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A study of a robotic hand with tendon driven fingers

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SUMMARY
In the present paper, a model of an underactuated robotic hand with tendon driven fingers is proposed. The aim of the project was to study the feasibility of building a mechanical hand with four or five fingers, the movement of which is achieved using a single linear actuator. The mechanism was first modelled in order to study the possible improvement in the ability of a "robotic hand" powered with a single actuator in regard to grasping objects with complex shapes and also in achieving a strong grip on objects. Next, a model of the finger was studied in order to optimize of its parameters. Finally, a five-fingered robotic hand was modelled for potential application as a human hand prosthesis. Our studies on the dynamic and kinematic behaviour of a single finger mechanism permitted us to make the first prototypes of the mechanism. In addition to modelling studies, we also present a prototype of the modelled robotic hand that was developed in order to optimize functionality and simplicity of construction.

KEYWORDS: Robotic gripper; Tendon driven gripper; Robotic hand; Human prosthesis; Underactuated mechanism.

1. Introduction

In the past decade, robotics has drawn considerable inspiration from biology. In particular, much effort has been made to develop hardware that replicates natural mechanisms.

One of the fields of robotics that have taken inspiration from biology is the development of the gripper, with the goal of improving the dexterity of its components to the best possible extent.

In general, a robotic gripper can grasp objects in different ways, the two main types being the power grasp and the dexterous grasp.

The grasp of the human hand is always adapted to the specific type of task that is required to be performed as well as to the nature of the grasped object. For lifting heavy objects or delivering a large force of actuation, a robust grasping mechanism is needed, whereas for lifting lighter objects, a more dexterous grasp can potentially be used. For these reasons, research and industry have focused on developing robotic hands that imitate the human hand.

A high-performance robotic gripper that is inspired by the human hand should have the following characteristics:

- High number of degrees of freedom (DOFs);
- Capability of different types of grips with varying precision and strength;
- Ability to deliver a very strong force during the grasping, but at the same time, be capable of precision movements;
- Ability to adjust the force and speed in accordance with the nature of different objects for both gripping and moving;
- Sensors for force, position, and speed of actuation, as well as temperature etc.

In the development of dexterous robotic hands, two principal research goals can be distinguished in the literature: development of an anthropomorphic hand and an efficient manipulator.

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The development of an anthropomorphic hand has the goal of making the hand look and function as human-like as possible. For example, this is relevant when a prosthetic hand is being developed.

When the hand is meant to serve a certain dexterous manipulation function, the 'hand' is used instead of any other gripper only because it meets the functional requirements, but resemblance of the gripper to a real human hand is optional and is realized in only the simplest possible manner.

In refs. [1], and [4], provide a summary of the evolution and state of the art in the field of robot hands and further classify robotic hands focusing on the extent of their anthropomorphism and dexterity.

One of the characteristic features in the evolution of robotic hands was the transition to "underactuated" robotic hands that use fewer actuators than the number of degrees of freedom of the system.

The experimental prosthetic hand presented by,[3] performs passive adaptive grasping; i.e. it demonstrates the ability of the robotic fingers to conform to the shape of an object held within the hand.

Brown and Asada,[2] collected a variety of human hand postures and employed principal component analysis to calculate the synergies between fingers; they termed these principal hand postures "eigenpostures". They presented a novel mechanism design to combine the eigenpostures and drive a 17-degree-of-freedom, 5-fingered robot hand, using only 2 DC motors.

Gosselin *et al.*[5] and Baril *et al.*,[6] presented the design and experimental validation of an underactuated anthropomorphic robotic hand with 15 degrees of freedom, employing a single actuator.

Catalano *et al.*,[7] presented the first implementation of the UNIPI-hand, a prototype that implements the idea of adaptive synergies for actuation with a high degree of integration, in a humanoid shape.

Carbone,[8] presented stiffness modelling and analysis in robotic systems applied to grasping tasks and computed a Cartesian stiffness matrix.

Kawamura *et al.*,[9] proposed a grasping method for a polyhedral object using a hand-arm system with hemispherical fingertips, using a non-holonomic rolling constraint formulation between each fingertip and the object surface.

In this paper, we present a model of a mechanism for an underactuated robotic hand, based on a tendon driven system. By means of this mechanism, it is possible to employ just one actuator to actuate a four finger robotic hand. The grasping method was adapted to the shape of grasped object, and each finger was designed to grasp the object with the same force.

The paper begins with a description of a model for virtually testing the functionality of the proposed robotic hand. This is followed by a description of constructive solutions for prototyping the robotic hand, in the final section of the paper.

2. Simple Finger Model

The main functional characteristics of grippers and robotic hands are linked to the structure of the articulated finger that is adopted in different solutions. For this reason, the study of the model of finger represents the first step in defining the model of the robotic hand. It was decided to adopt a model of a finger articulated with an endoskeletal mechanical structure in which the relative motion between the chain links was ensured by kinematic revolute pairs.

The finger is constituted by four rigid links connected together by means of three hinges. Of these four links, one is fixed and is termed as the metacarpal link, the other three are moveable and constitute the three phalanges *viz.* the proximal, medial, and distal, phalanges of the articulated finger, respectively. The system is driven by a single tendon that is supposed to be inextensible and linked to the last phalanx (distal) and slides on a train of pulleys up to the single remote actuator of the system. Since the tendon only works in traction, the mechanism provides for a series of elastic elements (springs) that allow the system to return to the undeformed configuration when the actuating force is released.

