Modeling and Simulation of Multi-frictional Interaction Between Guidewire and Vasculature

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Abstract. In the cardiovascular interventional operation, the surgeon steers the tip of a long-thin guidewire to reach the clinical targets while traveling through the inner of blood vessels, and performs a wide range of minimally invasive procedures. However, real-time simulating the physical deformation behaviours of guidewire caused by a large areas of frictional contact between guidewire and vasculature during insertion is a challenge task. From the microscopic view, this paper built a novel multi-frictional contact dynamics model based on flexible multi-body system to address the multi-frictional interaction between them. In the model, guidewire and vascular formed a flexible multi-body system and the process of contact and collision could be divided into three stages, including contact detection, contact handling and separation. In the first stage, a continuous collision detection algorithm based on an adaptive layer was proposed to obtain a set of “point-surface” contact pairs quickly. After confirming the contact areas, a multi-frictional contact dynamics algorithm based on nonlinear equivalent spring damping was put forward. In the normal direction, nonlinear spring damping model was used to compute the spring restoring force and nonlinear damping force. In the tangential direction, sliding friction, static friction and rolling friction were calculated during the collision between two bodies by coulomb friction model. Finally, all frictional forces in the contact areas were added to the physical models of guidewire for further simulating various non-linear deformation behaviors. The experimental results show that this algorithm is feasible and could simulate the multi-frictional interaction between guidewire and blood vessels very well with real-time performance.

Keywords: Flexible multi-body system · Guidewire · Multi-frictional contact · Equivalent spring-damper model · Physical simulation

1 Introduction

Minimally invasive vascular surgery(MIVS) is a revolutionary breakthrough in modern medical procedures, which has received more and more attention in

recent years. MIVS uses vascular interventional instruments, such as guidewire, catheter, etc. to insert into blood vessels and perform the operation under the guidance of medical imaging equipments like X-ray, CT, MRI and ultrasound. Attribute to the advantages of little hemorrhage, minimal wound, fast rehabilitation and less complications comparing to traditional open surgery, MIVS has been widely adopted to treat angiographic, angioplasty, thrombectomy, treatment of cancer, vascular malformation and so on [1].

With the rapid development of virtual reality technology, VR systems have been increasingly applied in almost every industry by virtual of its own advanced technology, especially in medical field. Introducing VRT into clinical skills training of MIVS, the virtual training simulator provides a realistic virtual environment to trainees with visual, hearing and haptic sense interface, and makes junior doctors master kinds of clinical performance skills and hand-eye co-ordination in a short time for the purpose of achieving better training effect. In the system, the models of guidewire and vasculature are the most important components. Simulating the contact interaction between them not only could reproduce the living clinical operation situation in the visual, but also could make doctors apperceive the inner structure of blood vessels by the haptic devices for hand-sense training. Beyond all doubt, it is extremely significant to do the dynamics simulation for the contact and collision between guidewire and blood vessels using effective and high-precision methods.

In the flexible multi-body system, it is needed to regard objects as the flexible bodies with large overall motion and nonlinear deformation due to the complex dynamics behaviors [2]. Obviously, guidewire and vasculars both are deformable objects. They form a flexible multi-body system during the process of guidewire insertion and their contact interaction is a typical multi-frictional contact of flexible multi-body system. In the microscopic view, the surfaces of guidewire and vasculature are consist of a number of polygons. When guidewire inserting, the contact areas between them are generated by many contact pairs and the contact forces appear at the same time. Just under such contact forces, guidewire and vascular happen to do the nonlinear deformation. The whole process of collision and contact between them could be summed up as follow. At the moment of contacting, the contact areas are small and disperse along the shaft of guidewire and only few contact-pairs work. In the compression stage, contact areas increase gradually and more and more contact-pairs take effect. In the separating process, contact areas become smaller and contact-pairs are separated gradually.

Until now, many researchers all over the world have researched the interaction between guidewire and vascular deeply and made a lot of achievements. However, most of the studies focused on the guidewire physical model and only considered the collision contact situation on the control nodes of guidewire [3–5]. In fact, the collision contacts between them not only occurs at the control nodes, but also at the shaft between two adjacent control nodes. This paper does the further discuss on the collision and contact between guidewire and blood vessels from the microscopic view, and make dynamics simulation of their multi-frictional interaction in real time.

