Configuration Design and Verification of Soft-rigid Hybrid Hand with ab/ adduction Movement

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Configuration design and verification of soft-rigid hybrid hand with ab/ adduction movement

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Abstract: Dexterous hand, as robot end effecter, is gradually showing unparalleled potential. In this paper, we proposed a novel configuration for the movement of the robot thumb metacarpal joint. Then, the force transfer efficiency of the finger structure is analyzed to reduce the demand for motor torque and realize the integration of ten motors inside the palm. Additionally, With the help of a soft-rigid hybrid palm, the contact area of the grasping object and the load capacity has increased considerably. Finally, the integrated verification is carried out on the home-made service robot, which can obtain reliable grasping of objects of various shapes and different surface features. What's more, the robotic hand flexibly operates the infrared thermometer to measure the temperature of the water in the cup which shows a great application prospect in the field of service and industry.

Keywords: Soft-rigid hybrid •Dexterous hand •Thumb •Palm

1. Introduction

The revolutionary changes brought about by robots in the industrial sector are already evident to all [1]. On the other hand, it is gradually entering all areas of human society, including healthcare [2] and services [3], among others. In this process, the ability to have end-effectors that are as flexible as human hands to perform complex tasks is a major obstacle limiting its further development. The robotic hand is a device that can realize local precise control and flexible grasping goals[4-8]. Research on robotic dexterous hands is well advanced. In this paper, the thumb and palm configurations are studied and discussed for the application-oriented dexterous hand. Katarincic [9] pointed out that without the complex movement of the thumb, the hand could not complete the grasping with a large load. Chalon [10] fully analyzed the structure of thumb from three aspects of biomechanical data, anatomy, and medical knowledge, and then applied it to the arm and hand system. Whether it is a two-finger [11,12], three-finger [13] or five-finger [14-16] dexterous hand, at least one finger has been designed to move closer to the function of the thumb. Emphasis is placed on its

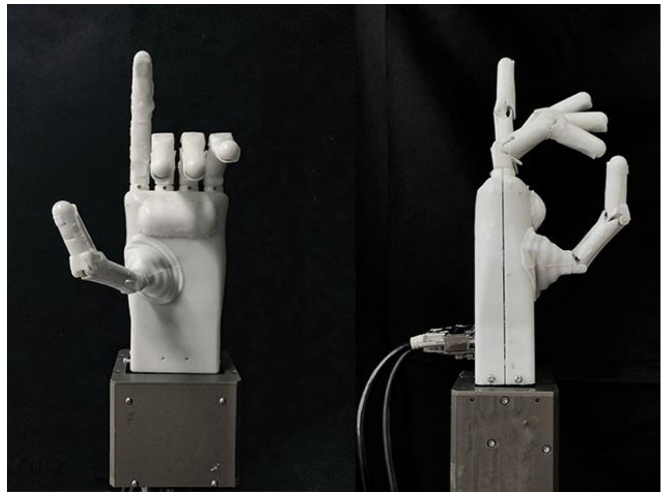

Figure 1. Front view and side view of soft-rigid hybrid hand

distinctive degrees of freedom and even the drive mechanism, extending its working space to improve the gripping and handling performance of the dexterous hand.

Besides, Thomas Feix [17] found that 75% of the 16 positions of manual power grasping required the participation of the palm. Therefore, optimizing the structure of the palm is also an important way to improve the grasping ability of the dexterous hand. Dai, J.S [18] proposed the cell transformation mechanism can be applied to the palm, and the palm configuration can be changed autonomously, which greatly improves the grasp flexibility and grasp range. However, the overall structure is complicated, and the strength of the palm is greatly weakened. The palm of Barrett Hand [19] adds a rotated degree of freedom around the center of the palm, then according to the object shape adaptive change its fingers configuration. The segmented palm designed by NASA [20] also increases two degrees of freedom in the palm, with two rotating metacarpal joints, enabling the operation of a screwdriver for space missions.

Existing dexterous hands still have a lot of room for improvement in grasping variety and carrying capacity. In this paper, a flexible dexterous hand with ab/adduction movement of the thumb metacarpal joint is designed, with two active and one passive degrees of freedom, which greatly improves the variety of grasping and operation of the dexterous hand. From

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the inspiration of nature and the study of a human hand, many researchers have also adopted the design method of the multi-material composite robot [21]. Aiming at the shortcomings of traditional rigid robot palm grasping, this paper designed a palm of the hands made up of rigid "bones" and soft "skin"(Figure 1). On the one hand, the layout of the five fingers is carefully designed to get a larger grasp range. On the other hand, considering the contact position of fetching, add silicone structure on the palm to increases the contact area, thus improving the maximum grasping capacity of the dexterous hand. Finally, the comprehensive performance of the dexterous hand was verified on the service robot by grasping different objects and manipulating the infrared thermometer.

The main contribution of this paper is concluded as follows:

1. The configuration design of the thumb ab/adduction movement is proposed, and the improvement of dexterity is analyzed from the perspective of the workspace.

2. The modular finger configuration design is put forward, and its effectiveness is verified by the force transfer efficiency experiment.

3. The soft- rigid hybrid palm is designed which increases the contact area with the object and the maximum grasping load of the dexterous hand.

2. Configuration design

2.1 Thumb Design

The human thumb has 5 degrees of freedom which plays a crucial role in the grasping ability of the hand [10]. The abduction and adduction motion of the thumb is the key to realize finger contraption and to complete shape closure during grasping. Therefore, in this paper, based on the study of the thumb motion rule of the human hand, the motion of the abduction and adduction of the thumb metacarpal joint was designed which achieves a range of motion of 40°.

We designed 3 degrees of freedom for the thumb. The proximal interphalangeal joint(PIP) are passive degrees of freedom, which rotates together with the metacarpal phalangeal joint(MCP). The direction of movement of the basal carpometacarpal joint(BC) is perpendicular to the other two joints, which greatly increases the workspace of the thumb. As shown in Figure 2 below, the motion of the BC joint is in the XOZ plane, while the motion of the MCP joint is in the YOZ plane.

The next challenge is how to implement the design idea. The robot thumb can be divided into the distal phalanx(DP), proximal phalanx(PP) and metacarpal phalanx(MP) with three joints as human thumb. Since the metacarpal phalanx is also playing the role of a rack, bearing the torque transfer from

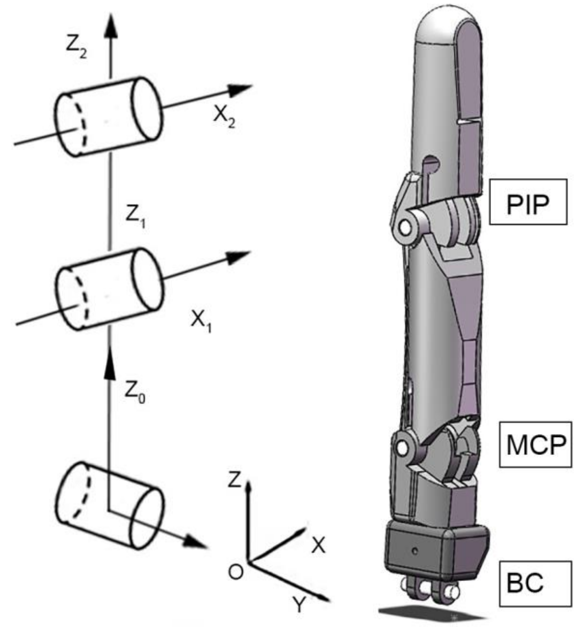

Figure 2. Schematic diagram and 3D model of the thumb

the upper joint, the rotation pair here is required to be stronger. Thus the double-cylinder hollow fixing frame is adopted, with the pin as the rotating shaft, the torsional spring as the pose restoring device, and the hole near the inside of the palm of the thumb seat as the fixing point of the driving rope. In this way, when the motor is running, the thumb seat will be pulled and rotate to the palm. Otherwise, it will rotate on the other way under the force of torsional spring only.