A configuration was chosen such that all the hinges were installed in a central position with respect to the thickness of each phalanx, including the pulleys that were also installed centrally with respect to the length of each phalanx. The elastic elements, which were also installed in alignment with the hinges, were inserted on the structure so as allow rotation around the points of application. In this way, the springs were actuated exclusively by traction.

In Fig. 1, a simplified illustration of the finger mechanism is shown.

Table I. Computational parameters for the evaluation of the inverse dynamics model.

	Proximal	Medial	Distal
Phalanx mass	m = 70 g	m = 50 g	m = 30 g
Spring stiffness	K = 15000 N/m	K = 5000 N/m	K = 1100 N/m

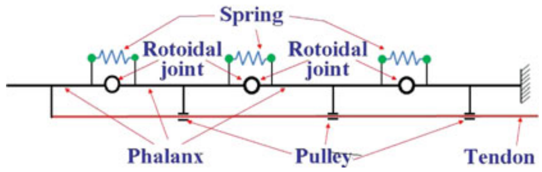

Fig. 1. Scheme of the finger mechanism.

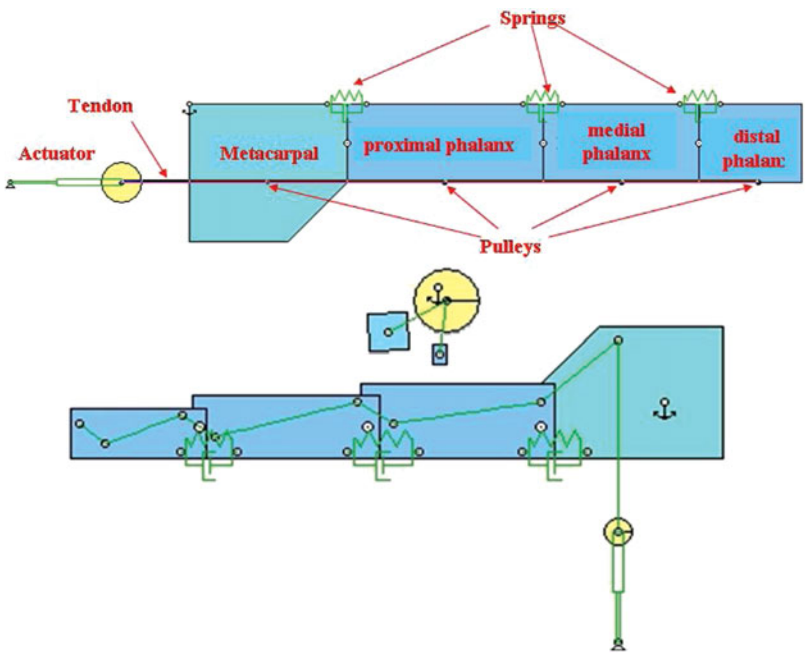

Fig. 2. Finger model in undeformed configuration.

This finger model represents a system with a single degree of freedom which enables two under-actuated degrees of freedom, since the single tendon is moved by a single actuator.

A model of finger articulation was developed using software for the simulation of mechanical systems (WM 2D ^{TM}), with the objective of achieving a kinematic mechanism which can be fully controlled by a single actuator.

The articulated finger was modelled schematically by approximating the phalanx with rectangular blocks and the metacarpus as an irregular polygon. Additionally, the hinges and pulleys were added in the positions described previously. Finally the elastic elements were simulated as “spring-damper” pairs.

Figure 2 presents the finger model in its undeformed configuration.

In Table I the parameters of the finger model are listed. Parameters were chosen to ensure necessary stiffness required to return to the undeformed configuration.

By varying the stiffness of the springs, for the same load applied via the actuator, the system can take on different configurations. With a load of 30 N and a set of stiffnesses sufficient to return to the initial undeformed configuration, the system assumes the configuration shown in Fig. 3.

By changing a stiffness associated with the medial phalanx to a value of K = 10000 N/m, the system assumes a different configuration, shown in Fig. 4.

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Table II. Maximum rotations experienced by phalanges in a human finger.

Phalanx	Angle	Maximal rotations
Proximal	θ_1	86°
Medial	θ_2	105°
Distal	θ_3	78°

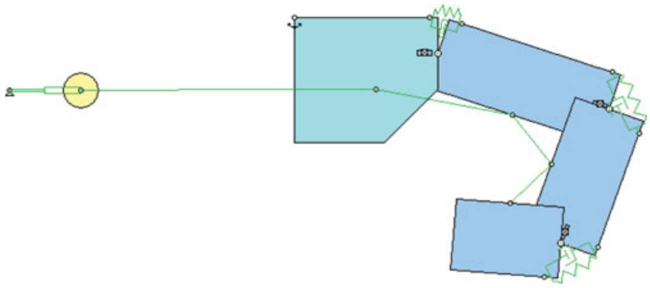

Fig. 3. Finger configuration with a force of 30 N and initial stiffnesses required to return to the initial configuration.

