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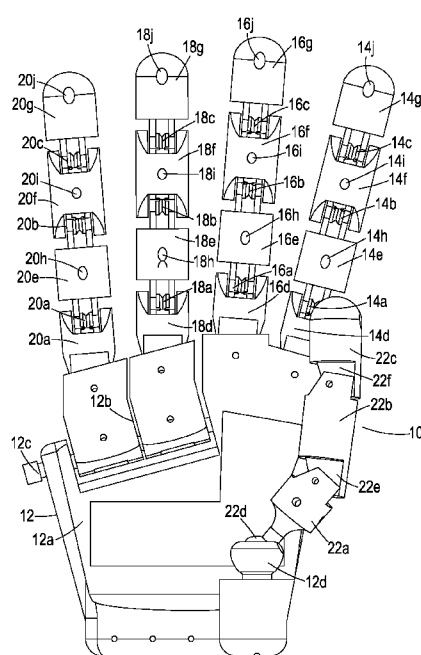
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ANATOMICAL JOINT

FIELD

- 5 The present invention provides an anatomical ball joint particularly, but not exclusively, for use in an artificial or robotic hand.

BACKGROUND

- 10 The human hand requires the synergistic movement of twenty seven bones and co-activation of thirty seven muscles in order to function effectively. Through at least twenty four Degrees of Freedom (DOFs), the human hand is able to perform dextrous and precise tasks in an efficient manner. While other mammals such as monkeys may have a basic grasping function, it is the structure and functionality of the human hand which sets humans apart from other animals in terms
15 of the ability to undertake sophisticated object manipulation.

- It is recognised that the thumb joint accounts for forty percent of the dexterity of the human hand and plays a crucial role in object manipulation. Despite this, robotic hands typically rely on the use of hinged joints for all digits, including thumbs, thus limiting the DOFs available. As the number of DOFs
20 in a robotic hand increases, the grip strength and stability of the robotic hand has been found to decrease.

- A number of robotic hands have successfully integrated four long fingers to provide simple grasping motion but naturalistic thumb kinematics in robotic hands has not been realised. Many robotic
25 hands implement the thumb as two hinge joints that are mounted off-axis with respect to the fingers to emulate thumb capabilities. Such thumb arrangements cause un-naturalistic motion and the assumption that base frame location movement is needed. One such configurations requires a user to manually adjust grip in order to switch from a cylindrical to a lateral grasp. Since there are no clear guidelines for the design of an anthropomorphic robotic hand and especially for the thumb,
30 current state of the art robotic hands do not fully embrace the versatility of the human thumb.

- Notwithstanding the above, the development of anthropomorphic end effectors is important in order for a human operator of a robotic hand to map natural manipulation behaviours and skills into commands for the device. The present invention seeks to address the aforementioned problems.

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SUMMARY OF INVENTION

- A first aspect of the invention provides an anatomical joint comprising a base and an end effector, wherein the end effector is movable relative to the base by way of a ball joint defined at least in part
40 by a ball and socket, wherein the socket comprises a sidewall having at least one cut out therein such that less than 70% of the ball is encapsulated within the socket in the region of the at least one cut out.

Preferably, 60% or less of the ball is encapsulated within the socket in the region of the one or more cut out. More preferably, 50% or less of the ball is encapsulated within the socket in the region of the at least one cut out.

- 5 Use of a ball and socket arrangement provides a superior range of motion over hinged joints and thus provides significantly increased functionality, particularly when used in a robotic or prosthetic hand. Three DOFs are provided by the ball and socket arrangement comprising two rotational DOFs, specifying a directional axis that allows for planar movements, and an additional DOF providing rotation about the directional axis. The ball joint thus provides adduction/abduction,
10 flexion/extension and rotational motion to the end effector.

Configuring the ball joint such that only part of the ball is encapsulated by the socket in a defined region provides a greater range of motion than those ball joints in the prior art where the ball of the disclosed ball joints is fully encapsulated by the socket.

- 15 The at least one cut out may be defined by a pair of diametrically opposed cut outs in the sidewall of the socket.

