Proceedings of 2022 IEEE
International Conference on Mechatronics and Automation
August 7 - 10, Guilin, China

Study on Force Feedback for Virtual Vascular Interventional Surgical System based on Multi-data Fusion

Zhentao Wang [1], Jian Guo [1,2*]
Shuxiang Guo[1,2,3*]
and Yu Song[1]

[1]Tianjin Key Laboratory for Control Theory & Application Complicated Systems and Intelligent Robot Laboratory
Tianjin University of Technology
Binshui Xidao Extension 391, Tianjin,300384,China
jasonsongrain@hotmail.com; 932069088@qq.com.

[2] Shenzhen Institute of Advanced Biomedical Robot Co., Ltd.
No.12, Ganli Sixth Road, Jihua Street, Longgang District
Shenzhen,518100,China
*corresponding author: jianguo@tjut.edu.cn;

[3] Key Laboratory of Convergence Medical Engineering System and Healthcare Technology,The Ministry of Industry and Information Technology,School of Life Science
Beijing Institute of Technology
No.5, Zhongguancun South Street, Beijing,100081, China
*corresponding author: guoshuxiang@hotmail.com

***Abstract* - In the virtual vascular interventional surgery training system, the force feedback information received by the trainer's hand is an important indicator that affects the user's training effect. Due to the complex structure of the blood vessel, it is difficult to perform a mechanical analysis after the collision between the catheter guide wire and the blood vessel, so the force feedback accuracy in the existing training system is poor. Rigorous mechanical analysis is difficult to achieve in the entire virtual training system, so a multi-data weighted fusion algorithm is used in this paper.Firstly, each component force in the blood vessel is simulated, and then compared with each force in the actual environment. On the premise of minimum total mean square error, each component force is assigned an optimal weight. Finally, a feedback force is synthesized and fed back to the hand of the trainer.The effectiveness of the method is verified by comparing with the force feedback in the existing training system.**

***Index Terms* - virtual vascular surgery, force feedback, multi-data fusion, accuracy**

I. INTRODUCTION

Current high speed development of human society, people need to face the life pressure is growing, it also became one of the leading causes of patients with vascular disease increases gradually, belongs to the minimally invasive surgery treatment, cardiovascular interventional surgery first from his thigh artery inserted into the sheath tube, catheter through the sheath pipe thread, again into the arteries along the blood vessels to the coronary artery, under the X-ray images, Diagnosis of coronary artery disease and treatment of stenosis or obstruction by balloon dilation or stent implantation. Therefore, in order to increase the surgical proficiency of novice doctors, virtual vascular interventional surgery training system emerges as The Times require and becomes the main means for doctors to improve their skills.

The training system for vascular interventional surgery doctors based on VR is a system integrating simulation technology, computer graphics, human-machine interface technology and other technologies. Through human-machine interaction, doctors can experience the feelings of real surgical operations. This not only improves the user's surgical skills, but also greatly reduces the surgical error. The virtual training system mainly uses CT of patients to reconstruct patients' blood vessels in 3d to obtain vascular models, and then uses modeling software to model medical instruments such as catheters and guidewires. Then, the models of blood vessels and medical instruments are imported into the virtual environment, and then the characteristics of real blood vessels are added to the virtual environment. Doctors can simulate surgery repeatedly through VR doctor training system, which is beneficial to reduce the training cycle and training cost of doctors and achieve good training results[1].

Due to the complex vascular environment in the human body, when the guide wire catheter and the blood in the blood vessel come into contact with the blood vessel wall, a variety of different forces will be generated. These forces cannot be simply added or subtracted to obtain a comprehensive force, but it is necessary to design a A more reasonable method to synthesize these forces makes it closer to the force that the operator feels during the actual operation, so as to ensure the authenticity of the force feedback of virtual vascular interventional surgery.

