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Paper:

Study of an Underactuated Mechanical Finger Driven by Tendons

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This paper presents an investigation on the influence of the design parameters in an underactuated mechanical finger driven by un-extendable tendons. The study was carried out using simulations and experimental tests. The aim of the study is to analyze the behavior of the finger during its closing motion. Hence, this study can help in correctly designing fingers for underactuated grasping devices. Various design aspects and parameters were taken into account to optimize the dynamic behavior of the mechanism in the simulation. The actions of the tendons were modelled with the forces that the tendon exerts on the phalanges.

Keywords: underactuated fingers, grasping devices, human hand, prosthesis

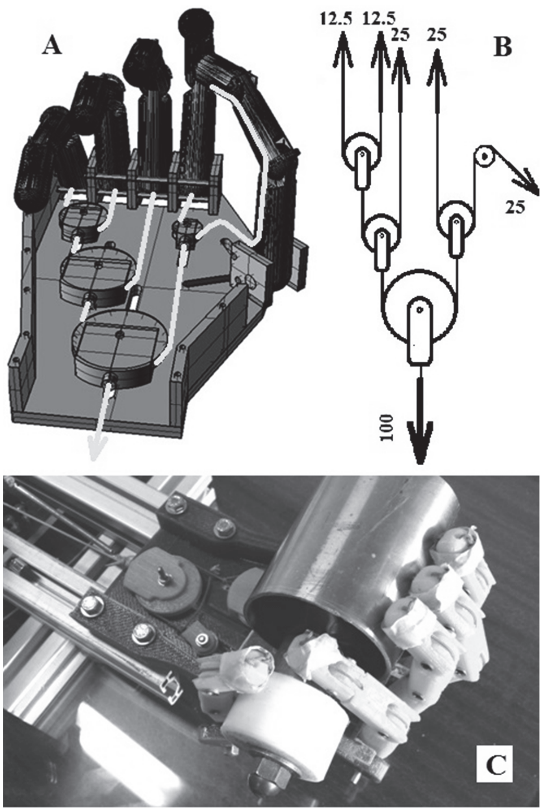

Fig. 1. Underactuated hand: A) CAD model. B) Differential system. C) Prototype.

1. Introduction

Over the last few decades, grasping devices based on the human hand have been widely studied and developed, both for robotic hands and for industrial and agricultural purposes [1–9]. Bicchi [10] attempted to summarize the evolution and state of the art in the field of robot hands.

Moreover, the availability of small, powerful, and lightweight actuators and servomotors has permitted the development of grasping devices in general and human hand prostheses in particular, with better performances than that of earlier ones [11–17].

Most of the mechanical hand prostheses are based on one of the following two main criteria:

- Adopting a rather small number of actuators, typically four or five [1, 2, 12–14].
- Adopting a single actuator with elastic extendable tendons [3, 4, 15].

Gosselin et al., instead, presented the design and experimental validation of a robotic hand anthropomorphically underactuated, with 15 degrees of freedom and a single actuator [18].

Another possibility was proposed by Brown and Asada 2007 [5]. They listed a series of human hand postures and used the principal component analysis to calculate the synergies between the fingers, and called these hand postures "eigenpostures." They presented a new mechanism design to combine the eigenpostures and drive a robot hand with 17 degrees of freedom and five fingers, using only two DC motors.

The authors of this paper developed a new mechanical hand, the Federica mechanical hand, based on a self-adaptive patented scheme (patents No.0001415546 and No.102015000059873, the latter pending) [19–22] and briefly described in **Fig. 1**, which shows a prototype and a CAD design depicting its working principle.

The device has been already presented in some papers [22], and thus we will provide a very concise description here. Essentially, it uses only one actuator and

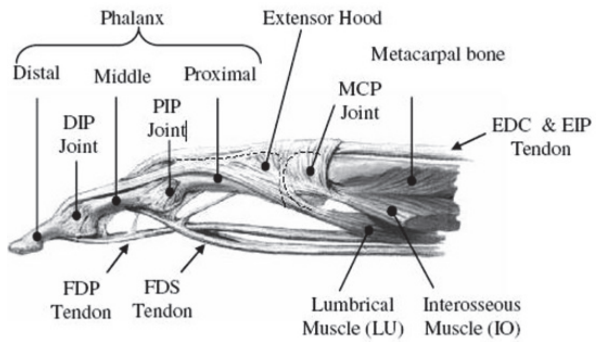

Fig. 2. The human finger.

un-extensible tendons, thanks to the differential mechanism shown in **Fig. 1**.

The device has some advantages that can be summarized as follows:

1. Since only one actuator is necessary, owing to the adaptive mechanism, it is particularly simple to control the device.
2. The grasping force can be controlled by just controlling the force exerted by the only actuator.
3. The inextensible tendons allow each finger to grab the object with a force that does not depend on the configuration of the finger or on the configuration of the other fingers. This does not always happen in the devices using extensible elastic tendons. In fact, when using the latter, the fingers having phalanges with higher relative rotations will exert a grasping force that is lower than that exerted by fingers having phalanges with lower relative rotations.

The device, that was conceived and developed by the authors, similar to most of the other devices makes use of underactuated fingers. For this reason, the finger design has been the object of several studies. This design implies that some parameters are critical for both the kinematic and the dynamic behavior of the finger itself and, consequently, for correct grasping. Many studies are aimed at obtaining a finger design that combines a reduced diversity of parts with the need to build five kinematically different fingers [23].

The finger behavior and the force that it can apply during grasping tasks are some of the most important aspects in the operation of mechanical hands, as evidenced by papers such as [24, 25].

This paper presents a study of the fingers used in the mechanical hand described above. In particular, the paper describes the design of the tendon system and the model developed to analyze the behavior of the finger.

