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A CNNs-based of Force and Torque Identification Model for Vascular Interventional Surgery Robot

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Abstract – At present, vascular interventional surgery is still the most popular way to treat cardiovascular and cerebrovascular diseases, and it is currently the most recognized. During the traditional vascular interventional procedure, the surgeon needs to makes a judgment on the contact of the catheter in the human body with the inner wall of the vascular lumen according to the information of the catheter operation force felt by the operation, and then make an adjustment decision for the surgical operation. If the surgeon judges that the operating force is abnormal according to experience, he will stop pushing or twisting the catheter, and then perform the action of retreating to avoid damage to the vessel wall or rupture of the aneurysm. This paper proposes a variable-coefficient follow-up control method based on force and torque identification. By inputting the samples of forces and torques in the previous 50 sampling points into a convolutional neural network, the risk probability of the operating force and torque is obtained, which is used to calculate the following coefficient of master-slave system to ensure the safety of the surgery. Experiments have shown that the operating force and torque during surgery are reduced by 20.8% and 14.2%.

Index Terms –Vascular Interventional Surgery Robot，Force and torque detection，Convolutional neural network.

I. INTRODUCTION

Vascular intervention surgery is widely accepted in many surgery due to the advantages of less trauma, fewer complications, less bleeding, safety, rapid postoperative recovery and reliability [1]. However, surgeons are exposed to X-rays for a long time, and surgeons need to wear heavy lead clothes in traditional interventional procedures, which is very detrimental to the health of surgeons. In recent years, robotic-assisted vascular interventional surgery system are very popular. The robotic-assisted vascular interventional surgery system consists of a master manipulator and a slave catheter controller. Surgeons can operate the master-side manipulator of master-slave interventional robot system in the operating room that is far from X-rays radiation [2]. Master-side manipulator collects the surgeon's surgical operation and sends the signal to the master computer. The master computer then converts the operation into a control command and sends the control signal to the lower computer for controlling the slave operator, which realizes the axial and rotational movement of the catheter.

There are several representative interventional robotic assisted systems. The Hansen Medical company made the Artisan Extend Control Catheter [3]. The CorPath GRX system was proposed by the coth [4]. The Amigo navigation catheter system was introduced by Catheter Robotic firm [5]. Stereotaxis firm introduced a remote Magnetic Navigation system called the Stereotaxis Niobe [6]. Yu Song et al. put forward a novel interventional robotic assisted system with haptic force feedback [7]. Shuxiang Guo et al. introduced a new kind of interventional robotic assisted system, the system uses master-slave structure and can achieve remote operation [8-9]. Jian Guo et al. used the fiber optic sensor to detect the force of the catheter tip and proposed a real-time force feedback device according to the principle of damping between a coil and a permanent magnet. And a operation safety early warning system was proposed based on the force feedback and fiber optic sensor [10]-[12]. Xuanchun Yin et al. firstly put forward an operator-centered human-computer interaction concept and used magnetorheological fluid to create force feedback [13]. Yan Zhao proposed a new method, which used the strain gauges to detecting operating torque information of the slave manipulator [14]-[15]. LS Zhang et al. put forward a force detection device based on strain and a novel clamping mechanism with electromagnetic braking for the slave-side catheter manipulator of the interventional robotic assisted system [16-17]. Yu Wang et al. proposed an operation training system based on virtual reality to train the unskilled surgeon [18]. Jin Guo et al. put forward a novel interventional robotic assisted system with force feedback and a visual feedback system for the operating force [19]. Yuan Wang et al. put forward a catheter-operated surgical system, which can detect the catheter insertion resistance on-line and provide force feedback to the surgeon [20-21]. Xianqiang Bao et al. introduced a new kind of remote interventional robotic assisted system based on catheter and guide wire cooperation [22-23]. Yu Wang proposed a virtual reality system for training doctors [24-25].