We roughly divide these forces into four categories: the collision force when the guidewire catheter collides with the blood vessel wall, the frictional force generated when the collision occurs, the blood flow resistance generated when the catheter guidewire contacts the blood, and the object in contact with the blood[2],[3]. Viscous resistance due to movement in a viscous fluid. To measure these forces in the virtual surgery training system, we need to first establish a mathematical model corresponding to each force, and finally use a multi-data fusion method to synthesize each force into a comprehensive force and feed it back to the interface to realize the virtual vascular interventional surgery training system. visual feedback.

II. OverView of The training system

A. System Overview

The training system for vascular interventional surgeons is based on virtual reality technology and human-computer interaction technology[4]. The virtual environment of the system was constructed by 3d reconstruction of CT data of real patients to obtain vascular model and 3DMAX modeling to obtain catheter guide wire model. The training system controls the movement of the catheter guide wire in the virtual environment through the operation information of the primary end, and simulates the force received by the catheter guide wire in the virtual environment through collision detection and force feedback model, and feeds the virtual force back to the primary end operator, so as to provide force feedback for doctors[5][6]. At the same time, the training interface in the virtual environment displays various sports information, providing visual feedback for doctors.

Figure 1 shows the overall framework of the training system for vascular interventional surgeons. The system can be divided into two parts, one is the main hardware and the other is the virtual environment[7]. First, the doctor operates the master terminal operator in the hardware platform, and transmits the motion signal of the master terminal operator to the PC through the control unit through serial communication. Then, the PC according to the movement of the message control the movement of catheter thread in the virtual environment, and then through the collision detection and force feedback model to calculate the virtual force, and virtual environment will movement information transmitted to the control unit via a PC, the control unit to control the main terminal operator force feedback force feedback device, in the process of training, The training system also provides doctors with intuitive visual feedback. Force feedback and visual feedback can not only ensure the training effect of doctors, but also ensure the reality of training.

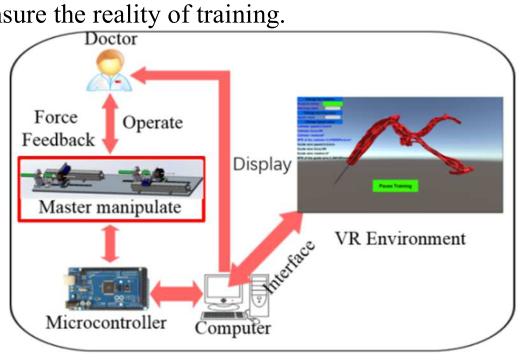


Fig.1 Complete training system concept map

B. Virtual environment platform

Unity3D is currently the most professional game engine in the world, which can create visualized 2D and 3D animations in real time, as shown in Figure 2.2. Developers can build various virtual environments on the platform of Unity3D to interact with actual devices[8]. It is widely used in medical education. Its development language is simple, and it is easier to implement functions through the process-oriented C# language compared to C language. At the same time, the mode of importing models is also more user-friendly, directly dragging the required model into the scene[9]. A good physics engine can also better simulate the physical properties of objects.

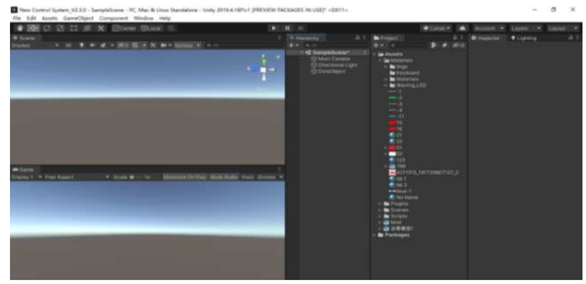


Fig.2 Schematic diagram of unity3D interface

III Simulation method of various forces in virtual vascular environment

The force feedback of the training system not only needs to use the force-tactile feedback structure of the main end manipulator to generate the feedback force, but also needs the corresponding model in the virtual environment to simulate the mechanical influence of various environmental factors in the blood vessel on the catheter guide wire. It is the collision force between the catheter and the guide wire that collides with the vessel wall and the friction force generated after the collision, which is also a function that every vascular interventional surgery training system needs to have. At the same time, with the increase of the depth of the catheter guide wire inserted into the blood vessel and the thickness of the blood vessel, the blood flow resistance and viscous resistance of the catheter guide wire will also change accordingly[10]. In order to improve the authenticity of the training system, this paper also gives the blood flow resistance. Simulation method with viscous drag.

