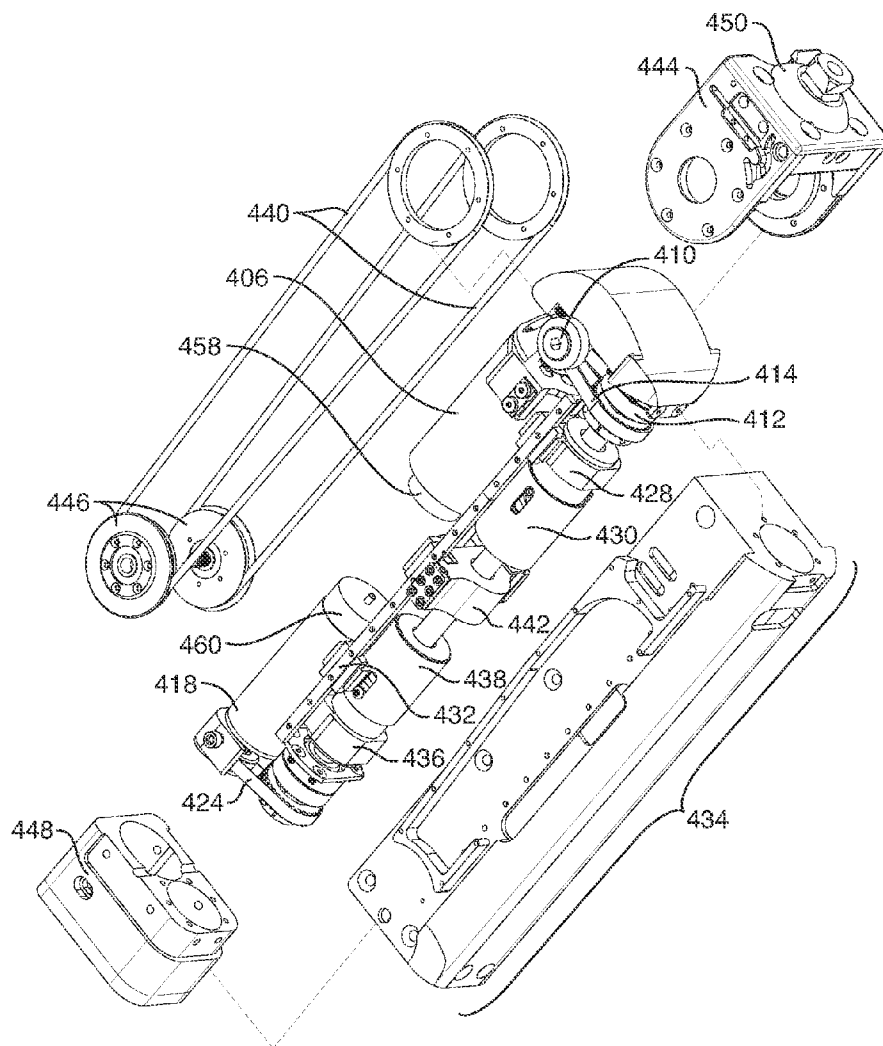


FIG. 6

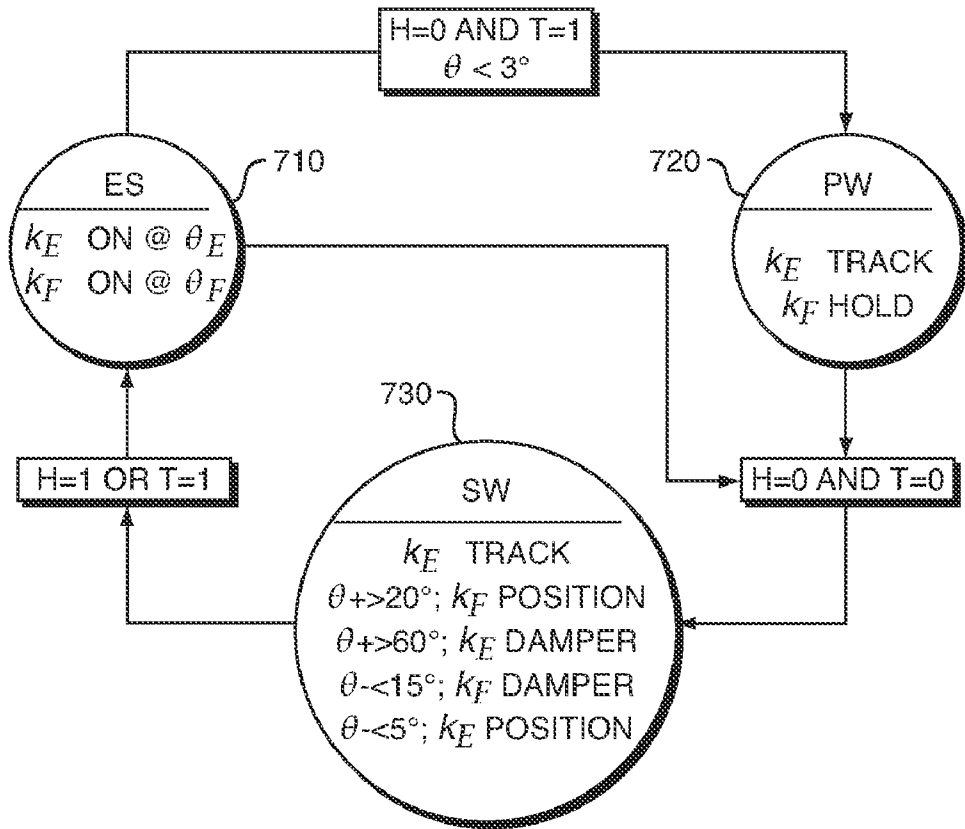


FIG. 7A

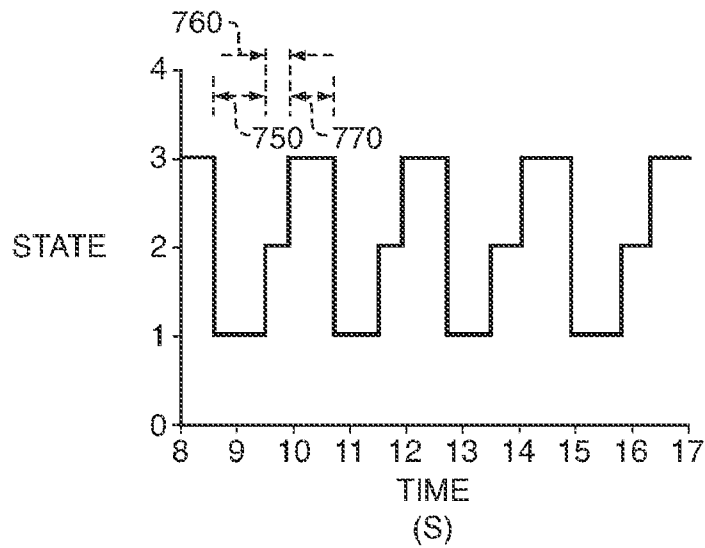


FIG. 7B

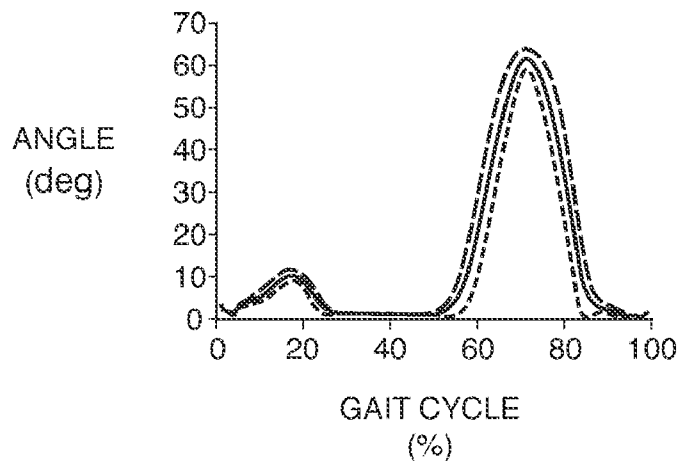
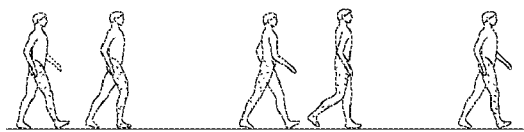