The current method for judging the state of operating force is mainly judging whether the force is in a safe range according to the absolute value of the force. This method has many disadvantages. On the one hand, the length of the catheter inserted into the blood vessel is different and the force of the catheter is different. On the other hand, the force of the catheter entering the large blood vessel and the small blood vessel is also very different. The impact of blood flow, friction, and the absolute value of the force at a certain moment to determine whether the force is in a safe state has a lot of issues. Meanwhile, whether the force received by the catheter at a certain moment is in a safe range has a great relationship with the tendency of the catheter to be stressed, but not just depends on the force at a certain moment. Therefore, in this paper, the method of convolutional neural network is used to extract the characteristics of force and torque over a period of time, and the risk probability of the force and torque is obtained.

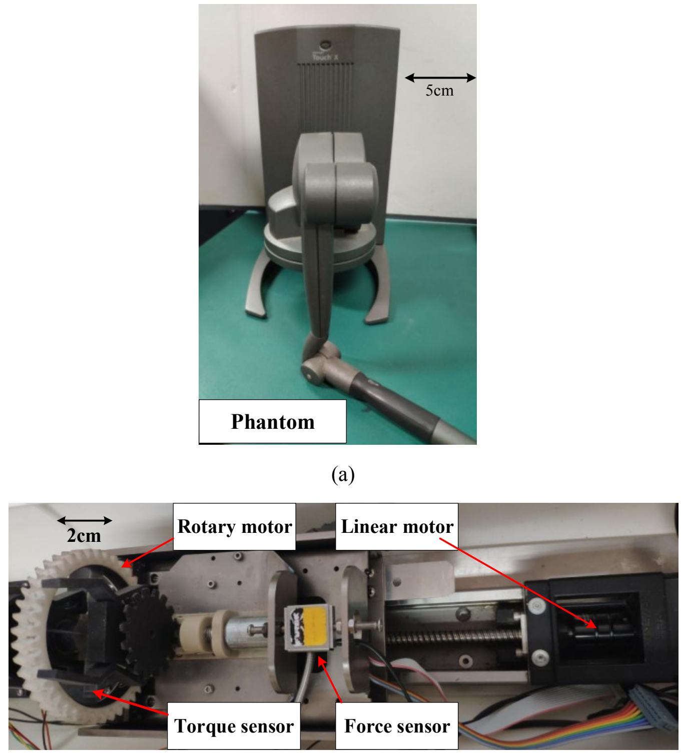
In this paper, a CNNs-based of force and torque identification algorithm for vascular interventional surgery robot is proposed to reduce the operating force and torque. In section II, design of the force and torque identification algorithm is elaborated. In section III, the performance of the proposed algorithm is verified by experiments and the results are discussed. In section IV, the research work of the paper is summarized and the future work is raised.

II. Design of the Force and Torque Identification Algorithm

A. Over view of catheter operation system

During the interventional procedure, surgeons decide the operation of the catheter not only through the DSA angiography image, but also according to the operating force and torque. When the catheter is stressed abnormally, the surgeon tends to slow down the catheter at this time. It is to protect the vessel wall from damage. Because the vascular environment in the human body is very complicated, surgeons decide whether the catheter is stressed abnormally, often not only based on the force of the catheter at a certain moment, but also based on the operating force and torque a period of time before. For example, when the catheter enters a small blood vessel from a large blood vessel, the force of the catheter will gradually increase at this time, and the force of the catheter is not abnormal. The surgeon does not need to be slow down at this time. If the operation is scaled, the normal operation skills of the surgeon will be affected. Therefore, the convolutional neural network is used to determine whether the force of the catheter is in an abnormal range, which solves the complicated and unpredictable force of the catheter. According to the trend of the catheter over a period of time, it can be predicted whether the current state of the catheter is safety or not. If the current state is not safe, the slave operating will be reduced, which is used to reduce the operating force of the catheter during the interventional procedure and increasing the safety of the operation.

The force is detected by the commercial force sensor (FUTEK). It can transmit the force from the slave-catheter to the agilent digital multimeter (34410A) in the form of voltage. The agilent digital multimeter is connected to the master computer through the USB serial port. The agilent digital multimeter will measure the voltage value and send it to the master computer.



