Proceedings of 2021 IEEE
International Conference on Mechatronics and Automation
August 8 - 11, Takamatsu, Japan

Development of a Fixture for the Vascular Interventional Surgical Robotic System

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***Abstract* - At present, with the acceleration of the pace of life and the increase of work pressure, cardiovascular and cerebrovascular diseases are getting closer and closer to people. In recent years, vascular interventional surgery has developed into an important method for the treatment of cardiovascular and cerebrovascular diseases. However, traditional interventional surgery has extremely strict requirements for doctors, and doctors who perform interventional operations for a long time will suffer a lot of radiation. Using vascular interventional surgery robots to assist doctors in surgery can make up for many shortcomings of traditional surgical procedures. Therefore, the market has the demand for surgical robots which is becoming more and more urgent. Based on the previous research of the research team, this paper proposes a vascular interventional surgery robot system with a bionic clamp. The robot uses a gear slider structure to push and retract the guide wire catheter. Its clamp is mainly used to clamp and twist the catheter and guide wire, and adopts a portable design, and finally realizes the rapid replacement of the catheter and guide wire.**

Index Terms - Vascular intervention surgery robot, Bionic fixture, ADAMS simulation

I. Introduction

With the acceleration of the pace of life, the increase of work pressure and the irregularity of living habits, the number of patients with cardiovascular and cerebrovascular diseases is increasing year by year. In our country, a large number of patients die from cardiovascular and cerebrovascular diseases every year. Successful professional treatment may also leave many sequelae. This type of disease has become more and more common in life. Its characteristics of high disability, high morbidity, high mortality, and high surgical cost have severely reduced the quality of life of patients and families, and have a huge impact on patients' body and mind. The impact has also brought a heavy burden to the society [1]. At present, with the continuous development and breakthrough of technologies in various fields, vascular interventional surgery has become an important means to treat many cardiovascular and cerebrovascular diseases. However, traditional vascular interventional surgery already requires the operation with the help of X-rays. In order to avoid radiation, doctors often need to wear heavy lead garments, which is extremely inconvenient, and this type of operation requires very high professional standards and comprehensive capabilities of the doctors, resulting in very few doctors who can perform interventional operations. In order to make up for the various shortcomings of traditional interventional surgery, vascular interventional surgery robots have emerged. Most vascular interventional surgery robots adopt a master-slave design. The doctor manipulates the master at the master side to control the slave side to finally push, retract, and retreat the catheter. Various actions such as clamping and twisting [2]. The clamp is one of the most important components of the vascular interventional surgical robot. It is mainly responsible for clamping and twisting the catheter and guide wire. The force feedback function of most vascular interventional surgical robots is also realized by the clamp. The clamp is important for the robot. There are various clamps for vascular interventional surgical robots that have been developed, but most of the clamps use a holding mechanism to clamp the catheter and guide wire, and the entire rotation of the clamping mechanism realizes the twisting of the catheter and guide wire.

There are usually three types of problems with similar clamps that are difficult to solve: 1. In order to make the holding mechanism rotate smoothly, the catheter often needs to be inserted from the inside of the clamp. During the threading process, it is not only easy to deform the catheter and guide wire, but also easily contaminate the catheter and guide wire. Which seriously increases the risk of surgery. 2. Wire entanglement is likely to occur during the rotation of the clamp. Once this problem occurs, it will be difficult to perform the operation again, and the severer will cause irreparable damage to the patient. 3. Various specifications of catheters and guide wires are needed during the operation. The tracing method is not conducive to the replacement of catheter guide wires and reduces the doctor's work efficiency.

Therefore, this paper proposes a vascular interventional surgical robot system based on a bionic fixture, which clamps and twists the catheter and guide wire by simulating the motion of a human hand. The clamp realizes the clamping and twisting of the catheter and guide wire by simulating human hand movements, which solves the various problems of the previous clamps, improves the portability and the efficiency of catheter replacement, and completely solves the problem of wire winding. Its various performance indicators are better than the previous generation fixture. Finally, it can achieve effective clamping and twisting of the catheter without damaging it [3].