For the two interphalangeal joints of the thumb, we use a coupled degree of freedom, which will be driven by a rope on one motor to achieve rotation motion.

2.2 Other Fingers Design

Unlike the thumb, the other four fingers are similar in function, with only slight differences in length. Therefore, this paper unifies the structure of the remaining four fingers to improve the reliability of the system.

Considering the joint composition and shape size of human fingers, a set of finger shapes composed of three knuckles and connected by rotating pairs were designed by Solidworks(2018) as shown in Figure 3.

Our main concern is the efficiency of the rope drive under this structure. So, static analysis is carried out. Taking the

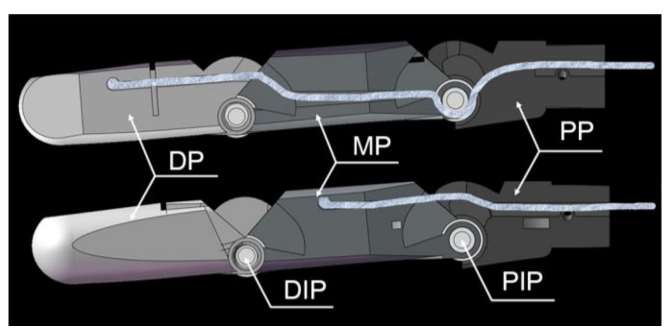

Figure 3. Configuration design of other four fingers

index finger as an example, the torque balance equation of the joint is established, and then the transmission efficiency between the fingertip pressure and th1e internal force of the transmission rope is obtained. The meaning of symbols is as follows:

F_1: soft rope passing by on the driving force;

F_2: external force on fingers;

M_1: restoring torque of the spring;

M_2: friction torque of the rotating shaft;

L_1: the distance between the driving force action direction and rotation axis;

L_2: the distance between the direction of action of external force and the axis of rotation;

θ: the angle at which the first joint of the finger is rotated;

ω: the ratio between the actual and theoretical values of the external forces that the driving force can withstand;

Since the origin of coordinates is the torque balance of point O, the center of the rotating axis, the following formula (with the clockwise torque as positive) can be obtained.

From the analysis above, the equations are given below:

$$\begin{cases} \sum M = F_1 * L_1 - F_{2Real} * L_2 - M_1 * \theta - M_2 * \theta \\ \sum M = F_1 * L_1 - F_{2Theory} * L_2 - M_1 * \theta \end{cases} \quad (1)$$

To avoid the interference of redundant factors, it is known that when the fingers are extended in a natural state, the spring return moment M_1 and friction moment M_2 are ignored. The distance between the driving force action line and the rotating shaft L_1 is 6.5mm, and the distance between the external force action line and the rotating shaft L_2 is 22mm. Therefore, when the driving force F_1 is 10N, the fingertip pressure $F_{2Theory}$ is about 2.83N, and when the driving force F_1 is 15N, the fingertip pressure $F_{2Theory}$ was about 4.24N, and the distal knuckle joint transformation efficiency η was about 28%.

2.3 Soft-rigid Hybrid Palm Design

The function of the palm, first of all, is to serve as a frame of five fingers, bearing the force of each finger. Secondly, the configuration of the palm directly determines the positioning layout of the five fingers. If the finger configuration is determined, it further determines the size of the closed space of the five fingers, which plays a decisive role in the grasping range of the dexterous hand. Last but not least, most dexterous hands use fingers or fingertips for grasping planning, and the palm does not participate in the grasping task. By analyzing the grasping action of the hand, it can be concluded that the strong grasping with the palm is the most reliable and effective grasping method, and the maximum grasping load can also be effectively improved under the same fingertip output force. We will verify this in chapter III.

Based on the above understanding, the palm structure is designed as shown in the figure below. Mainly divided into two parts. The upper palm is used to fix the thumb and forefinger, and its four driving motors (CHR-16GR-050, Chihai motor, China). The fixed slot and the upper gland of the motor are designed to ensure the reliable and effective fixation of the drive source. For the special structure of the thumb, a wire hole is made in the inside of the palm, and the driveline and the sensor signal line are separated. Two convex shaft holes were designed for the base of the thumb on the inside of the palm to fix the thumb. For the index finger and other fingers, two semicircular closure structure is mainly used for fixation. The pins are used for radial fixation and the boss - groove structure is used for axial fixation.

The lower hand is used to fix the middle finger, ring finger and little finger, and its six driving motors. These four fingers are the same distance apart from the thumb. According to the different position of the fingers, the six motors are strewn at random, resulting in emissions, the overall structure is compact and effective, the motor rotating head is facing the fingers, reducing the tension loss caused by the Angle, and improving the force conversion efficiency. Under the motor, holes are left for DB9 and DB25. DB wire is a common integrated wire. We used two groups. The wire in DB25 is the driving power line of the motor. The wire in DB9 is the signal line of each sensor. With a voltage of 5V, it is a relatively weak point, which realizes the separation of strong and weak electricity and guarantees the reliability, efficiency, and safety of the dexterous hand system.

To ensure the strength of the palm as a frame, we use the photosensitive resin material with deposition molding technology. Palm's hardness is relatively high, at the same time does not have the freedom of movement.

Based on the analysis of grasping action, the palmtop soft structure as shown in the figure below is designed and molded with silicone material. On the one hand, this structure needs to have a certain degree of flexibility to ensure that the grasping object can be covered passively in the grasping process, to increase the contact area, and improve the grasping ability. On the other hand, the stiffness of the structure also needs to be guaranteed. If the stiffness is too low, like a balloon, it cannot provide enough support reaction force when contacting the grasping object, which will lead to direct contact with the rigid palm after being compressed. At this time, the protection of the grasping object will also greatly decline, and there is a risk of damage.

To solve the above problems, first of all, the hardness of silicone materials needs to be selected and deployed. The dragon skin silicone rubber used by the research group for a long time can be adjusted by changing the ratio of curing agent.

On the other hand, the design of the palmtop soft structure is also an effective means to improve its stiffness. The strength and stiffness of the structure can be improved effectively by the inspiration of common stiffeners in engineering. We added a heavy plate structure on the back of the soft structure instead

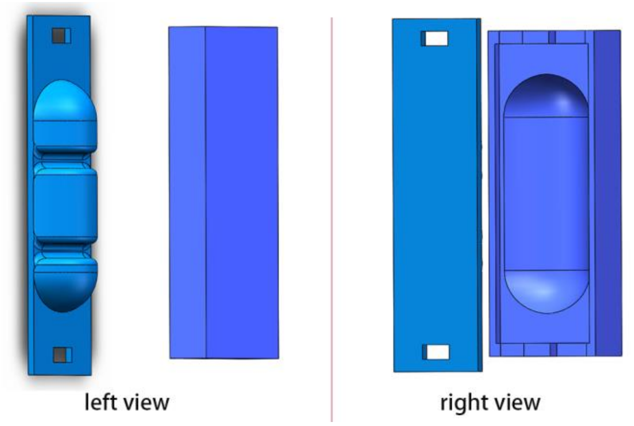

Figure 4. Design of silicone pouring mold

of a hollow bulge. By setting the contrast group, it was found that the two reinforcement slots (The thickness is 2mm and is rounded at 4mm, with a 20mm interval between the two slots.) as reinforcing rib and the silicon rubber with a hardness of 20(Shore hardness) had the advantages of both passive compliance and sufficient supporting force.

