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Design of a tendon-driven robotic hand with an embedded camera

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Abstract— **This paper designs a new five-fingered robotic hand with a camera. Several morphological features of the human hand are integrated to improve the appearance of the hand. The drive system of this hand is under-actuated to eliminate the weight of the hand and to embed all the actuators inside the palm. Despite of this under-actuation, this hand can grasp objects in several different ways. In addition, the two different transmissions are adopted to drive the fingers according to their roles. These transmissions help not only to improve drive efficiency but also to secure the space of the embedded camera.**

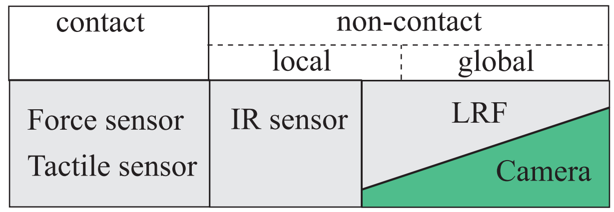

Fig. 1. Classification of sensors

I. Introduction

Multi-fingered robotic hands have been developed for the last few decades to realize dexterous motions that cannot be realized by a simple gripper. These robotic hands traditionally have more than two fingers and equip with actuators whose number is almost equivalent to that of the joints. The actuators of these robotic hands are placed on the forearms [1], [2], [3], [4], [5], [6], [7] to assemble the robot hands in the similar size of the human hand or on the palm at the sacrifice of the size, weight or power [8], [9].

In contrast, under-actuated robotic hands have been developed to decrease the size and weight of the hands with the sacrifice of the hand functions [10], [11], [12], [13], [14], [15]. These robotic hands have fingers with soft gripper mechanisms that adaptively wind around an object using a small number of actuators [16]. Therefore, the hands can grasp a variety of objects using one or a few actuators that are placed on the palm and they are applied for prosthetic hands and high speed grippers. However, the function of these robotic hands is limited to at most power grasp and simple tip grasp.

To build an under-actuated robotic hand, we focus on three important points; one is to introduce some features of appearance of the human hand into the shape of the robotic hand because the appearance of the hand increases the frequency of usage and the adaptivity of the hand to object shapes.

The second point is to realize many different grasps with the hand. Recently, geometric shapes of a hand have been analyzed to obtain the principal components of static shapes of the hand called hand synergies [17] and the obtained components were used to design drive systems of the robotic hands for power and precision grasps [18] [19]. A prosthetic hand that can realize lateral grasp was developed, but the position of the thumb must be manually changed [20]. An underactuated robotic hand was designed using a mechanical selector and an actuator to realize multiple grasps [21]. The mechanical selector was used to manually select the pattern of the bending fingers. Recently, a controller-based design approach was proposed to realize multiple grasps using under-actuated mechanisms such as lateral grasp that requires the adduction/abduction of the thumb [7]. We will design a new robotic hand based on this approach.

The last point is to integrate sensors into a robotic hand. Figure 1 shows a classification of sensors used in robotic hands. Robotic hands frequently equip with finger-tip force sensors [10] and tactile sensors [22], [23]. These sensors are used to observe contact situations for improving the stability of grasps while some grasping controllers can guarantee the grasp stability without using these sensors [24].

Infrared ray sensors were used to detect an object in a short range such as in front of the palm and between the fingers [25]. A laser range finder (LRF) for a robotic hand was developed to recognize a object [26]. This LRF is smaller than the commercial ones but is still too large to be embedded inside the palm of a hand because of the size of lasers. Another candidate to obtain global information is a camera. Unlike the force and tactile sensors, it is difficult for grasping controllers to compensate the global information. Therefore, it is important to integrate these sensors into a robotic hand. Boivin and Sharf [27] designed a hand with a camera can detect the object pose based on the database. However, this robotic hand was designed for the operation on the space station, thus was relatively easy to secure a place for a camera.