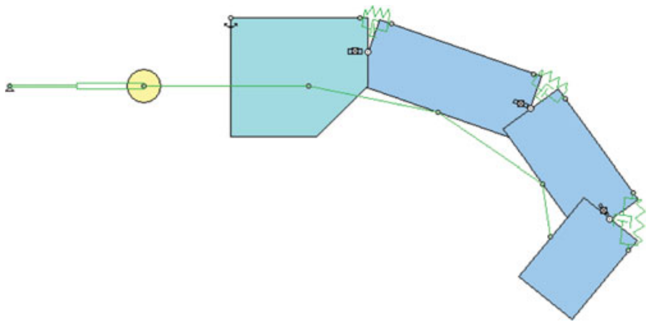

Fig. 4. Finger configuration with a force of 30 N and modified stiffnesses required to return to the initial configuration.

3. Analysis of Geometric Parameters of Finger

The structure of the finger can be optimized by varying its geometrical parameters in order to minimize the total shortening of the tendon. This analysis includes the dynamic analysis of the mechanism in order to determine the optimal configuration for operation of the system.

3.1. Determination of domain of guides

The positions of the guides must be such that they ensure a certain extent of maximum finger folding. In Table II the maximum rotations of the three phalanges, starting from the straight configuration of the finger, are shown. The values shown are those expected for a human finger.

In order to allow these conditions, constraints were applied to the position of the guides. In the following sections, for simplicity only the x and y coordinates of the position of the guides of the three phalanges were taken into consideration.

When the positions of the guides along the axes x are analysed, it is necessary that they ensure the maximum angles of rotation for the phalanges. In Fig. 5, the blue segment shows the guides of the tendon on the phalanges in the longitudinal position.

By assigning a range of variation at position of the guides along the y axis, the domain of the same guides becomes an area.

This is presented in Fig. 6.

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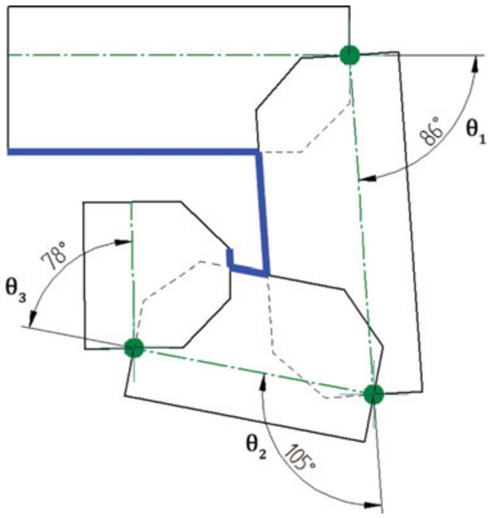

Fig. 5. Domain along the x axes of the guides.

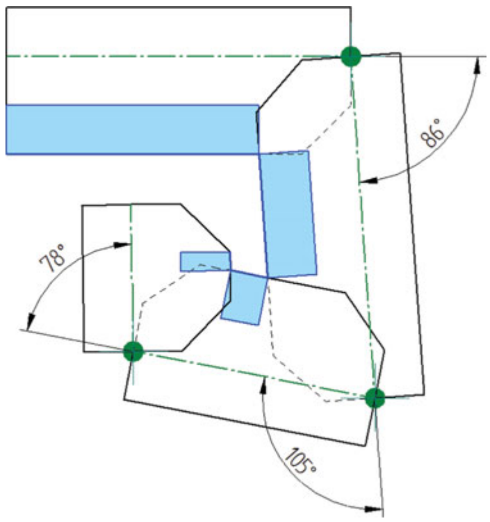

Fig. 6. Domain along the x and y axes of the guides.

3.2. Analytical study

It is necessary to explicitly link the total shortening of the tendon Δtbs(θ) and the coordinates of the guides. Δtbs(θ) is obtained as the sum of its parts i.e. Δtbsi(θ), contributed by the rotations of the individual phalanges.

It is assumed the problem as two-dimensional. It is assumed that the transverse position of the guides is always centred with respect to each phalanx. In this situation the shortening of the tendon is a function of the vertical coordinates (y_{vi}) and of the longitudinal coordinates (x_{vi}) that describe the location of all the guides, in the local coordinate references of each phalanx.

$$\Delta tbs(\theta) = f(\theta_p, \theta_m, \theta_d, , x_{vM}, y_{vM}, x_{vp}, y_{vp}, x_{vm}, y_{vm}, x_{vd}, y_{vd}) \tag{1}$$

where

$\{\theta_p, \theta_m, \theta_p\}$ are the rotations of proximal, medial and distal phalanges;
$\{x_{vM}, y_{vM}\}$ are the coordinates of metacarpal guide;
$\{x_{vp}, y_{vp}\}$ are the coordinates of proximal guide;
$\{x_{vm}, y_{vm}\}$ are the coordinates of medial guide;
$\{x_{vd}, y_{vd}\}$ are the coordinates of distal guide.

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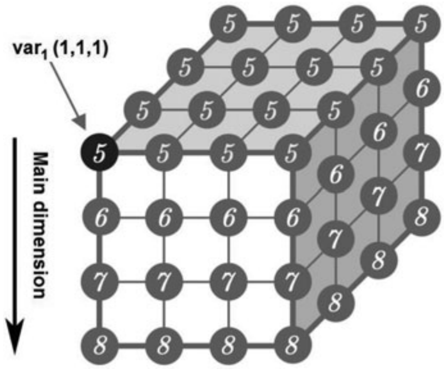

Fig. 7. Matrix relative to the first input variable, V1, in a case with three variables, with m = 4, V1min = 5, V1max = 8.