FIG. 8A

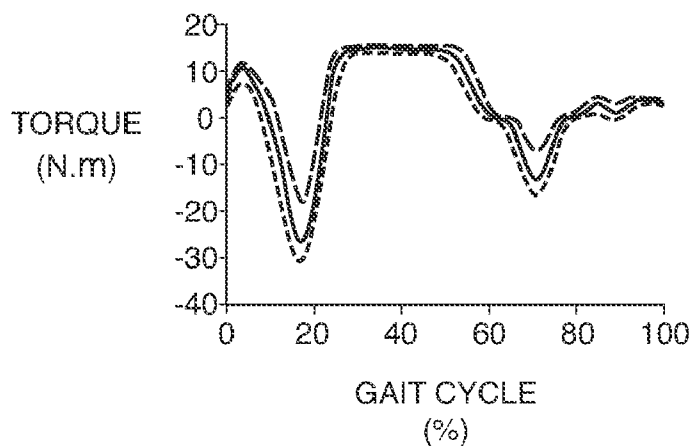


FIG. 8B

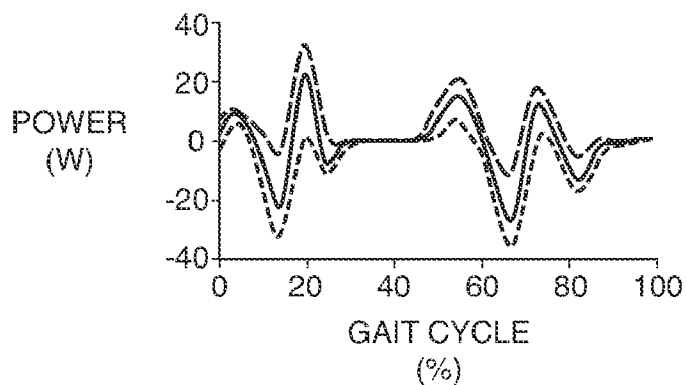


FIG. 8C

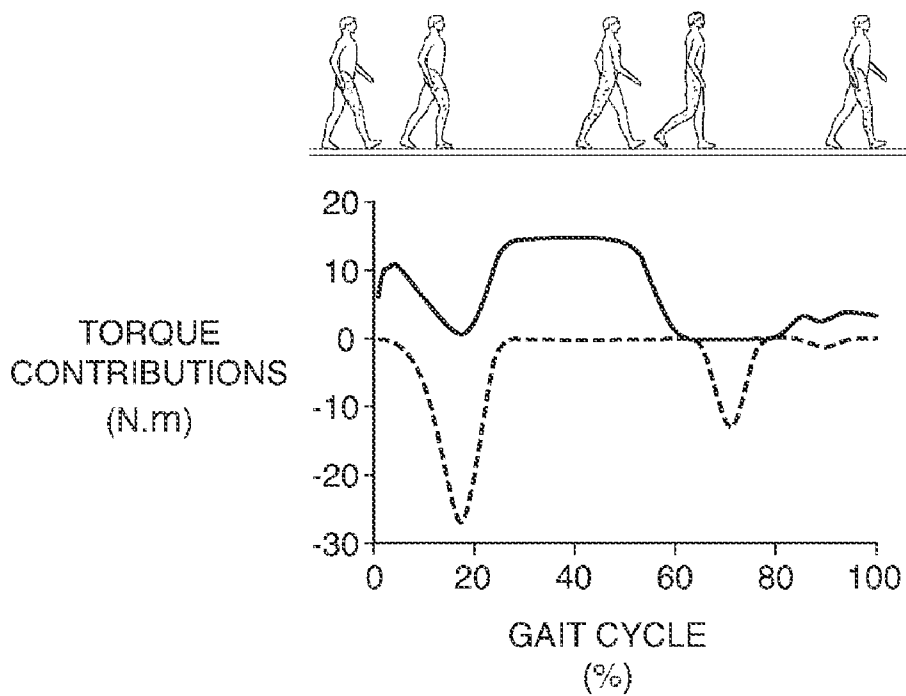


FIG. 8D

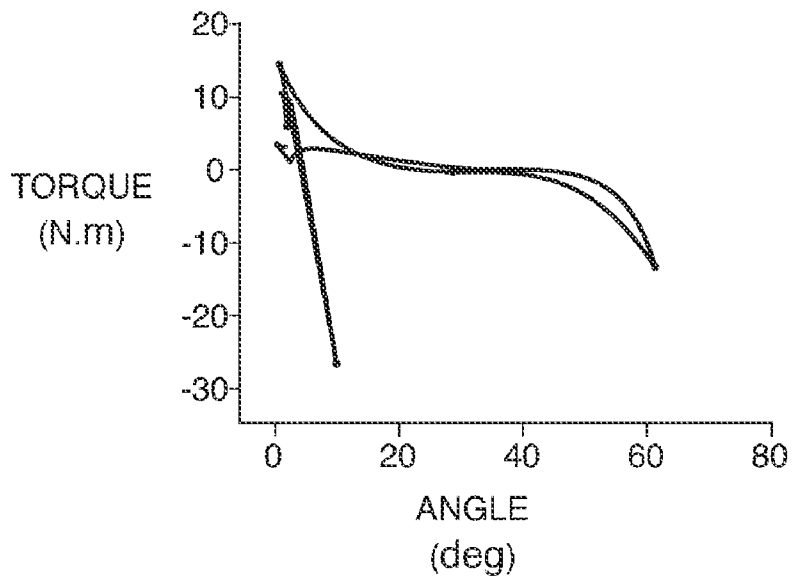


FIG. 8E

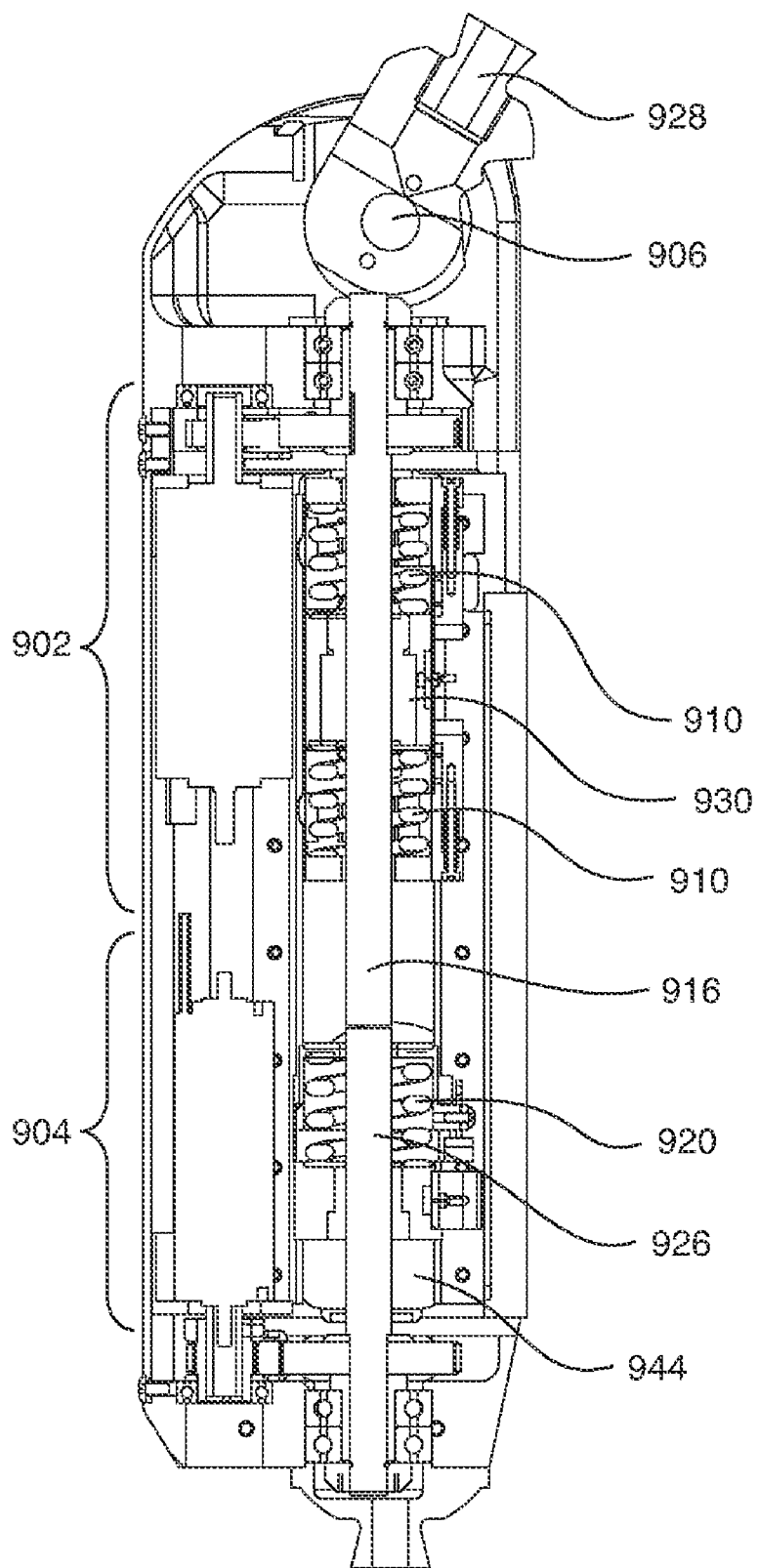


FIG. 9A

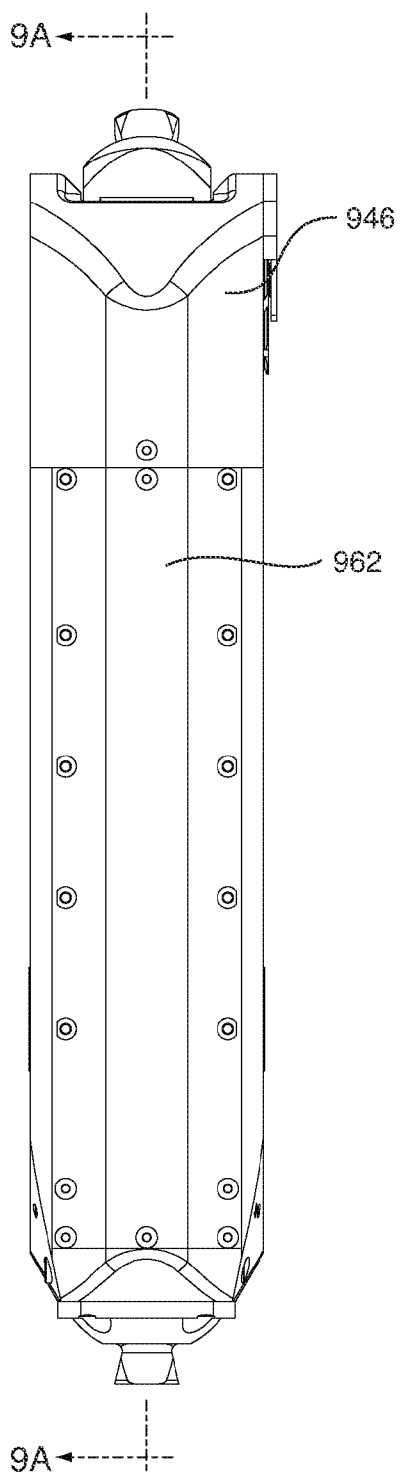


FIG. 9B

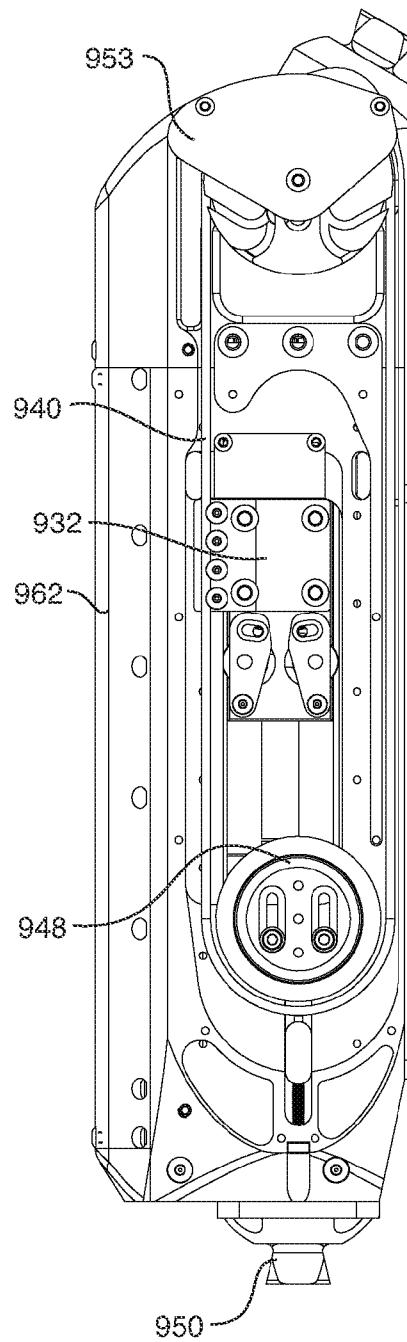


FIG. 9C

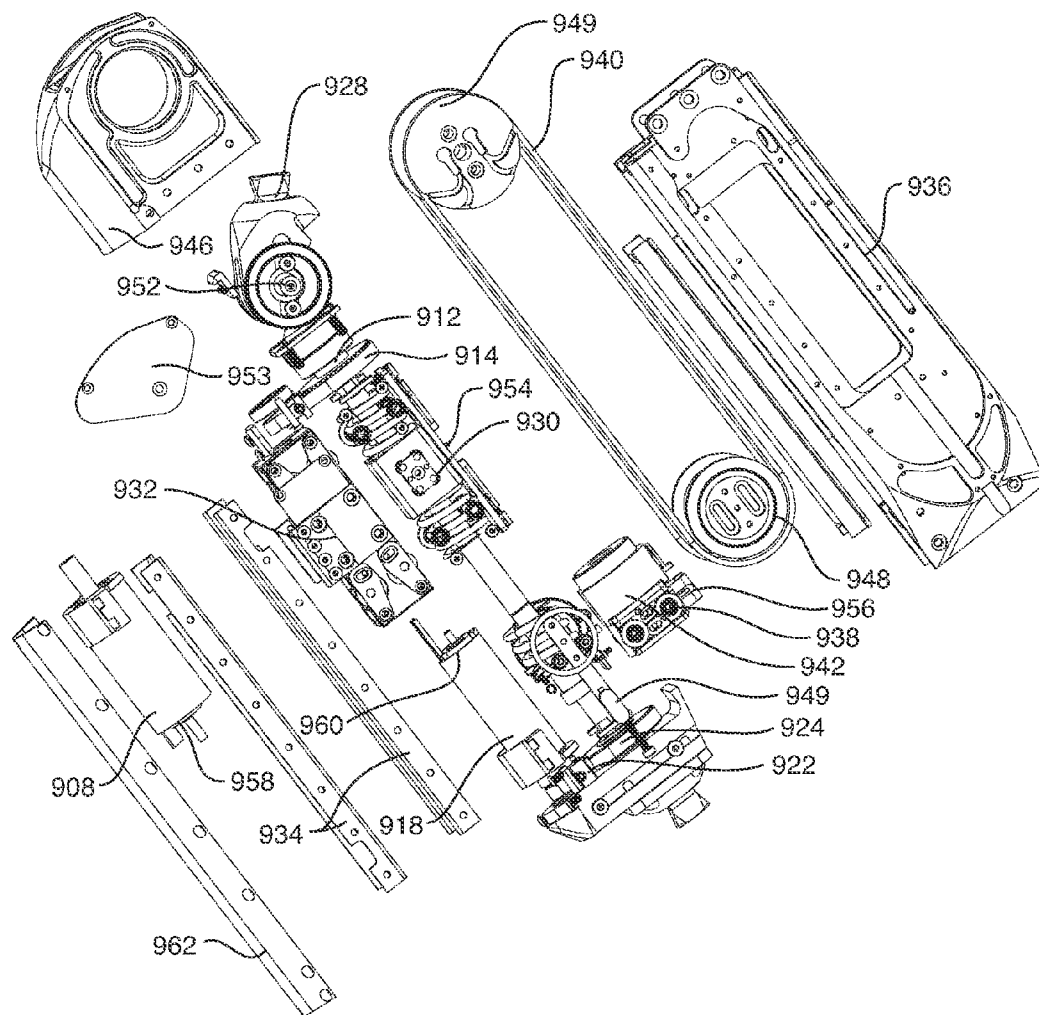


FIG. 10

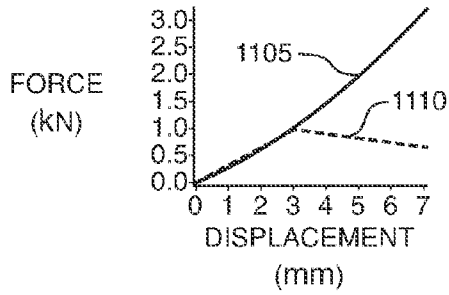


FIG. 11A

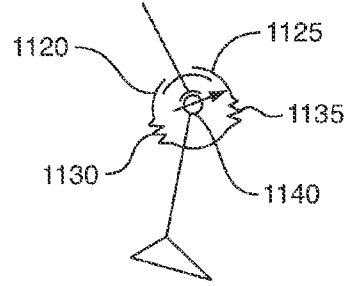


FIG. 11B

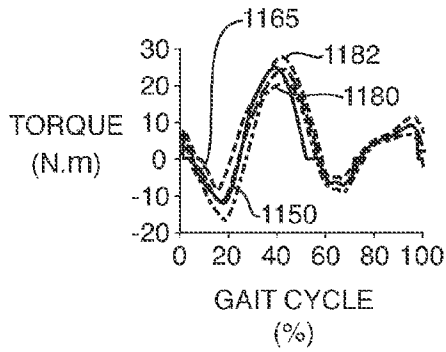


FIG. 11C

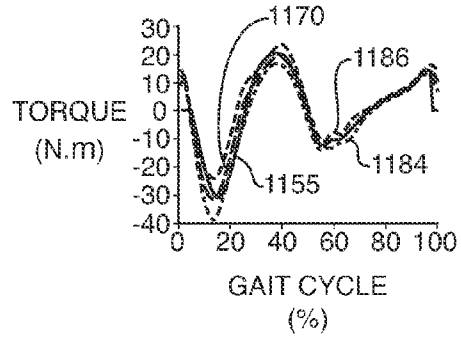


FIG. 11D

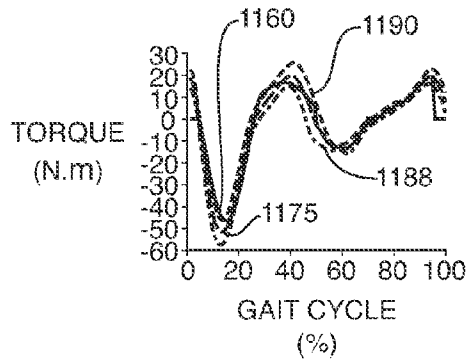


FIG. 11E

POWERED ARTIFICIAL KNEE WITH AGONIST-ANTAGONIST ACTUATION

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Ser. No. 61/148,545, filed Jan. 30, 2010, the entire disclosure of which is herein incorporated by reference in its entirety.

[0002] This application is a continuation-in-part of co-pending U.S. patent application Ser. No. 12/608,627, filed Oct. 29, 2009, which is a continuation of U.S. patent application Ser. No. 11/642,993, filed Dec. 19, 2006, now abandoned, which claims the benefit of U.S. Prov. Pat. App. Ser. No. 60/751,680, filed on Dec. 19, 2005, now expired, and is a continuation-in-part of U.S. patent application Ser. Nos. 11/395,448, 11/495,140, and 11/600,291, listed below, and 11/499,853, now