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AN UNDERACTUATED MECHANICAL HAND PROSTHESYS BY IFToMM ITALY / Niola, V., Rossi, C., Savino, S., Carbone, G., Gasparetto, A., Quaglia, G.. - ELETTRONICO. - (2015). (The 14th IFToMM World Congress Taipei, Taiwan October 25-30, 2015) [10.6567/IFToMM.14TH.WC.PS13.005].

Availability:

This version is available at: 11583/2657734 since: 2016-11-29T11:05:40Z

Publisher:

Published

DOI:10.6567/IFToMM.14TH.WC.PS13.005

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AN UNDERACTUATED MECHANICAL HAND PROSTHESIS BY IFToMM ITALY

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Abstract: *This paper describes a mechanical underactuated hand, whose design is under patenting. The proposed hand can be used as robot grasping end-effector and, mainly, as a human prosthesis. The proposed underactuated mechanism is based on an adaptive scheme, hence it permits to move five fingers with only one actuator. The actuator is connected to a set of pulleys that operate five tendons. Each tendon will move the phalanxes of a finger. The proposed mechanism permits each finger to adapt its configuration to almost any object shape so that each of the fingers will grasp the object independently on the configuration of the finger itself and independently on the configuration of the other fingers. The tendons are un-extendible so that each finger will grasp an object always with the same force, regardless of object shape. The overall grasping force will be controlled just by adjusting the input actuator torque. This paper also reports preliminary kinematic and dynamic studies aiming to a validation of the feasibility of the proposed design solution. Finally an early experimental prototype is shown.*

Keywords: robotic hand, mechanical prosthesis, underactuated systems kinematics and dynamics.

I. Introduction

In general, a robotic gripper can perform a grasping task in many different ways. The main distinction that is made in literature is between a power grasp and a dexterous grasp. The grasp of a human hand is always adapted to the type of task to perform and to the nature of the grasped object. For example, for grasping heavy objects or for delivering a large force a robust grasp is needed, while for lighter objects a different and more dexterous grasp can be used. For these reasons research and industries focus their attention on developing robotic hands that can mimic the human hand, for example, in terms of human-like shape, mainly for prosthesis, or in terms of human-like manipulation capabilities and dexterity in applications as robotic end-effector, [1-8].

In Bicchi [2] and in Lotti and Vasura [5] there is an attempt to summarize the evolution and the state of the art in the field of robot hands and to classify robotic hands focusing on their anthropomorphism and dexterity.

One of the characteristic features in the evolution of robotic hands was the transition to the "underactuated" robotic hands that have a number of actuators that is lower than the number of degrees of freedom of the system.

The experimental prosthetic hand presented by Dechev et al., [3] is able to perform passive adaptive grasp, that is, the ability of the fingers to conform to the shape of an object held within the hand. Brown and Asada [4] collected a variety of human hand postures and used the principal components analysis to calculate the synergies between fingers, they called "eigenpostures" these hand postures. 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. [6] presented the design and experimental validation of an anthropomorphic underactuated robotic hand with 15 degrees of freedom and a single actuator. Catalano et al. [8] presented the first implementation of the UNIPI-hand, a prototype which conciliates the idea of adaptive synergies for actuation with a high degree of integration, in a humanoid shape.

As based on literature and authors experience a robotic anthropomorphic hand should have the following main characteristics:

- a relatively high number of degrees of freedom (d.o.f.);
- capability to perform different types of grasping, precision and strength;
- to be able to adjust the force and speed in accordance with the different objects to be grasped and manipulated;
- to possess sensory feedback for example in terms of force, position, speed, temperature.

This paper describes a mechanism for an underactuated anthropomorphic robotic hand, based on a tendon driven system. By means of this mechanism is possible to use only one actuator to move a four finger robotic hand. The grasp is always adapted to the shape of grasped object, and each finger grasps the object with the same force.