II. STRUCTURE DESIGN OF ROBOT FOR VASCULAR INTERVENTION

The three-dimensional structure of the slave side of the robot proposed in this paper is shown in Fig. 1. It adopts a gear sliding table structure to push and retract the catheter and guide wire. It mainly plays the role of imitating the movement of the doctor's hand during the interventional operation. Very high flexibility, it can complete the cooperative operation of the catheter and the guide wire by simulating the hands of the doctor. The operation of the catheter and the guide wire is more stable and accurate than manual operation, and it is equipped with safety protection measures. Prevent unforeseen accidents during the operation [4].

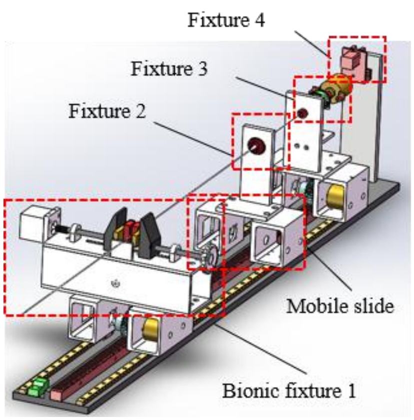


Fig. 1 The structure of the slave manipulator

There are various types of clamps and sensors on the slave side, and the clamps cooperate with each other. Fig. 2(a) shows the initial state of the clamp before the operation, clamp 1 and clamp 2 are jointly responsible for clamping the catheter, clamp 3 is responsible for clamping the guide wire at this time, and clamp 4 is loosened. Fig. 2(b) shows the process of pushing or rotating the guide wire. After the clamp 3 clamps the guide wire, the guide wire will advance with the advancement of the clamp and rotate with the rotation of the clamp. Fig. 2(c) shows that if the guide wire has been pushed to the extreme position due to the platform, but the doctor still needs to push the guide wire forward, the clamp 3 needs to be controlled to loosen the guide wire, and then back withdraw to the red dotted arrow in the figure to push the catheter again. At the same time, the clamp 4 always clamps the tail of the catheter to ensure that the catheter does not move. In order to prevent the guide wire from being displaced during the retreat of the clamp 3. Fig. 2(d) is the process of pushing or rotating the catheter. Fixture 1 and fixture 2 need to keep synchronized forward movement to push the catheter. Fixture 1 imitates the twisting of a human hand to make the catheter rotate. Fig. 2(e) shows that if the catheter has been pushed to the extreme position due to the platform, but the doctor still needs to push the catheter forward, clamp 1 needs to simulate a human hand to loosen the catheter, and then withdraw it back to the figure. The red dotted arrow is in order to push the catheter again. At the same time, the clamp 2 always clamps the tail of the catheter to ensure that the catheter does not move. To realize the clamping and twisting of the catheter and guide wire, the sensor is mainly used to collect the displacement information from the the displacement information of the slave side and the force of the catheter [5].

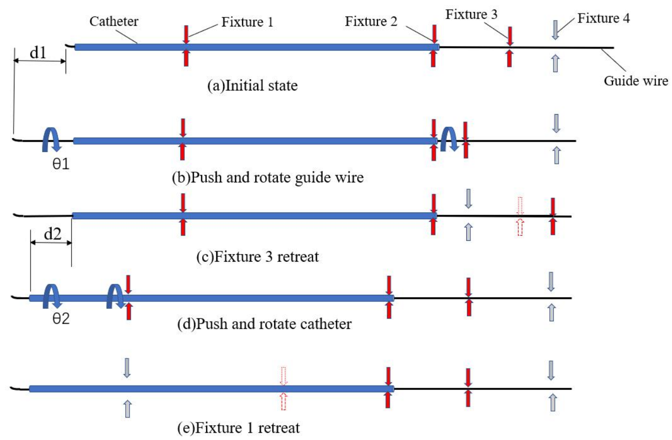


Fig. 2 Fixture coordination diagram

The overall three-dimensional structure of the designed bionic fixture is shown in Fig. 3. It adopts a modular design based on the principle of crank slider and realizes clamping and twisting of catheters and guide wires by simulating the actions of human hands [6].