There are three impediments that make it difficult to model and simulate the multi-frictional interaction between guidewire and blood vessels. First of all, a robust physical model of guidewire is needed to simulate various nonlinear deformation behaviors under the action of external forces accurately, including bending, twisting and stretching. Secondly, a continuous collision detection algorithm based on flexible multi-body system is needed to be proposed, which could obtain the contact areas during guidewire insertion quickly. Finally, a multi-frictional contact dynamics model based on flexible multi-body system is needed to calculate the contact forces accurately by the dynamics information of contact-pairs, especially the friction force.

In order to address these problems, we proposed a new multi-frictional interactive algorithm between guidewire and vascular based on flexible multi-body system. From the microscopic view, we introduced an adaptive layer into a continuous collision detection algorithm for obtaining the set of “point-surface” contact pairs quickly. Then a multi-frictional dynamics model based on nonlinear equivalent spring damping was proposed for calculating the friction force under various conditions, including sliding friction force, static friction force and rolling friction force. The experimental results show that this algorithm could simulate an insertion procedure very well with complex structure of vasculature in real time.

2 Related Work

Physical Models for Guidewire: guidewire is a kind of long-thin flexible object. Building its physical model is the same as simulations for 1D flexible objects, such as hair, tubes, ropes and cables. Its geometric structure is constrained controlled by a complex physical system in space, and it should not only take the bending deformation into account, but also the twisting deformation and stretching deformation around its centreline. In addition, the numerical stability and computation efficiency of the physical model are also needed to be considered.

In the recent years, foreign and domestic researchers have put forward a lot of good deformation algorithms for guidewire simulation based on physical model, which could be classified three main types, including hybrid mass-spring model [4,6,7], finite element based model [8–10] and elastic rod model [3,11,12]. On the basis of traditional mass-spring model, hybrid mass-spring methods add the bending force and the rotation of nodes into model. These algorithms are simple and good performance in real time, but the accuracy is low and it is easy to cause the oscillation. In the finite element based model, guidewire, with long-thin structure, is separated into several simple units, and it analyzes the dynamics of these discrete units instead of the whole structure. Though various deformation behaviors of guidewire could be simulated precisely by finite element methods, it is not suitable for some VR systems with real time requirement because of its complex calculation. The third kind of modeling approach is based on elastic rod model. As shown in Fig. 1, the discrete setting of centreline is used to describe a

guidewire as a set of control nodes $x_0, x_1, \dots, x_n$, which are connected by edges $e_0, e_1, \dots, e_{n-1}$, meeting $e_{i-1} = x_i - x_{i-1}$. The calculation speed of elastic rod model is depended on the number of these nodes. So, the adaptive method of node number is proposed in paper [3] for achieving both simulation efficiency and accuracy.

Fig. 1. Elastic rod model

The calculation principle of elastic rod model is introduced as follow. Let x_i^k, v_i^k be the current position and velocity of node i at the time step k respectively, $x_i^k \in \mathbb{R}^{3n}$, $v_i^k \in \mathbb{R}^{3n}$. So the position and velocity at the next time step $k+1$ are:

$$x_i^{k+1} = x_i^k + \Delta t v_i^k + \Delta t^2 \left(\left(\frac{1}{2} - \beta \right) a_i^k + \beta a_i^{k+1} \right) \quad (1)$$

$$v_i^{k+1} = v_i^k + \Delta t \left((1 - \gamma) a_i^k + \gamma a_i^{k+1} \right) \quad (2)$$

where $0 \leq \beta \leq 1, 0 \leq \gamma \leq 1$ are constants for calculating the integration, a_i^{k+1} is acceleration, which could be obtained by Eq. (3):

$$F(x_i^{k+1}, v_i^{k+1}) = M a_i^{k+1} \quad (3)$$

Then, Eq. (3) is linearized by Newton-Raphson iteration.

$$F(x_i^k, v_i^k) + \frac{\partial F}{\partial x}(x_i^{k+1} - x_i^k) + \frac{\partial F}{\partial v}(v_i^{k+1} - v_i^k) \approx M a_i^{k+1} \quad (4)$$

Finally, substituting Eqs. (1) and (2) into Eq. (4), we could get the values of a_i^{k+1} , x_i^{k+1} and v_i^{k+1} .

Considering the above, we can draw a conclusion that elastic rod model could simulate all kinds of complex contact deformations in real time with the advantages of precision and efficiency. Therefore, combining with the features of flexible multi-body system, we have further improved the physical model of guidewire based on our previous work [3], particularly discuss the collision detection of flexible multi-body system in depth from the microscopic view for obtaining the multi-contact areas between guidewire and blood vessels.