Preliminary kinematic and dynamic studies have been carried out for validating the feasibility of the proposed design solution. Finally an early experimental prototype is shown. A patent application has been filed for the proposed robotic hand design solution with the patent claim no. NA2013A000002 that has been presented on Jan.16, 2013.

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II. Description Of The Proposed Hand

In this section the device is presented together with a brief exposition of the theoretical studies on which the development of the device itself was based [9-12].

II.1 The Finger Mechanism

Most of the choices adopted during the design phase of the hand device were based on the results obtained from a model derived from the finger model presented in [9].

A scheme of the finger mechanism is shown in figure 1.

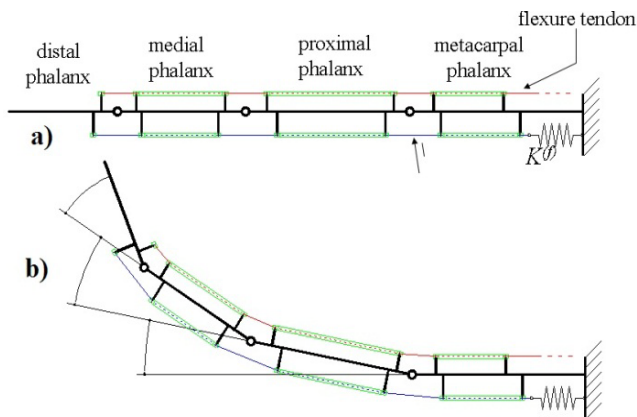


Fig.1- Scheme of the underactuated finger

It consists of four rigid links connected together by means of three hinges. Of these four links, one is fixed and is indicated with the term metacarpal, the remaining three are movable and constitute the phalanges, respectively proximal, medial and distal. The system is actuated through a single tendon, supposed inextensible and linked to the last phalanx (distal), which slides on a set of guides up to the one remote actuator.

Each finger of the hand is a planar system composed of four rigid links connected together (mutually constrained) by three hinges free of friction (fig. 1). Of these four links, one is fixed and is indicated with the term metacarpal, the remaining three are movable and constitute respectively the proximal, medial and distal phalanx. Each finger is equipped with a flexural and an extensor tendon, both having an end fixed (fastened, welded, secured) to the distal phalanx. All the phalanges, furthermore, are provided with a couple of cylindrical guides along which the tendons can freely slide when the finger deforms. We assume that both the tendons are inextensible, free of thickness and have zero bending stiffness. In this hand model, each finger has only three degrees of freedom.

In Fig 2 a simulation of the finger made by means of the multi-body code WM 2D™ is shown. In the figure the grasping of an object is simulated; the object consists in a circle held by two orthogonal elastic constraints. This simulates the self-adaptability of the underactuated finger to an object that moves or changes its shape during the grasping. From Fig.2 it is possible to observe that each of the three phalanges correctly adapt its rotation to the object shape and to the object position respect to the finger itself. Moreover, in the same figure, the force in each of the elastic constraints (computed by multi-body the code) is also plotted; in this way the resultant of the grasping force can be also computed.

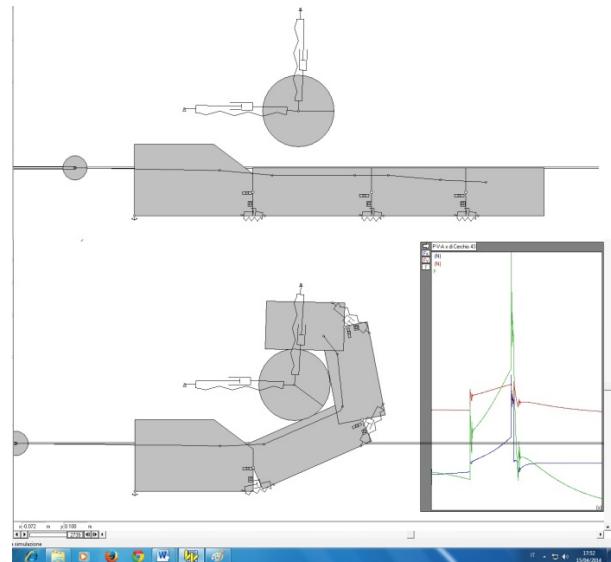


Fig.2- WM 2D™ model and simulations

Investigations were carried out in order to determine both the kinematic and the dynamic behavior of the underactuated finger [9-13].