Figure 4 shows the 3D model of the mold formed by silica gel casting, which is divided into left and right perspectives to show the upper-end cover and the lower end container respectively. There are matching grooves and bulges at both ends to ensure the positioning accuracy after closing the cover. The 3D printer was used for printing and molding, and the selected material was PLA. First, pour the evenly mixed 30g dragon skin silicone into the lower container, then press down the upper cover. The excess silica gel will overflow from all sides, and the reverse airflow method can ensure that the surface of the solidified silica gel is smooth without bubbles. After molding, there is a redundant silicone film at the edge, using laser cutting machine cutting processing. The result is a palm-centric silicone soft structure that is glued to the inside of the palm.

The molded silicone has 3 air cavities (2 quarter-spheres and 1 semi-cylindrical shape) and 2 reinforced ribs, the overall wall thickness of 2mm (the wall thickness changes of the fillet section is not discussed), in this case, the air cavity bears the function of grasping the object when the shape and the reinforced ribs are to ensure that the palm of a certain degree of rigidity needs, after experimental verification, the role of the two parts of each other, showing a better grasping effect.

3. Experiment results

3.1 Thumb workspace

The workspace of the thumb plays a decisive role in the flexibility of the grasp of the dexterous hand. Based on the above configuration design of the thumb, Determine the DH parameters of the thumb as shown in the table below.

The scope of θ_1 is 0°~120°; The scope of θ_2 and θ_3 are 0°~68°; The scope of θ_4 is -180°~180°.

Table 1 Thumb knuckle size

Variant \ Linkage	1	2	3	4
θ	θ_1	θ_2	θ_3	θ_4
a_i	0.33	0.49	0.51	0
α_i	-90°	0	0	0
d_i	0	0	0	0

We use the Denavit-Hartenberg formalism [22]. Firstly, the length of the connecting rod, the twist angle of the connecting rod, the distance between the two connecting rods and the range of the included Angle of the two connecting rods were stored in the D-H parameter matrix, and then the forward kinematics simulation function of Matlab(R2018a) was used to calculate the forward kinematics of robot in fingertip workspace. The calculated image is shown in Figure 5.

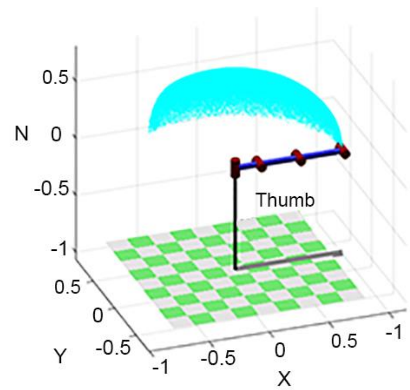

Figure 5. The workspace of the thumb

3.2 Force Transfer Efficient

The following experiments are carried out to determine the transfer efficiency of the actual motor tension to the fingertip pressure.

As shown in Figure 6, the left figure measures the relationship between motor pull and operating time, and the

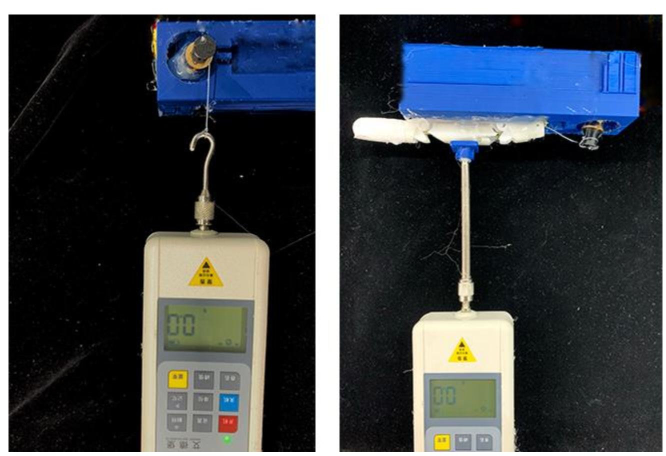

Figure 6. The platform for measuring the motor force(left). The platform of measuring finger force(right)

relationship between the output force of the near-end joint and the running time of the motor on the right. Through the same parameters in two sets of experiments: the motor running time, and then the relationship curve between the motor pull and the near-end joint output force, that is, the force conversion efficiency is obtained.

Select a rope of the same length as the driving rope at the near end, and use a sensitive pull pressure gauge placed horizontally to measure the relationship between the rope tension and the driving time of the motor. During the experiment, ensure that the driving rope is parallel to the horizontal plane, and the axis of the tensile machine is inline with the rope. The state of taking the rope straight and pulling 0N is the initial state, remember that the moment is 0s.

Control the motor at 0.5s per interval to turn 0.5s, read the number of push/pull meter, repeat three experiments, and take its average value as a reference. The data from the two sets of experiments are shown in Figure 7.

It can be seen from the experimental data for the proximal knuckle when the motor driving force F_1 is 10N, the fingertip pressure F_{2Real} is about 2.76N, when the driving force F_1 is 15N, the fingertip pressure F_{2Real} is about 4.26N, the distal knuckle conversion efficiency η is about 28%, and the relative error between the conversion efficiency and the theoretical value ω is 3.9%. The reasons for the error are: the influence of frictional moment, part fatigue strength and precision of the experimental instrument are ignored in the theoretical calculation.

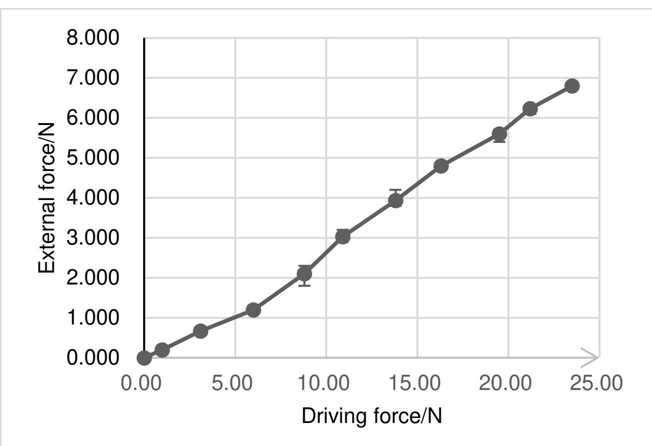

Figure 7. Graph of motor Driving force and External force of the finger

3.3 Contact Area

This section mainly through experiments to verify the palmtop soft structure to grasp the increase of the contact area and the corresponding changes in the maximum grasp load.

We used fluorescent labeling to measure the contact area. Cylinder grasping posture is the best way to show the contact area, so we use a 1.5L water bottle as the object to be grabbed. First, apply the white fluorescent powder evenly to the inside

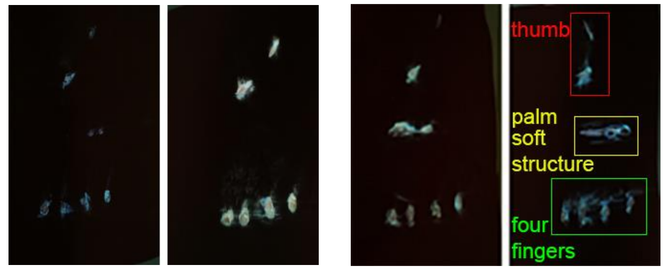

Figure 8. The two pictures on the left are the fluorescent images of the contact area of the robotic hand grasping the water bottle without the palmtop soft structure. From top to bottom are the two joints of the thumb, palm, and four fingertips. In the two pictures on the right, there is the palmtop soft structure with obvious contact on the palm area

of the dexterous hand, including the part that fingers and palms may touch. To ensure that the fluorescent powder can be transferred to the surface of the water bottle during the grasping process, we use a relatively rough cloth to cover the surface of the water bottle to improve the retention rate.