2. The Finger Design

Figure 2 shows a human finger. As it is possible to observe, it has two flexor tendons for three phalanges, i.e., for three degrees of freedom. Therefore, the human finger is also underactuated.

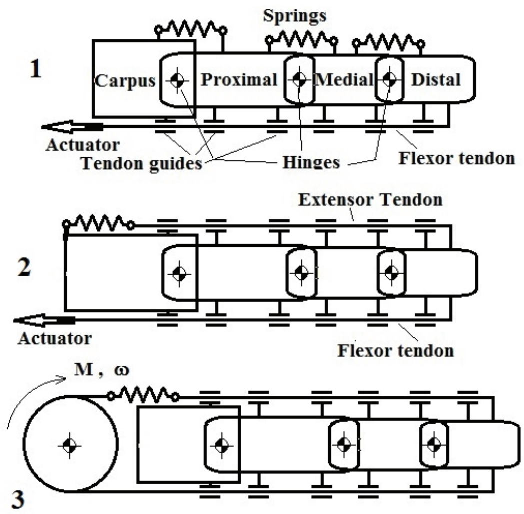

Fig. 3. Scheme of the finger model.

Like most prosthetic fingers, the device developed by the authors has only one flexor tendon. **Fig. 3** shows a scheme of the possible finger configurations.

Three possible solutions are reported:

1. One flexor tendon and three springs acting as the extensor tendon (upper part of the figure).
2. One flexor tendon and one extensor tendon; the latter is linked to a spring, which is linked to the carp (middle part of the figure).
3. One flexor tendon and one extensor tendon; both tendons are constituted by only one wire that is wrapped around a pulley moved by a motor. Along the extensor tendon, a spring is placed in order to compensate the different elongation of the extensor tendon in relation to the flexor tendon (lower part of the figure).

All the design solutions above were tested during the design and building of the early prototypes.

Solution 1 presents the advantage of being simpler; the springs can be made by relatively simple leaf springs. Nevertheless, it is the most problematic when it comes to obtain a correct sequence of the phalanges closure. As it will be shown in this study, this aspect is crucial for the correct working of the finger when grasping an object.

Solution 2 permits the achievement of a correct sequence of the phalanges closure easily. However, it presents some disadvantages, as will be shown later.

Solutions 1 and 2 present a common disadvantage: in order to rotate the phalanges, the actuator uses a part of its work to tighten the spring(s).

Solution 3 showed the most suitable behavior, with the three phalanges that wrap the objects. In addition, the spring is not significantly tightened since its function is merely to compensate the slightly different tendon elongations.

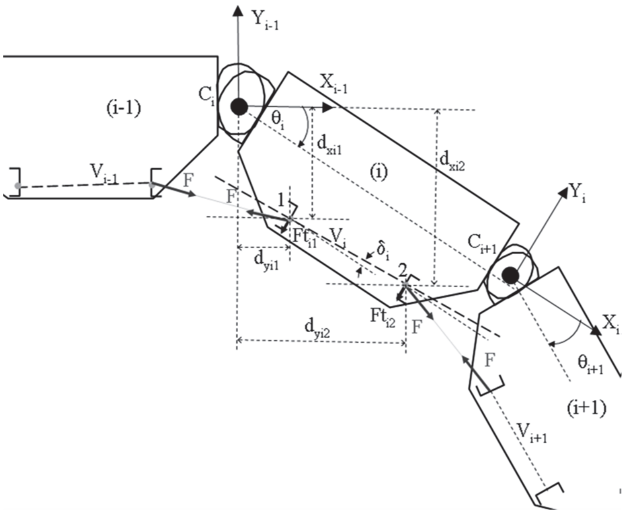

Fig. 4. Actions of tendon on a generic phalanx.

3. Simulation of Finger Dynamics

Because it is sub-actuated to a higher degree than the human finger (only one flexor tendon), the mechanical finger needs a correct design to obtain a correct rotation sequence of the phalanges, even when no object is grasped. A wrong sequence, in fact, does not permit to grasp anything at all, while a correct one makes it possible to grasp almost any object. This occurs whatever the orientation of the hand is (hence, for any direction of the weight of the phalanges) and, practically, whatever the orientation of the object is.

In general, during the finger flexure, the proximal phalanx must initially show the wider rotation, then the medial, and finally the distal. An initial wide rotation of the distal phalanx makes the finger "wrap" on itself somehow and the finger is not capable to grasp almost anything.

In the following results, this aspect will be clearly shown.

3.1. Action of the Traction Tendon

As described previously, some parameters play a significant role in the dynamic of the finger, and among these, the position of the tendon guides with respect to the phalanges and the hinges is crucial.

The action of the traction tendon, given by the tendon itself, permits the phalanges of the finger to be closed.

On each one of the phalanges, the action of the tendon is exerted at the entry and at exit of the seat of the tendon itself. In **Fig. 4**, these two points of the guide of the tendon are indicated as points 1 and 2. The components of the traction force F apply a torque on the hinge of the phalanx, as seen in **Fig. 4**. By means of geometric considerations, it is possible to determine the direction of the tendon in the points 1 and 2, the components of the traction force perpendicular to the tendon guideway direction Ft_{i1} and Ft_{i2}, and the distances d_{xi1}, d_{yi1}, d_{xi2}, and d_{yi2}, represented in **Fig. 4**.