In one embodiment the ball of the ball joint is at least partially hollow. Preferably, a channel is defined through the ball.

- The hollow ball, or channel, permits tendons to pass through the ball joint without coupling and thus enables each tendon passing through the ball joint to be controlled individually thus enabling independent control of multiple joints of the end effector. The ability to pass tendons through the ball and over the ball permits movement through more degrees of freedom than in the prior art and additionally the stiffness of the ball joint so as to control freedom of movement of the ball relative to the socket.

In one embodiment the ball is split into four conductive quadrants and the socket defines a conductive region in permanent contact with the ball in use, wherein a signal representative of a quadrant being in contact with the conductive region of the socket is transmitted upon a respective quadrant moving into contact with the conductive region of the socket.

- 35 In another embodiment the ball is split into four quadrants, each quadrant defining a different colour or colour shade, and the socket defines an optical sensor, wherein a signal representative of the optical sensor detecting a particular colour or colour shade associated with a respective quadrant is transmitted upon a respective quadrant moving into the vicinity of the optical sensor.

Splitting the ball into quadrants, whether conductive or optical, and enabling movement of the ball relative to the socket to be monitored by way of determining changes in conductivity of the ball in contact with the socket or in the colour or colour shade of the ball quadrants enables the real time position of the ball relative to the socket, and consequently the real time position of an end effector, to be monitored.

In one embodiment the ball joint comprises a first ball joint defined by a first ball and a first socket and a second ball joint defined by a second ball and a second socket, wherein the first ball and the second ball are connected by an interconnecting portion and wherein the each of the first ball joint and second ball joint are moveable independently.

5

Provision of two or more ball joints arranged sequentially permits actuation of different elements of an end effector. In the illustrated embodiment this could be separate digit portions of an artificial hand to provide realistic control of the artificial hand and advanced grip and manipulation capability.

10 In one embodiment the ball and the socket define a smooth interface.

In order to maintain the kinematic properties of the ball joint and to replicate a human joint it is desirable to provide a smooth interface between the ball and the socket.

15

FIGURES

Figure 1 shows a view of a robotic hand assembly including a first thumb embodiment;

20 Figure 2 shows a cross-section of the thumb of figure 1;

Figure 3 shows an internal view of a tendon control strategy of the thumb of figure 1;

Figure 4 shows a view of a second thumb embodiment;

25

Figure 5 shows an embodiment of ball and socket joint configured to transmit electrical or optical signals.

DESCRIPTION

30

An embodiment of the invention is illustrated in figure 1 which illustrates a robotic hand (10) comprising a palm, or base, (12), an index finger (14), a middle finger (16), a ring finger (18), a small finger (20) and a thumb (22). The ring finger (18) and small finger (20) are connected to a palm arch (12b) which in turn is connected to the palm (12). The main features of the hand can be manufactured using any suitable material and manufacturing process. One such example is 3D printing using ABS.

35

Each of the index finger (14), middle finger (16), ring finger (18) and small finger (20) comprise hollow cylinders consisting of three joints (14a, 14b, 14c in the case of the index finger and correlated accordingly for the middle finger (16), ring finger (18) and small finger (20)). Each joint provides hinged motion by way of a pair of tendons associated with each joint. Taking the index finger (14) as an example, a first phalanx section (14d) extends from the palm (12) and is immovable relative to the palm (12).

40

A first hinged joint (14a) separates the first phalanx section (14d) from a second phalanx section (14e). A pair of tendons, one either side of the index finger (14), run either side of the first hinged joint. This can be more clearly seen in figure 2. Each tendon passes over a pulley associated with the first hinged joint (14a) and terminates at a respective tendon attachment (14h).

5

A second hinged joint (14b) separates the second phalanx section (14e) from a third phalanx section (14f). A pair of tendons, one either side of the index finger (14), run either side of the second hinged joint (14b). Each tendon passes over a pulley associated with the second hinged joint (14b) and terminates at a respective tendon attachment (14i).

10

A third hinged joint (14c) separates the third phalanx section (14f) from a fourth phalanx section (14g). A pair of tendons, one either side of the index finger (14), run either side of the third hinged joint (14c). Each tendon passes over a pulley associated with the second hinged joint (14c) and terminates at a respective tendon attachment (14j).