A. *The collision force between the catheter guide wire and the vessel wall*

The collision force simulation method used in the virtual training system of this laboratory is based on the spring-resistor model, which is shown in Figure 3. The virtual damper is used to realize the self-recovery of the blood vessel wall, and the virtual spring is used to realize the compression and tension state of the blood vessel wall[11]. During the operation of the entire model, ΔX is calculated using the displacement of the collision area caused by the deformation of the vessel wall. The collision force calculation model can be obtained by analyzing the model：

$$F = Kx + Dx \tag{1}$$

Among them, F is the external force of the system, K is the elastic coefficient of the virtual spring, D is the damping coefficient of the virtual damper, and x is the change in position, which is the deformation amount △X in Figure 3. Different tissues have different elastic and damping coefficients. In the previous research in the laboratory, combined with the structure of the blood vessel wall, the collision force calculation model of the system was obtained:

$$F_c = E \cdot S \cdot \Delta X / X \tag{2}$$

The above formula E is the elastic modulus of the blood vessel wall, S is the contact area between the catheter or guide wire and the blood vessel wall, ΔX is the deformation of the blood vessel wall, and X is the thickness of the blood vessel wall. According to the investigation and comparison of various parameters in the previous study, the elastic modulus E of this system is set to 5kPa. The radius of the catheter model is determined to be 0.24cm, the radius of the guide wire model is 0.1cm, the S in the collision force calculation model of all catheters is 0.0576πcm^2, and the S in the collision force calculation model of the guide wire is 0.01π. The vessel wall thickness was 0.4 mm, and the maximum amount of deformation was assumed to be 0.3 cm.

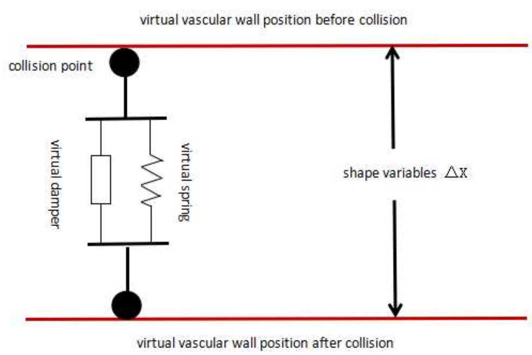


Fig.3 Collision force model

B.*The friction between the catheter guide wire and the vessel wall*

There is no calculation method of friction force in the virtual training system of this laboratory. Combined with the collision model proposed above, this paper proposes a friction force simulation method. As shown in Figure 4. The upward arrow indicates the collision force of the catheter guide wire after it collides with the vessel wall. The friction force simulation adopts the micro-element method. First, the collision part between the catheter guide wire and the blood vessel wall is divided into small sections, and then each small section is regarded as a collision point to calculate the collision force at this point, and the collision force is multiplied by the blood vessel wall. The friction coefficient of , obtains the friction force value at this point, and finally obtains the final friction force through the integration method. The specific friction model is as follows:

$$F_f = \mu F_C \tag{3}$$

$$F_{fz} = \int_0^x \mu F_c d_x \tag{4}$$

Where F_c is the collision force on the segment, F_f is the friction force on the segment, F_{fz} is the total friction force, and x is the total length of the collision.