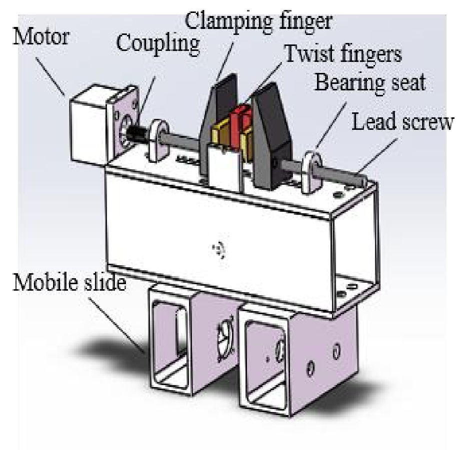


Fig. 3 The structure of Bionic fixture

The clamp used in the previous generation catheter is shown in Fig. 4. It mainly controls the clamping and unclamping of the catheter through the rotation of the clamp motor control cam, and realizes the twisting action of the catheter through the rotation of the clamp itself. The clamp designed in this paper compared with the previous generation of clamps, it has the following advantages: 1. Improves the portability of the catheter and guide wire, and doctors can replace the catheter more quickly. 2. The twisting motion is used to complete the twisting of the catheter, which solves the problem of the previous generation of clamps. The wire winding problem caused by the rotation of the 3. Integrating the clamping module and the twisting module together makes the clamp simpler and more reliable [7].

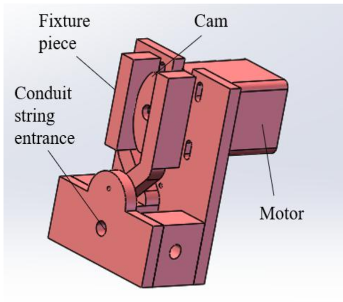


Fig. 4 The structure of previous generation fixture

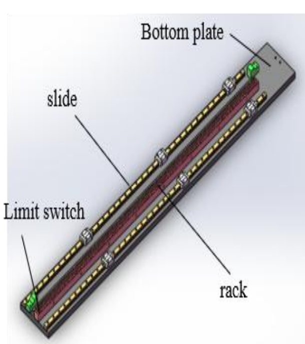
The structure of each part of the robot will be described in detail below.

A. *Push Mechanism Design*

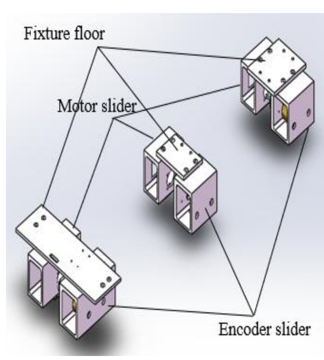
The push mechanism is mainly composed of proximity switches, sliding rails, sliding tables, motors, racks, gears, base plates, photoelectric encoders, etc. The sliding table can move freely on the slide. Each sliding table is independent of each other and is not affected by each other. It has a high degree of flexibility.

As shown in Fig. 5(a), the designed bottom plate has a length of 112cm. Two one-meter-long slide rails and one one-meter-long inclined rack are fixed on the bottom plate respectively. The slide rail adopts Taiwan Silver Slide, which has low noise. High precision, low friction, etc. are its main advantages. The rack has international level 5 accuracy, and its strong rigidity, high precision, and durability are its major advantages

As shown in Fig. 5(b), the hollow cuboid of the sliding table is processed by aluminum alloy, and a movable sliding table is composed of two such rectangular frames. The movable sliding table is driven by a motor, and the motor shaft, two frames and helical gears are connected together by a connecting shaft. In the end, the helical gear can move back and forth on the rack due to the rotation of the motor shaft, thereby driving the entire sliding table to move back and forth on the slide.