U.S. Pat. No. 7,313,463, which claims the benefit of the filing date of U.S. Prov. Pat. App. Ser. No. 60/705,651, filed on Aug. 4, 2005, and is a continuation-in-part of U.S. patent application Ser. No. 11/395,448, listed below, the entire disclosures of which are incorporated by reference herein in their entirety.

[0003] This application is also a continuation-in-part of U.S. patent application Ser. No. 11/395,448, entitled "Artificial human limbs and joints employing actuators, springs, and Variable-Damper Elements", filed on Mar. 31, 2006 by Hugh M. Herr, Daniel Joseph Paluska, and Peter Dilworth. U.S. patent application Ser. No. 11/395,448 claims the benefit of the filing date of U.S. Prov. Pat. App. Ser. No. 60/666,876, filed on Mar. 31, 2005, and the benefit of the filing date of U.S. Prov. Pat. App. Ser. No. 60/704,517, filed on Aug. 1, 2005.

[0004] This application is also a continuation-in-part of U.S. patent application Ser. No. 11/495,140, entitled "An Artificial Ankle-Foot System with Spring, Variable-Damping, and Series-Elastic Actuator Components", filed on Jul. 29, 2006 by Hugh M. Herr, Samuel K. Au, Peter Dilworth, and Daniel Joseph Paluska. U.S. patent application Ser. No. 11/495,140 claims the benefit of the filing date of U.S. Prov. Pat. App. Ser. No. 60/704,517, filed on Aug. 1, 2005, and was also a continuation-in-part of U.S. patent application Ser. No. 11/395,448.

