UNDERACTUATED ANTHROPOMORPHIC GRIPPING MECHANISM

FIELD OF THE APPLICATION

[0001] The present application relates to anthropomorphic gripping mechanisms, also known as a prosthetic hand, robotic hand, a gripper, a grasping mechanism, and to underactuated mechanisms for actuating their fingers.

BACKGROUND OF THE ART

[0002] Various design factors are considered during the design of anthropomorphic gripping mechanisms. Indeed, such gripping mechanisms must reproduce as much as possible the human hand, often with limited degrees of actuation available. However, the human hand is complex and may for instance perform various types of grasps, partly due to the large number of sensors and signals provided by the brain. The challenge therefore remains to produce a gripping mechanism that is human hand like, relatively light and with an enhanced level of self-adaptability, despite design considerations such as underactuation, synchronization, assembly, etc.

SUMMARY OF THE APPLICATION

[0003] It is therefore an aim of the present disclosure to provide a gripping mechanism that addresses issues associated with the prior art.

[0004] Therefore, in accordance with an embodiment of the present application, there is provided an underactuation mechanism for a gripping mechanism with at least two fingers, each finger being actuatable into a gripping action, the underactuation mechanism comprising: at least a first floating member having at least three connection points, with the at least three connection points being in a triangular arrangement, a first one of the connection points being connected to an input transmission component transmitting a degree of actuation to the first floating member; and at least a first output transmission component being in moving engagement with a second one and a third one of the connection points to move relative to the second and third connection points with friction constraints between the first output transmission component and the second and third connection points, the first output transmission component having a first end connected to at least a first one of the fingers, and a second end connected to at least a second one of the fingers to transmit the degree of actuation to the fingers.

[0005] Further in accordance with an embodiment of the present disclosure, a second floating member has at least three connection points in a triangular arrangement, the first end of said first output transmission component being connected to one of the three connection points of the second floating member, with a second output transmission component being in moving engagement with a second one and a third one of the connection points of the second floating member, and with a first end of the second output transmission component being connected directly to the first one of the fingers, and a second end of the second output transmission component being connected directly to a third one of the fingers.

[0006] Still further in accordance with an embodiment of the present disclosure, a third floating member has at least three connection points in a triangular arrangement, the second end of said first output transmission component being connected to one of the three connection points of the third floating member, with a third output transmission component being in moving engagement with a second one and a third one of the connection points of the third floating member, and with a first end of the third output transmission component being connected directly to the second one of the fingers, and a second end of the third output transmission component being connected directly to a fourth one of the fingers.

[0007] Still further in accordance with an embodiment of the present disclosure, an abutment is provided for each one of the fingers, the abutments being on either the finger or the output transmission component connected to the finger; and a mechanical selector has at least one slot with a wider portion for allowing the abutments to pass therethrough and a throat portion for blocking a movement of the abutments, the slot being positioned to be displaceable between a first position in which the throat portion is aligned with at least one of the abutments, and at least a second position in which the wider portion is aligned with at least one of the abutments.

[0008] Still further in accordance with an embodiment of the present disclosure, the input transmission component is a tendon fixed to the first connection point of the first floating member.

[0009] Still further in accordance with an embodiment of the present disclosure, the at least one output transmission component is a tendon.

[0010] Still further in accordance with an embodiment of the present disclosure, at least the second and the third connection points of the at least one floating member are rods, the moving engagement being a sliding contact of the tendon against the rods.

[0011] Still further in accordance with an embodiment of the present disclosure, the at least one floating member is a triangular plate, and the rods are normal to the triangular plate.

[0012] In accordance with another embodiment of the present disclosure, there is provided at least one transmission component connected to at least two outputs for transmitting a degree of actuation to the at least two outputs; an abutment for each one of the outputs, the abutments being on either the output or the transmission component connected to the output; and a mechanical selector having at least one slot with a wider portion for allowing the abutments to pass therethrough and a throat portion for blocking a movement of the abutments, the slot being positioned to be displaceable between a first position in which the throat portion is aligned with at least one of the abutments, and a second position in which the wider portion is aligned with at least one of the abutments.

[0013] Still further in accordance with an embodiment of the present disclosure, the at least one transmission component is at least one tendon.

[0014] Still further in accordance with an embodiment of the present disclosure, the abutments are fixed to the at least one tendon.

[0015] Still further in accordance with an embodiment of the present disclosure, the abutments are balls.

[0016] Still further in accordance with an embodiment of the present disclosure, the at least one transmission component passes through said at least one slot, and wherein the at least one transmission component is generally normal to a plane of the mechanical selector at said at least one slot.

[0017] Still further in accordance with an embodiment of the present disclosure, the mechanical selector has a plate in which the slots are defined, the plate moving along its plane when displaced between the first position and the second position.

[0018] In accordance with yet another embodiment of the present disclosure, there is provided a gripping mechanism comprising: the underactuation mechanism as described above; at least two fingers actuatable into a gripping action, the at least two fingers being the at least two outputs; and an actuation mechanism comprising said at least one transmission component connected to the at least two fingers for transmitting a degree of actuation to the at least two fingers to actuate the gripping action.

[0019] In accordance with yet another embodiment of the present disclosure, there is provided a gripping mechanism comprising: at least two fingers actuatable into a gripping action; an actuation mechanism for transmitting a degree of actuation to the at least two fingers to actuate the gripping action; a palm supporting the actuation mechanism and adapted to interface the at least two fingers to a support, the palm defining receptacles; and a base connected to each said fingers, the bases being received in said receptacles at the junction between each of the at least two fingers and the palm, the bases comprising a covering material with greater compliance than a surrounding material of the receptacles.

[0020] Still further in accordance with an embodiment of the present disclosure, each said base has a rigid core covered by the covering material.

[0021] Still further in accordance with an embodiment of the present disclosure, the covering material is a polyurethane foam having a density between 25 and 35 lb/ft^3.

[0022] In accordance with yet another embodiment of the present disclosure, there is provided a gripping mechanism comprising: a palm; at least two fingers connected to the palm and actuatable into a gripping action; a thumb connected to the palm and actuatable into a gripping action by a tendon connected at a first end to a phalanx of the thumb; an actuation mechanism for transmitting a degree of actuation to the at least two fingers to actuate the gripping action; and a lever pivotally mounted to the palm and connected to the actuation mechanism and to a second end of the tendon of the thumb, whereby a movement of the actuation mechanism causes a movement of the thumb through the tendon and lever and the fingers to produce a gripping action.

[0023] Still further in accordance with an embodiment of the present disclosure, the thumb is pivotally mounted to the palm by a pivot, the tendon passing through the pivot joint.

[0024] Still further in accordance with an embodiment of the present disclosure, the actuation mechanism comprises a tendon having a first end adapted to be connected to a degree of actuation, a second end connected to the palm, with a portion of the tendon between the first end and the second end being wrapped around a joint between the lever and actuation mechanism.

[0025] In accordance with yet another embodiment of the present disclosure, there is provided a finger of a gripping mechanism comprising: at least one phalanx adapted to be movably connected to a palm of the gripping mechanism, to move relative to the palm in a gripping action as a response to a degree of actuation; a tendon having a first end adapted to be connected to an actuation mechanism for receiving a degree of actuation therefrom, and a second end in the at least one phalanx; and a joint operatively connected to the at least one phalanx, the joint having a portion being selectively displaceable relative to the at least one phalanx and being connected to the second end of the tendon such that a displacement of the joint relative to the at least one phalanx modifies a distance between the first end and the second end of the tendon as respectively attached to the actuation mechanism and to the joint to adjust a tension in the tendon.

[0026] Still further in accordance with an embodiment of the present disclosure, at least two of said phalanges are rotatably connected to one another, with the joint being operatively connected to a distalmost one of said phalanges relative to the gripping mechanism.

[0027] Still further in accordance with an embodiment of the present disclosure, the joint has a translational degree of freedom provided by a threaded fastener.

[0028] Still further in accordance with an embodiment of the present disclosure, a head of the threaded fastener is at a tip of a distalmost one of said phalanges.

[0029] Still further in accordance with an embodiment of the present disclosure, a proximalmost one of the phalanges is pivotally connected to the gripping mechanism.

[0030] Still further in accordance with an embodiment of the present disclosure, a static tendon is between a distalmost one of the phalanges and the gripping mechanism to bias the finger away from the gripping action.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] Fig. 1 is a perspective view of an anthropomorphic gripping mechanism in accordance with an embodiment of the present disclosure;

[0032] Fig. 2 is a schematic view of an underactuation mechanism of the gripping mechanism of Fig. 1;

[0033] Fig. 3 is an elevation view of the gripping mechanism of Fig. 1, with an interior of the palm exposed and the thumb removed;

[0034] Fig. 4 is a schematic view of an operation of a floating stage of the underactuation mechanism of Fig. 2 illustrating different types of underactuation;

[0035] Fig. 5 is a schematic view of the principle of mechanical programmability, showing the relation between an underactuated mechanism and a mechanical selector of the gripping mechanism of Fig. 1;

[0036] Fig. 6 is a schematic view of different modes of operation of an example of a mechanical selector of Fig. 5;

[0037] Fig. 7 is a graphic representation of an operation of a lever of the gripping mechanism of Fig. 1, showing the attachment points of the thumb's tendon, the main actuation and the underactuation mechanism ;

[0038] Fig. 8 is a side view of a finger of the gripping mechanism of Fig. 1, in accordance with an embodiment of the present disclosure;

[0039] Fig. 9 is a perspective view of the finger of Fig. 8 as assembled to a base of the gripping mechanism of Fig. 1;

[0040] Fig. 10 is a sequence view of a thumb base in accordance with an embodiment of the present disclosure;

[0041] Fig. 11 is an elevation view of a friction applying mechanism for a proximal phalanx of the thumb base of Fig. 10;

[0042] Fig. 12 an elevation view of the gripping mechanism of Fig. 1, with an interior of the palm exposed; and

[0043] Fig. 13 is a perspective view of a distal phalanx of the gripping mechanism of Fig. 1, showing a connection between tendon and the distal phalanx.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0044] Referring to the drawings and more particularly to Fig. 1, an anthropomorphic gripping mechanism in accordance with embodiments of the present disclosure is generally shown at 10. The anthropomorphic gripping mechanism 10 may also be known as a prosthetic hand, robotic hand, a gripper, a grasping mechanism, etc. For simplicity purposes, reference is made hereinafter to the gripping mechanism 10. The gripping mechanism 10 comprises a palm 12, fingers 14 and a thumb 16. The palm 12 is the interface between the support or arm (e.g., wrist) that may be for instance a socket, and the fingers 14 and the thumb 16. Hence, a socket adaptor is shown at 15 as one of the possible connector configuration to connect the gripping mechanism 10 to a wrist or to most sockets. A cover plate 17 may be removably secured to the palm 12, to provide and close off an access to the various submechanisms in the palm 12, as described hereinafter. The gripping mechanism 10 is shown as having four of the fingers 14, although more or less of the fingers could be provided as well. Degrees of actuation are typically transmitted via the wrist or socket adaptor 15 to which the palm 12 is connected, to actuate the displacement of the fingers 14 and the thumb 16. It is shown in Fig. 1 that a tendon projects out of the socket adaptor 15, which tendon may be used to transmit a degree of actuation to the sub-mechanisms, as descried hereinafter.