The components of the forces Ft_{i1} and Ft_{i2} along the axis X_{i-1} and Y_{i-1} are the following:

$$\begin{cases} F_{i1}^x = Ft_{i1} \cdot \sin(\theta_i + \delta_i) \cdot \left(1 - contact^-(i)\right) \\ F_{i1}^y = -Ft_{i1} \cdot \cos(\theta_i + \delta_i) \cdot \left(1 - contact^-(i)\right) \\ F_{i2}^x = Ft_{i2} \cdot \sin(\theta_i + \delta_i) \cdot \left(1 - contact^-(i+1)\right) \\ \qquad + F \cdot \cos(\theta_i + \delta_i) \cdot \left(contact^-(i+1)\right) \\ \qquad \cdot \left(1 - contact^-(i)\right) \\ F_{i2}^y = -Ft_{i2} \cdot \cos(\theta_i + \delta_i) \cdot \left(1 - contact^-(i+1)\right) \\ \qquad + F \cdot \sin(\theta_i + \delta_i) \cdot \left(contact^-(i+1)\right) \\ \qquad \cdot \left(1 - contact^-(i)\right). \end{cases} \quad \ldots\ldots (1)$$

In Eq. (1), the function $contact^-(i)$ and $contact^-(i+1)$ indicate the achievement of the limit switches respectively for the phalanx (i) and for the phalanx ($i+1$). When a phalanx reaches its mechanical limit, the forces that acted on that phalanx are transferred to the preceding phalanx; therefore, each generic function $contact^-$ is equal to "0" when there is no contact with the mechanical limit and it is equal to "1" when there is contact with it.

If the torque on the hinge (i) is CF_i, it is possible to write:

$$CF_i = -F_{i1}^x \cdot d_{xi1} + F_{i1}^y \cdot d_{yi1} - F_{i2}^x \cdot d_{xi2} + F_{i2}^y \cdot d_{yi2}. \quad (2)$$

In the latter equation, angles θ_i and δ_i are, respectively, the rotation angle of phalanx (i) and the angle between the direction of the traction tendon guide and the direction of the X_{i-1} axis.

The signs of the relationship Eq. (2) are determined by the convention that was chosen for the positioning of the frames.

Hence, observing Eq. (2), it is possible to understand that the closure sequence of the finger can be optimized by setting adequate distances d of the tendon guides from the hinges.

3.2. Action of the Antagonist Tendon

The antagonist tendon is opposed to the traction tendon action and it allows the finger to return to an extended configuration, as shown in **Fig. 5**. This tendon is fixed to the last phalanx, the distal one, and it flows through guides positioned on the upper side of the finger. The medial and the proximal phalanges end with a pulley on which the antagonist tendon wraps itself. Therefore, the actions that the antagonist tendon generates are different for the distal phalanx and for the medial and proximal phalanges.

On the distal phalanx the action of antagonist tendon has the direction x and a value FR, and its point of application is the tendon attachment point, as seen in **Fig. 5**.

On the medial and proximal phalanges, the action of the antagonist tendon has a direction that depends on the rotation angle of the successive phalanx and its point of application is in the hinge of the successive phalanx.

Equation (3) describes the antagonist tendon actions on

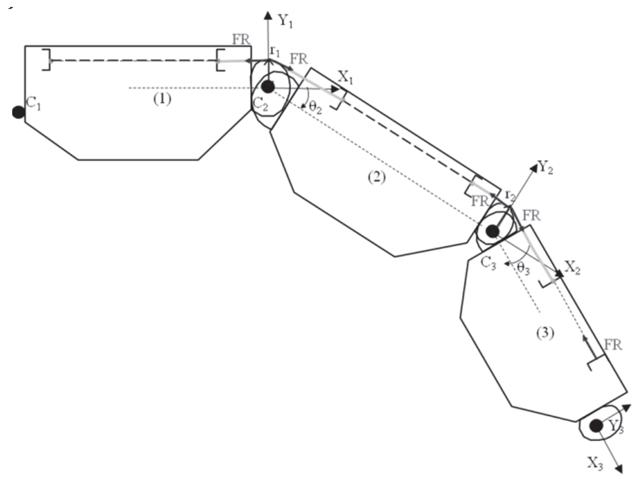

Fig. 5. Action of the antagonist tendon.

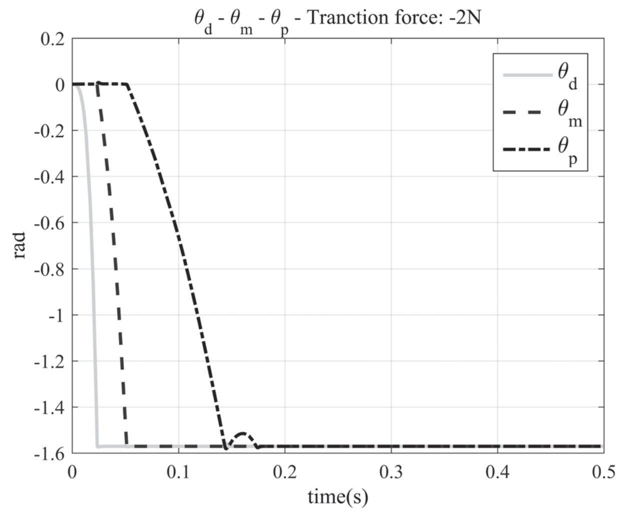

Fig. 6. Simulation results; $d_y = 0.0045$ m.

Table 1. Parameters of model with different phalanges.

Phalanx	Parameters	
	Mass [kg]	***Length [m] – distance between previous and next hinge***
proximal	0.01	0.045
medial	0.0055	0.030
distal	0.0030	0.025

the three phalanges.

$$\begin{cases} F_{A3x} = FR; \;\; F_{A3y} = 0 \\ F_{A2x} = FR(1-\cos\theta_3); \;\; F_{A2y} = FR\sin\theta_3 \\ F_{A1x} = FR(1-\cos\theta_2); \;\; F_{A1y} = FR\sin\theta_2 \end{cases} \quad . \quad (3)$$

where;

- F_{Aix} is the component of the action of the antagonist tendon on phalanx i in direction x;
- F_{Aiy} is the component of the action of the antagonist tendon on phalanx i in direction y;
- θ_i is the rotation angle of phalanx (i);
- FR is the action of antagonist tendon.

