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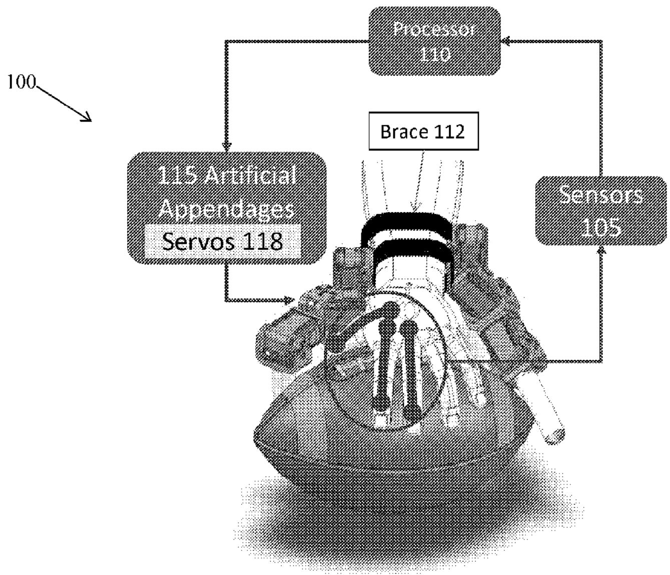

FIG. 1

(57) Abstract: An apparatus augments functionality of a human hand with at least one supernumerary artificial appendage. The apparatus includes a brace configured to be coupled to a human arm, a supernumerary artificial appendage attached to the brace, and sensors configured to be coupled to different parts of a human hand and to detect information about at least one of posture, position, velocity, acceleration, force, and torque of the human hand. The apparatus also includes a processor coupled to the sensors and the supernumerary artificial appendage. The processor determines at least one of posture, position, velocity, acceleration, force, and torque for the supernumerary artificial appendage based on outputs from the sensors, and sends at least one control signal configured to operate the supernumerary artificial appendage according to the determined at least one of posture, position, velocity, acceleration, force, and torque.

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APPARATUS AND METHOD FOR AUGMENTING FUNCTIONALITY OF A HUMAN HAND USING SUPERNUMERARY ARTIFICIAL APPENDAGES

Related Applications

[0001] The present application claims priority to U.S. Provisional Application No. 61/824,509, entitled "Apparatus and Method of Supernumerary, Wearable Robotic Fingers" and filed on May 17, 2013, which is hereby incorporated by reference in its entirety.

Technical Field

[0002] The present solution relates to supernumerary artificial appendages that supplement the functionality of a human hand.

Background Art

[0003] It is known in the prior art to create prosthetic devices that function as substitutes for natural body parts. For example, if a person loses a finger in an accident, he or she may wear a prosthetic finger in lieu of the lost finger. In this manner, prosthetic devices enable users to regain some of the functionality lost from their previously whole hand. Further, such devices have been designed to be controlled by specific hand muscle movements. For example, the devices may include sensors that detect the neural signals generated by the user's hand muscle, and base the prosthetic's movement on such signals. Thus, operating a prosthetic device requires a new user to train his or her hand muscles to accommodate the device's requirements. In this manner, a user typically must perform unnatural and unintuitive muscle movements to control the prosthetic fingers.

Summary of the Embodiments

[0004] In accordance with one embodiment of the invention, an apparatus augments functionality of a human hand with at least one supernumerary artificial appendage. The apparatus includes a brace configured to be coupled to a human arm, a supernumerary artificial appendage attached to the brace, and sensors configured to be coupled to different parts of a human hand and to detect information about at least one of posture, position, velocity, acceleration, force, and torque of the human hand. The apparatus also includes a processor coupled to the sensors and the supernumerary artificial appendage. The processor determines at least one of posture, position, velocity, acceleration, force, and torque for the supernumerary artificial appendage based on outputs from the sensors, and sends at least one control signal configured to operate the supernumerary artificial appendage according to the determined at least one of posture, position, velocity, acceleration, force, and torque.

[0005] The supernumerary artificial appendage may be positioned on the brace to couple the supernumerary artificial appendage to a human wrist. In some embodiments, the supernumerary artificial appendage exhibits multiple degrees of freedom. Further, the supernumerary artificial appendage may include at least one actuator that actuates an artificial joint based on the at least one control signal from the processor.

[0006] In various embodiments, a sensor in the plurality of sensors detects a position of a human finger, a human palm, or a human wrist. In further embodiments, the sensor detects a position of a thumb, index finger, or center finger of a human hand. The sensor may detect an angle of (i) a joint of a human finger or (ii) a joint of a human wrist.

[0007] The apparatus may also include at least one of (i) a force sensor that detects a contact force exerted by a tip of a human finger, (ii) a pressure sensor that detects a pressure at a human palm, or (iii) a torque sensor that detects a torque at a joint of a human finger. In these embodiments, the processor determines the posture for the supernumerary artificial appendage based on the outputs from the plurality of sensors that detect the information about the posture of the human hand and an output from the force sensor, pressure sensor, torque sensor, or any combination thereof.

[0008] The apparatus may also include at least one of (i) an accelerometer that detects an orientation of a human palm or (ii) a gyroscope that detects movement of the human palm. In these embodiments, the processor determines the position for the supernumerary artificial appendage based on the outputs from the plurality of sensors that detect the information about the posture of the human hand and an output from the accelerometer, an output from the gyroscope, or both.

[0009] Further, the processor may send the at least one control signal to position the supernumerary artificial appendage to aid a human hand in (i) grasping an object, (ii) manipulating an object, or (iii) performing a task in conjunction with human fingers.

[0010] In accordance with one embodiment of the invention, a method augments functionality of a human hand with at least one supernumerary artificial appendage. The method includes receiving output signals from sensors. Each output signal indicates different information about at least one of posture, position, velocity, acceleration, force, and torque of a human hand. The method includes determining at least one of posture, position, velocity, acceleration, force, and torque for the supernumerary artificial appendage based on the output signals from the sensors. Further, the method includes sending at least one control signal to operate the supernumerary artificial appendage according to the determined at least one of posture, position, velocity, acceleration, force, and torque.

[0011] The method may include receiving an output signal indicating a position of a human finger, a human palm, or a human wrist. The method may include receiving an output signal indicating a position of a thumb, index finger, or center finger of a human hand. In some embodiments, the method includes receiving an output signal indicating an angle of (i) a joint of a human finger or (ii) a joint of a human wrist. Further, the method may include receiving an output signal from a force sensor, which indicates a contact force exerted by a tip of a human finger. Additionally, the method may include receiving an output signal from a torque sensor, which indicates a torque at a joint of a human finger. In some embodiments, the method includes receiving an output signal from an accelerometer, which indicates an orientation of a part of a human hand. The method may include receiving an output signal from a gyroscope, which indicates movement of a human palm.

[0012] Further, the method may send the at least one control signal to an actuator for actuating an artificial joint in the supernumerary artificial appendage. The at least one control signal may position the supernumerary artificial appendage to aid a human hand in (i) grasping an object, (ii) manipulating an object, or (iii) performing a task in conjunction with human fingers.

[0013] In accordance with another embodiment of the invention, an apparatus augments functionality of a human hand with at least one supernumerary artificial appendage. The apparatus includes a brace configured to be coupled to a human arm, and first and second supernumerary artificial appendages attached to the brace. The first supernumerary artificial appendage includes a first plurality of actuators, and each actuator corresponding to a different joint in the first appendage. Likewise, the second supernumerary artificial appendage includes a second plurality of actuators, and each actuator corresponding to a different joint in the second appendage. Further, the second supernumerary artificial appendage is attached to the brace at a position opposite to the first artificial appendage.

[0014] The apparatus also includes sensors configured to be coupled to different parts of a human hand and to detect information about at least one of posture, position, velocity, acceleration, force, and torque of the human hand. Additionally, the apparatus includes a processor coupled to the sensors and the supernumerary artificial appendage. The processor (i) determines, for each joint in the first and second supernumerary artificial appendages, at least one of posture, position, velocity, acceleration, force, and torque for the joint based on outputs from the sensors, and (ii) sends, to each actuator in the first and second supernumerary artificial appendages, a different control signal configured to position the joint corresponding to the actuator.

[0015] The sensors may include force sensors that detect contact forces exerted by tips of human fingers. In some embodiments, the sensors include an accelerometer that detects an orientation of a human palm, a gyroscope that detects movement of a human palm, or both. Additionally, the sensors may include a pressure sensor that detects a pressure exerted at a human palm. Further, the sensors may include a torque sensor that detects a torque at a joint of a human finger.

Brief Description of the Drawings

[0016] The foregoing features of embodiments will be more readily understood by reference to the following detailed description, taken with reference to the accompanying drawings, in which:

[0017] FIG. 1 depicts a schematic drawing of a device that augments functionality of a human hand using a supernumerary artificial appendage;

[0018] FIGS. 2-4 depict exemplary embodiments and uses of the apparatus described in FIG. 1;

[0019] FIGS. 5-10 depict use examples in which the apparatus described in FIG. 1 supplements the grasp of a human hand;

[0020] FIGS. 11-13 depict use examples in which the apparatus described in FIG. 1 performs an auxiliary task in conjunction with the human hand;

[0021] FIG. 14 depicts exemplary positions of a human hand and supernumerary artificial appendages while grasping objects, in which the positions are recorded as experimental data for determining interrelationships between positions of the human hand and positions of the supernumerary artificial appendages;

[0022] FIG. 15 depicts exemplary results of principle component analysis performed upon collected experimental data;

[0023] FIG. 16 depicts data indicating the accuracy of a control algorithm for supernumerary artificial appendages; and

[0024] FIG. 17 depicts an exemplary flow diagram for using the apparatus described in FIG. 1.

Detailed Description of Specific Embodiments

[0025] Illustrative embodiments enhance the natural abilities of a human hand. When a person wears such illustrative embodiments, they may assist him or her in grasping, holding, and/or manipulating various objects, whether the user's hand is fully functional and healthy, or missing fingers or otherwise exhibiting suboptimal dexterity. To that end, illustrative embodiments include devices having supernumerary artificial appendages, and when a user wears the device, the device actuates the supernumerary artificial appendages to move with the user's hand in a coordinated manner to help the user accomplish various tasks.