[0045] **Underactuation Mechanism 20**

[0046] The palm 12 encloses various sub-mechanisms performing different functions of the gripping mechanism 10. Referring concurrently to Figs. 2 to 5, one such sub-mechanism is the underactuation mechanism 20. The underactuation mechanism 20 is used to transmit an actuation input into a plurality of outputs, such as the movements of the fingers 14 and/or of the thumb 16.

[0047] In order to increase the adaptability of the gripping mechanism 10 to object shapes without increasing the number of actuators, underactuation may be used to allow an adaptive distribution of the forces between the fingers 14. By underactuation, it is meant that there are more degrees of freedom at output that the degrees of actuation at input. According to an embodiment of the present disclosure, the fingers 14 are tendon-driven, with the underactuation mechanism 20 interrelating the fingers 14 to an input action with tendons. The fingers 14 may have alternative driving configurations (e.g., gears, links, etc), yet still be actuated by the underactuation mechanism 20. The thumb 16 may be coupled to an independent input, or to the same input as the fingers 14.

[0048] In the embodiment of Figs. 2 and 3, the underactuation mechanism 20 comprises a double-stage floating-rod configuration. A first-stage floating member 21 has points 21A, 21B and 21C in a triangular arrangement. Point 21A is connected to a tendon or like transmission component applying actuator force F_a, while points 21B and 21C are fixed rods, pins or like arcuate surfaces (referred to as rods hereinafter for simplicity). In an embodiment, the points on the floating members are rods projecting from the floating member to be normal relative to a plane of the floating member. For instance, the tendon connected to the point 21A may be the tendon extending out of the socket adaptor 15 of Fig. 1, transmitting the degree of actuation. With the expression floating, it is meant that the member 21 is generally unconstrained and free to move within bounds. For instance, the floating members described herein may move along their respective planes and rotate about an axis normal to their respective planes.

[0049] Two second-stage floating members 22 and 23 respectively have points 22A, 22B, 22C and 23A, 23B and 23C in triangular arrangements. Points 22A and 23A are interconnected by a tendon 24 fixed thereto, and slidingly contacting the surface of points 21B and 21C. A tendon 25 slidingly contacts points 22B and 22C and is connected at opposed ends to two different fingers 14, to transmit force F_1 and F_2, with points 22B and 22C being fixed rods or like arcuate surfaces. A tendon 26 slidingly contacts points 23B and 23C and is connected at opposed ends to two different fingers 14, to transmit forces F_3 and F_4, with points 23B and 23C being fixed rods or like arcuate surfaces.

[0050] The triangular floating members 21, 22 and 23 point away from the fingers 14 to obtain a stable mechanism. Moreover, although two stages are shown, it is considered to provide a single stage (with floating member 21) for a gripping mechanism with a pair of the fingers 14, or three or more stages with an appropriate amount of fingers 14. A gripping mechanism with an odd number of fingers 14 could also be configured to operate with the underactuation mechanism 20, for instance by having solely the floating member 22 in the second stage, with the tendon 24 being connected directly to one of the fingers 14 at one end, and to the floating member 22 at the other end.

[0051] The fixed rods 21B, 21C, 22B, 22C, 23B and 23C introduce a friction constraint against the sliding contact of the tendons 24, 25 and 26 sliding against their cylindrical bodies during underactuation between outputs, to synchronize the relative closing motion of the fingers 14. The friction can be adjusted by changing the materials of the tendons or the rods or by modifying the winding of the cable on the pins (for instance by adding more rods, increasing the diameter of the rods, etc.). With the underactuation mechanism 20, two different phenomena can occur to produce the underactuation. Either the triangular-arrangement floating members 21, 22 and/or 23 rotate, either the tendons 24-26 slides on the respective rods.

[0052] In order to obtain a desired behaviour of the gripping mechanism 10 during underactuation, friction and attachment points on floating parts have to be properly adjusted. Considering a typical case for which the fingers are initially closing freely before reaching an object, for instance with reference to Fig. 4, the first phenomenon usually occurs (rotation of triangular-arrangement floating members 21, 22 and/or 23) while the other one occurs later (tendons 24-26 sliding on the pins) when the difference between two consecutive outputs reaches a given value. If the difference between the outputs remains small, it is possible that the second phenomenon does not occur. In that case, the floating members 21, 22 and/or 23 simply rotate to a stable configuration. On the other hand, if the difference between two outputs is too large at the early stage of actuation, it is possible that the first phenomenon of underactuation never occurs. Indeed, this can happen if the mechanism 20 is actuated very quickly while having one input blocked. In that case, the dynamic effects change the behaviour of the mechanism 20 and the tendons can start sliding on the pins before the floating members even start to rotate. Since this sequence of action is not likely to occur in most of the situations, it will not be discussed in further detail.

[0053] Referring to Figs. 2 and 4, a quasi-static analysis is now set forth to explain the behaviour of the underactuation mechanism 20. Considering only one floating member 22, the condition to prevent the tendon 25 from sliding on the 22B and 22C can be written from the capstan equation as follows :

$$\frac{\max(F_1, F_2)}{\min(F_1, F_2)} \leq e^{\mu\gamma} \qquad (1)$$

where F_1 and F_2 are the external forces applied on the floating member 22, μ is the coefficient of friction between the tendon 25 and the pins 22B and 22C, and γ is the total angle swept by all turns of the tendon 25, measured in radians ($\gamma = \pi$ in our case since we only use two pins 22B and 22C, and vertical outputs are assumed). The objective is to obtain a combination of values of μ and γ high enough to prevent the tendon 25 from sliding on the pins 22B and 22C before the fingers 14 reach an object (as shown in Fig. 4). This leads to a suitable synchronization of the fingers' closure, which is desired in order to approach the objects properly.

Referring to Fig. 2, if two identical small floating members 22 and 23 are provided and all outputs are equal, the distribution of the forces is given by :

$$F_1 = F_2 = F_3 = F_4 = \frac{F_a}{4}. \tag{2}$$

Then, when external forces are not equal, an uneven distribution of the forces occurs. Since the size of the rods is small relative to the size of the floating members, the distribution of the forces between the outputs provided by the mechanism 20 can be approximated with the equations:

$$F_1 = \frac{c_{p1}c_{p2}F_a}{c_{p1}c_{p2} + c_{p1}c_{m2} + c_{m1}c_{p2} + c_{m1}c_{m2}} \tag{3}$$

$$F_2 = \frac{c_{m1}c_{p2}F_a}{c_{p1}c_{p2} + c_{p1}c_{m2} + c_{m1}c_{p2} + c_{m1}c_{m2}} \tag{4}$$

$$F_3 = \frac{c_{p3}c_{m2}F_a}{c_{p3}c_{p2} + c_{p3}c_{m2} + c_{m3}c_{p2} + c_{m3}c_{m2}} \tag{5}$$

$$F_4 = \frac{c_{m3}c_{m2}F_a}{c_{p3}c_{p2} + c_{p3}c_{m2} + c_{m3}c_{p2} + c_{m3}c_{m2}} \tag{6}$$

where

$$c_{pi} = \cos(\alpha_i + \theta_i) \qquad i = 1, 2, 3 \tag{7}$$

$$c_{mi} = \cos(\alpha_i - \theta_i) \qquad i = 1, 2, 3. \tag{8}$$

If $\theta_i = 0$, then all the attachment points (e.g., 22A, 22B and 22C for floating member 22) form a line instead of a triangle. In that case, the ratio of outputs F_1/F_2 is equal to 1 for any value of the angle α. It is important to mention that these equations obtained by static models are used to visualize the distribution of the "available forces" among the outputs depending on the configuration of the mechanism 20. From another point of view, the forces F_1 to F_4 can be considered as inputs rather than outputs of the mechanism 20. In that case, the output is the entire configuration of the mechanism 20 (the angles α_i and the vertical motion of each floating member) and the inputs are the five forces and the distance of the actuation (vertical movement of the attachment point of F_a). That being said, it is also important to understand that the forces are usually not constant during actuation, for instance when the fingers 14 come in contact with an object. Therefore, in order to predict the final configuration of the mechanism 20, all forces are needed at each step of the actuation.

[0054] If the condition shown in Eq. (1) is reached for one or some floating members 21-23, the second mode of underactuation occurs (the tendon starts to slide on the pins). The same mode can occur at the first stage of the mechanism 20 (with the larger triangular-shaped floating member 21) if the following condition is not satisfied :

$$\frac{\max(F_1 + F_2, F_3 + F_4)}{\min(F_1 + F_2, F_3 + F_4)} \leq e^{\mu\gamma}. \tag{9}$$

[0055] As mentioned earlier, it is possible to predict the orientation of one floating member if the coefficient of friction and the external forces are known. In the first situation, the condition in Eq. (1) is always satisfied so the tendon never slides on the pins. Thus, the final configuration α of the floating member is given by :

$$\alpha = \theta - \arctan\left(\frac{F_1 - F_2\cos(2\theta)}{F_2\sin(2\theta)}\right). \tag{10}$$

In the second situation, the tendon starts to slide on the pins before the floating member reaches this angle (the equality in Eq. (1) is satisfied). In that case, the floating member will stop rotating instantly and its final configuration is now given by the following relations. If F1 > F2:

$$\alpha = \theta - \arctan\left(\frac{e^{\mu\gamma} - \cos(2\theta)}{\sin(2\theta)}\right). \tag{11}$$

Now if $F_1 < F_2$, the final angle of the floating member is found with :

$$\alpha = \theta + \arctan\left(\frac{e^{\mu\gamma}\cos(2\theta) - 1}{e^{\mu\gamma}\sin(2\theta)}\right). \tag{12}$$

[0056] The mechanism 20 has many practical advantages. First, it facilitates the assembly of the gripping mechanism 10 since the finger tendons do not have to be attached directly to the underactuation mechanism 20, but are simply wrapped around their respective attachment points. With the use of the underactuation mechanism 20, only two tendons, namely 25 and 26 in Fig. 2 are used for the four fingers 14. Also, the range of possible underactuation is independent from the distance between the outputs since the tendons can slide on the respective pins. Finally, an other advantage of the underactuation mechanism 20 is that it may be fully floating, i.e., it operates without any slider mounted on the body of the palm 12. Sliders may increase the friction in the system and may be undesirable in some embodiments.