3.3. Closure Sequence of the Finger

By studying the dynamical equilibrium of each phalanx, it is possible to analyze the dynamic behavior of the finger during a closing task in function of the above parameters.

Hereafter, the results of the dynamical equilibrium of the finger with three different phalanges, whose parameters are similar to those of a human finger, are reported. The parameters of the finger are listed in **Table 1**.

The traction tendon guides in the three phalanges are aligned, as well as the hinges, and thus the distance from the hinges along the Y-axis of the start and the end of the guide, in each phalanx, is constant, and its value is 0.0045 m.

The stiffness and damping, with which the forces of the mechanical stops can be calculated, were estimated with a simulation, assuming values able to ensure that the phalanges do not exceed their stop positions of 0.005°

Figure 6 shows the behavior of the three phalanges when a traction force of 2 N is applied, with a linear law with respect to time from 0 to 2 N in 0.02 seconds.

The phalanges have a precise closing sequence: first the distal phalanx; then, when this has reached the limit, the motion of the medial one starts, until this last reaches its limit and the proximal phalanx starts. The closing sequence is d-m-p: distal-medial-proximal.

In order to modify the dynamic sequence of closure of the finger phalanges, it is necessary to modify the torques that act on the phalanges. This was made by keeping constant the traction force and by varying the geometrical position of the start and end of the guide of the traction tendon. Therefore, the torque that acts on each phalanx can be varied with the same traction force, and the closing sequence is modified.

Some simulations were carried out by changing the distances from the hinges, along the Y-axis, of the start and end of the guide. Another parameter that can be changed to analyze the closing sequence of the phalanges is the starting angle and the mechanical stop of each phalanx. In the previous simulations, this angle was 0° for all phalanges, but if there is a starting angle different from 0°, the torque that acts on the phalanx changes, and the phalanx itself can start to move earlier. Henceforth, the results are reported.

By changing both parameters, it is possible to modify the dynamical behavior of the finger by changing the closing sequence of the phalanges.

In **Fig. 7**, the distance of the guides from the hinges along the Y-axis of all phalanges is 0.003 m and the starting angles are $-20°$ for the proximal phalanx, $-10°$ for the medial phalanx, and 0° for the distal phalanx. It is possible to observe a different closing sequence of the phalanges, which is m-p-d: medial-proximal-distal.

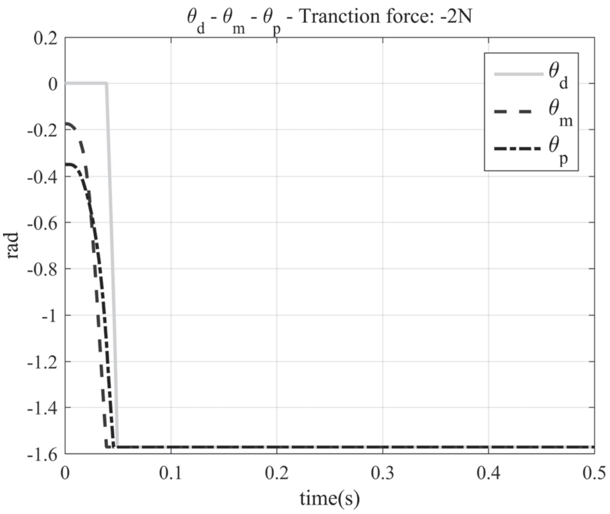

Fig. 7. Simulation results; $d_y = 0.003$ m.

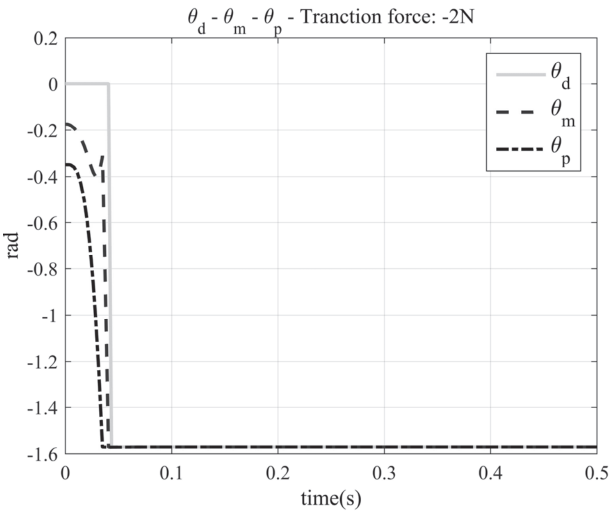

Fig. 8. Simulation results; $d_y = 0.0025$ m.

In **Fig. 8**, the distance of the guides from the hinges along the Y-axis of all phalanges is 0.0025 m and the starting angles are $-20°$ for the proximal phalanx, $-10°$ for the medial phalanx, and $0°$ for the distal phalanx.

With these parameters, there is a different closing sequence of the phalanges, which is p-m-d: proximal-medial-distal.

This closing sequence of the phalanges is better suited to all kinds of gripping operations.

The results of this simulation were particularly useful for choosing the design parameters of a mechanical hand prototype using underactuated fingers implemented with tendons.

4. Finger Models

To analyze the dynamics of the finger, some models of the finger itself were developed. In this paper, two models, 2D and 3D, are presented.

