A tendon-driven prosthetic hand using continuum structure*

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***Abstract*—In the current research of prosthetic hands, many degrees of freedom have been omitted in order to simplify the design and reduce the weight, such as the abduction degrees of freedom of the four fingers except the thumb, which impairs the range of mobility of the prosthetic hand to some extent. This paper presents TN hand, a 3D printed, tendon-driven prosthetic hand. We use continuum structure as the finger joint. The other four fingers except the middle finger can perform flexion/extension and abduction/adduction movements, which benefits hand mobility. The design and manufacture of the fingers were elaborated and the finger stiffness was tested through experiment. Then the ability of manipulating daily objects of TN hand was verified based on hand taxonomy. In addition, there is enough range of mobility for the TN hand to perform column chords due to the ability to abduct fingers.**

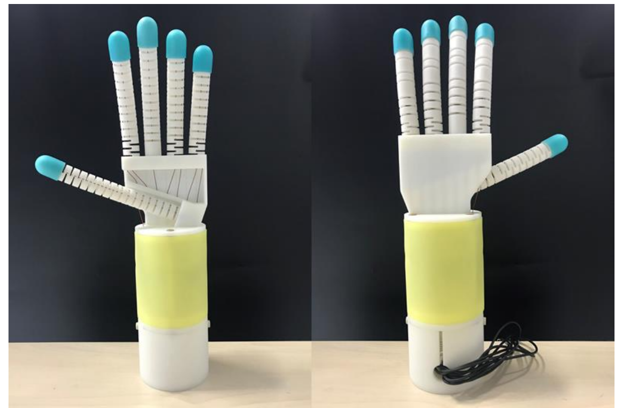

Figure 1. TN Hand

I. Introduction

The research of prosthetic hand has been ongoing for more than half a century. However, the performance of the current robotic hands is still not comparable to those of human hands yet [1]. One reason is that robotic hands, especially for prosthetic hands, do not have as many degrees of freedom as human hands. Implementing high numbers of degrees of freedom to robotic hands often leads to complicated designs, as added actuators bring addition to weight and probability of hardware failure, therefore decreases the practicality because the prosthetic hand is too heavy to wear. As a result, many of the current prosthetic hands omitted many degrees of freedom. The widely used commercial prosthetic hands i-limb and Bebionic can only perform both abduction/adduction(ab/d) and flexion/extension(flex/ex) motions in its thumb, the remaining fingers can only perform flexion and extension, which impairs hand mobility [2].

In this paper, we proposed the prototype of TN hand (Tendon-driven Nylon hand), whose fingers were 3D-printed using nylon (Fig. 1). All four fingers except the middle finger can perform both flex/ex and ab/d movements while the middle finger can only be bent. When human perform a typical grasp, the abduction mechanism of the fingers should leave the middle finger fixed [3], so we accepted the lack of ab/b degrees of freedom in the middle finger in this prototype. This design ensures the prosthetic hand's range of mobility while keeping the number of actuators reasonable.

A continuum structure was used to build the joint of TN hand (Fig .2), bringing about a high passive compliance to the hand, which has been proved conducive to grasp [4]. This type of continuum structure has been used to perform the removal of osteolysis formed behind the acetabular shell of primary total hip arthroplasties [5]. Increasing the number of notches of a joint can increase the maximum bend angle, or vice versa; this structure allows easy customization of a finger by changing its parameters. Every finger of TN hand was built by 3D printing integrally with an external diameter of 16mm and an internal diameter of 8mm.

II. The Tendon-driven Finger

In this section, we take the index finger as an example to describe the design of the fingers of TN hand. We use a continuum structure as the joint of the finger. This structure has a hollow pipe, a small hole on the pipe wall for tendon's passing through, a staggered notch structure on the pipe for generating deformation and can produce bending deformation under tension of tendon.