[0057] The use of several inputs in the gripping mechanism 10 is not always possible or desirable, for instance if it is used as an upper limb body-powered prosthesis (i.e., a prosthetic hand). In such prostheses, the use of underactuated fingers 14 can increase the adaptability of the gripping mechanism 10. If underactuation is also introduced between the fingers 14, for instance with the underactuation mechanism 20 shown in Fig. 2, the overall functionality of the gripping mechanism 10 can be improved without introducing additional inputs.

[0058] In another embodiment of the underactuation mechanism 20, cables or links can be directly attached to the pins, forming a revolute joint. The behaviour is equivalent to the preferred embodiment with $e^{\mu\gamma}=\infty$. The underactuation mechanism visible in Fig. 12 uses this principle at the first stage, for floating member 21'.

[0059] As alternatives to the tendon and rod (i.e., fixed pulley) configuration discussed above, other solutions are considered such as chains and idler sprockets with friction constraints at the axle of the idler sprockets, tendons and idler pulleys with friction constraints at the axle of the idler pulleys, etc.

[0060] **Mechanical Selector 30**

[0061] In order to perform the proper type of grasp with the gripping mechanism 10 depending on the object to be grasped, the palm 12 may enclose another sub-mechanism such as a mechanical selector 30. The mechanical selector 30 is used to block one or some outputs (i.e., one or more of the fingers 14) of the underactuation mechanism 20. Fig. 5 shows a diagram of the principle of the mechanical programmability, while Fig. 6 illustrates the three possible configurations of a typical mechanical selector 30. Fig. 3 shows an image of the inside of the gripping mechanism 10, where the corresponding components can be seen. The mechanical selector 30 is an elongated plate having a plurality of slots 31 therein, with the slots having a throat portion 32 and/or a wide portion 33. The mechanical selector 30 operates in combination with a blocking member 35 (such as a small ball) attached on the tendons 25 and 26. The elongated plate is oriented generally transversally relative to the tendons 25 and 26, with the tendons 25 and 26 passing through the slots 31. The elongated plate can slide or translate along its length, to align portions of the slots 31 with the balls 35. By blocking one or some of these balls 35, the transmission of input to the related fingers 14 is also blocked.

[0062] The blocking is achieved by the engagement of the balls 35 with the periphery of the throat portion 32 of the mechanical selector 30. In Fig. 6, there is illustrated three modes for the mechanical selector 30. The operation of the mechanical selector 30 is as follows: a switch (manual or actuated) is used to select the desired type of grasp (i.e., the operating mode) before operating the gripping mechanism 10, with an action on the switch displacing the mechanical selector 30. Assuming that the balls 35 in Fig. 6 are associated from left to right with the index finger to the little finger, mode M1 blocks the movement of all but the index finger as all balls 35 save for the left-side ball 35 are aligned with the throat portions 32. Mode M2 allows the movement of all fingers as the balls 35 are aligned with the wide portions 33. Mode M3 allows the movement of all but the index finger as all balls 35 save for the left-side ball 35 are aligned with the wide portions 33. Actuation of the fingers 14 in mode M3 would provide the grasping as shown in Fig. 3, with the index finger pointing.

[0063] If the mechanical selector 30 and the thumb 16 are both used in a gripping action, their configurations dictate the reaction of the gripping mechanism 10 to the actuation without using any motor. There are many possibilities for the blocking patterns of the outputs ($2^4 = 16$). Therefore, the gripping mechanism 10 can be mechanically programmed to operate in 16 different modes with this approach. It is pointed out that more modes would be possible with greater distances between the outputs and/or with more outputs (fingers), or with the use of multiple elongated plates superposed one on the other. Moreover, since three modes (e.g., M1, M2, and M3) can be achieved with one mechanical selector 30 as in Fig. 6, the number of possible different selectors is obtained using the binomial formula, which leads to:

$$C_n^k = \frac{n!}{k!(n-k)!} = \frac{16!}{3!(16-3)!} = 560. \tag{13}$$

[0064] Accordingly, by replacing the selector 30 with a another one configured differently, it would allow different grasping possibilities for the gripping mechanism 10. The mechanical selector 30 may have an open end and passage between slots 31 to be inserted in a gripping mechanism 10 once the fingers 14 are already connected to the tendons 25 and 26 (because of its open end). There exists many other ways to block outputs of the gripping mechanism 10, but the mechanical selector 30 and the balls 35 are compactly implemented in the palm 12 of the gripping mechanism 10.

[0065] **Fingers 14**

[0066] Referring now to Figs. 8 and 9, one of the fingers 14 is shown in greater detail. Because the number of degrees of actuation is often limited, especially in prosthetic or robotic applications, underactuated fingers are quite practical. For anthropomorphic grippers such as the gripping mechanism 10 and one of its contemplated uses, a configuration with pulleys and tendons is simpler, more compact and lighter than a configuration using linkages. In order to increase the mechanical resistance, self-adaptability to object shapes, functionality and "natural appearance" of such fingers (indirectly of grippers too), the introduction of a compliant base 40 combined with resilient coverings 41 (e.g., silicone) for the phalanges is considered. According to the illustrated embodiment of Fig. 9, the base 40 may have a rigid core 40A for a compliant covering 40B (e.g., silicone or like resilient material). For instance, the compliant covering may be a firm quick-recovery super-resilient polyurethane foam with a density ranging between 25 and 35 lbs/ ft^3. and have a thickness of about 1/32 inch (0.031 inch) (0.8 mm), and a firmness of 30-60 psi at 25% deflection.

[0067] Figs. 8 and 9 show a typical configuration for the underactuated finger 14 with its coverings 41 and compliant base 40. For illustrative purposes, the finger 14 shown has three phalanges, although it is possible to have fewer or more phalanges in the fingers 14. The underactuated finger 14 of Figs. 8 and 9 is composed of three cylindrical phalanges 42 with only one tendon 43 for actuation, which tendon 43 is attached in the distal phalanx, the tendon 43 being for instance an end portion of any one of the tendons

25 and 26 of Fig. 2. An elastic cable 44 applies a biasing force on the distal phalanx to ensure the passive opening of the finger 14. The elastic cable 44 may run at the back of the finger 14, which helps reducing the size of the phalanges 42 without affecting their mechanical resistance.

[0068] The operation of the mechanical finger 14 consists in pulling the tendon 43 and because there is underactuation between the phalanges 42, external forces dictate the behaviour of the finger 14. The sequence of closure (proximal phalanx closes first, then middle and then distal) is determined by the size of the pulleys at the joints. Also, the maximum opening and closing of the finger is limited by mechanical stops. For instance, a maximum open configuration is shown in Fig. 8, giving the finger 14 a relatively natural appearance and decreasing the amount of energy needed for its operation.

[0069] By providing the finger 14 with the compliant base 40, a smoother gripping mechanism 10 is obtained, with an increased mechanical resistance. The soft material (i.e., resilient and deformable) inserted between a rigid slot or receptacle 45 in the palm 12 and a rigid base of the finger (see Fig. 2) is used to cushion impacts, which increases the overall mechanical resistance of the gripping mechanism 10. Moreover, the resulting compliance gives a more natural appearance to the gripping mechanism 10 and also increases the adaptability to object shapes. Another advantage of this arrangement is that it facilitates the assembly since the finger 14 can be inserted directly into the palm 12 once assembled. Once the finger 14 is inserted in the palm 12, its rigid base is provided with a screw or like fastener at its bottom to ensure that the finger 14 cannot come out, while the head of the screw may move freely in its hole. This way, three axes of rotation are obtained relatively to a point located in the compliant base 40, which acts similarly to a spherical joint.

[0070] Contact friction and contact compliance have a significant positive impact on the ability to hold and grasp of an underactuated gripping mechanism. For instance, stable pinch grasping with underactuated grippers may only be possible with the use of curved distal phalanges, combined with mechanical limits or torsional springs, or with the use of a parallel mechanism in the finger, if there is insufficient contact friction. However, curved distal phalanges and a parallel mechanism are hardly implementable in anthropomorphic hands because of the importance of the appearance (which must approach that of the human hand). Accordingly, the coverings 41 are made of a material increasing the contact friction and contact compliance. In an embodiment, the coverings 41 are made of a soft material (e.g., 16A Shore hardness silicone). The desired geometry of the coverings 41 may be obtained by molding, for instance with molds obtained with rapid plastic prototyping or any other appropriate manufacturing process. The covering 41 of the distal phalanx may be thicker to increase the compliance, since the distal phalanx contributes the most to grasp stability.

[0071] The finger 14 described with components 40-45 is one of numerous finger configurations that may be used in the gripping mechanism 10. For instance, any appropriate type of finger may be used with the underactuation mechanism 20.

[0072] **<u>THUMB 16</u>**

[0073] In many recent anthropomorphic hands, the thumb is allowed to be reoriented to either perform lateral, palmar, pinch or tripod grasps. This feature provides more possibilities to a gripping mechanism since more prehensile tasks can be achieved, as described hereinafter. PARAGRAPHE DÉPLACÉ

[0074] Referring to Fig. 1, the thumb 16 may be composed of three phalanges 60 (or more or less of such phalanges 60), with for instance only the middle and distal ones being part of the general actuation. The proximal joint can be manually operated with the other hand or by applying the thumb on a fixed surface. The passive opening of the actuated phalanges may be disassociated from the fixation of the proximal phalanx, thereby allowing the thumb to be fixed in more than two configurations, and further allowing proper cable stiffness for the different tasks.

