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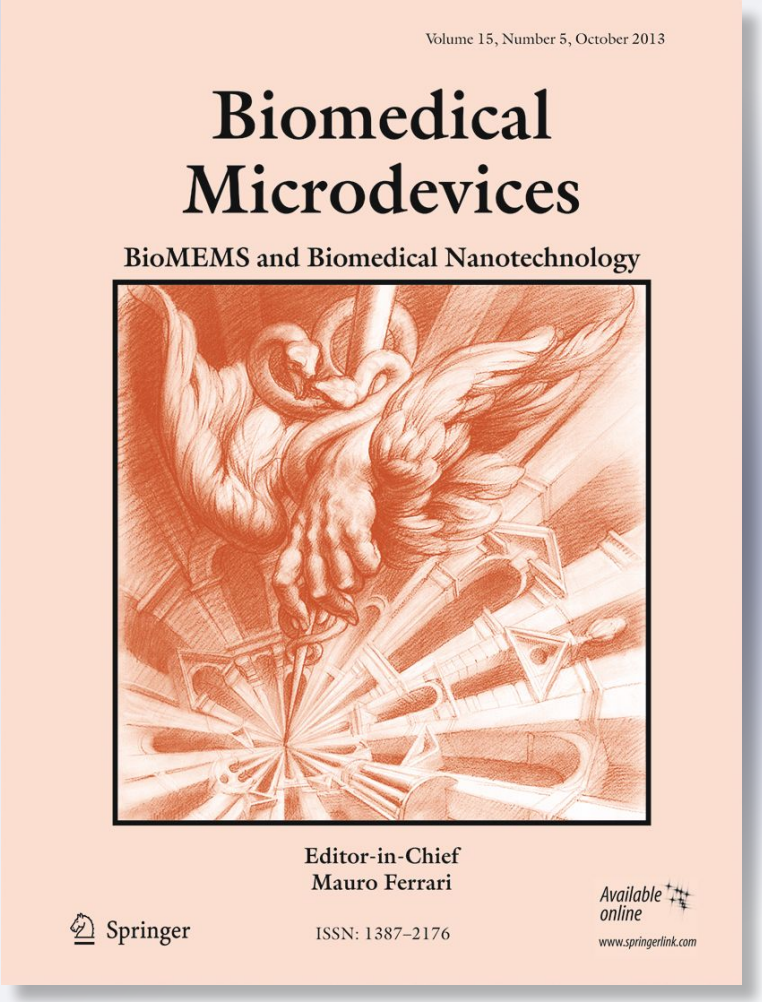

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Compensatory force measurement and multimodal force feedback for remote-controlled vascular interventional robot

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Abstract
Minimally invasive vascular interventional surgery is widely used and remote-controlled vascular interventional surgery robots (RVIRs) are being developed to reduce the occupational risk of the intervening physician in minimally invasive vascular interventional surgeries. Skilled surgeon performs surgeries mainly depending on the detection of collisions. Inaccurate force feedback will be difficult for surgeons to perform surgeries or even results in medical accidents. In addition, the surgeon cannot quickly and easily distinguish whether the proximal force exceeds the safety threshold of blood vessels or not, and thus it results in damage to the blood vessels. In this paper, we present a novel method comprising compensatory force measurement and multimodal force feedback (MFF). Calibration experiments and performance evaluation experiments were carried out. Experimental results demonstrated that the proposed method can measure the proximal force of catheter/guidewire accurately and assist surgeons to distinguish the change of proximal force more easily. This novel method is suitable for use in actual surgical operations.

Keywords Minimally invasive vascular interventional surgery · Remote-controlled vascular interventional robot (RVIR) · Force measurement · Force feedback

1 Introduction

Minimally invasive vascular interventional surgery, in which special slender instruments are inserted through small skin incisions, is widely used because it can reduce pain of patients and allow for quick recovery. However, the minimally invasive vascular interventional surgery causes several difficult problems for surgeons, such as heavy radiation-shielded garments, partial protection against radiation (Whitby and Martin 2005), and chronic back/neck pain (Klein et al. 2009). Fortunately, surgeons can be released from the risks of radiation and heavy radiation-shielded garments when the robotic technologies are used in the minimally invasive surgery. Moreover, the precision of the surgical procedures can also be improved (Taylor and Stoiariovici 2003). Therefore, remote-controlled vascular interventional robots (RVIRs) have received increased attention and interest in the field of minimally invasive vascular interventional surgeries.

Several research groups have been devoted to the study of RVIR. Arai et al. (Arai et al. 2002; Tercero et al. 2010) presented a catheter system to operate catheter by a linear stepping mechanism and allow for magnetic tracking. Jayender et al. (Jayender et al. 2006, 2008) investigated autonomous robot-assisted insertion of an active catheter instrumented with Shape Memory Alloy (SMA) actuators using image guidance. A bidirectional steerable catheter developed by Fu et al. (Fu et al. 2009, 2011) was integrated with two magnetic position-tracking sensors and can provide tracking information. Several other research groups (Tanimoto et al. 2000; Cercenelli et al. 2007; Marcelli et al. 2008; Park et al. 2010;

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Zakaria et al. 2013; Feng et al. 2015; Tavallaei et al. 2016; Srimathveeravalli et al. 2010) have also been devoted to the study of RVIRs. In addition, four commercial RVIRs have been developed by Corindus Vascular Robotics (Carrozza 2012), Hansen Medical (Riga et al. 2013), Catheter Robotics Inc. (Khan et al. 2013), and Stereotaxis Inc. (Faddis et al. 2002), respectively.

In our previous research, several novel active catheter systems were developed. These systems incorporated a miniature force sensor that was mounted on the catheter tip and was capable of accurately detecting the distal force of catheters (Guo et al. 1995, 2008, 2016). Several prototypes or devices of RVIRs were designed to operate catheters with two degrees of freedom (DOFs), measure the proximal force, and accurately realize the force feedback (Xiao et al. 2008; Bao et al. 2016, Guo et al. 2018a, b; Zhao et al. 2018). Moreover, two novel RVIRs based on cooperation of catheters and guidewires were presented and evaluated through in-human experiments (Bao et al. 2017, 2018a, b). They could complete complex surgeries and realize force feedback. Meanwhile, two operation training systems were developed to train new surgeons and two safety operation methods were proposed based on the systems (Yin et al. 2016; Guo and Guo 2016; Zhang et al. 2018).