In this paper, we design a novel tendon-driven robotic hand with a camera inside the palm. The drive system of this robotic hand is designed based on a special under-actuated tendon-driven mechanism [7] that use special cross-coupling pulleys to connectedly move the joints and only three actuators to reduce the weight of the hand. Nevertheless, this hand could grasp object in four different configurations. However, this hand did not adequately realize morphological feature of the human hand and could not generate large grasp

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force. Therefore, we integrate several morphological features of the human hand into the hand. In addition, we design drive systems of the fingers to be suitable for their control purposes. These improvements are also useful in obtaining a space where a camera is embedded.

Section II explains the basic kinematics and functions of the robotic hand. Section III designs hand arches of the human hand into the robotic hand as the morphological features. Section IV designs drive systems of the fingers and section V describe an embedded camera inside the palm.

II. Kinematics and basic functions of the robotic hand

Figure 2 shows the kinematic structure of a robotic hand. The robotic hand has the thumb and four fingers. The thumb has three joints; the carpometacarpal (CMC), the intercarpal (IP) and midcarpal (MP) joints. Each joint has one degree of freedom (DOF). The CMC joint realizes the circumduction and the joint axis is orthogonal to the axes of the IP and MP joints for flexion and extension. In contrast, each finger has the three parallel joints to realize the flexion and extension. The link lengths of each finger are adjusted to be suitable to the index, middle, ring and little fingers.

This robotic hand is designed based on grasp functions and can realize the four basic grasps: two-fingered and three-fingered pinches, power grasps and lateral pinch, as shown in Fig. 3 [7]. In the initial position of the hand, the thumb is placed in front of the index finger. In the power grasp, the fingers curl up and the IP and MP joints of the thumb bend toward the fingers. In the two-fingered and three-fingered precision grasps, the CMC joint needs be inclined at 45 degrees from the initial position. Then, all the fingers move toward the pinching position and the thumb moves toward the fingers as the pad of the thumb contacts with those of the fingers. The difference between the two-fingered and three-fingered pinches is the motion of the fingers; only the index finger moves in the two-fingered pinch and the index and middle fingers move in the three-fingered pinch. Thus, at least, the index finger must move independently from the rest of the fingers. In the lateral pinch, all the fingers first curl up as the power grasp. Then, the CMC joint of the thumb is inclined at 90 degrees and the IP and MP joints move as the pad of the thumb contacts with the side of the index finger. Therefore, the hand needs to have four independent DOFs; one for the index finger, one for the rest of the fingers and two for the thumb. The MP and IP joints of the fingers and the thumb move connectedly and the CMC joint of the thumb must independently move to some discrete angles from the MP and IP joints.

The connected motions of distal IP (DIP), proximal IP (PIP) and MP joints are realized by two pairs of the cross-coupling tendons, as shown in Fig. 4 (a) [28]. The blue and red tendons are connected to elastic elements instead of actuators and constrain the ratio of the joint movements in the free space. Therefore, the all the joints of the fingers naturally realizes extension and flexion when the green tendons are pulled. In addition, the elastic elements of the cross-coupling

