Design and experimental verification of underactuated prosthetic hand

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***Abstract*—Underactuated prosthetic hand has attracted growing attention due to its light weight and easy control. In this paper a single linear motor is used to drive the prosthetic hand, and the palm of the hand has three arches similar to that of human hands. Besides a series of experiments were carried out to test the power grasp and the precision grasp function of the prosthetic hand. The factors influencing the success rate of power grasp and the stability of precise grasp are analyzed, and the direction to improve its performance and usability is given.**

Keywords—prosthetic, underactuated, flexible, biomimetic

I. INTRODUCTION

Most major upper-limb amputees (ULAs) are fitted with prostheses after the amputation[1], however, in long-term use, the rate of prosthesis deprecation is still high[2]. The reasons for prosthetic abandonment include: the difference between the perceived needs of ULAs and the functionality of prosthetics; And consumers' double high standards for the form and function of prosthetic hands[3].

The biomimetic form of prosthetic hands is a basic requirement in the design of prosthetic hands, and in addition, the dexterity and ease of manipulation of their functions are also important aspects of prosthetic hand design, which however have been contradictory in many previous designs. Therefore, how to achieve dexterous grip control through simple operation form is an important subject worth studying.

To achieve dexterity with simple manipulation at the same time, principal component analysis (PCA) was used to analyze the motion characteristics of the human hand when performing activities of daily living (ADLs), thus effectively achieving dimensionality reduction[4,5]. According to the above method, prosthetic hands can achieve highly biomimetic motion features based on under-actuation. This inspired scientists to add mechanical compliance to the design of prosthetic hand which allow the hand to adapt the device's configuration during the interaction with the environment. Improving passive compliance in mechanical mechanisms intrinsically implements these synergies, and this method has been widely used in rigid prosthetic hands recently[6-8]. Beyond that, soft robots have attracted growing attention due to their compliant structure and safe operation. Therefore many soft-robotic grippers have been designed and tested, and the results show that the compliance of flexible structure is of great help to improve grip stability[9]. Additionally, flexible structures are usually manufactured by 3D printing or casting with low cost and light weight.

Therefore, giving full play to the advantages of flexible structure in the design of prosthetic hand can simplify both the structure of the prosthetic hand and the control of the prosthetic hand. At present, there are two main driving modes of flexible prosthetic hand, pneumatic and line-driven, but flexible prosthetic hands that are worn on the stump of ULAs have rarely reported.

In this paper, we present a new underactuated prosthetic hand based on the continuum structure proposed in [10] and explore the methods to improve its bionics and synergy. Experiments were carried out to test the grip performance of the prosthetic hand and indicate directions for further optimization of prosthetic hands. The design of the underactuated scheme will be presented in Section II, followed by the grasp function test of the prosthetic hand in Section III. Experimental results on the fabricated gripper will be presented in Section IV, with conclusions in Section V.

II. DESIGN

The underactuated prosthetic hand has humanlike size with the weight of 273.2g (excluding power supply and microcontroller development board) and is driven by a single linear motor. The

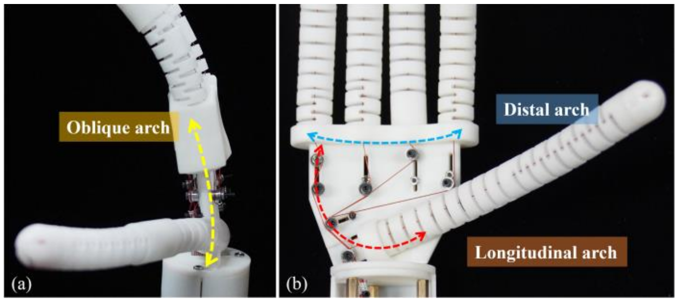

Fig. 1. (a) The yellow line represents the oblique arch of the prosthetic hand. (c) The blue line represents the distal arch and the red line represents the longitudinal arch of the prosthetic hand.

finger structure of the prosthetic hand designed in this paper is identical to that of the TN hand[10] and has the same kinematic characteristics; the palm is biomimetically designed with reference to the human hand structure, and guide pulleys are set on the palm for the purpose of under-actuation.