Three rounds of cylinder grasping were performed in the absence of the palmtop soft structure and the presence of the palmtop soft structure. The fluorescent powder was left on the cloth on the surface of the bottle. After the light processing and the two-dimensional expansion of the cloth, keeping the same shooting position, angle, and scale, the contact area as shown in Figure 8. Calculate the number of pixels in the fluorescent part in Photoshop, and get the contact area of 2805 and 4647 in the two cases.

By increasing the contact area of 65.67%, the effectiveness of the palmtop soft structure is proved.

Besides, the effect of the palmtop soft structure on the maximum grasping load of the dexterous hand was further verified.

The cylinder grasping position is also used. The 1.5L water bottle is used as the grasping object, and the grasping weight is changed by changing the volume of internal water. After three times of grasping verification, the maximum grasping load is 0.73 kg without the palmtop soft structure. In the case of the palmtop soft structure, the maximum grasping load was 1.51kg, an increase of 106.85%.

3.4 System Verification

This section mainly introduces the construction of the dexterous hand module and control system and carries out integrated verification on the home-made service robot of the research group to demonstrate the grasping ability of the dexterous hand.

In terms of driver selection, the common DC motor driver size is relatively large, so the L298N chip is chosen as the driver chip. 10 motors, using 2 dual L298N motor drive module and 1 single L298N motor drive module. The chip has the characteristics of strong driving ability and strong anti-interference ability, which is suitable for this kind of multi-motor, small space driving working scene. The built-in 7805 chip in the module can provide 5V voltage to the single-chip

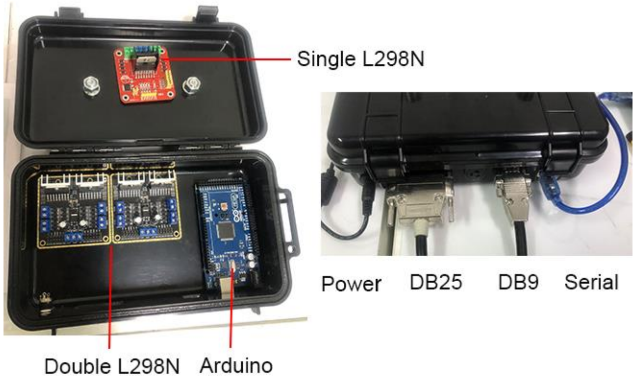

Figure 9. The left figure is the inside view of the control cabinet. The right figure is the external wiring. From left to right, there is Power line, DB25(motor driveline, 12V), DB9(sensor signal line, 5V) and Serial port line

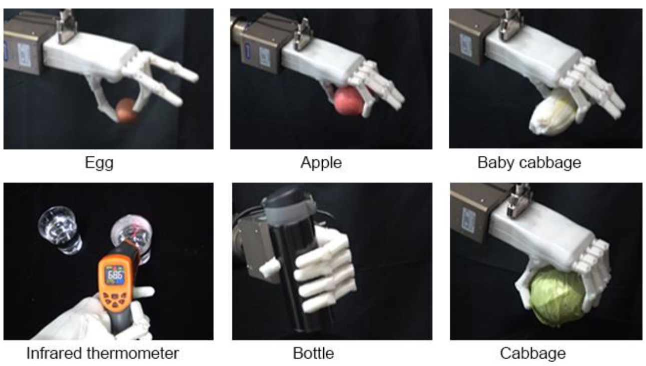

Figure 10. Demonstrations of robotic hand grasp diversity and smart operation

microcomputer. The module uses a large-capacity filter capacitor and a continuous-current protection diode.

A circular film pressure sensor(D1016, 2kg, Rouxi Technology, China) is attached to the fingertip and is used to sense the fingertip contact force when grasping an object. After receiving the grab command, each joint begins the corresponding action, if the fingertip contact force is detected to exceed the threshold, the grab action will be stopped urgently, and the crawl failure will be determined. The threshold will be adjusted to different grabbed objects, and the threshold of fragile is relatively low to ensure the integrity of the grab and the safety of the human-computer interaction.

The dexterous hand is verified by integrated on a homemade service robot as shown in Figure 10. On the one hand, objects with different surface characteristics such as egg, apple, baby cabbage and a water bottle are precisely grasped. On the other hand, a smart operation is also a piece of cake for our robotic hand. Firstly, it holds the thermometer firmly by four fingers and palm except for the index finger. Secondly, the index finger bends to the press launch button and then we can read the temperature of two glasses of water on the screen of the thermometer. The whole process is smooth and natural.

4. Conclusion

In this paper, a configuration design for the thumb ab/adduction movement is proposed, and the improvement of thumb agility is verified by calculating the workspace. A modular finger with rope transmission with two degrees of freedom is designed, and the problem of joint coupling motion in rope transmission is solved. It is verified that the force transmission efficiency of the finger structure is 28%, which reduces the requirement of torque of the motor, and facilitates the modular integration of the whole hand. The soft-rigid coupled palm is designed. With deformable silicone structure added on the palm, it is equivalent to providing a passive degree of freedom for the palm. On the one hand, this soft structure can produce passive deformation when it comes into contact with the object, which has a certain flexibility and improves the contact area with the object by 65.67%. On the other hand, through the structural design of reinforcement, it can also provide enough supporting force, which increases the maximum grasping load of the dexterous hand by 106.85%.

However, the analysis of the silicone structure is not comprehensive. Only one case of a cylinder grasping water bottle has been analyzed and tested. The configuration design and analysis of silicone structure need further in-depth study. In future work, we will focus on the configuration design and optimization of the silicone structure. With the help of the finite element method to analyze the deformation, we can improve its range of adaptability. In a variety of grasping attitude and under the condition of different grab objects, it will achieve better crawl ingenuity and smooth operation.

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: Zhe Liu was in charge of the whole project and particularly the configuration design and fabrication. Zeyi Zhang assisted with grasping demonstrations and picture processing. Weihong Liu and Guozhen Huang were responsible for the control system and algorithm. Diansheng Chen was responsible for the mathematical guidance; Yongkang Jiang revised the manuscript and made some improvements.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Figures