A. Design

The design of the index finger with a length of 105 mm is shown in Fig .2. An index finger of a human hand has three joints, namely DIP, PIP and MCP joints. These three joints can be bent/straighten and the MCP joint can also be abducted / adducted. We divided the MCP joint into two joints, namely MCP-A (MCP-Abduction) and MCP-B (MCP-Bending) joint, so the index finger of the TN hand has four joints. The finger is actuated by two tendons. One tendon is responsible for actuating the DIP, PIP and MCP-B joints to produce bending motion when being pulled, and the other tendon can be pulled to actuate the MCP-A joint to generate abduction motion. The

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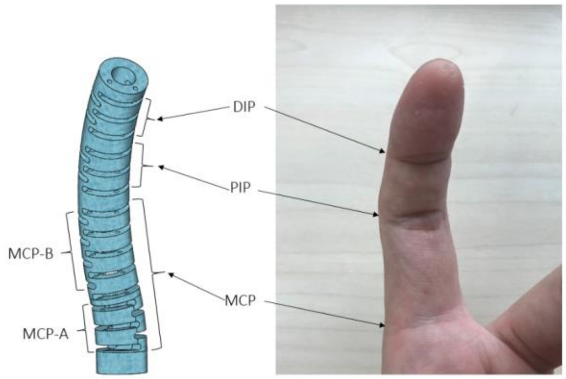


Figure 2. The Index Finger of TN Hand and Human Hand

TABLE I. MATERIAL PROPERTIES

Properties	Finger material (Nylon)	Palm material (Resin)
Elongation at break（%）	38	16-18
Tensile strength （MPa）	48.1	51.21
Tensile modulus （MPa）	1646	2136
Bending strength （MPa）	43.5	93.5
Bending modulus （MPa）	1431	2155.31

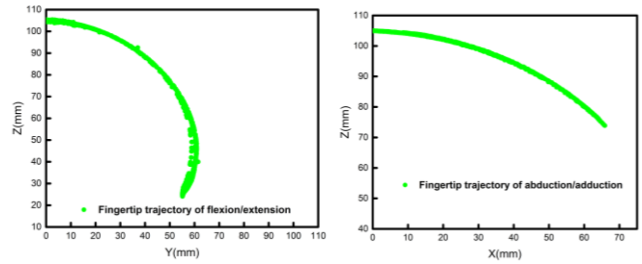
fingers will extend and be adducted under their own elasticity by releasing the corresponding tendon.

B. Manufacture

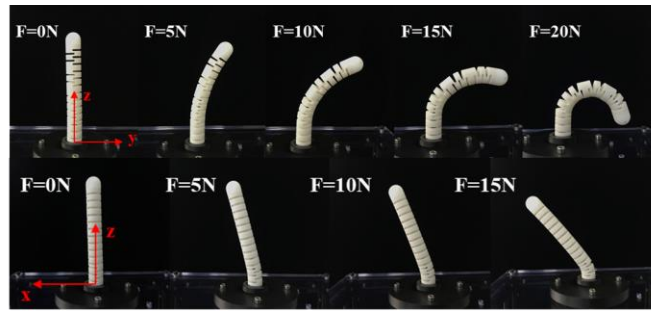
We use selective laser sintering (SLS), a mature 3D printing technology to fabricate the fingers. The material is critical. In general, for underactuated prosthetic hands, two tendons are needed to actuate the fingers to flex and extend respectively, such as [6], which increases the number of actuators. Benefit from the development of elastic materials, we used nylon, a widely accepted 3D printing material to fabricate the fingers. Table 1 shows the properties of the nylon used for TN hand. This material exhibits good elasticity in a state of sufficiently thin. When the fingers are flexion or abducted, they enter a state of energy storage as an elastic body, causing the extension or adduction of them when the tendon is relaxed.

C. Fingertip trajectories and tension

We explored the motion of the finger through experiments. First, we studied the trajectory of the fingertip in flex/ex and ab/d motions respectively. The method is using a stepper motor with a speed of 0.05m/s to pull the finger to bend. When the finger bends to the maximum angle, the motor returns to the original position, releasing the tendon to restore the finger to its original shape. The process was repeated 5 times and a marker was fixed at the distal end of the finger to record the trajectories. Then we used the same method to test the fingertip's trajectory of the abduction / adduction motion. The results are shown in Fig. 3a. In addition, we conducted experiments to investigate the relationship between the tension of tendon and the finger's motions. An S-type tension sensor was attached to the tendon to record the tension. The results are shown in Fig. 3b.