(b)

Fig. 1. Master-slave system structure. (a) Master controller of the system. (b) Slave operator of the system.

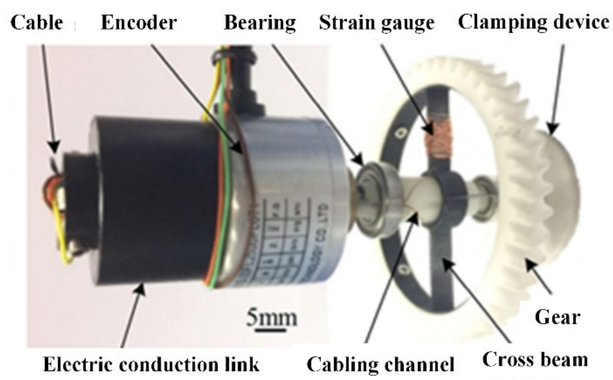


Fig. 2. The structure of torque sensing device[14].

As shown in Fig.2, the torque sensing unit is located between the rotational driving herringbone gear and the catheter clamping unit. The torque sensing unit involves a cross beam as the elastic element, a strain gage as the sensing cell. The cross beam synchronously acts as the elastic cell of the sensing system and gear spokes. During robot assisted interventional procedure, the catheter is clamped by the clamping unit, which is fixed with the cross beam. The operating torque is transmitted to the elastic cross beam through the clamping unit [14].

The strain gauge will be connected to the a Wheatstone bridge. The Wheatstone bridge can amplify the change in resistance due to strain gauge deformation. The operating torque must be detected when the clamping device and sensing

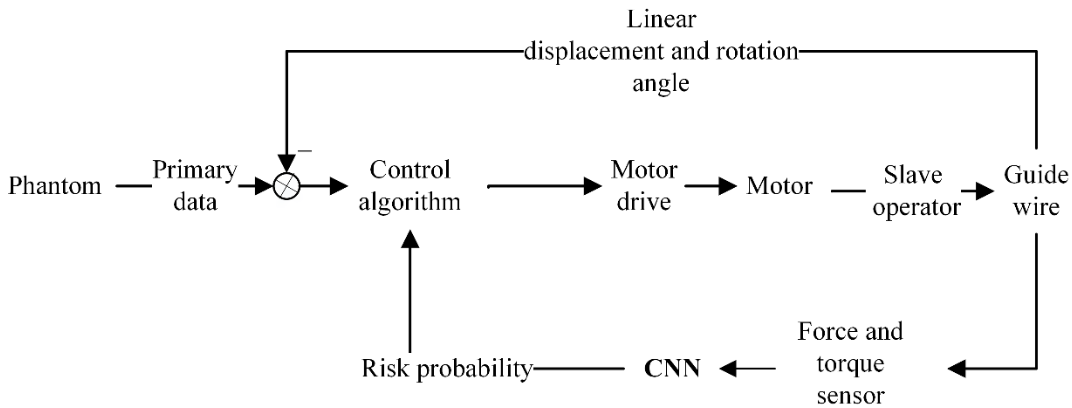


Fig. 3. Control flow chart of the proposed system.

device are being rotated, so the wire of the resistance strain gauge will path through a channel of the conductive slip ring to connect to the Wheatstone bridge. Then the output voltage signal of the Wheatstone bridge is amplified by Agilent Digital Multimeter(A34410).

During the robot assisted vascular interventional surgery, The surgeon operates the master controller (phantom). The master phantom collects axial displacement and angle displacement of the surgeon's operation, and transmits the surgical operation information to the master computer. the force and torque information detected by the force and torque sensor is seed to the master computer. The master computer will input the force of 50 sampling moments into the convolutional neural network. After the softmax layer of the convolutional neural network, the risk probability of the force and torque will be output. Using this risk probability P, the surgical operation information of the master-side is scaled and sent to the slave computer, which will let the slave-side slow down to avoid damage to blood vessels.

