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An under-actuated robotic hand for multiple grasps

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Abstract— **In this paper, an under-actuated robotic hand is designed for realizing several different grasps. Three special transmissions are developed to realize the compact joint connected motion, connected motion among fingers and adduction/abduction. These transmissions reduce the volume and weight of the hand while maintain functions necessary for realizing desired grasps. The developed robotic hand can choose three different opposed positions of the thumb to realize four different grasps. Experiments are conducted to confirm that the robotic hand moves fast and stably grasp objects.**

I. INTRODUCTION

A hand is small but one of the complex organs with more than 20 degrees of freedom (DOF) and manipulates objects by concertedly actuating the joints of the fingers. In the last few decades, many multi-fingered robotic hands have been developed for dexterous manipulation and, roughly speaking, they can be categorized into two groups: One is a full-actuated robotic hands that can control almost all the joints independently [1], [2], [3], [4], [5], [6]. These robotic hands have many actuators, placed on the fore arms or inside the hand itself, by the sacrifice of the hand size or of the actuation power. These hands can manipulate any objects if the control system would be appropriately designed. The other is under-actuated robotic hands that use as few actuators as possible to decrease the size and weight of hands [7], [8], [9]. The under-actuated robotic hands mainly focus on the application to prosthetic hands that can pinch an object (precision grasp) and adaptively grasp an object with the palm (power grasp) using the soft gripper mechanism [10]. The fingers and thumb of almost all the robotic hands are limited to move in a plane. Recently, a myoelectric control method was proposed to identify the different grasps including lateral pinch that requires adduction/abduction of the thumb [11]. This method offers amputees to realize more natural grasps than conventional ones but requires prosthetic hands to add actuation for adduction/abduction of the thumb.

In this paper, we focus on an intermediate approach where a robotic hand can grasp an object in several ways by using as less actuators as possible. We first consider desired grasping functions and analyze them. Then, we design appropriate transmissions to eliminate actuators and integrate them into a robotic hand. Similar approaches have been undertaken based on the principal components analysis of hand motions to obtain main coordinated joint movements [12]. This approach was called hand synergies and applied to design robotic hands for adaptive grasping and was succeeded to grasp several objects in an encompassing gesture [13], [14]. This approach using the hand synergies focuses on kinematic shapes of the hand. However, it is unclear how this approach guarantee the gripping force during the grasp [12]. Adaptive synergies were introduced to generate the contact force, where the equilibrium point of the grasp was estimated smaller than the size of a grasped object, and realized pinching and envelop grasp using a fixed thumb-finger opposition [14]. However, as this approach did not discuss how to determine the internal forces, it is unclear whether this approach guarantees the stability of the grasps, especially in the case of precision grasps. In contrast, our approach focuses on the DOF of hands and the thumb-finger oppositions to realize stable desired grasping controllers, based on the passivity-based approaches [15], [16]. The structure of these controllers provides us the number of actuators to adjust the gripping force.

Some prosthetic hands can grasp an object in different thumb configurations, where the adducted/abducted motions of the thumbs must be manually created [17], [18] or requires an additional actuator [19]. In contrast, our approach uses a solenoid instead of an actuator to create different thumb configurations using a joint locking mechanism. A joint locking mechanism was first proposed to fix the joints in plane. This mechanism is useful in changing the finger shape and increasing the admissible grasping force using an electrostatic brake after the hand firmly grasps [20]. In contrast, our mechanism locks the carpometacarpal (CM) joint to change the thumb-finger oppositions.

In this paper, we design a five-fingered under-actuated robotic hand with the adducted/abducted function of the thumb. This robotic hand uses only three actuators and a solenoid for two-fingered and three-fingered precision grasps, power grasp and lateral pinch that requires changes of opposed configurations of the thumb. We analyze these four grasps from the viewpoint of the driving DOF and determine actuation required in Section II to design the hand. Then, in Section III, we design a special pulley transmission to realize connected motions between the joints and between the fingers. We also design a special locking mechanism to switch the opposed position of the thumb and to realize the grasp motion after the switching. Then, we combine them to make the robotic hand. In Section IV, Experiments are conducted to validate the utility of the developed robotic hand.