[0026] In general, unlike conventional prosthetic devices, which enable a person to regain some of the lost functionality of a damaged limb, the supernumerary appendages supplement the user hand's normal functionality. Further, the supernumerary appendages may enable the user to perform tasks that are ordinarily difficult to accomplish using a single healthy human hand. For example, when a user holds a large, unwieldy object, the device may arrange the supernumerary artificial appendages to reinforce the user's grasp. In another example, the device may arrange the supernumerary artificial appendages to perform an auxiliary task that assists the user's primary task (e.g., hold a bottle in place while the person unscrews the cap, cut the stem of an apple while the person holds the apple). In this manner, the device enables the user to attain objectives beyond what the user is capable of achieving in his or her usual capacity.

[0027] Further, the appendages are physically tailored for the tasks undertaken by the human hand. The appendages may include multiple joints, thereby providing multiple degrees of freedom for the appendages' posture. Further, each section connected by the joints may have a different form factor. These parameters enable the appendages to adopt a wide variety of positions and postures to supplement the user's hand.

[0028] Additionally, various embodiments of the device advantageously operate according to the posture, position, velocity, acceleration, force, and/or torque of the user's hand, or parts thereof. In this manner, unlike the prior art, operating the device may be an intuitive and seamless experience for a user. Specifically, sensors on the device record various metrics of the user's hand. By analyzing these metrics, the device determines at least one of posture, position, velocity, acceleration, force, and torque for the supernumerary artificial appendages that aid the user in a task. Put another way, the device infers, based on data regarding metrics of the artificial appendages based on arrangements of the human hand, desired motion (and thus, desired arrangements) for the artificial appendages to assist the user. In effect, in the course of the user's normal activities, the device operates the supernumerary artificial appendage so that the appendages behave as if they were additional fingers. As the user continues to move, the device updates its recorded metrics and rearranges the supernumerary artificial appendages accordingly.

[0029] Turning now to the figures, FIG. 1 depicts a schematic representation of a device 100 that augments functionality of a human hand using a supernumerary artificial appendage. The device 100 includes sensors 105a, 105b, 105c (collectively, "105") that, together with a processor 110, sense various positional and inertial data of the human hand. A brace 112 couples with the processor 110 and a supernumerary artificial appendage 115 and its actuator 118. When the user wears the device 100, the sensors 105 may couple with different parts of the user's hand. The sensors 105 detect and forward various metrics of the user's hand to the processor 110. Based on these metrics, the processor 110 determines an appropriate subsequent arrangement (e.g., posture, position, velocity, acceleration, force, and/or torque) for the supernumerary artificial appendage 115. The processor 110 responsively forwards a control signal to an actuator 118 of the supernumerary artificial appendage 115, which then operates the supernumerary artificial appendage 115 accordingly. Further, the sensors 105 continually monitor the metrics of the hands, and as a result, the processor 110 and actuator 118 continually update the operation of the supernumerary artificial appendage 115.

[0030] Each sensor 105 may detect a different metric of the user's hand. In some embodiments, a sensor 105 detects the position of a part of a hand. For example, one of the sensors 105 may determine the position of a finger, palm, or wrist. The sensor 105 or another sensor 105 also may be configured to determine an angle of a joint of the hand, such as a joint in a finger or a joint in the wrist. In some embodiments, a sensor 105 determines the angles of multiples joints in a given human finger (e.g., the first and second joints). Although they may be configured to be coupled to any finger of a hand, the sensors 105 may also be configured to be coupled to a particular finger (e.g., thumb, index finger, third finger). In various embodiments, the sensors 105 measure the inward circumduction of a thumb, the abduction of a finger, or the flexion of joints (e.g., metacarpophalangeal, interphalangeal).

[0031] In additional embodiments, a sensor 105 may detect a pressure exerted by a part of a hand. For example, the sensor 105 may be configured to determine the pressure exerted by the tip of a human finger. Such a sensor 105 may be a force sensor 105. In some embodiments, a force sensor 105 may detect a color change in a finger nail bed and determine an amount of force being applied to the finger. In other examples, the sensor 105 may determine the pressure exerted by the palm, back of the hand, or side of the hand. Additionally, the sensor 105 may be a torque sensor. This type of sensor may measure a torque at a part of the hand, such as a finger joint or wrist. In various embodiments, a sensor 105 detects an orientation of a part of a hand. For example, the sensor 105 may be an accelerometer that determines whether a part of a user's hand (e.g., palm, finger) is facing up or down. Further, the sensor 105 may be a gyroscope that detects movement of a part of a hand. The device 105 may use any type of sensor 105 that measures a metric of a part of the hand. In some embodiments, a sensor 105 may be a stretch sensor that measures joint angles of a finger. As other examples, the sensor 105 may be a bend sensor, or a liquid-embedded elastomer electronic (LE3), which may include elastomer sheets embedded with channels of conductive liquid. The sensor 105 also may be a fiber Bragg grating (FBG) strain sensor that measures the curvature of a joint, or an optical linear encoder (OLE). In another embodiment, a sensor 105 may include an inertial sensor, such as a microelectromechanical (MEMS) accelerometer or gyroscope. Specific exemplary sensors 105 include Bi-Flex Sensors™ manufactured by Images Scientific Instruments of Staten Island, New York; Bend Sensor® manufactured by Flexpoint Sensor Systems of Draper, Utah; and Flexiforce® Sensors manufactured by Tekscan, Inc. of Boston, Massachusetts.

[0032] The device 100 may include any of the sensors 105 described herein, in any combination. For example, in any given device 100, one or more types of sensors 105 may be coupled to the same part of the hand. A device 100 may provide a separate set of force sensor 105 and accelerometer 105 for each of the user's fingers. Additionally, in some embodiments, the device 100 may couple a separate torque sensor 105 to each of the user's finger joints. Further, the device 100 may couple an accelerometer 105 and gyroscope to the user's palm. In this manner, the device 100 may include any number and combination of sensors 105 described herein, as desired.

[0033] The sensor 105 may send output signals to the processor 110 via wireless or wired communication. For example, the sensor 105 may include a wire that connects output ports of the sensor 105 with the processor 110. In another example, a sensor 105 may be equipped with a wireless communicator. In that case, the sensor 105 may send wireless output signals to the processor 110 according to any protocols that would be appreciated by one of ordinary skill in the art.

[0034] In various embodiments, the sensors 105 may be attached to a securing apparatus that couples each individual sensor 105 to a different part of a user's hand. For example, the sensors 105 may be located on the brace 112 at positions corresponding to opposite sides of the wrist, the center of the palm, the finger joints, and the finger tips. In another example, the sensors 105 may be attached to a glove at positions corresponding to parts of interest. In the latter example, the sensors 105 may be stretch sensors positioned along the lengths of the fingers such that each sensor 105 detects the angles for each joint in its corresponding finger. To determine the position of the supernumerary artificial appendage 115, the processor 110 retrieves and executes instructions from a local memory.

[0035] After experimentation, the inventors discovered that the postures, positions, velocities, accelerations, forces, and torques of the supernumerary artificial appendage 115 and those of the portions of the hand are interrelated. As described below, the supernumerary artificial appendage 115 and parts of the hand often exhibit "bio-artificial synergies," as described in more detail in reference to FIGS. 14-15. Because of this finding, the inventors were able to develop a behavioral model for the supernumerary artificial appendage 115, where the desired metrics of the supernumerary artificial appendage 115 could be determined from the known metrics of parts of the hand. Further, the inventors then were able to create a control algorithm for the supernumerary artificial appendage 115 based on this model, among other potential types of models.

[0036] To operate the supernumerary artificial appendage 115, the processor 110 forwards a control signal to the appendage 115 that operates the appendage 115 according to a desired posture, position, velocity, acceleration, force, and/or torque. In some embodiments, processor 110 forwards the signal to an actuator 118. The actuator 118 may move a part of an appendage 115. To orient a part of the appendage 115, the actuator 118 may rotate a joint coupled to the appendage 115. The actuator 118 may increase or decrease the angle formed by the joint to position the section of the appendage 115. In some embodiments, the actuator 118 may control an amount of torque exerted by a section of the appendage 115.

[0037] In some embodiments, an appendage 115 may include one or more sensors 105 that communicate with the processor 110. For example, the appendage 115 may include a sensor 105 that detects a pressure at its distal end. In this manner, this sensor 105 may measure the contact force exerted by the tip of the appendage's 115. In another example, the appendage 115 may include a torque sensor 105 that detects a torque at a joint of the appendage 115. Each of the sensors 105 may forward collected data to the processor 110, which may adjust the control signals sent to the appendage's 115 actuators to achieve the desired arrangement of the appendage 115.

[0038] In various embodiments, a supernumerary artificial appendage 115 may include multiple joints and multiple actuators 118. The number of actuators 118 may depend on the number of degrees of freedom (which may correspond to the number of joints) in the appendage 115. Each actuator 118 may operate a different joint in the appendage 115. In addition, each actuator 118 may receive a separate control signal from the processor 110, which the actuator 118 may use to arrange its associated joint and, by extension, its section of the appendage 115.

[0039] Servos are an exemplary type of actuators. For example, an appendage 115 may include the the Dynamixel AX-12A, manufactured by Robotis of Seoul, South Korea. This servo provides a maximum torque of 1.5 Nm, as well as the capacity to position the joint within a range of 300 degrees. Other servos 118 exhibiting different maximum torques and different ranges of motion may also be used. Pneumatics are another exemplary type of actuators. In some embodiments, each joint in an appendage may be coupled to a custom motor that controls the joint, though other various types of actuators may be used. The supernumerary appendage 115 may be attached to the brace 112 in a number of ways. For example, the appendage 115 may be positioned on the brace 112 so that, when worn, the brace 112 couples the appendage 115 to the user’s wrist. Alternatively, the appendage 115 may be coupled, via the brace 112, to other parts of the user’s arm, such as the user’s forearm or hand. In some embodiments, the appendage 115 may be coupled to the side of a user’s hand. Thus, the supernumerary artificial appendage 115 may be positioned to be coupled to any part of the user’s arm. In some embodiments, the device 100 includes two supernumerary artificial appendages 115 attached to the brace 112 to be positioned on opposite sides of the user’s hand.

