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An Anthropomorphic Underactuated Robotic Hand with 15 Dofs and a Single Actuator

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Abstract— **This paper presents the design and experimental validation of an anthropomorphic underactuated robotic hand with 15 degrees of freedom and a single actuator. First, the force transmission design of underactuated fingers is revisited. An optimal geometry of the tendon-driven fingers is then obtained. Then, underactuation between the fingers is addressed using differential mechanisms. Tendon routings are proposed and verified experimentally. Finally, a prototype of a 15-degree-of-freedom hand is built and tested. The results demonstrate the feasibility of a humanoid hand with many degrees of freedom and one single degree of actuation.**

I. INTRODUCTION

Over the last decades, numerous research initiatives addressed the challenge of designing and building versatile robotic hands. Pioneer designs include: the Utah/MIT hand [1], the Stanford/JPL (Salisbury's) hand [2], the DLR hands [3], the Okada hand [4] and several others. As pointed out by many authors, such a design exercice involves finding a compromise between versatility and simplicity in order to obtain relevant practical systems [5].

In order to reach an ideal compromise, one approach consists in reducing the number of degrees of freedom, thereby decreasing the number of actuators. Examples of hands based on this philosophy include the SSL hand [6], the DIES-DIEM hand [7], the Cassino finger [8], the Belgrade/USC hand [9], the TBM hand [10], and the KIST gripper [11] (based on a deformable-platform parallel manipulator). Although reducing the number of degrees of freedom reduces the complexity, it also significantly affects the versatility of the hands.

Another approach consists in using a small number of actuators without decreasing the number of degrees of freedom. In other words, fewer actuators than degrees of freedom are included in the design. A possible implementation of this principle consists in actuating the dofs in sequence with the help of clutches, such as in the hands from Nanyang University [12] with one actuator (but seven clutches) and such as in the UPenn Hand [13]. However, the use of clutches makes these systems still relatively complex.

Another possible implementation of the above concept, commonly referred to as *underactuation*, can be obtained through the use of passive components such as springs and mechanical limits. This approach leads to a mechanical adaptation of the hand to the shape of the object to be grasped. Several underactuated hands have been proposed in the literature — see for instance [14], [15], [9], [16], [17]. Underactuation in grasping is also sometimes referred to as *mechanical intelligence* [13], [18] because it leads to automatic adaptation to the shape of the grasped objects without requiring sensors or complex control.

With the recent advances in humanoid robotics, there is a strong need for anthropomorphic hands — i.e. with 4 fingers and a thumb arranged as in a human hand — that are light, compact, easy to control and yet versatile enough to grasp a broad variety of objects. Considering the current state of the art of actuator and sensor technology, underactuation can be considered as one of the most promising avenues for the development of such hands.

In this paper, the design of an anthropomorphic underactuated robotic hand with 15 dofs and a single actuator is addressed. The objective of this work is to investigate the possibility of building a versatile hand with one single actuator. In other words, the objective is to push the concept of underactuation to its limit in order to assess its applicability in humanoid robotics. However, it should be pointed out that although the general characteristics of the hand designed here are anthropomorphic, it is not intended to perfectly replicate the human hand, as opposed to what is as proposed in [19].

This paper is organized as follows: first, the force transmission analysis and optimization of the fingers is presented. Then, differential mechanisms are introduced in order to produce the underactuation between the fingers. Other design issues are also addressed. Finally, the prototype is described and preliminary experimental results are presented.

II. FORCE TRANSMISSION DESIGN OF THE FINGERS

Before addressing the global design of the hand, the fingers are first considered. In order to grasp objects by making contact with the phalanges (not only the tip of the fingers), underactuated three-phalanx fingers are used in this design. In other words, a single tendon is used to close a given finger. The finger is normally open and its opening motion is ensured by springs included in the joints. This approach is typical of tendon-driven fingers found in the literature. Tendons are used in order to provide a compact and light transmission between the actuator and the phalanges.