15

Each pair of tendons associated with the index finger (14) is connected to a respective motor which may be a linear motor or rotary motor, for example. Driving a motor, for example a motor configured to drive the tendons associated with the first hinged joint (14a), in a first direction causes the second phalanx section (14e) to move in a first direction relative to the first phalanx section (14d). Driving the same motor in a second direction causes the second phalanx section (14e) to move in a second direction in a second direction relative to the first phalanx section (14d). Each of the first, second and third hinged joints (14a, 14b, 14c) is independently movable through driving respective motors associated with each hinged joint. In some embodiments, one or more of the hinged joints (14a, 14b, 14c) may be coupled together.

20

The palm (12) comprises a fixed portion (12a) and a palm arch (12b) which is movable independently of the fixed portion of the palm (12), ring finger (18) and small finger (20) to which the palm arch (12b) is attached. The palm arch (12b) is mounted on an axis (12c) passing through the palm (12) perpendicularly to the longitudinal axis of the ring finger (18) and small finger (20). The palm arch (12b) defines two independently movable joints which can be moved together or separately. Each joint is associated with an electric motor permitting movement of each joint through a defined range of motion.

25

The thumb (22) comprises a ball-in-socket arrangement whereby a socket (12d) is defined by the palm and a ball (22d) is defined by an end of the thumb (22). The thumb (22) further comprises two hinged joints (22e, 22f), one between a first phalanx section (22a) and second phalanx section (22b) of the thumb (22) and another between the second phalanx section (22b) and a third phalanx section (22c) of the thumb.

30

As can be seen in figure 2, the ball part (22d) of the ball-in-socket arrangement is hollow and a passage (22g) is defined between the palm (12) and the hinged joint (22e) between the first phalanx section (22a) and second phalanx (22b) section. Each of the second phalanx section (22b) and third phalanx section (22c) are also hollow.

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A first pair of tendons (22g) (as shown in figure 3) for controlling the second phalanx section (22b) of the ball joint (12d, 22d) extends from the palm (12) (or external to the palm) through the ball joint (12d, 22d) and the first phalanx section (12a) and terminates at the second phalanx section (22b). Each tendon of the first pair of tendons (22g) is coupled to a first common motor (not shown). A second pair of tendons (22h) for controlling the third phalanx section (22c) extends from the palm (12) (or external to the palm) through the ball joint (12d, 22d), first phalanx section (22a) and second phalanx section (22b). Each tendon of the second pair of tendons (22h) terminates at the second phalanx section (22b). A third pair of tendons (not shown) for controlling the ball joint (12d, 22d) itself extends from the palm (12) (or external to the palm) over the ball joint (12d, 22d) to control adduction/abduction and flexion/extension of the thumb (22). Each tendon of the second pair of tendons (22h) is coupled to a second common motor (not shown) and each tendon of the third pair of tendons is coupled to a third common motor (not shown). Synergistic movement of the first pair of tendons (22g), second pair of tendons (22h) and third pair of tendons is required to move the thumb to a particular end point location. The third pair of tendons is arranged as antagonistic tendons to avoid rotation of the thumb (22) around its central axis.

Each of the first, second and third common motors is positioned either within the palm (12) or external to the palm. In some embodiments the common motors associated with the hinged joints (22e, 22f) are positioned within the thumb (12) itself with wiring for the motors extending through the thumb (12), particularly through the channel (22g) through the ball part (22d) of the ball joint (12d, 22d) to a power source.

Table I below shows the range of motion of each of the fingers (12, 16, 18, 20) and thumb (22).