B. The proposed force and torque identification network

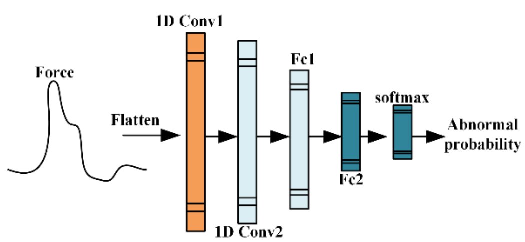


Fig. 4. Operating force state recognition model

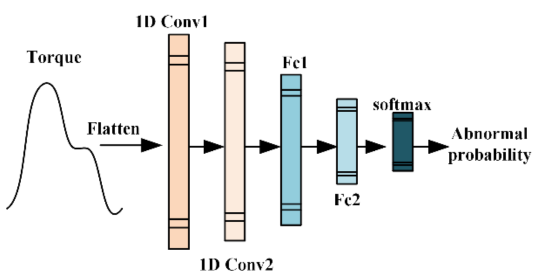


Fig. 5. Operating torque state recognition model

During the traditional vascular interventional procedure, the surgeon needs to make a judgment on the contact of the catheter with the vascular wall in the human body according to the information of the catheter's operation force, and makes an adjustment decision for the surgical operation. If the surgeon judges that the operating force is abnormal according to experience, the surgeon will slow down the speed of pushing the catheter, which is to avoid damaging the vessel wall or rupture of the aneurysm.

In this paper, the catheter operating force state is divided into two states: when the catheter encounters an obstacle (such as a thrombus) or is severely squeezed with the vessel wall, the catheter operating force is abnormally increased, and the catheter operating force state is defined as an abnormal state. Otherwise the state of the catheter will be defined as normal. Because the contact force between the catheter and the vessel wall in the human body is complex and variable, it is difficult to identify it effectively by simple threshold method [26]. Therefore, an operational force state recognition model based on 1D CNN (one-dimensional convolutional neural network) is proposed. In addition to considering the instantaneous operating force at the current moment, the trend characteristics of the operating force at the previous moment of the current moment are extracted, and the effective identification of the catheter operating force state is realized.

The proposed catheter operating force and torque state recognition model structure is shown in Fig. 4 and Fig. 5. The axial operating force and operating torque of the catheter use the same network structure, but the weights are not shared. At present, the catheter operating force and torque are defined as F_{ti} and τ_{ti}, and the sequence of the catheter operating force and the torque sequence at the current time (before) are defined as F_t and τ_t. The feature is firstly input into a two-layer one-dimensional convolution network for feature extraction. The two-layer fully-connected layer is used as a classifier, and the full-connection layer output is normalized to an interval as an input of a layer of softmax layer, and converted into a catheter axial operation. The force and operating torque state are the probability of anomalies. The first layer 1D CNN is shown in equations (1) and (2):

$$\eta_i^l([F_t]) = \sigma\left(b_i^l + \sum_k \sum_u \eta_k^{l-1}([F_t]) W_{ki}^{F,l}(u)\right) \tag{1}$$

$$\eta_i^l([\tau_t]) = \sigma\left(b_i^l + \sum_k \sum_u \eta_k^{l-1}([\tau_t]) W_{ki}^{\tau,l}(u)\right) \tag{2}$$

Where η_i^l is the i feature output of the Layer l one-dimensional convolutional network; η_k^{l-1} is the k feature output of the Layer l one-dimensional convolutional network. $W_{ki}^{F,l}, W_{ki}^{\tau,l} \in R$ is the ki convolution kernel of Layer l one-dimensional convolutional network in the axial operation force identification network and the operational torque identification network. b_i^l is the bias term; $\sigma(\cdot)$ is the activation function, this paper uses the ReLU activation function.