To analyse the trend of the function in Eq. (1), it is necessary for each configuration of the finger, $\{\theta_p,\theta_m,\theta_p\}$, to be derived with respect to the 8 variables that represent the coordinates of the guides. In this way it is possible to find the minimal shortening of the tendon that makes it possible to reach the finger configuration $\{\theta_p,\theta_m,\theta_p\}$. The analysis was repeated for different finger configurations in order to obtain the optimal position of each guide necessary to ensure a minimal shortening of the tendon.

An algorithm was developed to analyse the coordinates of the guides. The principal steps of this algorithm are defined as follows:

- Discretize the domain defined by the coordinates of the guides.
- For each finger configuration, to calculate the total shortening of the tendon as many times as the number of all the possible combinations of the input variables are (finite number).
- Find the minimum total shortening between all possible to know what are the coordinates of the guides that determined it.
- Repeat the process by changing the configuration of the finger.

If "m" indicates the desired level of detail in the discretization of the domain, the algorithm creates a n-dimensional matrix whose dimensions have m elements, for each of n input variables (i.e. the coordinates of the guides),. Each matrix has a principal dimension relative to one of the coordinates of the guides and this dimension is a vector of m elements equidistant from minimum to maximum value possible as per the limits of the coordinate system of the guide.

For example, if there are three input variables, the matrix corresponding to the first input variable, V1, assuming m = 4, $V1_{min} = 5$, and $V1_{max} = 8$, is a matrix of size 4× 4× 4, as shown in Fig. 7.

Also the total shortening of the tendon, $\Delta tbs(\theta)$, is represented with an n-dimensional matrix that has mn different elements. Each element of this matrix is representative of one of the possible cases of configuration of the guides of the tendon. Inside the matrix $\Delta tbs(\theta)$, the minimum element is localized by means of n indices, which identify the value corresponding to the configuration which produces the minimum shortening of the tendon.

The calculation of the total shortening is performed several times by varying the angles θi.

A detailed analysis can be done by varying the angles of the phalanges by the same percentage of its maximum values, instead of varing the three angles, θ_1, θ_2, and θ_3; in this way, a percentage of folding of the entire finger will be considered.

3.3. Optimization

An analysis of the shortening of the tendon to vary the folding of the finger and the 8 variables representative of the coordinates of the guides of the tendon was conducted.

The results are summarized in Fig. 8 where the shortening of the tendon is reported as a function of the percentage finger folding.

The tendon shortening for a given finger folding depends on the position of the guides. So, in the figures the blue line refers to the guide positions that allow minimum possible tendon shortening while the red line refers to the maximum tendon shortening.

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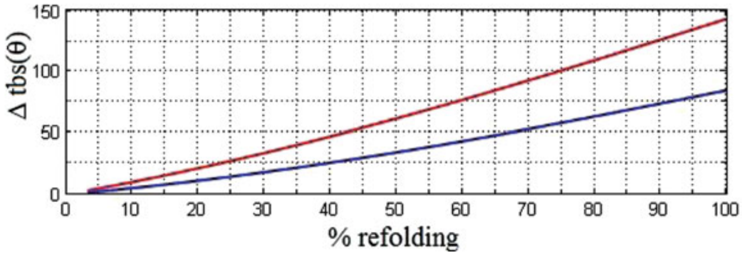

Fig. 8. Tendon shortening versus percentage finger refolding.

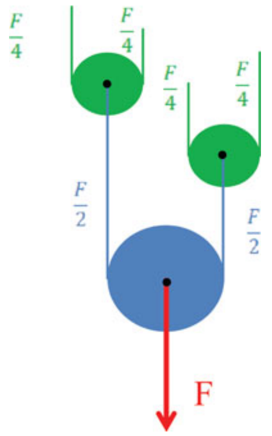

Fig. 9. Tendon driven mechanism.

The analysis of the shortening of the tendon is fundamental to optimize the operations of the more complex multi-finger mechanism.

4. Actuator System with Tendon Driven Mechanism

Multi-finger devices can be designed by replicating the structure of the serial chain of the finger a number of times as per the requirement of the number of fingers that need to constitute the system.

In the simplest case, it is possible to operate each finger with a remote actuator.

An actuator system with a tendon driven mechanism was studied in order to distribute the force generated by a single actuator to each of the multiple fingers of the system.

For a four-fingered robotic hand, the proposed force distribution system consists of three pulleys of which two are equal in size, and a third is larger. The actuator is connected to a drive pulley (i.e the major pulley) which is in-turn connected to the two minor pulleys. The forces on the sides of the two secondary pulleys is equal to one quarter of the force that the actuator applies to the main pulley.

A simplified illustration of the tendon driven mechanism is shown in Fig. 9.

For this system, it is possible to mathematically define the relationships between the displacements and the rotations of the pulleys, and the shortening of the tendons.

4.1. One pulley system

Let us consider a generic pulley, of radius R. Starting from an initial configuration in which both ends of the tendons have the same position, it is assumed to reach a configuration in which the ends of the two tendons have moved two different quantities: X_1 and X_2, with $X_1 > X_2$. This situation is shown in Fig. 10.