II. GRASP CHOICE

In this section, we analyze the grasps and kinematics to design a robotic hand. In Cutokosky's taxonomy [21], grasps

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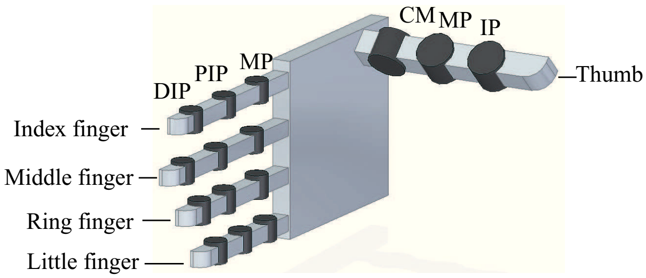

Fig. 1. Joint configuration of a robotic hand

can be roughly classified into precision and power grasps that are differentiated into sixteen concrete grasps according to objects' shapes, the number of fingers and so on.

Most of the under-actuated robotic hands have some fingers opposed to the thumb that cannot adduct/abduct because the joint for adduction/abduction is perpendicular to the remaining joints and makes it complicated to design the robotic thumb. Each finger has a soft gripper mechanism and is driven by at most one actuator. These under-actuated hands realize a simple power grasp thanks to the mechanism and some precision grasps by synchronizing the flexion of the fingers and thumb. However, these robotic hands cannot realize lateral pinch, where the pad of the thumb is placed onto the side of the index finger to grasp a thin object, because of lack of the adduction/abduction. Therefore, we design an under-actuated robotic hand that can realize lateral pinch in addition to two-fingered and three-fingered pinches and a power grasp. First, we consider about features of each grasp to determine the number of actuators. In this approaches, we assign the minimal DOAs to realize the passivity-based controllers for the above grasps [16]. These controllers are useful to adjust the grip force.

In the two-fingered pinch, the thumb needs to be placed to oppose to the index finger. Then, the thumb and index finger synchronously approach each other. It is known that the hand needs at least two degrees of actuation (DOA) to dynamically stabilize object in the two-fingered pinch under the rolling kinematic constraints [15]. Therefore, we need to assign the actuators to the thumb and index finger separately. In three-fingered pinch, the thumb must oppose the index and middle fingers. We need to actuate the index and middle fingers independently to distinguish the two-fingered and three-fingered pinches. In power grasp, the thumb moves laggardly to curl over the remaining fingers after the fingers curl up. Thus, the thumb and remaining fingers must be actuated independently. In lateral pinch, the thumb laterally abducts and the remaining fingers curl up. Then, the thumb approaches to the side of the index finger to pinch a thin object. The kinematic constraint between the side and the thin object can be regarded as a planar contact with friction [2]. Thus, the fingers need one DOA, and, in contrast, the thumb needs two DOAs for abduction and flexion. From the observation, the following features are needed to realize the grasps:

1) The thumb adducts and abducts to change the opposed positions. The number of the opposed positions is at most the number of the grasps.
2) In all the grasps, the thumb needs an independent DOA for flexion.
3) The index finger moves independently from the middle finger to execute two-fingered and three-fingered precision grasps separately.
4) The ring and little fingers as well as the middle finger curl up in power grasp and lateral pinch. In three-fingered grasp these two fingers can takes any configuration if they do not disturb the grasp. Therefore, the three fingers can always move synchronously.
5) Each finger needs at most one actuator if the finger takes an appropriate initial position and all the joints in the finger move connectedly.
6) The four grasps do not require the four fingers to adduct/abduct.