In order to avoid the current moment of operation and torque annihilation during the convolution operation, the force is the input of the first layer of the fully connected layer, and the output of the first layer of the fully connected layer is the input of the second layer of the fully connected layer. The output of the Layer 2 fully connected layer is then input to the Softmax layer for normalization, as shown in equation (3)-(8):

$$\eta^{f_1} = \sigma\left(b^{f_1} + W^{F,f_1}([\eta^2, F_{ti}])\right) \tag{3}$$

$$\eta^{f_1} = \sigma\left(b^{f_1} + W^{\tau,f_1}([\eta^2, \tau_{ti}])\right) \tag{4}$$

$$\eta^{f_2} = \sigma\left(b^{f_2} + W^{F,f_2}\eta^{f_1}\right) \tag{5}$$

$$\eta^{f_2} = \sigma\left(b^{f_2} + W^{\tau,f_2}\eta^{f_1}\right) \tag{6}$$

$$P_{ti}^F = \exp(\eta^{f2}) \Big/ \sum\nolimits_0^1 \exp\left(\eta^{f2}\right) \tag{7}$$

$$P_{ti}^\tau = \exp(\eta^{f2}) \Big/ \sum\nolimits_0^1 \exp\left(\eta^{f2}\right) \tag{8}$$

Where η^2 is the output of the second layer of the one-dimensional convolutional layer, and the η_k^{l-1} is the output of the first and second layers of the fully connected layer, W^{F,f_1}, W^{τ,f_1}, W^{F,f_2} and W^{τ,f_2} respective the weight of the first layer and second fully connected layer of the axial operating force identification network and torque identification network, b^{f_1} and b^{f2} is the bias term, $\sigma(\cdot)$ is the activation function. This paper uses the ReLU activation function, which P_{ti}^F is the probability that the axial operating force state at the current moment is abnormal, and P_{ti}^τ is the the probability that the operating torque state at the current moment is abnormal.

Before the abnormality of the catheter operation force, according to the probability that the catheter operation force is abnormal, the master-slave mapping relationship of the vascular interventional surgery robot is dynamically adjusted, which can realize the refinement operation of the catheter to achieve the purpose of reducing the risk of surgery.

At the same time, in order to improve the safety factor of the operation, a threshold value is set for the abnormality of the operating force state. When the threshold value is exceeded, the master-slave mapping coefficient is set to zero, that is, the slave robot is locked. In this way, the operation can be guaranteed from the perspective of the catheter operating force.

The main phantom collects the surgeon's operation X_{dt}, and then sends the master operation to the master computer. At the same time, the force and torque sensor from the end transmits the value of the collected torque to the agilent digital multimeter. The digital multimeter will passed the force and torque to the master computer, and the master computer inputs the value of the force of the 50 sampling points recorded into the convolutional neural network. The convolutional neural network outputs the risk posssibility P1 and P2 of the force and torque. When the risk factor is greater than a certain value, the slave side needs to be locked, so the safety factor of the set force and torque is pmax. And only when the risk possibility is bigger than pmin, we begin to think that there is danger.

$$\text{P1}=\begin{cases} 1, & p\max \le p1 \le 1 \\ p1, & p\min \le p1 \le p\max \\ 0, & 0 \le p1 \le p\min \end{cases} \tag{9}$$

$$\text{P2}=\begin{cases} 1, & p\max \le p2 \le 1 \\ p2, & p\min \le p2 \le p\max \\ 0, & 0 \le p2 \le p\min \end{cases} \tag{10}$$

