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A Novel Coupled and Self-adaptive Anthropomorphic Robot Finger with a Dual-oblique-Belt Mechanism

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Abstract—Traditional spring-tendon-driven self-adaptive prosthesis hand, such as the Stark Hand, uses multiple springs to realize self-adaptive grasping, and uses tendon to drive finger extension. Its grasping force is related to joint angle, and its grasping force is not adjustable, which affects its use effect. This paper develops a novel coupled and self-adaptive anthropomorphic robot finger with a dual-oblique-belt mechanism (COSA-DOB finger). The COSA-DOB finger consists of a base, three phalanges, three joint shafts, a motor, a transmission mechanism, two gears, seven transmission wheels, two transmission belts and two springs. This paper presents the motion process and grasping force analysis of the finger, and discusses the grasping performance of COSA-DOB finger. The experimental results show that the COSA-DOB finger can achieve three-joint coupled and self-adaptive grasping. In the finger, three joints rotate at the same time, suitable for the accurate grasping of the end phalange. When the proximal phalange contacts the object, the proximal joint stops rotating, and the next joint continues to rotate … until the end phalange contacts the object, so as to realize the force-type envelope grasping of the object. For objects of different shapes and sizes, the finger self-adapts. According to the different positions of the object, the finger can automatically switch between the two modes of the coupling grasping and the self-adaptive grasping.

Keywords: Robot hand, prosthetic hand, Coupling grasping, Self-adaptive grasping, Underactuated finger.

I. INTRODUCTION

The lack of hand will have a great impact on people's daily life, so the development of anthropomorphic artificial hand is of great value. The human hand has more degrees of freedom, which can be combined with the sensory system of musculocutaneous skin to accomplish the task of dexterous grasping. For objects of different shapes and sizes, appropriate grasping can be carried out. Some of them use the end phalange to pinch accurately, and some use the force envelope to grasp. Such complex structure and perceptual control feedback system make it difficult to replicate. Because of this complexity, since the 1950s, most robotic hand prostheses have adopted humanoid skeleton structure with relatively small changes. Users have established standards for robotic hand prostheses, including humanoid appearance, low weight, low cost, silent operation, and the ability to perform most of the tasks required in daily life. At present, many of the available commercial robotic prostheses exceed the acceptable weight limit, and have high cost, so they are not suitable for wide-scale application.

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In order to imitate the high flexibility, reliability and wide applicability of human hands as much as possible, since the 1980s, researchers have developed dexterous hands with more degrees of freedom, of which MIT is the most famous. The Utah/MIT hand [1] has high anthropomorphic structure and complex and changeable operation functions, and has high academic research value. However, its online control is almost impossible to achieve, which limits its application in industrial production. Since then, the research of dexterous hand has become a hotspot in this field, with many achievements, such as Gifu hand II [2], DLR-HIT hand [3], NAIST hand [4], Robonaut hand [5], KIST hand [6]. Dexterous hand often uses a single motor to drive each degree of freedom, so it has high accuracy. However, with the increasing demand for robotic hand, complex transmission devices and control sensors make it huge in structure and complex in algorithm, which makes it more and more difficult to be used as a prosthesis for the disabled in daily life.

In this case, researchers try to use fewer motors to drive more joints. Another new concept of robot hand, underactuated robot hand, was first proposed by LAVAL University in the 1990s, and they proposed a novel SARAH hand [7]. Because the number of underactuated hand motors is lower than the number of joint degrees of freedom, the motor can be placed inside the palm, and the larger motor can be used to obtain greater grip. Such characteristics make it have high application prospects and have been put into use in the field of industrial support, such as a Robotiq hand [8] developed by Laval University, GR2 Gripper [9], Yale University's SDM hand [10-11] and Outhampton hand [12].

However, in the research and development of anthropomorphic hand, under-actuated anthropomorphic finger is mostly two-joint finger structure, and most of them only have limited grasping mode, there is still much room for improvement. For under-actuated robot hand, the main grasping modes are as follows: coupling grasping, parallel grasping and self-adaptive grasping, which are adopted for different grasping situations. At present, some achievements have been made in the grasping mode fusion of two-joint robot hands, such as LARM hand [13], TH-3R hand [14], COSA hand [15] and PASA hand [16]. They integrate coupling grasping mode or parallel grasping mode with the self-adaptation so as to improve the performance of the finger.