A. *Bionic Palm Design*

Pre-shaping characteristics of the hand are important for successful grasp. Not only does finger play a role in hand pre-shaping, but the shaping of the palmar concavity is also critical. The palmar arches provide a postural base to the hand and may play an integral role in finger joint movements and the assurance ofa stable grasp[11]. Therefore, in order to improve the grasping performance of the prosthetic hand, the radian characteristics of the palm of the hand are taken into account in the design so that the curvature of the palm can match the bending of the fingers to form the pre-shaping feature of the hand.

The palmar concavity results from the formation of three arches that run in different directions as shown in Fig. 1 Since the angle variation range of distal arch is the smallest (140°~150° in spherical grasp and 135°~145° in cylindrical grasp) when grasping, the angle of distal arch is set as a fixed value of 140°[11]. Modulations in longitudinal arch angle is directly related to the outreach movement of the thumb, and the

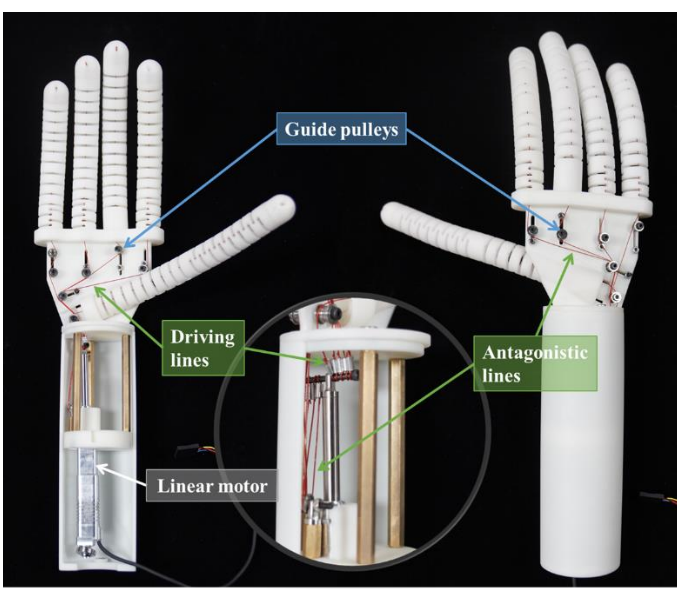

Fig. 2. The underactuated prosthetic hand.

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deformation of oblique arch can be observed when applying a load to the prosthetic hand, which is related to the flexibility of the palm material.

B. *Underactuated Structure*

The finger structure of the prosthetic hand in this paper is the same as that of TN hand, and each finger has bending and abduction freedom except the middle finger, so the reachable movement space is three-dimensional. As shown in Fig. 2, the prosthetic hand is driven by a single linear motor. Therefore, when the object is not grasped, the fingertip of each finger should move along a fixed trajectory, while in the actual grasping, the compliance of the finger will greatly increase the diversity of finger trajectory.

In addition, the reset line (antagonistic line) on the opposite side of the driving line is added to each finger, which is of great help to improve the grasp performance of the prosthetic hand. On the one hand, the reset line allows the finger to reduce its reset time during extension, while ensuring that the finger can still maintain its original posture after multiple flexions; on the other hand, the reset line can provide antagonistic effect: when adjusting the initial position of the finger, the stiffness of the finger can be changed by adjusting the length of the reset line, which helps the prosthetic hand to adapt to different stiffness objects.

For a flexible prosthetic hand, the compliance of its own structure can help to increase the contact area with the object, so the driving lines and reset lines in the flexible prosthetic hand proposed in this paper are directly connected to the linear motor after bypassing several guide wheels without using the differential mechanism mentioned above. Additionally, benefiting from the nature of the finger structure of this prosthetic hand: the center line length of the finger remains unchanged upon flexion [10], when the finger flexes or extends, the length of the drive lines and reset lines vary by the same amount, so that the drive lines and reset lines can be driven by a motor at the same time.