(a)



(b)

Figure 3. Kinematics of the index finger. (a) Fingertip trajectories. (b) Images of the index finger during flexion and abduction motions.

D. Stiffness

One crucial characteristic of the finger is stiffness, i.e. the ability to resist deformation under external force. Several experiments were performed to test the stiffness of the finger. The experimental setup is shown in Fig .4. The first experiment was conducted when the finger bend to 0, 45, 90 and 135 degrees respectively. A digital force meter was used to apply lateral force to the finger. The force meter was fixed on a linear guide which can offer a horizontal move and a marker is fixed on the fingertip to record the displacement. During the experiment, the lateral force applied was varied from 0N to 1N with an interval of 0.1N. Under each force value, the displacement of fingertip was recorded. The second experiment was conducted when the finger was abducted to 0, 25 and 50 degrees respectively.

The experimental results are shown in Fig. 5. Each experiment was repeated 3 times and the results were averaged. The measured displacement data at different angles were linearly fitted and the reciprocal of the slope of the fitted line represents the stiffness. It can be seen from the figures that both during the bending and abduction motions, the stiffness of the finger increased with the angle's increase. When the bending angle of the finger is 135° the displacement is 0.74 mm with a lateral force of 1N and the reciprocal of slope is 0.860 N/mm, which is more than 27 times larger than the stiffness at 0° during bending motion. The result shows that the finger is comparatively soft in its straight state, which implies better compliance. On the contrary, when the bending or abduction angle is larger, it is relatively hard and has stronger resistance to deformation.