Since the objective of this project is to design an anthropomorphic hand, the length (and hence the ratio) of the different phalanges are determined *a priori*, using anthropometric data. The dimensions of the index finger were established as follows: the length of the proximal phalanx is 45 mm, the

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length of the middle phalanx is 25 mm and the length of the distal phalanx is 15 mm. The width of the phalanges is set to 15 mm. The other fingers of the hand are obtained by scaling the length of the index finger while using the same width for all fingers.

A. Static Modelling of the Fingers

One of the key issues in the design of the fingers is their force transmission characteristics [20]. According to the latter reference, the force transmission between the actuator — here the force on the tendon at the base of the finger — and the contact forces on the phalanges can be written as:

$$\mathbf{f} = \mathbf{J}^{-T}\mathbf{T}^{-T}\mathbf{t} \tag{1}$$

where $\mathbf{f} = [f_1, f_2, f_3]^T$ is the vector of phalanx normal contact forces with the object, matrix $\mathbf{J}$ is a lower triangular matrix characteristic of the contact locations — and friction, if modelled — referred to as the Jacobian matrix of the finger, matrix $\mathbf{T}$ is the transmission matrix characterizing the transmission used (here a tendon) and its geometry — position of the guides — and vector $\mathbf{t} = [T_a, T_2, T_3]^T$ is the vector of actuating torques at the joint, namely the torque T_a produced by the tendon on joint 1 and the elastic torques produced by the springs on joints 2 and 3, namely T_2 and T_3. The analytical expression of the matrices defined above can be found in [21] for linkage-driven fingers and tendon-driven fingers.

Using (1), it is possible, for a given posture of the finger and a given contact situation, to determine the contact forces on the phalanges and therefore assess the force transmission characteristics of the finger. The latter will depend on the geometry of the transmission, namely the position of the tendon guides on the phalanges. The geometric parameters associated with the guides are represented schematically in Fig. 1. Parameter d_i represents the distance from the pivot of phalanx i to the tendon guide located on phalanx i while angle ϕ_i represents the angle between the central axis of phalanx i and the line connecting the centre of joint i and the guide mounted on phalanx i.

B. Optimization of the Geometric Parameters

As mentioned above, (1) can be used to determine the contact forces. Therefore, it is possible to calculate the contact forces as a function of the geometric parameters for a given configuration. One has:

$$f_i = f_i(d_1, d_2, d_3, \phi_1, \phi_2, \phi_3), \qquad i = 1, 2, 3 \tag{2}$$

and the latter equation can be repeated for a series of contact situations corresponding to typical grasps. Similarly to what was proposed in [17] and [22], the analysis is performed on a series of circular objects of different radii and different positions with respect to the base of the finger. If m different grasping configurations are considered[1], the contact force on the ith phalanx of the jth grasping configuration is noted f_{ij}.

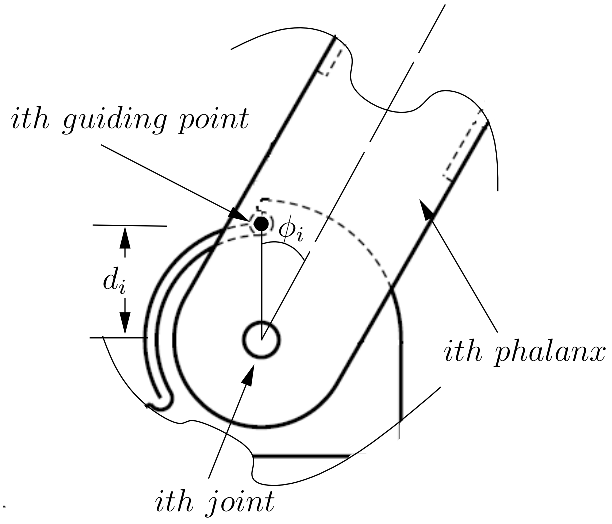

Fig. 1. Geometric parameters defining the position of the tendon guides.