Collision Dynamics Models: Fast and accurate collision response is a key difficulty to compute multi-frictional contact forces. And this kind of algorithms mainly include three categories:

- (1) Impulse-momentum methods [13]. These methods can easily and effectively get the system motion state after colliding by solving generalized impulse-momentum equation and coefficient of restitution equation. However, it cannot obtain collision forces and system dynamics state with time changing during the collision.

- (2) Methods based on additional constraints [14,15]. Generally, these methods introduce a Lagrange multiplier to build all kinds of constraint boundary conditions of collision and friction, and substitute these conditions into differential-algebraic equations of multi-body system to obtain the dynamical variables and contact forces. Though these methods could satisfy contact constraint conditions accurately, system overhead will increase substantially with poor real time performance because an additional degree of freedom will be introduced for every constraint.
- (3) Methods based on penalty function [16,17]. These methods assume that the deformation is constrained in the neighborhood of contact areas, and use the penetration depth and penetration velocity as the parameters for collision force computation between two bodies by introducing quasi-static contact theory. So penalty-based methods are the approximate methods to use contact force element to replace the complex deformation in contact areas.

Let x be a point of object A, and $\delta(x)$ is the penetration depth into object B, the penalty-based equation is:

$$F(x) = k\delta(x) \quad (5)$$

Where k is contact stiffness, the higher value of that, the smaller value of $\delta(x)$. From the equation (5), it is obvious that the computation of penalty-based methods is easy without adding freedom degree of constraint equations and updating the stiffness matrix for every object. But the accuracy of these methods largely depend on the choosing of penalty factor. In order to solve this problem, augmented Lagrange method [18] is adopted wildly, which is shown in Eq.(6). Due to the additional factor λ , augmented Lagrange method becomes insensitive to contact stiffness k .

$$F(x) = k\delta(x) + \lambda \quad (6)$$

In conclusion, if using constraints-based methods(like LCP algorithms) to process collision response between guidewire and blood vessels, it will need large additional computation to calculate LCP equations and hard to run in real-time, even though it could simulate the multi-frictional contact between them accurately. Therefore, we adapt penalty-based method as the dynamics model to address their collision for achieving the real time performance of virtual training system for MIVS.

3 Fast Continuous Collision Detection

To calculate multi-frictional contact forces between guidewire and blood vessels during insertion, the contact areas should be obtained firstly. In other words, it needs to get the set of “point-surface” contact pairs in the contact areas.

In our virtual training simulator, the physical model for guidewire is based on discrete elastic rod model, as shown in Fig. 1. The body of that is constructed by many standard structure of cylinders with radius r . The vasculature model

is a 3D polygon mesh with thousands of irregular triangular faces, which is reconstructed by 3D rotational X-ray images captured from a real patient. From the microscopic view, when guidewire inserting into blood vessels, the contact areas may appear under the surface of control nodes and the shaft of guidewire between two adjacent control nodes.

In order to get the set of “point-surface” contact pairs between guidewire and vasculature quickly, taking the section of guidewire between two adjacent control nodes x_i and x_{i+1} as a example, we construct a size-adaptive layer at the bottom of the cylinder for accelerating continuous collision detection with size $(L'_i \times w \times h)$ and orientation $\vec{n}l_i$, which is shown in Fig. 2. Where the adaptive value L'_i is the length of bounding box of layer, which is computed by recursion dichotomy algorithm. The adaptive value w is the width of bounding box of layer and related to the size of lumen of blood vessels at the control node x_i , which could be got by pre-extracting the centreline of blood vessels. The experiential value range is $0.25r \leq w \leq 2r$, the bigger size of lumen, the smaller value of w . The value h is the height of bounding box of layer, which is set as a constant.

Fig. 2. The size and orientation of layer

Fig. 3. “point-surface” contact pairs

After confirming the size and orientation of layer, we proposed a layer-based continues collision detection algorithm to obtain the set of “point-surface” contact pairs between guidewire and vascular quickly. Next, we will use the section of guidewire between two adjacent control nodes x_i and x_{i+1} to describe this algorithm as following:

- Step 1: Building an AABB hierarchical bounding volume tree by recursion to divide the whole vascular model into several mesh units.
- Step 2: Using Sphere-AABB collision detection method to check the collision and contact situation at the control node x_i and x_{i+1} .