If X_A is the displacement of the centre of the pulley, and therefore the actuator stroke, the quantities X1 and X_2, are related to X_A and to the rotation θ of the pulley, by the following relations:

$$x_1 = x_A + \vartheta \cdot R \tag{2}$$

$$x_2 = x_A - \vartheta \cdot R \tag{3}$$

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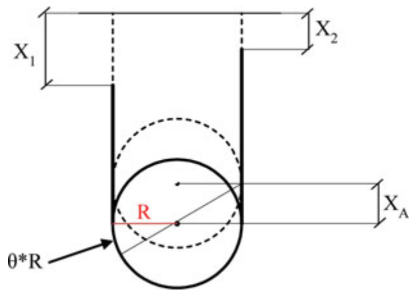

Fig. 10. The single pulley system.

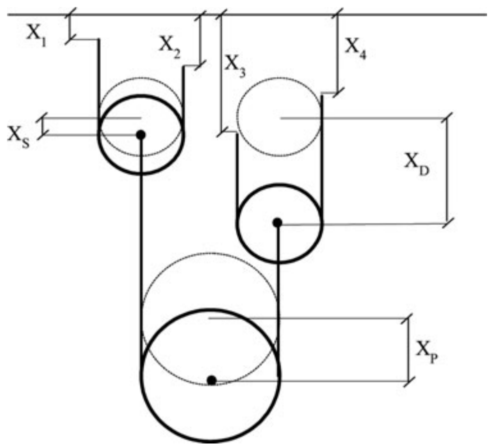

Fig. 11. The three pulley system.

By Eqs. (2) and (3) is possible to calculate the displacement and the rotation of the pulley:

$$\vartheta = \frac{x_1 - x_A}{R} \tag{4}$$

$$X_A = \frac{x_1 + x_2}{2} \tag{5}$$

4.2. Three pulley system

If we consider a three pulley system (see Fig. 11), X_S, X_D and X_P are the displacements of the centres of the pulleys, respectively (i.e. left, right and main pulley). Further, θ_S, θ_D and θ_P are their respective rotations. X_1, X_2, X_3 and X_4 are the displacements of the ends of the tendons.

The following relations can be written:

$$X_S = \frac{x_1 + x_2}{2} \tag{6}$$

$$X_D = \frac{x_3 + x_4}{2} \tag{7}$$

$$X_P = \frac{x_1 + x_2 + x_3 + x_4}{4} \tag{8}$$

If the four displacements are equal, none of the three pulleys rotates, while, if they were different, the pulleys will rotate to a suitable angle to ensure the desired configuration.

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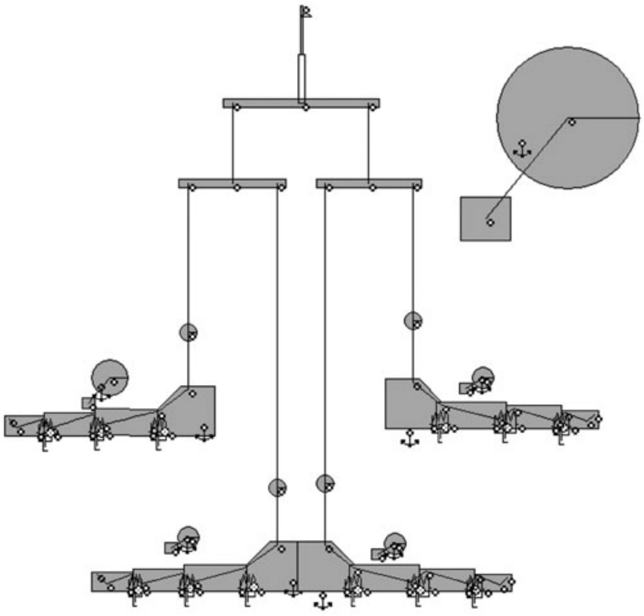

Fig. 12. Four finger hand in the open position.

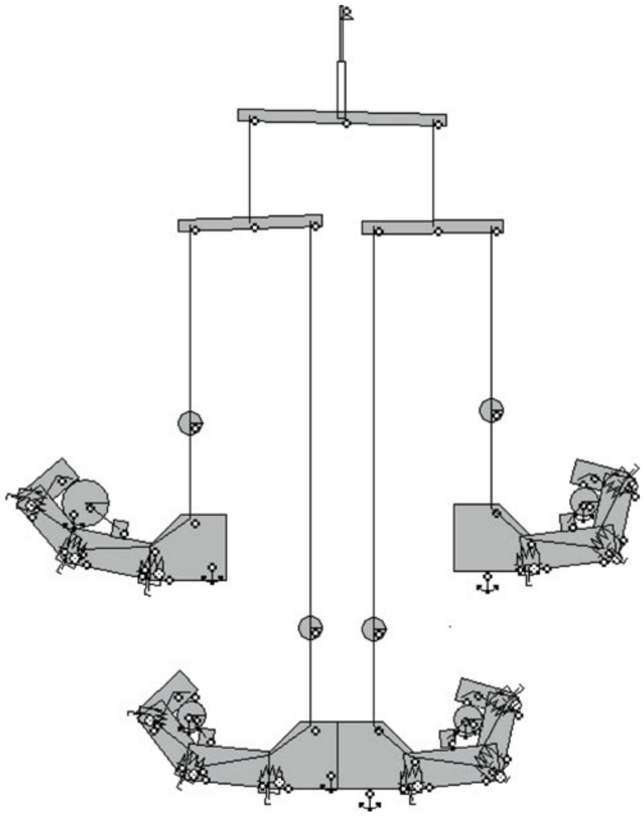

Fig. 13. Four finger hand grasping an object.