[0040] Although this description discusses a single appendage 115, any number of appendages 115 may be incorporated into various embodiments. Discussion of a single appendage 115 thus is for simplicity purposes only. In some embodiments, the device 100 includes two appendages 115. One appendage 115 may have a similar form factor as a human thumb, and the other appendage 115 may have a similar form factor to the last finger on the hand (e.g., pinky finger). Moreover, one or more of the appendages 115 may have more than one section. For example, an appendage 115 may have two or three sections separated by joints, with separate actuators 118 located at each joint. In various embodiments, an appendage 115 may exhibit three degrees of freedom, although other numbers of degrees of freedom may be implemented. For example, the appendage 115 may have freedom of movement in the three directions of a conventional Cartesian coordinate system. Other examples permit rotation of the appendage 115, and/or sections thereof.

[0041] In some embodiments, an appendage 115 may include an object at its distal end, such as a tool, and one or more actuators to operate the object. For example, the appendage 115 may include a clipper, and an actuator may open and close the clipper's blades based on control signals from the processor 110. In another example, the appendage 115 may include a suturing tool. Based on control signals from the processor 110, an actuator 118 may operate the suturing tool to create sutures in an object. If the appendage 115 includes a wire feeder, the actuator 118 may operate the wire feeder to expend or retract wire. In a further example, the appendage 115 includes a holder, and the actuator 118 positions the holder to keep another object in place. These embodiments are merely examples, and other types of tools and operations using such tools may be incorporated in the device 100.

[0042] Further, although the device 100 is described as having a single processor 110, the device 100 may include any number of processors 110 as required by the ultimate application. Among other things, the processors 110 may include a single core or multiple cores. The device 100 may use any number of type of processor 110 capable of executing the control algorithm for the supernumerary artificial appendages 115.

[0043] In various embodiments, the user may wear the device 100 by attaching the brace 112 to a portion of his or her body. For example, the user may wrap the brace 112 around his or her wrist. In another example, the user may place his or her hand into a glove.

[0044] The brace 112 may be produced according to any conventional manufacturing method as would be considered feasible by one of ordinary skill in the art. For example, the brace 112 may be 3D printed (e.g., created via fused deposition modeling) or injection molded. To enhance comfort and ease of use, the brace 112 preferably is lightweight. For example, the brace 112 may weigh less than about 250 grams. The brace 112 illustratively is designed to distribute the weight of the supernumerary artificial appendages 115 evenly across the user's hand, wrist, forearm, or any combination thereof. Other embodiments, however, may not distribute that weight evenly.

[0045] FIGS. 2-4 depict exemplary embodiments of the device described in FIG. 1. Specifically, FIG. 2 shows one implementation in which the device 200 includes sensors 105 that measure the pressures exerted by fingertips, the angles of the fingers' joints, and the angles of the wrist's joints. The sensors 105 send these measurements to the processor (not shown), which determines the arrangements of the two supernumerary artificial appendage 115 of the device 200. In this embodiment, both of the supernumerary artificial appendages 115 are attached to a brace 112 that couples the appendages 115 to the user's wrist. The supernumerary artificial appendages 115 are positioned to be coupled to generally opposite sides of the user's hand. Further, these supernumerary artificial appendages 115 have multiple segments connected by different joints. Thus, the processor 110 may determine the arrangements for each segment of the supernumerary artificial appendages 115, including the rotation and extension needed for each joint to position the segments accordingly. To position the appendages 115, the processor 110 first sends control signals to each actuator 118 in the supernumerary artificial appendages 115. The actuators 118 respond by moving the joints of the appendages 115a and 115b to the desired positions and orientations. Further, the sensors 105d on the appendages 115 measure the contact force exerted by the appendages' 115 tips, and the sensors 105d may forward measured data to a processor 110. The processor 110 may adjust the control signals sent to the actuators 118 so that the appendages 115 exert the desired force.

[0046] Fig. 3 depicts another exemplary device 300 with two supernumerary artificial appendages 115. As in the device 200 of Fig. 2, the supernumerary artificial appendages 115 are attached to a brace 112 that is worn on the user's wrist or forearm. Due to the supernumerary artificial appendages' 115 positions on the brace 112, the supernumerary artificial appendages 115 are coupled to the wrist or forearm. Again, the supernumerary artificial appendages 115 are located on generally opposite sides of the user's hand. Since these supernumerary artificial appendages 115 have more segments, and thus more joints, than the supernumerary artificial appendages 115 depicted in Fig. 2, the processor (not shown) may arrange these supernumerary artificial appendages 115 with a greater degree of precision. Further, the supernumerary artificial appendages 115 of device 300 have heterogeneous segments. Each segment may have a different form factor and/or be composed of different materials. For example, the end segments may have form factors configured for gripping an object and include materials with high coefficients of friction to aid the grip.

[0047] Fig. 4 depicts another exemplary device 400. In addition to the brace 112, this device 400 includes a glove to which stretch sensors 105 have been attached. Thus, each stretch sensor 105 may obtain metrics for its corresponding finger. In this embodiment, the three stretch sensors 105 obtain metrics for the user's thumb, index finger, and third finger, although in other embodiments, the device 400 includes a stretch sensor 105 for each finger. Further, the stretch sensors 105 are electrically coupled to the processor (not shown) via wires. The processor 110 may process signals from the stretch sensors 105 and arrange the supernumerary artificial appendages 115 according to any of the steps described herein.

[0048] FIGS. 5-10 show a variety of different exemplary uses of the device 100 described in FIG. 1. In these examples, the device 100 aids a user's hand in grasping an object. FIG. 5 depicts a device 500 in which a single supernumerary artificial appendage 115 supports an object held by the user, i.e., a cup. In this example, the supernumerary artificial appendage 115 props up the bottom of the object. FIGS. 6-10 depict devices 600, 700, 800, 900, and 1000 in which two supernumerary artificial appendages 115 supplement a user's grasp. In some of these examples, the devices 600, 700, and 800 position the supernumerary artificial appendages 115 to clasp the object. In the remaining examples, the devices 900 and 1000 position the supernumerary artificial appendages 115 to grip the sides of the object, thereby reinforcing the user's hold.

[0049] FIGS. 11-13 show a variety of other exemplary uses of the device 100 described in FIG. 1. In these examples, the device 100 performs an auxiliary task in conjunction with the human hand. For example, FIG. 11 shows the supernumerary artificial appendage 115 with an on-board clipper 130. As the user grasps an object, such as an apple, the processor 110 and actuators 118 position the blades of the clipper 130 around the object's stem. The processor 110 and actuators 118 may also operate the clipper 130 to cut the stem.

In this manner, the cutter 130 performs a task separate, but complementary to, the task of the user's hand. As the user grips the object, the clipper 130 cuts the stem of the same.

[0050] In FIGS. 12-13, the supernumerary artificial appendage(s) 115 hold an object in place as a user manipulates it. FIG. 12 depicts the supernumerary artificial appendage 115 with a holder 130, and the holder 130 may keep a screw in place while the user operates a drill, and FIG. 13 depicts the supernumerary artificial appendages 115 holding a computer tablet device while the user types into a keypad. In various other examples, the supernumerary artificial appendages 115 may hold an object as the user opens it (e.g., untwists a cap from a bottle).

[0051] Turning now to control of the supernumerary artificial appendages 115, the control algorithms for the device 100 are derived from experimental data that models advantageous behaviors of the supernumerary artificial appendages 115 with respect to behaviors of the parts of the hand. Without wishing to be bound by theory, these exemplary algorithms are based on principles of synergy. In the context of human hands, different groups of muscles exhibit biological synergy since they may be activated by a single control signal. In light of the synergies demonstrated among various groups of muscles, a hand may accomplish numerous and complex movements based on the manner in which control signals are deployed. In fact, a small number of such signals may produce a wide range of movements. Each of these movements depends on the specific sequence and/or superimposition of control signals relayed to the applicable groups of muscles.

[0052] In the context of various embodiments, when the inventors modeled desired behaviors of the supernumerary artificial appendages 115, they discovered that the supernumerary artificial appendages 115 demonstrated synergies with the natural fingers of the human hand. Because the supernumerary artificial appendages 115 do not actually have muscle groups or nerves, these synergies are artificial (e.g., “bio-artificial”). By accounting for these interrelationships in the appendages’ 115 control function(s), the device 100 may control its supernumerary artificial appendages 115 to behave as if they were natural extensions of the human hand, i.e., as if they had muscle groups and joints that functioned in tandem with parts of the user’s natural hand. In particular, the inventors created an exemplary control algorithm for determining the arrangement of the supernumerary artificial appendages 115 based on the arrangement of the user’s natural hand.

[0053] An engineer or other developer who is developing the algorithm may wear a device capable of capturing metrics of the user’s hand and supernumerary artificial appendages 115. In some embodiments, the developer may wear a device 100 equipped with a data glove capable of capturing the metrics. An exemplary data glove is ShapeHand, manufactured by Virtual Realities, Ltd., of League City, Texas. For example, the data glove may include fiber optic sensors that capture metrics, such as positions of the user’s wrist, finger tips, and finger joints. Exemplary fiber optic sensors include sensors manufactured by Measurand, of Toronto, Canada. In other examples, the data glove may include any of the sensors 105 described herein. In some embodiments, the memory of the device 100 is reprogrammed for capturing metrics about the parts of the hand and the supernumerary artificial appendages 115. In further embodiments, the device 100 is connected to a computing device running a program for capturing and recording the metrics.