[0005] This application is also a continuation-in-part of U.S. patent application Ser. No. 11/600,291, entitled "Exoskeletons for running and walking", filed on Nov. 15, 2006 by Hugh M. Herr, Conor Walsh, Daniel Joseph Paluska, Andrew Valiente, Kenneth Pasch, and William Grand. U.S. patent application Ser. No. 11/600,291 claims the benefit of the filing date of U.S. Prov. Pat. App. Ser. No. 60/736,929, filed on Nov. 15, 2005, and is a continuation-in-part of U.S. patent application Ser. Nos. 11/395,448, 11/499,853, and 11/495,140.

[0006] The present application claims the benefit of the filing date of each of the foregoing patent applications and incorporates the disclosure of each of the foregoing applications herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0007] This invention was made with U.S. government support under Grant Number VA241-P-0026, awarded by the

United States Veterans Administration. The government has certain rights in this invention.

FIELD OF THE TECHNOLOGY

[0008] The present invention relates to artificial joints and limbs for use in prosthetic, exoskeletal, orthotic or robotic devices and, in particular, to powered artificial knee joints.

BACKGROUND

[0009] Most commercial lower-extremity prostheses and orthoses are passive and cannot provide positive mechanical power to replicate joint biomechanics during the gait cycle. Existing approaches to the design of powered knee systems have focused mainly on the use of single motor-transmission systems directly coupled to the joint. Such direct-drive designs, however, require high electrical power consumption in order to fully emulate the mechanical behavior of the biological knee joint even during level-ground ambulation. One reason for this lack of energetic economy is inadequate use of the passive dynamics of the leg, and elastic energy storage and return of tendon-like structures.

[0010] Knee prostheses for above-knee amputees can be classified into three major groups: passive, variable-damping, and powered. Passive prosthetic knees do not require a power supply for their operation, and are generally less adaptive to environmental disturbances than variable-damping prostheses. Variable-damping knees do require a power source, but only to modulate damping levels, whereas powered prosthetic knees are capable of performing non-conservative positive knee work.

[0011] Variable-damping knees offer several advantages over mechanically passive designs, including enhanced knee stability and adaptation to different ambulatory speeds. Although variable-damping knees offer some advantages over purely passive knee mechanisms, they are nonetheless incapable of producing positive mechanical power and therefore cannot replicate the positive work phases of the human knee joint for such activities as sit-to-stand maneuvers, level-ground walking, and stair/slope ascent ambulation. Not surprisingly, transfemoral amputees experience clinical problems when using variable-damping knee technology, such as, for example, asymmetric gait patterns, slower gait speeds, and elevated metabolic energy requirements compared to non-amputees.

SUMMARY

[0012] Current approaches to the design of powered prostheses, orthoses, exoskeletons, and robotic legged systems have focused mainly on the use of single motor-transmission systems directly coupled to the joints. Such direct-drive designs require high electrical power consumption to fully emulate the mechanical behavior of the human leg. The biomimetic knee presented here leverages passive dynamics, and uses elastic energy storage and return of tendon-like structures, to minimize the electrical power requirements. The knee is capable of replicating human-like knee mechanics during level ground walking at low electrical power consumption from an onboard power supply.

[0013] In one aspect, the invention is a knee prosthesis that comprises an agonist-antagonist arrangement of two series-elastic actuators positioned in parallel. The prosthetic knee design is motivated by a variable-impedance prosthetic knee model, comprising two series-elastic clutch mechanisms and

a variable-damper. Human gait data are utilized to constrain the model's joint to move biologically. Model parameters are then obtained using an optimization scheme that minimizes the sum over time of the squared difference between the model's knee joint torque and biological knee values. The optimized values are then used to specify the mechanical and finite state control design of the agonist-antagonist knee prosthesis. Two preferred embodiments have been developed.

[0014] Because of its architecture, the knee according to the invention can be controlled to behave as agonist-antagonist, series-elastic clutch elements during the stance phase of the gait cycle, and as a variable-damper during the swing phase, resulting in an energetically-economical artificial knee device for level-ground walking. The knee embodiments are fully motorized with series-elastic force sensing, thus, knee joint torque can be directly controlled for more energetically expensive tasks, such as stair and ramp ascent gaits, as well as standing from a seated posture. Hence, the knee architecture is designed to accommodate non-conservative, high mechanical power movements, while still providing for a highly economical level-ground walking mode.

[0015] In one aspect, the invention disclosed is a powered knee prosthesis comprising a knee joint that is rotatable and coupleable to an artificial leg member, a series-elastic flexion actuator connected to the knee joint in parallel with the leg member, for applying a force to cause rotation of the knee joint, resulting in flexion of the leg member, a series-elastic extension actuator, connected to the knee joint in parallel with the leg member on the opposite side of the leg member from the flexion actuator, for applying a force to cause rotation of the knee joint, resulting in extension of the leg member, and a controller for independently energizing the flexion motor and the extension motor at different times to control the movement of the knee joint and coupled leg member. The flexion actuator comprises the series combination of a flexion motor and a flexion elastic element and the extension actuator comprises the series combination of an extension motor and an extension elastic element. In a preferred embodiment, at least one sensor is employed to provide feedback to the controller. Sensors preferably include, but are not limited to, those responsive to angular displacement and acceleration of the knee joint, torque at the knee joint, compression of the flexion elastic element, compression of the extension elastic element, rotation of the flexion motor, rotation of the extension motor, and/or contact with the walking surface.

[0016] In one preferred embodiment, the flexion actuator and the extension actuator are unidirectional, and the flexion elastic element and the extension elastic element are series springs. In another preferred embodiment, the flexion actuator is unidirectional, the extension actuator is bidirectional, the flexion elastic element is a series spring, and the extension elastic element is a set of pre-compressed series springs. In another preferred embodiment, particularly adapted for variable-speed walking, the flexion elastic element is a non-linear softening spring and the extension elastic element is a non-linear hardening spring.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Other aspects, advantages and novel features of the invention will become more apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings wherein:

[0018] FIGS. 1A and 1B graphically depict representative knee biomechanics in level-ground walking, with FIG. 1A

being the knee angle, torque, and power curves of a study participant with intact knee joints plotted against percent gait cycle during level ground walking at a self selected speed and FIG. 1B being a plot of knee torque vs. knee angular position, showing the five phases of gait;

[0019] FIG. 2A is an exemplary embodiment of a variable-impedance prosthetic knee model, according to one aspect of the invention;

[0020] FIG. 2B depicts optimization results from the model of FIG. 2A, plotted against the biological torque data from FIGS. 1A-B;

[0021] FIG. 3 is a simplified mechanical schematic of a powered agonist-antagonist knee, according to one aspect of the present invention;

[0022] FIGS. 4A-C are lateral view, sagittal plane cut view, and posterior view schematics, respectively, of the mechanical design of an exemplary embodiment of an active knee prosthesis, according to the present invention;

[0023] FIG. 5 is an exploded view of the main components of an exemplary embodiment of the active knee prosthesis of FIGS. 4A-C;

[0024] FIG. 6 is another exploded view of the main components of an exemplary embodiment of the active knee prosthesis of FIGS. 4A-C;

[0025] FIG. 7A is a schematic of a finite-state controller for level-ground walking implemented to replicate the intact knee behavior shown in FIGS. 1A-B, according to one aspect of the present invention;

[0026] FIG. 7B graphically depicts knee finite-state control transitions during amputee level-ground walking for the controller of FIG. 7A;

[0027] FIGS. 8A-E depict results obtained from a preliminary gait evaluation of the powered prosthesis during level-ground walking at a self-selected speed, according to one aspect of the present invention;

[0028] FIGS. 9A-C are lateral view, sagittal plane cut view, and posterior view schematics, respectively, of the mechanical design of another exemplary embodiment of an active knee prosthesis, according to the present invention;

[0029] FIG. 10 is an exploded view of the main components of an exemplary embodiment of the active knee prosthesis of FIGS. 9A-C;

[0030] FIG. 11A is a plot of the results of an optimized non-linear polynomial fit for the force vs. displacement behavior of the series-elastic elements of an active knee according to the present invention;

[0031] FIG. 11B depicts an exemplary embodiment of a variable-impedance prosthetic knee model for variable-speed walking, according to one aspect of the invention; and

[0032] FIGS. 11C-E graphically depict prosthetic knee model output torque compared to the biological knee torque data for three different walking speeds, using the model of FIG. 11B.

DETAILED DESCRIPTION

[0033] A variable-impedance knee prosthesis according to the invention has two series-elastic actuators arranged in parallel in an agonist-antagonist arrangement. The prosthetic knee model comprises a variable damper and two series-elastic clutch units spanning the knee joint. A variable-impedance control design produces human-like knee mechanics during steady-state level-ground walking. Because of the variable-impedance nature of the prosthesis, electrical power requirements are modest while walking, allowing for an ener-

getically-economical powered knee. In one application, a variable-impedance knee prosthesis according to the invention is advantageously employed as a part of a non-tethered biomimetic robotic leg.

[0034] As used herein, the following terms expressly include, but are not to be limited to:

[0035] “Actuator” means a type of motor, as defined below.

[0036] “Agonist” means a contracting element that is resisted or counteracted by another element, the antagonist.

[0037] “Agonist-antagonist actuator” means a mechanism comprising (at least) two actuators that operate in opposition to one another: an agonist actuator that, when energized, draws two elements together and an antagonist actuator that, when energized, urges the two elements apart.

[0038] “Antagonist” means an expanding element that is resisted or counteracted by another element, the agonist.

[0039] “Biomimetic” means a human-made structure or mechanism that mimics the properties and behavior of biological structures or mechanisms, such as joints or limbs.

[0040] “Dorsiflexion” means bending the ankle joint so that the end of the foot moves upward.

[0041] “Elastic” means capable of resuming an original shape after deformation by stretching or compression.

[0042] “Extension” means a bending movement around a joint in a limb that increases the angle between the bones of the limb at the joint.

[0043] “Flexion” means a bending movement around a joint in a limb that decreases the angle between the bones of the limb at the joint.