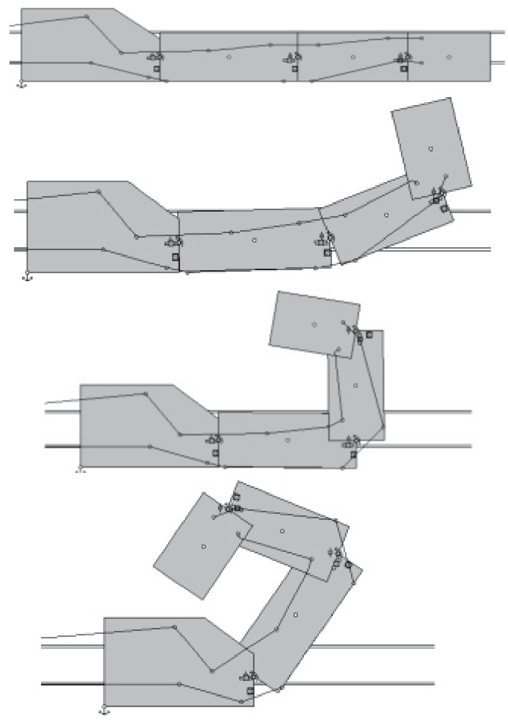

Fig. 9. Finger model with incorrect parameters.

4.1. 2D Model

In **Figs. 9**, **10**, and **11**, different configurations of a 2D finger model are reported. The model consists in rigid bodies linked with hinges.

In **Fig. 9**, a model with an incorrect design of the above-mentioned parameters is shown.

In the figure, the early wide rotation of the distal phalanx and its consequences are clearly shown.

In **Fig. 12**, the positions of the centers of the phalanges from the carpal hinge are reported non-dimensionalized with respect to the finger length.

After a number of simulations, a correct choice of tendon parameters and hinges positions could be made. In **Fig. 10**, a correct closing sequence is shown, and **Fig. 13** displays the trajectories equivalent to those in **Fig. 10**.

With a good choice of the parameters, grasping tests of objects were performed.

In **Fig. 11**, an example of those tests is reported. The model of the finger is that reported in **Fig. 10**, while the object consists in a circular rigid body, representing the section of the object in the plane of motion of the finger. This circular body is linked to fixed points by means of two orthogonal links, each one consisting of a spring and a damper, in order to simulate the possibility that the object or the hand moves during the grasping action.

The tendons scheme is that reported as solution 3 in **Fig. 3**. The pulley was simulated by means of two linear actuators (A and B in the figure) having equal and opposite laws of motion.

It is possible to observe the correct wrapping of the object by the finger phalanges, even if the relative positions of the object and the hand change during the grasp task.

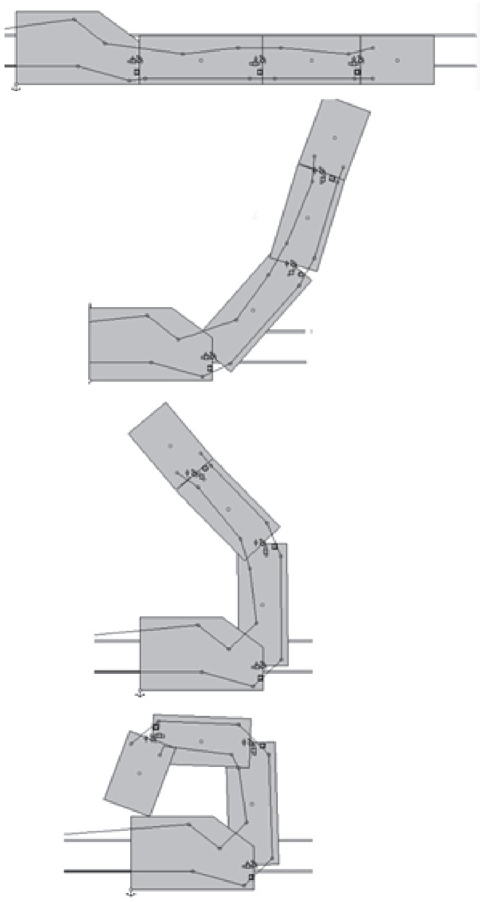

Fig. 10. Finger model with correct closing sequence.

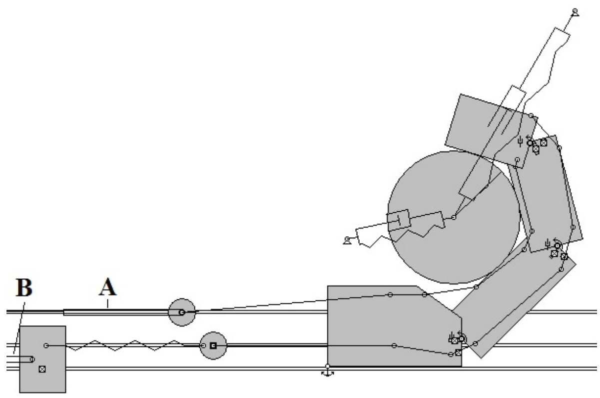

Fig. 11. Grasping simulation.

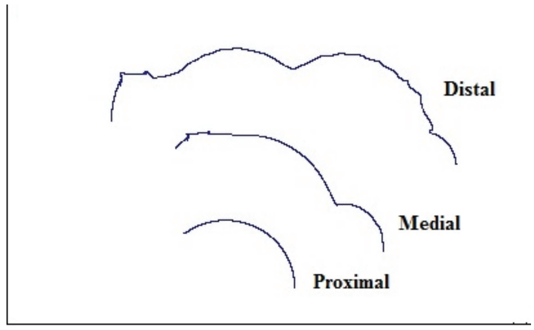

Fig. 12. Trajectories of the centers of the phalanges for a not correct closing sequence of the finger.