[0054] To obtain the data itself, the developer may arrange his or her hand for a task (e.g., position his or her fingers, orient the hand, exert desired forces through the fingertips), arrange the supernumerary artificial appendages 115 in a manner that aids the developer in the task, and record all of the metrics (e.g., at least one of posture, position, velocity, acceleration, force, and torque) for the arrangement. The developer then may arrange the appendages 115 manually. In some embodiments, the developer may control the supernumerary artificial appendages 115 using a software program such as Labview, as manufactured by National Instruments of Austin, TX. The developer may instruct Labview to move the supernumerary artificial appendages 115 until they reach the desired arrangement. Then, Labview may record the metrics of the supernumerary artificial appendages 115 (e.g., angles of each joint) for each desired arrangement, as well as the metrics of the developer's hand. For example, the metrics may include the nineteen (19) joint angles among the developer's fingers, and six (6) joint angles for the supernumerary artificial appendages 115, although the metrics may include any of the exemplary metrics described herein.

[0055] For any given arrangement of the hand, the developer may record data for one or more potentially desired arrangements of the supernumerary artificial appendages 115. For example, as depicted in FIG. 14, while the developer grasps a bottle, the supernumerary artificial appendages 115 may sufficiently support the bottle from more than one position. The developer may collect data for one arrangement, reposition the supernumerary artificial appendages 115 to another supplemental arrangement, and collect data for that arrangement. In another example, the developer may grasp the top of a soccer ball and arrange the supernumerary artificial appendages 115 at a few locations that would help the developer retain the ball. The developer may record metrics regarding the parts of his or her hand and the supernumerary artificial appendages 115 in these arrangements. In another example, the developer may grasp the top of a football, arrange the supernumerary artificial appendages 115 to aid the developer's hold, and record metrics.

[0056] In some embodiments, the developer may retain all of the data for further analysis. In other embodiments, for any given arrangement of the hand, the developer may average the data for the supernumerary artificial appendages 115 to reduce the amount of data used in subsequent analysis. For example, the developer may record data for five potential arrangements of the supernumerary artificial appendages 115 when the developer is performing a particular task, and then average the data. The developer may store the average in conjunction with the arrangement of the developer's hand and discard the originally collected data.

[0057] Although the examples of FIG. 14 depict a developer grasping different objects, metrics may also be collected when the developer performs other tasks. For example, the supernumerary artificial appendages 115 may secure the position of an object used in a task. The appendages 115 may apply pressure to secure a workpiece in place as the developer drills a hole. In some additional examples, the appendages 115 may hold a screw or nut in place while the developer secures it with a screwdriver or wrench, grasp the base or body of a jar as a developer unscrews its lid, or grasp a bottle as a developer removes its cap with a bottlecap remover. The developer may position the appendages 115 to hold a book open while the developer turns its pages. In another example, the developer may position the appendages 115 to support a container from the bottom as the developer stirs its contents with a spoon. The appendages 115 may support different sides or the bottom of a box as the developer carries the box.

[0058] In this manner, the user may obtain data regarding useful, advantageous arrangements for the supernumerary artificial appendages 115, with respect to the user's own hand.

[0059] Principle component analysis (PCA) may reveal the existence of interrelationships between arrangements of the parts of the hand and desired arrangements of the supernumerary artificial appendages 115. In particular, PCA of the collected data may determine the most significant variables that account for variance within the collected data. The collected data may be entered into a matrix X, such as

[0060] $$\mathbf{X} = [\mathbf{x}^1, \cdots, \mathbf{x}^N] \in \Re^{r \times N}$$

[0061] where $x^i = [x_1, L, x_r]^T$ describes the mean-centered joint angles of the hand and supernumerary artificial appendages 115, and *N* corresponds to the number of data sets collected. Using the eigenvectors (vi) and eigenvalues λi) of the covariance of X, then XX^T may be approximated by

[0062] $$\mathbf{X}\mathbf{X}^T \cong \lambda_1 \mathbf{v}_1 \mathbf{v}_1^T + \lambda_2 \mathbf{v}_2 \mathbf{v}_2^T + \cdots + \lambda_s \mathbf{v}_s \mathbf{v}_s^T$$

[0063] where s <= r < N. The accuracy of this approximation represents the percentage of the data variance that is accounted for by the principle components. Using the eigenvalues, the accuracy may be represented as

[0064] $$\mu = \frac{\lambda_1 + \lambda_2 + \cdots \lambda_s}{\lambda_1 + \lambda_2 + \cdots \lambda_r}$$

[0065] FIG. 15 depicts exemplary results of principle component analysis performed upon collected experimental data. The analysis demonstrates that for the arrangements used in the experiments, arrangements of the supernumerary artificial appendages 115 are correlated with the arrangements of parts of the hand. This result confirms that movement of the supernumerary artificial appendages 115 and hand are interrelated.

[0066] In particular, FIG. 15 illustrates the μ for each of the first six principle components. When the five fingers of a user hand and two supernumerary artificial appendages 115 are considered together, two principle components may account for about 81.5% of the variance in the position data (e.g., 66.6% for the first component, and 14.9% for the second). Put another way, two degrees of freedom may account for 81.5% of the possible positions of the user hand and supernumerary artificial appendages 115. The first component may correspond to in-phase motion of the five fingers, the supernumerary artificial appendages 115, or both, whereas the second component may correspond to out-of-phase motion of the five fingers, the supernumerary artificial appendages 115, or both.

[0067] Further, PCA confirms not only that the collected data may be modeled using a small number of variables, but the scope of arrangements (and thus movements) may be satisfactorily represented using a particular number of control signals. FIG. 15 is associated with collected experimental data that accounted for nineteen finger joints and six supernumerary artificial appendage 115 joints, thereby resulting in twenty five (25) degrees of freedom. FIG. 15 also demonstrates that the amount of variance accounted for in principle components diminishes greatly after the third one. In this manner, a developer may create a functional model and control algorithm for the artificial appendages 115 based on two or three principle components, thereby reducing the number of degrees of freedom from twenty five (25) to two or three. FIG. 15 reveals that accounting for the fourth principal component would provide slight improvements in functionality.

[0068] To model the interrelationships, in some embodiments, the collected data is first inserted into two separate matrixes, one including data collected regarding the user's five fingers and the other including data collected regarding the supernumerary artificial appendages' 115. The former is an input matrix X, while the latter is an output matrix Y.

[0069] $$\mathbf{X} = [\mathbf{x}^1, \cdots, \mathbf{x}^N] \in \Re^{n \times N}$$

[0070] $$\mathbf{Y} = [\mathbf{y}^1, \cdots, \mathbf{y}^N] \in \Re^{m \times N}$$

[0071] Again, where $x^i = [x_1, \ldots, x_n]^T$ describes to the mean-centered joint angles of the user's fingers and where $y^i = [y_1, L, y_m]^T$ corresponds to the mean-centered joint angles of the supernumerary artificial appendages 115. *n* and *m* correspond to the number of degrees of freedom in the fingers and artificial appendages 115, respectively, and *N* corresponds to the number of data sets collected.

[0072] Then, unit vectors in the input and output space are determined to maximize the correlation between projections of the hand arrangements on the input unit vectors and projections of the supernumerary artificial appendage arrangements on the output unit vectors. The unit vector in the input space may represented as:

[0073] $v \in \Re^{nxl}$

[0074] Projections of the arrangements of the user's hand onto the theoretical unit vector in the input space may be represented as:

[0075] $$z^i = \mathbf{v}^T \mathbf{x}^i$$

[0076] The unit vector in the output space may be represented as:

[0077] $w \in \Re^{mxl}$

[0078] Further, projections of the arrangements of the supernumerary artificial appendages 115 on the theoretical unit vector in the output space may be represented as:

[0079] $s^i = \mathbf{w}^T \mathbf{y}^i$

[0080] To determine the directions of the input and output vectors that exhibit the strongest correlations between the arrangements of the user's hand and the arrangements of the artificial appendages 115, the following equation must be solved:

[0081] $$\mathbf{v}^o, \mathbf{w}^o = \arg\max_{\substack{|\mathbf{v}|=1 \\ |\mathbf{w}|=1}} \sum_{i=1}^{N} z^i s^i = \arg\max_{\substack{|\mathbf{v}|=1 \\ |\mathbf{w}|=1}} \mathbf{v}^T X Y^T \mathbf{w}$$

[0082] In more detail, v^o is the unit eigenvector associated with the maximum eigenvalue of matrix XY^TYX^T, while w^o is the unit eigenvector associated with the maximum eigenvalue of matrix YX^TXY^T. This pair of eigenvectors gives the most significant component for correlating the hand and artificial appendage 115 arrangements. Applying partial least squares (PLS) regression to these equations results in a series of unit vectors in the order of descending significance. As discussed above, since much of the data variance may be expressed through the first three principle components, a developer may select the three pairs of unit vectors for the control algorithm. In some embodiments, the control algorithm may be expressed by

[0083] $y = Ax$

[0084] wherein A is a matrix that includes the series of unit vectors obtained by partial least squares regression.

[0085] Although the principle component analysis and subsequent model of the interrelationships, ultimately used for the appendages' control algorithm, are described herein with respect to joint angles of the user and appendages, similar steps may be applied to any other metric described herein. For example, a developer may collect data that also includes the velocity of the user's hand, torque exerted at the user's finger joints, and the desired torques to be exerted by the appendages' joints. In this manner, the developer may create a control algorithm that arranges not just the appendages joint angles, but the torques exerted by each joint. The methodologies described herein may be extended to account for any other metric of the user's hand and artificial appendage.

[0086] FIG. 16 depicts data indicating the accuracy of a control algorithm for supernumerary artificial appendages 115, the control algorithm determined using the steps described herein. As demonstrated by the circular data points, for a control algorithm created via partial least squares regression that utilizes three principle components, the positions of artificial appendages 115 observed while collecting experimental data substantially matches the positions obtained when the algorithm is applied to the appendages 115.

[0087] FIG. 17 depicts an exemplary flow diagram of a method for using the device described in FIG. 1. First, the method receives output signals from position sensors, where each output signal indicates at least one of posture, position, velocity, acceleration, force, and torque of a different part of a human hand (step 1701). The output signal may indicate a position of a finger, palm, or wrist, and/or an angle of a joint of the hand, such as a joint in a finger or a joint in the wrist. The output signal may indicate the inward circumduction of a thumb, the abduction of a finger, or the flexion of joints (e.g., metacarpophalangeal, interphalangeal).