The positions of the guides must be located in order to ensure always a certain maximum refolding. In order to allow this condition, there are some constraints for the position of the guides. By assigning a range of variation to the tendon guides position along the y axis, the domain of the guides themselves becomes an area.

In particular, in Fig. 3 the “Denavit and Hartenberg” representation of the finger model is shown, together with the computed domain along the x and y axes of the tendon’s guides.

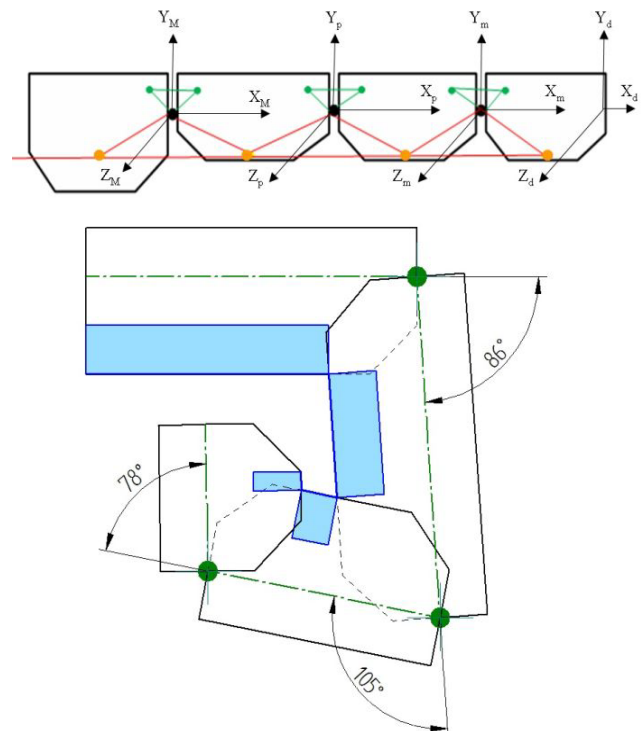


Fig.3- D-H representation and optimum computed domain of the tendon guides

II.2 The Hand Mechanism

In Fig. 4 the CAD drawings of the first prototype of the hand are shown.

The hand was designed by using simple elements that guarantee the cheapness and simplicity of operation. In particular, the hand is composed by five fingers, each made of three phalanxes hinged to each other by pins, which represent the different articulations of a human finger. The finger is closed by means of an inelastic tie-rod as shown in Fig. 7. In the lower part of the figure one of the tendons inside the finger is represented with a dotted line; the tendons mechanism are also shown. Hence the working principle of the hand mechanism is evident.

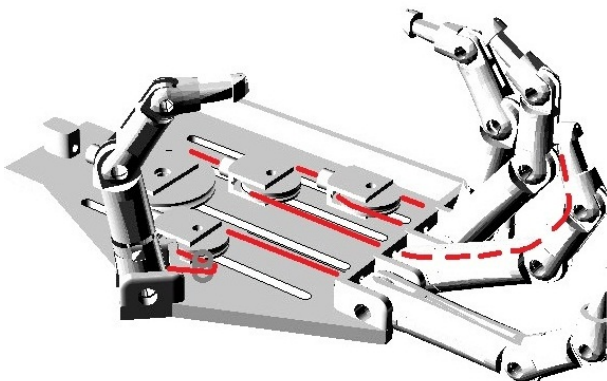
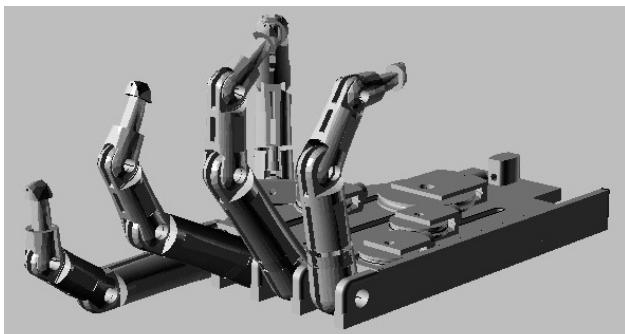