[0044] “Motor” means an active element that produces or imparts motion by converting supplied energy into mechanical energy, including electric, pneumatic, or hydraulic motors and actuators.

[0045] “Plantarflexion” means bending the ankle joint so that the end of the foot moves downward.

[0046] “Spring” means an elastic device, such as a metal coil or leaf structure, which regains its original shape after being compressed or extended.

[0047] Human Knee Biomechanics in Level Ground Walking FIGS. 1A and 1B graphically depict representative human knee biomechanics in level-ground walking. In FIG. 1A, the knee angle, torque, and power curves of a male study participant (Mass=81.9 kg) are plotted against percent gait cycle during level ground walking at a self selected speed (1.31 m/sec). Plotted are mean (solid line; N=10 gait trials) about one standard deviation (dashed lines). In FIG. 1B, knee torque is plotted vs. knee angular position showing the five phases of gait. Key gait events separating the five phases are: heel strike (HS) 105, maximum stance flexion (MSF) 110, maximum stance extension (MSE) 115, toe off (TO) 120, and maximum swing flexion (MWF) 125.

[0048] As seen in FIGS. 1A and 1B, five distinct stages or gait phases have been used to describe knee biomechanics in level-ground walking. These gait phases are described as follows:

[0049] (1) Beginning at heel strike (HS) 105, the stance knee begins to flex slightly (~15 degrees). This Stance Flexion 130 phase allows for shock absorption upon impact. During this phase, the knee can be modeled as a spring (linear torque vs. angle slope; see FIG. 1B), storing energy in preparation for the Stance Extension phase 135.

[0050] (2) After maximum stance flexion (MSF) 110 is reached, the knee joint begins to extend (15% gait cycle), until maximum stance extension (MSE) 115 is reached (42% gait

cycle). This knee extension period is called the Stance Extension phase 135. During Stance Extension 135, the knee acts as a spring (linear torque vs. angle slope; see FIG. 1B), having a similar stiffness to that of Stance Flexion 130. Here, stiffness is not actual joint stiffness but rather a quasi-static stiffness defined as the slope of the torque vs. angle curve.

[0051] (3) During late stance or Pre-Swing 140 (from 42% to 62% gait cycle), the knee of the supporting leg begins its rapid flexion period in preparation for Swing Flexion phase 145. During Pre-Swing 140, as the knee begins to flex in preparation for Toe-off 120, the knee acts as a spring (linear torque vs. angle slope; see FIG. 1B), but having a relatively lower stiffness than that during Stance Flexion 130 and Extension 135.

[0052] (4) As the hip is flexed, the leg leaves the ground and the knee continues to flex. At Toe-off 120, the Swing Flexion phase 145 of gait begins. Throughout this period (from 62% to 73% gait cycle), knee power is generally negative as the knee’s torque impedes knee rotational velocity (see FIG. 1A). Thus, during Swing Flexion 145, the knee can be modeled as a variable damper.

[0053] (5) After reaching a maximum flexion angle (~60 degrees) during Swing Flexion 145, the knee begins to extend forward. During Swing Extension 150 (from 73% to 100% gait cycle), knee power is generally negative to decelerate the swinging leg in preparation for the next stance period. Thus, as with Swing Flexion 145, the knee during Swing Extension 150 can be modeled as a variable damper. After the knee has reached full extension, the foot, once again, is placed on the ground, and the next walking cycle begins.

[0054] Quasi-passive Prosthetic Knee Model and Optimization. Given the knee biomechanics described, there is a clear need for a variable-impedance knee prosthesis, capable of varying both damping and stiffness, that can produce human-like knee mechanics during steady-state level-ground walking. An example of such a prosthesis is the exemplary knee model, shown in FIG. 2A, comprising two antagonistic mono-articular series-elastic clutches 205, 210 (to model the stance phase knee mechanics) and one variable-damping element 215 (to model the swing phase mechanics). In the model, series springs 220, 225 can each be engaged by activating its respective clutch 205, 225, or disengaged by opening that clutch. As model constraints, each clutch can only be engaged once during each gait cycle. Additionally, once a clutch has been engaged, it only can be disengaged when the series spring has released all its energy and the force on the clutch is zero.

[0055] The series-elastic clutch model parameters were varied in order to match biomechanic behavior of the knee joint. The model parameters are two spring constants (k_E , k_F) corresponding to the extension and flexion spring stiffness, and the relative knee extension and flexion angles (θ_E and θ_F), at which the extension and flexion springs become engaged during stance. By convention, the extensor spring tends to extend the knee joint when engaged, whereas the flexor spring tends to cause the knee to flex. The knee model was fitted to biomechanical data using an optimization scheme that minimized the sum over time of the squared difference between the model’s knee joint torque and biological knee values. More specifically, the cost function used for the optimization was

$$E_{cost}(k_F, k_E, \theta_E, \theta_F) = \sum_{i=1}^{100} \left(\frac{\tau_{bio}^i - \tau_{sim}^i}{\tau_{bio}^{max}} \right)^2 \quad (1)$$

where τ_{bio}^i and τ_{sim}^i are the angular torques applied about the knee joint at the i th percentage of gait cycle from the biological torque data and the knee model, respectively, and τ_{bio}^{max} is the maximum biological torque at the joint during the gait cycle. Cost function (1) was minimized with the constraint that the extensor spring always engages at heel strike ($\theta_E=0$). This constraint was applied to limit knee buckling at heel strike as a safety measure for the amputee.

[0056] The determination of the desired global minimum for cost function (1) was implemented by first using a genetic algorithm to find the region containing the global minimum, followed by an unconstrained gradient optimizer to determine the exact value of that global minimum. After optimizing cost function (1) by varying the parameters of the series-elastic clutch elements, the model's variable damper was used to achieve perfect agreement between the prosthetic knee model and biological torque values in regions where the series-elastic components were not able to absorb sufficient negative mechanical power. The biological knee torque values were obtained from an inverse dynamics calculation using kinetic and kinematic data from ten walking trials of a healthy 81.9 kg, 1.87 m tall subject walking at 1.31 m/s.

[0057] FIG. 2B shows optimization results from the model of FIG. 2A, plotted against the biological torque data from FIGS. 1A-B. As shown in FIG. 2B, upper plot 245, optimized net torque output 250 of the knee model is compared to the torque profile of an intact human knee joint, with both mean 255 and one standard deviation 260, 265 shown (N=10 gait trials). Biological data, adopted from FIGS. 1A-B, are from a study participant (mass=81.9 kg) with intact limbs walking at a self-selected speed (walking speed=1.31 m/sec). Shown in lower plot 270 are the torque contributions from the extension 275 and flexion 280 springs of the series-elastic clutch elements, as well as from the variable damper 285. The optimizer gave an extension spring stiffness equal to $k_E=160$ N·m/rad, a flexion spring stiffness equal to 137 N·m/rad, and a knee engagement angle for the flexion spring equal to 0.27 radians (15.46 degrees).

[0058] The model's torque output agrees well with experimental values. As constrained by the optimization procedure, the extension spring engages at heel strike, storing energy during early stance knee flexion. As the knee begins to extend, the flexion spring is engaged, storing energy as the extension spring releases its energy. During the swing phase, the model's variable damper exactly matches the biological torque values in regions of negative power. At mid and terminal swing phase, the power is positive in the biological data, and thus, the damper outputs zero torque in these gait regions.

[0059] A simplified mechanical schematic of an agonist-antagonist knee according to one aspect of the present invention is shown in FIG. 3. As depicted in FIG. 3, agonist-antagonist active knee prosthesis 300 comprises two unidirectional, series-elastic actuators, series-elastic extension actuator 305 and series-elastic flexion actuator 310. Each unidirectional actuator 305, 310 of knee prosthesis 300 consists of a motor 315, 320 and a series spring 325, 330, connected via a transmission 335, 340. The extension and flexion

motors 315, 320 can be used independently to control the knee angle at which each series spring 325, 330 is engaged. Knee joint 345 between upper leg 350 and lower leg 355 is coupled to a linear carriage, that is free to move along the length of the device, by a cable drive transmission. This carriage can be engaged on either side by the extension and flexion springs 325, 330, each of which are positioned by a ball screw driven by an electric motor. In a preferred embodiment, both unidirectional, series-elastic actuators 305, 310 feature transmissions 335, 340 comprised of a 2:1 belt drive coupled to a ball screw (Nook industries, 10x3 mm).

[0060] The principles of the exemplary knee model of FIG. 2A have been embodied in two exemplary preferred physical embodiments. In one preferred embodiment, shown in FIGS. 4A-C, an agonist-antagonist active knee prosthesis comprises two unidirectional, series-elastic actuators. FIGS. 5 and 6 are exploded view of the main components of the exemplary embodiment of an active knee prosthesis of FIGS. 4A-C.

[0061] As depicted in FIGS. 4A-C, 5, and 6, the unidirectional actuators are extension actuator 402 and flexion actuator 404. Extension actuator 402 of the knee prosthesis consists of extension motor 406 and series spring 408, connected via a transmission. The extension actuator is proximal to knee joint 410. The extension transmission consists of timing pulley 412 and belt 414 drive system coupled to precision ball-screw 416 drive. Flexion actuator 404 of the knee prosthesis consists of flexion motor 418 and series spring 420, connected via a transmission. The flexion transmission consists of a timing pulley 422 and belt 424 drive system coupled to precision ball-screw 426 drive. Extension actuator 402 and flexion actuator 404 can be used independently to control the knee joint 410 angle at which each series spring 408, 420 is engaged.