The optimization of the geometric parameters is then performed by maximizing an objective function, η, defined as follows:

$$\begin{aligned}
\eta_1 &= \frac{1}{m}\sum_{i=1}^{m} \mathbf{g}_i^T \mathbf{W} \mathbf{g}_i && (3)\\
\eta_2 &= \frac{1}{m}\sum_{i=1}^{m} \left[\frac{f_{1i} + f_{2i} + f_{3i}}{\max(f_{1i}, f_{2i}, f_{3i})}\right] && (4)\\
\eta_3 &= 1 \quad \text{or} \quad 0 && (5)\\
\eta &= \eta_1^2 \eta_2 \eta_3 && (6)
\end{aligned}$$

where $\mathbf{g}_i$ is the net reaction force on the object produced by phalanx forces f_{1i}, f_{2i} and f_{3i} in the ith grasping configuration and $\mathbf{W}$ is a weighting matrix. Performance index η_1 represents the magnitude of the force applied on the object by the finger (with a weighting factor between the components used to grant more importance to forces directed towards the palm and the thumb). This index is used in order to obtain fingers that can correctly resist to external forces on the object from any direction. Performance index η_2 is used in order to obtain fingers in which the distribution of the forces among the phalanges is as uniform as possible, thereby avoiding large local forces on fragile objects. Finally, performance index η_3 is equal to 1 when the grasp is successful and to 0 if there is ejection of the object. Indeed, incorrectly designed underactuated fingers can roll under the object and eject it [20].

Finally, the optimization problem is written as:

$$\max_{(d_1,d_2,d_3,\phi_1,\phi_2,\phi_3)} \eta \tag{7}$$

and the latter problem is solved numerically using a constained gradient-based technique. Constraints are used to

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[1] In this work 6 different sizes of circular objects lying on the same surface are used for the optimization. The diameter of the circles vary from 40 mm to 90 mm, which covers the expected size of objects to be grasped with an enveloping grasp.

TABLE I

OPTIMAL PARAMETERS OF THE FINGERS.

d_1	d_2	d_3	ϕ_1	ϕ_2	ϕ_3
10.5 mm	4.5 mm	2.5 mm	30^o	45^o	45^o

ensure that the guiding points are located on the physical phalanges. The optimization converges to a solution that provides the geometric parameters associated with the guiding points of the tendon on the phalanges. The final design of the finger is shown in Fig. 2. The final results are given in Table I.

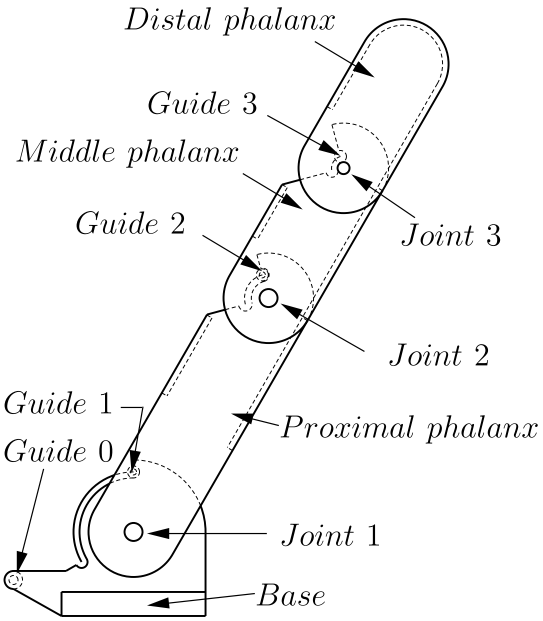

Fig. 2. Final geometric design of the finger.