III. EXPERIMENT

This section will introduce the methods of experiments were conducted to test functions and motion characteristics of the prosthetic hand, in preparation for analyzing the effects of flexion degree and stiffness on grasp performance as well as for further optimization design.

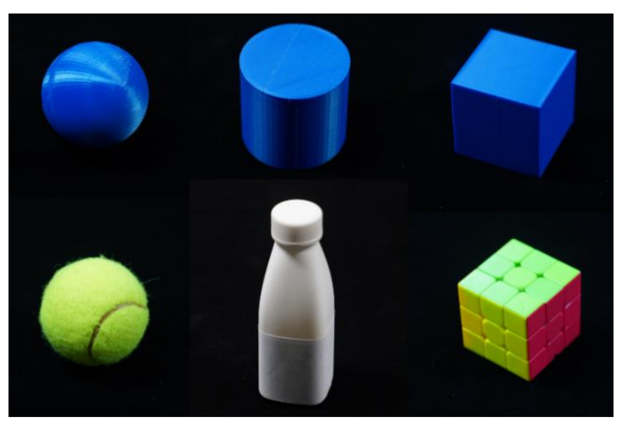


Fig. 3. Six objects selected for grasping test.

A. Power Grasp Test

The objects selected for the grasping test are shown in Fig. 3 ,including a sphere with a diameter of 80mm, a cylinder with a diameter of 75mm and a height of 70mm, a cube with a side length of 70mm, as well as daily items corresponding to the above geometries: a tennis, a bottle and a magic cube. The microcontroller board used for the prosthetic hand is Arduino Uno and the MyoWare™ Muscle Sensor (AT-04-001, SparkFun Electronics, USA) is used to measure muscle activation with acquisition frequency of 1000Hz.

In the experiment healthy subject was asked to use the prosthetic hand to grasp, transfer and place the six objects in Fig. 2 with one hand. The initial position of the object is about 30cm away from the target position. If the object falls during grasping or transfer, it is a failure. Record the success rate of operation of each object and repeat the experiment by changing the displacement of the linear motor while keeping the initial posture of the prosthetic hand unchanged. It should be noted that only the prosthetic hand is allowed to contact the object during the above operation, and the subject have to hold the prosthetic hand in one hand.

The electromyographic (EMG) sensor is attached to the brachioradialis muscle of the right arm of the subject. Before the experiment, the subject needs to control the contraction and relaxation of brachioradialis muscle according to the instructions, and a reasonable threshold is set according to the changes of the EMG signal. When the value of EMG signal is greater than the threshold the prosthetic hand needs to flex; and if the EMG value is less than the threshold, the prosthetic hand needs to be opened.

B. Stability Test of Precision Grasp

The prosthetic hand is fixed on the experimental platform to accurately grasp a light object (regardless of its gravity) and the end of the tension sensor is connected with the object grasped by the prosthetic hand. pull it out horizontally with external force. Pull the tension sensor horizontally to record the external force when grasping instability and repeat for ten times to take the average value. Change the displacement of the linear motor and repeat the above experiment.

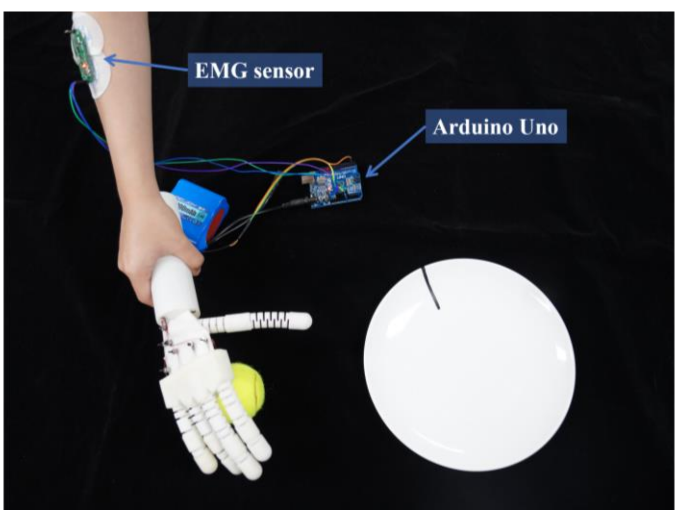


Fig. 4. Subject was using the prosthetic hand to grasp a tennis.