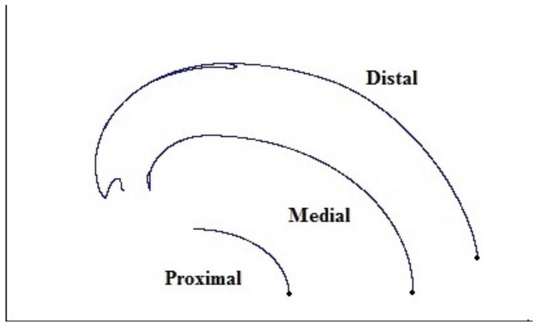

Fig. 13. Trajectories of the centers of the phalanges for a correct closing sequence of the finger.

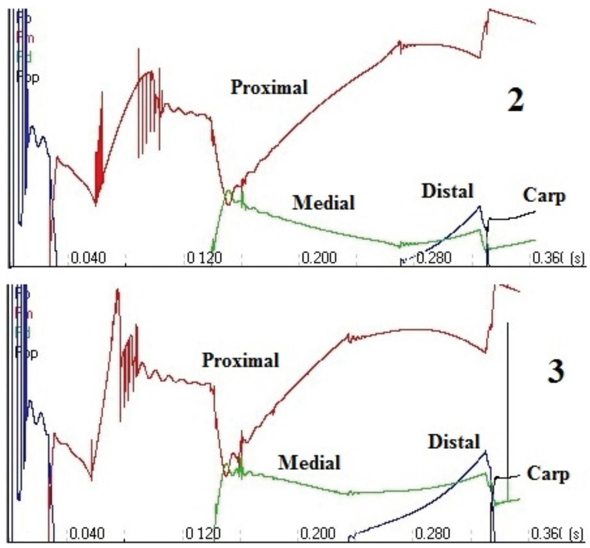

Fig. 14. Contact forces between phalanxes and grasped object.

Finally, the different behavior of the solutions 2 and 3 reported in **Fig. 3** were simulated.

In **Fig. 14**, the contact forces between each phalange and the grasped body during the grasping action are reported non-dimensionalized with respect to the flexion tendon force.

As it is possible to observe, solution 3 generally permits a higher contact force between the object and the phalanges, especially with respect to the distal one.

Figure 15 represents the force exerted by the tendon:

- Curve 2 is the force exerted by the flexion tendon for solution 2 in **Fig. 3**.
- Curve 3 is the force exerted by the flexion tendon minus the force exerted by the extension tendon for solution 2 in **Fig. 3**; this force multiplied by the pulley radius, represents the torque on the pulley.

As it is possible to observe, solution 3 implies a considerably lower actuator work with the same grasping forces.

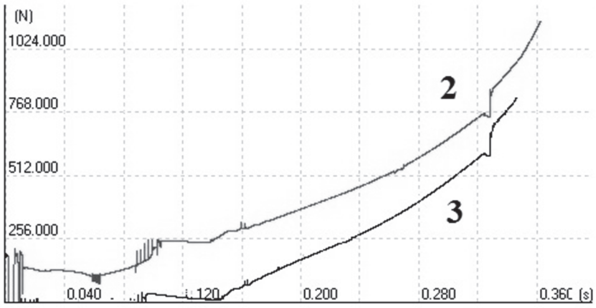

Fig. 15. Tendon force during the grasping task.

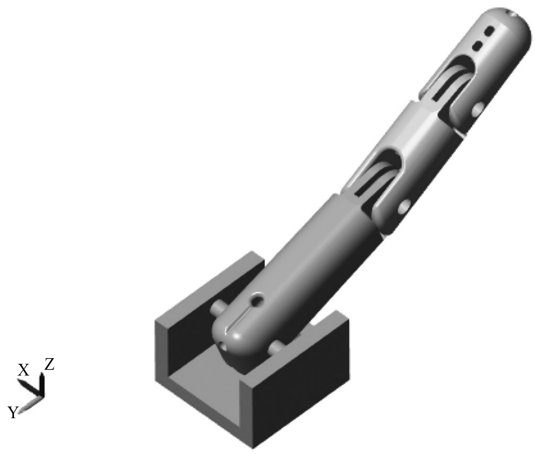

Fig. 16. 3D multibody finger model.

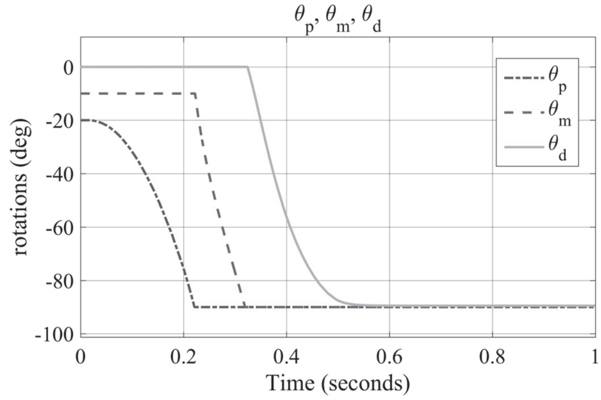

Fig. 17. Rotation angles of the three phalanges. Antagonist tendon with spring element stiffness of 2.8 N/mm.

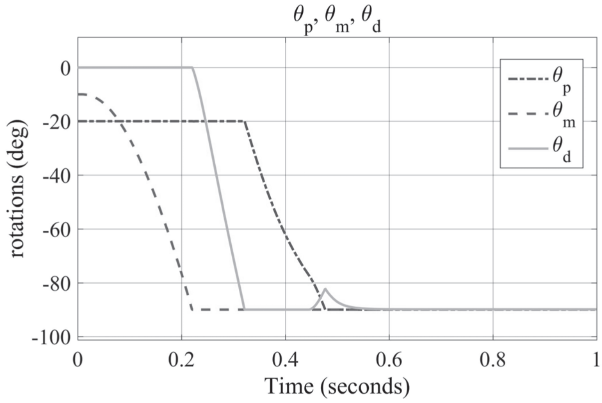

Fig. 18. Rotation angles of the three phalanges. Antagonist tendon with spring element stiffness of 0.5 N/mm.