[0088] The method also determines at least one of posture, position, velocity, acceleration, force, and torque for the supernumerary artificial appendage based on the output signals from the position sensors (step 1702). For example, the method may apply a control algorithm created by any of the steps described herein. The method also sends at least one control signal to arrange the supernumerary artificial appendage (step 1703). The control signal may actuate a actuator 118 to position an appendage, or a section of an appendage.

[0089] Although various embodiments have been described herein in reference to supernumerary artificial fingers that may be coupled to a human hand or arm, the artificial appendages may be coupled to other parts of the human body. In some embodiments, the appendages may even be detached from the human body. For example, the appendages may be positioned remotely from the user. In these embodiments, to obtain data for developing a control algorithm for the appendage, the developer may position his or her hand, position the supernumerary artificial appendages 115 in a manner that aids the developer in a task, and record all of the metrics. For example, the developer may collect data to operate the artificial appendage for controlling machinery, such as construction equipment. To obtain a set of data, the developer may arrange his or her hand, arrange the artificial appendage relative to construction equipment, and collect metrics, as discussed herein. By collecting data regarding user hand behaviors and related artificial appendage behaviors in this manner, a developer may create a control algorithm for remotely operating construction equipment. Further industrial embodiments may be contemplated and fall within the scope of this disclosure. The developer may create the control algorithm according to principle component analysis and partial least squares regression, according to any of the methods described herein.

[0090] Various embodiments of the present invention may be characterized by the potential claims listed in the paragraphs following this paragraph (and before the actual claims provided at the end of this application). These potential claims form a part of the written description of this application. Accordingly, subject matter of the following potential claims may be presented as actual claims in later proceedings involving this application or any application claiming priority based on this application. Inclusion of such potential claims should not be construed to mean that the actual claims do not cover the subject matter of the potential claims. Thus, a decision to not present these potential claims in later proceedings should not be construed as a donation of the subject matter to the public.

[0091] The embodiments of the invention described above are intended to be merely exemplary; numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in any appended claims.

What is claimed is:

1. An apparatus for augmenting functionality of a human hand with at least one supernumerary artificial appendage, the apparatus comprising:

a brace configured to be coupled to a human arm;

a supernumerary artificial appendage attached to the brace;

sensors configured to be coupled to different parts of a human hand and to detect information about at least one of posture, position, velocity, acceleration, force, and torque of the human hand;

a processor coupled to the sensors and the supernumerary artificial appendage, wherein the processor (i) determines at least one of posture, position, velocity, acceleration, force, and torque for the supernumerary artificial appendage based on outputs from the sensors, and (ii) sends at least one control signal configured to operate the supernumerary artificial appendage according to the determined at least one of posture, position, velocity, acceleration, force, and torque.

2. The apparatus of claim 1, wherein the supernumerary artificial appendage is positioned on the brace to couple the supernumerary artificial appendage to a human wrist.

3. The apparatus of claim 1, wherein the supernumerary artificial appendage exhibits multiple degrees of freedom.

4. The apparatus of claim 1, wherein the supernumerary artificial appendage includes at least one actuator that actuates an artificial joint based on the at least one control signal from the processor.

5. The apparatus of claim 1, wherein a sensor in the plurality of sensors detects a position of a human finger, a human palm, or a human wrist.

6. The apparatus of claim 5, wherein the sensor detects a position of a thumb, index finger, or center finger of a human hand.

7. The apparatus of claim 5, wherein the sensor detects an angle of (i) a joint of a human finger or (ii) a joint of a human wrist.

8. The apparatus of claim 1, further comprising at least one of (i) a force sensor that detects a contact force exerted by a tip of a human finger, (ii) a pressure sensor that detects a pressure at a human palm, or (iii) a torque sensor that detects a torque at a joint of a human finger, wherein the processor determines the posture for the supernumerary artificial appendage based on the outputs from the plurality of sensors that detect the information about the posture of the human hand and an output from the force sensor, pressure sensor, torque sensor, or any combination thereof.

9. The apparatus of claim 1, further comprising at least one of (i) an accelerometer that detects an orientation of a human palm or (ii) a gyroscope that detects movement of the

human palm, wherein the processor determines the position for the supernumerary artificial appendage based on the outputs from the plurality of sensors that detect the information about the posture of the human hand and an output from the accelerometer, an output from the gyroscope, or both.

10. The apparatus of claim 1, wherein the processor sends the at least one control signal to position the supernumerary artificial appendage to aid a human hand in (i) grasping an object, (ii) manipulating an object, or (iii) performing a task in conjunction with human fingers.

11. A method for augmenting functionality of a human hand with at least one supernumerary artificial appendage, the method comprising:

receiving output signals from sensors, each output signal indicating different information about at least one of posture, position, velocity, acceleration, force, and torque of a part of a human hand;

determining, by the processor, at least one of posture, position, velocity, acceleration, force, and torque for the supernumerary artificial appendage based on the output signals from the sensors; and

sending, by the processor, at least one control signal to operate the supernumerary artificial appendage according to the determined at least one of posture, position, velocity, acceleration, force, and torque.

12. The method of claim 11, wherein receiving the output signals from the sensors comprises:

receiving an output signal indicating a position of a human finger, a human palm, or a human wrist.

13. The method of claim 11, wherein receiving the output signals from the sensors comprises:

receiving an output signal indicating a position of a thumb, index finger, or center finger of a human hand.

14. The method of claim 11, wherein receiving the output signals from the sensors comprises:

receiving an output signal indicating an angle of (i) a joint of a human finger or (ii) a joint of a human wrist.

15. The method of claim 11, wherein receiving the output signals from the sensors comprises:

receiving an output signal from a force sensor, the output signal from the force sensor indicating a contact force exerted by a tip of a human finger.

16. The method of claim 11, wherein receiving the output signals from the sensors comprises:

receiving an output signal from a torque sensor, the output signal from the torque sensor indicating a torque at a joint of a human finger.

17. The method of claim 11, wherein receiving the output signals from the sensors comprises:

receiving an output signal from an accelerometer, the output signal from the accelerometer indicating an orientation of a part of a human hand.

18. The method of claim 11, wherein receiving the output signals from the sensors comprises:

receiving an output signal from a gyroscope, the output signal from the gyroscope indicating movement of a human palm.

19. The method of claim 11, wherein sending the at least one control signal comprises

sending the at least one control signal to an actuator for actuating an artificial joint in the supernumerary artificial appendage.

20. The method of claim 11, wherein sending the at least one control signal comprises

sending the at least one control signal to position the supernumerary artificial appendage to aid a human hand in (i) grasping an object, (ii) manipulating an object, or (iii) performing a task in conjunction with human fingers.

21. An apparatus for augmenting functionality of a human hand with at least one supernumerary artificial appendage, the apparatus comprising:

a brace configured to be coupled to a human arm;

a first supernumerary artificial appendage attached to the brace, wherein the first supernumerary artificial appendage includes a first plurality of actuators, each actuator corresponding to a different joint in the first appendage;

a second supernumerary artificial appendage attached to the brace at a position opposite to the first artificial appendage, wherein the second supernumerary artificial appendage includes a second plurality of actuators, each actuator corresponding to a different joint in the second appendage;

sensors configured to be coupled to different parts of a human hand and to detect information about at least one of posture, position, velocity, acceleration, force, and torque of the human hand;

a processor coupled to the sensors and the supernumerary artificial appendage, wherein the processor (i) determines, for each joint in the first and second supernumerary artificial appendages, at least one of posture, position, velocity, acceleration, force, and torque for the joint based on outputs from the sensors, and (ii) sends, to each actuator in the first and second supernumerary artificial appendages, a different control signal configured to position the joint corresponding to the actuator.

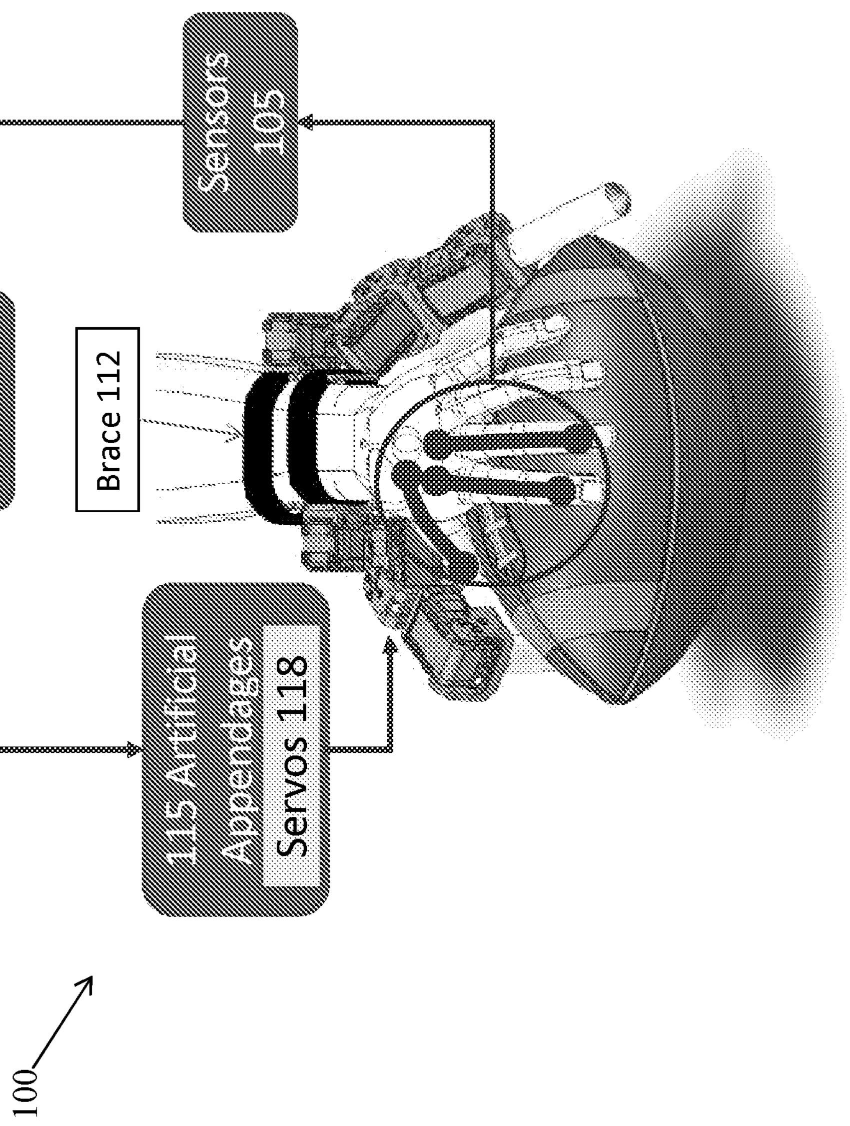
22. The apparatus of claim 21, wherein the sensors include force sensors that detect contact forces exerted by tips of human fingers.