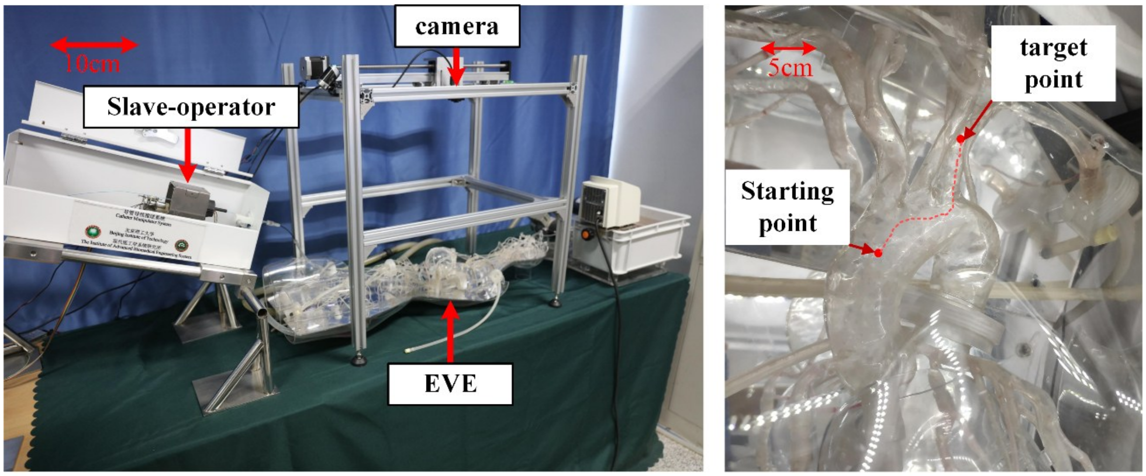
In order to ensure the safety of the operation, the force and torque simultaneously detect the risk factor, taking the value with the bigger coefficient as the final risk factor.

$$\text{P} = \max\left(\text{P1}, \text{P2}\right) \tag{11}$$

The final risk factor takes the bigger values of P1 and P2, and then the operating command sent by the master computer to the slave computer is X_{dt} *(1-P), and then the axial displacement and angle displacement feedback from the slave end constitutes a closed loop system.

III. EXPERIMENTAL DETAILS AND RESULTS

In order to verify the validity of the designed algorithm, the following experiments were designed. Phantom was used as the master controller, and the operation was performed in the EVE. And use the phantom to control the slave catheter to complete the process of getting through the aortic arch, and get into the ascending blood vessels, which is a representative interventional procedure. The experiment was carried out 10 times in total. The control algorithm with force and torque recognition algorithm based on CNNs was compared with the control algorithm without force and torque recognition algorithm. The experimental results are shown in the table I. and the average value was obtained. The results in table I show that the average operating force of the catheter was reduced by 20.8% and the maximum operating force was reduced by 16.6%. The average operating torque was reduce by 14.2%, and the maximum operating torque was reduced by 20.1%.



(a) (b)

Fig. 6. Experiment setup. (a) Overall view of the experimental device. (b) Surgical operation route.

TABLE I.
THE OPERATING FORCE AND TORQUE OF VASCULAR INTERVENTIONAL SURGERY ROBOT SYSTEM WITHOUT FORCE AND TORQUE RECOGNITION ALGORITHM AND WITH FORCE AND TORQUE RECOGNITION ALGORITHM

	Average Operating Force(N)	Maximum Operating Force(N)	Average Operating Torque(mN.m)	Maximum Operating Torque(mN.m)
System Without Force And Torque Recognition Algorithm	0.713	1.121	15.11	30.02
System With Force And Torque Recognition Algorithm	0.565	0.935	13.53	23.98
Reduced Proportion	20.80%	16.60%	14.20%	20.10%

IV. DISCUSSION

During the vascular interventional surgery, the surgeon operates the catheter under the X-ray images to reach the target. There are no vascular wall in the X-ray images, so the surgeon will judge the surgical status according to the force and torque. The force and torque is a very important surgical information for the surgeon to decide the surgical operation. When the force is abnormal according to the experience of the surgeon, they will operate the catheter more carefully with slower speed according to the force and torque. The surgeon determine whether the water temperature is abnormal or not according to the force and torque in a period. So the judgment method according to the threshold of the torque and force is defective.

This paper introduces a novel CNNs-based of force and torque identification model for vascular interventional surgery robot. The input is the force and torque sampled in a period time. And the output of the network is the risk factor of force and torque. The master-slave following coefficient is inversely proportional to the risk factor. To protect blood vessels from damage, when the risk factor is larger than the maximum threshold, the slave robot will stop moving. The identification method proposed in this paper is close to the doctor's judgment method, and it is suitable for different blood vessels in various surgical procedures by increasing the sample data entered into the network.