In this paper, a novel coupled and self-adaptive humanoid finger with a dual-oblique-belt mechanism is proposed, which has stable grasp, large grasp force and good adaptability to different shapes of objects. Using double transmission belt mechanism, three-joint coupling adaptive grasping is accomplished by wheel rotation and oblique belt transmission, which has good grasping effect. In the following chapters, the design concept, working principle, concrete structure, dynamics and kinematics analysis will be introduced.

II. DESIGN OF COSA-DOB FINGER

A. Design concept

The coupling grasping mode and self-adaptive grasping mode are two most common used grasping types for the underactuated robot hands.

1)Coupling grasping mode

Coupling grasping means that when the first phalange rotates, the second phalange which is coupled to it rotates at the corresponding angle according to a certain coupling ratio, while the third phalange also rotates relative to the first phalange. The coupling ratio depends on the specific design of the transmission mechanism. Coupling grasping mode realizes three phalanges linkage grasping, which is suitable for the accurate grasping of the end phalange, and has a good grasping effect for small-sized objects.

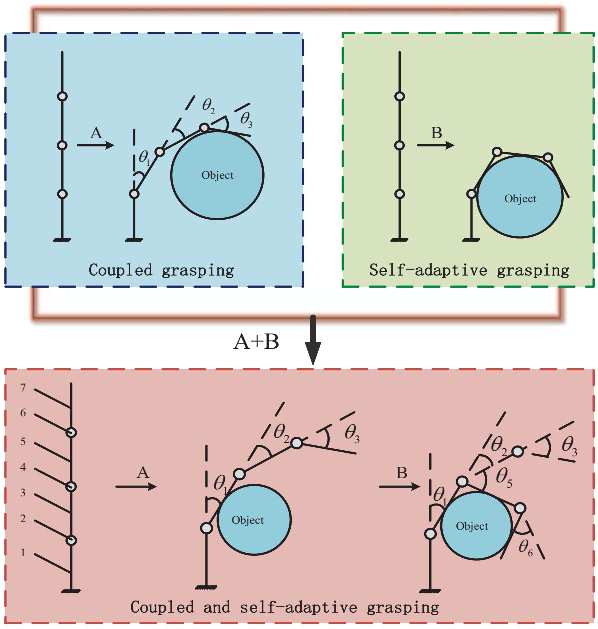


Figure 1. The COSA grasping mode : integration of two grasping modes 1-Base; 2-First shaft; 3-First phalange; 4-Second shaft; 5-Second phalange; 6-Third shaft; 7-Third phalange.

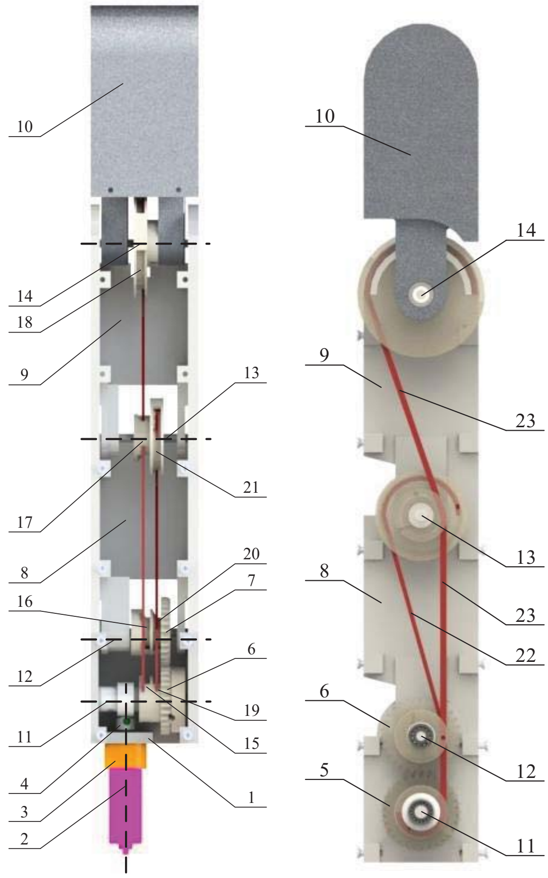
2) Self-adaptive grasping mode

Self-adaptive grasping means that for objects of different shapes and sizes, fingers can adapt to their curves during the grabbing process. When the first phalange touches the object, the first joint stops rotating, and the second joint continues to rotate until the second phalange touches the object, so as to realize the grip of the force envelope of the object. With the concept of self-adaptation, it is easy to realize the general grasping in the industry production.