23. The apparatus of claim 21, wherein the sensors include an accelerometer that detects an orientation of a human palm.

24. The apparatus of claim 21, wherein the sensors include a gyroscope that detects movement of a human palm.

25. The apparatus of claim 21, wherein the sensors include a pressure sensor that detects a pressure exerted at a human palm.

26. The apparatus of claim 21, wherein the sensors include a torque sensor that detects a torque at a joint of a human finger.



Sensors 105
Processor 110
Brace 112
115 Artificial Appendages
Servos 118
100

FIG. 1

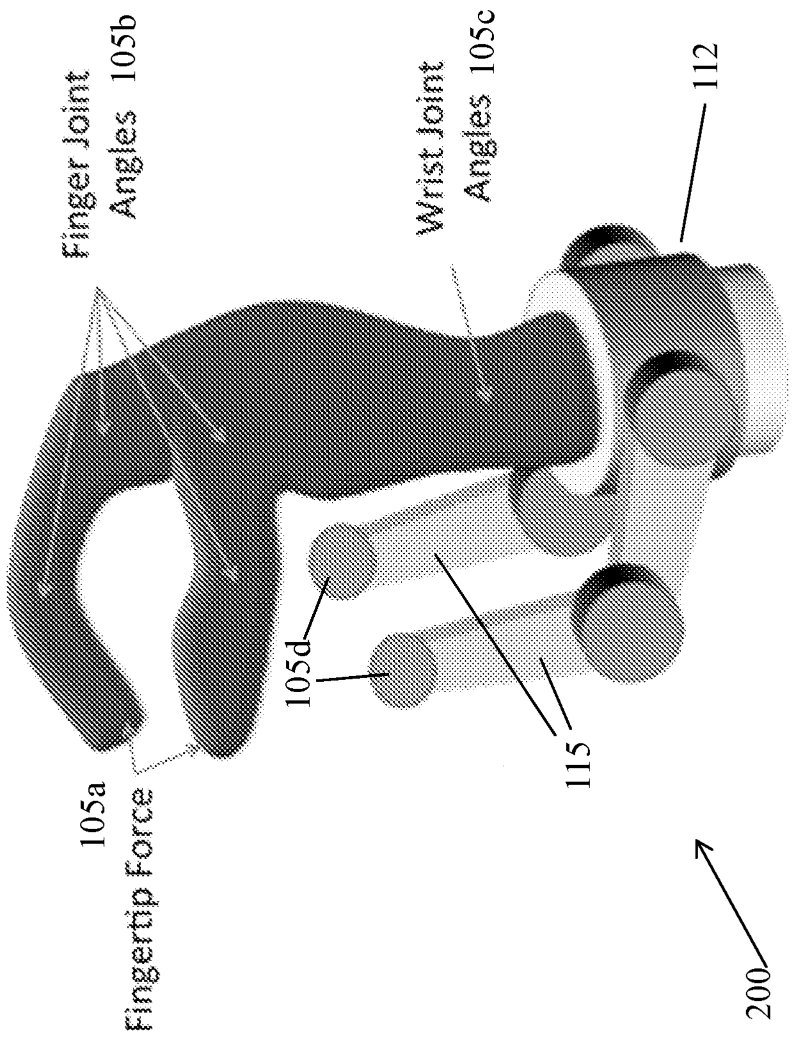

Finger Joint
Angles 105b
Wrist Joint
Angles 105c
112
105a
Fingertip Force
105d
115
200

FIG. 2

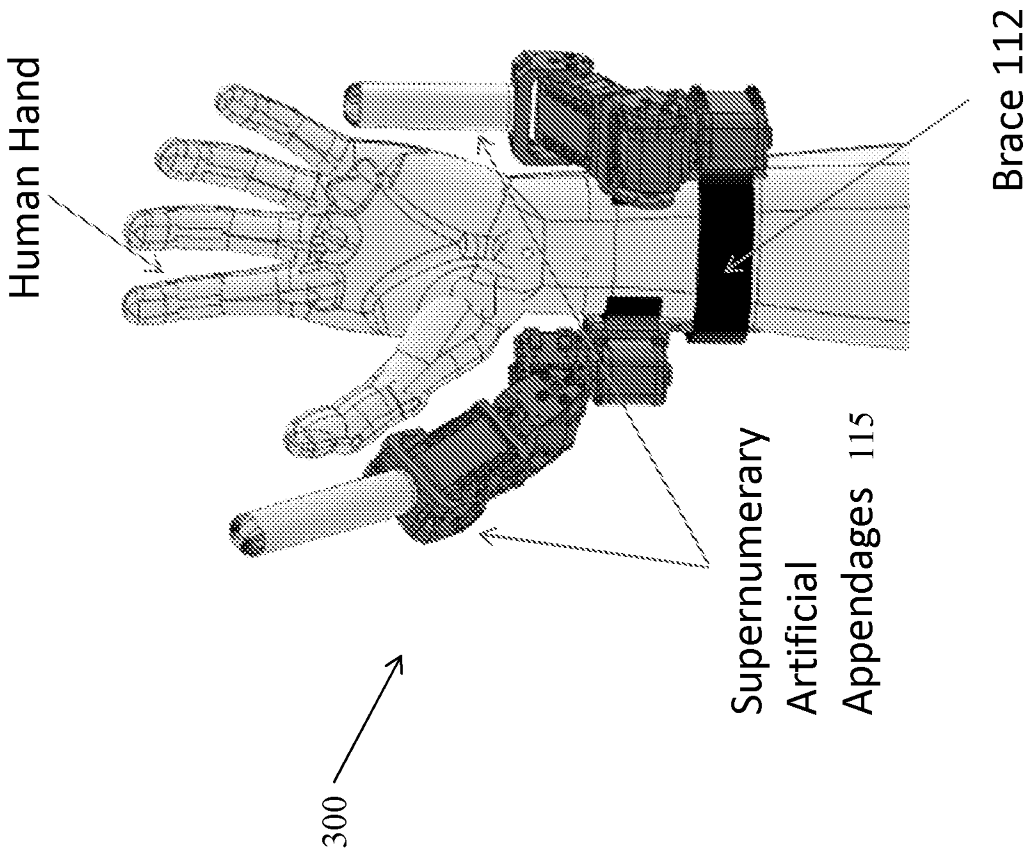
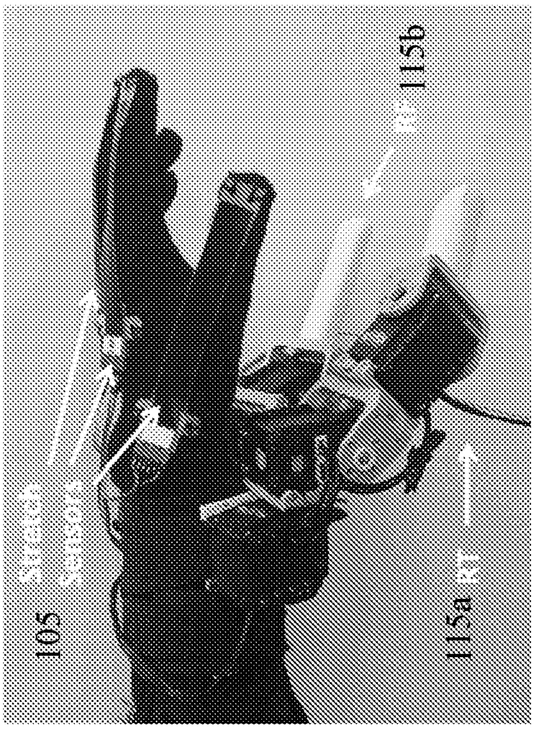