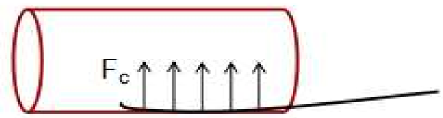


Fig.4 Friction model

C. *Blood flow resistance on the guide wire of the intravascular catheter*

Blood flow resistance is also an indispensable part of the training system. When blood flows in blood vessels, it will be subject to certain resistance, which is generally difficult to measure and needs to be obtained by specific calculation. Generally, it cannot be measured directly, but can only be obtained by calculation. The generation of blood flow resistance is due to the consumption of energy due to friction during blood flow, which is generally expressed as heat energy. This lost energy can no longer be converted into energy in the blood, so the pressure of blood flowing through the blood vessels gradually decreases.

Since the blood vessel is of irregular shape, the calculation of it is relatively complicated. According to the research of Cai Jiayin of Shanghai Jiaotong University, a section of blood vessel can be approximated as a combination of countless short enough round tubes[12]. When the blood vessel is simplified into a circular tube structure, the Poiseuille equation can be well used to calculate the blood flow resistance. The simplified circular tube model is shown in Figure 5.

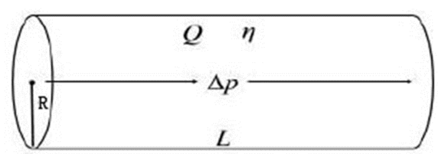


Fig.5 Simplified Circular Tube Model of Blood Vessels

According to the results of the French doctor Poiseuille who published his own research on blood flow in blood vessels, when an incompressible viscous fluid flows laminarly along a horizontal circular tube, the flow through it is proportional to the pressure difference applied at both ends of the tube, which is proportional to the radius of the circular tube. It is proportional to the fourth power and inversely proportional to the length of the round tube.

$$dQ = vds = v \cdot 2\pi rdr = \frac{(P_1 - P_2)}{4\eta l}\left(R^2 - r^2\right) \cdot 2\pi rdr \tag{5}$$

$$Q = \int_0^R \pi \frac{(P_1 - P_2)}{2\eta l}\left(R^2 - r^2\right) rdr \tag{6}$$

$$Q = \frac{\pi R^4 (P_1 - P_2)}{8\eta l} \quad (7)$$

Where Q is the blood flow, v is the blood flow rate, R is the radius of the blood vessel, r is the radius of the object in the blood vessel, P_1-P_2 is the blood pressure difference between the two ends of the circular tube after the blood vessel is simplified, that is, ΔP in Figure 5, η is the blood viscosity coefficient, l is the length of the vessel segment.

Blood flow resistance formula:

$$R_B = \frac{\Delta P}{Q} \quad (8)$$

where R_B is the blood flow resistance, Q is the blood flow, and ΔP is the blood pressure difference.

From formulas (7) and (8), the blood flow resistance can be deduced as:

$$R_B = \frac{8\eta l}{4\pi R^4} \quad (9)$$

where η is the blood viscosity coefficient, l is the length of the blood vessel segment, and R is the radius of the blood vessel. After consulting the data, the blood viscosity coefficient used in this system is 4.16kPa·s/L[13].

D. Viscous Resistance of Intravascular Catheter Guide Wires

In a viscous fluid, when an object moves at a uniform speed, a layer of liquid will be attached to the surface of the object, and there will be internal friction between the liquid layer and the adjacent fluid, and the object must overcome this resistance when moving in this fluid. In the blood vessel, the catheter and guide wire must overcome the influence of blood flow during the movement process.

As mentioned in the previous section, the shape of the blood vessels is irregular, and the blood vessels can be approximately regarded as the combination of countless short enough circular tube structures. Since the overall diameter of the catheter and the guide wire does not change, the viscous resistance of the catheter and the guide wire in the blood vessel movement can be regarded as the sum of the viscous resistance of each blood vessel segment. The schematic diagram is shown in Figure 6.