C. Design of the thumb

The kinematic architecture of the thumb is distinct from that of the other fingers. In addition to the 3 degrees of freedom of the other fingers, the thumb includes one dof for abduction. This dof is not actuated and can be locked in a preferred position. This is so that the geometric design of the thumb emulates the human thumb. In principle, the planar optimization procedure used in the preceding subsection for the other fingers cannot be applied directly to the thumb because of its spatial motion. However, in practice, the closing motion of the thumb is taking place in a plane and the results given above are therefore used for the last three degrees of freedom of the thumb. Based on experimentation, the abduction motion of the thumb was locked in a configuration that brings the thumb in opposition with the index and middle finger.

III. UNDERACTUATION BETWEEN THE FINGERS

As pointed out in the introduction, one of the objectives of this work is to investigate the possibility of building an anthropomorphic robotic hand that can be driven by a single actuator. To this end, the fingers designed in the preceding section must be driven commonly, i.e., underactuation must be introduced between the fingers and not only within each finger. Although using a single actuator is clearly an oversimplification of the actuation paradigm of the human hand [23], [24], it is an assumption that may lead to results that are applicable in practice. It is also recalled that one of the objectives of this work is to explore extreme cases of underactuation, a concept that should not be confused with the kinematic coupling (or synergy) studied in [24].

Several mechanical principles can be used to provide underactuation between different fingers [25]. One mechanism that is commonly used in tendon-driven hands is the so-called ‘sliding pulley’. This mechanism allows the force provided by one tendon to be distributed evenly among two outputs. Cascading such mechanisms then allows the distribution of an actuating force between a series of fingers.

In the design of the differential mechanism used to perform the underactuation between the fingers, the challenge is to obtain a cascade of sliding pulleys that will produce the proper force distribution between all of the fingers. Since the thumb is opposing the other fingers, it should be capable of producing a larger force, that is a force equivalent to the sum of the forces from the fingers. Therefore, the first sliding pulley divides the force equally between the thumb and all the other fingers. Then, the force is divided equally between the remaining fingers using two other stages of sliding pulleys. As a result, in principle 50 % of the actuation force is applied to the thumb and 12.5 % of the actuation force is applied to each of the other fingers. This is shown in Fig. 3 where the corresponding tendon routing is illustrated.

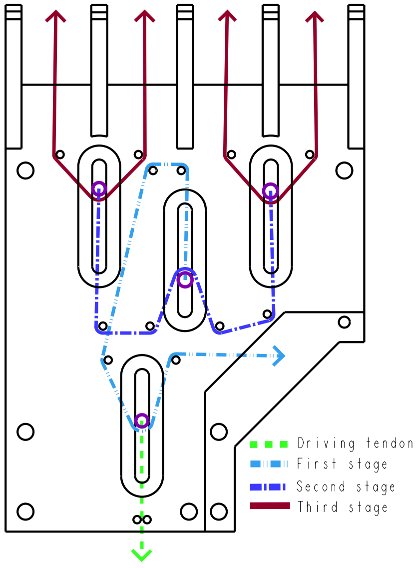

Fig. 3. Tendon routing in the first version of the hand.

In a first prototype of the hand, the tendon routing described above was implemented. However, experiments performed with this prototype showed that the system of distribution of the forces was not adequate. Due to the friction forces in the tendon system distributing the forces between the fingers, the thumb was closing too easily and the grasping was not always completed properly. The excessive friction can be explained by the numerous stages of sliding pulleys and the additional routing needed to compact the system so that it can be included in the palm.

In order to improve the behaviour of the hand, the routing of the tendons was modified. In the modified scheme, the underactuation between the thumb and the other fingers is eliminated. Indeed, the tendon driving the thumb is directly attached to the first sliding pulley. The other fingers are driven through two stages of sliding pulleys. Hence, it is noted that the second version of the hand has in fact only 14 dofs. This is illustrated in Fig. 4. Since the underactuation between the thumb and the other fingers is lost, the closing of thumb and the fingers is synchronized, which tends to push the object towards the centre of the hand. In prosthetic applications, the position of the object relative to the hand is not fixed because the user provides compliance. Assuming that the object is free to move relative to the hand, 50 % of the actuation force is directed to the thumb and 50 % to the four fingers. Once the grasp is performed, if the object is pushed towards the fingers, for example by gravity, the actuation force directed to the fingers will increase and the force directed to the thumb will decrease. This variable distribution of the forces provides stability with respect to external forces. Therefore, the underactuation between the thumb and the opposed fingers is not necessary. In fact, the resulting coupling even leads to some advantages. Finally, because the routing of the tendons is simpler, friction is reduced.