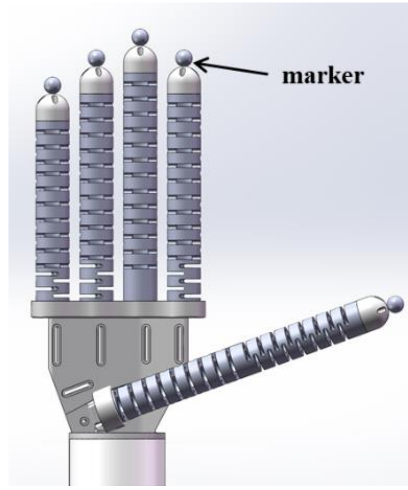


Fig. 5. Placement of markers on each finger of the prosthetic hand.

C. Fingertip Trajectory Test

As shown in Fig. 5 markers were fixed on the fingertips of the prosthetic hand, and the Polaris Vega® (NDI Inc., Waterloo, Ontario, Canada) was used to track the position of the markers. Record the movement track of the fingertips in the opening and closing action of the prosthetic hand without grasping the object. Keeping the initial posture of the prosthetic hand unchanged, change the displacement of the linear motor, and record the initial position of the fingertips as well as the position after flexion.

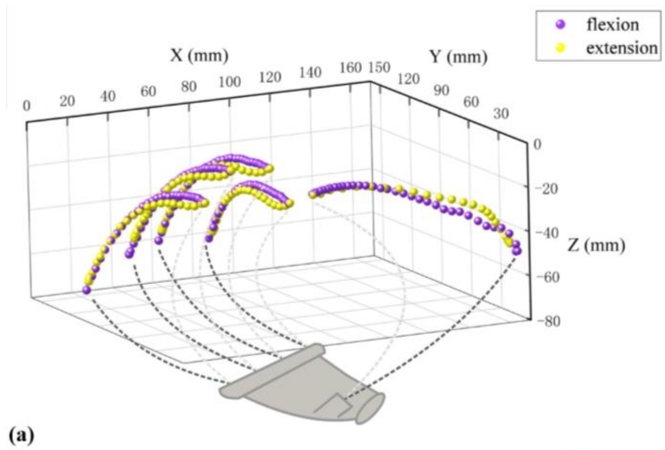
The trajectories can be used to analyze the influence of the degree of flexion of the prosthetic hand in the grasping process on the success rate of power grasping and the stability of precision grasping.

IV. Result and Discussion

A. Kinematic Characteristics of Prosthetic Hand

When the displacement of the linear motor is 14mm, the opening and closing trajectory of the fingertip is shown in Fig. 6 (a). The flexion trajectories of the fingertips of the index, middle, ring, and little fingers are highly coincident with the reduction trajectory, whereas the extension trajectory of the thumb is significantly different from the flexion trajectory. This is related to the number of driving lines of each finger. Except for the thumb, each finger is driven by only one pair of driving lines (a driving line and a reset line), and theoretically, the movement track of the fingertip is only related to length variation of the driving lines when the object is not grabbed.

However, there are two pairs of thumb driving lines, corresponding to the extension-adduction and flexion-extension movements of the thumb, so the motion space of the thumb is three-dimensional. The trajectory of the thumb tip is determined when the length of the two pairs of driving lines changes at the same speed, but in actual movement, the friction force on the driving line will lead to the inconsistent change speed of the length of the two pairs of driving lines, resulting in the low coincidence of the motion trajectory of the thumb fingertip in the reciprocating movement. Since the length change of each pair of driving lines is constant, the initial and final fingertip