The collision between the catheter tip and the blood vessel during the surgery practice is important in minimally invasive vascular interventional surgery. The lack of force feedback is a major challenge in telesurgery because the success of the surgery mainly depends on the detection of collisions by a skilled surgeon in operation (Yin et al. 2016). The force feedback is reconstructed on the master side by using the force signals measured on the slave side. Therefore, the accuracy of force measurement is vital to the force feedback. However, few of RVIRs provide force feedback to the operator; most of these robots that provide force feedback use friction wheels to capture proximal force measurements (such as Beyar et al. 2006; Fu et al. 2011; Bian et al. 2014). It is difficult to accurately measure the proximal force because slippage between friction wheels and the catheter/guidewire exists when the friction wheels are used to capture proximal force measurements. In our previous research, we proposed a novel method to measure the proximal force by using static connection and conical clamping principle (Bao et al. 2018a). The experimental results show that it can measure the proximal force accurately. Unfortunately, we only considered the static influence factors (e.g. static friction, gravity) instead of dynamic influence factor (e.g. rotation of catheter and guidewire) and this dynamic influence factor will have a great effect on force measurement.

In minimally invasive vascular interventional surgeries, the damage of blood vessels is not conducive for patients to recover quickly. Unfortunately, the blood vessels will suffer from collision trauma to some extent after surgeries, even though the surgeries are very successful. This is mainly due to the fact that the change of proximal force of catheter/guidewire is extremely small and the just noticeable difference (JND) for the surgeon is finite. The surgeon cannot quickly enough distinguish whether the proximal force exceeds the safety threshold of blood vessels or not, and thus it results in badly damage to the blood vessels.

Based on the analysis above, some problems inevitably exist and they are summarized as follows.

(1) Force measurement: Skilled surgeon performs surgeries mainly depending on the detection of collisions. The force measurement is vital to the detection of collisions. The proximal force of catheter/guidewire is affected by static and dynamic factors and it is difficulty to be measured accurately.
(2) Force feedback: Damage to blood vessels is not conducive for patients to recover quickly. The surgeon should quickly and easily distinguish whether the proximal force exceeds the safety threshold of blood vessels or not. A novel force feedback method is needed to assist surgeon to distinguish the change of proximal force more easily and clearly.

In this paper, a novel method comprising compensatory force measurement and multimodal force feedback (MFF) was proposed to address these two challenges. The remainder of this paper is organized as follows. System description of a RVIR for minimally invasive vascular interventional surgery is presented in Section 2. Section 3 presents the compensatory force measurement and MFF. Calibration experiments for the MFF are conducted in Section 4. In Section 5, performance of the proposed method is evaluated through experiments. Finally, the conclusions are given in Section 6.

2 System description

The RVIR is a telerobotic system and it is composed of a master controller and a slave manipulator. The schematic diagram of the RVIR is shown in Fig. 1 (Bao et al. 2018a). The master controller is located on the master side and the surgeon can operate it without wearing heavy radiation-shielded garments. When an operator operates the master controller on the master side, the master controller will capture the movement information (i.e. linear motion, rotary motion) from the operator and send those signals to the control unit on the master side. The control unit on the master side processes these signals and communicates with the other control unit on the slave side through cable or network. The slave manipulator gets the control signals from the control unit on the slave side and replicates the operation of operator (i.e. linear motion, rotary motion). The catheter and guidewire move and rotate in the blood vessels, and perform a surgery. Meanwhile, the slave manipulator measures the force of catheter and guidewire during the process and send

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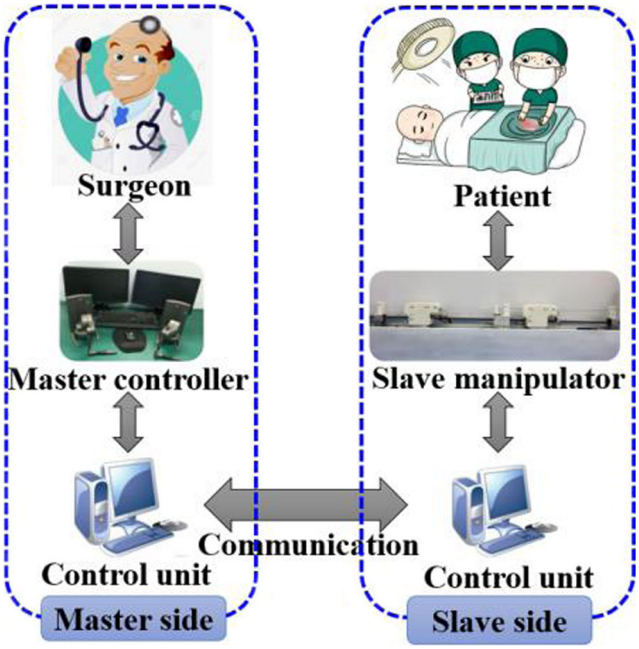

Fig. 1 Schematic diagram of the RVIR

these signals to the master controller through control unit (just like movement information exchange between control units). The master controller obtains the control signals and reconstructs force feedback. Then, the operator can perform the operation more easily and fluently by using the force feedback.

2.1 Master controller

To capture the control signals imparted by the surgeon and reconstruct the force feedback of the catheter and guidewire, respectively, the master controller performs four functions: it collects catheter operation data from the surgeon, it collects guidewire operation data from the surgeon, it reconstructs catheter force feedback, and reconstructs guidewire force feedback. Considering these requirements, two commercial haptic devices (Geomagic® TouchTM X, 3D Systems, Inc., USA) are used as the catheter haptic device and guidewire haptic device. The catheter haptic device and guidewire haptic device work together and be used as the master controller. The catheter haptic device collects catheter operation data imparted by a surgeon and reconstruct catheter force feedback. Similarly, the guidewire haptic device captures guidewire operation data from a surgeon and realizes the guidewire force feedback for the surgeon. The master controller is shown in Fig. 2 (Bao et al. 2018a).