There are three cases in collision detection with the radius of sphere r the same as the guidewire:

- ① If the collision spheres at x_i and x_{i+1} both collide with vascular, the large contact area under the surface of cylinder may appear.
- ② If only the collision sphere at x_i collides with vascular, the small contact area under the surface of cylinder near the x_i may appear. And it needs to resize the layer in this circumstance.

- ③ The same as ②. If only the collision sphere at x_{i+1} collides with vascular, the small contact area under the surface of cylinder near the x_{i+1} may appear. And it needs to resize the layer in this circumstance.

Step 3: Computing L'_i by recursion dichotomy algorithm to build the size-adaptive of layer.

Let x'_{i+1} be the midpoint of x_i and x_{i+1} , $x'_{i+1} = \frac{1}{2}(x_i + x_{i+1})$. We set $x'_{i+1} = x_{i+1}$ to do the recursive computation by step 2 until convergence to the extreme right node $x'_{i+1_{max}}$. Then, we could get the normal vectors of collision triangles $\vec{n}_i$ and $\vec{n}_{i+1_{max}}$ at node x_i and $x'_{i+1_{max}}$, the length of layer $L'_i = p(x'_{i+1_{max}}) - p(x_i)$ and the orientation of layer $\vec{nl}_i = \vec{n}_i + \vec{n}_{i+1_{max}}$.

Step 4: Getting the set of collision triangles with center position and normal vector by the method of layer-AABB collision detection.

Step 5: Finally, we use these collision triangles information ($pos_j, norm_j$) to create corresponding rays, and do the intersection computation between rays and guidewire to obtain the set of “point-surface” contact pairs.

As shown in Fig. 3, the distance between collision triangle and corresponding intersection point p_i is $len_i = p_i - pos_j$. We could get the final accurate “point-surface” contact pairs by setting a threshold value H , satisfying $len_i \leq H$.

4 Multi-frictional Contact Dynamics

Guidewire slides on the vascular wall by external force after insertion, and multi-frictional interaction between them happens as shown in Fig. 4. With guidewire inserting slowly, the amount of “point-surface” contact pairs increasing gradually and more and more contact pairs work. In the contact area Ω , the reaction forces from vascular wall to guidewire contain the normal constraint force F_N^i and the tangential constraint force F_T^i , where F_N^i is the normal pressure of contact pair i along the normal direction of collision triangle, and F_T^i is tangential resultant force of contact pair i , including sliding friction force, static friction force and rolling friction force.

From Sect. 3 we have obtained the accurate contact areas which are consisted of a few “point-surface” contact pairs. Then we add two directions resultant forces F_N and F_T as a total resultant forces $F = F_N + F_T$, to the control nodes of guidewire for simulating various nonlinear deformation behaviors, where F_N is the normal resultant constraint force in Ω near the control node of guidewire with $F_N = \sum F_N^i$, and F_T is the tangential resultant constraint force with $F_T = \sum F_T^i$. F_N and F_T form a friction cone with 2φ apex angle, meeting $\tan \varphi = \frac{F_T}{F_N}$, as shown in Fig. 4. When one of control node of guidewire and vascular is under the stable critical state in Ω , the apex angle of that reaches the maximum $2\varphi_f$. Here φ_f is called the frictional angle, satisfying:

$$\tan \varphi_f = \frac{F_{max}}{F_N} = \frac{\mu_{static} \cdot F_N}{F_N} = \mu_{static} \quad (7)$$

Where μ_{static} is static friction coefficient, which is relative to the material property of guidewire and vascular. When the angle θ between the normal direction and the external resultant forces acting on the control node i meeting $\theta < \varphi_f$, the node i will under viscous status because of satisfying the frictional self-locking condition.

Fig. 4. Multi-frictional contact dynamics

Fig. 5. Equivalent spring damping model

4.1 Contact Dynamics in the Normal Direction

In the normal direction of contact area, we build a nonlinear equivalent spring damping model to compute the continues collision contact force between guidewire and blood vessels quickly with time, as shown in Fig. 5. In this algorithm, the collision contact model is taken as spring damping model, the collision force is used to describe spring contact force and the damper is adopted to simulate energy loss during the contact process. In fact, the equivalent spring damping model is using penalty function method to deal with constraints.