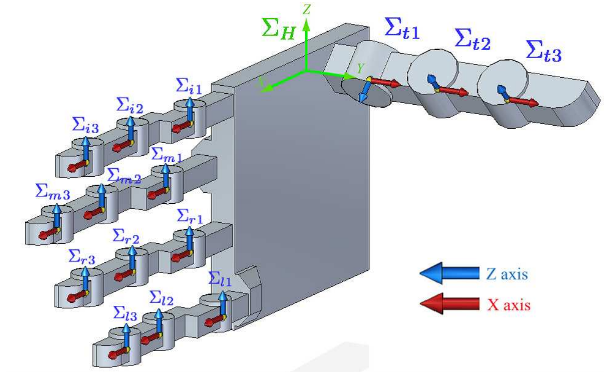

Fig. 2. Kinematics of the robotic hand

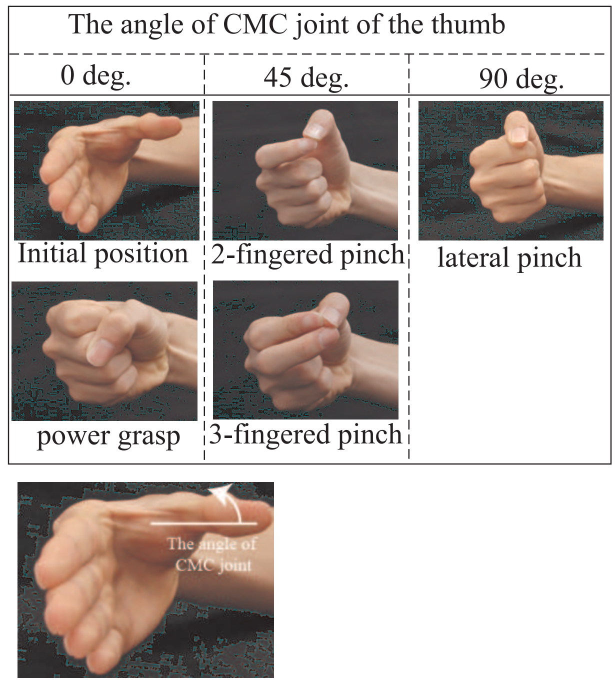

Fig. 3. Basic functions of the robotic hand and the CMC joint angles.

tendons absorb the external force when the finger contacts with the environment. Thus, the fingers can adaptively grasp an object.

The thumb also adopted the cross-coupling tendons, thus the CMC, MP and IP joints move connectedly. However, in the case of the thumb, the posture of the CMC joint must be chosen independently from the three discrete postures, as shown in Fig. 3. To realize this feature, a notch mechanism is designed, as shown in Fig. 4 (b). This mechanism has a movable bar (red box) and a gear with notches. The CMC joint is immobilized by inserting the movable bar into one of the notches and, then, the IP and MP joints can move independently of the CMC joint.

III. Morphological designs of the hand

In this section, two morphological designs are introduced to change the shape of the hand. It is well known that the human hand naturally forms a convex shape when it is

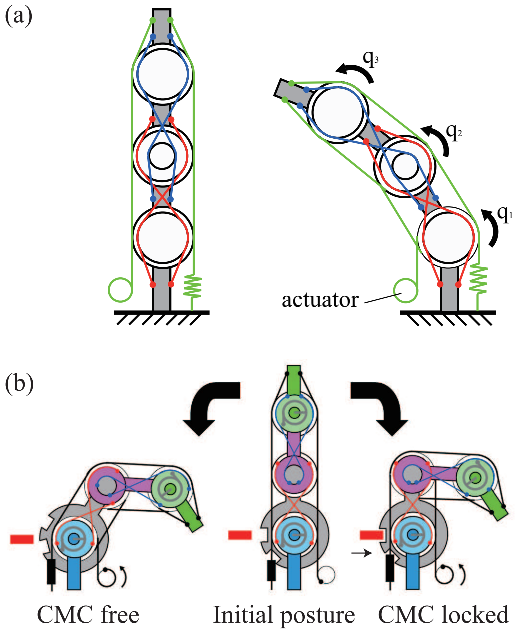

Fig. 4. (a) Cross coupling tendons and (b) notch mechanisms.

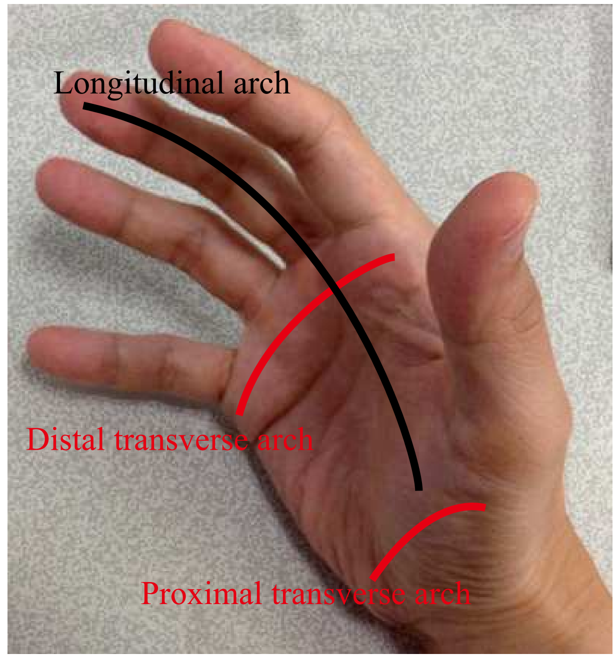

Fig. 5. Arches in the hand.