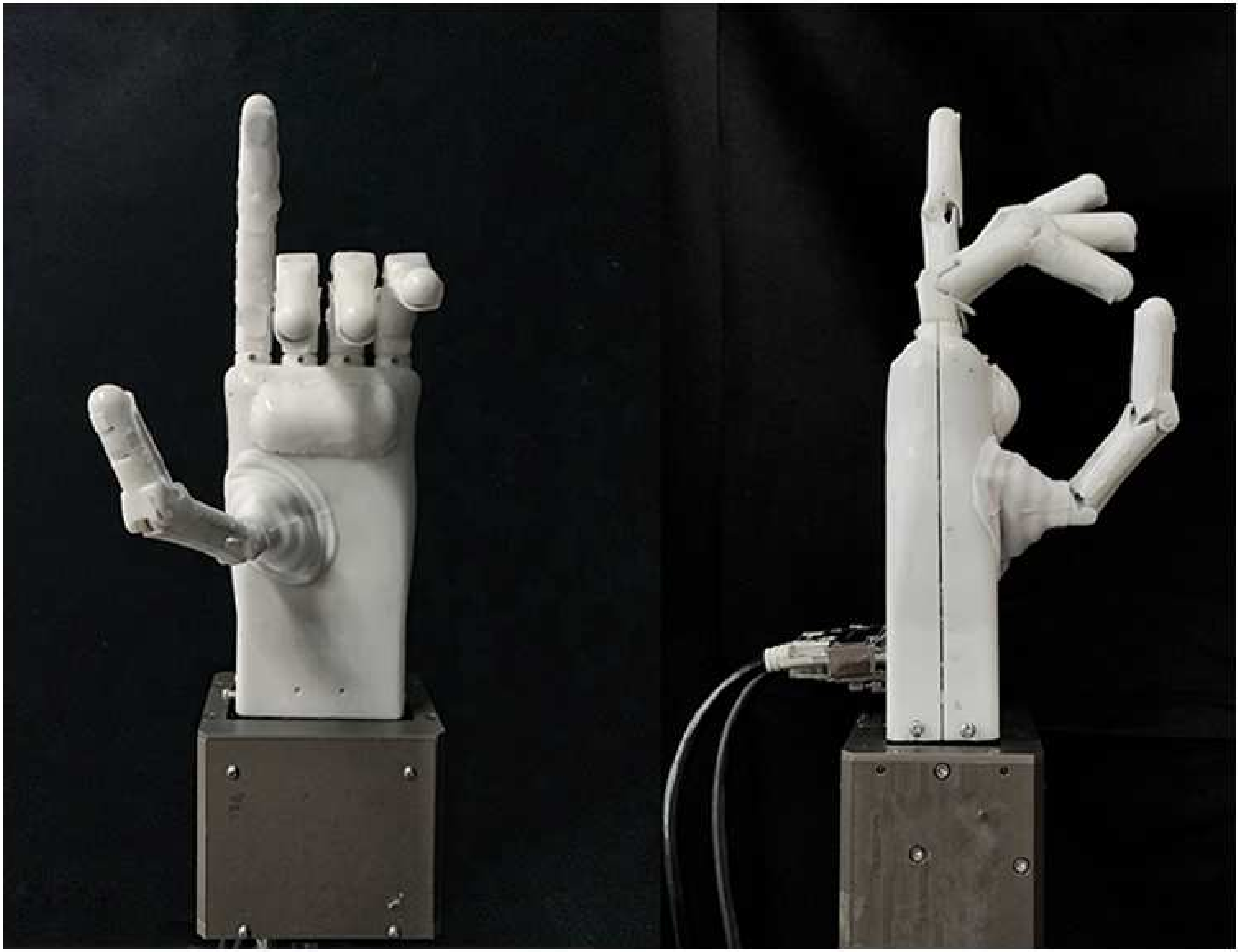

Figure 1

Front view and side view of soft-rigid hybrid hand

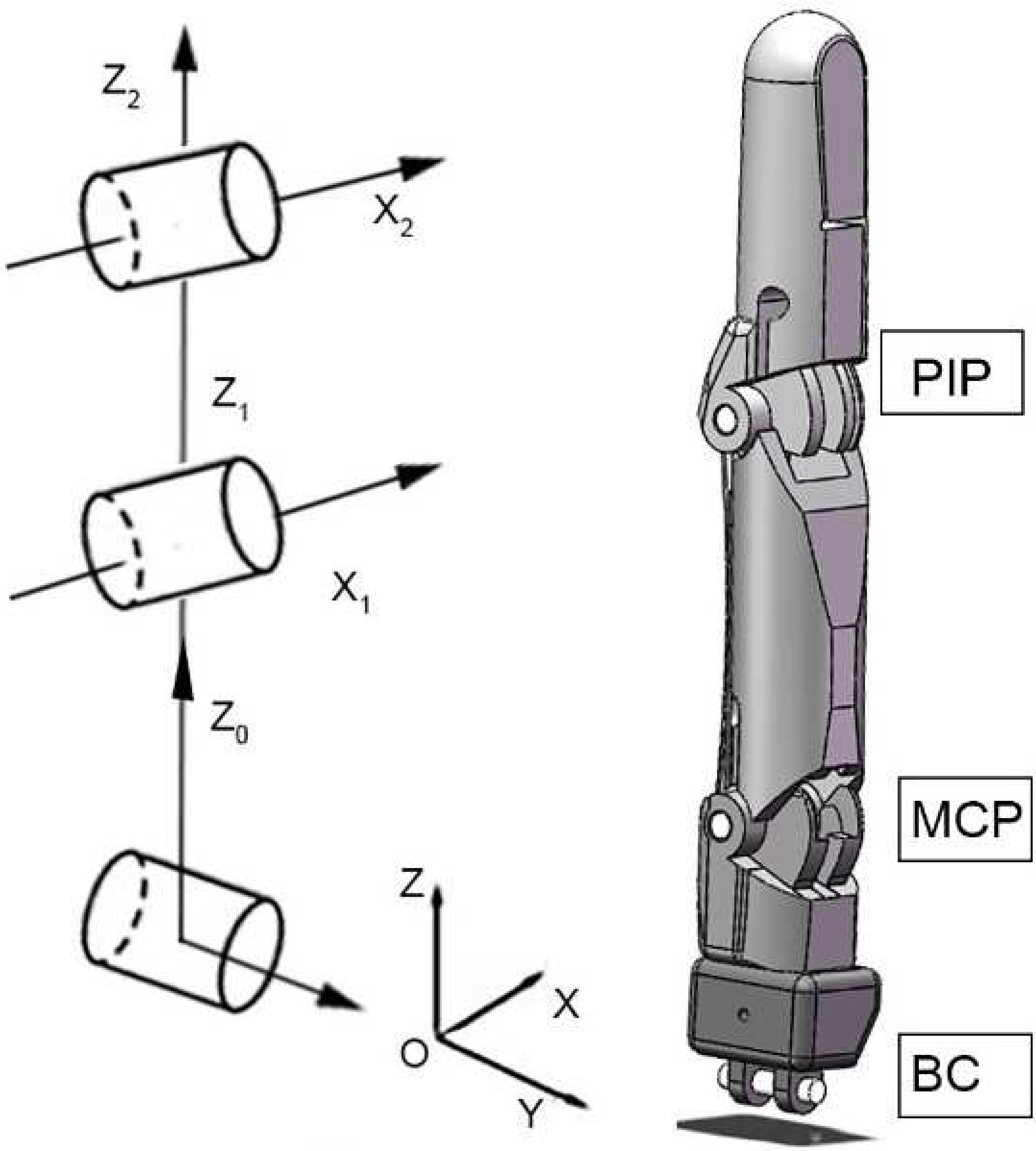

Figure 2

Schematic diagram and 3D model of the thumb