The equations of nonlinear equivalent spring damping model is:

$$F_N = \Sigma F_N^i \quad (8)$$

$$F_N^i = (f_k^i + f_d^i) \cdot L(\partial_i) \quad (9)$$

$$L(\partial_i) = \begin{cases} 0, & \partial_i \geq 0 \\ 1, & \partial_i < 0 \end{cases} \quad (10)$$

$$f_k^i = k \cdot |\partial_i|^n \quad (11)$$

$$f_d^i = -c_i \cdot |\partial_i|^n \cdot \dot{\partial}_i \quad (12)$$

Where f_k^i is the spring contact force of contact pair i with contact stiffness k , which is relative to the material of contact surface and geometry. $L(\partial_i)$ is logic function to make a judgement on whether contact or not according to the penetration depth ∂_i . $\dot{\partial}_i$ is the penetration velocity of contact pair i . f_d^i is nonlinear damping force. c_i is damping coefficient which is relative to coefficient of restitution and the initial velocity of collision. According to [19], we set $c_i = 3(1 - e^2)/4v_{i-}$, where e is coefficient of restitution and v_{i-} is the initial velocity of collision point i .

4.2 Contact Dynamics in the Tangential Direction

In the tangential direction of contact area, the frictional contacts between guidewire and vascular mainly contain sliding contact, adhesive contact and rolling contact. Therefore, frictional contact force of contact pair i in the tangential direction originates from three parts: sliding friction force $f_{sliding}^i$, static friction force f_{static}^i and rolling friction force $f_{rolling}^i$, the equation of that is listed as below:

$$F_T^i = f_{sliding}^i + f_{static}^i + f_{rolling}^i \quad (13)$$

Sliding/static Friction Force: It is a kind of resistance force when guidewire slides or has a sliding trend on the inner-surface of vascular. So coulomb friction model based sliding/static friction force of contact pair i is:

$$f_{sliding/static}^i = \text{sgn}(v_i) \cdot \mu \cdot F_N^i \quad (14)$$

Where $\text{sgn}(v_i)$ is a sign function, which is relative to the relative velocity of collision point, μ is friction coefficient, including sliding or static friction coefficient, and F_N^i is normal contact force of contact pair i . When guidewire sliding on the blood vessels, if some of control nodes are under viscous status, the friction coefficient of contact area near these nodes should be set from sliding friction coefficient to static friction coefficient because of $\mu_{sliding} < \mu_{static}$.

About the friction coefficient μ , J. Schroder [20] have published the friction coefficient between guidewire and catheter with different types and different materials. However, there are no relative literatures have been published about the friction coefficient between guidewire with different materials and blood vessels with different types of lesions. Because the friction coefficient of guidewire almost the same as vascular, we refer to [20] and set the sliding and static friction coefficient to compute sliding/static friction force between guidewire and blood vessels, $\mu \in [0.01, 0.48]$.

Rolling Friction Force: Rolling friction is more complex. Modern rolling friction theory considers that when a object is rolling under external force, it not only exists normal pressure but also tangential force in contact area, so the contact area is divided into the micro-sliding area, where only exists rolling, and adhesive area, where exists rolling and sliding. And rolling friction force is mainly produced by two factors: elastic hysteresis and viscous effect [21]. That is to say, rolling friction force is a kind of resistance on the surface between guidewire and vascular when they happens relative motion or the trend of relative motion by the normal force and torque.

Guidewire has a standard cylinder structure with radius r and length l between two adjacent nodes. The rolling frictional moment M_i of contact pair i is directly proportional to the normal contact force F_N^i between two contact bodies:

$$M_i = K_i \cdot F_N^i \quad (15)$$

$$K_i = \left[\frac{2\alpha}{3\pi} + \frac{\sigma_b + \sigma_{s/2}}{6H_{vessel}} \right] \left[\frac{4rF_N^i}{\pi l} \left(\frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right) \right] \quad (16)$$

Where K_i is rolling friction coefficient, and its value is set in literature [21], α is elastic hysteresis coefficient, H_{vessel} is hardness of vascular wall, σ_b is maximum tensile stress of adhesive point, σ_s is tensile stress of center contact point, v_1 and v_2 are Poisson ratio of two contact bodies, E_1 and E_2 are elastic modulus of two contact bodies.

Finally, the resultant moment $M = \sum M_i$ of all contact pairs near the control node is calculated and added to guidewire model for further simulating twisting deformation of guidewire caused by rolling.