[0062] Series-elastic extension actuator 402 motorized element (extension electric motor 406) can be a brushed DC motor (such as Maxon's RE40 motor) or brushless DC motor (such as Maxon's EC-powermax 30). The extension motor directly drives a timing pulley-belt drive 412, 414 mechanism. This mechanism has a 1:2 transmission ratio. Timing pulley-belt drive mechanism 412, 414 actuates the rotation of ball-screw 416 (such as Nook industries, 10x3 mm). When ball-screw 416 of extension actuator 402 rotates, there is a linear displacement of coupled ball-nut housing 428. Ball-nut housing 428 is directly attached to extension series spring cage 430. Extension series spring cage 430 securely contains extension spring 408. Thus, when there is a linear displacement of coupled ball-nut housing 428, the extension series spring cage can have a linear displacement. The ball-nut housing moves along two linear precision steel guide rails 432 with minimal friction due to the linear bearings incorporated in the ball-nut housing. Each of the two precision guide rails 432 is attached to a corresponding inner lateral wall of main knee frame 434.

[0063] Series-elastic flexion actuator 404 motorized element (flexion electric motor 418) can be a brushed DC motor (such as Maxon's RE40, RE30 motors) or brushless DC motor (such as Maxon's EC-powermax 30 or 22). The extension motor directly drives a timing pulley-belt drive 422, 424 mechanism. This mechanism has a 1:2 transmission ratio. Pulley-belt drive mechanism 422, 424 actuates the rotation of ball-screw 426 (such as Nook industries, 10x3 mm). When ball-screw 426 of flexion actuator 404 rotates, there is a linear displacement of coupled ball-nut housing 436. Ball-nut housing 436 is directly attached to flexion series spring cage 438.

Flexion series spring cage **438** securely contains flexion spring **420**. Thus, when there is a linear displacement of coupled ball-nut housing **436**, the flexion series spring cage can have a linear displacement. Ball-nut support **436** moves along two linear precision steel guide rails **432** with minimal friction due to the linear bearings incorporated in the ball-nut housing. Each of the two precision guide rails **432** is attached to a corresponding inner lateral wall of the main knee frame **434**.

[0064] Knee joint **410** rotation is coupled to the linear displacement of linear carriage **442** attached to a cable drive transmission. The cable drive transmission is comprised of two steel cables **440**. The two ends of each of steel cables **440** are attached to knee joint clevis support **444**. Each cable loops around its corresponding joint pulley **446** located on each side of the knee. Each lateral joint pulley **446** has its axis attached to lower adaptor **448**. Linear carriage **442** is supported and guided on two steel precision rail guides **432**. Each rail runs along an inner lateral wall of main knee frame **434**. Low friction between the precision rails and linear carriage **442** is obtained by the linear bearings incorporated inside linear carriage **442**. Steel cables **440** allow the coupling of linear displacement from linear carriage **442** to the rotary motion of knee joint **410**.

[0065] Linear carriage **442** can be independently be engaged by extension spring **408** and flexion spring **420** by means of their linear motion. Both springs are independently positioned by driving action of their corresponding series-elastic actuator. Each of series-elastic actuators **402**, **404** are capable of providing sufficient power for both level-ground walking and more energetically expensive tasks such as stair ascent.

[0066] All actuation mechanisms are fully supported by an aluminum structure that corresponds to knee main frame **434**, which has a design that resembles the lower limb anatomical envelope. The knee main frame has lower adaptor **448** that allows conventional and advanced robotic foot-ankle prosthesis to be attached to it. The coupling of knee joint clevis support **444** and the knee main frame produces the rotational degree of freedom that corresponds to knee joint **410**. Knee joint clevis support **444** allows the mounting of a standard prosthetic pyramid adaptor **450**, so that the knee prosthesis can be attached to a regular transfemoral socket and be worn by an amputee.

[0067] Based on such functional requirements, the design parameters for knee size, angular range, and maximum torque values for the embodiment of FIGS. **4A-C**, **5**, and **6** are listed in Table 1.

TABLE 1

Height	33 cm
Medio-Lateral Width	7 cm
Anterior-Posterior Width	7 cm
Total Weight	3 Kg
Flexion Angle range	0-120 deg
Max Output torque	130 Nm

[0068] Real-time feedback information to the on-board controller is provided by onboard intrinsic sensors. The sensors utilized by the embodiment of FIGS. **4A-C**, **5**, and **6** are listed in Table 2.

TABLE 2

Measurement	Sensor
Knee angle	Digital encoder
Motor displacement	Digital encoder
Spring compression	Hall effect
Heel/Toe contact	Force sensitive resistor foot pad

[0069] The angular displacement of the knee is measured indirectly with digital linear encoder **452** that is fixed on the external left side of knee main frame **434**. The rotary motion of knee joint **410** is coupled to the displacement of linear carriage **442** via steel cable **440** transmission. The compression of each of the series elastic actuator's springs **408**, **420** is measured with a corresponding hall-effect sensor **454**, **456**. These sensors measure the magnetic field change that occurs when there is a change to the proximity of a magnet that is attached to each of spring cages **430**, **438** while springs **408**, **420** are being compressed. The rotation of each motor is measured by motor digital encoder **458**, **460** attached to the back of corresponding motor **406**, **418**. The interaction with the ground is measured with a force sensitive footpad (not pictured). This footpad allows detection of when the leg is on or off the walking surface and it assists the controller in determining what gait phase the user wearing the robotic knee prosthesis is in.

[0070] All electronics are implemented on a single on-board micro-controller based system. Motors are driven by H-bridge controllers with speed governed by 20 kHz pulse width modulation (PWM) and powered by DC battery (such as a six cell Lithium polymer battery (22.2V nominal). Analog sensors were read through a 10-bit analog to digital converter (ADC). The system is controlled by an on-board micro-controller such as AVR) and could be monitored by either USB and/or Bluetooth. All processing is performed on-board and power is supplied by a relatively small battery (mass=0.15 kg). The prototype is completely self-contained and does not require tethering.

[0071] Finite-State Control Strategy. A finite-state controller for level-ground walking was implemented to replicate the intact knee behavior shown in FIGS. **1A-B**. This state machine is depicted in FIG. **7A**. Three states are shown with control actions and transitional conditions. The three states of the controller are Early Stance (ES) **710**, Pre-Swing (PW) **720** and Swing (SW) **730**. A quasi-passive equilibrium point control was implemented for states ES **710** and PW **720**, while during the SW state **730** variable-damping control was employed. Transitions between states were determined primarily by three measurements: heel ground contact, toe ground contact, and knee angle.

[0072] For state transition and identification, the system relied on the following variables:

Heel contact (H). H=1 indicates that the heel is in contact with the ground, and H=0 indicates the off-ground status.

Toe contact (T). T=1 indicates that the toe is in contact with the ground, and T=0 indicates the off-ground status.

Knee angle (θ) is the relative angle of the knee joint. All knee angles are flexion angles. Angles θ_E and θ_F define the angles at which the extension and flexion springs become engaged during stance, respectively. Further, θ_+ is the angle of the knee during swing flexion, and θ_- is the angle of the knee during swing extension.

[0073] Descriptions for each state are as follows: Early Stance (ES) **710** begins at Heel Strike (HS). When the heel contacts the ground ($H=1$), the extension motor shaft is locked using a high PD gain control with a desired shaft velocity equal to zero. The extension spring is then engaged with a spring equilibrium angle equal to the knee's position at heel strike θ_E . The extension spring then stores energy during early stance knee flexion in preparation for knee extension. During knee flexion, the equilibrium point of the flexion spring θ_F is servoed via position control to closely track the linear carriage linked to the knee output joint. When the knee is maximally flexed in early stance, the knee begins to extend, and the flexion motor shaft is locked. The flexion spring then becomes engaged with a spring equilibrium angle equal to the knee's position at maximum knee flexion θ_F . Initially, energy is released from the extension spring and subsequently stored in the flexion spring.

[0074] Pre-Swing (PW) **720** begins as the heel leaves the ground ($H=0$) and the knee angle becomes small ($\theta < 3^\circ$). In this state, the equilibrium point of the extension spring θ_E is position controlled under zero load, tracking closely the linear carriage as the knee flexes in preparation for the swing phase. The flexion spring keeps holding its current equilibrium position θ_F (motor shaft locked). Thus, as the knee flexes throughout PW, the energy stored in the flexion spring is released.

[0075] Swing (SW) **730** begins at toe off ($T=0$). The extension spring equilibrium angle θ_E continues to track the knee angle under zero load. As the knee flexes beyond 20 degrees ($\theta_+ > 20^\circ$) the flexion spring equilibrium angle θ_F is servoed under zero load to a position corresponding to $\theta = 15^\circ$. When the knee flexes past 60 degrees ($\theta_+ > 60^\circ$), the extension spring is engaged. A low gain damping control on the extension motor shaft causes the extension motor and transmission to backdrive, acting as a variable damper to reduce hyper-flexion of the knee. Once the knee begins to extend and has an angle of less than 60 degrees ($\theta_- < 60^\circ$), the extension spring equilibrium angle θ_E then once again tracks the linear carriage under zero load to follow the knee throughout its extension. As the knee continues to extend past 15 degrees in late swing, the flexion spring is engaged. Here again, a low gain damping control on the flexion motor shaft causes the flexion motor and transmission to backdrive, acting as a variable damper to smoothly decelerate the swing leg until the flexion spring reaches an equilibrium angle θ_F is of 3 degrees. When the knee extends in swing beyond 5 degrees ($\theta_- < 5^\circ$) the extension spring equilibrium angle θ_E is servoed to 3 degrees, in preparation for engagement and energy storage at heel strike of the subsequent gait cycle.

[0076] The finite-state control diagram indicating transitions for the state machine of FIG. 7A is shown in FIG. 7B. The diagram in FIG. 7B exemplifies controller state transition performance for three consecutive, level-ground walking cycles of the implemented controls strategy in the embodiment of FIGS. 4A-C, 5, and 6. The control states for level-ground walking are defined as follows: Early Stance (ES-State 1) **750**, Pre-Swing (PW-State 2) **760**, and Swing (SW-State 3) **770**. The system went through the state sequence 1-2-3 (ES-PW-SW) for each walking cycle. The controller transitions robustly from states 1-2-3 across three consecutive walking cycles.

[0077] Results obtained from a preliminary gait evaluation of the powered prosthesis during level-ground walking at a self-selected speed (0.81 msec) are presented in FIGS. 8A-E.