5. Multi-Finger Model

By means of the same software for the simulation of mechanical systems, a four finger hand was simulated.

The four finger hand model is shown in Fig. 12. On the same figure, a section of an object to be grasped is also shown (see, Fig. 12, top right). Further, to simulate an object whose shape changes

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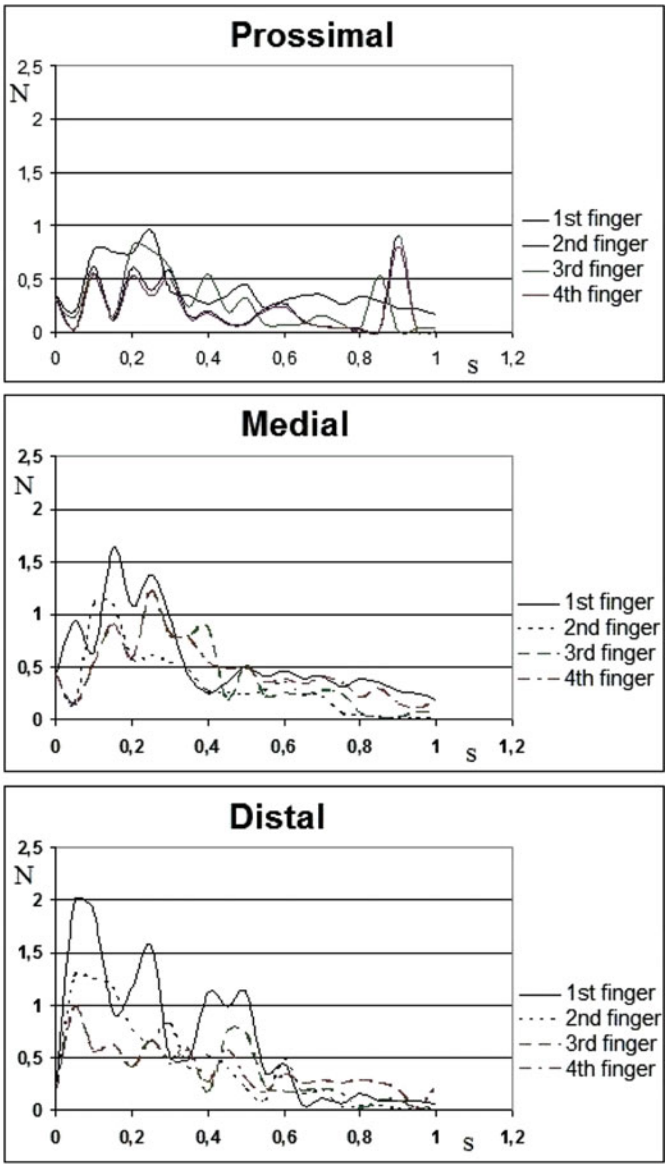

Fig. 14. Forces exerted by each falange.

during the grasping process, the section of the object to be grasped was modelled to be composed of a fixed circle and a square linked to the said circle by means of an articulated rod. Finally, in Fig. 13, it is shown that each finger grasps circles and squares having different dimensions. this is simulative of the process of grasping an object having different cross sectional sizes in correspondence of any finger.

Figure 13 shows the hand after the grasping an object. It is possible to observe that the position of the squares in the figure is altered, simulative of a changing object shape during the grasping process.

In Fig. 14 the forces exerted by each of the phalanges of each finger are reported.

It is possible observe that the maximum force exerted by any phalange ranges between 1 N and 2 N i.e. each phalange practically exerts the same force, independent of the position it assumes during the grasping process. This means that the maximum force that will stress the object can be easily controlled by regulating the force exerted by the actuator.

5.1. First CAD prototype

By means of a CAD software a prototype of the finger and three models for a four finger hand were developed.

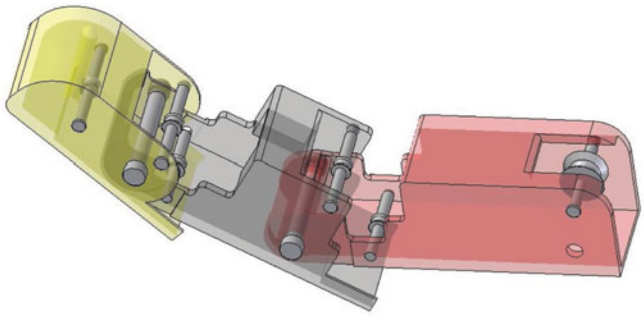

Fig. 15. Finger prototype.