V. CONCLUSIONS

This paper proposes a force and torque recognition model based on convolutional neural network for the robot-assisted interventional surgery. The force and torque received by the catheter over a period of time input to the network, and the network output the force and torque risk possibility of the current state. It is used to estimate the risk factor of the force and torque of the catheter during the robot-assisted interventional procedure. This risk possibility is used to adjust the proportional coefficient of motion between the master controller and slave-side in the surgical robot system. When the risk possibility is increase, the current force and torque are in an unsafe state. At this time, the follow-up coefficient is reduced, and the movement of the slave side is smaller than the master controller, which can reduce the operating force and torque and increase the safety of the interventional surgery. The result shows that the system with force and torque recognition algorithm based on CNNs can improve the safety of the robot-assisted interventional procedure. Therefore, in the future work, a more reasonable human-computer interaction system will be proposed to increase the friendliness of surgeon and the safety of the surgery.

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REFERENCES

[1] S. Guo, Y. Wang ,N. Xiao and Y. Zhao, “A novel master-slave robotic system with close loop control for vascular interventional surgery,” *in Proceedings of 2018 IEEE International Conference on Mechatronics and Automation*, pp.591-596, August 5-8, Changchun, China, 2018.

[2] L. Zhang, S. Guo, H. Yu, L. Zhang and T. Tamiya, “Design and performance evaluation of collision protection-based safety operation for a haptic robot-assisted catheter operating system,” *Biomedical Microdevices*, Vol.20, No.3, DOI: 10.1007/s10544-018-0266-8, 2018.

[3] N. Xiao, J. Guo, S. Guo and T. Tamiya, "A robotic catheter system with real-time force feedback and monitor," *Australasian Physical & Engineering Sciences in Medicine*, Vol.35, No.3, pp. 283-289, 2012.

[4] L. Cercenelli, B. Bortolani and E. Marcelli, "CathROB: A Highly Compact and Versatile Remote Catheter Navigation System," *Applied Bionics and Biomechanics*, DOI: 10.1155/2017/2712453, pp. 1-13, 2017.

[5] M. Lópezgil, R. Salgado, T. Datino, J Figueroa and Merino JL, “Cavo-tricuspid isthmus radiofrequency ablation using a novel remote navigation catheter system in patients with typical atrial flutter,” *Europace*, Vol.16, No.4, pp.558-562, 2014.

[6] M. A. Zenati and M. Mahvash, "Robotic systems for cardiovascular interventions," *Medical Robotics: Minimally Invasive Surgery*, DOI:10.1533/9780857097392.78, pp. 78-89, 2012.

[7] Y. Song, S. Guo, X. Yin, L. Zhang and Y. Wang, “Design and performance evaluation of a haptic interface based on MR fluids for endovascular tele-surgery,” *Microsystem Technologies*, DOI: 10.1007/s00542-017-3404-y, pp. 1-10, 2017.

[8] S. Guo, Y. Song and X. Yin, “A novel robot-assisted endovascular catheterization system with haptic force feedback,” *The IEEE Transactions on Robotics*, DOI 10.1109/TRO.2019.2896763, 2019.

[9] Y. Song, S. Guo, X. Yin, L. Zhang, H.Hirata, H. Ishihara, T.Tamiya, “Performance evaluation of a robot-assisted catheter operating system with haptic feedback,” *Biomedical Microdevices*, Vol.20, No.2, DOI: 10.1007/s10544-018-0294-4, 2018

[10] J. Guo, S. Guo, N. Xiao, X. Ma and S. Yoshida, "A novel robotic catheter system with force and visual feedback for vascular interventional surgery," *International Journal of Mechatronics and Automation*, Vol.2, No.1, pp. 15-24, 2012.

[11] J. Guo, S. Guo, L. Shao, P. Wang, Q. Gao, “Design and performance evaluation of a novel robotic catheter system for vascular interventional surgery,” *Microsystem technologies*, Vol.22, No.9, pp.2167-2176, 2015.