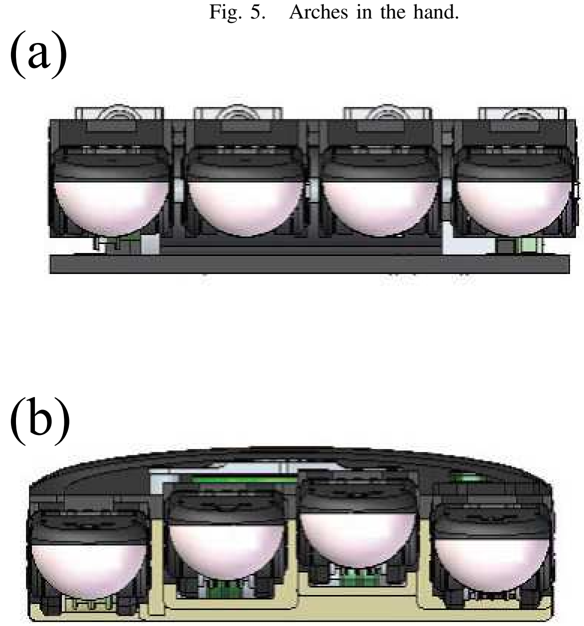

Fig. 6. Morphological arch structure of the hand. (a) The previous design in [7]. (b) The arch of the developed hand.

relaxed and that the convex shape increases the stability of the grasping [29]. The convex shape consists of the three arches; the longitudinal, proximal transverse and distal transverse arches, as shown in Fig. 5. The proximial transverse arch is realized by the CMC joints of the fingers inside the palm. However, the designed robotic hand does not have any CMC joints of the fingers. The longitudinal arch is partially realized by the cross-coupling structure in Section II, but the kinematics of the hand is not adequately optimized.

Therefore, in the next subsections, we design the position of the MP joints of the finger to introduce the distal transverse arch and to improve the longitudinal arch of the hand.

A. The distal transverse arch of the hand

Based on the observation of the human hand, we realized the following two points to build the distal transverse arch:

- The peak of the arch is at the middle fingers.
- The position of the MP joint of the index finger is shifted to the back from that of the little finger.

Therefore, we designed this arch, as shown in Fig. 6 (b), to form more natural arch than the straight alignment of the MP joints, adopted in the previous design, as shown in Fig. 6 (a) [7].

B. The longitudinal arch of the hand

In the hand design, the joint axes of the DIP, PIP and MP joints usually lie on the same line to simply Denavit-Hartenberg convention at the initial position, as shown in Fig. 7 (left). However, from the anatomical point of views, the epiphysis of the proximal phalanx is larger than that of the middle pahalanx, the rotational center of the MP joint is shifted to the palm of the hand, as shown in Fig. 7 (right). The positions of the MP joints increase smoothness of the arch of the hand. The left and right photos in Fig. 8 show the current and previous designs of the hands, respectively. The surface of the palm side is curved more smoothly than that of the previous design when the fingers bend.

IV. Finger Drive System

As described in Sec. II, we use two actuators to drive all the four fingers; one actuator is used for only the index finger and the other is used for the rest of the three fingers. The most important motion of the index finger is the two-fingered pinch that requires precise torque control rather than large grasping force. In contrast, the main role of the rest of the

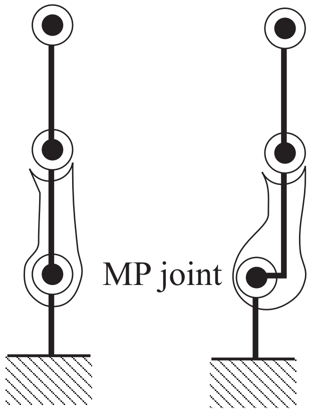

Fig. 7. MP joint position of the fingers. (left) conventional straight finger, and (right) modified MP joint position.