2.2 Slave manipulator

The slave manipulator is composed of a linear motion platform, a catheter manipulator (CM), a guidewire manipulator (GM), and three assistant grasping mechanisms (Fig. 3) (Bao et al. 2018a). The CM is used to perform linear and rotary motion of catheter and capture the force measurement of the catheter. Similarly, the GM is developed to perform linear and rotary motion of guidewire and capture the force measurement of the guidewire. The assistant grasping mechanism 1, 2 and 3 are designed to prevent the catheter/guidewire from moving randomly without restriction in the linear direction when CM/GM releases the catheter/guidewire. Moreover, the assistant grasping mechanism 3 can also prevent the end of the catheter from drooping and keep the catheter and guidewire almost coaxial (in line) by supporting the end of the catheter.

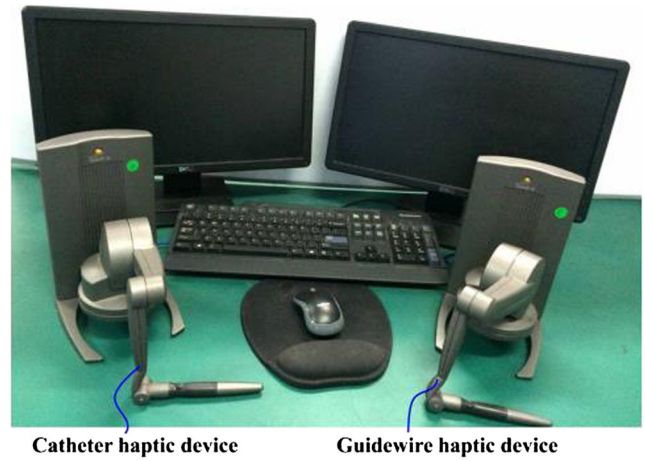

Fig. 2 Master controller, including a catheter haptic device and guidewire haptic device

3 Method

We firstly propose a novel method comprising compensatory force measurement and multimodal force feedback (MFF), and the configuration of the proposed method is shown in Fig. 4.

3.1 Compensatory force measurement

When the RVIR is used to perform surgeries, the slave manipulator operates catheter/guidewire on the slave side and measure the proximal force of catheter/guidewire. However, the measured force (F_M) is affected by many factors (e.g. static friction, gravity, dynamic friction, rotation of catheter/guidewire), and thus the F_M is not the "real" proximal force. The "unreal" proximal force will make it difficult for surgeon to take full advantage of the dexterity. To measure the proximal force accurately, we proposed a novel force measurement mechanism shown in Fig. 5a. In the force measurement mechanism, some general and special bearings (i.e. thrust bearing, linear bearing, linear slide, ball spine, and needle bearing) are used to reduce the influence on the force measurement. This influence is mainly caused by linear and rotary motion of

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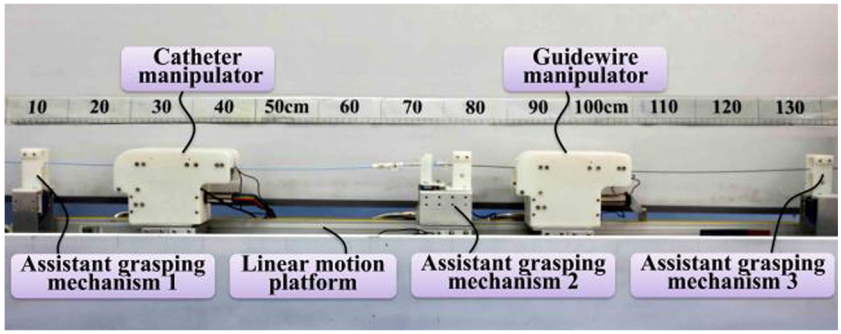

Fig. 3 Physical prototype of the slave manipulator

catheter/guidewire. The schematic diagram of force measurement mechanism and force analysis are shown in Fig. 5b. Based on the force analysis in Fig. 5b, the "real" proximal force of catheter/guidewire (F_R) can be obtained by

$$F_R = F_M + F_1 + F_2 + F_3 \tag{1}$$

where F_1 is the friction force generated by the linear slide, F_2 is the friction force generated by the ball spline A linked to the electromagnetic clutch, and F_3 is the friction force generated by the ball spline B linked to the motor.

The ball spline can transmit the torque almost without restriction in linear direction and the linear bearing can support the grasper with small friction. The restriction and friction will influence the accuracy of force measurement. To address this challenge, conventional compensation method is typically used by subtracting a static value at the beginning of the force measurement. However, the conventional compensation method cannot accurately compensate the force because dynamic factors exist. The dynamic factors will have bad effect on the accuracy of force measurement, such as rotational speed of catheter/guidewire (Stribeck 1902). These restriction and friction affected by these uncertain factors, and the relations could be written as follows:

$$F_1 = \psi(f, G_1, \eta_1) \tag{2}$$

$$F_2 = \phi(n_2, f, G_2, \eta_2) \tag{3}$$

$$F_3 = \varphi(n_3, f, G_3, \eta_3) \tag{4}$$

where ψ is an uncertain function for F_1, f is the proximal force of catheter/guidewire, G_1 is the gravity of components on the linear slide, η_1 is the lubrication of the linear slide, ϕ is an uncertain function for F_2, n_2 is the rotational speed of ball spline A, G_2 is the gravity of components on ball spline A, η_2 is the lubrication of ball spline A, φ is an uncertain function for F_3, n_3 is the rotational speed of ball spline B, G_3 is the gravity of components on ball spline B, and η_3 is the lubrication of ball spline B.