Fig.4- CAD design of the proposed device

In Fig. 5 the scheme of the pulley system that permits the self-adapting of the fingers to the object shape during the grasping is shown, together with the distribution of the force between the fingers of the hand. The repartition of the actuating force F allows to reach a configuration in which the force for each finger is:

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

The tendons, made of inelastic tie rod passing through a system of pulleys, distribute the gripping tension between the fingers, thus permitting the fingers to adjust themselves to the size and shape of the grasped object.

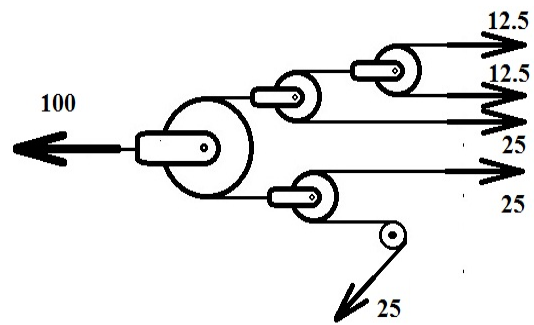


Fig.5- Pulleys system

The rotation of the pulleys, in fact, will occur at any contact of each phalanx with the gripped object. Once each phalanx enters into contact with the gripping object, the finger is aligned in such a way to tighten the object and ensure its grip. Thanks to the larger pulleys installed on the palm of the hand, the force is distributed also to the other fingers; the set will move up until each phalanx is in contact with the object to be taken, achieving the gripping.

The design of the hand was first studied by means of the multi-body code WM 2D™ again. In Fig. 6 the five finger model is shown. The model is essentially made by five fingers; each of them is almost equal to the one shown in Fig.1. The tendons are linked to the common linear actuator by means of rocker arm; each of the latter represents one of the pulleys of the pulley system. Since the rocker arms rotations are very little, the tendons kinematics does not differ significantly from the one of the pulley system.

In the upper part of Fig. 6 the hand is represented open, while in the lower part an object is grasped. The latter is represented in the simulation by means of the black fixed bodies; these represent the sections of the object in correspondence of each of the fingers. As it is possible to observe, in the shown simulation, the object section are very different in shape and position respect to the finger.

In the lower part of Fig. 6 the grasping is shown. As it can be observed, each of the fingers adapts its phalanxes rotation to the shape of the section the object presents to each of the fingers. This behavior is permitted because once a finger stops touching the object, the rotation of a pulley (or of the rocker arm in the simulation) does not increase the tendon push but permits the other tendons to move until the contact is reached by the other fingers. In other words, the system of pulleys permits that each of the non-extendible tendons is pulled always with the same amount of the actuator's force but its displacement is self-adapted to the phalanxes rotation required to grasp that section of the object.

Figs. 7 to 10 show the simulation results for the thumb, the index, the middle and the ring finger, respectively, in terms of the force that is applied to the main tendon (plot 1), the displacement of the main tendon (plot 2), the displacement of the finger tendon (plot 3) and the force applied the finger tendon (plot 4). In particular, the curves in Figs. 7 to 10 refer to the grasping task that is shown in Fig.6. As it is possible to observe, despite the dynamical effects during the transient phase, the force distribution is in good agreement with the design values.