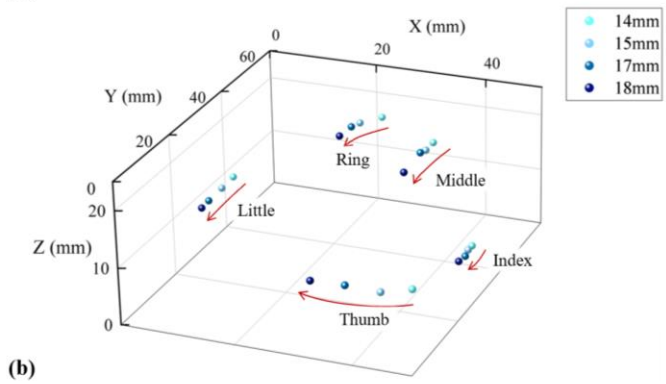


Fig. 6. (a) The opening and closing trajectory of the fingertip. (b) Convergence of fingertip position during sustained flexion.

positions of the prosthetic hand remain basically unchanged after several open and close movements, which also verifies the effect of the reset lines on maintaining the initial posture of the prosthetic hand.

The experiment records the position of the prosthetic fingertips corresponding to different displacement of the linear motor when the object is not grasped. As shown in Fig. 6 (b), as the displacement of the linear motor increases, the fingers are more gathered while the bending degree increases, which is consistent with the motion characteristics of the human hand, whereas in previous designs of prosthetic hands, the four fingers usually remain parallel in bending without such convergence. The convergence characteristic of prosthetic hand in this paper is due to the optimization of palm configuration.

B. *Success Rate of Power Grasp*

In the experiment, the grasping success rates of six experimental objects corresponding to the displacement of linear motor of 14mm, 15mm, 16mm and 17mm are tested respectively, as shown in Fig. 7. For the six objects selected in the experiment, the grasping success rate increases with the increase of linear motor displacement, which is more obvious in the grasping of non-spherical objects. In addition, when grasping spherical objects, this prosthetic hand can achieve a high success rate even when the fingers are less bent, which fully reflects the features and advantages of the prosthetic hand's convergence. The above results indicate that increasing the convergence of the finger of the prosthetic hand can improve the success rate of power

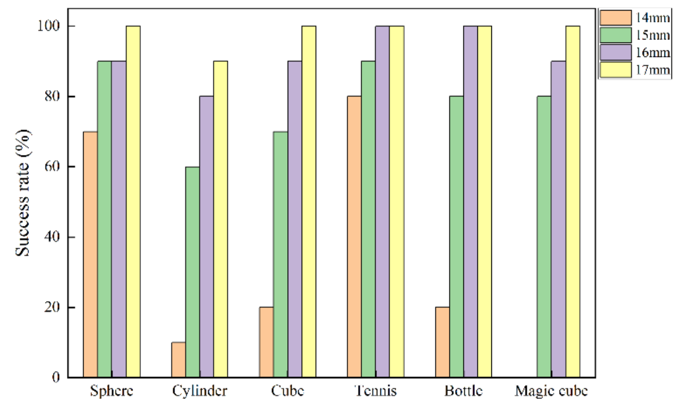


Fig. 7. The grasping success rates of six experimental objects corresponding to different displacements of linear motor.

grasping, which is of great significance to improve the ability of the prosthetic hand to perform ADL.

The compliance of the prosthetic hand plays an important role in power grasping. With the traction of the driving line, both fingers and palms will produce elastic deformation. The fingers will bend first and continue to slide along the surface of the object to achieve a larger envelope and contact area after touching the object. If the linear motor is still moving forward when all fingers are restricted by the object, the palm of the hand will bend inwards. Since the stiffness of the palm is greater than that of the finger, the grabbing power of the fingertips will increase at the same time, thus increasing the success rate of the power grasping.

In addition, the feeling of the participants using the EMG sensor in the experiment is also one of the factors affecting the success rate of grasping. When grasping an object, the subject tends to continue to exert a high intensity force in order to maintain the stable grip of the object, which can be seen in Fig. 6. The electromyogram obtained shows that the intensity of the electromyogram signal is much higher than that required to maintain the flexion of the prosthetic hand. After the experiment, some subjects responded that the grasping process was laborious and the forearm felt sore. Therefore, improving the compliance of EMG control and reducing the operation burden of users are the key to improve the availability of prosthetic hand in the future.