These restriction and friction should be compensated and thus we use compensatory force (F_C) to realize accurate force measurement:

$$F_C = \psi(f, G_1, \eta_1) + \phi(n_2, f, G_2, \eta_2) + \varphi(n_3, f, G_3, \eta_3) \tag{5}$$

Hence, the "real" proximal force of catheter/guidewire can be obtained by

$$F_R = F_M + F_C. \tag{6}$$

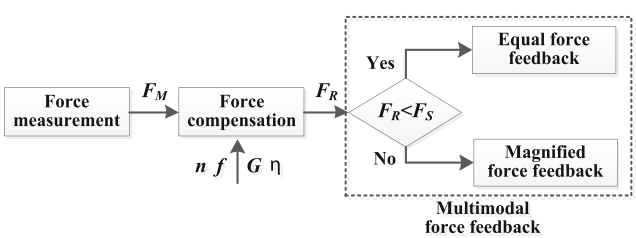

Fig. 4 Configuration of the compensatory force measurement and multimodal force feedback

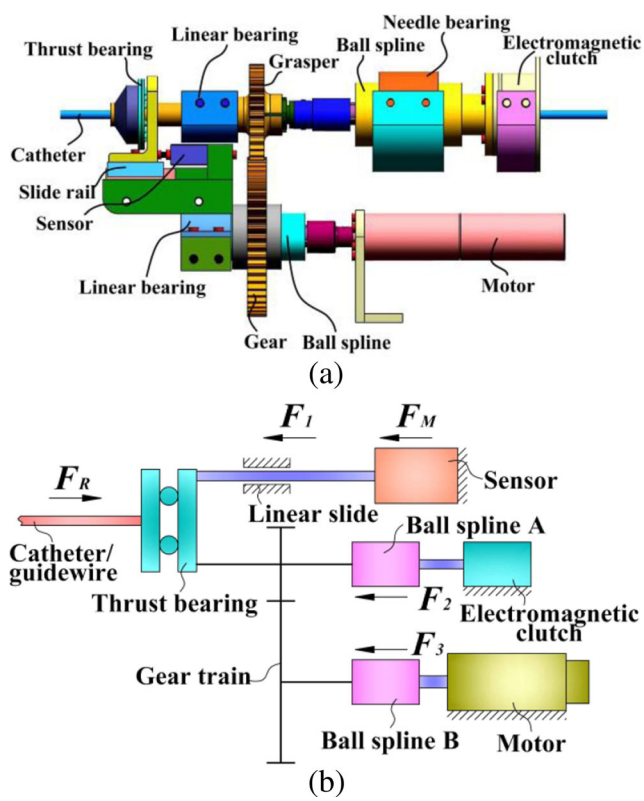

Fig. 5 **a** Virtual prototype of the force measurement mechanism in CM; **b** schematic diagram of force measurement mechanism and force analysis

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3.2 Multimodal force feedback

When surgeon performs a surgery, the proximal force of catheter/guidewire varies with the operation. During the operation, the change of the linear and rotary motion for catheter/guidewire results in that the proximal force of catheter/guidewire varies frequently and intricately. Moreover, the change of proximal force of catheter/guidewire is extremely small and thus it is difficult for surgeon to distinguish the change of proximal force. The blood vessels will suffer from collision trauma to some extent after surgeries, even though the surgeries are very successful. If the surgeon cannot distinguish the change of the proximal force accurately, the blood vessels will be badly damaged. It will not conducive for patients to recover quickly and it may even cause medical accidents.

In our previous research, we adopted a normal method that captures the proximal force on the slave side and achieves the force feedback on the master side (Bao et al. 2018a). The measured force and generated force have the same values and directions. It is a conventional force feedback (CFF) and is normally used in robotic force feedback. However, the surgeon can obtain the same force as the proximal force of catheter/guidewire and thus it is difficult for surgeon to distinguish the change of proximal force.

To assist surgeon to distinguish the change of proximal force more easily, a multimodal force feedback (MFF) is proposed and shown in Fig. 4. When the surgeon operates the master controller on master side, the force applied to the surgeon was divided into two patterns: equal force feedback pattern and magnified force feedback pattern. If the proximal force of catheter/guidewire is less than the safety threshold of blood vessel, the equal force feedback pattern works and the surgeon will be imparted by a force which is same with the "real" proximal force of catheter/guidewire. If the proximal force of catheter/guidewire exceeds the safety threshold of blood vessel, the magnified force feedback pattern will start to run and the force applied to the surgeon will be amplified several times. The amplified force can assist the surgeon to distinguish the change of proximal force. Therefore, it will reduce the damage of blood vessels especially when the proximal force exceeds the safety threshold. The force feedback can be obtained by

$$F_M = \begin{cases} F_R & F_R < F_s \\ F_S + n(F_R - F_S) & F_R \geq F_s \end{cases} \quad (7)$$

where F_M is the force generated by master controller, F_R is the "real" proximal force of catheter/guidewire, F_S is the safety threshold of blood vessels, and n is the magnification times of force feedback ($n > 1$).

4 Calibration experiment

The "real" proximal force of catheter/guidewire can be measured accurately by using the compensatory force measurement method. The compensatory force (F_C) can be obtained from the Eq. (5). However, these functions (i.e. ψ, ϕ and φ) in the Eq. (5) cannot be analyzed theoretically and thus we will establish the relations through experiments.

4.1 Experimental set-up

Figure 6 shows the experimental set-up for compensatory force measurement. A wire was used to connect the CM and a standard weight. The standard weight tends to pull the CM because of the gravity force. Therefore, the CM can measure different static forces by using diverse standard weights. However, the value of the force captured by the CM is different from that of the gravity force of the standard weight because some influence factors inevitably exist, such as the friction force generated by the linear slide, the weight of the wire, and the friction force generated by the pulley. To measure the "real" force applying to the CM, a force sensor (Gamma, ATI Industrial Automation, Inc., US) was used. The force sensor was connected to the CM with a steel rod. When the standard weight pulls the shell of the CM in +x direction, the steel rod will pull the sensing unit of the CM in -x direction. The direction of the proximal force of catheter/guidewire is in -x direction during surgeries. Hence the force captured by the sensor has the same direction as the proximal force of catheter/guidewire. The F_C was achieved by subtracting the force obtained by the force sensor from the force captured by the CM.