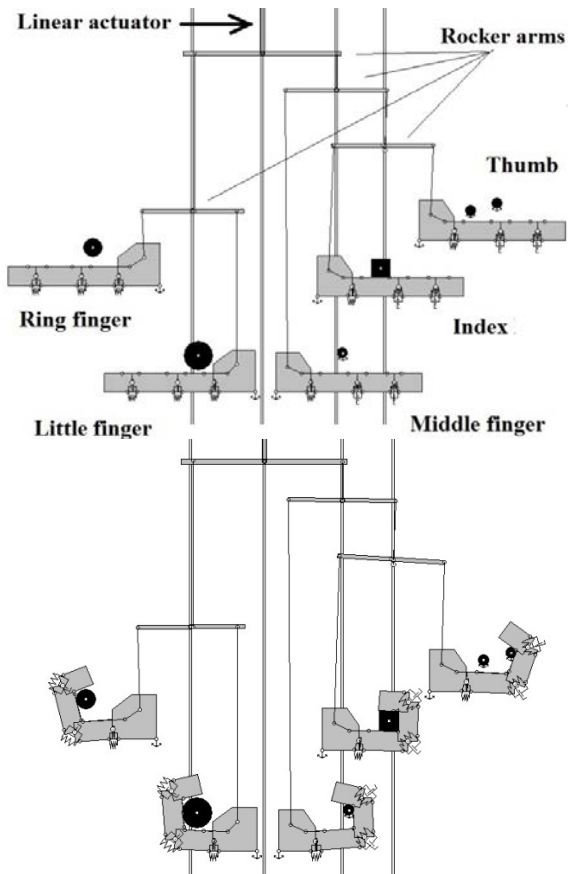


Fig.6- WM 2D™ model and simulations

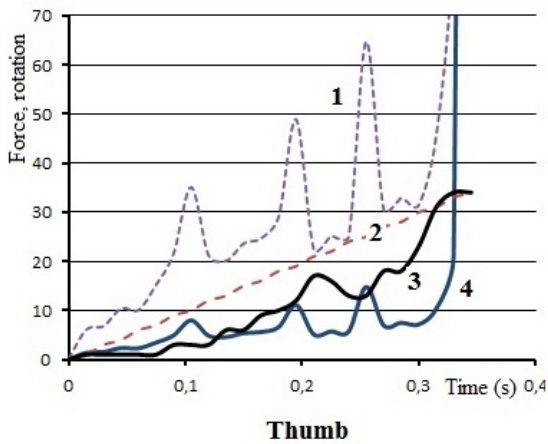


Fig.7- Plot of tendons forces and displacements: thumb

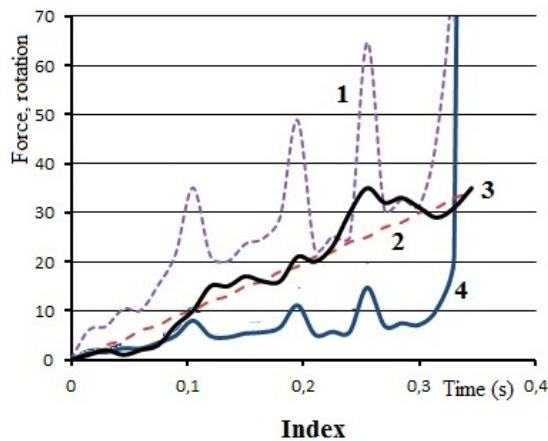


Fig.8- Plot of tendons forces and displacements: index

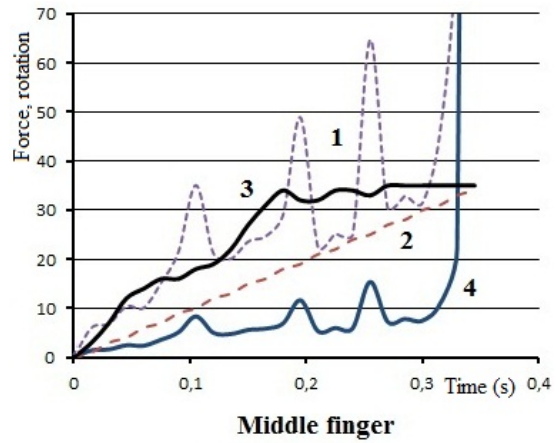


Fig.9- Plot of tendons forces and displacements: middle finger

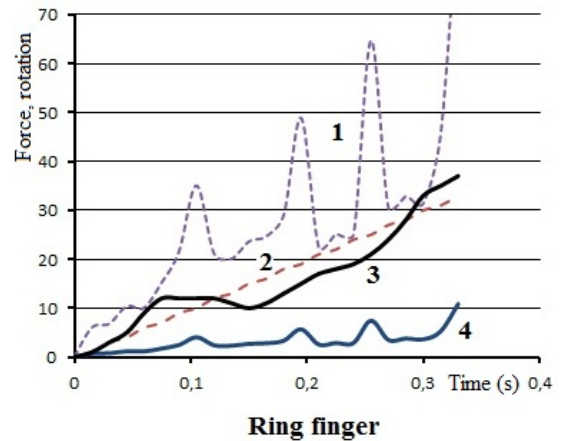


Fig.10- Plot of tendons forces and displacements: ring finger

In the same figures, plot 3 in particular, shows how the finger phalanxes self-adapt themselves to the object shape.

III Built Hand Prototypes

In this section recent prototypes are reported. All the prototypes were made in PLA by means of a 3D printer; the tendons were made by an almost inextensible yarn having 0.8 mm diameter, commonly use to sew heavy sails. In Fig. 11 a picture of an early hand prototype is shown. In the upper part of the figure the hand grasps an object that is made of three cylinders having different diameters. In the lower part of the figure the dimension of the object are shown and the grasping of the same object but upside down with respect to the previous picture. As it is possible to observe, the phalanxes of each of the fingers correctly rotate in order to adapt themselves to the object shape. Several grasping tasks can be successfully carried out by means of the proposed hand. Some examples of feasible grasping tasks have been reported in Fig.12.