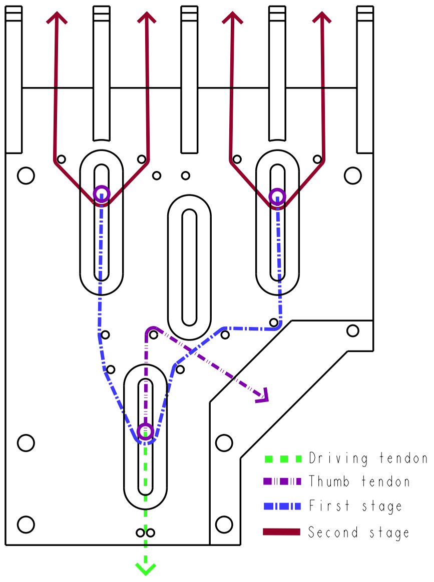

Fig. 4. Tendon routing in the second version of the hand.

IV. DESIGN ISSUES

Several practical design issues must also be considered in order to obtain a proper behaviour of the hand. First, the tendons used must be very stiff and provide low friction when sliding. In the prototypes built during the course of this work, the tendons used were stiff kite cables, which provide high stiffness, flexibility and low friction.

The radius of the pulleys and pins around which the tendons are guided should also be sufficiently large to avoid large friction forces. In the prototypes developed in this work, a minimum radius of 1 mm was used.

Since the hand is underactuated, springs and mechanical limits are used to maintain the fingers normally open. The springs should be as soft as possible in order to limit the actuation forces required to compress them. They should only be sufficiently stiff to provide the opening motion.

It should be pointed out that the prototypes developed in the course of this work were built of plastic using rapid prototyping (Fused Deposition Modelling). This technique allowed the fabrication and demonstration of the prototypes within a short period of time. The different components of the hands were built separately and then assembled. The critical components (e.g. the guiding pins) are made of metal.

The coefficient of friction of the plastic is very low. Therefore, in order to increase the stability of the grasps against external forces, rubber padding was added on the contact surfaces of the fingers.

Finally, the prototypes developed were equipped with a handle in order to provide manual actuation of the hand. By pressing on the handle, a user can then provide the single input actuation force and test the hand on a variety of objects. This principle made the testing and demonstration of the hand simple and effective. The stroke of actuation as well as the stroke of the sliding pulleys is 25 mm for the full closing of the fingers and thumb.

V. EXPERIMENTAL VALIDATION

The final prototype of the underactuated hand is shown in Fig. 5. The mass of the hand, including the handle, is approximately 0.4 kg. In Fig. 6, a series of examples of grasps that were performed with the anthropomorphic underactuated hand are shown. The grasps are generally firm and stable and have a human-like appearance. The hand performed well for enveloping grasps, which involve contact with all the phalanges. However, the hand often performed poorly with pinch grasps of small objects, which involve contact with only the tip of the fingers.

As for any hand using underactuated fingers, the forces involved in a grasp significantly vary depending on the size and shape of the object. However, in order to give a general idea of the forces involved, the forces on a grasped object were measured for the second version of the hand. The object is a cylinder with a diameter of 60 mm. In order to avoid uncertainties in the distribution of the forces between the thumb and the fingers, the object is pushed against the fingers and the thumb is not involved. The actuation is applied by suspending weights and the force on the object is measured by a dynamometer. Two situations are studied. First, the fingers are closed towards the object, which reproduces the conditions corresponding to the grasping of an object. Second, the object is pushed towards the fingers, which