[0075] Moreover, the thumb may be configured to remain fixed in any position between its two limits, as in Fig. 10, thereby bringing more possibilities to the gripping operations. For instance, a lateral configuration could produce a lateral grasp while a vertical one could result in a power or tripod grasp, depending on object size and position relatively to the gripping mechanism 10 during actuation. In this case, moving the thumb 16 somewhere between these two limits could lead to other types of grasps (ex. Pinching only with the index) or to a modification of an existing one.

[0076] In order to obtain this behaviour, an elastic cable is used for the passive opening of the actuated phalanges, the elastic cable being attached to the proximal phalanx. A separate mechanism 61 is used to introduce the appropriate amount of friction at the proximal joint (see Fig. 11) (i.e., a set screw applying frictional force on the proximal phalanx 60, for instance through a friction pad in order to minimize wear). In an embodiment, the axes of the proximal and middle joint are not parallel, and the same tendon 62 is used to operate the thumb 16 in all its configurations, whereby pulleys and rods are used to properly guide the cable. Thus, the positioning of a small rod within the base of the thumb 16 also has to be determined in order to obtain the required difference in cable length between the two limit configurations of the thumb shown in Fig. 10 (otherwise the cable would become slack). As shown in Fig. 10, when the thumb 16 is in the lateral configuration, the tendon 62 crosses the proximal joint and when it is in its upward position, the same tendon 62 passes over the proximal joint. This geometric arrangement may be necessary to avoid inducing undesired torques on the thumb 16. According to an embodiment of the present disclosure illustrated in Fig. 10, the routing of the tendon 62 actuating the thumb 16 is such that it may pass through a pivoting point 63 at which the configuration of the thumb 16 can be changed from palmar to lateral. Therefore, it is possible to reorient manually the thumb 16 to place it in one of these configurations (using the other hand for instance) while not requiring an additional degree of actuation. Alternatively, the orientation adjustment of the thumb 16 may be motorized. This feature makes the hand versatile by opening a broader range of grasps.

[0077] **LEVER 70 FOR ACTUATION OF GRIPPING MECHANISM**

[0078] Referring to Figs. 3, 7 and 12, a lever 70 may be used to actuate the movements of the thumb 16 and the fingers 14. Coupling the thumb 16 with the other fingers 14 may be practical, as they work in opposition with each other. The coupling may also facilitate the prediction of their relative positions during actuation. This may allow a gripping mechanism to suitably achieve pinch grasps.

[0079] According to an embodiment of the present disclosure, the thumb's 16 tendon 62 (Figs. 10 and 11) may be directly connected to the actuation. The thumb's tendon 62 can be slightly loosened, so that its closure starts slightly after that of the fingers 14.

[0080] Alternatively, as shown in the embodiments of Figs. 3, 7 and 12, a lever 70 may be used to couple the thumb 16 with the fingers 14 in the gripping mechanism 10. The positions of attachment points on the lever 70 dictate the gripping behaviour of the thumb 16 of the gripping mechanism 10. The use of the lever 70 provides the flexibility to adjust the distribution of the forces/velocities between the thumb 16 and the other fingers 14. With this solution, no loosening is needed in the tendon 62 to obtain the desired synchronization. Referring to Fig. 3, the lever 70 is shown as being pivotally mounted to the palm 12 at 71. An end 72 of the lever 70 is pivotally connected to the floating member 21 of the underactuation mechanism 20, while the thumb's tendon 62 is attached at point 73 on the lever 70. In Fig. 3, the thumb 16 is removed for clarity, while it is present in Fig. 12. According to an embodiment, with reference to Fig. 3, one of the attachment points for the thumb is shown at 74, while the other is shown at 75 Other configurations are considered as well.

[0081] A mathematical model of the lever 70 may be found with the schematic drawing shown in Fig. 7, in which f_p, f_d and f_a are respectively the forces exerted by the thumb 16, fingers 14 and degree of actuation. All these forces may be considered as inputs to the mechanism 10 since f_p and f_d are external forces. In grasping applications, these forces depend on the shape of the object to be grasped and on the disturbances applied on it. Depending on the combination of all the forces, the lever 70 will move to the proper configuration (angle Ψ) to obtain a stable grasp. The relationship between forces of the thumb 16 and the fingers 14 is unknown since it depends on the geometry of the grasp and on the external forces applied to the object grasped. However, in order to be able to visualize the effect of some parameters of the lever, a proportional relation may be assumed between these two forces, namely:

$$f_p = K f_d. \tag{14}$$

[0082] Then, with the moment equilibrium equation of the lever 70 about its pivot 71, the relationship between the three forces is found during the actuation of the lever, which can be written as :

$$\begin{aligned} f_p a_1 \cos\left(-\psi_0 + \psi - \phi_1\right) + f_d a_2 \cos\left(-\psi_0 + \psi - \phi_2\right) - \\ f_a a_3 \cos\left(-\psi_0 + \psi\right) = 0 \end{aligned} \tag{15}$$

where variables α_i are the lever arms defined in Fig. 7. Solving for f_p and f_d:

$$f_p = \frac{K f_a a_3 \cos\left(-\psi_0 + \psi\right)}{K a_1 \cos\left(-\psi_0 + \psi - \phi_1\right) + a_2 \cos\left(-\psi_0 + \psi - \phi_2\right)} \tag{16}$$

$$f_d = \frac{f_a a_3 \cos\left(-\psi_0 + \psi\right)}{K a_1 \cos\left(-\psi_0 + \psi - \phi_1\right) + a_2 \cos\left(-\psi_0 + \psi - \phi_2\right)}. \tag{17}$$

By inspection of the above equations, it can be observed that if the three attachment points of the forces are on the same line crossing the pivot ($\varnothing_1$ and $\varnothing_2$ = 0), the forces f_p and f_d no longer depend on the configuration of the lever 70, namely :

$$f_p = \frac{K f_a a_3}{K a_1 + a_2} \tag{18}$$

$$f_d = \frac{f_a a_3}{K a_1 + a_2}. \tag{19}$$

In this case, the distances from the attachment points to the pivot (α_i; i = 1; 2; 3) dictate the distribution of the forces provided by the lever 70 (basic principle of any lever). These distances are used to adjust the closure of the thumb 16 relative to the fingers 14 in order to obtain the desired synchronization. As mentioned earlier, the forces f_p and f_d are considered as inputs to the mechanism 20 and hence the shape of the lever 70 affects the relative velocities of closure of the tendons, rather than the distribution of their forces.

[0083] Consider now the effect of the parameter $\varnothing_i$ on the distribution of the forces/velocities during the actuation. In order to isolate the effect of this parameter, equal distances are fixed between the pivot and the attachment points (α_i = 1, i = 1; 2; 3). To simplify the visualization, it is proposed to fix $\varnothing_1 = \varnothing_2 = \varnothing$. For grasping applications, this is preferable since varying the distribution of the forces/velocities between the thumb and the fingers during the actuation is generally not desired. Then, an equal distribution of the output forces (K = 1) is assumed, but this has no effect on the results since the sum of the output forces is considered. It should be noted that the lateral displacements of the tendons are not considered in the model, since their lateral displacements are negligible compared to the size of the lever. A practical advantage, for grasping applications, of the model is that the fingers 14 can be forced to close rapidly while offering a higher grasping force (less displacement) once the fingers are closed (using a negative value of angle $\varnothing$). In the model, if the positions of the attachment points are all aligned with the pivot ($\varnothing_1 = \varnothing_2 = 0$), the forces do not vary with the actuation (this was shown previously using Eqs. (18) and (19)). This can also be desirable in some applications.

[0084] The use of the lever 70 to couple the thumb 16 with the fingers 14 in anthropomorphic grippers constitutes an effective solution when the number of actuators is limited since it provides several possibilities and offers flexibility to the designer. As shown with the model derived above, a proper geometric design leads to the desired distribution of the forces/velocities between the thumb 16 and the fingers 14 during the actuation.

[0085] In order to multiply the available force of the gripping mechanism 10, instead of attaching the actuation cable 80 directly to the lever at 72 (e.g., as in Fig. 3), it is possible to wind the tendon around this joint (e.g., on the shoulder of a shoulder screw) and to attach the tendon somewhere at the base of the palm. Fig. 12 shows this principle. This arrangement may provide approximately two times more force to the gripping mechanism 10, as the actuation distance also increases by the same amount.

[0086] All features presented above were implemented in the gripping mechanism 10. The gripping mechanism 10 may be underactuated and may be used with body-powered prostheses (e.g., actuated with the use of a harness). The gripping mechanism 10 may be modified to feature a myoelectric control, as a single motor can drive the actuation tendon (motor driven tendon). One of the objectives of this initiative is to explore the level of functionality that can be obtained with a gripping mechanism, by combining many features without the use of any motor. The prototype of the gripping mechanism 10 has 16 degrees of freedom, with 3 possible inputs. In fact, two of these inputs are manually operated (for instance with the other hand) by the user prior to the actuation. Indeed, the rotation of the thumb 16 from its proximal joint and the lateral movement of the mechanical selector 30 are not part of the main actuation. In an embodiment, the thumb 16 and the mechanical selector 30 have to be placed in the proper configuration before actuating the gripping mechanism 10 to obtain the desired operating mode. With the mechanical selector 30 currently implemented in the palm 12, the gripping mechanism 10 can perform lateral, pinch, extension, tripod and power grasps, it can point with the index (all other fingers 14 are closed, see Fig. 3).

[0087] In addition, the gripping mechanism 10 offers self-adaptability to object shapes since it is underactuated. The compliant finger bases 40 (Fig. 9) also help this adaptability while increasing the overall mechanical resilience of the hand. The design of the fingers 14 combined with their coverings 41 gives the gripping mechanism 10 a human hand appearance and a good ability to hold and grasp objects. The compact and lightweight components also simplify the assembly since the fingers 14 can be assembled before being inserted into the palm 12. Finally, the use of a lever 70 combined with the proper mechanism to underactuate the fingers 14 leads to a proper distribution of the forces and to an effective synchronization in the entire gripping mechanism 10.

[0088] According to another embodiment, there is provided a technique to fix the tendons in the distal phalanges, for instance in the gripping mechanism 10. In order to facilitate the assembly of the gripping mechanism 10, the attachment of the fingers' tendon in the distal phalanges may be adjustable, while being tight enough to remain fixed at its original configuration. The technique may take into account the design constraints related with the phalanges and tendons: the phalanges may be made in a material that does not have sufficient strength to anchor a set screw. Moreover, the material of the tendon may have a low coefficient of friction, making the surface of the tendon "slippery".