5 Experimental Results

We have developed a virtual training system for MIVS to verify the algorithm of multi-frictional contact between guidewire and blood vessels. The system mainly includes guidewire dynamics module, continuous collision detection module, multi-frictional contact dynamics response module, virtual force feedbacks module etc., and the architecture of that is shown in Fig. 6.

Fig. 6. System architecture of virtual training simulator

In this paper, based on previous work [3], we further improve the multi-area continuous collision detection from the microscopic view, and the rendering results of guidewire physical deformations including bending, twisting and stretching deformation are shown in Fig. 7.

We design two experiments to test our algorithm. Experiment 1: guidewire is inserted into a straight regular cylinder model, which is a standard 3D mesh made by 3dmax with r 1.8 cm and 35000 triangles, as shown in Fig. 8(a). Experiment 2: guidewire is inserted into a blood vessels model, which is reconstructed 3D rotational X-ray images captured from a real patient with 30420 triangles. This vasculature model is a part of aorta near the heart including aortic arch,

Fig. 7. Rendering results of guidewire

as shown in Fig. 9(a). Then we will analysis the multi-frictional contact between guidewire and blood vessels from two aspects: collision detection, multi-frictional contact forces.

(1) Collision detection. In experiment 1, guidewire slides forward on the inner surface of cylinder under external force, and the rendering result of its physical deformations as shown in Fig. 8(b). Guidewire is close to the inner surface of the cylinder by the action of gravity and the set of “point-surface” contact pairs is obtained quickly by the continues collision detection algorithm. With increasing of the insertion length of guidewire, the number of contact pairs increases linearly. From Fig. 8(c), we can see that the contact pairs distribute regularly just below the guidewire.

Fig. 8. Simulation of multi-frictional interaction between guidewire and cylinder

In experiment 2, guidewire slides on the vascular wall under the external force, the rendering result of that as shown in Fig. 9(b). The same as Exp. 1, with increasing of the insertion length of guidewire, the number of “point-surface” contact pairs increases linearly. From Fig. 9(c), we can see that the contact pairs distribute irregularly under the guidewire due to the irregular triangles of blood vessel model.

Fig. 9. Simulation of multi-frictional interaction between guidewire and blood vessels

(2) Multi-frictional contact forces. In experiment 1, guidewire is inserted into cylinder with a constant speed of 2.0 cm/s. As in the Fig. 10 of Exp. 1, before the inserted length less than 3.0 cm, the total friction is close to zero because guidewire does not collide with the cylinder. Then, guidewire is inserted continually and the friction is almost growing linearly with the slop of about 0.005. From the curve of Exp. 1, we can see that adding rolling friction has an influence on computing the multi-frictional contact forces between them. The green curve shows the result of adding rolling friction, which is more oscillating than the blue curve without rolling friction because of viscous effect.

Fig. 10. The relationship between friction and distance (Color figure online)

In experiment 2, guidewire is inserted into blood vessel with a constant speed of 2.0 cm/s. As in the Fig. 10 of Exp. 2, the same as Exp. 1, before the insertion length less than 5.0 cm, the total friction is close to zero because guidewire does not collide with the blood vessel. Then, guidewire is inserted continually and the friction almost growing linearly at the straight anterior of the blood vessel with the slop of about 0.004, but the friction suddenly increases when guidewire reaches the first turning of the blood vessel at the insertion length 16.0 cm. Then guidewire is inserted continually and the friction almost growing linearly

again with the slop of about 0.032. Similarly, the green curve of Exp. 2 is more oscillating than red curve by the viscous effect of rolling friction.

The frame rate of our virtual training system is over 60fps on an *Intel®Core™* 4 CPU i5-3337U @1.8 GHz machine with 4G memory since our algorithm is efficient for real-time computations.

6 Conclusion

The real-time multi-frictional contact simulation has important significance in the training system of cardiovascular interventional operation. From the microscopic view, our paper proposed a multi-frictional contact algorithm between guidewire and blood vessels based on the flexible multi-body dynamics. The algorithm computes the frictions from normal direction and tangential direction in the contact areas. In normal direction we get the normal contact force by nonlinear spring damping model, and in tangential direction we calculate the sliding, static and rolling friction by the Coulomb friction model. The experimental results show that this algorithm could simulate the multi-frictional contact between guidewire and blood vessels very well in real time, especially in the complex vascular structures.

Acknowledgements. his work was supported by NSFC of China under Grant No. 61402278, 61303093, the Shanghai Natural Science Foundation under Grant No. 14ZR1415800 and the Innovation Program of Shanghai Municipal Education Commission (No. 14YZ023).