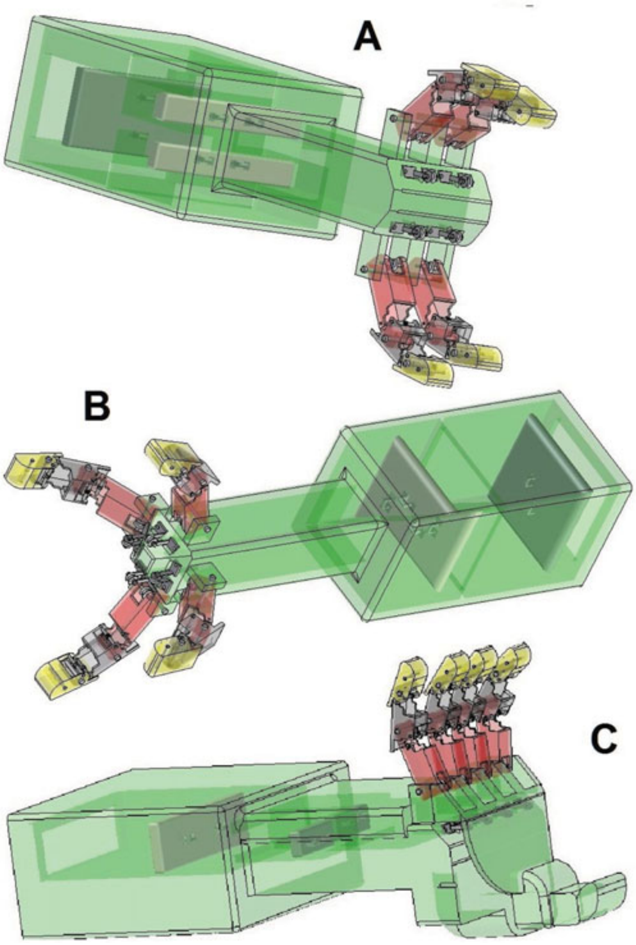

Fig. 16. Prototypes of robot hand with four fingers.

The three phalanges were connected together and to the palm by means of two joints made with a pin. All three phalanges were modelled with a pulley for the passage of the tendon at the joint with the previous phalanx, but disposed to the internal part of the finger. The proximal and medial phalanges were also designed to have a pulley at the back of the finger Inside the distal phalanx, corresponding with the back of the finger and at its end, a pin was positioned onto which the tendon was fixed.

The finger prototype is shown in Fig. 15.

All three prototypes of the robot hand were connected to the same type of arm. This arm consisted of two profiles with different rectangular cross sections, connected together. The first one had a smaller section and was connected to the palm of the hand, while in the second one had a larger section and housed the actuator (see Fig. 16).

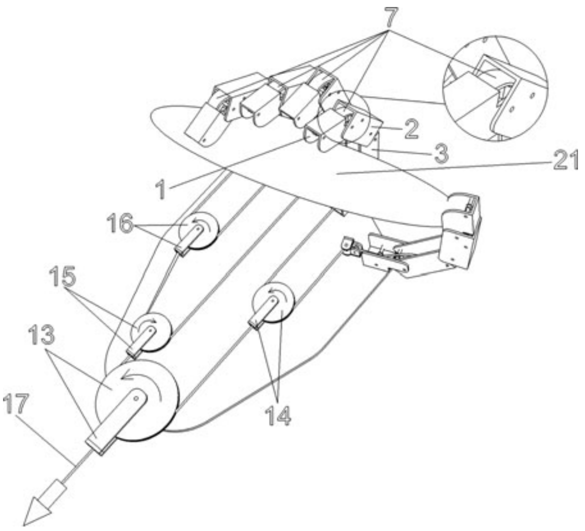

Fig. 17. Illustration of the prosthetic hands during the process of gripping an object of any shape.

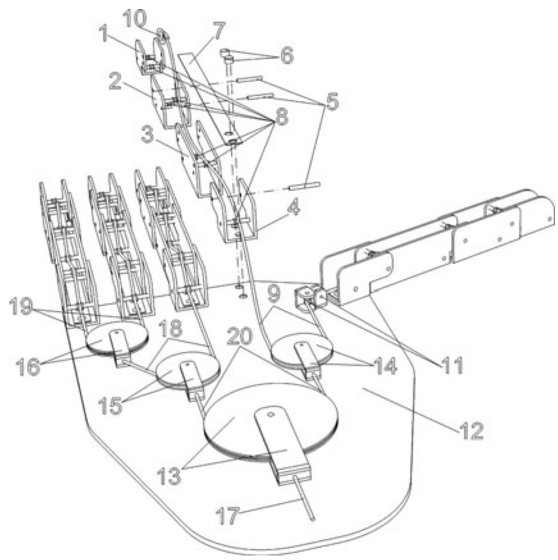

Fig. 18. The assembly of prosthetic hands, and exploded view of a finger.

The first prototype of the hand with four fingers was inspired by the parrot foot in terms of its construction with two pairs of opposing fingers (see Fig. 16(A)).

The second prototype (Fig. 16(B)) had the fingers oriented at 90° apart from each other and had greatly improved gripping ability.

The third prototype has humanoid form with the opposable thumb fixed, this solution is the closest to the idea of a human prosthesis, Fig. 16(C).

6. Hand Prosthesis Prototype

The tendon drive mechanism described above and the developed robotic hand prototype were embodied into a simple hand prototype that was possible to be actuated with a single actuator, making it a valid design for a hand prosthesis.

The prosthesis was composed of simple elements that guarantee both cost effectieness and simplicity of operation. The prosthesis was composed of five fingers, consisting of U-profiles hinged to each other by linchpins, which together were capable of the different articulations of a human finger (see Figs. 17 and 18).