(a) Bottom plate



(b) Sliding table

Fig. 5 The structure of sliding table and bottom plate

B. *Design of the Clamping Part of the Fixture*

The design of the clamp adopts the principle of modularization, which is divided into upper and lower parts. It is convenient to disassemble and saves the space occupied by the clamp. The clamp is inspired by people riding a bicycle and refers to the principle of the crank slider structure to simulate manually clamp and twist the catheter and guide wire. The clamping part is shown in Fig. 6, consisting of the upper base plate, motor, slide, screw, clamping finger, and corrugated hand wheel. The slide is laid in the middle of the upper base plate, and the left clamping finger is installed on the left screw and is composed of Driven by the motor, when the motor shaft rotates forward, the left clamping finger can move to the right, and the right clamping finger is mounted on the right screw and controlled by the corrugated handwheel. When the corrugated handwheel is rotated clockwise, the right clamping finger can move towards the right. Move to the left, and the left and right clamping fingers cooperate to complete the clamping of the catheter. In order to realize the force feedback function, lay slides on the left and right clamping fingers, then install the twisting finger drive plate marked in yellow on the clamping finger, and install the red twisting finger on the twisting finger drive plate. The pressure sensor is installed on the drive plate. When the front end of the catheter is stressed, the twisting finger will produce a slight backward displacement and hit the pressure sensor, thereby realizing the force feedback function.

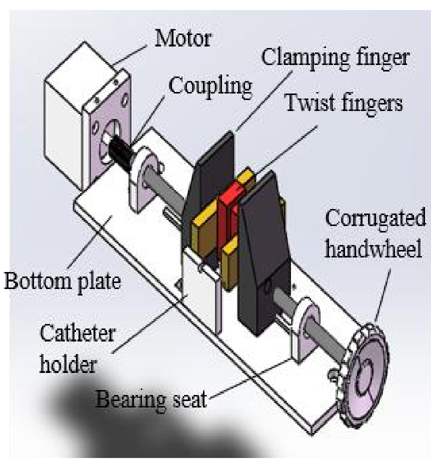


Fig. 6 Fixture clamping module

C. *Design of the Twisting Part of the Fixture*

The clamping device twisting module is shown in Fig. 7. It refers to the principle of bionics and adopts the principle of deformed crank slider. Due to the transmission effect of the conveyor belt, the rotation of the motor will drive the two driving wheels to rotate in the same direction. The two driving wheels are connected to the two twisting fingers through two connecting rods. Due to the opposite installation position, when the motor rotates, it is like a person's legs are pedaling a bicycle. One connecting rod moves upwards to drive the side twisting to move upwards, and the other connecting rod moves downwards to drive the side twisting to move downwards, thus imitating human hand movements [8].

