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A Preliminary Study of Vibration Feedback for Robot-assisted Endovascular Surgery

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***Abstract* – The study of haptic perception is significant and general for robot-assisted endovascular surgery. During actual surgical procedure, feedback information has advantages in monitoring the insertion process, providing direct instruction for surgeons, and improving operation safety. In this work, a new implementation of haptic perception named vibration feedback is concepted and proposed based on micro vibration motor. Related working principles and kinetic analysis of vibration feedback are descripted based on three kinds of vibration patterns. Two kinds of experiments are conducted to determine suitable parameters of duty cycle for vibration feedback and test the using performance in human model. Experimental results indicate that the proposed vibration feedback is feasible and helpful to offer a haptic perception. Moreover, benefiting from the micro size of vibration motor, this study also has potential value for some research fields like small wearable device, micro haptic feedback, multi-level feedback perception for robotic systems.**

Index Terms – Vibration feedback, Robot-assisted endovascular surgery, Haptic perception, Feedback control.

I. INTRODUCTION

Lately, cardiovascular disease is a main cause of mortality and medical prescription due to the severities of cardiac arrest and cardiac ischemia. Robot-assisted Endovascular Surgery (RES) is a developing treatment method to improve radiation exposure for surgeons and reduce surgical pain for patients as a solution of minimally invasive procedure [1]. Particularly, master-slave structure makes the remote endovascular surgery is possible, which embraces several benefits including complete intraoperative monitoring, smooth surgical procedure, and fast postoperative recovery. Especially under the current social environment of pandemic, the technology of RES will play a significant role to cure the cardiovascular diseases [2].

Up to now, with the efforts of global research groups, RES is undergoing great improvement based on different operating systems [3]-[5], commercial devices [6]-[7], and clinical trials [8]. The related works of remote-controlled RES robots can be categorized into two classes: mechanical design of master-slave structure [9]-[10] and improvement of operating performance [11]-[12]. Most research groups focus on the implementation of robotic movements, i.e., newly manipulating designs for both master manipulator (operating side for surgeon) and slave manipulator (surgical side for patient), which can be able to control medical instruments (catheters and guidewires) to conduct the treatment procedure. For the mechanical design, for instance, Yan et al [13] used a humanoid finger-functional parallel gripper to realize flexible grasping and good performance for in-hand operating. Zhou et al [14] developed a surgeon's habits-based novel master manipulator, which is possible to provide axial and circumferential force feedback independently. A smart material named magnetorheological (MR) fluid [15] is adopted to offer various haptic sensation when conducting a surgery. Moreover, Shi et al [16] presented a haptic robot-assisted catheter operating system with a spring-based haptic interface as an accurate solution of force feedback. As for the enhancement of operating performance, Lyu et al [17] proposed a deep learning-based guidewire-compliant control method to reduce the average operating force (by 44.0%) and shorten operating time (by 44.0%). Jin et al [18] developed an effective active suppression method to ensure a safe operation based on different behaviours. Yang et al [19] explored possibility of cloud communication-based vascular intervention, which can finish robot-assisted surgery under the condition of long distance. In addition, Bao et al [20] utilized a multilevel operation strategy to reduce blood vessel damage, ensure surgical safety, and allow for continuous operation. Analysing above efforts these studies have made some improvements for RES to a certain and finished haptic feedback based on force information. However, a clear drawback, they do not consider other-form realization of feedback perception to improve operating safety and real feedback experience. Hence, it is important to add another perception into RES as a novel haptic sensing solution.

In this work, the main contribution is that a preliminary study of vibration feedback is explored and proposed based on vibrating motor to provide a sensation of vibration for surgeons, monitor the actual surgical condition, and ensure the operation safety for RES.

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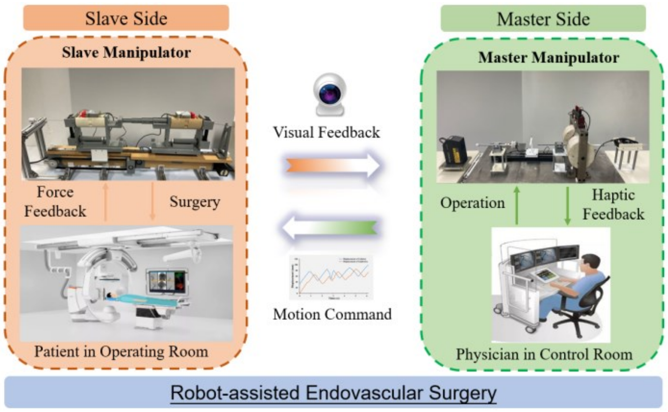


Fig. 1 Conceptual diagram of the robot-assisted endovascular surgery.