Due to the fact that the rotational speed of catheter/guidewire varies during surgeries, these experiments were carried out with different rotational speed of catheter/guidewire. Previous research has shown that the maximum proximal force of catheter/guidewire is lower than 2 N and the maximum rotational speed of catheter/guidewire is lower than 630°•s^{-1} during surgeries (Bao et al. 2018a; Thakur et al. 2009). Therefore, when a standard weight was used to pull

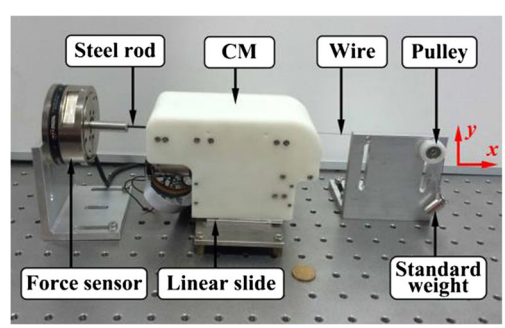

Fig. 6 Experimental set-up for calibration of the compensatory force measurement method

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the CM, the CM and force sensor measure forces at different rotational speed of catheter/guidewire conditions (0–630°•s^{-1}, 15°•s^{-1} increment for each experiment). Ten times of repetition were carried out for each rotational speed. In addition, different standard weights (0-225 g, 15 g increment for each experiment) were used to pull the CM sequentially.

4.2 Experimental results

When different standard weights were used to pull the CM, the forces applying to the CM are different with the gravity force of these standard weights. The forces applying to the CM using different standard weights were measured by the force sensor and listed in Table 1.

The results for the relationship between compensatory force (F_C), force applying to CM, and rotational speed of catheter/guidewire are shown in Fig. 7. In this figure, the black dots represent the F_C at different forces applying to the CM and different rotational speed of catheter/guidewire conditions. The three-dimensional surface was constructed by using curve fitting (least squares) in MATLAB. The surface establishes a functional relationship between F_C, force applying to CM, and rotational speed of catheter/guidewire, and the equation of the surface is as follows:

$$\begin{aligned} F_C(\omega, F_M) = {} & p_{00}\omega^5 + p_{01}\omega^4 F_M + p_{02}\omega^3 F_M^2 + p_{03}\omega^2 F_M^3 + p_{04}\omega F_M^4 \\ & + p_{05}\omega^4 + p_{06}\omega^3 F_M + p_{07}\omega^2 F_M^2 + p_{08}\omega F_M^3 + p_{09} F_M^4 \\ & + p_{10}\omega^3 + p_{11}\omega^2 F_M + p_{12}\omega F_M^2 + p_{13} F_M^3 + p_{14}\omega^2 \\ & + p_{15}\omega F_M + p_{16} F_M^2 + p_{17}\omega + p_{18} F_M + p_{19} \end{aligned} \tag{8}$$

where ω is the rotational speed of catheter/guidewire (the unit of speed is rad/s), $F_M$is the force applied to CM (the unit of force is N), the p_{mn} is the coefficient for equation and the valve of the coefficient is shown in Table 2.

4.3 Discussion

To evaluate whether the fitting equation meets surgery requirements or not, error analysis for Eq. (8) was carried out. Ten sets of data including ω, F_M and F_C(real compensatory force) were randomly selected. The $F_C(\omega, F_M)$(calculated compensatory force) was obtained through Eq. (8) and then compared with the F_C. The error between $F_C(\omega, F_M)$ and F_C were also calculated by subtracting F_C from $F_C(\omega, F_M)$ (shown in Table 3). The maximum error and average error are 0.1197 N and 0.05334 N, respectively. In addition, we got the "real" proximal force of catheter/guidewire F_R via Eq. (6). Since the F_R is the force applied to surgeon and the error between $F_C(\omega, F_M)$ and $F_C$will affect the sense of operation, we got the relative error through dividing F_R by the error. As shown in Table 3, the maximum relative error and average relative error are 8.49 and 4.54%, respectively. Previous research shows that the perceptual resolution in force discrimination, as measured by the JND, is 7–10% over a range of 0.5–200 N (Jones 2000). Considering the relative error for the fitting equation, we may argue that the Eq. (8) meets surgery requirements.

During surgeries, the "real" proximal force of catheter/guidewire is the force measured by force sensor in Fig. 6, and we can obtain the "real" proximal force by using the rotational speed of catheter/guidewire and Eq. (6), (8).

Figure 7 shows the relationship between the compensatory force, force applying to CM, and rotational speed of catheter/guidewire. The figure indicates that the compensatory force has a positive correlation with the force applied to CM. This phenomenon was also found in our previous research (Bao et al. 2018a). We think it is mainly due to the following reason. The sensing unit in CM will deform when it is used to measure the force. This deformation will offset part of the force applied to the sensing unit in CM and thus it results in smaller measured force. When larger force was applied to the sensing unit, the larger deformation results in higher relative measurement error. Hence the compensatory force is larger when larger force is applied to CM. In addition, the force applied to CM also affects the force measurement in some other ways, but this influence is currently uncertain, such as clearance between components, location and lubrication for balls in bearings.

Meanwhile, Fig. 7 indicates that the compensatory force has a certain correlation with the rotational speed of catheter/guidewire. This correlation meets the tendency of the Stribeck curve to some extent but they are not exactly the same (Stribeck 1902; Lu et al. 2006). We think the reason is that some uncertain factors exist (e.g. friction of gear train, friction of linear slides, torque of catheter/guidewire) and these factors affect the correlation between the compensatory force and rotational speed of catheter/guidewire.