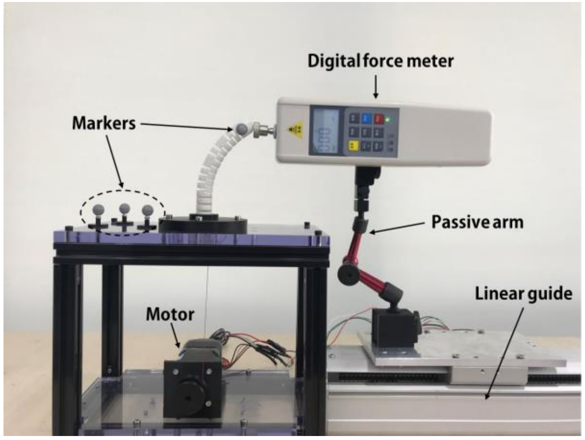


Figure 4. The stiffness testing platform

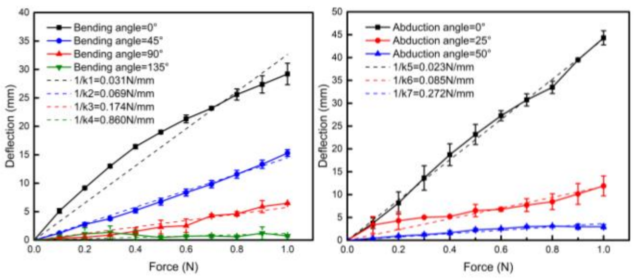


Figure 5. Comparison of force-deflection at different angles

III. THE PROPOSED PROSTHETIC HAND

We developed TN hand using the underactuated fingers mentioned in the previous section. The fingers are made of nylon material and the palm is made of resin material which is comparatively hard. The material properties of palm are shown in table I. When the hand is fully opened naturally, it is fan-shaped with the middle finger as the center, so the middle finger can be considered motionless during such process. Therefore, when we design the proposed hand, the middle finger with a length of 115mm has no ab/d freedom, and the remaining four fingers can be bent and abducted. The design of the ring finger is basically the same as that of the index finger, except that the direction of abduction is opposite to that of the index finger. The little finger is similar to the ring finger, but its length is 92 mm, shorter than ring finger, which is closer to the characteristics of human hands. Because there is no PIP joint in the human thumb, we use two joints to generate thumb's flexion and abduction and our thumb has a length of 135 mm. All fingers have the same diameter and notch size. An Arduino UNO was used as the controller of TN hand, and 9 linear servo motors were used as its actuators. The middle finger is driven by only one motor to bend, and the other four fingers are driven by two motors separately to bend and abduct. There is a rubber finger sleeve at the end of each finger, with a thickness of 0.5mm, to increase the friction at the fingertip. We use 0.5mm diameter stainless steel wire as the tendon of the hand. The weight of the whole prosthetic hand is light, which is 160g without actuate system and 0.67kg with the actuate system.

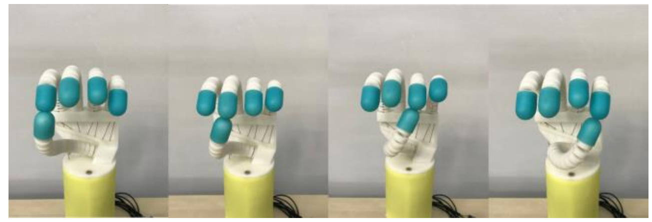


Figure 6. Image of the thumb touching the 4 fingertips

A. Thumb mobility

The mobility of the thumb is crucial to the integral function of a hand. We tested the mobility of the thumb by using the thumb to touch the distal end of the other four fingers, that is, to perform a pinch with the other four fingers. As shown in Fig .6, the thumb of the TN hand can complete these movements, which indicate that the thumb of TN hand has adequate mobility.

B. Object grasping

Grasping is a fundamental operation for human hands. Researchers have studied and classified the gripping movements of human hands previously. We conducted object grasping experiment using TN hand based on hand taxonomy [7] which consists of 16 grasp type. There were 10 objects used in the test: a plate, a key, a PLA disc (thickness of 10 mm, diameter of 100 mm), a rubber ball (diameter of 78 mm), a bulb (diameter of 51 mm), a pen (diameter of 13 mm), a large PLA cylinder (diameter of 110 mm), a small PLA cylinder (diameter of 50 mm) and a cuboid box(186 mm long, 47 mm wide and 35 mm high). The heaviest object in the experiment is the big cylinder, which weighs 0.3KG. The test results are shown in Fig .7.

The hand is able to perform 15 grasp types out of 16. The "light tool" grasp can't be completed, which needs finger pulp to fill the cavity formed by the bent fingers. It is worth noting that when TN hand grasps a spherical object, i.e. completes a spherical grasp, because of the existence of the MCP-B joints and passive compliance, the contact points between fingers and object are more scattered, which leads to more evenly

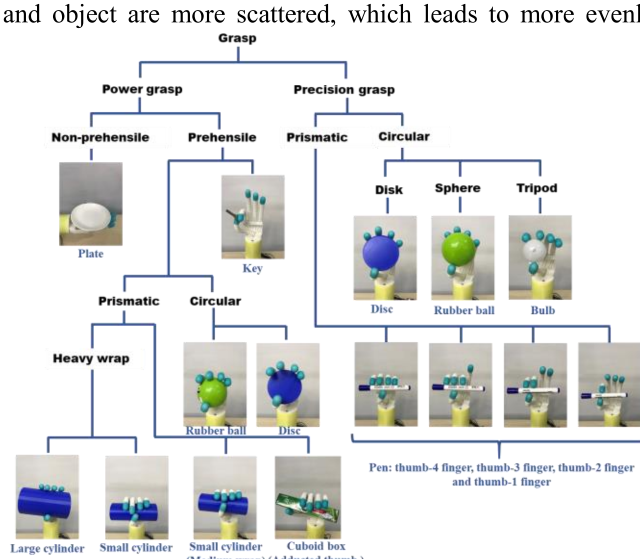


Figure 7. The hand taxonomy realized by TN hand

distributed force on the grabbed object, allowing the grasp to be more stable.