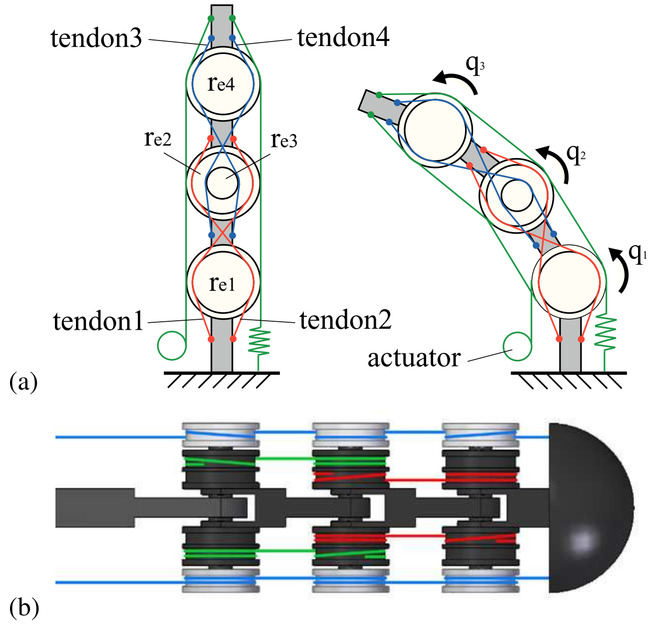

Fig. 2. The conventional robotic fingers [16]. (a) Cross-coupling tendons and the connected motion of the robotic finger. (b) Tendon-routing using six-pulley layers.

Therefore, we determine the joint configuration of the robotic hand as shown in Fig. 1. The thumb has the CM joint for adduction/abduction and the metacarpophalangeal (MP) and the interphalangeal (IP) joints for flexion/extension. The fingers have MP, proximal IP (PIP) and distal IP (DIP) joints that move in the same direction. To design a robotic hand satisfying the above requirements, all the joints of each finger move connectedly, and the MP joint of the thumb must take some given configurations before opposition. Thus, we need two, one and one DOFs for the thumb, index finger and remaining three fingers, respectively.

III. Design of a robotic hand

In this section, we design transmissions for connected motions among joints and among fingers and for the thumb.

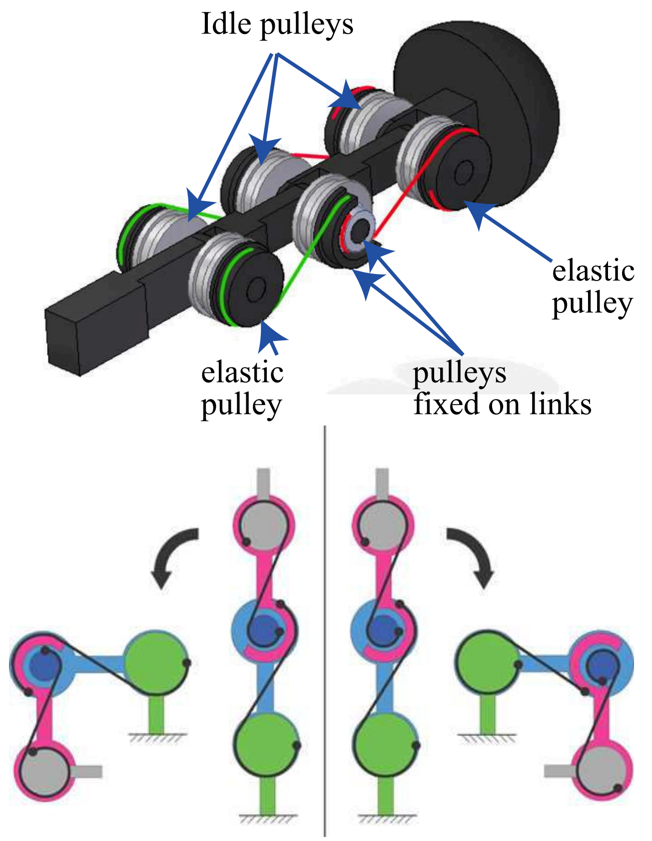

Fig. 3. The tendon-routing of the developed robotic fingers. (top) A schematic model of the double pulley transmission. The elastic pulleys add the elasticity to all the cross-coupling tendons. (bottom) The joint and tendon configurations of the finger when the finger stretches and bends.