As to the design concept of the COSA-DOB finger, two grasping modes are fused to improve the grasping performance, as shown in figure 1. According to the different positions of the object, coupling grasping is implemented before the first phalange touching the object. After the first phalange touching the object, self-adaptive envelope grasping is automatically carried out.

B. Structure of COSA-DOB finger

According to the design concept, the couple grasping mode and self-adaptive grasping mode will be integrated in a three joints finger. The coupled of three phalanges is realized with the specific ratio belt driving mechanism and the self-adaptive of the second phalange and the third phalange are implemented with two torsional spring. Based on that, the detailed structure has been shown in the 3D assembling model in Figure 2.



a) b)

Figure 2. Structure of the COSA-DOB finger
1-base; 2-motor; 3-reducer; 4-worm; 5-worm gear; 6- first gear; 7-second gear; 8-1st phalange; 9-2nd phalange; 10-3rd phalange; 11-transition shaft; 12-1st shaft; 13-2nd shaft; 14-3rd shaft; 15-21-1-7th wheel; 22-1st transmission belt; 23-2nd transmission belt; 24-1st torsional spring; 25- 2nd torsional spring.

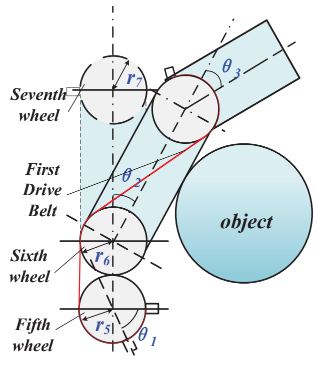
The connection relations are: Motor is fixed on the base, and through the worm and gear transmission mechanism, drive the transition shaft. The first wheel, the fifth wheel, the first gear are fixed on the first shaft; the second wheel, the sixth wheel and the second gear are fixed together; the third wheel and the seventh wheel are fixed together, and the second gear and the first phalange, the seventh wheel and the second phalange are respectively connected by the first and second torsional springs. The first wheel and the fourth wheel are meshed through second transmission belt, similarly, the fifth wheel and the seventh wheel are meshed through first transmission belt.

C. Working principle of COSA-DOB finger

The grasping process of COSA-DOB finger includes two stages: three joint coupling grasping and self-adaptive grasping. According to the structure of COSA-DOB finger, the working principle is as follows:

1) Three joint coupling grasping

Z_1 --- Number of teeth for first gear;
Z_2 --- Number of teeth for second gear;
θ_1 --- The rotation angle of the transition shaft;
θ_2 --- The rotation angle of the first phalange during coupling grasping mode;
θ_3 --- The rotation angle of the second phalange during coupling grasping mode;
θ_4 --- The rotation angle of the third phalange during coupling grasping mode;
r_1-r_7 --- The radius of first to seventh wheel;
t_1 --- Coupling ratio between second phalange and first phalange;
t_2 --- Coupling ratio between third phalange and first phalange.



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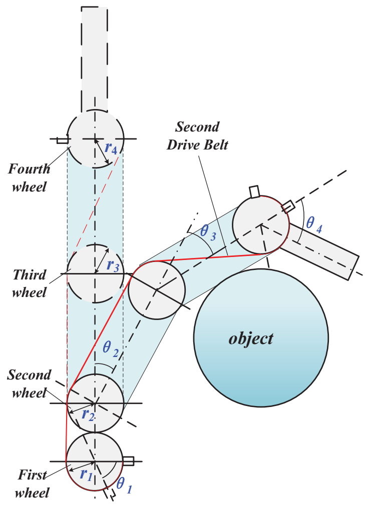

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Figure 3. Three joint coupling grasping process