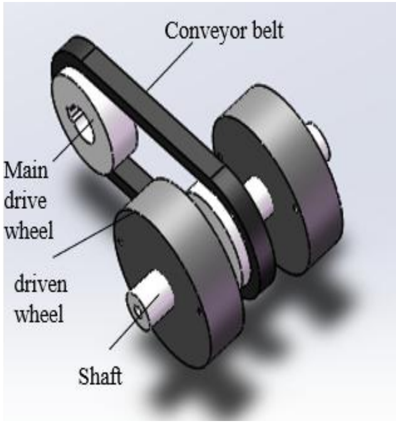


Fig. 7 Fixture twisting module

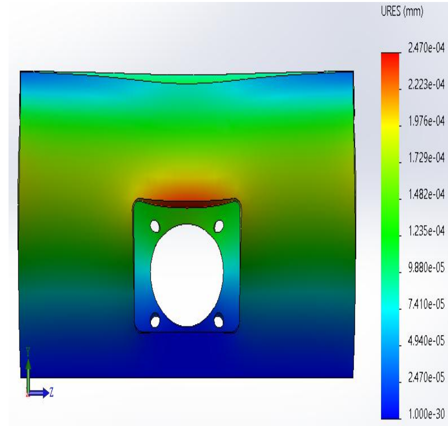


Fig. 8 Stress analysis diagram of sliding

D. *Design of Disposable Elastic Sterile Sleeve*

Since the catheter needs to enter the body during the operation, the part of the clamp contacting the catheter needs to be non-toxic and sterile. Refer to the sterile gloves worn by the doctor during the operation. The outer surface is covered with an elastic sterile cover, the sterile cover can be treated as a consumable after the operation, and the surface friction coefficient of the sterile cover can be changed according to different the catheter and guide wires, and the sterile cover can also be replaced when replacing the catheter and guide wire. It has the advantages of low cost, simple and convenient, quick disassembly and so on. [9][10].

III. The Stress Analysis of Fixture

A reasonable clamp will be subject to many restrictions in the design process. The clamp structure should have strong stability and anti-interference, and there should be no too much deformation during the process of clamping and twisting the catheter. In order to further determine the clamp whether the material and design principles of the structure are reasonable, the SOLIDWORKS software is used to analyze the stress of some important structures [11]. The fixture adopts an up-and-down structure. The movable sliding table is not only responsible for pushing the catheter forward, but also shouldering the heavy responsibility of supporting the entire fixture. Therefore, stress analysis of the moving sliding table is carried out first. The mobile sliding table in this paper is mainly made of aluminum alloy as raw material through metal processing.

This material is light in weight and strong in compression. Its ultimate tensile strength is 124mpa, flexural ultimate strength is 228mpa, and elastic coefficient is 68.9gpa. The pine ratio is 0.330. After simulating the downward pressure of the fixture on the sliding table, after selecting the supporting surface, apply a pressure of 50N in the longitudinal direction [12]. The deformation of the sliding table obtained through simulation calculation is shown in Fig. 8. It can be seen from the figure. that the sliding table has undergone slight deformation. It can be seen from the figure. that the maximum deformation of the sliding table is 2.470e-04 mm. According to the analysis of the results, the structure and design of the sliding table fully meet the required requirements.

During the movement of the clamp, the two connecting rods mainly transmit the force of the driving wheel to the two twisting fingers, and finally realize the upward movement of one twisting and the other downward movement to complete the axial movement of the catheter. During the movement, the connecting rod needs to have strong stability and cannot undergo excessive deformation, otherwise it will affect the serious twisting effect. The connecting rod is subjected to stress analysis. The stress analysis result is shown in the Fig. 9. When a force of 30N is applied to it in the longitudinal direction. It can be seen from the Fig. 9 that the maximum deformation of the connecting rod is 1.165e-06mm. From this analysis, it can be seen that the connecting rod can completely transmit the power of the driving wheel to the twisting finger, which meets the design requirements [13].

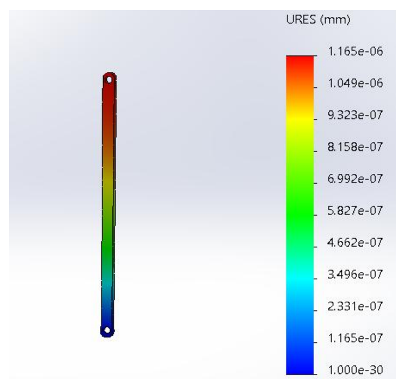


Fig. 9 The stress analysis of the connecting rod

IV. Experiments and Assessments

In order to analyse the kinematics of the fixture, draw the movement diagram as shown in Fig. 10, where M and N are the two twisting fingers of the fixture, P and Q are the two connecting rods, the length is L, and the position is A. The angle between time and the vertical direction is θ_3, the angle between OA and the horizontal direction is θ_1, and the circle with radius R is the driving wheel that drives the connecting rod. It rotates clockwise at speed V, and the horizontal sub-speed at position A is $V\cos\theta_2$. After a period of time, the connecting rod moves from position A to position A', and the connecting rod drives the twisting finger to rise for a certain distance. With the center of the drive wheel as the origin, the horizontal direction as the X axis, and the vertical direction as the Y axis, a coordinate system as shown in Fig. 10 is established. When the driving wheel rotates clockwise at speed V, it can be seen from the Fig. 10.