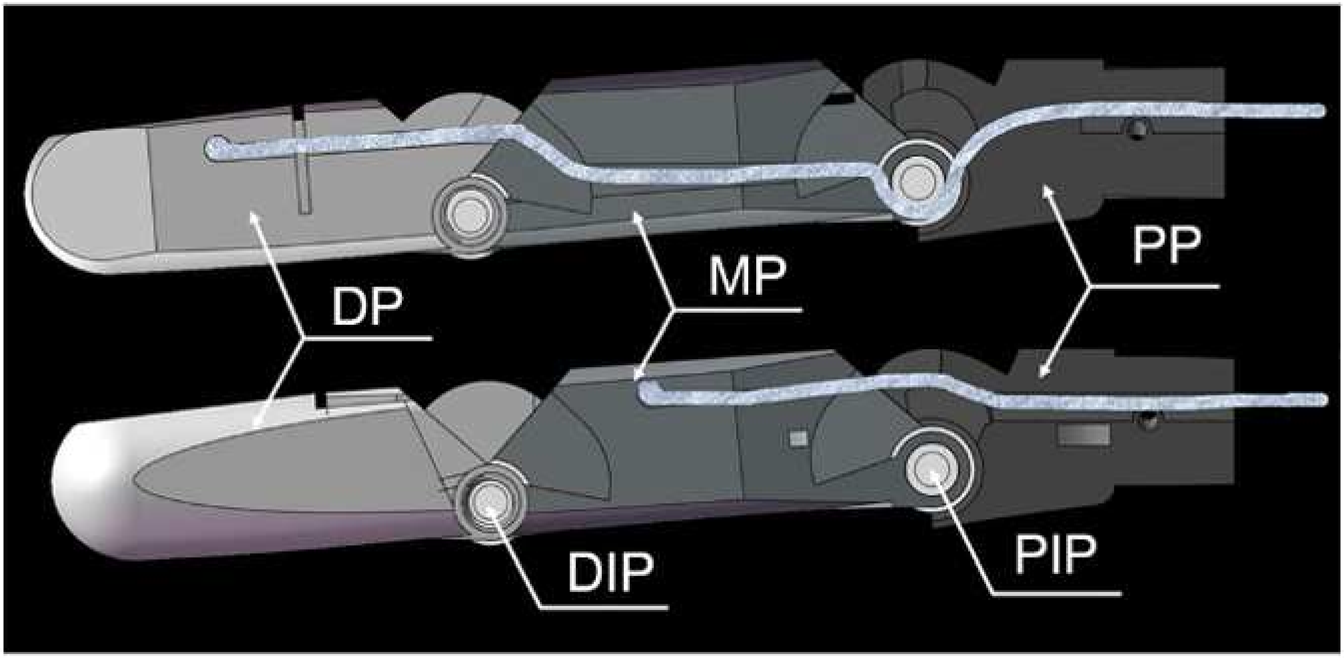

Figure 3

Configuration design of other four fingers

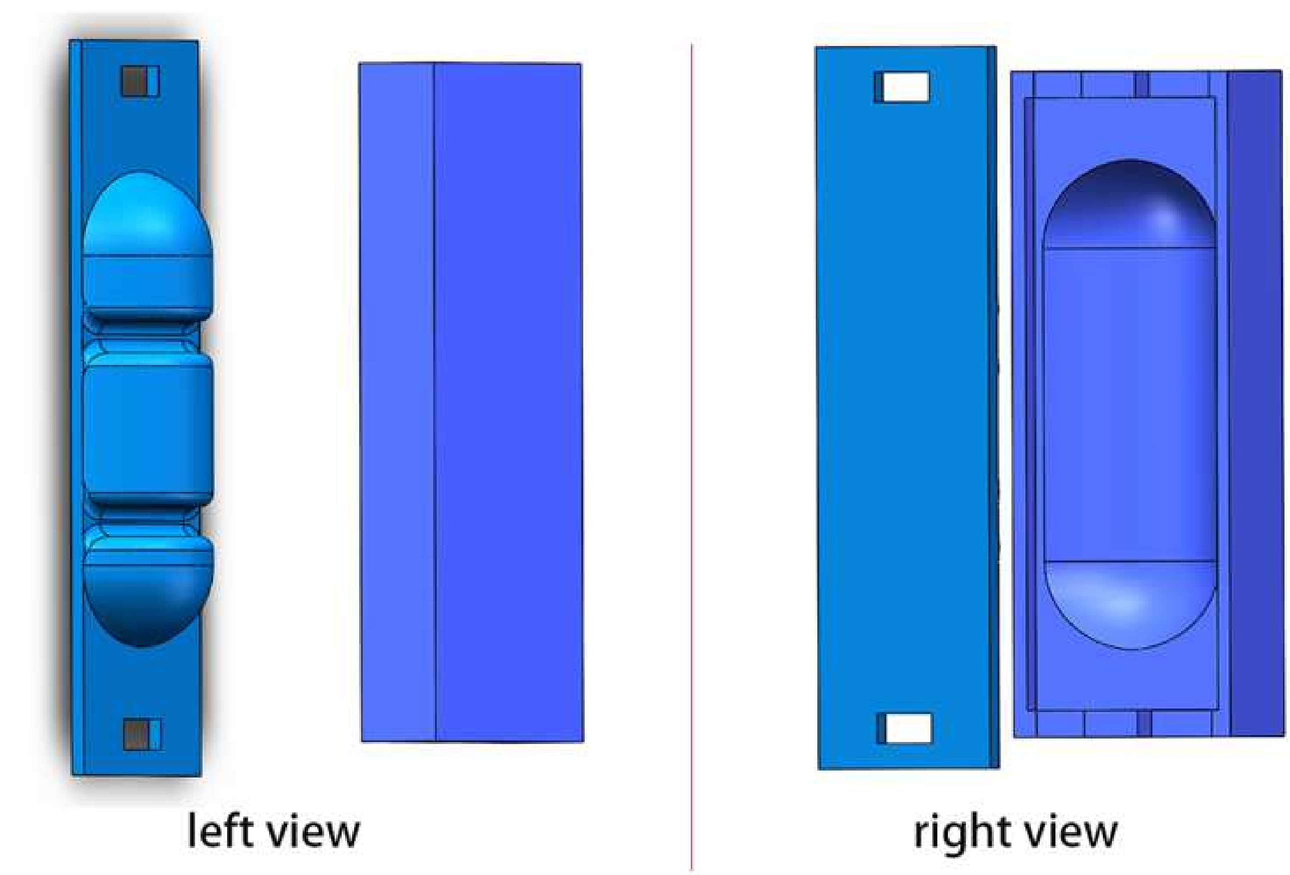

Figure 4

Design of silicone pouring mold

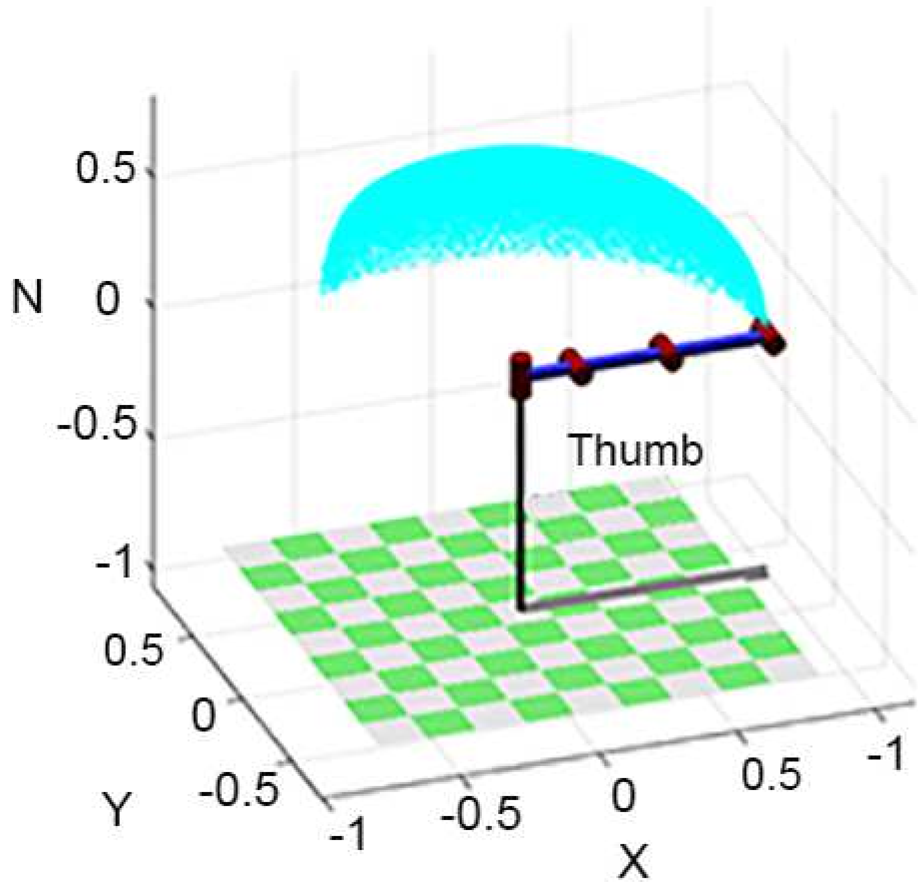