The coupled rotation from the first to the third phalange is realized through two groups of pulley drive mechanisms, according to the meshing relationship between pulleys, the following relations can be obtained:

$$\frac{\theta_1}{\theta_2} = \frac{Z_2}{Z_1} \tag{1}$$

According to the mesh relationship of the pully transmission mechanism, one can obtain the equations:

$$r_1\theta_1 + r_2\theta_2 + r_3\theta_3 = r_4\theta_4 \tag{2}$$

$$r_5\theta_1 + r_6\theta_2 = r_7\theta_3 \tag{3}$$

$$t_1 = \frac{\theta_3}{\theta_2} \tag{4}$$

$$t_2 = \frac{\theta_4}{\theta_2} \tag{5}$$

For simplified the calculation, assuming that the dimensions of the wheels fulfill the following relationships:

$$Z_1 = Z_2 \tag{6}$$

$$r_1 + r_2 + r_3 = r_4 \tag{7}$$

$$r_5 + r_6 = r_7 \tag{8}$$

One can obtain that:

$$t_1 = \frac{\theta_3}{\theta_2} = 1 \tag{9}$$

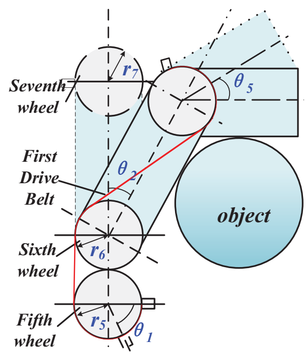
$$t_2 = \frac{\theta_4}{\theta_2} = 1 \tag{10}$$

That is to say:

$$\theta_1 = \theta_2 = \theta_3 = \theta_4 \tag{11}$$

θ_5 --- The rotation angle of the second phalange during the self-adaptive grasping mode;
θ_6 --- The rotation angle of the third phalange during the self-adaptive grasping mode.

When the three-joint coupling grasping is completed, if only the first phalange touches the object, then the second phalange and the third phalange successively carry out the self-adaptive envelope grasping mode, its working principle is shown in Figure 4.



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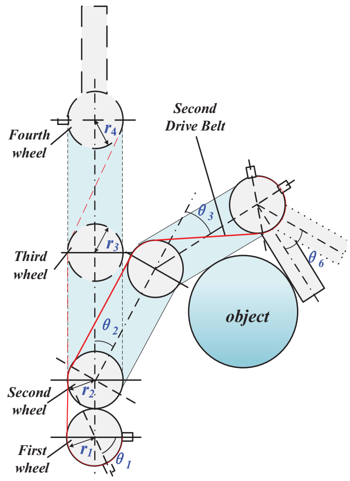

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Figure 4. Self-adaptive grasping process

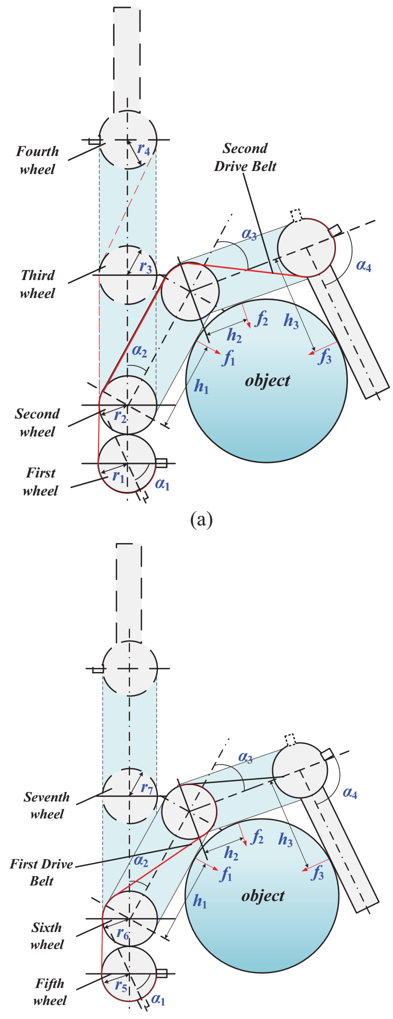
The driving wheel of each phalange is connected with the phalange through the torsional spring, and when the phalange is blocked, the torsional spring is stretched to complete the self-adaptive grasping action of each phalange.

Based on the principle described above, the coupling grasping and self-adaptive grasping have been successfully combined in the three-joints finger. Thus the COSA-DOB finger has larger application field and better grasping stability compared with the exciting robot hands.

III. MECHANICAL ANALYSIS

In this section, the parameters which have impact on the grasping forces of all three phalanges will be considered and discussed in detail. Force analysis of the COSA-DOB finger grasping a ball will be performed to evaluated the ptendonrty of the finger.