C. Playing column chords

The dexterity of hands is also shown in other aspects besides grasping, such as playing musical instruments. In this section, we choose to play column chord to test the dexterity of TN hand. Some researchers have done researches on piano playing by manipulator before, but the goal of this kind of research is either a robot dedicated to piano playing or a prosthetic hand playing one key at a time. As far as we see, few researches employ prosthetic hands to play column chords. Column chords require fingers to play several different keys simultaneously. In this case, if the fingers of the prosthetic hand can't produce abduction motion, it cannot complete the performance of column chords because the distance between keys of different chords is different.

We selected six common column chords from the first-order chords in C-key to test TN hand, as shown in Fig .8a. For contrast, Fig .8b shows the action of playing these chords by human hand and Fig .8c shows the TN hand playing column chords. We can see from the results that playing different column chords requires different distance between the fingertips of the hand which means different angles between fingers. For instance, Cmaj7 requires the little finger, ring finger, index finger and thumb pressing four keys at the same time and the distances are the same, which is the width of a piano key. Csus2 requires that the little finger and ring finger play the two adjacent keys while the thumb press the keys at a relatively far distance of twice the width of a key. All of 6 column chords are played with finger's abduction in

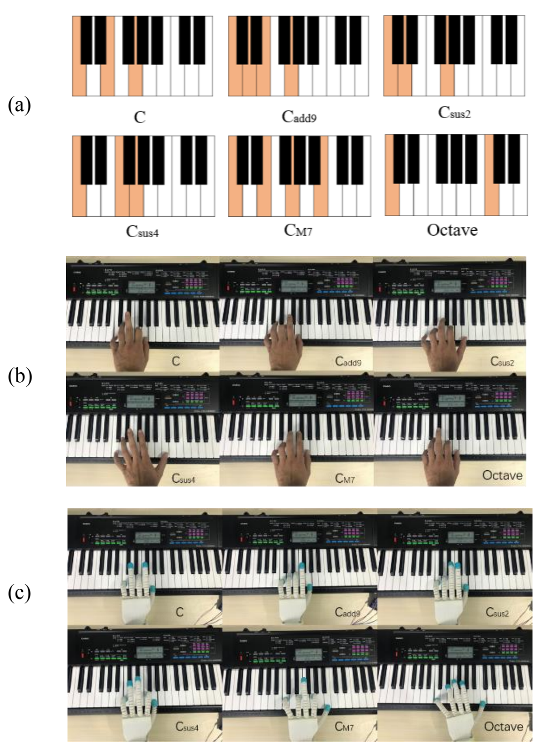


Figure 8. Comparison of playing column chords by human hand and TN hand. (a) Keys for 6 column chords. (b) Images of human hand playing column chords. (c) Images of TN hand playing column chords

varying degrees, which shows the motion of finger's abduction is important to play column chords for hand. TN hand successfully plays all 6 column chords, which is proof of its range of mobility.

IV. Conclusion And Discussion

In this paper, TN hand, a kind of tendon-driven prosthetic hand is proposed. We use continuum structure as finger joint and the finger can be abducted. The finger can be customized by changing the parameters of the joint as needed. We tested the kinematic parameters of the finger and measured the stiffness of it through experiments. In the part of hand performance, we investigated the thumb's mobility by touching the other four fingertips. Then experiment of grasping manipulation was carried out based on hand taxonomy, which confirmed that TN hand can complete the grasping of most daily objects. Finally, we used the TN hand to play column chords, and successfully played six column chords.

The ultimate goal of an artificial hand is to replace human hand. However, due to the complexity of human hand and the limitations of structure design, control method, actuator and sensor techniques, the gap between prosthetic hand and human hand is still huge. Besides grasping daily objects, human hands can also do plenty of other tasks, such as playing musical instruments. In order to simplify the design and control, reduce the weight and so on, many prosthetic hands omit the abduction degrees of freedom of human fingers. However, the abduction motion of a finger is crucial for the range of mobility in human hands. TN hand is simple in design and easy to manufacture with abduction degrees of freedom. However, the study is still in the early stage. In the future, we will continue to improve our prosthetic hand.

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