[0089] Referring to Fig. 13, an embodiment is shown for the connection of the tendon 43 to a distal phalanx 90. In the illustrated embodiment, a translation joint may be formed in the distal phalanx 90, with a slider 91 being slidingly received in a groove 92. The tendon 43 is wound around the slider 91, or fixed to the slider 91 is any appropriate manner. Other ways of securing the tendon 43 to the slider 91 are considered as well.

[0090] With the tendon 43 attached to the slider 91, screw 93 is screwed in the slider 91. Hence, the rotation of the screw 93 causes the slider 91 to move linearly and adjust the tension in the tendon 43. Other methods and configurations for connecting the tendon 43 or other transmission component to the fingers are considered as well, such as a winch-like joint in the distal phalanx 90, upon which the tendon 43 is wound. In other words, the tension adjustment in the tendon 43 is performed by connecting an end of the tendon 43 to a movable portion of a joint within the distal phalanx 90. The movable portion of the joint is moved (e.g., translated, rotated) thereby modifying a distance between the attachment points of the tendon to adjust the tension in the tendon 43.

CLAIMS:

1. An underactuation mechanism for a gripping mechanism with at least two fingers, each finger being actuatable into a gripping action, the underactuation mechanism comprising:

at least a first floating member having at least three connection points, with the at least three connection points being in a triangular arrangement, a first one of the connection points being connected to an input transmission component transmitting a degree of actuation to the first floating member; and

at least a first output transmission component being in moving engagement with a second one and a third one of the connection points to move relative to the second and third connection points with friction constraints between the first output transmission component and the second and third connection points, the first output transmission component having a first end connected to at least a first one of the fingers, and a second end connected to at least a second one of the fingers to transmit the degree of actuation to the fingers.

2. The underactuation mechanism according to claim 1, further comprising a second floating member having at least three connection points in a triangular arrangement, the first end of said first output transmission component being connected to one of the three connection points of the second floating member, with a second output transmission component being in moving engagement with a second one and a third one of the connection points of the second floating member, and with a first end of the second output transmission component being connected directly to the first one of the fingers, and a second end of the second output

transmission component being connected directly to a third one of the fingers.

3. The underactuation mechanism according to claim 2, further comprising a third floating member having at least three connection points in a triangular arrangement, the second end of said first output transmission component being connected to one of the three connection points of the third floating member, with a third output transmission component being in moving engagement with a second one and a third one of the connection points of the third floating member, and with a first end of the third output transmission component being connected directly to the second one of the fingers, and a second end of the third output transmission component being connected directly to a fourth one of the fingers.

4. The underactuation mechanism according to any one of claims 1 to 3, further comprising:

an abutment for each one of the fingers, the abutments being on either the finger or the output transmission component connected to the finger; and

a mechanical selector having at least one slot with a wider portion for allowing the abutments to pass therethrough and a throat portion for blocking a movement of the abutments, the slot being positioned to be displaceable between a first position in which the throat portion is aligned with at least one of the abutments, and at least a second position in which the wider portion is aligned with at least one of the abutments.

5. The underactuation mechanism according to any one of claims 1, wherein the input transmission component is a tendon fixed to the first connection point of the first floating member.

6. The underactuation mechanism according to any one of claims 1 to 5, wherein the at least one output transmission component is a tendon.

7. The underactuation mechanism according to claim 6, wherein at least the second and the third connection points of the at least one floating member are rods, the moving engagement being a sliding contact of the tendon against the rods.

8. The underactuation mechanism according to claim 7, wherein the at least one floating member is a triangular plate, and the rods are normal to the triangular plate.

9. An underactuation mechanism comprising:

at least one transmission component connected to at least two outputs for transmitting a degree of actuation to the at least two outputs;

an abutment for each one of the outputs, the abutments being on either the output or the transmission component connected to the output; and

a mechanical selector having at least one slot with a wider portion for allowing the abutments to pass therethrough and a throat portion for blocking a movement of the abutments, the slot being positioned to be displaceable between a first position in which the throat portion is aligned with at least one of the abutments, and a second position in which the wider portion is aligned with at least one of the abutments.

10. The underactuation mechanism according to claim 9, wherein the at least one transmission component is at least one tendon.

11. The underactuation mechanism according to claim 10, wherein the abutments are fixed to the at least one tendon.

12. The underactuation mechanism according to any one of claims 9 to 11, wherein the abutments are balls.

13. The underactuation mechanism according to any one of claims 9 to 12, wherein the at least one transmission component passes through said at least one slot, and wherein the at least one transmission component is generally normal to a plane of the mechanical selector at said at least one slot.

14. The underactuation mechanism according to claim 13, wherein the mechanical selector has a plate in which the slots are defined, the plate moving along its plane when displaced between the first position and the second position.

15. A gripping mechanism comprising:

the underactuation mechanism according to any one of claims 9 to 14;

at least two fingers actuatable into a gripping action, the at least two fingers being the at least two outputs; and

an actuation mechanism comprising said at least one transmission component connected to the at least two fingers for transmitting a degree of actuation to the at least two fingers to actuate the gripping action.

16. A gripping mechanism comprising:

at least two fingers actuatable into a gripping action;

an actuation mechanism for transmitting a degree of actuation to the at least two fingers to actuate the gripping action;

a palm supporting the actuation mechanism and adapted to interface the at least two fingers to a support, the palm defining receptacles; and a base connected to each said fingers, the bases being received in said receptacles at the junction between each of the at least two fingers and the palm, the bases comprising a covering material with greater compliance than a surrounding material of the receptacles.

17. The gripping mechanism according to claim 16, wherein each said base has a rigid core covered by the covering material.

18. The gripping mechanism according to any one of claims 16 and 17, wherein the covering material is a polyurethane foam having a density between 25 and 35 lb/ft^3.

19. A gripping mechanism comprising:

a palm;

at least two fingers connected to the palm and actuatable into a gripping action;

a thumb connected to the palm and actuatable into a gripping action by a tendon connected at a first end to a phalanx of the thumb;

an actuation mechanism for transmitting a degree of actuation to the at least two fingers to actuate the gripping action; and

a lever pivotally mounted to the palm and connected to the actuation mechanism and to a second end of the tendon of the thumb, whereby a movement of the actuation mechanism causes a movement of the thumb through the tendon and lever and the fingers to produce a gripping action.

20. The gripping mechanism according to claim 19, wherein the thumb is pivotally mounted to the palm by a pivot, the tendon passing through the pivot joint.

21. The gripping mechanism according to any one of claims 19 and 20, wherein the actuation mechanism comprises a tendon having a first end adapted to be connected to a

degree of actuation, a second end connected to the palm, with a portion of the tendon between the first end and the second end being wrapped around a joint between the lever and actuation mechanism.

22. A finger of a gripping mechanism comprising:

at least one phalanx adapted to be movably connected to a palm of the gripping mechanism, to move relative to the palm in a gripping action as a response to a degree of actuation;

a tendon having a first end adapted to be connected to an actuation mechanism for receiving a degree of actuation therefrom, and a second end in the at least one phalanx; and

a joint operatively connected to the at least one phalanx, the joint having a portion being selectively displaceable relative to the at least one phalanx and being connected to the second end of the tendon such that a displacement of the joint relative to the at least one phalanx modifies a distance between the first end and the second end of the tendon as respectively attached to the actuation mechanism and to the joint to adjust a tension in the tendon.

23. The finger according to claim 22, comprising at least two of said phalanges rotatably connected to one another, with the joint being operatively connected to a distalmost one of said phalanges relative to the gripping mechanism.

24. The finger according to any one of claims 22 and 23, wherein the joint has a translational degree of freedom provided by a threaded fastener.

25. The finger according to claim 24, wherein a head of the threaded fastener is at a tip of a distalmost one of said phalanges.

26. The finger according to any one of claims 22 to 25, wherein a proximalmost one of the phalanges is pivotally connected to the gripping mechanism.

27. The finger according to any one of claims 22 to 26, comprising a static tendon between a distalmost one of the phalanges and the gripping mechanism to bias the finger away from the gripping action.

ABSTRACT

An underactuation mechanism for a gripping mechanism with at least two fingers, each finger being actuatable into a gripping action. The underactuation mechanism comprises at least a first floating member having at least three connection points, with the at least three connection points being in a triangular arrangement, a first one of the connection points being connected to an input transmission component transmitting a degree of actuation to the first floating member. At least a first output transmission component is in moving engagement with a second one and a third one of the connection points to move relative to the second and third connection points with friction constraints between the first output transmission component and the second and third connection points, the first output transmission component having a first end connected to at least a first one of the fingers, and a second end connected to at least a second one of the fingers to transmit the degree of actuation to the fingers.