T --- Torque provided by reduced motor, *N*;
i --- Reduction ratio of worm gear transmission mechanism;
η --- Overall transfer efficiency;
α_1 --- Rotational angle of the transition shaft, *rad*;
α_2 --- Angle of the first phalange with regard to base, *rad*;
α_3 --- Angle of the second phalange with regard to base, *rad*;
α_4 --- Angle of the third phalange with regard to base, *rad*;
k --- Stiffness coefficient of torsional springs, *N.mm/rad*;
h --- Vertical distance from distal shaft to action point of force on distal phalange, *mm*;
f_1 --- Reactive force of object against first phalange, *N*;
f_2 --- Reactive force of object against second phalange, *N*;
f_3 --- Reactive force of object against third phalange, *N*;
h_1 --- Vertical distance from first shaft to action point of force on first phalange, *mm*;
h_2 --- Vertical distance from second shaft to action point of force on second phalange, *mm*;
h_3 --- Vertical distance from third shaft to action point of force on third phalange, *mm*;
F_1 --- The tension force in the first drive belt, *N*;
F_2 --- The tension force in the second drive belt, *N*.



(b)

Figure 5. Force analysis of COSA-DOB finger

There are several situations for the COSA-DOB finger grasping the object, take the grasping process of a ball as an example, the COSA-DOB finger can catch the object with the maximum of three contact points. If the second phalange hasn't got in touch with the object when the self-adaptive grasping process is finished, it is still possible for the COSA-DOB finger to perform a stable grasping with two contact points. Generally speaking, as the most common situation, the three points contact situation has been shown in figure 5.

The second driving belt drives the distal phalange rotating, thus a reacting force f_3 is performed on the distal phalange from the object. According to the torque regard to the distal phalange is balanced, one can obtain the relationship between f_3 and F_1 as follows:

$$F_1 r_4 = f_3 h_3 \tag{12}$$

Similarly, the second phalange is dragged by the first driving belt around the second shaft. So the equation of F_2 can be derived from the torque balance principle to the second shaft.

$$F_2 r_7 = f_2 h_2 + k\left(\frac{\alpha_3}{t_1} - \alpha_2\right) \quad (13)$$

The gear makes the torsional spring deform elastically, pulls the first finger to rotate, extrudes each other with the object, and generates the action force f_1. According to the balance of the moment to the first shaft, the following relations can be obtained:

$$f_1 h_1 = k\left(\frac{\alpha_4}{t_2} - \alpha_2\right) \quad (14)$$

The total COSA-DOB finger is driven by only one motor, so it provides all the power for the mechanism generating the contact forces to the grasping object and the deformation of the torsional spring, considering the torque balance of the whole mechanism with regard to the transition shaft, one can obtain the equation which expresses the relationship of F_1, F_2, f_1 and T.

$$T\eta i = F_1 r_1 + F_2 r_5 + f_1 h_1 \quad (15)$$

Moreover, consider the reaction forces exerted on the object should be balanced in the x direction, so it can also be derived that the f_1, f_2 and f_3 should have the relationship as follows:

$$f_1 \cos\alpha_2 + f_2 \cos(\alpha_2+\alpha_3) + f_3 \cos(\alpha_2+\alpha_3+\alpha_4) = 0 \quad (16)$$

By combining equation (12-16), the following expression of the reaction forces f_1, f_2 and f_3 can be obtained:

$$f_1 = \frac{k\left(\frac{\alpha_4}{t_2} - \alpha_2\right)}{h_1} \quad (17)$$

$$f_2 = \frac{M - N + P - Q}{h_1\left[r_4 r_5 h_2 \cos(\alpha_2+\alpha_3+\alpha_4) - h_3 r_1 r_7 \cos(\alpha_2+\alpha_3)\right]} \quad (18)$$

Where,

$$M = T\eta i r_7 r_4 h_1 \cos(\alpha_2+\alpha_3+\alpha_4),$$

$$N = k\left(\frac{\alpha_4}{t_2} - \alpha_2\right) r_4 r_7 h_1 \cos(\alpha_2+\alpha_3+\alpha_4),$$

$$P = k\left(\frac{\alpha_4}{t_2} - \alpha_2\right) \cos\alpha_2 h_3 r_1 r_7,$$

$$Q = k\left(\frac{\alpha_3}{t_1} - \alpha_2\right) r_4 r_5 h_1 h_2 \cos(\alpha_2+\alpha_3+\alpha_4).$$

$$f_3 = -\left[\mathrm{K} + \frac{\mathrm{U}+\mathrm{V}-\mathrm{W}}{L}\cos(\alpha_2+\alpha_3)\right] \quad (19)$$