Table I

Joint	MCP	PIP	DIP	Opposition	CMC
Ring finger & Small Finger	+/- 25°	0-90°	0-90°	-15+35°	-
Index Finger & Middle Finger	+/- 25°	0-90°	0-90°	-	-
Thumb	0-90°	-	0-90°	-	+/-65°

Actuation and Control Testing

The robotic hand was under-actuated using seven motors to control twenty out of twenty four DOFs in an intuitive manner by coupling Distal Interphalangeal (DIP), Proximal Interphalangeal (PIP) and Metacarpophalangeal (MCP) joints. In order to test the kinematic and functional capabilities of the device, the motors were mounted on an external support acting as the forearm. Tendons were attached midway on each phalanx and the other end was directly mounted on standard sized servo motors (HighTech HS-422, Hitech RCD Inc., Poway, CA) using springs to avoid tendon slack. For the index finger (14), middle finger (16), ring finger (18) and small finger (20), DIP, PIP and MCP joints were coupled together, thus each finger was actuated via one motor, which allowed for flexion and extension. The two additional artificial joints that allowed for palm-arch capabilities were coupled on

the corresponding MCP joints of the ring finger (18) and small finger (20). At this stage, the DOFs responsible for adduction/abduction for the index finger (14), middle finger (16), ring finger (18) and small finger (20) were physically blocked. The thumb (22) was fully actuated using three servo-motors. All servo-motors were connected to a micro-controller (Arduino Mega 2560, Arduino, Italy) with an external battery supply (4 x AAA) to satisfy the voltage and current requirements of both the artificial hand servos and the micro-controller. Controlling the high-dimensional structure of the artificial hand in an intuitive effortless manner is still an unsolved issue in the context of robotic tele-operation and prosthetics.

As a first step, a graphical user interface (GUI) was developed in Matlab, allowing for manual joint-by-joint control. The GUI included a range of pre-defined grasps. Using the GUI to operate multiple DOF proved to be time-consuming and unintuitive. Additionally, when using a pre-defined posture to grasp an object, manual adjustments of joints were required to avoid slippage of the held object. We choose to actuate our hand by streaming, real-time joint angles from twenty two sensors embedded in a dataglove. Using a Dataglove to control the developed hand, allowed the user to exploit visual feedback to learn kinematic motions of appropriate digits. This in turn, compensates for the inability of the artificial hand to move base-frames locations when manipulating pre-held objects. The index finger (14), middle finger (16), ring finger (18) and small finger (20) were calibrated to zero when fully extended while the thumb's zero location was set at the joint's central axis. Using one to one mapping for the index finger (14), middle finger (16), ring finger (18) and small finger (20), each joint of the artificial hand was receiving real-time data from the corresponding sensor on the Cyber-Glove allowing for flexion and extension. For the thumb, where the CMC joint is actuated by two servos, the two sensors on the Dataglove that measure adduction/abduction were mapped on the two motors.

a) Grasping Objects: : The first step taken to visually represent the dexterous capabilities of the robotic hand was to perform the thirty three most commonly used grasps in activities of daily living from the GRASP project . The grasp taxonomy classifies grasps according to: opposition, virtual finger assignments, types in terms of power and lastly according to the position of the thumb. Given the mechanical robustness and reliability of the EthoHand to hold objects of daily life using all five digits we limited it to objects that weigh less than 2.3 kilograms.

b) In-hand Manipulation of Objects: One of the primary aims of this project is to introduce the naturalistic concept of in-hand manipulation. In this direction, the robotic hand was challenged to replicate and perform novel moves that current state of the art prosthetic and robotic hands lack. Manipulating pre-held objects in real life requires precise simultaneous control of multiple digits and sensory feedback interaction. In the case of prosthetic hand users, visual feedback is primarily used. Using Dataglove the EthoHand was able to mimic four novel in-hand manipulations such as palm-arch opposition, rotate a pre-held ball, rotate a screwdriver and precise tapping on the screen of a mobile device. By performing these moves we show the precision and fine dexterous capabilities of our thumb's design.