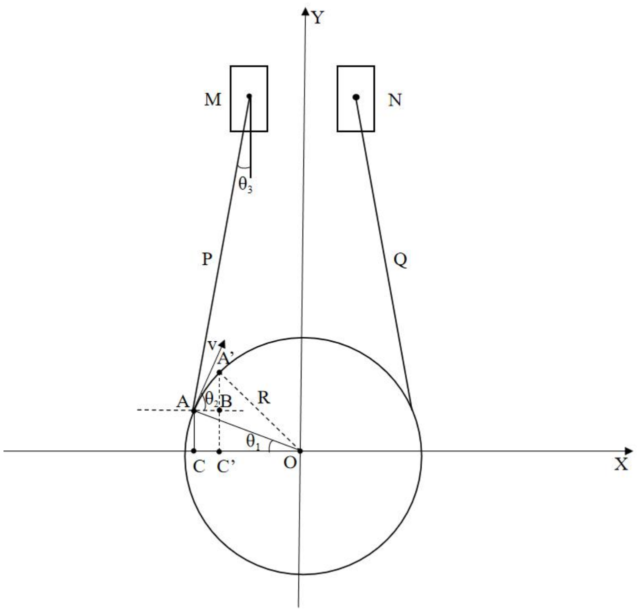


Fig. 10 The movement diagram of the fixture

$$\mathrm{OA} = \mathrm{R} \tag{1}$$

$$OC = R\cos\theta_2 \tag{2}$$

$$AC = R\sin\theta_2 \tag{3}$$

It can be deduced from this:

$$OD = R\cos\theta_1 - vt\cos\theta_2 \tag{4}$$

$$A'D = \sqrt{R^2 - (R\cos\theta - vt\cos\theta_2)^2} \tag{5}$$

$$A'C = \sqrt{R^2 - (R\cos\theta_1 - vt\cos\theta_2)^2} - R\sin\theta_1 \tag{6}$$

The twisting refers to the vertical distance of the far point relative to the Y axis:

$$X_{\mathrm{B}} = L\cos\theta_3 + \sqrt{R^2 - (R\cos\theta_1 - vt\cos\theta_2)^2} \tag{7}$$

Derivation of X_B can get the speed formula of twisting finger:

$$v_{\mathrm{B}} = \frac{2v(R\cos\theta_1 - vt\cos\theta_2)}{\sqrt{R^2 - (R\cos\theta_1 - vt\cos\theta_2)^2}} \tag{8}$$

It can be concluded that the displacement and speed of the twisting finger are determined by the parameters of V, R, L, and θ. When the twisting finger rises, the displacement and speed mainly change with the time t and the angle of θ [14].

In order to further verify the reliability, stability, and rationality of the structure proposed in this paper, simulations are carried out with ADAMS software. On the one hand, ADAMS is an application software for virtual prototype analysis. Users can use this software to easily analyse the statics, kinematics and dynamics of the virtual mechanical system. On the other hand, it is a virtual prototype analysis and development tool. Its open program structure and multiple interfaces can become a secondary development tool platform for users in special industries to analyse special types of virtual prototypes. The clamping part of the fixture mainly depends on the accuracy and quality of the screw. Therefore, the movement of the twisting finger is mainly analysed. This paper uses ADAMS to establish a virtual prototype of the bionic fixture. According to the actual movement, constraints such as load and motion pairs are added to the virtual prototype, and then the simulation is performed. Finally, the displacement of the twisting finger is obtained.

Fig. 11 shows the angle of the drive wheel rotating with time. It can be seen from the Fig. 11 that the angle of the drive wheel changes linearly with time. When the twisting finger rotates 90 degrees, the twisting finger will reach its apex.