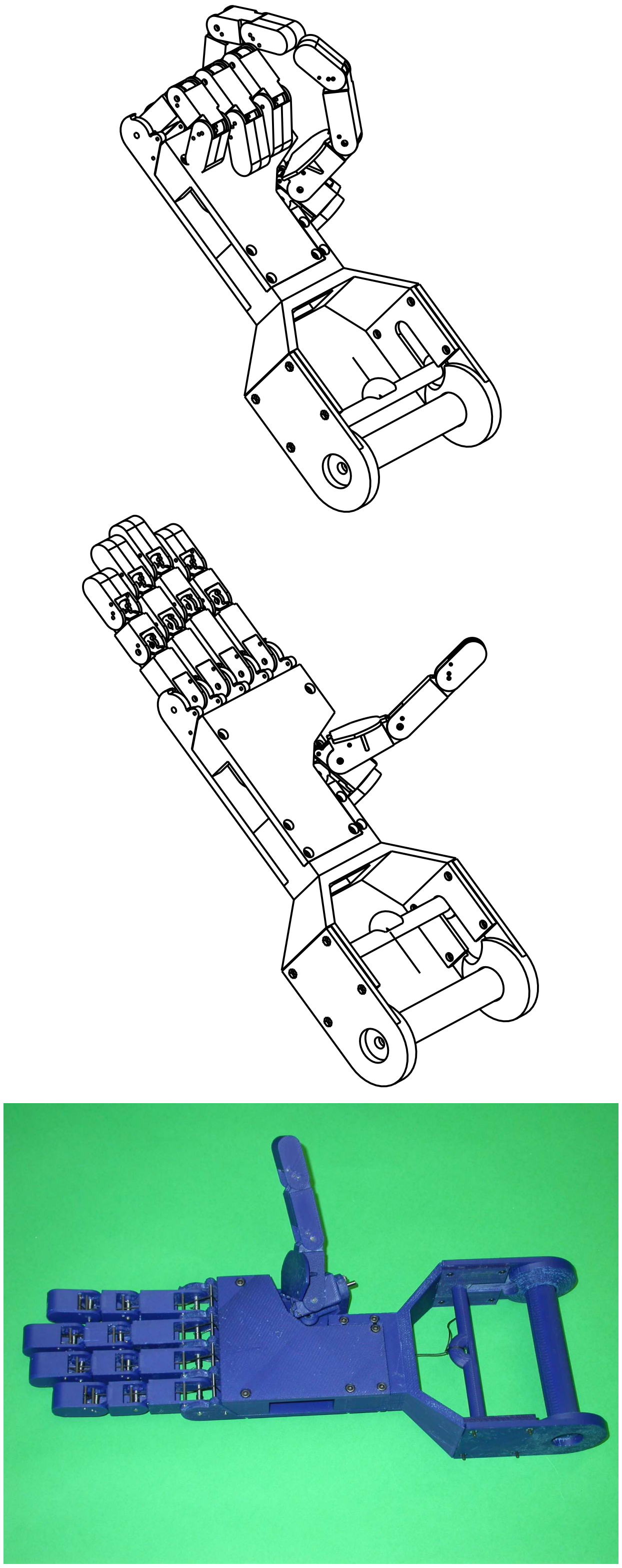

Fig. 5. Prototype (CAD model and photograph) of the 15-dof underactuated hand.