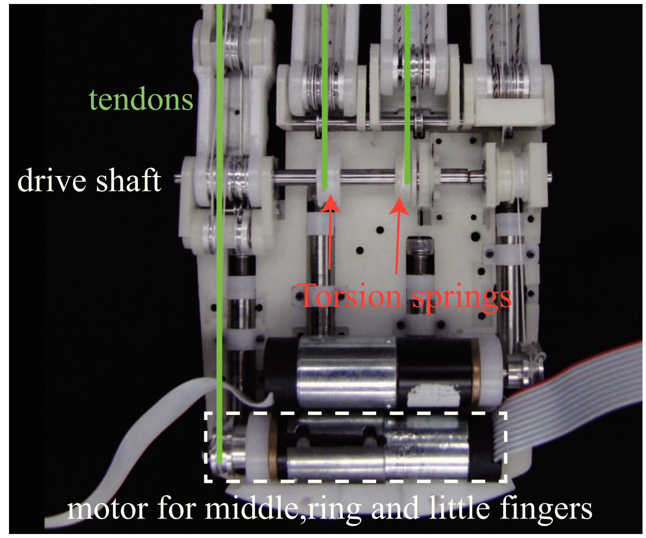

Fig. 4. A connected Transmission between the middle, ring and small fingers. Two torsion springs are attached to the drive shaft and the pulleys for the ring and middle fingers.

TABLE I

PULLEY DIAMETERS

	proximal (mm)	elastic (mm)	inner (mm)	outer (mm)
fingers	–	9	5	11
thumb	5	9	5	11

A. Transmission Design of the fingers

Figure 2 (a) shows the basic mechanism of the robotic finger [22]. Each finger has three joints but is actuated by only one actuator. Therefore, every joint must move connectedly. When the fingers contact with the environment, elastic elements in the passive tendons absorb the external force and help the hand to adaptively grasp an object. The connected motion among the joints can be implemented by a mechanism using the cross-coupling tendons [22]. Two pairs of the cross-coupling tendons are used between DIP and PIP joints and between PIP and MP joints, as shown in Fig. 2 (b). Thus, four tendons are needed to realize this connected motion. In addition, we need two more tendons to drive the joints. Therefore, as a result, we need six pulley layers to realize the transmission. The six pulley layers make the finger thick and are undesirable for robotic fingers. Therefore, we would like to eliminate some of them.

As shown in Fig. 2 (b), each pulley layer for the cross coupling tendon has a vacancy space in the MP or DIP joint, and the PIP joint is only the joint that all the six tendons go through. To make the finger slim, we design a double-pulley transmission consisting of the inner and outer pulleys at the PIP joint, as shown in Fig. 3. A pair of cross-coupled tendons is aligned as the section-sign shape in the single layer by connecting the distal and proximal cross-coupled tendons to the inner and outer pulleys, respectively, as shown in Fig. 3. The pulleys on the first and the third joints are elastic pulleys that are connected to the links through the torsion springs. The inner and the outer pulleys on the second joints are fixed on the proximal and distal links, respectively. The idle pulleys in the inside layers are for antagonistic active and passive tendons. Therefore, the five passive tendons are connected to the elastic elements. All the joints in the finger bend at most 90 degrees, as shown in Fig. 3 (bottom), thus these tendons can be placed without interfering with each other. As a result, the two layers are eliminated and the transmission of each finger slimmed down to only four layers. The diameters of the pulleys are described in table I. Thus, the ratio of the transmission of the MP, PIP and DIP joints is given as 11:9:5, respectively.

B. Connected Transmission design among the fingers

As described in Section II, the middle, ring and small fingers are driven by only one actuator using a transmission among the fingers. The transmission must firmly drive the fingers even if one of the fingers stops the motion because of the contact with the environment. Otherwise, the hand cannot adaptively grasp an object. Thus, elastic elements are needed between the drive shaft and each finger [7]. The middle and ring fingers often contact with objects before the little finger does when the hand grasps convex-shaped objects such as a ball. Therefore, the elastic elements are inserted between the middle finger and shaft and between the ring finger and shaft. In contrast, the little finger is directly connected to the drive shaft, as shown in Fig. 4.

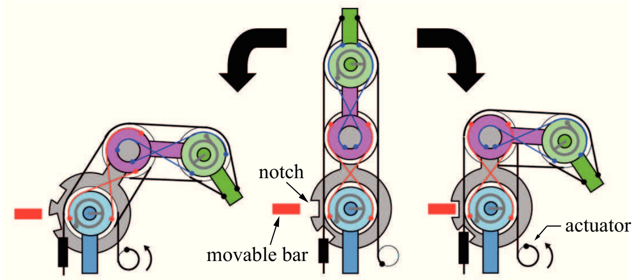

Fig. 5. A locking mechanism of the thumb. (middle → left) All the joints move connectedly when the locking mechanism does not work. (middle → right) The CM joint is stopped but the remaining joint move connectedly when it works.