Generally, many factors affecting the force measurement exist and these factors also interact with each other. The

Table 1 Different types of standard weights and force applying to CM

Serial number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Standard weight/g	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225
Force applying to CM/N	0.097	0.234	0.371	0.518	0.675	0.832	0.949	1.126	1.283	1.39	1.547	1.704	1.841	1.998	2.155

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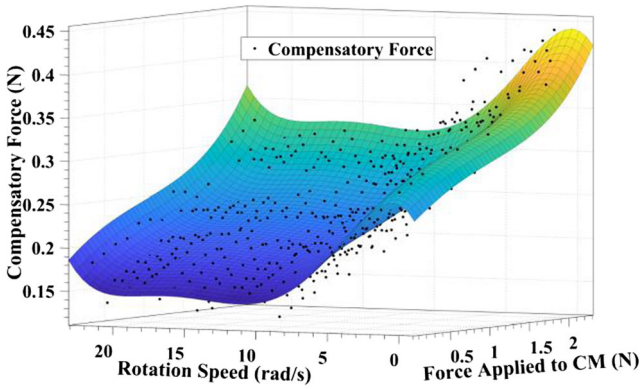

Fig. 7 Results for the calibration experiment

influence of each factor and the interaction of them are complicated and cannot be currently analyzed theoretically. Therefore, we established the equation through experiments. The "real" proximal force can be obtained by the equation and thus we may argue that this equation can be used to improve measurement accuracy in the actual surgical operations.

5 Performance evaluation

Two types of experiments were carried out to evaluate the performance of the proposed method. First, experiment I was conducted to test whether the RVIR can capture the proximal force of catheter/guidewire accurately by using the compensatory force measurement method. Then, experiment II was carried out to evaluate the performance of the MFF method.

5.1 Force measurement experiment

5.1.1 Experimental set-up

The experimental set-up for the force measurement is shown in Fig. 8. The CM was mounted on a linear slide and a 1.8-mm diameter steel rod was grasped by the CM. The steel rod was used in place of the 5F catheter to avoid the measurement errors introduced due to elastic properties of the catheter. A force sensor was also used and mounted on the base. The steel rod was attached to the force sensor. When a time-varying dynamic force is applied to the shell of the CM, the CM and force sensor will capture simultaneous force signals. An operator pushed the shell of the CM while the gear (in the CM) rotated at random speed and the force signal was captured by the CM. In addition, the force captured by the CM was then compensated by the proposed compensatory force measurement method (Eq. (6), (8)) and compared with the force measured by force sensor. Meanwhile, the force captured by the CM was also compensated by conventional compensation and then compared with the force measured by force sensor.

5.1.2 Experimental results

The result of time-varying force measurement is shown in Fig. 9. The red line represents the force measured by the force sensor ("real" force); the blue line represents the force compensated by conventional compensation (conventional compensatory force); the black line represents the force compensated by the proposed compensatory force measurement method (proposed compensatory force). The maximum relative error and the average relative error between conventional compensatory force and "real" force is 17.75 and 8.97%, respectively. The maximum relative error and the average relative error between proposed compensatory force and "real" force is 11.16 and 7.58%, respectively.

5.1.3 Discussion

When the proposed compensatory force measurement method was used, the average relative error, especially the maximum relative error was less than those using the conventional compensatory method. We think the main reason is that the conventional compensatory method compensates the force only by subtracting a static value at the beginning of the force measurement, and the proposed compensatory force measurement method compensates the force by considering the dynamic factors. Actually, the measured force is affected by not only the static factors but also dynamic factors, and the influence of dynamic factors vary with the change of rotational speed, the force applied to CM etc.

As shown in Fig. 9, the relative error for conventional compensatory method is higher when larger force was applied to the CM. We think the main reason is that the sensing unit in

Table 2 Coefficients for Eq. (8)

Coefficient	p_{00}	p_{01}	p_{02}	p_{03}	p_{04}	p_{05}	p_{06}
Value	9.159×10^{-3}	-2.861×10^{-5}	-4.720×10^{-5}	1.586×10^{-5}	1.860×10^{-5}	-6.057×10^{-3}	4.214×10^{-5}
Coefficient	p_{07}	p_{08}	p_{09}	p_{10}	p_{11}	p_{12}	p_{13}
Value	1.624×10^{-5}	1.250×10^{-5}	1.480×10^{-3}	-3.552×10^{-2}	3.590×10^{-5}	7.342×10^{-5}	6.653×10^{-3}
Coefficient	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}	p_{19}	
Value	4.227×10^{-2}	-1.277×10^{-4}	3.088×10^{-3}	-2.561×10^{-3}	2.903×10^{-2}	2.059×10^{-1}	

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Table 3 Error analysis for Eq. (8)

Serial number	1	2	3	4	5	6	7	8	9	10
ω /rad•s^{-1}	5.760	15.708	2.618	1.047	12.566	21.991	10.472	18.326	0.5236	5.760
F_M/N	1.617	1.323	0.294	1.323	2.205	0.588	1.029	1.764	0.441	0.735
$F_C(\omega, F_M)$/N	0.2450	0.2068	0.2079	0.2469	0.2492	0.1661	0.2108	0.2157	0.2179	0.2136
RealF_C/N	0.3372	0.2428	0.2519	0.3666	0.2853	0.2061	0.2007	0.2384	0.2625	0.3016
Error/N	0.0922	0.036	0.044	0.1197	0.0361	0.04	−0.0101	0.0227	0.0446	0.088
F_R/N	1.9542	1.5658	0.5459	1.6896	2.4903	0.7941	1.2297	2.0024	0.7135	1.0366
Relative error/%	4.7180	2.2991	8.0601	7.0845	1.4496	5.0371	0.8213	1.1336	6.3397	8.4893

the CM will deform when it is used to measure the force. The deformation will offset part of the force applied to the sensing unit and it results in that the measured force is smaller than the real force. Moreover, when we periodically apply the force to the sensing unit, the sensing unit deforms periodically and the relative error changes periodically.

The curve of the conventional compensatory force and "real" force have the similar shape and they increase or decrease at the same time because the conventional compensatory compensates the force with a static value. Meanwhile, the shape of the proposed compensatory force curve is a little different with that for "real" force on some tiny details (i.e. the two curves do not always increase or decrease at the same time). This is mainly due to the fact that the proposed compensatory force was compensated by using proposed compensatory force measurement method and some tiny detail of the curve will be changed with dynamic compensation. Generally, when the proposed compensatory force measurement method is used, the maximum relative error and average relative error will be lower even though its curve differs with the "real" force curve on some tiny details.