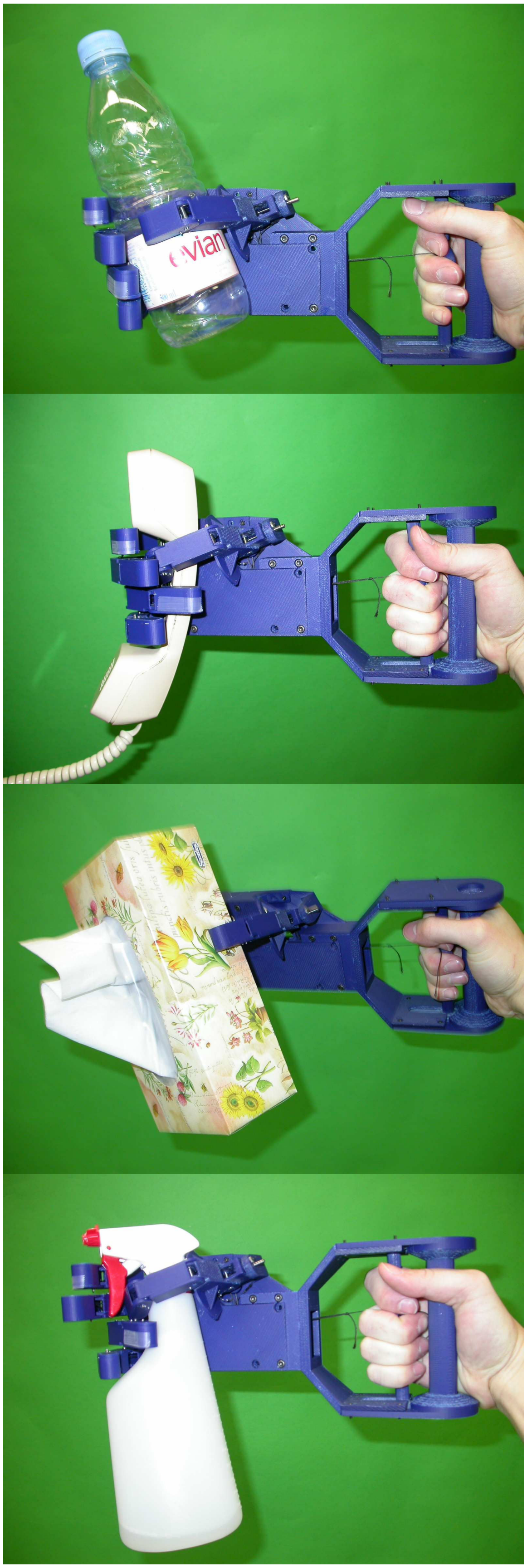

Fig. 6. Graping experiments with the 15-dof underactuated hand.

corresponds to an external force applied on a grasped object. In the first situation, the measured force on the object is 0.1 times the actuation force. In the second situation, the measured force on the object is 0.8 times the actuation force. The large difference is due to the friction in the system. The resulting force on the object that would be obtained without friction is computed as $\sqrt{0.1 \cdot 0.8} \simeq 0.28$ times the actuation force, which fits with the theory. Also, the resulting efficiency is computed as $\sqrt{0.1/0.8} \simeq 0.35$. This low efficiency decreases the capability to apply grasping forces. However, it increases the capability to resist to external forces once the grasp is made. For example, for an actuation force of 50 N, which is the maximum value tested, the grasping force applied by the fingers and the thumb would be half the measured value, that is only 2.5 N. However, the resisted external force once the grasp is performed is up to 40 N. The small applied force can be a problem if the external force is applied perpendicular to the fingers. As discussed previously, this is improved by applying rubber padding on the fingers.

In a video clip attached to this paper, a demonstration of some grasps is provided. In the last part of the clip, a ball is thrown and grasped (caught) three times. It should be noticed that since the ball's position with respect to the hand is different from one catch to another, the final grasp is also different in each case. Nevertheless, each of the grasps is stable and human-like.

VI. CONCLUSION

This paper presented the design and experimental validation of an anthropomorphic underactuated robotic hand with 15 degrees of freedom and a single actuator. The design is based on underactuated three-degree-of-freedom tendon-driven fingers which were optimized for force transmission capabilities. The fingers are driven through a cascade of differential mechanisms that provide underactuation between the fingers. The result is an effective, light and compact anthropomorphic hand that is capable of grasping a broad variety of objects. With the recent advances in humanoid robotics, it is believed that the concept presented in this paper can be very useful in human-like robots. Future work includes the development of an actuated version of the hand that could be mounted on a robot for further autonomous testing.

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