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Some small pulleys were hinged alternately, first from below and then from above, inside each U-profile which closed the fingers through the actuation of a inelastic tie-rod passing alternately through the lower side and then the upper side of the small pulleys (see Figs. 17 and 18).

Five elastic metallic yarns acting as leaf springs were fixed on a single extremity to the base and on each profile of each finger, which allowed elastic extension of each finger when the main inelastic tie rod was released (see Figs. 17 and 18).

The five fingers constituting the human hand prosthesis were fixed on a base i.e. element 12 in Fig. 18.

An inelastic tie rod (i.e. element 9 in Fig. 20) passing through the distribution pulley (element 14 of Figs. 17 and 18) was employed to distribute the gripping tension between the thumb and index finger.

In Fig. 18 it is possible to see that in a similar manner the gripping tension is distributed between the fingers, in particular:

- between ring finger and little finger by means of an inelastic tie rod (i.e. element 19) and distribution pulley (i.e. element 16);
- between middle finger and distribution pulley (i.e. element 16) by means of inelastic tie rod (i.e. element 18) and distribution pulley (i.e. element 15);
- between two distribution pulleys (i.e. elements 14 and 15), by means of inelastic tie rod (i.e. element 20) and distribution pulley (i.e. element 13).

The pulley (i.e. element 13) is linked to the tie rod (i.e. element 17) which is the only one that is actuated to allow the grasping action of the hand.

The rotation at hinges continues until each phalanx come into contact with the gripped object. Once each phalanx enters into contact with the gripped object, the fingers are aligned in such a manner that facilitates tightening of the object and ensures its grip. The larger pulleys installed on the palm of the hand distribute forces to the other fingers and move up until each phalanx is in contact with the object to be grasped, thus achieving the gripping action desired.

The scheme of the force distribution between the fingers of the hand reported in Fig. 9 was modified to introduce a fifth finger using an additional pulley system. The actuating force, F, was redistributed into individual finger forces as follows:

F/4 on the thumb;
F/4 on the index finger;
F/4 on the middle finger;
F/8 on the ring finger;
F/8 on the little finger.

With the proposed distribution of the forces to the five fingers, each finger was designed to exert the same closing force on a grasped object. Hence, the same gripping force was possible on object having almost any shape, in any orientation and in any position with respect to the robotic hand. In fact, a number of simulations showed that in different situations the fingers wrapped around the object, closing in on themselves and inhibiting any object movement in the equilibrium conditions. During grasping, if the object is not symmetrical or not symmetrically disposed respect to the hand, a higher force exerted by the thumb will pull the object through the fingers.

A number of finger prototypes were made using different design strategies and materials, in order to test the kinematics of function. The prototype using solid Plexiglas was found to be most efficacious. This prototype exhibited a good compromise between simplicity and effectiveness and also permits to easily locate low friction guides.

One of these prototypes is shown in Figs. 19 and 20. In Fig. 19 shows the finger in its fully extended state, which was achieved using the elastic steel wire inserted into the finger, closer to the hinges.

In Fig. 20 the pulling force applied to the tendon (upper wire in the figure) provides the moment to rotate each phalanx. As explained before, each phalanx rotates until it reaches in contact with the object to be grasped.

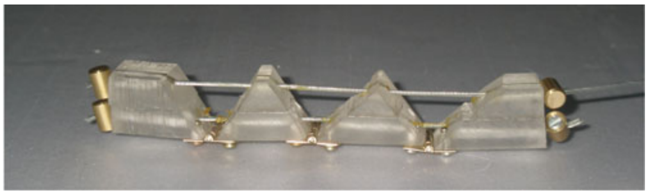

Fig. 19. Prototype of the finger in extension configuration.

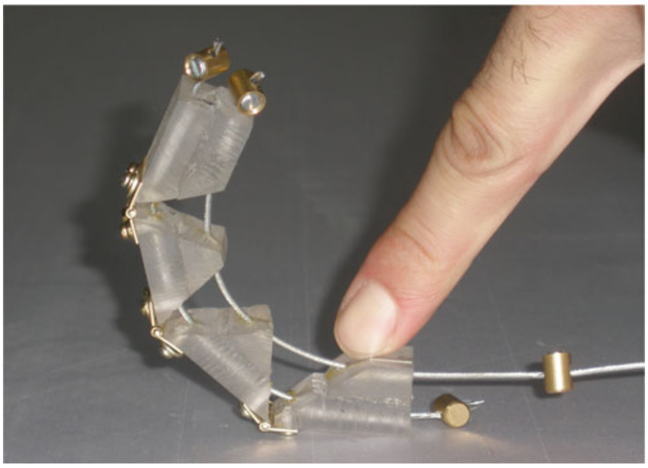

Fig. 20. Prototype of the finger in grip configuration.

7. Conclusions

A model of a tendon driven robotic gripper is proposed. The study demonstrates the feasibility of realizing a mechanical hand with four fingers, the movement of which is realized using a single linear actuator.

Moreover, the proposed mechanism allows each phalange to exert practically the same force, independent of the position it assumes during grasping. So the maximum force that will stress the object can be easily controlled by regulating the force exerted by the actuator.

Finally, the tendon drive mechanism was applied to a simple model of hand with five fingers, that could have application as a hand prosthesis.

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