c) Dexterity Evaluation & Comparison: We evaluate the dexterity of our hand, in the context of human anthropomorphism, i.e. the ability of an artificial device to mimic and execute action manifolds in a human-like manner. We measure the dexterity level of our hand following, which uses

the geometry of convex hull of the workspace, of each digit as a measure. The metrics of this approach are based on the relative coverages of human and robot finger phalanges workspaces as well as human and robot finger base locations workspaces. This particular procedure of assessing the anthropomorphism of robot hands, takes into account not only the end-point of each finger but also the configuration. We have compared our novel articulation of the thumb and index finger of our artificial hand with a state-of-the-art robotic hand (see Table II for results - below). We take the dexterity measure further by collecting physical manipulation data using optical motion capture systems, by attaching three markers on the three phalanges of the thumb and index finger. Table II shows that our novel articulation of the thumb results in a level of anthropomorphism of fifty seven percent, whereas the state of the art hand scores nineteen percent. We note that evaluation of dexterity with physical kinematic data shows a five percent drop in workspace volume for the thumb when compared with the simulations. This drop of percentage denotes that mechanical noise such as friction or slack in the tendons is present, preventing the ball-joint articulation to move to its predesigned range of motion. We propose strongly that in general robotic hand evaluations should use independent position measurements over simulated motions or internal sensors to validate performance capabilities.

Table II

	<u>Simulation</u>		<u>Kinematic Tracking</u>
	<u>State of the art thumb</u>	<u>Etho Thumb</u>	<u>Etho Thumb</u>
Proximal Phalanx	15%	56%	49%
Middle Phalanx	-	-	-
Distal Phalanx	22%	56%	50%
Total	19%	56%	50%
	<u>State of the art finger</u>	<u>Etho Finger</u>	-
Positions	34%	41%	-
Orientations	60%	62%	-
Total	47%	51%	-

The novel design of the thumb enabled the robotic hand to execute the thirty three most commonly used grasps in daily living. Moreover, the robotic hand has demonstrated control of precise and complex in-hand manipulation tasks such as texting on a smartphone without requiring movable joints locations nor sensory tactile feedback in tele-operation.

To demonstrate improvement, a systematic comparison across disciplines is required to act as a scientific robust method for comparing functional abilities of robotic/artificial hands and human hands. This sets the baseline foundation for evaluating engineering improvement. The dexterity and anthropomorphism of the robotic hand was quantified with respect to human, prosthetic and other robotic hands setting a cross-disciplinary precedent spanning the field of biorobotics. The present robotic hand design doubles dexterity measures beyond existing hand designs.

The hand can be controlled using inputs into a GUI or using a Dataglove. Tactile and haptic feedback is not required for successful control of the hand.

Figure 4 illustrates a second embodiment of thumb (100) for a robotic hand. The thumb comprises a connector (102) for interfacing with a robotic hand (not shown). The connector (102) incorporates a socket (104) configured to receive a ball (106), wherein a ball and socket joint is defined therebetween. The socket (104) acts as a receptacle for receiving the ball (106) and comprises two diametrically opposed cut outs (108) that expose the ball (106) in use thus permitting an improved range of motion of the ball (106) relative to the socket (104).

In the embodiment illustrated in figure 4, the ball (106) forms part of a double ended component (110) defined by a first ball (106a) and second ball (106b) connected by an interconnecting portion (112). The second ball (106b) of the interconnecting portion (110) forms part of a second ball joint. The combination of a first ball joint and second ball joint enables rotation at each ball joint together with one or both of adduction and abduction and/or flexion and extension.

Actuation of each ball joint (104, 106) is provided by way of tendon pairs driven by motors. The stiffness of each ball joint (104, 106) in the adduction/abduction and/or flexion/extension directions can be controlled by providing two pairs of tendons where one pair controls the adduction and abduction of the respective ball joint and the other pair controls the flexion and extension of the respective ball joint. The stiffness is provided by the motor resistance which can be specified accordingly.

In order to replicate the motion of a human joint the external surface of the ball (106) and the internal surface of the socket (104) of each ball joint (104, 106) are machined to provide a smooth surface with no appreciable grooves or other surface feature.