The remainder structure of this effort is shown as bellow. The system description is presented in Section II. The methodology of vibration feedback is described in Section III. Experimental results and discussion are proposed in Section IV. At last, Section V exhibits the conclusion of this work.

II. System Description

For the developed RES system, it is concepted as a master-slave design by two core components: master manipulator and slave manipulator. The conceptual diagram of robot-assisted endovascular surgery is shortly descripted in Fig. 1. The underlying purpose of RES is to separate surgeons from the conventional radiation-exposed surgical room and offer accurate movements to patients. The master side, as a remote operating method, is presented to capture operating information for a couple of surgical instruments (catheter and guidewire). Furthermore, most importantly, the master side needs to embrace the ability of reproducing tactile force for operators to guarantee a safe operation environment. The slave side (in control room) aims to finish the robot-assisted surgery by replicating the surgeon's operation. Meanwhile, visual feedback is able to guide the real operation procedure timely for the developed RES.

A. Master Manipulator

Fig. 2 is the developed master manipulator, which is mainly insisted by two types of operating units: guidewire operating unit and catheter operating unit, and a magnetic-controlled haptic interface [3]. The realization of haptic force feedback is a self-designed deformable soft structure under the supplied magnetic field generated by two coils. By varying the magnetic flux density, different sensation of haptic force can be obtained.

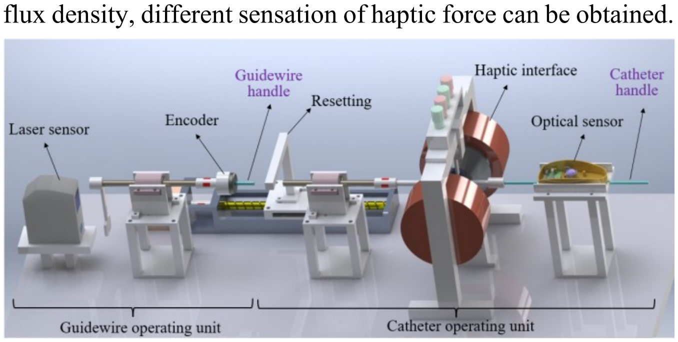


Fig. 2 The developed master manipulator for RES system.

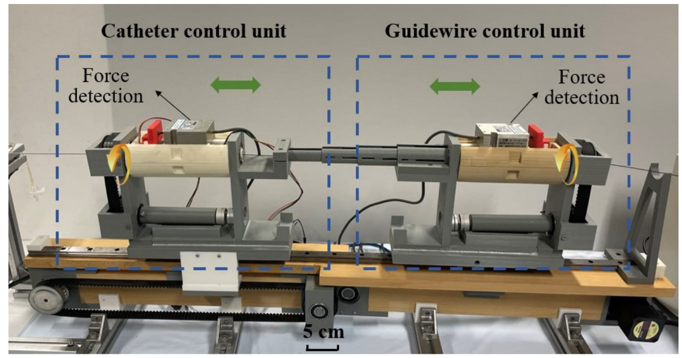


Fig. 3 The slave manipulator based on collective operating handles.

Benefiting from a laser sensor (LK-500, Keyence Inc., Japan), an encoder (MES020-2000p, MTL Inc., Japan), and an optical sensor (M-SBJ96, Fujitsu Inc., Japan), two types of operations (linear motion and rotation motion) for catheter and guidewire can be collected by the master manipulator. Note that two operating handles are rigid rods, it is easy to simulate the feeling of operating surgical instruments in practice. In addition, a resetting design based on a screw is proposed to provide a long-distance robot-assisted surgery.

B. Slave Manipulator

The slave manipulator of the RES system is shown in Fig. 3. It was designed to perform vascular surgery on behalf of traditional surgeon via the robotic manipulator, which is previous study of our group [21]. Since corresponding to operating units on mater side, the slave manipulator has a couple of control units as well. The linear movement and rotation movement are realized by stepping motors (ASM46AA, Oriental motor Inc., Japan). Based on the design of two control units, the robotic system can perform collaborative robot-assisted surgery. Benefiting from two control units, the system can complete individual or collaborative operating surgery, which is significant to satisfy different surgical needs. Besides, the proximal force information can be captured by load cells (TU-UJ5N, TEAC Inc., Japan) in real time when complete a surgery.