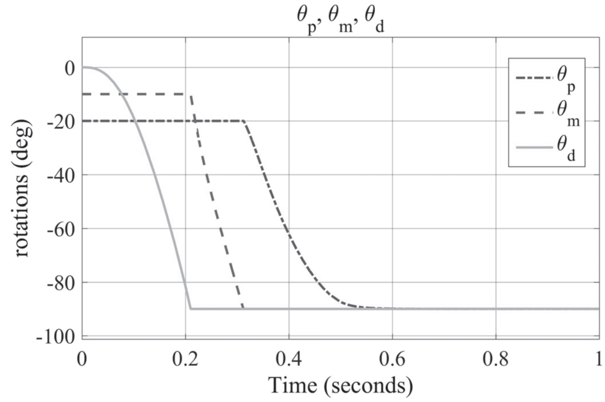

Fig. 19. Rotation angles of the three phalanges. Antagonist tendon with spring element stiffness of 0.1 N/mm.

4.2. 3D Model

A 3D multibody model, whose tendons scheme is that reported as solution 3 in **Fig. 3**, is shown in **Fig. 16**.

By means of this model, it was possible to analyze the dynamic behavior of a real underactuated mechanical finger. In fact, the components of this model were prototyped.

The 3D model allowed determining the definitive values of all parameters that characterize the dynamic behavior of the finger.

One of the most interesting results obtained using this multibody model, is the analysis of the behavior of the finger, as a function of the stiffness of the elastic element of the antagonist tendon.

The antagonist tendon is connected to the same motor of the actuator tendon, as given in solution 3 of **Fig. 3**. This makes it possible to exercise complete control on the actuator tendon displacement. It is necessary to introduce an elastic element, in order to not obstruct the different elongations of the two tendons, actuator and antagonist. If the presence of an elastic element is not considered, the finger stops when the elongation of the antagonist tendon is greater than that of the actuator tendon. The stiffness value of the elastic element causes a different behavior of the finger. An extremely large stiffness of the elastic element of the antagonist tendon stops the rotations of the phalanges like an inextensible tendon. With a stiffness $k = 2.8$ N/mm, the elongation of the antagonist tendon can be greater than the elongation of the traction tendon, and the finger can complete its closing sequence. In **Fig. 17**, it is possible to observe the rotation angles of the three phalanges during a closing task. It can be seen that the closing sequence is of the type p-m-d, which, as described before, is the most suitable for grasping tasks.

In **Figs. 18** and **19**, the results with stiffness $k = 0.5$ N/mm and $k = 0.1$ N/mm, respectively, are shown.

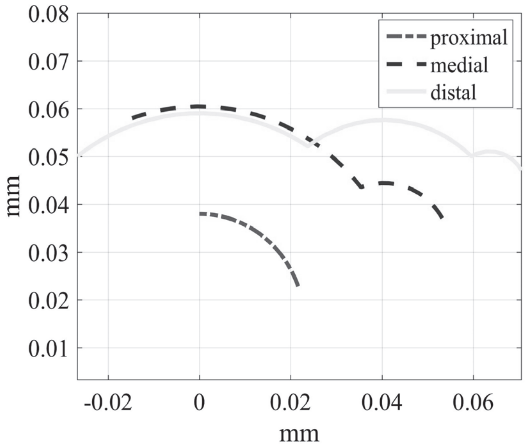

Fig. 20. Trajectories of the centers of the phalanges. Antagonist tendon with spring element stiffness of 0.1 N/mm.

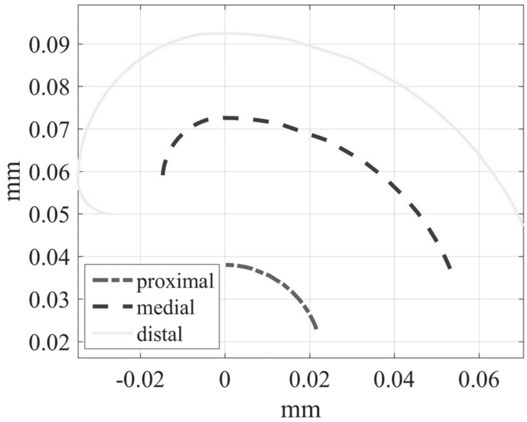

Fig. 21. Trajectories of the centers of the phalanges. Antagonist tendon with spring element stiffness of 2.8 N/mm.

It is possible to observe that the behavior of the finger changes with different k. In particular, the closing sequence becomes m-p-d and d-m-p, respectively.

Figures 20 and **21** show the trajectories of the centers of the phalanges during the closing task with different values of k. In particular, in **Fig. 20**, $k = 0.1$ N/mm and the diagram is similar to that obtained in **Fig. 12**, while in **Fig. 21**, $k = 0.5$ N/mm and the diagram is similar to that obtained in **Fig. 13**.

5. Experimental Results

In order to verify the results of the simulations, in particular the different closing sequences of the single finger, we built a prototype to carry out some tests.

In **Fig. 22**, a picture of the finger is shown. Both tendons are clearly visible.

In **Fig. 23**, the whole test rig is shown. It is essentially composed of the finger with the tendons and a pulley moved by a digital servomotor. The latter was controlled using an Arduino™ board and the block "Standard Servo Write."