Figure 5

The workspace of the thumb

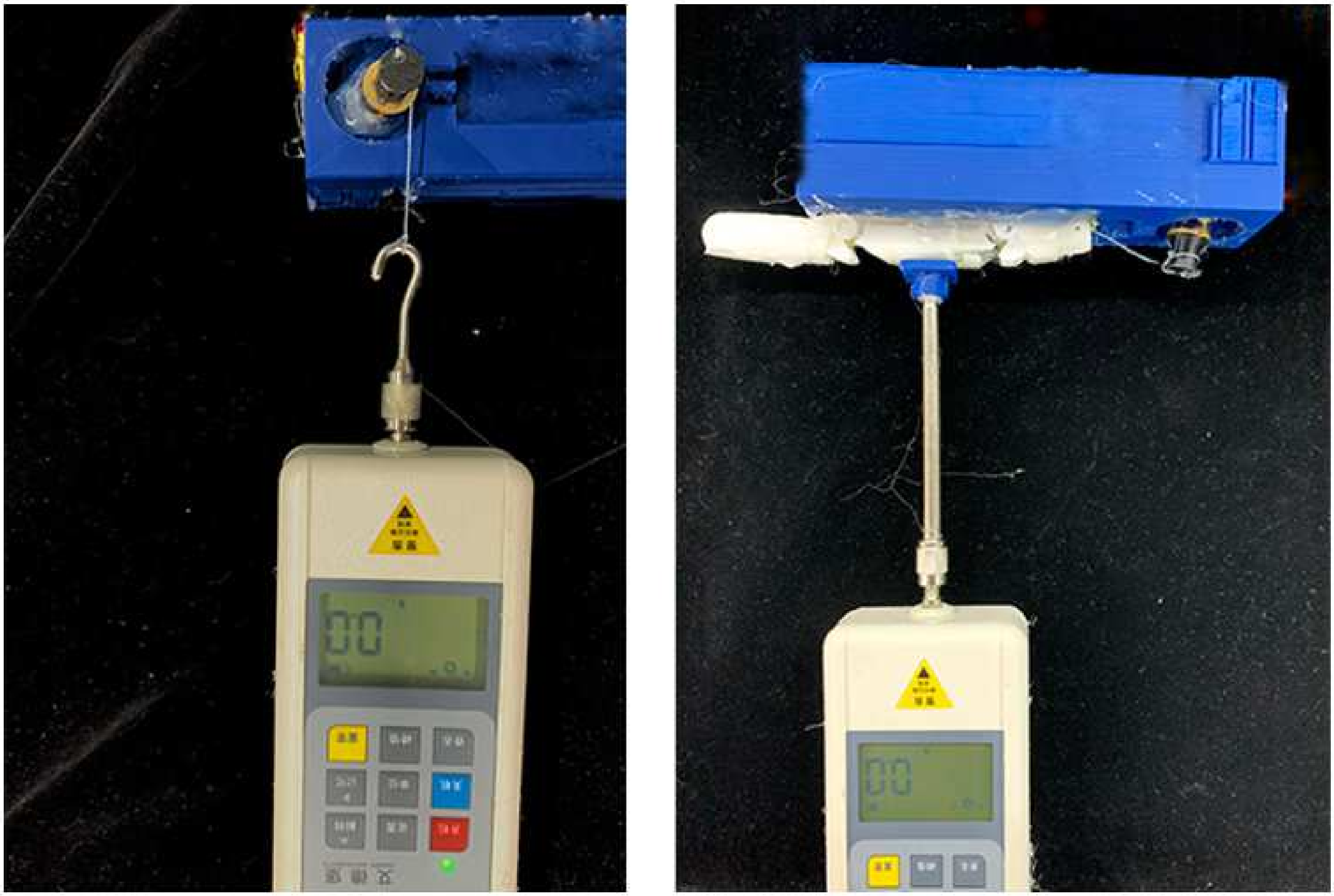

Figure 6

The platform for measuring the motor force(left). The platform of measuring finger force(right)