III. Methodology of Vibration Feedback

Conventional endovascular surgery robots only consider two kinds of feedbacks including haptic feedback and visual feedback for the perception feedback on master side. Aim to the goals for safe operation of robotic system, timeliness and accuracy of feedback perception, a novel approach of perception based on vibration feedback is concepted and analyzed in this section.

A. The Vibration Motor

Fig. 4 exhibits the details of flat-type micro vibration motor (RB-See-403, 3.0V DC, Japan), also known as a thin vibrating motor or a pancake motor, is a small electromechanical device used to produce vibration feedback in various applications like mobile phones, smart watches, fitness trackers, and other wearable devices. It is characterized by its thin and flat shape, which makes it particularly suitable for the applications where

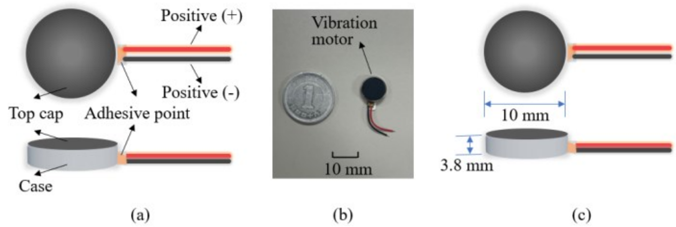


Fig. 4 The details of vibration motor. (a) elaborate components; (b) real layout; (c) dimension parameters. (Top view and main view)

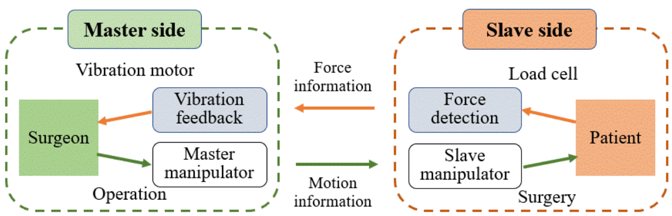


Fig. 5 The transfer model of vibration feedback for the robotic system.

space is limited. Hence, flat type micro vibration motor is a significant component in many different electronic devices and systems, providing an efficient and reliable way to produce vibration and specific haptic feedback in a thin and space-saving form factor. In this work, these advantages are taken full of considered to be used in the filed of vibration feedback for the developed RES.

B. *Working Principles and Kinetic Analysis*

At the beginning, it is essential to introduce the transfer model of vibration feedback for the developed RES, which is shown in Fig. 4. The underlying transfer principle is to build specific co-relationship between the force information (detected by load cell) and the vibration feedback (produced by vibration motor) so that surgeon can sense a newly feedback feeling when performs a surgery.

As for the working principle of vibration motor, when electricity is applied to the motor, the inner eccentric weight begins to rotate, causing the motor unit to vibrate regularly. The speed and intensity of the vibration can be adjusted by changing the voltage or frequency of the electrical signal. Consequently, the technology of PWM (Pulse-Width Modulation) is adopted to drive and control different vibration patterns based on the variable duty cycle.

Considering the actual surgical environment with different levels of force, probably causes some hazardous operations even occurs risks of puncturing the blood vessel, three kinds of patterns are proposed based on the value of detected force on slave side. The defined relationships between the collected force values and vibration patterns are exhibited in Table I. The detailed analysis of vibration feedback is shown as below:

TABLE I
THE DEFINED RELATIONSHIPS BETWEEN THE COLLECTED FORCE VALUES AND VIBRATION PATTERNS

Pattern items	Force value	Duty cycle (PWM)
Pattern 1 (safe zone)	$F(t) \leq F_{def1}$	D_{p1} (%)
Pattern 2 (potential zone)	$F_{def1} < F(t) \leq F_{def2}$	D_{p2} (%)
Pattern 3 (dangerous zone)	$F(t) > F_{def2}$	D_{p3} (%)

Remarks: $F_{def1} = 0.342\ N$ and $F_{def2} = 1.0\ N$ (by experiments), D_{p1}, D_{p2}, D_{p3} will be determined in Section IV

a) *Pattern 1 (safe zone)*. When the force is less than the defined small threshold $F_{def1} = 0.342\ N$, the corresponding operation is considered safe. In this case, the duty cycle of PWM is set to D_{p1} for a weak vibration perception.

b) *Pattern 2 (potential zone)*. While the force is less than the defined large threshold $F_{def2} = 1.0\ N$, the corresponding operation is believed to potential. By this situation, the vibration motor is driven via the PWM with duty cycle of D_{p2}, which is a middle level feeling of vibration feedback.

c) *Pattern 3 (dangerous zone)*. When the value of detected force is over F_{def2}, the corresponding operation is known as dangerous. In other words, operator needs to be reminded and take relevant protection behaviors. The duty cycle of PWM is set to D_{p2} for a stronger vibration touch.