Where,

$$K = \frac{k\left(\frac{\alpha_4}{t_2} - \alpha_2\right)\cos\alpha_2}{h_1 \cos(\alpha_2+\alpha_3+\alpha_4)},$$

$$U = T\eta i r_7 r_4 h_1 - k\left(\frac{\alpha_4}{t_2} - \alpha_2\right) r_4 r_7 h_1,$$

$$V = \frac{k\cos\alpha_2 h_3 r_1 r_7 \left(\frac{\alpha_4}{t_2} - \alpha_2\right)}{\cos(\alpha_2+\alpha_3+\alpha_4)},$$

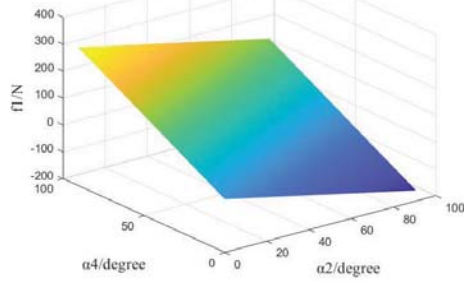
$$W = k\left(\frac{\alpha_3}{t_1} - \alpha_2\right) r_4 r_5 h_1 h_2,$$

$$L = h_1\left[r_4 r_5 h_2 \cos(\alpha_2+\alpha_3+\alpha_4) - h_3 r_1 r_7 \cos(\alpha_2+\alpha_3)\right].$$

Reaction force f_1, f_2 and f_3 with regard to the phalanges' angles α_2, α_3 and α_4 can be calculated with equation (17-19) respectively. The actual dimensions of the corresponding parameters of the COSA-DOB finger has been set as:

r_1=20mm; r_2=20mm; r_3=20mm; r_4=60mm; r_5=20mm; r_6=20mm; r_7=40mm; T=5000$N*m$; η=0.9; i=2; h_1=60; h_2=100; h_3=70; k=0.5$\pi N*m$.

Considering that the actual limit of the rotation angle, one should assume that the ranges of the angle α_2, α_3 and α_4 are all between 10 degree and 80 degree. In order to enable it to be graphically represented, make the following assumptions: $\alpha_3 = \alpha_2$+5 degree. Therefore, the diagrams of f_1, f_2 and f_3 changing with the variable α_2 and α_4 have been shown in figure 6.



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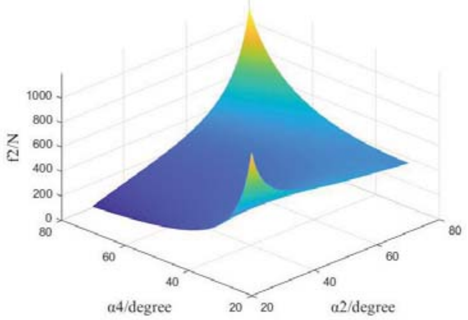

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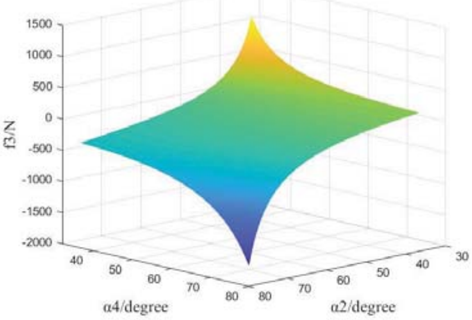

(c)

Figure 6. Force analysis of the COSA-DOB finger

IV. Prototype And Experiments

The prototype of the COSA-DOB finger has been manufactured and assembled. The grasping experiments results shows that the COSA-DOB finger can finish the coupling grasping and self-adaptive grasping successfully, and it can adapt to the objects with different sizes, shapes and materials.

Figure 7. Grasping experiments of the COSA-DOB finger.

V. Conclusions

In view of the shortcomings of the existing prosthetic hands for the disabled, a novel coupled and self-adaptive anthropomorphic robot finger (COSA-DOB finger) with a dual-oblique-belt mechanism is proposed.

The grasping performance of the COSA-DOB finger was studied. The grasping posture and relationship between grasping forces and angles are presented. The analysis shows that the COSA-DOB finger has high grasping stability when the system parameters are appropriate. The finger is suitable for the use of prosthetic hands for the disabled.

Under the cooperation of electromyography control, the new hand with COSA-DOB fingers will have further applications in other fields, such as industry, medical cooperation, geological and aerial exploration, etc.

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