[12] J. Guo, S. Guo, Y. Yu, “Design and characteristics evaluation of a novel teleoperated robotic catheterization system with force feedback for vascular interventional surgery,” *Biomedical Microdevices*, Vol.18, No.5, pp.1-16, 2016

[13] X. Yin, S. Guo, N. Xiao and T. Tamiya, “Safety operation consciousness realization of a mr fluids-based novel haptic interface for teleoperated catheter minimally invasive neuro surgery,” *IEEE/ASME Transactions on Mechatronics*, DOI: 10.1109/TMECH.2015.2489219, pp. 1043-1054, 2015.

[14] Y. Zhao, S. Guo, N. Xiao, Y. Wang and Y. Li, “ Operating force information on-line acquisition of a novel slave manipulator for vascular interventional surgery,” *Biomedical Microdevices*, Vol.20, No.33, DOI: 10.1007/s10 544-018-0275-7, 2018.

[15] S. Guo, Y. Zhao, N. Xiao and Y. Wang, “Vessel enhancing for a continuous dsa method towards endovascular interventional surgery,” *in Proceedings of 2018 IEEE International Conference on Mechatronics and Automation*, pp.608-613, August 5-8, Changchun, China, 2018.

[16] L. Zhang, S. Guo and H. Yu, “Performance evaluation of a strain-gauge force sensor for a haptic robot-assisted catheter operating system,” *Microsystem Technologies*, DOI: 10.1007/s00542-017-3380-2, pp. 1-10, 2017.

[17] L. Zhang, S. Guo and H. Yu, “Electromagnetic braking-based collision protection of a novel catheter manipulator,” *in Proceedings of 2017 IEEE International Conference on Mechatronics and Automation*, pp.1726-1731, August 6-9, Takamatsu, Japan, 2017.

[18] Y. Wang, S. Guo and T. Tamiya, “A virtual-reality simulator and force sensation combined catheter operation training system and its preliminary evaluation,” *International Journal of Medical Robotics and Computer Assisted Surgery*, Vol.13, No.3, DOI: 10.1002/ rcs.1769, 2017.

[19] J. Guo, S. Guo and Y. Yu, “Design and characteristics evaluation of a novel teleoperated robotic catheterization system with force feedback for vascular interventional surgery,” *Biomedical Microdevices*, Vol.18, No.5, pp.1-10, 2016.

[20] Y. Wang, S. Guo, N. Xiao, “Online measuring and evaluation of guidewire inserting resistance for robotic interventional surgery systems,” *Microsystem Technologies*, Vol.24, DOI:10.1007/s00542-018-3750-4, pp.3467-3477, 2018.

[21] S. Guo, Y. Wang, N. Xiao, “Study on real-time force feedback with a master-slave interventional surgical robotic system,” *Biomedical Microdevices*, Vol. 20, No.2, pp.1-10, 2018.

[22] X. Bao, S. Guo and N. Xiao, “Compensatory force measurement and multimodal force feedback for remote-controlled vascular interventional robot,” *Biomedical Microdevices*, Vol. 20, No.3, pp.1-11, 2018.

[23] X. Bao, S. Guo and N. Xiao, “A cooperation of catheters and guidewires-based novel remote-controlled vascular interventional robot,” *Biomedical Microdevices*, Vol. 20, No.1, DOI:10.1007/s10544-018-0261-0, 2018.

[24] Y Wang, S. Guo, Y. Li, T. Tamiya, Y. Song, “Design and evaluation of safety operation VR training system for robotic catheter surgery,” *Medical & Biological Engineering & Computing*, Vol.56, No.1, pp.25-35, 2017.

[25] Y. Wang, S. Guo, T. Tamiya, H. Hirata, H. Ishihara, X. Yin, “A virtual-reality simulator and force sensation combined catheter operation training system and its preliminary evaluation,” *The International Journal of Medical Robotics and Computer Assisted Surgery*, Vol.13, No.3, DOI: 10.1002/rcs.1769, 2016.

[26] J. Guo, X Jin and S. Guo, “Study of the operational safety of a vascular interventional surgical robotic system,” *Micromachines*, Vol. 9, No. 3, DOI: 10.1007/s10544-018-0321-5, 2018.