For the actual usage of vibration motor, it is important to conduct the kinetic analysis. The equation of simple harmonic vibration is described as

$$x(t) = Asin(\omega t + \varphi) \tag{1}$$

where $x(t)$ is the displacement at the moment t. A is the amplitude (maximum displacement). ω and φ represented angular frequency and phase angle of the motor, respectively. The amplitude A of vibration motor can be defined as

$$A = \frac{2F/\omega^2}{W} \tag{2}$$

where F is the exciting force for the periodic simple harmonic vibration. W is the weight of reference vibration (equated to motor weight). Calculating the equation (1) and equation (2), can obtain the result as

$$x(t) = \frac{2F/\omega^2}{W} sin(\omega t + \varphi) \tag{3}$$

Based on the above analysis, the duty cycle of PWM will influence the angular frequency ω directly. By varying the duty cycle, vibration feedback with different levels can be realized by the flat-type micro vibration motor. Comparing to previous works for RES, only designed haptic feedback and visual feedback, this effort tries to produce a new feedback perception entitled vibration feedback. This work probably has potential research value and application value for the field of haptic perception for other robotic systems.

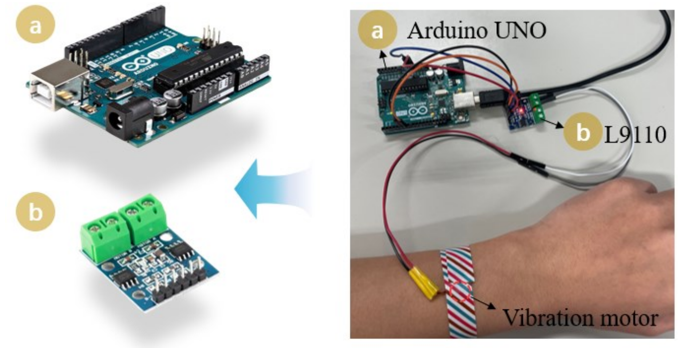


Fig. 6 Experiment setup for loudness and sensing. (a) Arduino UNO; (b) L9110 driven module.

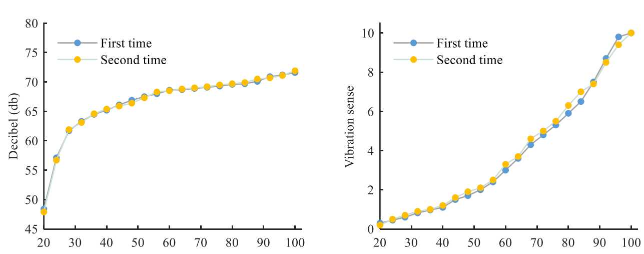
IV. Experiments and Discussion

In order to determine appropriate parameters of duty cycle and evaluate the performance of the proposed vibration feedback, two kinds of experiments are performed in this work. Moreover, a related scientific discussion of this effort is presented at the end of this section.

A. Vibration Loudness and Vibration Sensing Experiments

Aiming to decide suitable duty cycles to produce stable and comfortable vibration sensation, we conducted loudness and sensing experiments, which is shown in Fig. 6. Arduino UNO is used to be the controller and L9110 module is employed to provide different levels of PWM. The loudness is collected by decibel measurement software of Mobile phone. The vibration sensing is captured via the wrist of hand. The testing range is from 20% to 100% at a fixed growing step 4% (when the duty cycle is less than 20%, vibration motor does not work).

The results of loudness and sensing for two times experiments are shown in Fig. 7. Note that we define an index named vibration sense to represent the perception of wrist. When the motor does not vibrate, the vibration sense is scored as 0. Correspondingly, when the motor works under the duty cycle of 100%, the vibration sense is recorded as 10. From Fig. 7, we can see that both loudness and sensing are not linear growing with the increasing of duty cycle of PWM. Considering the noise generated by vibration motor and the comfort of vibration sensation in actual using environment, three parameters of duty cycle D_{p1}, D_{p2}, D_{p3} are determined to 28%, 40%, 60%, respectively. In other words, by shifting to different working patterns of vibration motor, it is easy to percept various haptic feedback (vibration) for RES.



(a) Vibration loudness (b) Vibration sensing

Fig. 7 Results of vibration experiments for two times.