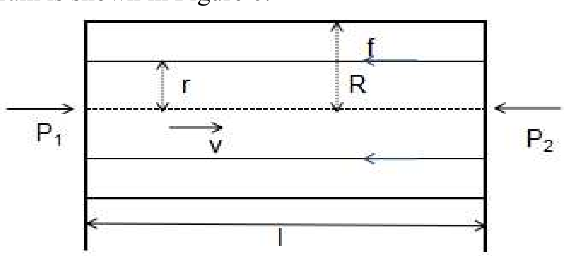


Fig.6 Viscous resistance schematic

Based on the results of various blood flow experiments, it can be seen that when the diameter of the blood vessel is greater than 1mm, the blood can be regarded as a homogeneous non-Newtonian fluid; when the diameter of the blood vessel is greater than 1mm and the shear rate is greater than $100s^{-1}$, the blood can be regarded as a homogeneous non-Newtonian fluid[14]. It is approximately regarded as a homogeneous Newtonian fluid; however, when the diameter of the blood vessel is less than 1 mm, the blood cannot be regarded as a homogeneous fluid. The blood vessels in this study belong to the arterial blood vessels, the shear rate is greater than $100s^{-1}$, and the diameters are all greater than 1mm. Therefore, the blood in the training system is regarded as an incompressible viscous Newtonian fluid. Therefore, the viscous and viscous resistance environment of blood flow can be modeled by Stokes' law. According to the Stokes formula in fluid mechanics, this resistance can be obtained as:

$$F_v = k\eta vl \quad (10)$$

Where F_v is the viscous resistance, k is the proportionality coefficient, η is the blood viscosity coefficient, v is the velocity of the blood flow relative to the velocity of the catheter or guide wire, and l is the length of the catheter or guide wire in the fluid.

When the blood vessel is cut into small enough pieces, the length of the catheter or guide wire in each blood vessel is also small enough to approximate the catheter guide wire in each blood vessel as a sphere. The Stokes scale factor of a sphere is known to be 6π. Then formula (10) can be simplified as:

$$F_v = 6\pi\eta vl \quad (11)$$

where η is the blood viscosity coefficient, v is the relative velocity of the blood flow velocity and the moving speed of the catheter guide wire, and l is the length of the catheter or guide wire in the fluid.

IV MULTI-SENSOR DATA FUSION ALGORITHM AND EXPERIMENTAL ENVIRONMENT

In order to obtain more accurate force feedback information in the virtual training system, after each force simulation model is available, a reasonable force synthesis algorithm is required to integrate each force into a comprehensive force and feed it back to the main end. Therefore, this paper proposes a multi-sensor data fusion algorithm to meet the requirements.

A. *Multi-sensor data fusion algorithm*

The main idea of this method is to assign the corresponding optimal weighting factor W_i (i=1, 2, ..., n) to each sensor based on the data measured by each sensor under the premise of the minimum total mean square error, with Find the final estimated value X' close to the real value X. Its schematic diagram is shown in Figure 7.

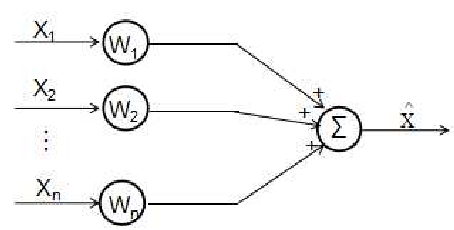


Fig.7 Schematic diagram of weighted fusion algorithm

Drawing on the idea of the above weighted fusion algorithm, each sensor represents the collision force, friction force, blood flow resistance and viscous resistance existing in the blood vessel respectively.When the guide wire is moving forward, the training system obtains the force value data of each component force through the force simulation method described above, and then obtains the comprehensive force value by using the weighted fusion algorithm.Then its comprehensive expression is as follows:

$$F_z = W_1 F_c + W_2 F_f + W_3 F_b + W_4 F_v \quad (12)$$

$$\sum_{i=1}^{4} W_i = 1 \quad (13)$$

Where F_z is the comprehensive force of the catheter guide wire, F_c and Ff are the collision force and friction force between the catheter guide wires, F_b and F_v are the blood flow resistance of the catheter guide wire, and W_i is the weight of each force. value.