C. Transmission Design of the thumb

The thumb requires two DOAs for controlling abduction/adduction of the CM joint and flexion/extension of the MP and IP joints [19]. However, it is undesirable to increase the number of actuators because actuators are one of the heaviest components in the hand. Therefore, we design a transmission to realize these two joint motions with an actuator. The key ideas are the following two points. The number of the opposed positions are at most the number of grasps. The grasp motion is implemented after determining the opposed position. We need the following features to realize these two points:

1) All the joints are moved connectedly.
2) The CM joint is fixed when it reaches to a desired configuration.
3) The remaining joints keep moving for grasp after the CM joint stops.

These features can be implemented using the mechanism, as shown in Fig. 5. The connected motion is realized by the cross-coupling mechanism in Section III-A. However, unlike the cross-coupling mechanism for the fingers, the CM joint must move faster more than double the MP and IP joints do to make the CM joint reach to a desired configuration before grasp. Therefore, the proximal elastic pulley is replaced to a small pulley. As described in Section III-A, the ratio of the connected motion can be adjusted by changing the pulley ratio. In this case, the pulley diameters are given in table I. Therefore, the ratio of the transmission of the CM, MP and IP joints is given as 99:45:25, respectively. The CM joint is perpendicular to the remaining joints, which differs from the configuration in Fig. 5, but the same mechanism can be used in this transmission by placing the pulleys appropriately.

When the CM joint reaches to an appropriate configuration, a movable bar driven by a solenoid is inserted to a notch on the CM joint to fix it. Then, the remaining joints move to bend the thumb toward the opposed point. Therefore, the hand can grasp an object after taking different thumb oppositions.

TABLE II
THE LINK LENGTHS OF THE FINGERS

finger	proximal (mm)	middle (mm)	distal(mm)
thumb	23	30	18
index	30	25	18
middle	40	25	18
ring	30	23	18
small	30	23	18

D. Actuation and specification

As shown in Fig. 6, this robotic hand has three actuators and one solenoid. The weight of the solenoid is 15 g, which is much lighter than that of actuator, 55 g, and is contributed to decrease the weight and the energy consumption. The tendons driven by the actuators are antagonistic to the springs, as shown in Fig. 2 (a). These springs are placed on the back of the hand, as shown in Fig. 7.

As shown in Fig. 8, the actuator for the thumb is placed behind the palm. The solenoid is placed on the basis of the robotic thumb and the movable bar is attached at the tip of the solenoid. There are three notches on the first link of the thumb to change different opposed positions, and the bar on the solenoid is inserted into and detached from the notches.

Figure 9 and table II show the developed robotic hand and the human hand and the length of the each link, respectively. The hand structure was determined based on the authors' hand and has the length of 202 mm and the width of 86 mm and the finger length between 87-95 mm. The weight is only 440 g, including all the actuators and the solenoid.

IV. Experiment

Experiments are implemented to validate the performance of the designed robotic hand. The precise motions can be confirmed in the attachment video file. We implemented four motions using combinations of the passivity-based controllers [16]; two-fingered and three-fingered pinches, power grasp and lateral pinch. Every grasps started from the same initial position, where the thumb is opposed to the index finger at the CM joint of 0° and all the fingers are stretched. Then, the hand moved to the final states of the grasps, as shown in Fig. 10. The CM joint moves 0, 45 and 90 degrees in the power grasp, two-fingered and three-fingered pinch and lateral pinch, respectively. The hand stably grasped a plastic cap, a bouncy ball, a 50 cl pet bottle and a key in two-fingered pinch (middle left), three-fingered pinch (middle right), power grasp (bottom left) and lateral pinch (bottom right), respectively.