(a) (b)

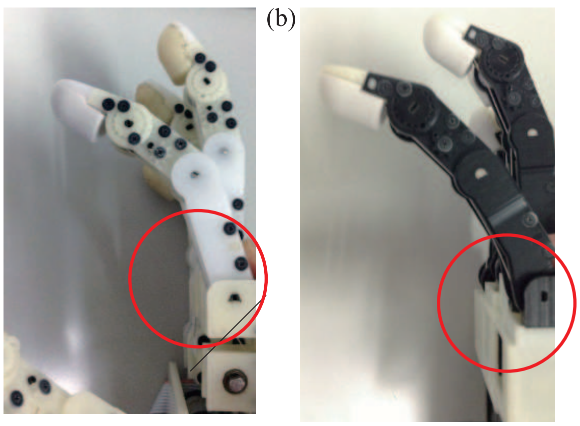

Fig. 8. Comparison of the longitudinal arches of the hands. (a) The old MP joint and (b) the new MP joint.

fingers is to adaptively grasp an object. Especially, it is well known that the middle and little fingers play an important role in generating grasping force. Thus, it is desirable to increase the efficiency of the transmission. Therefore, we use different transmission for these two drive systems.

Tendon-driven mechanisms are useful in decreasing the backlash and play in the transmission because they generate the bias force [30]. The tendon-driven mechanism has a pair of antagonistic tendons. To eliminate the number of actuators, one tendon is driven by an actuator and the other is connected to an elastic element, as shown in Fig. 9 (a). The spring is prolonged when the actuator pulls the tendon and the driving force is counterbalanced to the elastic force. Then, the effective actuator torque decreases, and the maximum grasping force becomes small. Therefore, we adopt this tendon-driven mechanism for the drive system of the index finger.

To avoid the torque loss by the counterbalance, the elastic elements of the antagonistic tendon must be eliminated, which requires connecting the antagonistic tendon to an actuator. However, we would like to avoid introducing an additional actuator. Therefore, the belt-pulley mechanism is adopted to drive the fingers, as shown in Fig. 9 (b). This drive system causes the backlash but can generate larger torque than the tendon-driven mechanism. At the basements of the three fingers, the actuator is connected to a drive shaft. Torsion springs are inserted between the drive shaft and the drive pulley of each finger to adaptively absorb the difference of the finger motions. Therefore, three elastic elements of the antagonistic tendons were eliminated from the back of the hand. Therefore, the three fingers can adaptively grasp an object using only one actuator. This sharing of the drive systems is useful not only in the assignment of the proper drive system but also in securing the space to embed a camera in the hand. The latter point will be discussed in the next section.

As shown in Fig. 11, the developed robotic hand can grasp objects using four different grasps; two-fingered and three-fingered pinches, power grasp and lateral pinch.

V. VISUAL SENSOR OF THE ROBOTIC HAND

In this section, we describe the process to determine the camera position. In the two-fingered and three-fingered pinches and power grasp, an object exists the space in front of the thumb and the index finger. Therefore, the camera should be placed to capture the space in front of the palm between the CMC joints of the thumb and the MP joint of the index finger. As shown in the previous design of Fig. 10 (a), the cylinder connected to the antagonistic tendon of the index finger was placed on the back under the index finger. However, this is the space that the camera should be placed. Therefore, the elastic element should be replaced to some other place. To achieve this replacement, the rotational passive element in Fig. 10 (b) is designed. In this case, the antagonistic tendon goes down and turns to the little finger using a small idle pulley and connected to a rotational passive element. Therefore, the space below the index finger can be used for embedding a camera. This passive element contains a drum connected to a torsion spring. Thus, this drum can absorb the external force when pretension is adequately added. The pretension can be adjusted by rotating the adjusting dial. Figure 12 shows the size of the hand and the camera position. The camera is fixed on the back of the hand and can observe the motion in front of the hand through the small window. This camera is 1/4 inch CMOS color image camera and the resolution is 640 x 480 pixels. The transmission rate is 30 flames per second. This camera has the wide angle of view and can capture the thumb, index finger and an object between them just before the two-fingered pinch is established, as shown in Fig. 13.