Human Hand
Brace 112
Supernumerary Artificial Appendages 115
300

FIG. 3



400

FIG. 4

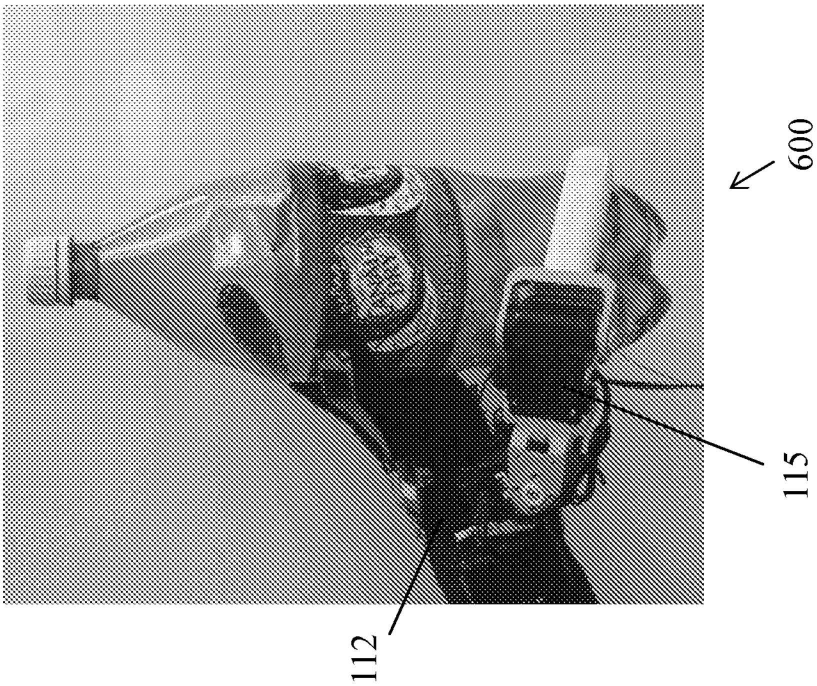


FIG. 6

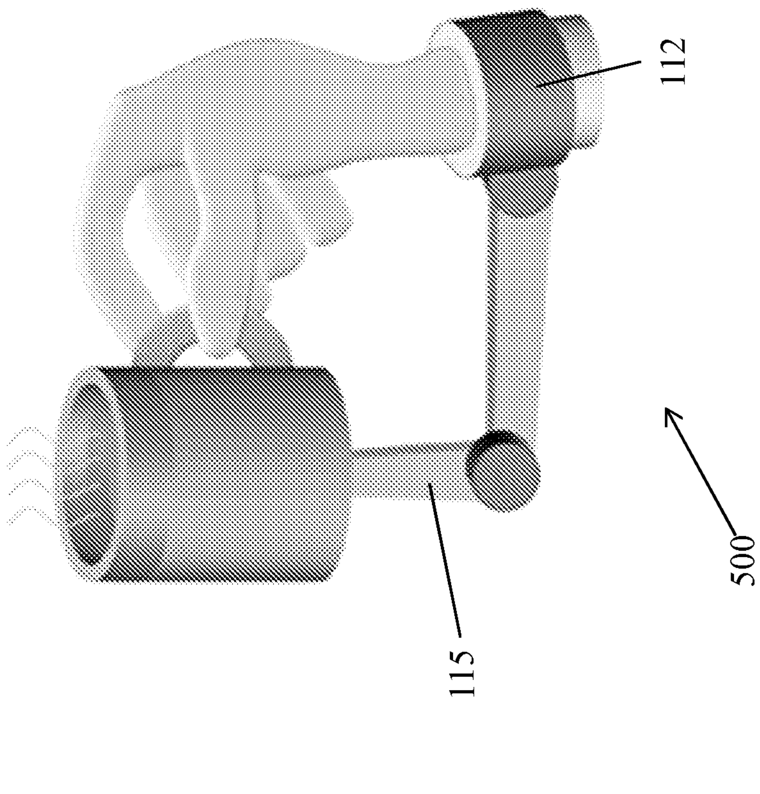


FIG. 5

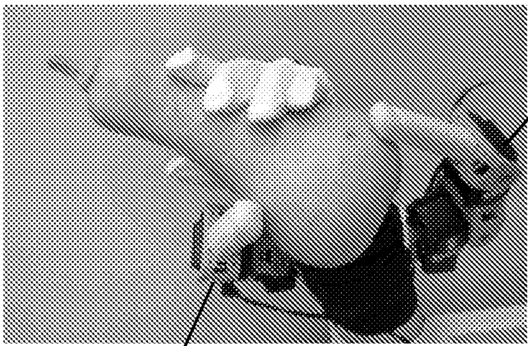


FIG. 8

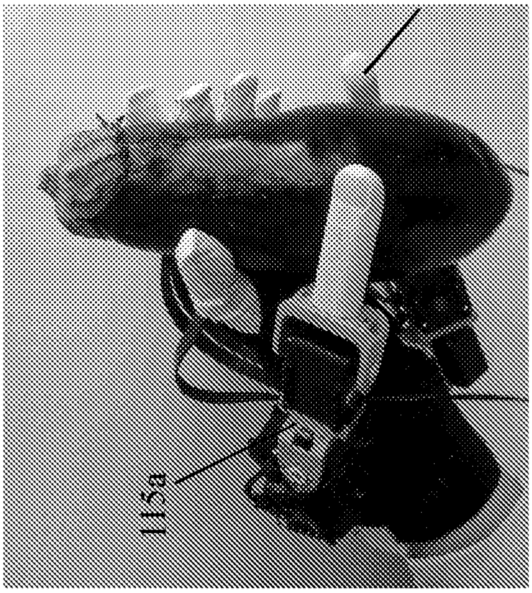


FIG. 7

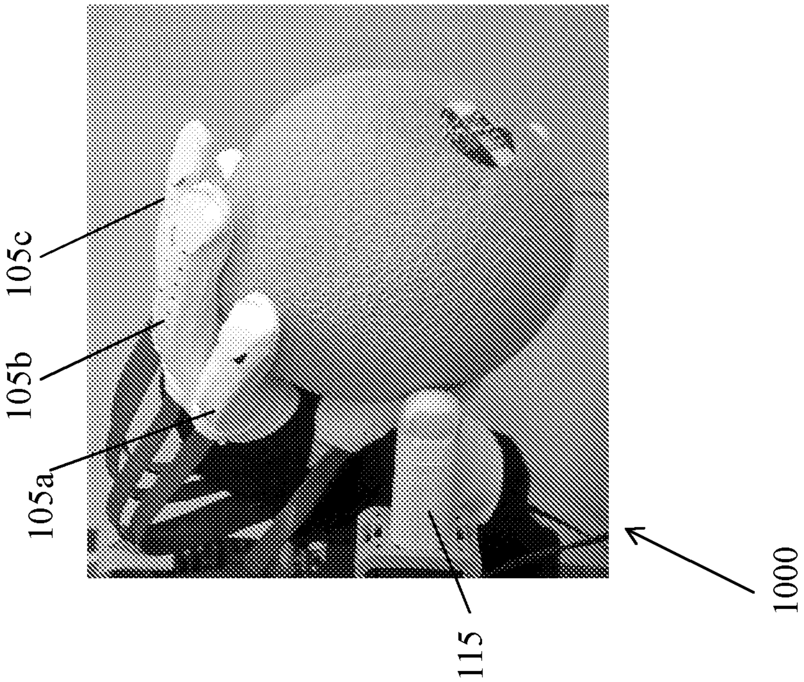


FIG. 10

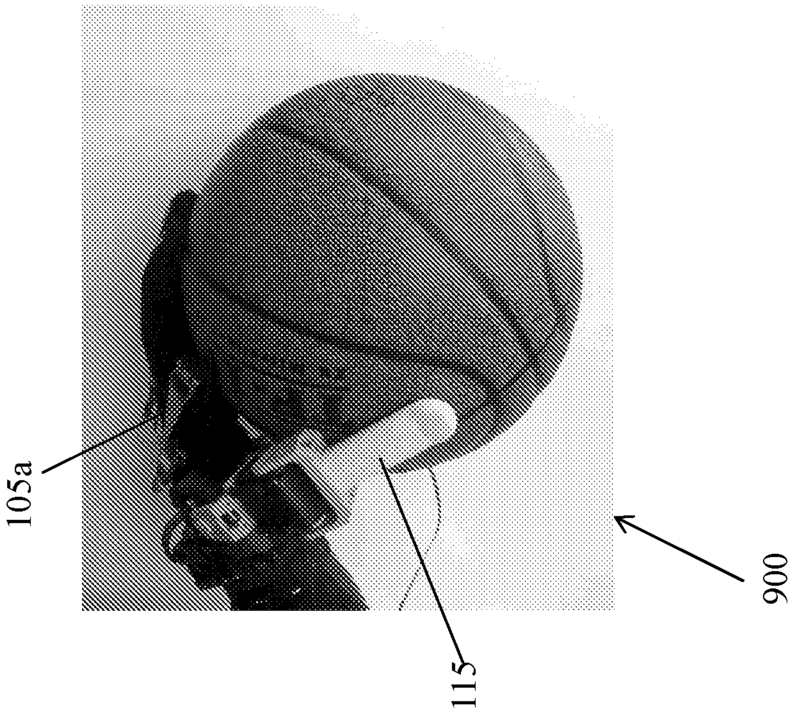


FIG. 9

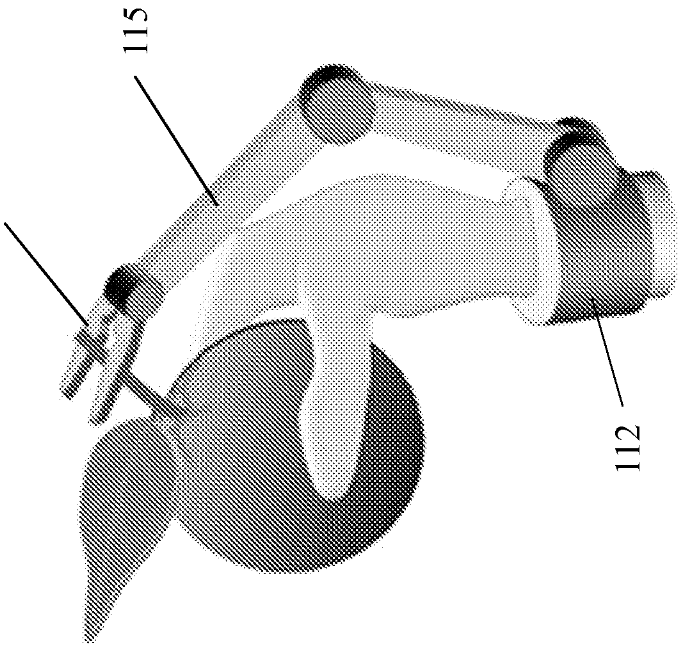


FIG. 11

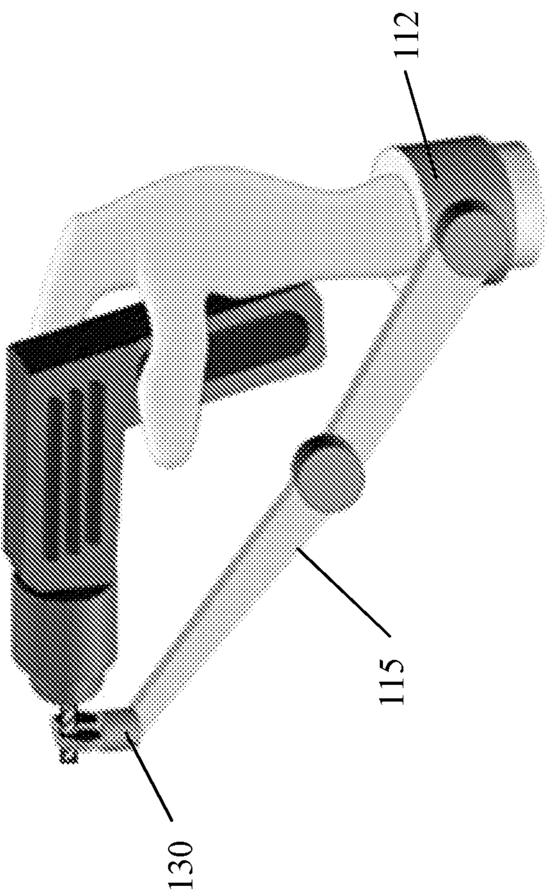


FIG. 12

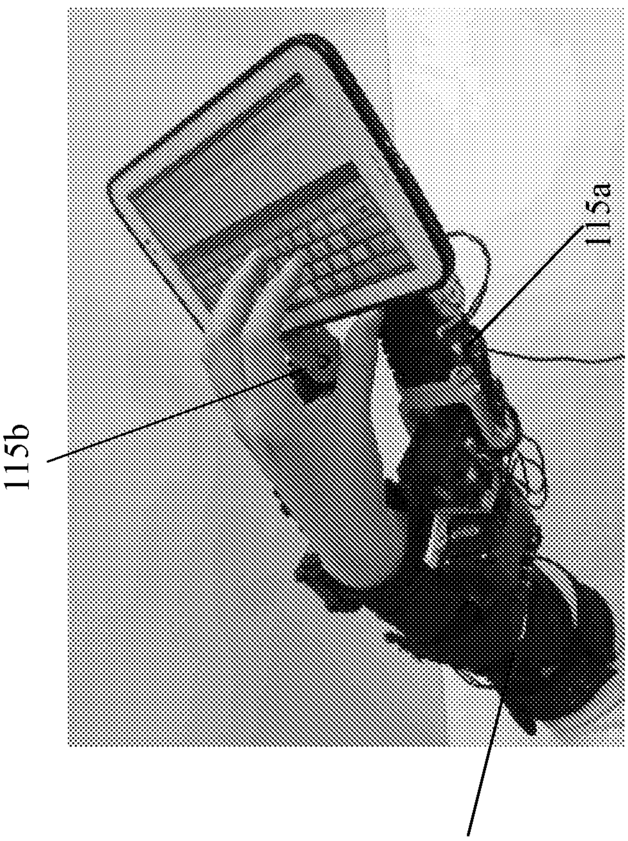


FIG. 13

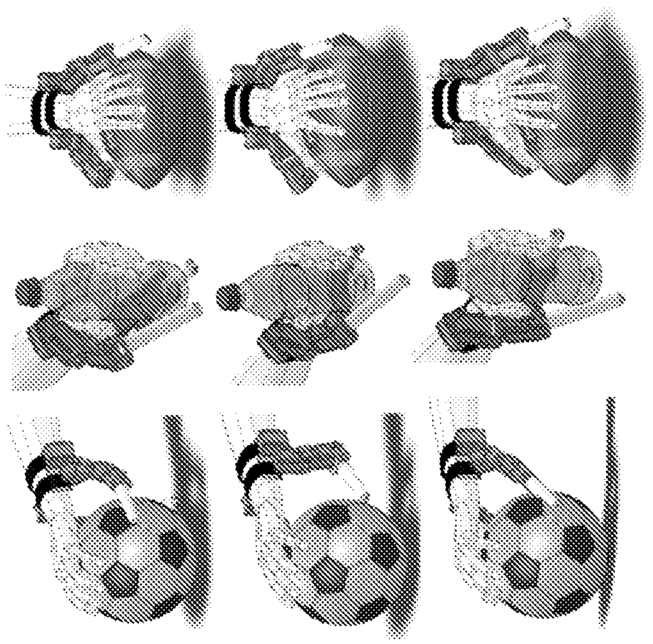


FIG. 14

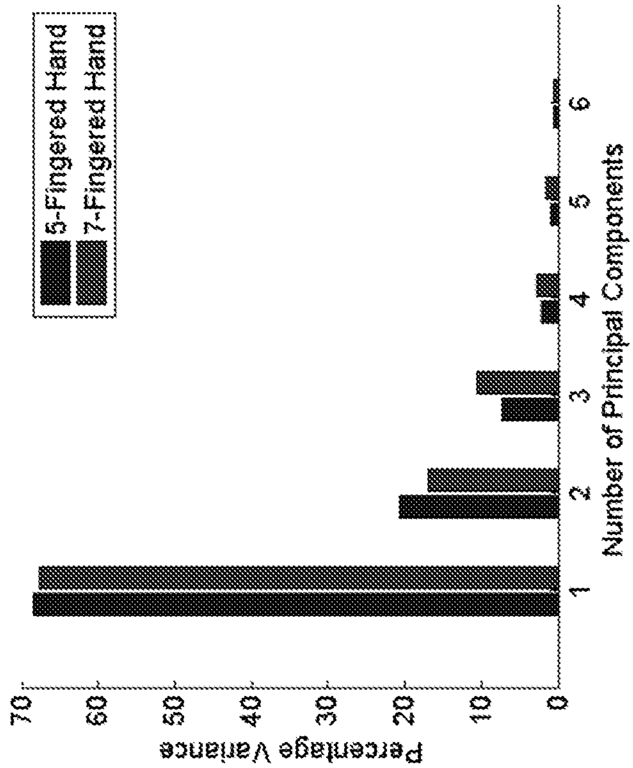

5-Fingered Hand
7-Fingered Hand
Percentage Variance
Number of Principal Components