V. Discussion

In this paper, we developed an under-actuated robotic hand with the almost same sizes of the human hand. The weight of the hand is 440 g, which is less than the admissible load, 500 g, of the prosthetic hand [23]. In contrast, the length of 202 mm is a little bit longer than the admissible length of 198 mm, but it will be possible to improve the design. The robotic hand developed the three special transmissions among the joints, among the fingers and for the thumb. These

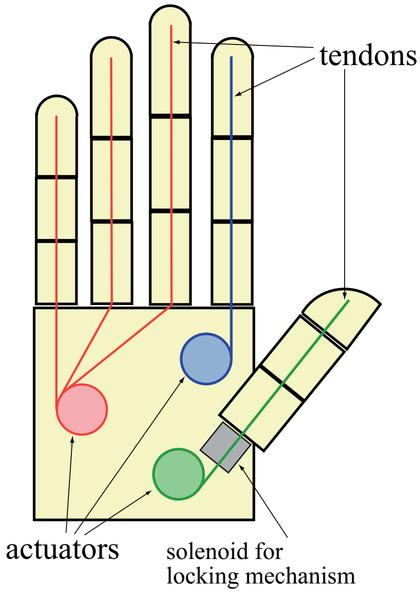

Fig. 6. Actuator arraignment

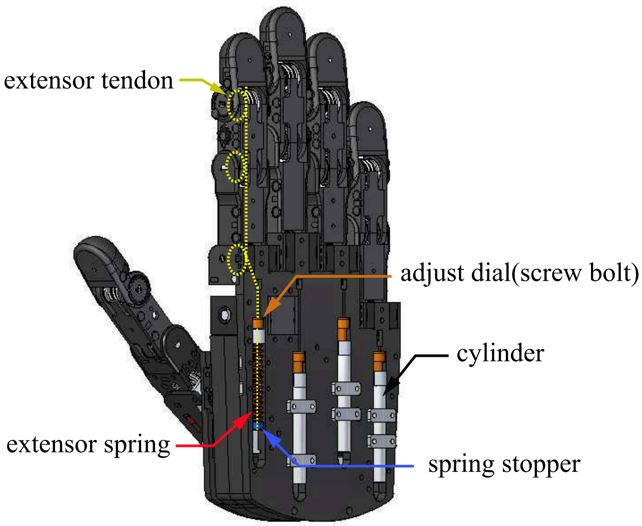

Fig. 7. Extensor spring

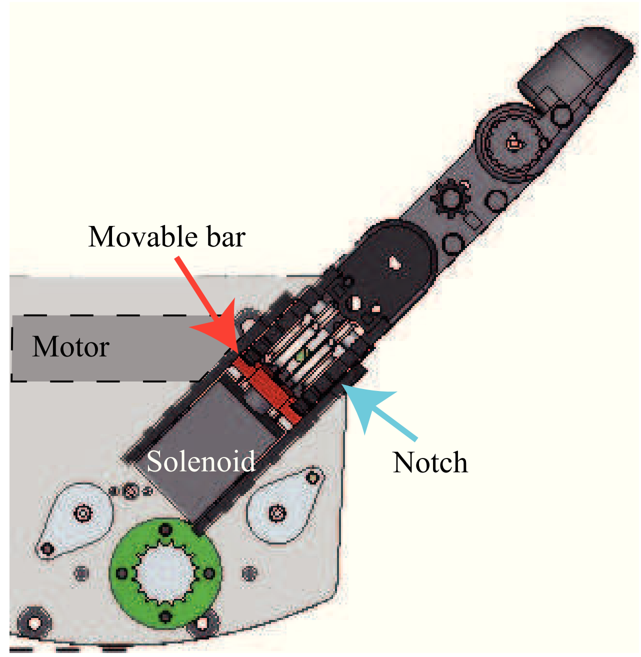

Fig. 8. The structure of the robotic Thumb

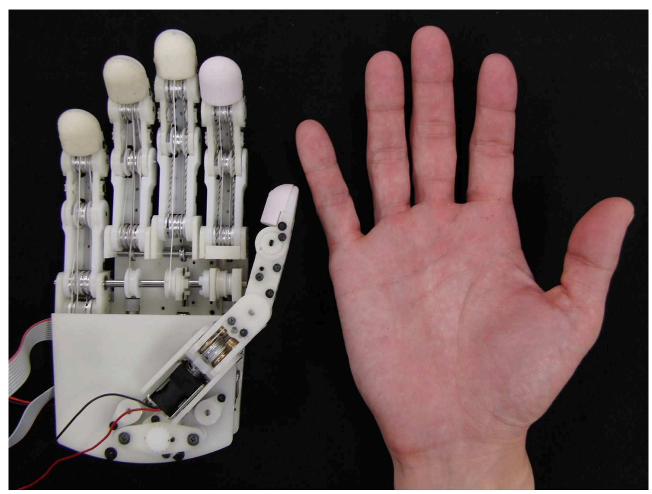

Fig. 9. Comparison with the human hand.

special transmissions enabled us to realize the four grasps by using only three actuators and one solenoid. Especially, the mechanism to realize the adduction/abduction is rare in conventional under-actuated robotic hands.