Prosthetic knee angle (FIG. 8A), net torque (FIG. 8B), and power (FIG. 8C) are plotted versus percent gait cycle (mean is solid line; one standard deviation is dashed line; $N=10$ gait trials) for level-ground walking (amputee participant mass=97 kg; walking speed=0.81 m/sec). In FIG. 8D, the torque contributions from the extension (lower line) and flexion (upper line) springs of the series-elastic actuators are plotted. In FIG. 8E, knee torque is plotted versus knee angular position, showing two characteristic stiffnesses during stance.

[0078] These prosthetic knee values show qualitative agreement with intact knee mechanics shown in FIG. 1A from a weight and height-matched non-amputee. Similar to the knee kinematics of an intact knee, as shown in FIG. 8A, the prosthetic knee exhibits early stance knee flexion (peak flexion angle of ~ 14.5 degrees) following by knee extension. At terminal stance, the prosthetic knee undergoes rapid knee flexion in preparation for the swing phase. During the swing phase, the knee extends to a peak flexion angle of ~ 61 degrees, before extending forward prior to heel strike. As shown in FIGS. 8B and 8C, prosthetic knee torque and power are negative during early stance knee flexion. For the intact knee data shown in FIG. 1A, knee torque and power are initially positive following heel strike, but quickly become negative as the knee continues to flex. The prosthetic knee exhibited a similar behavior at the beginning of early stance as shown in FIG. 8B. This occurred because the amputee initially extended the knee right at heel strike, engaging the flexion spring and but quickly continued to knee flex engaging the extension spring. Compressing the extension spring immediately after heel strike helped limit the knee from undergoing excessive buckling so as to better ensure the amputee wearer's safety. For both the intact and prosthetic knee, during stance knee extension, torque is initially negative and then becomes positive, and knee power is initially positive and then becomes negative. Still further, during pre-swing, torque and power are initially positive and then become negative in preparation for the swing phase. During swing, for both intact and prosthetic knees, power is generally negative to limit peak knee flexion (negative torque) and then to smoothly decelerate the swinging leg during swing extension (positive torque).

[0079] The torque contributions from each unidirectional, series-elastic actuator are plotted in FIG. 8D versus percent gait cycle. The flexion spring is briefly engaged right after heel strike due to amputee's short knee extension. At the instant stance knee flexion occurs, the extension spring is engaged, similar to the prosthetic knee model. During stance flexion, the flexion spring loses its energy quickly as it closely tracks the linear carriage linked to the knee output joint. Subsequently, the flexion spring is engaged again at peak knee flexion during early stance and stores energy during stance extension and pre-swing. In swing, the extension motor at peak knee flexion, and the flexion motor at terminal stance, are actively back driven to limit peak knee flexion and to smoothly decelerate the swinging leg at terminal stance, respectively. In FIG. 8E, prosthetic knee torque is plotted versus knee angular position. Like the intact human knee (FIG. 1B), the prosthesis has two characteristic stiffnesses during stance. During early stance flexion and extension phases, knee stiffness is relatively greater than during pre-swing.

[0080] The prosthesis knee embodiment of FIGS. 4A-C, 5, and 6 takes advantage of the incorporated series-elastic com-

ponents in combination with the variable-impedance control to minimize the electrical energy during walking. With this strategy the knee behavior demonstrates agreement between prosthesis and intact knee mechanics. With the combination of mechanical design architecture and control, the prosthesis' electrical motors do not perform positive work on the knee joint during level-ground walking, resulting in modest electrical power requirements.

[0081] Because of the variable-impedance prosthetic control during level-ground walking, the knee prosthesis' electrical power requirements low (8 Watts electrical) during steady-state walking trials at an average walking speed of 0.81 msec. Using step count monitoring systems, researchers have determined that active unilateral leg amputees walk 3060 ± 1890 steps per day. To estimate motor electrical power requirements ($\text{power} = \text{current} * \text{voltage}$), onboard motor current sensing was used to directly measure the current of each motor, and to estimate motor voltages, motor speeds, motor speed constants, and motor resistances were used. Assuming the case of an amputee walking for 5000 steps at a moderate walking speed, the size of the onboard battery can be estimated. A 0.13 kg Li-Polymer battery for example (energy density 165 Watt-hrs/kg), would enable 5000 steps of powered walking ($8 \text{ Watts} * 1.95 \text{ sec/cycle} * 5000 \text{ cycles} = 78 \text{ kJoules}$). This battery mass is over 5-fold smaller than the required battery other commercially powered knees.

[0082] In a second preferred embodiment, shown in FIGS. 9A-C, an active knee prosthesis comprises two actuators arranged in an agonist antagonist architecture. FIG. 10 is an exploded view of the main components of the exemplary embodiment of an active knee prosthesis of FIGS. 9A-C. In this embodiment of an active knee prosthesis according to the invention, the two actuators are one extension series elastic actuator 902 and one flexion actuator 904. Extension actuator 902 is bidirectional and flexion actuator 904 is unidirectional. Extension actuator 902, proximal to knee joint 906 of prosthesis, consists of extension motor 908 and a set of pre-compressed series springs 910, connected via a transmission. The extension transmission consists of timing pulley set 912 and belt 914 drive system coupled to precision ball-screw 916 drive. Unidirectional flexion actuator 904 of the knee prosthesis consists of flexion motor 918 and series spring 920, connected via a transmission. The flexion transmission consists of timing pulley set 922 and belt 924 drive system coupled to lead-screw 926 drive. Extension actuator 902 and flexion actuator 904 can be used independently to control the knee joint 906 angle at which series springs 910, 920 can be engaged.

[0083] The extension actuator's 902 electric motor 908 can be a brushed DC motor (such as Maxon's RE40 motor) or brushless DC motor (such as Maxon's EC-powermax 30). The extension motor directly drives a timing pulley-belt drive 914, 928 mechanism. This mechanism has a 1:2 transmission ratio. Timing pulley-belt drive mechanism 914, 928 actuates the rotation of ball-screw 916 (such as Nook industries, 10x3 mm). When ball-screw 916 of extension actuator 902 is rotated, there is a linear displacement of coupled ball-nut housing 930. Ball nut housing 930 is directly attached to extension series-elastic spring cage 932. Extension series-elastic spring cage 932 securely contains spring set 910 of two identical pre-compressed passive mechanical springs whose stiffness match that of the model's extension actuator. Thus, when there is a linear displacement of coupled ball-nut housing 930, extension series elastic cage 932 has a linear dis-

placement. Ball-nut housing 930 moves along two linear steel guide rails 934. Each of the rails is attached to a corresponding lateral wall housing 936. Spring cage 932 moves along the guide rails supported by its incorporated roller bearings 938. Extension actuator 902 is directly coupled to the rotary motion of knee joint 906, as it is attached to steel cable drive system 940.

[0084] The flexion actuator's 904 electric motor 918 can be a brushed DC motor (such as Maxon's RE40, RE30 motors) or brushless DC motor (such as Maxon's EC-powermax 30 or 22). The extension motor directly drives timing pulley-belt drive 922, 924 mechanism. This mechanism has a 1:2 transmission ratio. Pulley-belt drive mechanism 922, 924 actuates the rotation of lead-screw 926 (such as Nook industries, 10x3 mm). When lead-screw 926 of flexion actuator 904 is rotated, there is a linear displacement of coupled ball-nut housing 942. Ball-nut housing 942 is directly attached to flexion series spring cage 944. Flexion series spring cage 944 securely contains flexion spring 920. Thus, when there is a linear displacement of coupled ball-nut housing 942, the flexion series spring cage can have a linear displacement. Ball-nut housing 942 moves along two linear steel guide rails 934 with minimal friction due to rollers 938 incorporated in the ball-nut housing. Flexion actuator 904 is not directly coupled to the rotary motion of knee joint 906, however it can flex the knee when in action, back-drives the extension's series elastic spring cage 932.

[0085] Knee joint 932 is coupled to a set of two steel cable drives 940 connected to the extension's series elastic spring cage 932. The series elastic-cage is supported and guided by two steel precision guide rails 934. Steel cables 940 allow the coupling of linear displacement from series elastic spring cage 932 to the rotary motion of knee joint 906.

[0086] The two ends of each of steel cables 940 are attached to the knee joint's driving hubs 944. Driving hubs 944 are supported by knee joint housing 946. Each cable loops around its corresponding joint pulley 948 located on each side of the knee, distally from knee joint 906. Each lateral joint pulley 948 has its axis attached to its corresponding lateral wall 936. Each cable drive 940 can be independently tensioned by adjusting lateral joint pulley 948 by tuning the corresponding cable tensioner 949. Each of the series-elastic actuators 902, 904 is capable of providing sufficient power for both level-ground walking and more energetically expensive tasks such as stair ascent.

[0087] All actuation mechanisms are fully supported by an aluminum structure that corresponds to the assembly of lateral knee walls 936, upper pyramid adaptor 928 and lower pyramid adaptor 950. This structure provides a support frame that resembles the lower limb anatomical envelope. Lower pyramid adaptor 950 allows conventional and advanced robotic foot-ankle prosthesis to be attached to the knee prosthesis. The standard prosthetic upper pyramid adaptor 928 allows the knee prosthesis to be attached to a regular transfemoral socket and be worn by an above-knee amputee. The design of the prosthesis facilitates its maintenance as it is detachable side and front covers that allow easy access to the driving actuators and mechanisms.

[0088] The design parameters for knee size, angular range, and maximum torque values for the embodiment of FIGS. 9A-C and 10 are listed in Table 3.

TABLE 3

Height	32.8 cm
Medio-lateral width	6.8 cm
Anterior-posterior width	7 cm
Total weight	2.7 Kg
Flexion angle range	0-125 deg
Output torque	130 Nm

[0089] The knee's intrinsic sensory system provides feedback to the onboard control electronics. These sensors are listed in Table 4.