As shown in figure 5, one embodiment of ball and socket joint (104, 106) provides a ball divided into four (only two shown) conductive quadrants (106c, 106d) and a socket that is comprised of a conductive material (104a). As the ball (106) moves relative to the socket (104), different quadrants (106c, 106d) move into contact with the conductive region (104a) of the socket (104) thus generating a distinctive electrical signal per quadrant (106c, 106d). This electrical signal is transmitted to a processor to identify the position of the ball joint (104, 106) in real time. In another example, each quadrant (106c, 106d) of the ball (106) may be a different colour or colour shade and the socket (104) may define an optical sensor. As the optical sensor determines a difference in the colour or colour shade of the ball (106), the sensor transmits a signal to processor to identify the position of the ball (106) relative to the socket (104) in real time.

It will be appreciated that while the described embodiments relate to a robotic hand, the principles of an anatomical ball joint can be applied to other joints including, but not limited to artificial hips, knees, shoulders, elbows, knees, ankles and wrists.

CLAIMS

1. An anatomical joint comprising a base and an end effector, wherein the end effector is movable relative to the base by way of a ball joint defined at least in part by a ball and socket,
5 wherein the socket comprises a sidewall having at least one cut out therein such that less than 70% of the ball is encapsulated within the socket in the region of the at least one cut out.
2. An anatomical joint according to claim 1, wherein 60% or less of the ball is encapsulated within the socket in the region of the one or more cut out.
10
3. An anatomical joint according to claim 1 or claim 2, wherein 50% or less of the ball is encapsulated within the socket in the region of the one or more cut out.
4. An anatomical joint according to any of claims 1 to 3, wherein the socket comprises a body
15 having a pair of diametrically opposed cut outs therein.
5. An anatomical joint according to any preceding claim where the ball has a substantially smooth outer surface and the socket has a substantially smooth inner surface.
- 20 6. An anatomical joint according to any preceding claim, wherein a channel is defined through the ball joint.
7. An anatomical joint according to claim 6 further comprising a pair of tendons passing over the ball joint and terminating at the end effector.
25
8. An anatomical joint according to claim 7 further comprising at least one tendon configured to pass through the channel through the ball joint.
9. An anatomical joint according to claim 7 or claim 8, wherein the tendons are operable to
30 control rotational and flex of the joint.
10. An anatomical joint according to any of claims 7 to 9, wherein at least one tendon is attached to the joint in parallel.
- 35 11. An anatomical joint according to claim 10, wherein at least one tendon is attached such that it is perpendicular to the joint.
12. An anatomical joint according to any of claims 8 to 11, wherein the tendons are operable to control the stiffness of the joint.
40
13. An anatomical joint according to claim 6, wherein one or more electrical or optical cables passes through the channel in order to transmit and/or receive data.

14. An anatomical joint according to claim 6, wherein the ball is split into four conductive quadrants and the socket defines a conductive region in permanent contact with the ball in use, wherein a signal representative of a quadrant being in contact with the conductive region of the socket is transmitted upon a respective quadrant moving into contact with the conductive region of the socket.

15. An anatomical joint according to claim 6, wherein the ball is split into four quadrants, each quadrant defining a different colour or colour shade, and the socket defines an optical sensor, wherein a signal representative of the optical sensor detecting a particular colour or colour shade associated with a respective quadrant is transmitted upon a respective quadrant moving into the vicinity of the optical sensor.

16. An anatomical joint according to any preceding claim comprising a first ball joint defined by a first ball and a first socket and a second ball joint defined by a second ball and a second socket, wherein the first ball and the second ball are connected by an interconnecting portion and wherein the each of the first ball joint and second ball joint are moveable independently.

17. An anatomical joint comprising a base and an end effector, wherein the end effector is movable relative to the base by way of a ball joint defined at least in part by a ball and socket, wherein the socket is defined by a body having a side wall and an orifice for receiving 60% or less of the ball and wherein the side wall of the socket comprises at least one cut out therein.