In Fig. 13 a more recent prototype is shown. This second prototype has the following main improvements in order to obtain a better gripping for many object shapes:

- The thumb position respect the other finger was optimized also by increasing the thumb angle respect the hand longitudinal axis.
- The distal phalanx shape was changed.
- The sliding of the pulleys was improved.

This figure clearly shows the self-adapting mechanism. In both parts of the figure the actuator is set in the same

position.

In the upper part of the figure the hand is in the configuration given by the actuator only, while in lower part of the figure, without moving the actuator, the middle finger is stretched by the human hand. As it is possible to observe, the rotation of the pulleys (see e.g. the mark A) and the translation of them (see e.g. the mark B) permit the phalanges of the other fingers to adapt themselves to the new middle finger configuration. This is done without moving the actuator; in fact, as it is possible to observe, the position of the larger pulley (that is moved by the actuator) is exactly the same.

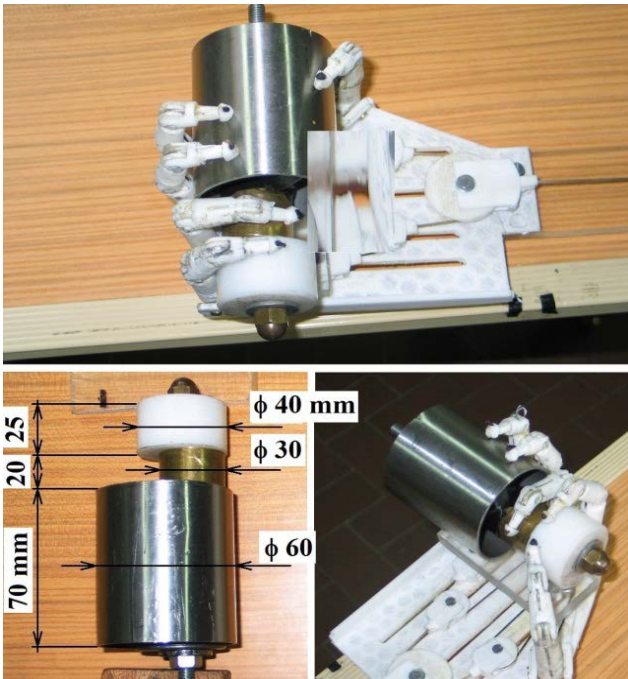


Fig.11- Hand prototype, grasping



Fig.12- Common use objects grasping.