5.2 Multimodal force feedback experiment

5.2.1 Experimental set-up

To test whether the surgeon can distinguish the change of proximal force easily, an operator operates the master controller on master side, while the slave manipulator replicates the operation on slave side. During the operation, the slave manipulator measures the proximal force of catheter and transmits the force signals to the control unit. These signals are processed by using the MFF method and transmitted to the master controller. The safety threshold of blood vessels was set to 1.0 N (i.e.$F_S = 1.0$ N) and the magnification times of force feedback was set to 2 (i.e.$n = 2$). The handle of the master controller (haptic device) is mounted on a force sensor (Gamma, ATI Industrial Automation, Inc., USA) through linear slider and fixed bracket, and thus the force sensor can capture the force feedback obtained by surgeons (Fig. 10). The force captured by the CM was compensated by compensatory force measurement method (Eq. (6), (8)) and then compared with the force measured by the force sensor.

In addition, to evaluate operation efficiency by using the multimodal force feedback method, operation efficiency experiments were conducted. A catheter (VER135°, Cordis Corporation, USA) and guidewire (RF*GA35153M, Terumo Corporation, JP) were used. They were operated by the RVIR from a starting position to a target position in a human body model (General Angiography Type C, FAIN-Biomedical, Inc. JP) (Fig. 11). The starting position is located at the femoral artery, and the target position is located at the left subclavian artery (shown in Fig. 11). A volunteer performed the operation by using the RVIR without force feedback (WFF), and then the volunteer preformed the same operation in turn by using CFF method (conventional force feedback) and the MFF method (multimodal force feedback). All the operation time

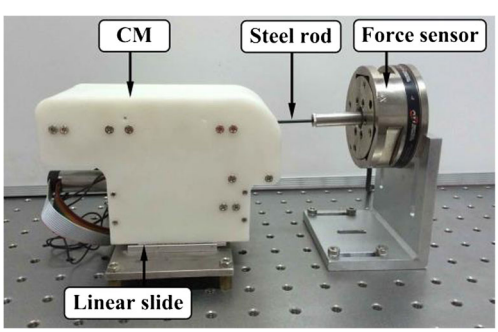

Fig. 8 Experimental set-up for force measurement experiment

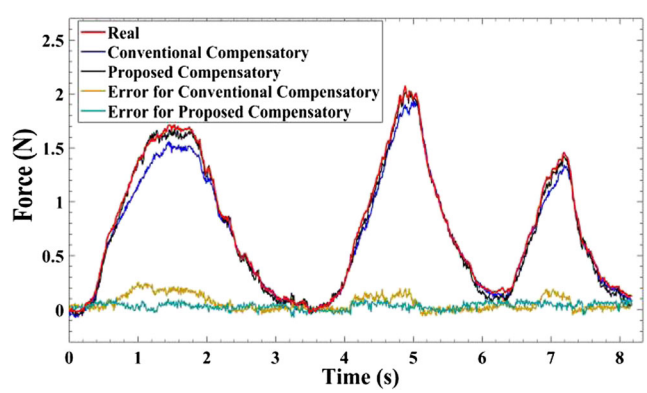

Fig. 9 Comparison for time-varying force measurement

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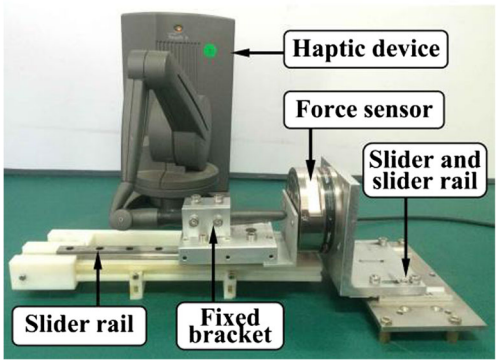

Fig. 10 Experimental set-up capturing the force feedback obtained by surgeons

was recorded. Ten volunteers participated in this experiment, and each volunteer has >1 year of experience in catheterization. Each operation was performed ten trials per volunteer.

5.2.2 Experimental results

Figure 12 shows the comparison of the compensatory force and the force feedback. The dotted blue line represents the force compensated by compensatory force measurement method (i.e. the "real" proximal force of catheter/guidewire); the solid red line represents the force obtained by surgeons.

The results of operation time by using the WFF, CFF and MFF are compared and shown in Fig. 13. The average measured time and the standard deviation of the measured time data were included in the compared results. When the CFF was used to perform the operation, the operation time is less than that using the WFF. The maximum operation time difference between them is 32 s, and the average operation time difference between them is 19.3 s. When the MFF was used to perform the operation, it costs less time than the WFF but costs more time than the CFF. The maximum operation time difference between MFF and CFF is 9 s, and the average operation time difference between MFF and CFF is 4.2 s.