The weight of the hand including the actuators and the camera is about 450 grams and the length is about 190 mm, which are almost the same as those of a commercial product [20].

VI. CONCLUSION

In this paper we designed a robotic hand with a camera to observe an object in front of the palm. This robotic hand was designed based on the under-actuated tendon-driven robotic

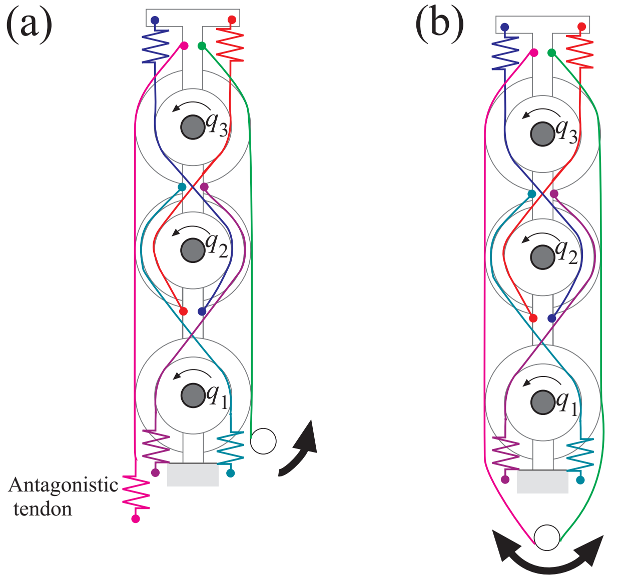

Fig. 9. Two different drive systems of the finger. (a) A tendon-driven mechanism for the index finger, and (b) a belt-pulley drive system for the middle, ring and little fingers.

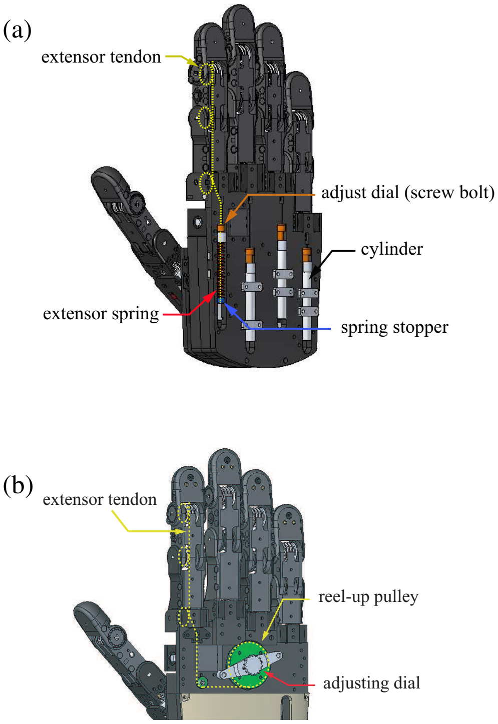

Fig. 10. Back structures of the hands. (a) The mechanism used in [7], and (b) The developed mechanism.

hand [7]. The distal transverse and longitudinal arch structures were adopted to improve the appearance of the hand. The drive systems of the fingers were functionally modified to take the roles of the fingers into account. The tendon-driven mechanism is suitable for precise torque control while reduces maximum torque. Therefore, this mechanism is suitable for controlling the index finger that is mainly used for precision grasp. In contrast, the belt-pulley mechanism