The simulation results and preliminary grasping tests have shown very encouraging results in terms of practical feasibility of the proposed hand. In conclusion, the system of pulleys works well and shows a satisfactory auto-adaptability of the so actuated fingers, in fact the mechanism permits each finger to adapt its configuration to almost any object surface. This allows to replicate several functions of a human hand. Finally it must be remarked that the use of un-extendible tendons permits to each finger to grasp the object always with the same force, independently of the fingers configuration, hence independently from the object surface shape. The force will be controlled just by the only actuator torque.

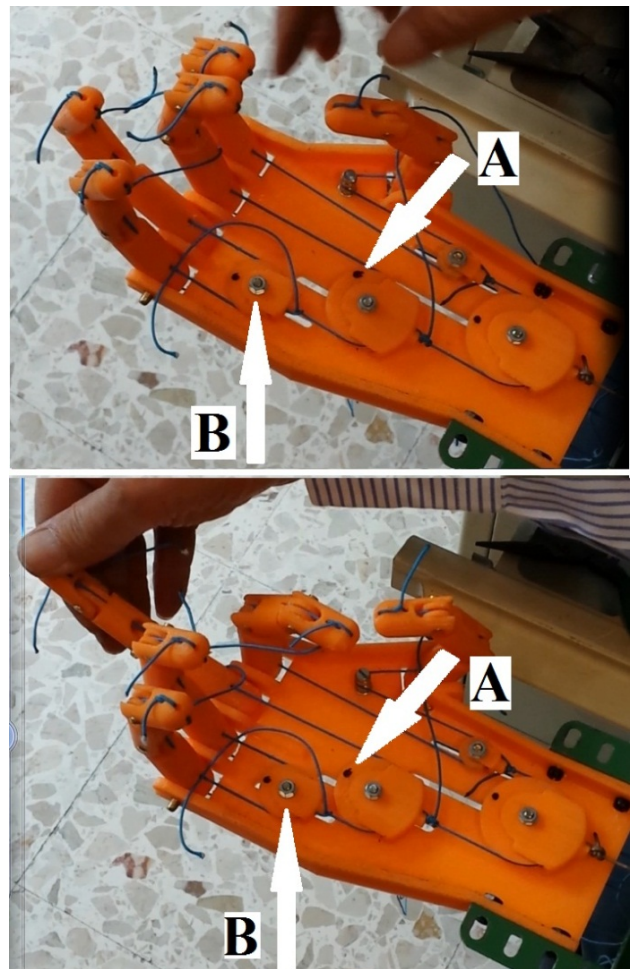


Fig.13- Self adapting of a recent prototype

IV. Conclusions

This paper describes a mechanical underactuated hand, whose design is under patenting. This hand can be used as a human prosthesis and also, with few modifications, as a robot grasping end-effector device. The proposed underactuated mechanism is based on an adaptive scheme that permits to move five fingers with only one actuator. Studies on kinematics and dynamics of an underactuated mechanical hand based on a multi-pulley system have been carried out. The mechanical behavior of the finger and of the whole hand were also studied by means of a proposed model and by means of a multilink model in Working Model 2D™ environment. The simulation results and preliminary grasping tests have shown very encouraging results in terms of practical feasibility of the proposed

hand. Further studies are in progress on different solution for the extension tendon mechanics.

Aknowledgments.

The paper represent a joint study of the whole IFToMM Italy Presidence Board.

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