70
60
50
40
30
20
10
0
1
2
3
4
5
6

FIG. 15

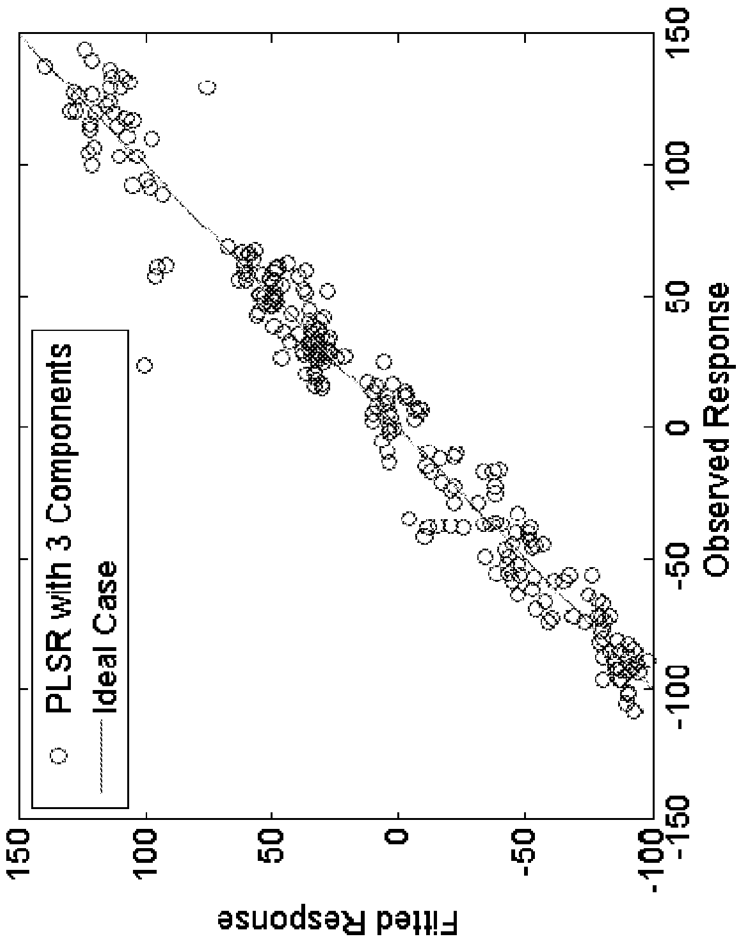

PLSR with 3 Components
Ideal Case
Observed Response
Fitted Response
150
100
50
0
-50
-100
-150

FIG. 16

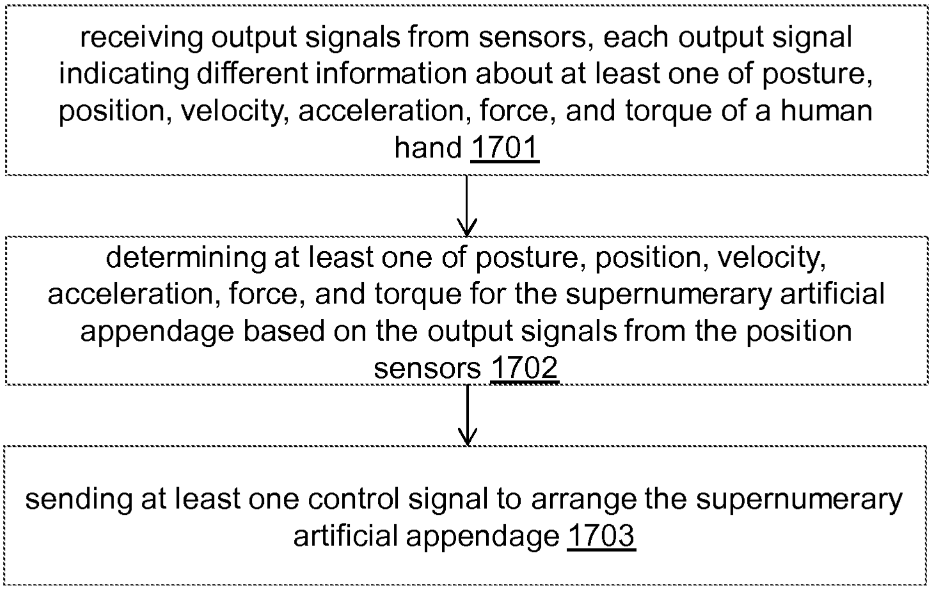

receiving output signals from sensors, each output signal indicating different information about at least one of posture, position, velocity, acceleration, force, and torque of a human hand 1701
determining at least one of posture, position, velocity, acceleration, force, and torque for the supernumerary artificial appendage based on the output signals from the position sensors 1702
sending at least one control signal to arrange the supernumerary artificial appendage 1703

FIG. 17