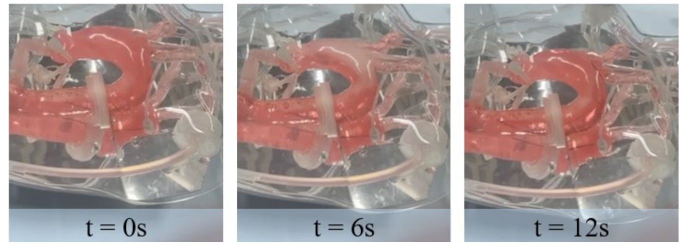


Fig. 8 Key operation points at different EVE experimental moments.

B. EVE Human Model Experiments

To verify the preliminary performance of vibration feedback, an endo vascular evaluator (EVE) human model is used to collect the force when insert medical instruments. Three key operation points ($t = 0s$, $6s$, *and* $12s$) are captured to exhibit the surgery procedure, which are shown in Fig. 8. Meanwhile, the proximal force measured by load cell is used to control three types of patterns for vibration feedback (the relationship is presented in Table I).

Totally, EVE experiments were conducted by two times. The detected force and three kinds of patterns are drawn in Fig. 9. The maximum value of force is less than 1.2 N at both two times experiments. To our best knowledge, the force information is possible to reflect the robot-assisted surgical situations (e.g., safe operation, potential operation, and dangerous operation). By adding different patterns of vibration feedback, it is easy to provide a fresh perception feedback for a haptic sensation or a warning feeling, which is significant for safe operation. In addition, benefiting from changing the duty cycle of PWM, vibration feedback is able to generate multi-level perception instead of conventional single haptic feedback.

C. Discussion

For the perception improvement of RES, vibration feedback as a newly feedback approach, is considered and studied in this work. Most traditional robotic systems [22]-[23] only designed haptic feedback and offered monitor feedback for operators. Consequently, working on new implementation of haptic feedback is vital to produce more accurate and multimodal perception for surgeons, especially doctors with different surgical experience. By this mean, vibration feedback is normal and controllable for operators with various ages or experience as a

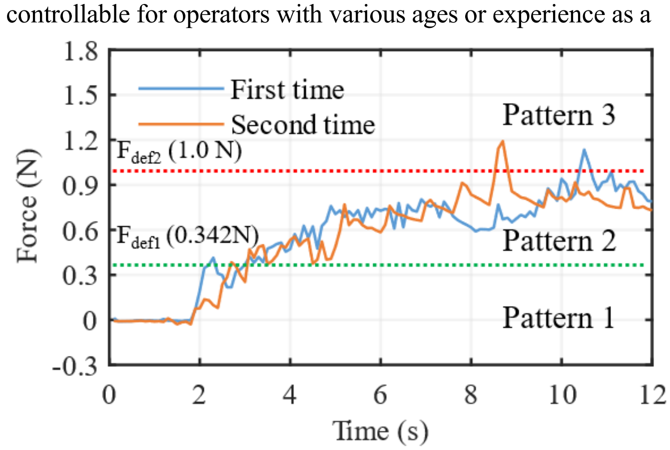


Fig. 9 Experimental results of force and vibration patterns.

vibration sensing at wrist or other body parts. In this paper, the detailed methodology of vibration feedback is presented in Section III including the elaborate description of vibration motor, working principle, relationship between the force value and vibration patterns, and the kinetic analysis of vibration. Furthermore, two kinds of preliminary experiments (loudness and sensing experiments, and EVE experiments) are conducted to test the performance of proposed vibration feedback to a certain. Although the using performance of vibration feedback does not perform deep testing by vivo experiments, the experimental results indicate that vibration is possible to offer another haptic perception for master-slave operating system. Considering the influence between vibration feedback and doctor's operation, the actual sensation and relationship are slight from trialists in this work.

V. Conclusion

In this work, a preliminary study of vibration feedback was proposed for the needs of surgical procedure monitoring. A flat-type micro vibration motor was introduced and adopted to provide vibration feeling when conducting robot-assisted surgery. We descripted the working principle of vibration motor based on three kinds of vibrating patterns and analyzed the related kinetic equation models. Moreover, two kinds of experiments are performed to decide appropriate control parameters of duty cycle and verify the feedback performance by two times operation. The EVE experimental results demonstrate that the proposed vibration feedback is feasible and stable to build multi-level monitoring of safe operation. Furthermore, the related study of this work may play an inspirational and potentially positive role to the implementation of haptic feedback, precise control of vibration sensation, and other perception fields of robotic systems.

In the future, it is needed to do further study on the development of complete vibration feedback system and the performance evaluation via biological experiments.

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