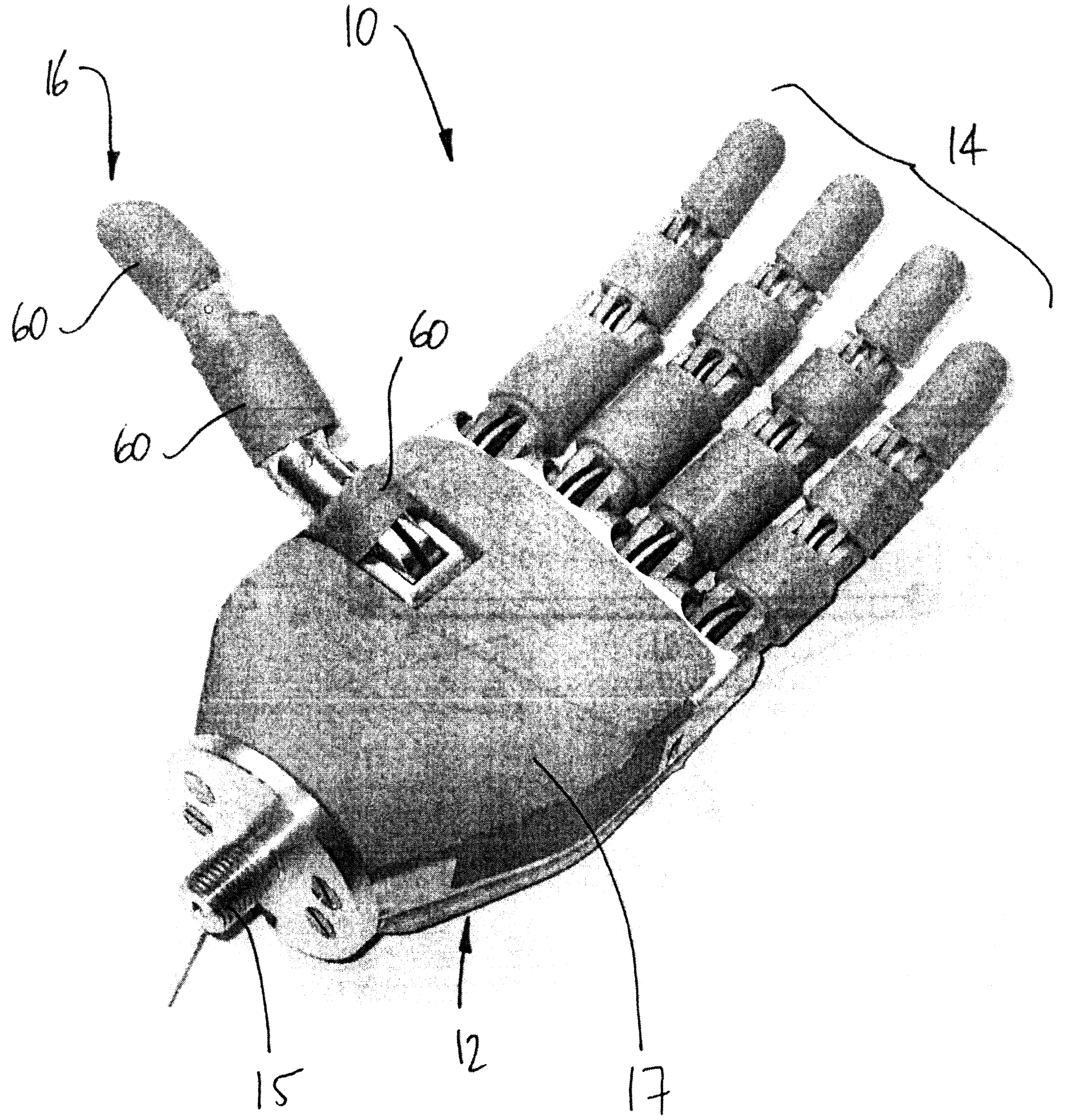
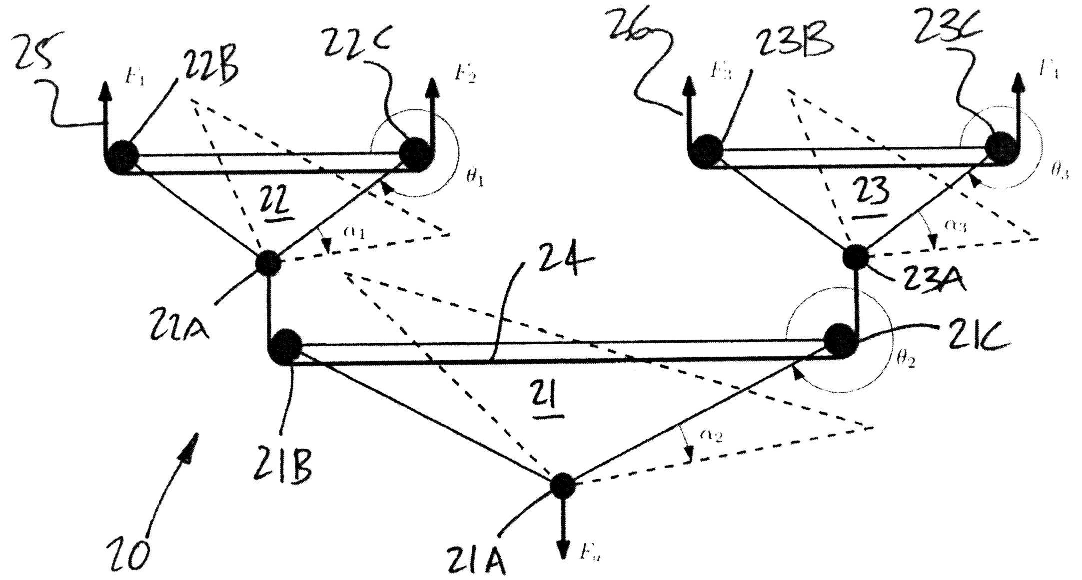


Fig. 1



25
F_1
22B
22C
F_2
26
F_3
23B
23C
F_4
θ_1
22
α_1
23
θ_3
α_3
23A
22A
24
21C
θ_2
21
α_2
21B
20
21A
F_o

Fig. 2

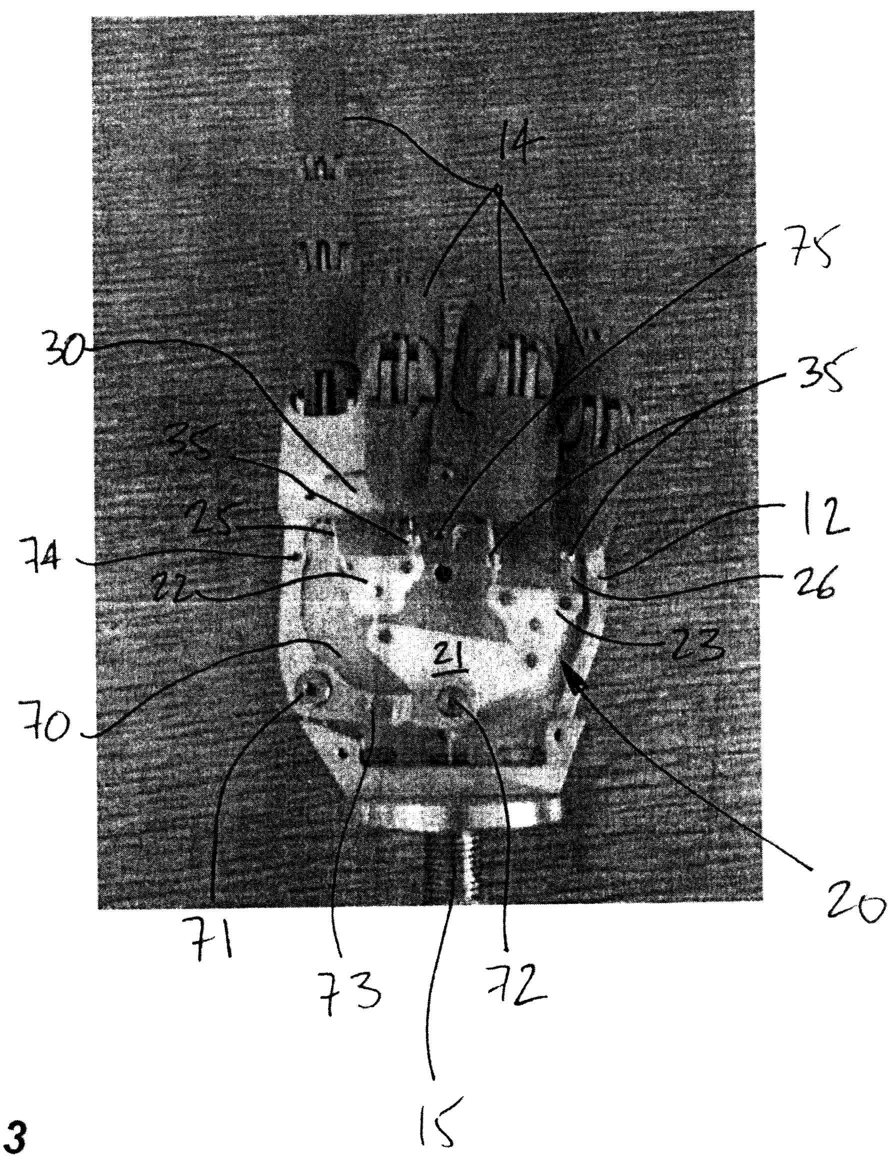
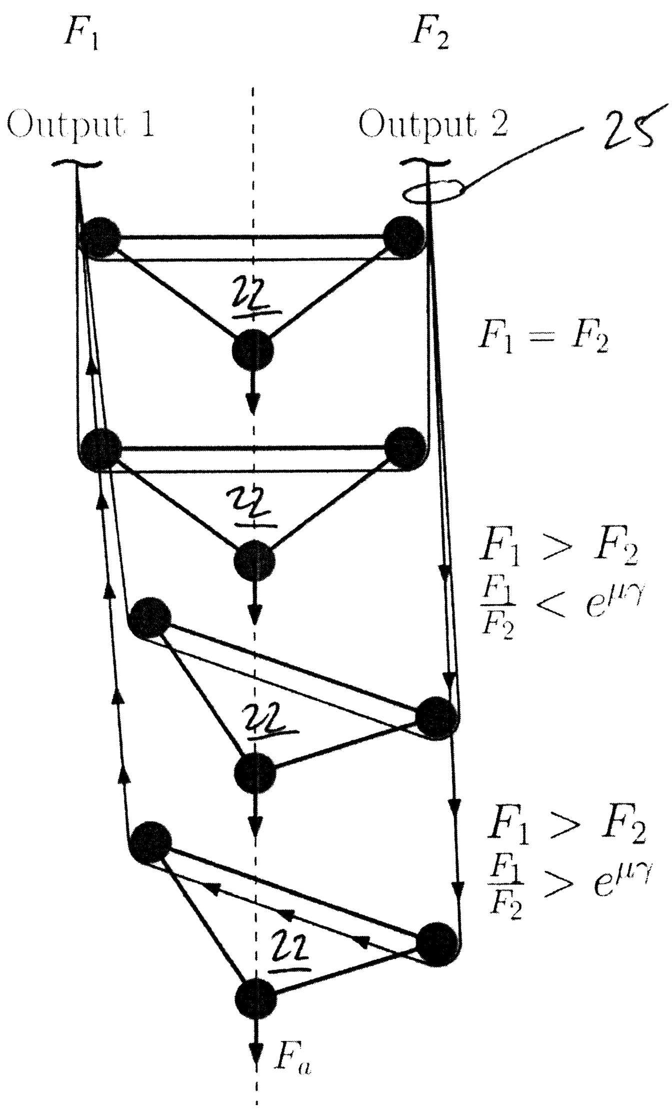