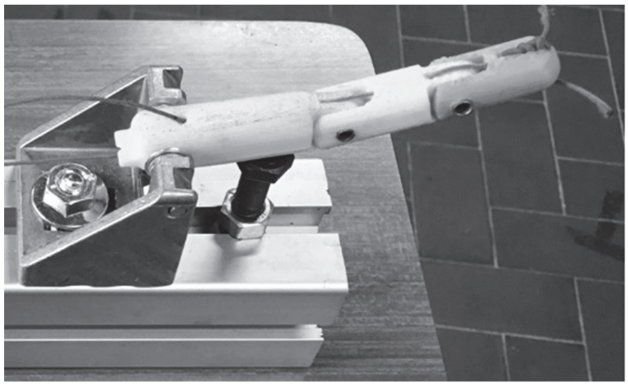

Fig. 22. Single finger prototype.

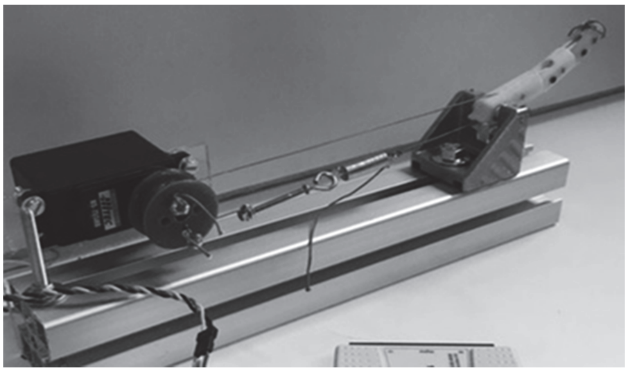

Fig. 23. Test rig of the single finger prototype.

The signal from the servo motor potentiometer was acquired in order to ensure that the servomotor law of motion was the one we had imposed; in addition, a video clip was recorded and processed with MATLAB in order to detect the closing sequence of the phalanges.

We were able to see clearly the two sequences:

1. Distal-medial-proximal, d-m-p
2. Proximal-medial-distal, p-m-d

In both tests, we used a servomotor law of motion that foresees a 30 mm tendon displacement in 3 s.

Sequence 1 is shown in **Fig. 24**.

The marked trajectories of the centers of each of the phalanges show a good agreement with those obtained in the simulations and reported in **Figs. 12** and **20**. It can be observed that in the experimental tests the proximal phalanx started to move before the medial phalanx stopped its motion, due to inevitable friction phenomena. For this reason, the trajectories of the distal and medial phalanges are slightly different from those shown in **Figs. 12** and **20**.

In **Fig. 25**, the test results of sequence 2 are shown.

In this case, the agreement between the experimental and simulation results of **Figs. 13** and **21** is evident.

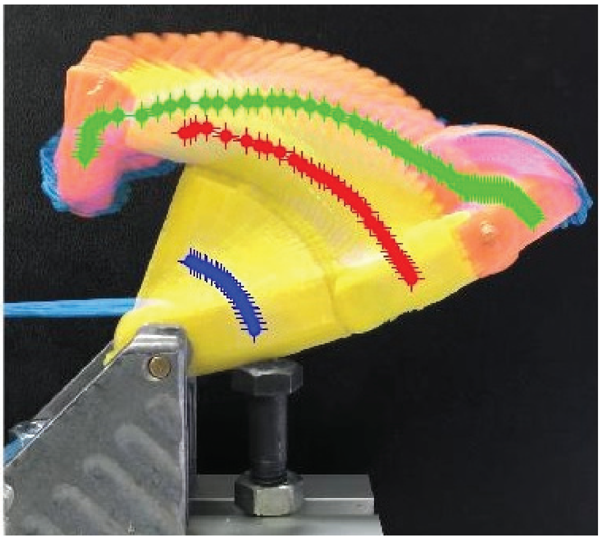

Fig. 24. Closing sequence 1.

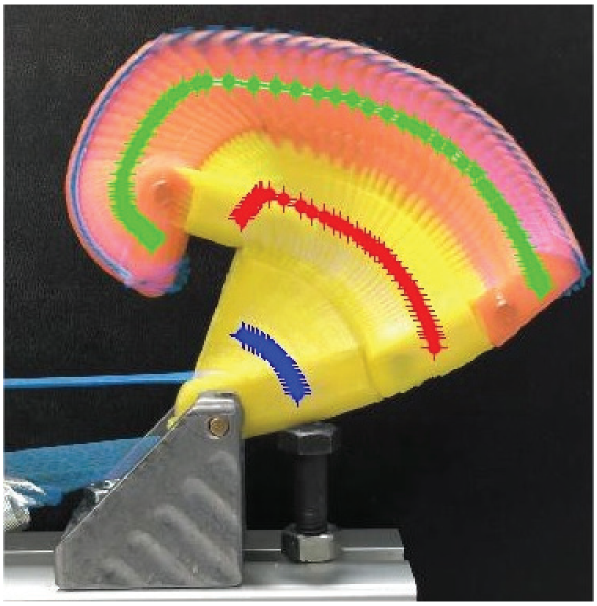

Fig. 25. Closing sequence 2.

6. Conclusion

This paper presents a study on an underactuated mechanical finger, highlighting the influence of the tendon system design on the behavior of the finger itself. The study was carried out using simulations of a multibody model and by experiments.

Essentially, the following results were obtained:

- A correct finger and tendon design is crucial to obtain correct grasping by an underactuated finger.
- The correct phalanges motion sequence is: proximal-medial-distal.
- The "closed circuit" tendon solution, shown in diagram 3 of **Fig. 3**, is the most advantageous one.
- Simulation results obtained by a multibody code are confirmed by the test results.

This last aspect permits the saving of a considerable amount of time when designing such devices. It also confirms the usefulness of the multilink codes, which were successfully used by the authors for studying several mechanical systems, ranging from ancient machines [26] to grasping devices [27–30], and for studying the possibility of applying a vision system into the analysis of the above presented mechanical systems [31, 32].

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