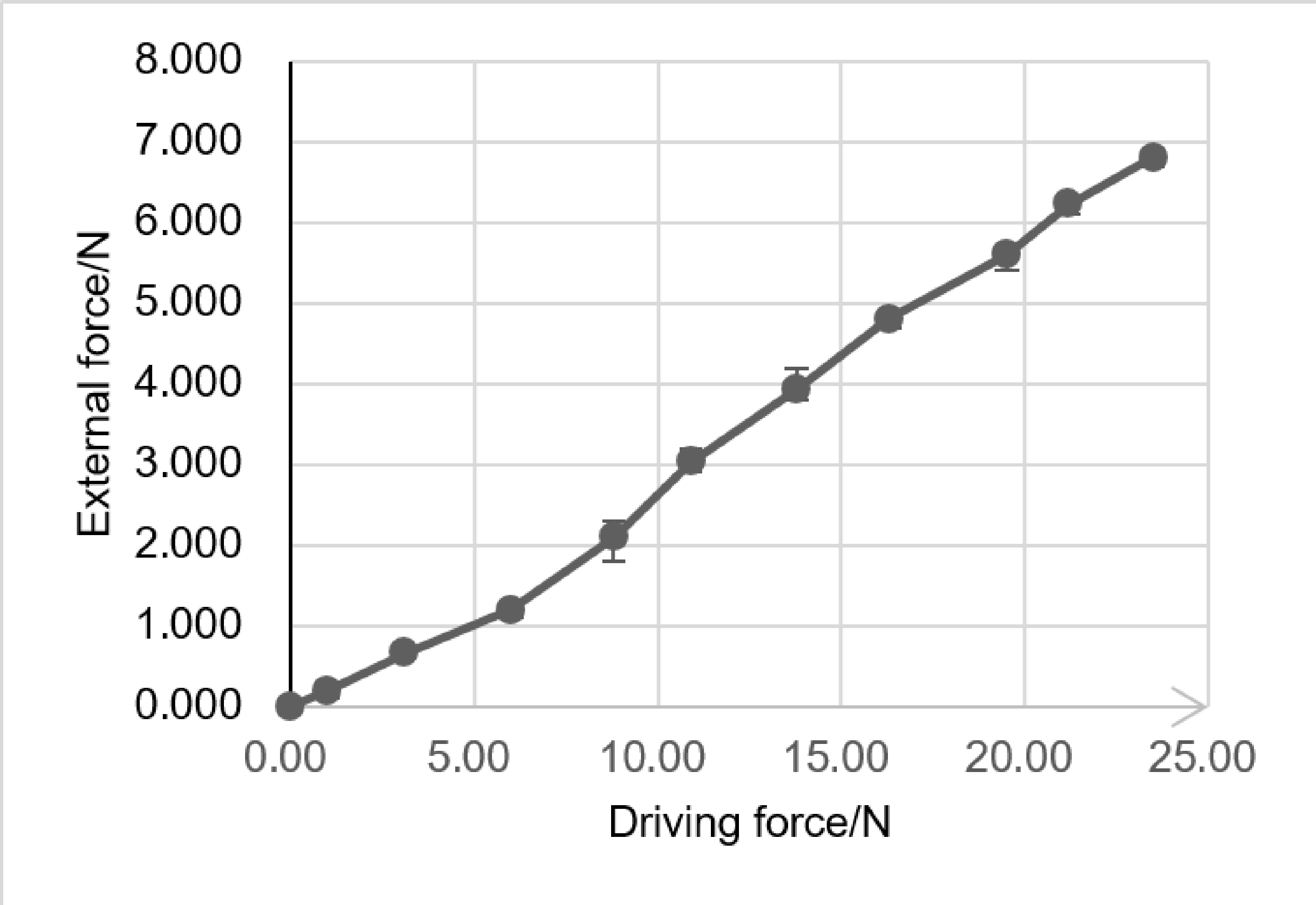

Figure 7

Graph of motor Driving force and External force of the finger

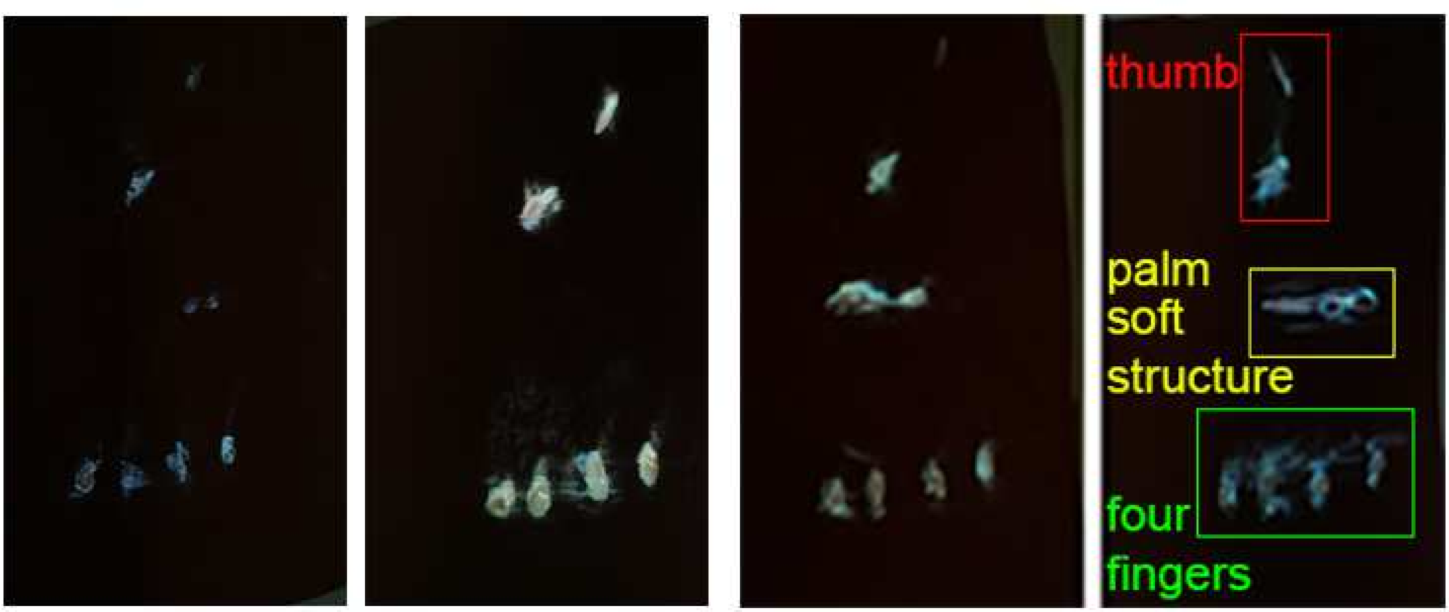

Figure 8

The two pictures on the left are the fluorescent images of the contact area of the robotic hand grasping the water bottle without the palmtop soft structure. From top to bottom are the two joints of the thumb, palm, and four fingertips. In the two pictures on the right, there is the palmtop soft structure with obvious contact on the palm area

Figure 9

The left figure is the inside view of the control cabinet. The right figure is the external wiring. From left to right, there is Power line, DB25(motor driveline, 12V), DB9(sensor signal line, 5V) and Serial port line

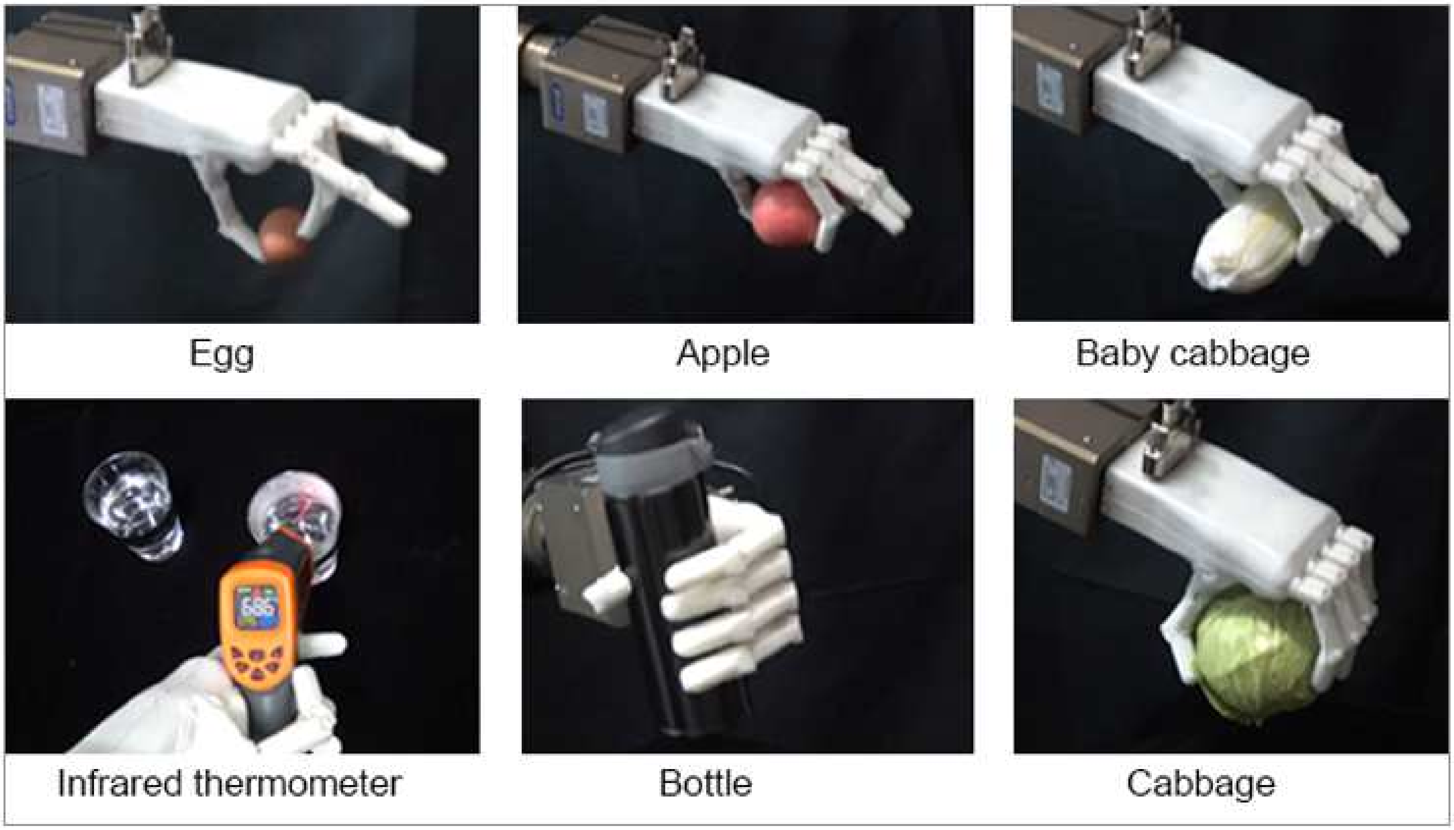

Figure 10

T Demonstrations of robotic hand grasp diversity and smart operation