Fig. 3



F_1
F_2
Output 1
Output 2
25
22
$F_1 = F_2$
22
$F_1 > F_2$
$\frac{F_1}{F_2} < e^{\mu\gamma}$
22
$F_1 > F_2$
$\frac{F_1}{F_2} > e^{\mu\gamma}$
22
F_a

Fig. 4

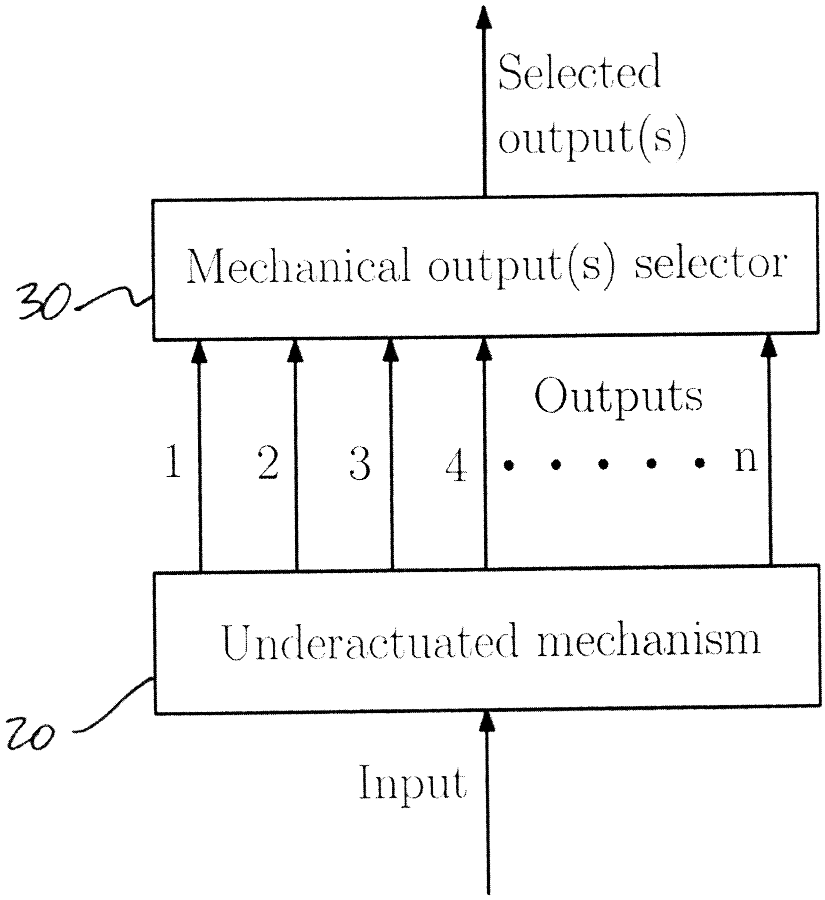

Selected
output(s)
Mechanical output(s) selector
30
Outputs
1
2
3
4
n
Underactuated mechanism
20
Input