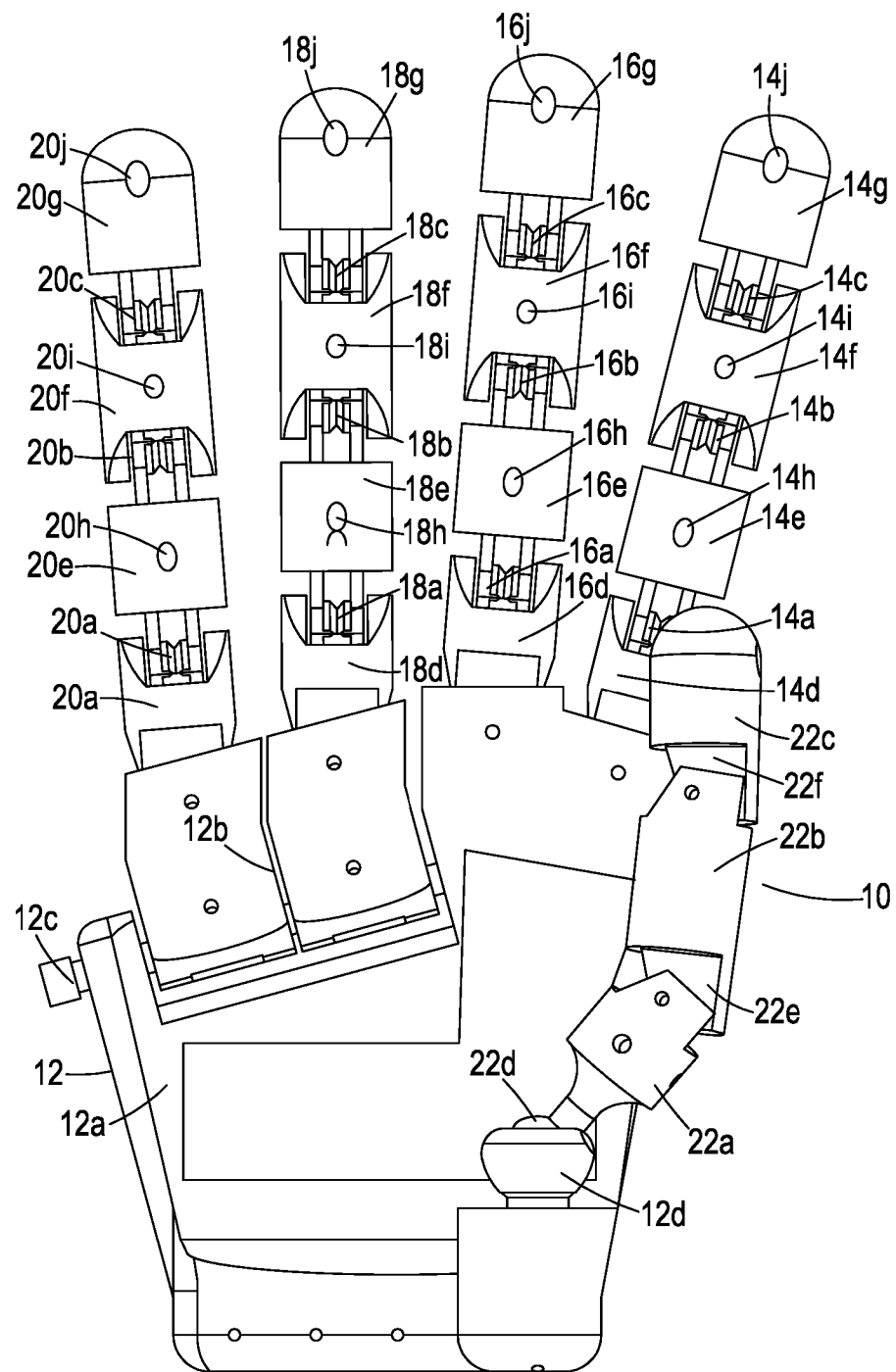


Fig. 1

2/3

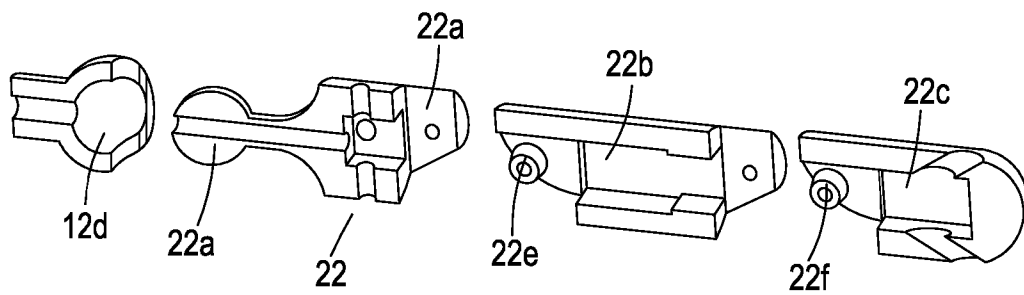


Fig. 2

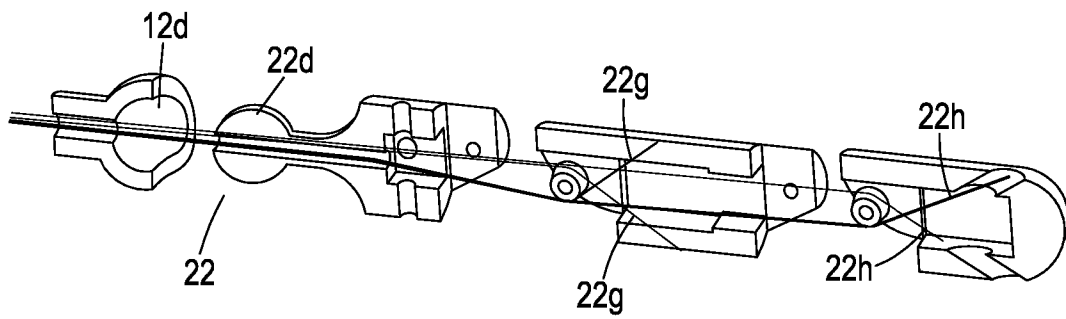


Fig. 3

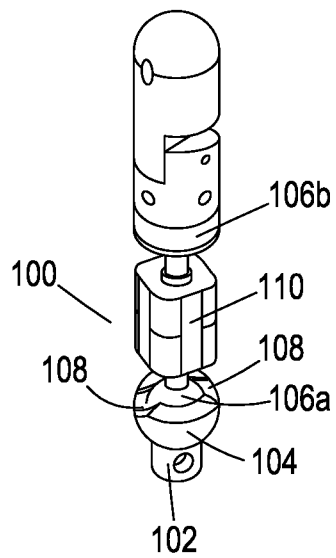


Fig. 4

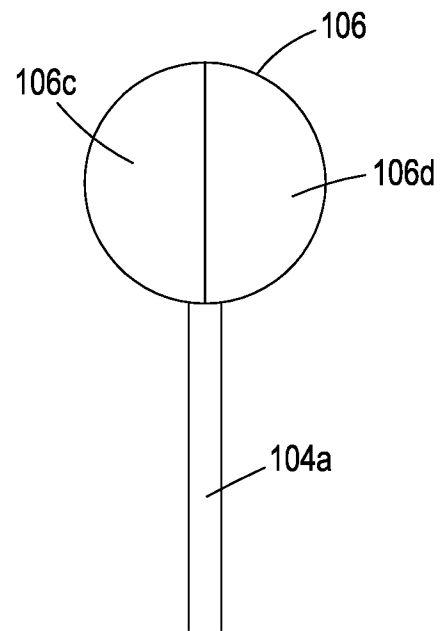


Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/051855

A. CLASSIFICATION OF SUBJECT MATTER
INV. B25J15/00 B25J17/02 B25J19/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B25J

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/071671 A1 (IHRKE CHRIS A [US] ET AL) 24 March 2011 (2011-03-24)	1-5,16,17
Y	paragraph [0030]	6-13
A	figures 3,4,4A	14,15
Y	US 4 246 661 A (PINSON GEORGE T) 27 January 1981 (1981-01-27)	6-13
A	column 2, line 55 - column 3, line 2 column 3, line 62 - column 4, line 34 figures 1,2,5,7	1-5,14-17
X	KR 2013 0055768 A (HYUNDAI MOTOR CO LTD [KR]) 29 May 2013 (2013-05-29) abstract; figures 2-4,6,9,10	1-5,16,17



Further documents are listed in the continuation of Box C.



See patent family annex.

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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