The total mean square error calculation expression:

$$\sigma^2 = \sum_{i=1}^{4} W_i^2 \sigma_i^2 \quad (14)$$

According to the theory of extreme value of multivariate functions, the condition that the total mean square error σ^2 is the smallest is obtained. The weight corresponding to each sensor is Wi (i=1, 2, ..., n). When the variance is smaller, the corresponding weight the larger the value. The minimum total mean square error σ^2_{min} is:

$$\sigma_{\min}^2 = \frac{1}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}} \quad (15)$$

The corresponding weighting factor W_i of each sensor is:

$$W_i = \frac{1}{\sigma_i^2 \sum_{k=1}^{n} \frac{1}{\sigma_k^2}}, i = 1,2,\cdots,n \quad (16)$$

B *The experimental environment*

In order to verify the effectiveness of the multi-data weighted fusion algorithm, we need to measure the various force data generated by the collision between the catheter guide wire and the blood vessel wall in the actual environment and in the virtual environment, but because it is difficult to achieve an ideal experimental environment in real life, it is impossible to The blood flow resistance and viscous resistance were measured, and it was difficult to measure the collision force and friction force, so the mechanical simulation software Adams was used to simulate the real values measured in the actual environment. In the literature[15], the rationality of using Adams to simulate the force process of guide wire collision in blood vessels has been verified. It is also a pity that the simulation of flowing liquid cannot be completed in Adams, so this paper only verifies the effectiveness of the above algorithm for the collision force and friction force.

The virtual training system used in this paper is built with Unity 3D. In order to ensure the consistency of the experimental environment in Unity and Adams, a small blood vessel model is re-established as shown in Figure 8.

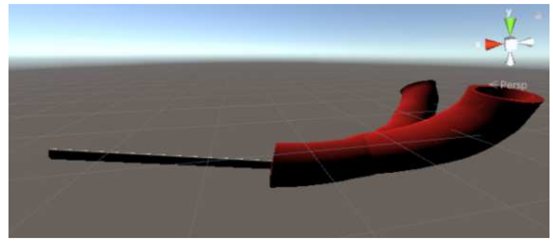


Fig.8 Catheter vessel model under Unity

Each motion state of the catheter is controlled by a script file edited by C#, and each parameter of the blood vessel is consistent with the parameters in the virtual training system.

The vascular interventional surgery training system in this laboratory is shown in Figure 9, which includes the main terminal operator, power supply, control unit, communication unit and virtual environment.

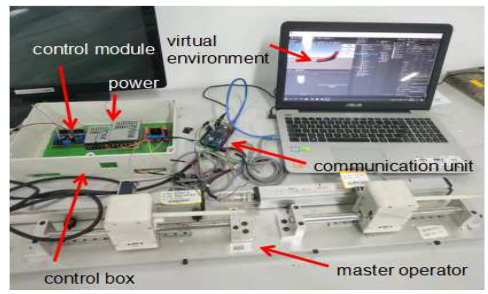


Fig.9 Vascular interventional surgery training system

The experimental environment under Adams is shown in Figure 10. The motion of the catheter is controlled by a forward motion pair, and the parameter settings such as the friction coefficient and equivalent stiffness of the blood vessel model are the same as those in the experiment in the Unity environment.

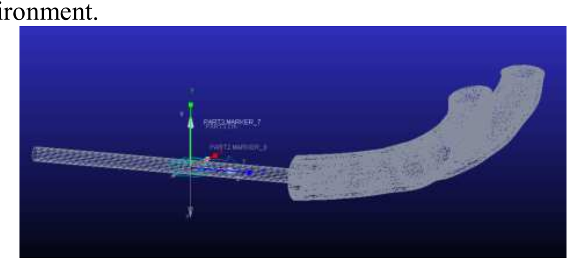
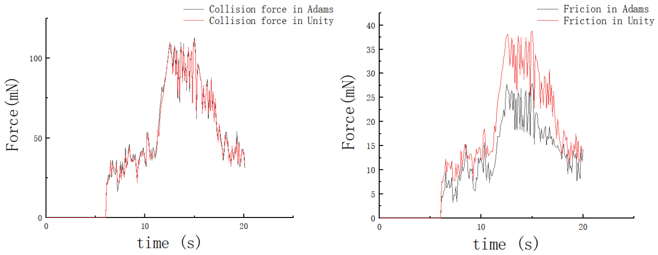