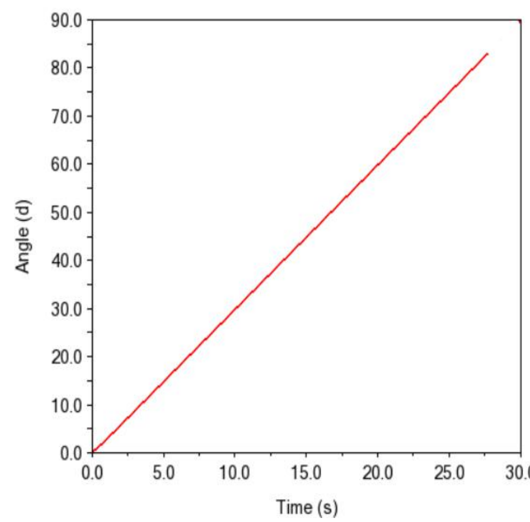


Fig. 11 Driving wheel rotation angle

Fig. 12 shows the speed of the twisting fingers. From the speed diagram, the smoothness of the twisting fingers can be further verified. It can be seen from the synthesis that movement speed of the fixture fully meets the design requirements.

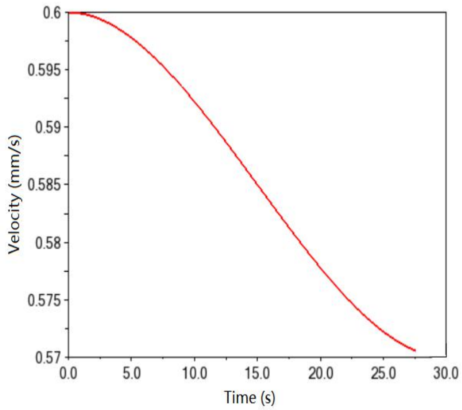


Fig. 12 Fixture movement speed

Fig. 13 shows the twisting finger displacement. The displacement of the twisting finger can be seen from the Fig. 13. The twisting finger can move linearly with the rotation of the driving wheel, and its speed will not change drastically. Therefore, it is successfully proved that the twisting finger has high stability.

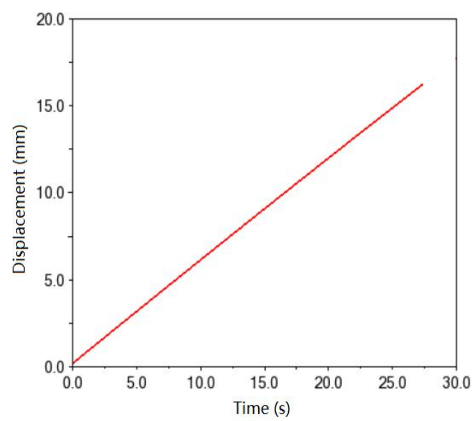


Fig. 13 Fixture movement displacement

The experimental results show that when the driving wheel of the fixture is controlled to move at a uniform speed, the driving wheel will drive the twisting finger to move at a speed less than the speed of the driving wheels, and its speed will continue to decrease, but the speed can be approximated as a uniform motion. The displacement time graph of the twisting finger is approximately linear. Finally, when the main end controls the movement of the driving wheel, the twisting finger can stably follow its synchronous movement without a large sudden change in speed. Therefore, it has been successfully proved that the fixture can stably twist the catheter, and its design principle is in line with the actual situation.

V. CONCLUSIONS

This paper proposed a new type of bionic clamp, which realized the clamping and twisting of the catheter and the guide wire by simulating the movement of the human hand. Through stress analysis, the reliability of the structure was proved. Finally, the kinematics analysis of the fixture and the kinematic simulation of the bionic fixture with ADAMS software were used to obtain the displacement and velocity images of its movement, which finally proved the smooth movement of the designed fixture.

ACKNOWLEDGMENT

This research is supported by National Natural Science Foundation of China (61703305), Key Research Program of the Natural Science Foundation of Tianjin (18JCZDJC38500) and Innovative Cooperation Project of Tianjin Scientific and Technological (18PTZWHZ00090).

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