TABLE 4

Measurement	Sensor
Ankle angle	Digital encoder
Motor displacement	Digital encoder
Heel strike	Strain gauge
Spring compression	Hall effect
Heel/Toe contact	Force sensitive resistor foot pad
Orientation/acceleration	Inertial measurement unit

The sensors monitor the angular displacement of knee joint 906, the displacement and deformation of each series elastic element and the force/contact interaction of the knee with the environment (ground) during walking.

[0090] The angular displacement of the knee is measured directly with absolute encoder 952 located at knee joint 906. This sensor 952 is mounted on encoder housing 953 that aligns with the joint rotation. The compression of each the series elastic actuator's springs 910, 920 is measured with corresponding hall-effect sensor 954, 956. These sensors measure the magnetic field change that occurs when there is a change to the proximity of a magnet attached to each of spring cages 932, 944 while springs 910, 920 are being compressed. The rotation of each motor is measured by motor digital encoder 958, 960 attached to the back of corresponding motor 908, 918. The interaction with the ground is measured with a force sensitive footpad (not pictured). This footpad allows detection of when the leg is in contact with the walking surface, and it allows the controller to determine what gait phase the user wearing the robotic knee prosthesis is in. Another method used to measure interaction with the ground is with the use of strain gauges mounted on the frame of the knee (specifically in shin cover 962) and through instrumented lower pyramid 950. This sensory information will provide information on forces and torques that interact in the knee and can provide information to calculate torque at the knee joint. This information will assist the controller in determining the gait phase. Another sensor that is considered for this embodiment is the use of an inertial measurement unit (not pictured) which attaches to the knee's main frame, allowing the controller identify orientation and acceleration during the gait cycle.

[0091] The electronic suite is self-contained providing autonomy to the knee prosthesis (non-tethered control). The electronics have been implemented in a group of five printed circuit boards (PCB's) that are assembled on the lateral and back walls of the knee. Two of these boards are dedicated to the control of the actuators, one board is in charge of overseeing the overall knee control strategy, one board is dedicated to the connection and communication with an external monitoring PC/laptop system and a final board that will be in charge of processing data of an inertial measurement unit

installed in the knee. The electronic suit is based on PIC microcontroller technology and is powered by a six cell lithium polymer battery with a 22.2 V nominal supply. Motor boards include brushless controllers with controls up to 20 KHz. The system behavior can be monitored and updated via USB or wirelessly via wi-fi interconnection.

[0092] Finite-state control strategy. Using five phases during the gait cycle, a knee control strategy for level ground walking has been established that exploits the quasi-passive knee model in order to mimic knee biomechanics with minimal energy consumption:

[0093] Beginning at heel strike, the stance knee begins to flex slightly (~15 degrees). This Stance Flexion phase allows for shock absorption upon impact. During this phase, the knee's extension actuator will engage its series elastic components by maintaining the spring equilibrium position as energy is stored during knee flexion. The motor in this case is acting as the engaging clutch.

[0094] After reaching maximum stance flexion, the knee joint begins to extend (~15% gait cycle), until maximum stance extension (MSE) is reached (~42% gait cycle). This knee extension period is called the Stance Extension phase. During Stance Extension, the flexion actuator positions its series spring such that when the knee starts to extend, energy is stored, allowing the energy in the extension spring to be transferred. This energy transfer allows to modulate the stiffness during stance. Is important to mention that as the flexion actuator's transmission includes a lead screw, as soon as it positions its linear spring, the motor doesn't provide anymore positive power, thus, minimizing overall energy consumption. This is effectively using the model's clutch engagement behavior in a "normally closed" setting.

[0095] During late stance or Pre-Swing (from ~42% to ~62% gait cycle), the knee of the supporting leg begins its rapid flexion period in preparation for the Swing phase. During Pre-Swing, as the knee begins to flex in preparation for toe-off, the energy stored in the flexion spring gets released assisting the user before toe-off.

[0096] As the leg leaves the ground and the knee continues to flex. At toe-off, the Swing Flexion phase of gait begins. Throughout this period (from 62% to 73% gait cycle), knee power is generally negative as the knee's torque impedes knee rotational velocity. Thus, during Swing Flexion, the knee's extension actuator allows is utilized as a regenerative element, the energy that is dampened during the swing phase can be stored in the on-board battery as the actuator is back driven and the leg is repositioned to start a new gait cycle.

[0097] After reaching a maximum flexion angle (~60 degrees) during Swing, the knee begins to extend forward. During Swing Extension (from ~73% to ~100% gait cycle), knee power is generally negative to decelerate the swinging leg in preparation for the next stance period. In this phase the extension actuator is utilized as an element to provide energy regeneration and improve the energetic efficiency of the knee prosthesis. During this phase, the flexion motor repositions the linear spring in preparation for the new gait cycle.

[0098] Prosthetic Knee Design for Variable-Speed Walking The active prosthetic knee embodiments described are intended for amputees with a capacity to ambulate at a K3 level (i.e. having the ability or potential for ambulation with variable cadence). In order to have a prosthetic knee that can adapt to amputee speed variations and still maintain an opti-

mal level of energetic economy, both series-elastic components have to be non-linear and adjusted to the amputee's weight.

[0099] To evaluate speed adaptation, the variable-impedance knee model was fitted to biomechanical data from an intact subject walking at 1.0 m/s, 1.3 m/s and 1.6 m/s speeds using the optimization scheme previously described. The optimization results provided linear stiffness values (at each walking speed) for both series-elastic components, including their engagement angles during the walking cycle. For each spring and walking speed, the maximum force-displacement data pairs were selected first. By plotting all data pairs in the same force vs. displacement space, it was then possible to estimate the optimal non-linear spring functions for the flexion and extension springs. FIG. 11A is a plot of the results of an optimized non-linear polynomial fit for the force vs. displacement behavior of the series-elastic elements of an active knee according to the present invention. In particular, a second order polynomial fit was implemented for the model's extension spring 1105, and a piece wise polynomial fit for the flexion spring 1110.

[0100] As suggested by the data in FIG. 11A, for a variable-speed walking application the extension series-elastic component of FIG. 2 has to be replaced by a non-linear hardening elastic component and the flexion component of FIG. 2 has to be replaced by a softening spring. FIG. 11B depicts an exemplary embodiment of a variable-impedance prosthetic knee model for variable-speed walking, according to one aspect of the invention. As shown in FIG. 11B, the model comprises two mono-articular series-elastic clutches 1120, 1125, two non-linear springs 1130, 1135, and variable-damping element 1140.

[0101] Utilizing these non-linear spring functions, the prosthetic knee model output torque was compared to the biological knee torque data. FIGS. 11C-E show this comparison for the three different walking speeds using the model shown in FIG. 11B. In FIGS. 11C-E, the net torque output of the optimized knee model 1150, 1155, 1160 is compared to the torque profile of an intact human knee joint, with both mean 1165, 1170, 1175 and one standard deviation 1180, 1182, 1184, 1186, 1188, 1190 shown for each speed (N=10 gait trials). Goodness of fit for the model is provided by the coefficient of determination R² at each walking speed. Biological data are from a study participant (mass=66.2 kg) with intact limbs walking at three different speeds: 1.0 m/s (FIG. 11C); 1.3 m/s (FIG. 11D); and 1.6 m/s (FIG. 11E). Walking speeds within a ±5% interval for each selected speed were accepted.

[0102] It will be clear to one of skill in the art of the invention that the prosthetic knee model for variable-speed walking may be physically implemented in a manner similar to the implementation of the embodiments described for the model of FIG. 2, using components and materials that will be readily apparent to one of skill in the art, and that any of the variations and modifications that would be suitable for the embodiments of FIGS. 4A-C and 9A-C would also be suitable for use in an implementation of the model of FIG. 11B.

[0103] Further, while preferred embodiments of the invention are disclosed, many other implementations will occur to one of ordinary skill in the art and are all within the scope of the invention. Each of the various embodiments described above may be combined with other described embodiments in order to provide multiple features. Furthermore, while the foregoing describes a number of separate embodiments of the apparatus and method of the present invention, what has been described herein is merely illustrative of the application of the principles of the present invention. Other arrangements, methods, modifications, and substitutions by one of ordinary skill in the art are therefore also considered to be within the scope of the present invention, which is not to be limited except by the claims that follow.

What is claimed is:

1. A powered artificial knee comprising, in combination: knee joint, the knee joint being rotatable and coupleable to an artificial leg member;
- a series-elastic flexion actuator, connected to the knee joint in parallel with the leg member, for applying a force to cause rotation of the knee joint, resulting in flexion of the leg member, the flexion actuator comprising the series combination of a flexion motor and a flexion elastic element;
- a series-elastic extension actuator, connected to the knee joint in parallel with the leg member on the opposite side of the leg member from the flexion actuator, for applying a force to cause rotation of the knee joint, resulting in extension of the leg member, the extension actuator comprising the series combination of an extension motor and an extension elastic element; and
- a controller for independently energizing the flexion motor and the extension motor at different times to control the position, impedance, and nonconservative torque of the knee joint and coupled leg member.
2. The prosthesis of claim 1, further comprising at least one sensor configured to provide feedback to the controller.
3. The prosthesis of claim 2, wherein the sensor is responsive to angular displacement of the knee joint, compression of the flexion elastic element, compression of the extension elastic element, rotation of the flexion motor, or rotation of the extension motor.
4. The prosthesis of claim 1, wherein the flexion actuator and the extension actuator are unidirectional.
5. The prosthesis of claim 4, wherein the flexion elastic element and the extension elastic element are series springs.
6. The prosthesis of claim 1, wherein the flexion actuator is unidirectional and the extension actuator is bidirectional.
7. The prosthesis of claim 6, wherein the flexion elastic element is a series spring and the extension elastic element is a set of pre-compressed series springs.
8. The prosthesis of claim 1, wherein the flexion elastic element is a non-linear softening spring and the extension elastic element is a non-linear hardening spring.
9. The prosthesis of claim 1, wherein the flexion actuator comprises a nonbackdriveable transmission.

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