References

1. Safian, R.D., Freed, M.S.: *The Manual of Interventional Cardiology*. Science Press, Royal Oak (2004)
2. Han, S., Hong, J.: Several key issues in flexible multibody dynamics with contact/impact. *Mech. Eng.* **33**(2), 1–7 (2011)
3. Tang, W., Lagadec, P., Gould, D., Wan, T.R., Zhai, J., How, T.: A realistic elastic rod model for real-time simulation of minimally invasive vascular interventions. *Vis. Comput.* **26**(9), 1157–1165 (2010)
4. Alderliesten, T., Konings, M.K., Niessen, W.J.: Modeling friction, intrinsic curvature, and rotation of guide wires for simulation of minimally invasive vascular interventions. *IEEE Trans. Biomed. Eng.* **54**(1), 29–38 (2007)
5. Spillmann, J., Harders, M.: Inextensible elastic rods with torsional friction based on lagrange multipliers. *Comput. Animation Virtual Worlds* **21**(3), 561–572 (2010)
6. Luboz, V., Blazewski, R., Gould, D.: Real-time guidewire simulation in complex vascular models. *Vis. Comput.* **25**(9), 827–834 (2009)
7. Huang, P., Chao, J., Xuwen, C., et al.: Catheter modeling in vr simulation of catheter ablation of atrial fibrillation. *J. Comput. Aided Des. Comput. Graph.* **24**(9), 1139–1144 (2012)
8. Nowinski, W.L., Chui, C.K.: Simulation of interventional neuroradiology procedures. In: *Proceedings of International Workshop on Medical Imaging and Augmented Reality*, pp. 87–94 (2001)

9. Ma, X., Jianhuang, W., Wang, S., et al.: Simulation training system for cerebrovascular interventional surgery. *Chin. J. Dial. Artif. Organs* **21**(3), 25–31 (2010)
10. Wan, T.R., Tang, W., Huang, D.: Real-time simulation of long thin flexible objects in interactive virtual environments. In: *Proceedings of the 18th ACM Symposium on Virtual Reality Software and Technology (VRST 2012)*, pp. 85–92 (2012)
11. Bertails, F., Audoly, B., Cani, M.P., et al.: Super-helices for predicting the dynamics of natural hair. *ACM Trans. Graph.* **25**(3), 1180–1187 (2006)
12. Bergou, M., Wardetzky, M., Robinson, S., et al.: Discrete elastic rods. *ACM Trans. Graph. (SIGGRAPH 2008)* **27**(3), 63:1–63:12 (2008)
13. Zhang, D., Angeles, J.: Impact dynamics of flexible-joint robots. *Comput. Struct.* **83**, 25–33 (2005)
14. Otaduy, M.A., Tamstorf, R., Steinemann, D., et al.: Implicit contact handling for deformable objects. *Comput. Graph. Forum (EUROGRAPHICS 2009)* **28**(2), 559–568 (2009)
15. Allard, J., Faure, F., Courtecuisse, H., et al.: Volume contact constraints at arbitrary resolution. *ACM Trans. Graph. (SIGGRAPH 2010)* **29**(4), 82:1–82:10 (2010)
16. Tang, M., Manocha, D., Otaduy, M.A., et al.: Continuous penalty forces. *ACM Trans. Graph. (SIGGRAPH 2012)* **31**(4), 107:1–107:9 (2012)
17. Harmon, D., Zhou, Q., Zorin, D.: Asynchronous integration with phantom meshes. In: *Proceedings of the 2011 ACM SIGGRAPH/ Eurographics Symposium on Computer Animation*, pp. 247–256 (2011)
18. Laursen, T.A.: *Computational Contact and Impact Mechanics: Fundamentals of Modeling Interfacial Phenomena in Nonlinear Finite Element Analysis*. Springer, Heidelberg (2002)
19. Hunt, K.H., Crossley, F.R.E.: Coefficient of restitution interpreted as damping in vibroimpact. *J. Appl. Mech.* **42**(2), 440–445 (1975)
20. Schroder, J.: Technology assessment: the mechanical properties of guidewirespart iii: Sliding friction. *CardioVasc. Intervent. Radiol.* **16**, 93–97 (1993)
21. Guo, J.: The mechanism of producing rolling friction force and its calculaton. *Lubr. Eng.* **01**, 19–24 (1998)