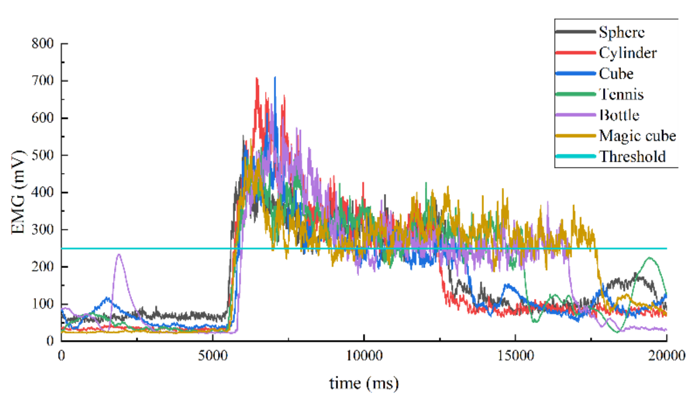


Fig. 8. Electromyography in six object grasping tests.

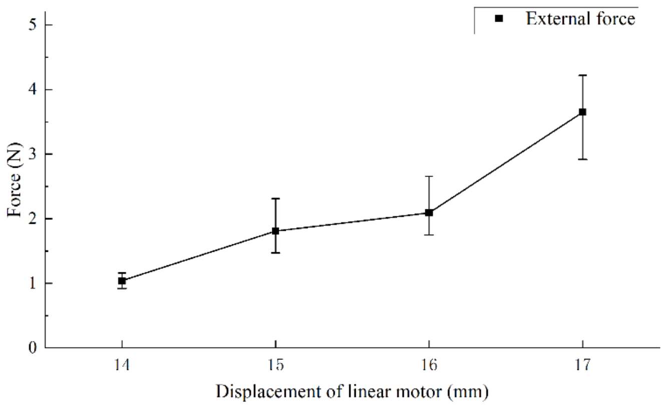


Fig. 9. External force when precise grasping is not stable.

C. Stability of Precise Grasp

The experimental results of the precise grasping test of the prosthetic hand are shown in Fig. 7. As the displacement of the driving line increases, the precision grip stability of the prosthetic hand increases significantly, which is related to the stiffness change of the finger during flexion. It has been described before: The stiffness of the finger increases with the increase of the bending angle[10]. When using this prosthetic hand to grasp an object, the stiffness of the finger is determined by the displacement of the linear motor, and the bending degree of the finger depends on the shape of the grasped object. When the displacement of the driving line is the same, the deformation of the finger from the non-grasping state to the grasping state is the source of the positive pressure exerted by the fingertip on the object, which is proportional to the detachment force measured in the experiment. Therefore, improving the stiffness of the prosthetic hand is conducive to improving the stability of accurate grasping.

V. Conclusion

This paper improves the structure design and driving scheme of the prosthetic hand based on TN hand[10]: the palm configuration was optimized biomically, and the validity of the configuration optimization is verified by the fingertip motion track test and the power grasping experiment; The antagonistic (reset) line on the opposite side of the finger drive line and movable guide pulleys are added to adjust the initial posture and initial stiffness of the finger; And the prosthetic hand is driven by a single motor, which can be controlled by EMG. The above design reduces the weight of the prosthetic hand and makes it more convenient for ULAs to use.

In the functional test of prosthetic hand, with the increase of the displacement of linear motor, the success rate of power grasping is significantly improved and the stability of precise grasping is also increased,. Adjusting the displacement of the linear motor can improve the compliance of the prosthetic hand to the shape of the object, but to further improve the grasping performance of the prosthetic hand, the stiffness of the finger needs to be adjusted by the antagonistic line to improve the compliance of the prosthetic hand to the stiffness of the grabbed object. The optimization of prosthetic hand in the future also includes improving the compliance of EMG control to reduce the operation burden of ULAs. In addition, the actuation would be improved by using a high torque steering motor to make the structure compact.

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