Fig.10 Catheter vessel model under Adams

V. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 11(a)(b) shows the curves of the collision force and friction force on the catheter guide wire in the Adams environment and the Unity environment respectively. At the initial time, the catheter did not collide with the blood vessel wall, and the blood resistance and viscous resistance were ignored, so the initial The force is 0 at all times, and then the collision occurs at about 6s, the force of the conduit increases gradually, and finally passes through the collision area at about 18s. The general trend of the friction force comparison chart is the same as that of the collision force. The large error in the middle part is because the collision force on the conduit is not completely perpendicular to the collision point when the collision occurs. The greater the collision force, the error of the friction force will follow increase. According to the above data and the above-mentioned multi-data fusion algorithm, the weights of the collision force and friction force can be calculated to be about 0.856 and 0.144, respectively.



(a).Collision force curve (b).Friction force curve

Fig.11 Curve diagram of collision force and friction force on catheter guide wire in different environments

Figure 12 below is a comparison chart of the comprehensive force obtained by using the required weight fusion in the virtual environment and the comprehensive force obtained without the algorithm and the comprehensive force in the Adams simulation environment. Figure 13 below shows the comparison of the error between using the fusion algorithm and not using the fusion algorithm after a collision.The average error is about 9.8mN, while it is 14mN when the algorithm is not used, so it is proved that this method has a certain improvement in the final comprehensive force feedback effect.

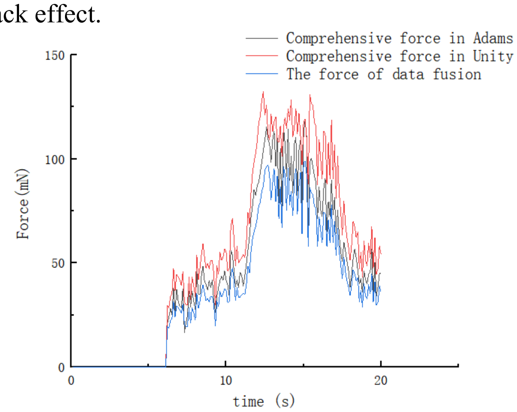


Fig.12 Comparison of comprehensive force in different situations

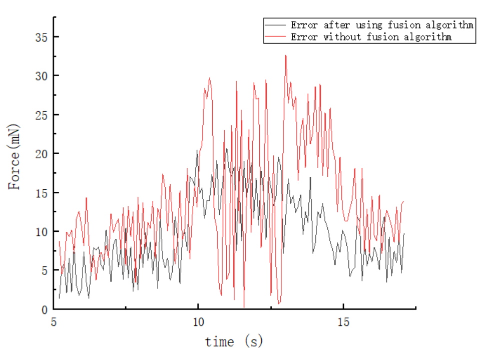


Fig.13 Comparison of errors after using the fusion algorithm and without using the algorithm

VI. CONCLUSION

In this paper, a multi-data weighted fusion algorithm is proposed to improve the accuracy of force feedback in the virtual training system. The algorithm can assign an optimal weight to each component force under the premise that the total mean square error of each force in the blood vessel is the smallest,according to different weights, each force is integrated into a comprehensive force to make it close to the actual value. Finally, the effectiveness of the algorithm is verified by comparing the calculated results with the comprehensive forces obtained from the simulation.

ACKNOWLEDGMENTS

This research is supported by National Natural Science Foundation of China (61703305 、 62103299) and Key Research Program of the Natural Science Foundation of Tianjin (18JCZDJC38500) and Innovative Cooperation Project of Tianjin Scientific and Technological Support (18PTZWHZ00090).

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