While we showed that the developed robotic hand has possibility for the use of a prosthetic hand, several problems still remain. First, the shape and the size of the robotic hand are not optimized and we will reduce the size and weight and introduce special structures such as the arch of the palm to improve the shape and functions. Second, the finger moves very quickly as shown in the attachment file while the grasping force is not so strong. The balance of the actuator speed and torque must be optimized. Third, the wrist mechanism is important to use the developed hand as the prosthetic hand. However, we have not developed it. Forth, we have not verified the adjustability of the gripping force and the robustness of the grasps. Finally, we have not discussed about interfaces for prosthetic use. In the future, we will improve the robotic hand and interfaces to solve these problems and verify the robustness of the grasps.

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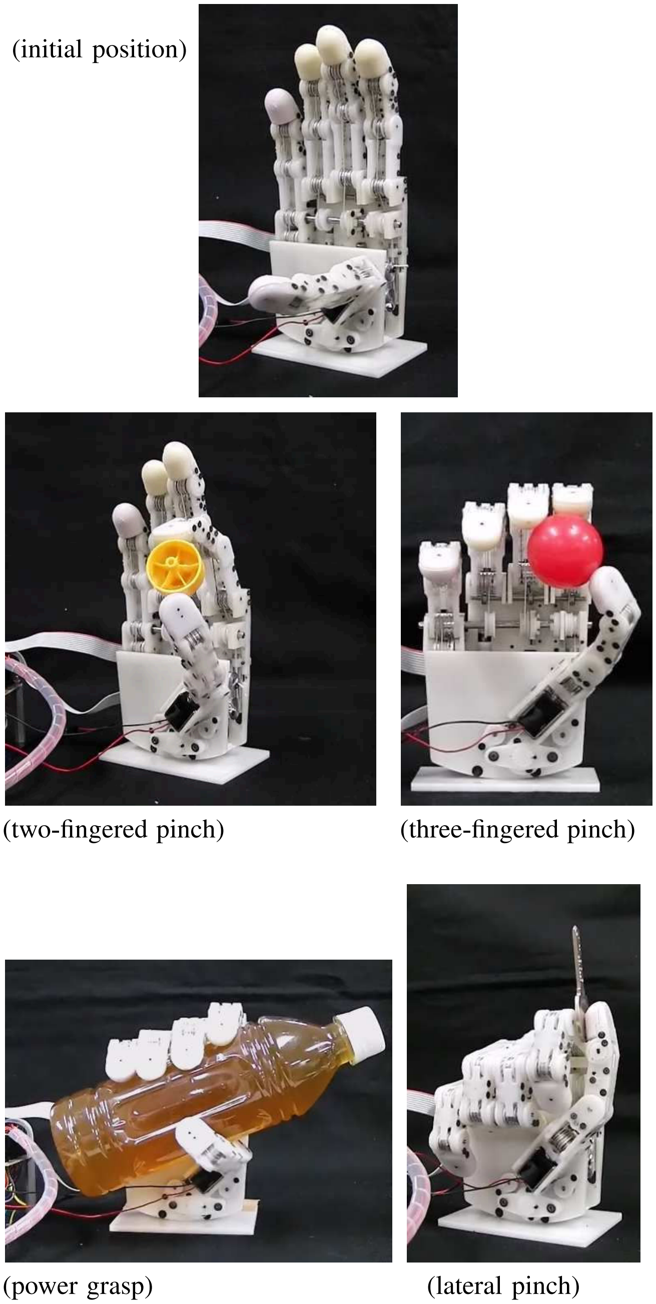

Fig. 10. Grasps using the developed under-actuated robotic hands.

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