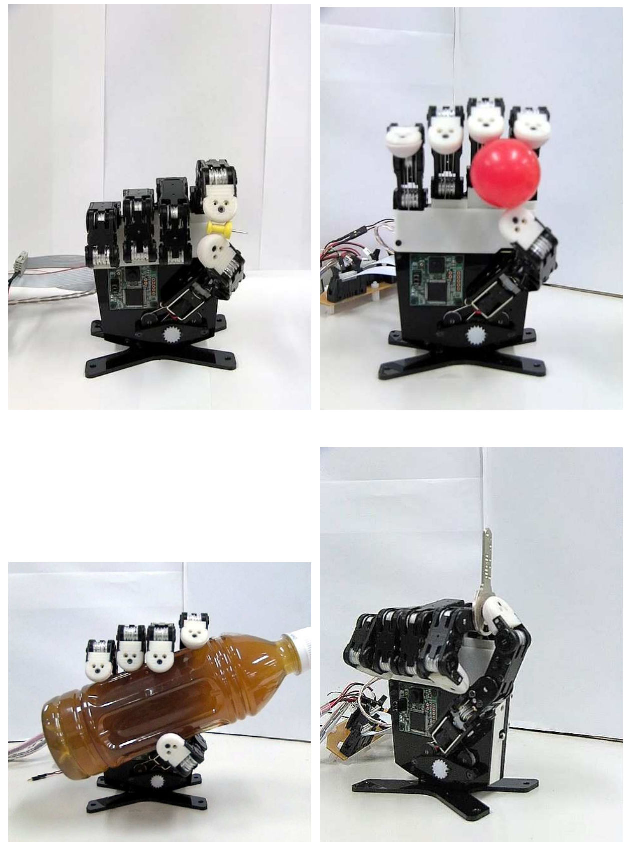

Fig. 11. Four grasps using a developed hand. (top left) two-fingered pinch, (top right) three-fingered pinch, (bottom left) power grasp and (bottom right) lateral pinch.

generates larger maximum torque while this mechanism is not suitable for precise motion control. Therefore, this mechanism is suitable for controlling the rest of the fingers that are mainly used for power grasp. This mechanism also helped to secure the space for embedding the camera inside the palm because it eliminated the springs for antagonistic tendons. We confirmed that the camera could observe an object in front of the palm, where the index finger and the thumb can pinch an object. The camera could be blind when the hand grasp a dirt object with the palm. Therefore, we will secure the basic grasping functions independent of the camera and basically use it to support the functions, e.g., by determining the moment where the hand starts grasping. It might be difficult to detect the distance between the palm and an object using only single camera. Thus, we will also add other sensors such as proximal sensors in addition to the camera.

We will develop a system for object recognition to determine the moment of grasps using the embedded camera.

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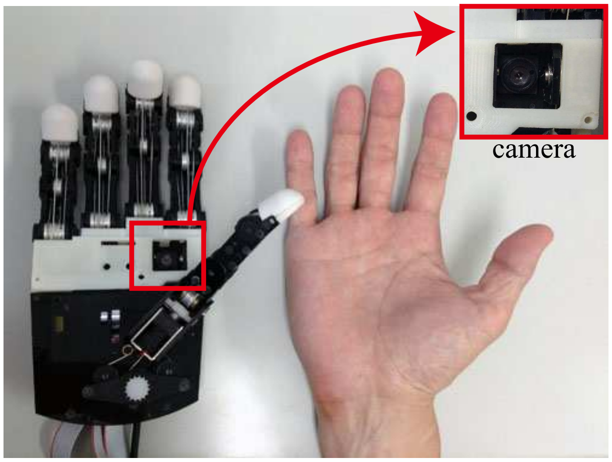

Fig. 12. Comparison of the developed hand with a camera and human hand

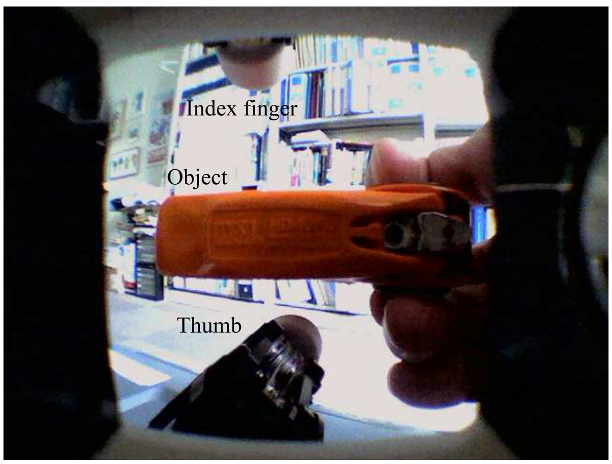

Fig. 13. The camera view inside the palm of the hand.

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