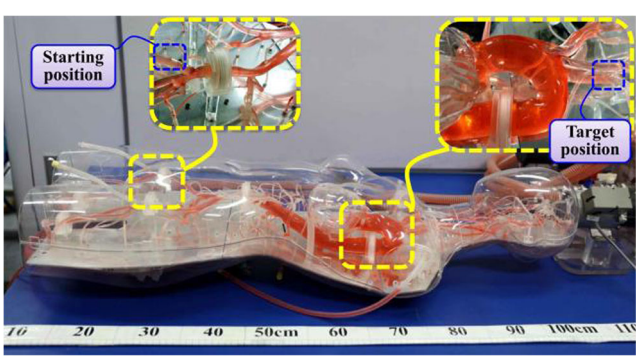

Fig. 11 Human body model for operation efficiency experiment

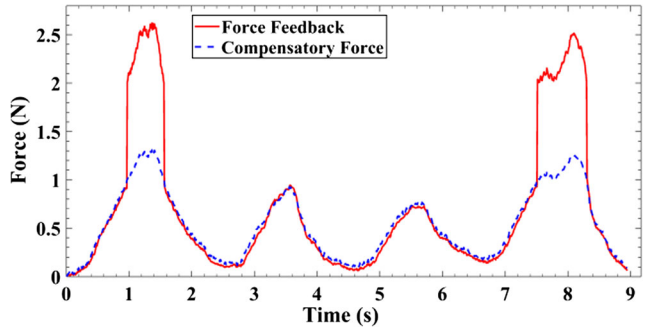

Fig. 12 Results for the compensatory force and MFF

5.2.3 Discussion

As shown in Fig. 12, during the 0–0.9 s, 1.5–7.4 s, and 8.3–9 s time intervals, the value of the force obtained by surgeons is almost the same as that of the "real" proximal force. During the 0.9–1.5 s and 7.4–8.3 s time intervals, the force obtained by surgeons increases drastically while the "real" proximal force exceeds the safety threshold of blood vessels (i.e. 1 N). The value of the force obtained by surgeons is two times larger that of the "real" proximal force. The enlarged force will assist surgeons to distinguish the change of proximal force more easily when the proximal force exceeds the safety threshold and the blood vessels would suffer from damage. However, to our knowledge, there is no report indicating the safety thresholds of blood vessels. In our previous research (Bao et al. 2018a), experiments were carried out in human body model and the experimental results indicate that the forces vary when the catheter or guidewire is located in different positions of blood vessels and the maximum force is lower than 2 N. Therefore, the safety threshold of blood vessels was set to 1.0 N and it is reasonable to evaluate the performance of MFF. In addition, when the MFF is used in actual surgical operations, the safety threshold and magnification times of force feedback should be selected according

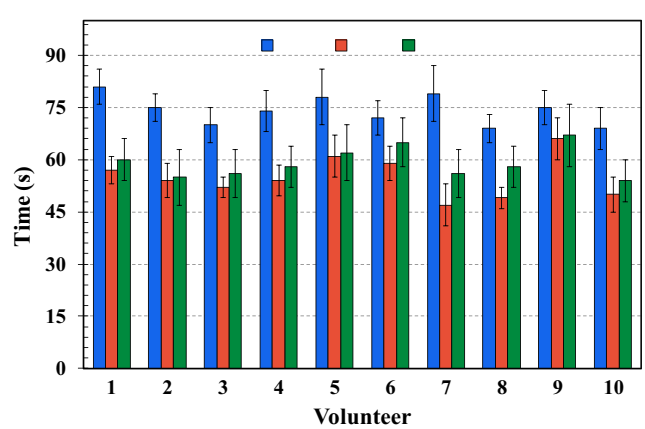

Fig. 13 Operation time for different methods in operation efficiency experiments (WFF: without force feedback; CFF: conventional force feedback; MFF: multimodal force feedback)

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to the practicalities, such as different positions of blood vessels, the operating habits of surgeons and the age of patients.

In the operation efficiency experiments, the operation time for different methods varies. As shown in Fig. 13, the operation time for WFF is more than that for CFF or MFF. This is mainly due to the fact that the volunteer can obtain more information about the operation (i.e. proximal force of catheter/guidewire) and the force feedback can assist him/her to operate the catheter/guidewire more easily.

Compared to operation using CFF, the mean operation time is much more when the MFF is used. In the operation using the MFF, the volunteer will obtain enlarged force when the proximal force exceeds the safety threshold of blood vessels. Hence the volunteer can distinguish the change of proximal force more easily. If the proximal force exceeds the safety threshold, the volunteer needs to pull back the catheter/guidewire and re-operate them again. However, if the volunteer cannot get to know the fact that the proximal force has exceeded the safety threshold, he/she would continue to push forward the catheter/guidewire and thus it would damage the blood vessels. In other words, the volunteer using the CFF performs fewer re-operations than using the MFF because he/she cannot easily distinguish whether the proximal force exceeds the safety threshold or not when the CFF is used. Therefore, the MFF costs more time than the CFF but the MFF is much safer than the CFF for patients. We think this re-operation time is acceptable because the proportion of the time is much low and the safety is absolutely the first priority for patients. In addition, the standard deviation for the MFF is less than that for the CFF. We think this is mainly due to the following reason. Whether the volunteer re-operates or not depends on the value of proximal force. If the proximal force exceeds the safety threshold, the re-operation will be needed. The situation that the proximal force exceeds the safety threshold occurs randomly and thus the re-operation appears randomly. Hence the standard deviation for the MFF is much bigger.

Generally, the MFF can assist surgeon to distinguish the change of proximal force more easily and can decrease the damage of blood vessels even though it costs a little more time than the CFF.

6 Conclusions

In this paper, a novel method comprising compensatory force measurement and MFF was proposed, and calibration experiments and performance evaluation experiments were carried out. The results proved that the proposed method can measure the proximal force of catheter/guidewire accurately and assist surgeons to distinguish the change of proximal force more easily. We may argue that this novel method is suitable for use in actual surgical operations.

In addition, this paper would provide some references for minimally invasive surgery. First, the multimodal force feedback can assist surgeons to distinguish the change of operational force more easily and it can be also used in other minimally invasive surgeries to reduce damage to patients. Second, we provide compensatory force measurement by compensating the dynamic effects and establish the equation through experiments. Similarly, force measurement will be affected by uncertain dynamic effects during other minimally invasive surgeries, the force can be compensated by similar method to improve the safety of surgeries.

However, several limitations exist in this research. First, the safety thresholds of blood vessels should be selected based on clinical data. Diverse blood vessels possess different safety thresholds and the safety thresholds need to be measured in surgeries. Moreover, the magnification times of force feedback in the MFF should be selected according to the practicalities, such as different positions of blood vessels and the operating habits of surgeons. Second, the function for the compensatory force measurement method was established without considering the torque of the catheter/guidewire. The torque of the catheter/guidewire is one of the dynamic factors and would affect the force measurement to some extent. Unfortunately, the torque of the catheter/guidewire cannot be measured online in our RVIR and thus we did not consider the influence of torque on force measurement. In the future, we will overcome the limitations and validate the compensatory force measurement and MFF in real in-vivo experiments on animals.

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