Fig. 5

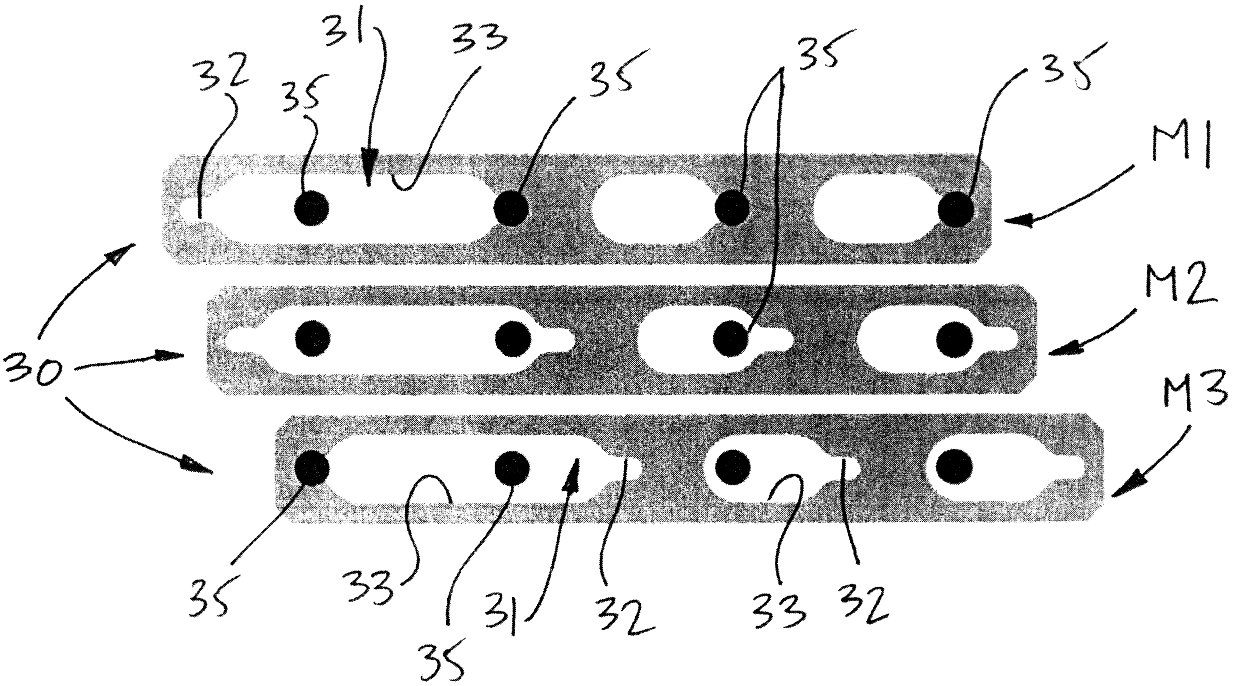


Fig. 6

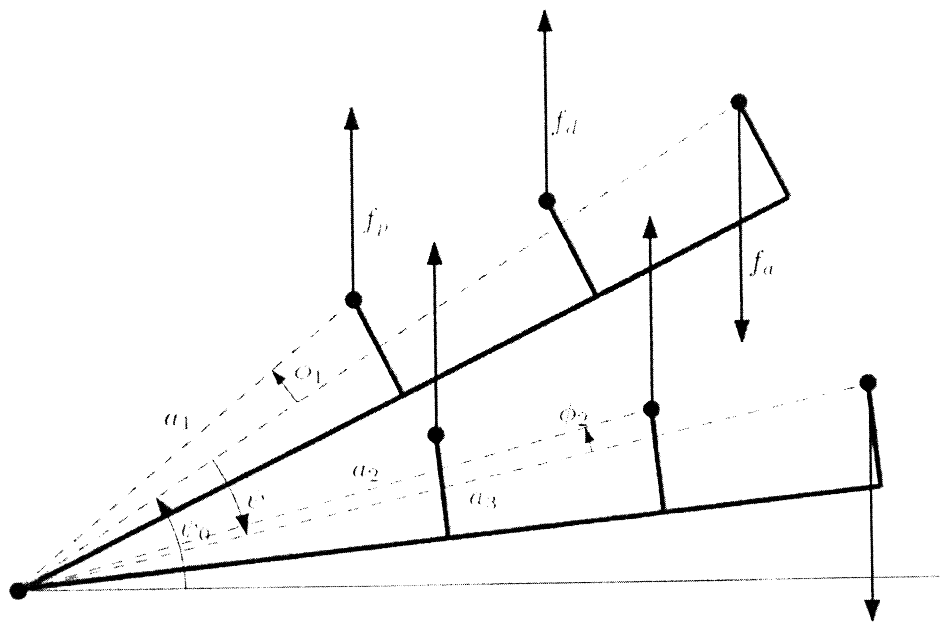


Fig. 7

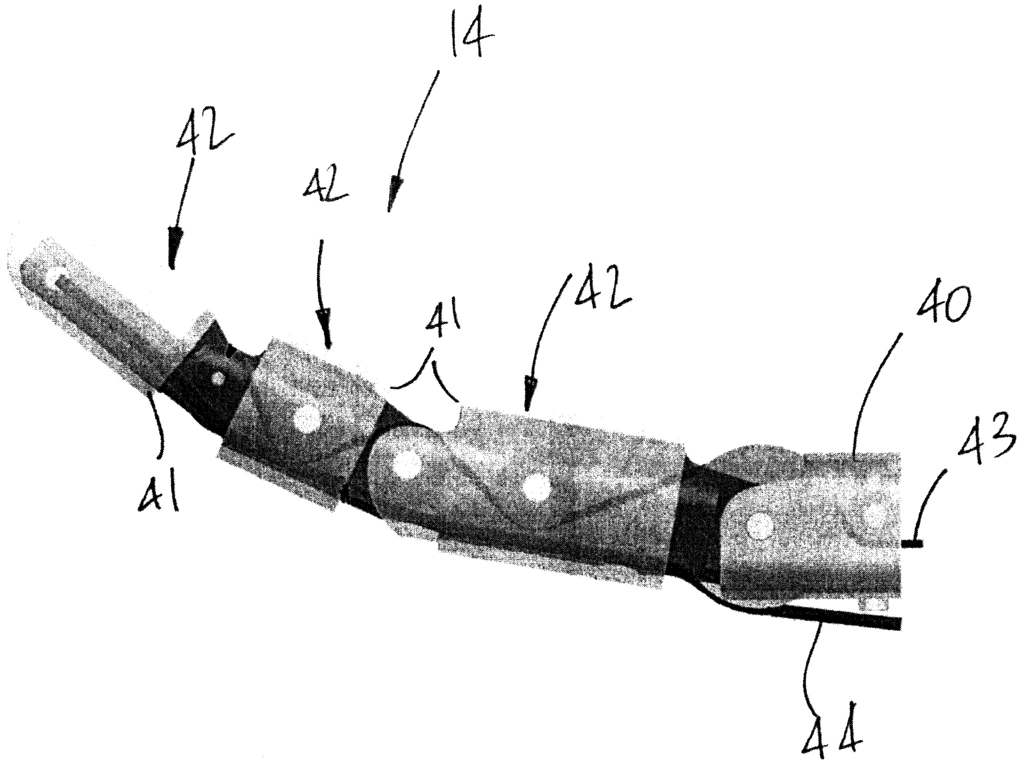


Fig. 8

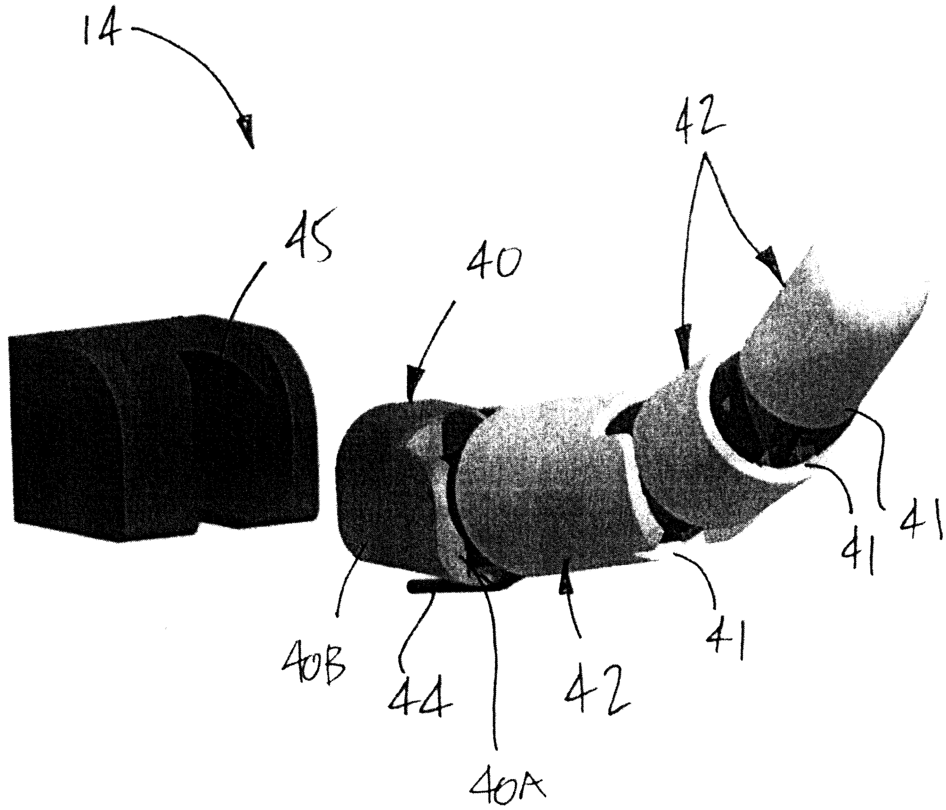


Fig. 9

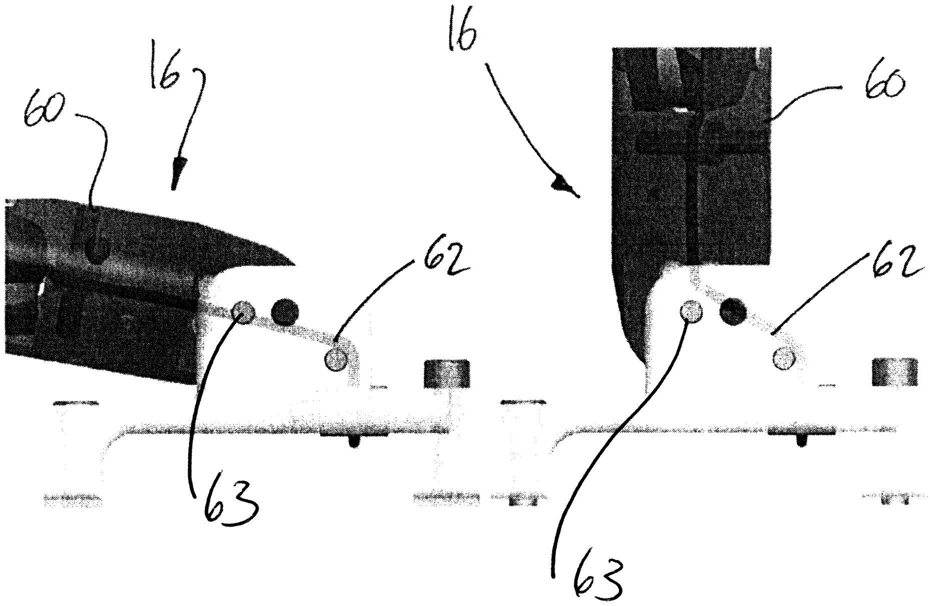


Fig. 10

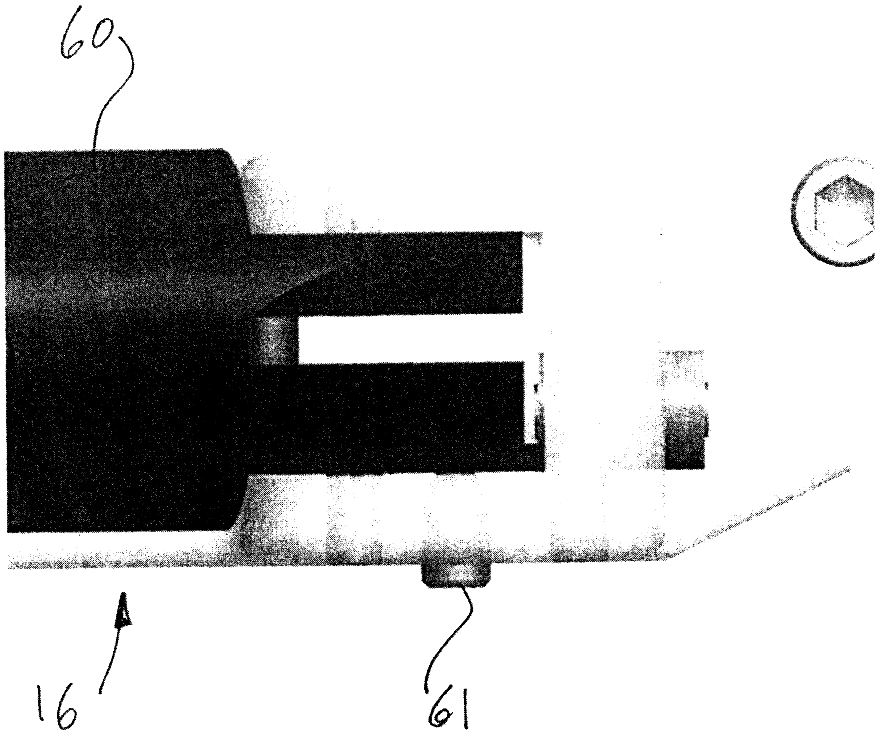


Fig. 11

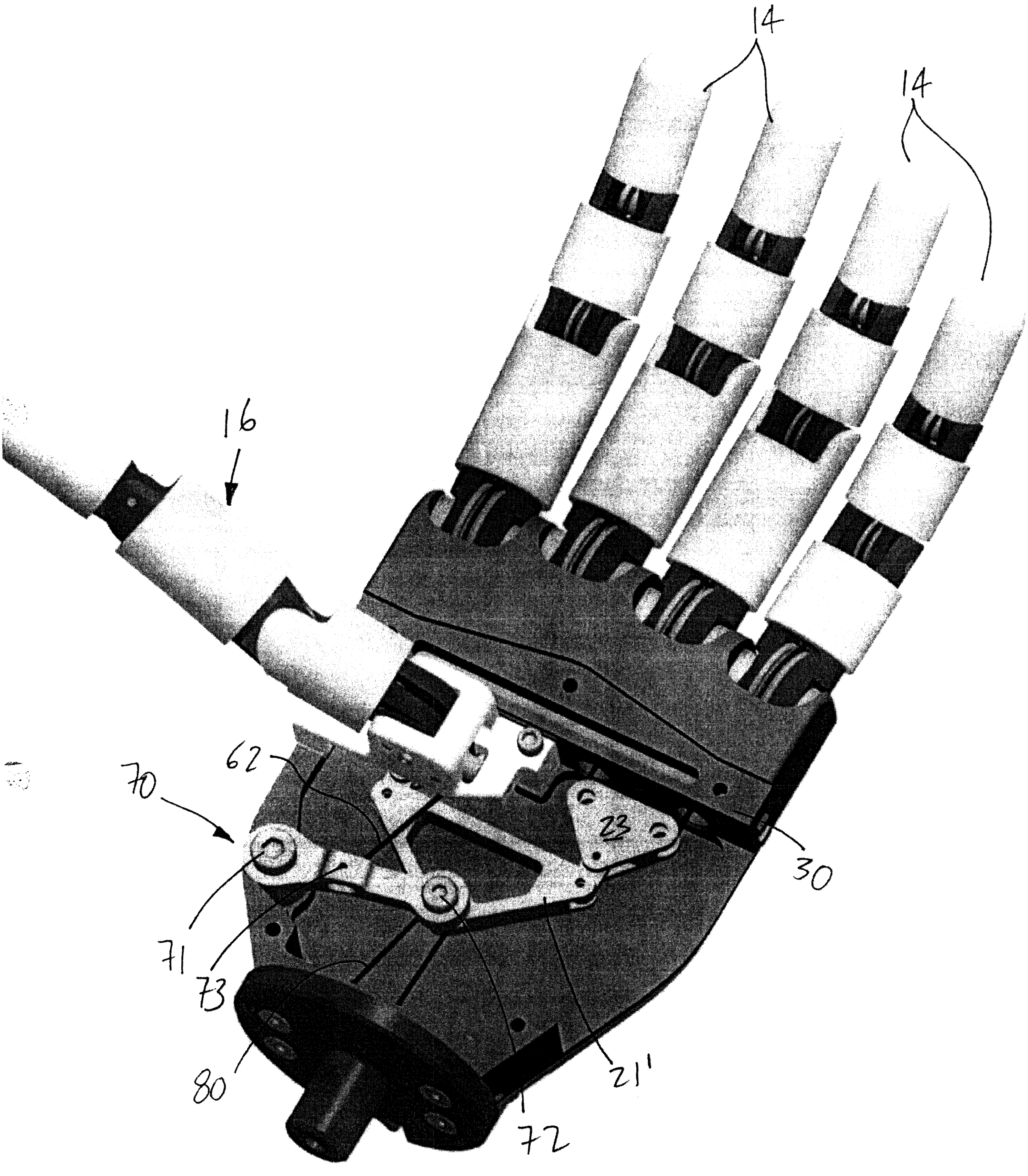


Fig. 12

FiG. 13