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Haptics-equiped interactive PCI simulation for patient-specific surgery training and rehearsing

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Abstract Despite the long history of medical simulations, suffering from the patient-specific heterogeneous heart physiological structure and complex intravascular procedures, it is still challenging for patient-specific percutaneous coronary intervention (PCI) surgery simulation. In this paper, we advocate a haptics-equiped interactive prototype system towards PCI surgeons training and patient-specific surgery rehearsing, which can afford trainees the opportunity to approximately experience the entire PCI procedures and customized emergency cases that might occur in common clinical settings. The full simulation covers tissue deformation, catheter and wire simulation, X-ray simulation, haptic feedback, and 3D realistic rendering, which in all give rise to the integrated physical, visual, haptic, and procedural realism. Our system can accommodate various comprehensive operations involved in PCI-related procedures, including feeding wires, releasing stents, injecting contrast medium, simulating X-ray, bleeding, etc. Moreover, our system framework is fully built upon CUDA, and thus can achieve real-time performance even on a common desktop. The high-fidelity, real-time efficiency and stableness of our system show great potentials for its practical applications in clinical training fields.

Keywords percutaneous coronary intervention (PCI), PCI surgery simulation, patient-specific surgery rehearsing, physically-based modeling, haptics

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1 Introduction

PCI is a well-recognized effective treatment for coronary heart diseases, which has become one of the major causes of death throughout the world. PCI procedures involve a wide range of complex intravascular operations, which usually requires surgeons to maintain proficiency via experiencing more situations. Moreover, PCI surgery tends to cause many potential life-threatening complications, it is very dangerous for new surgeons to directly conduct surgery on human patients. In the meanwhile, with the continued developing in simulation, visualization, and haptic interaction, virtual reality (VR) based simulation plays more and more significant role in clinical training and surgery rehearsing of higher risk clinical situations. However, existing surgical simulators are usually designed with different complexity under different motivations driven by the demands of various surgical training types. And most of the mature

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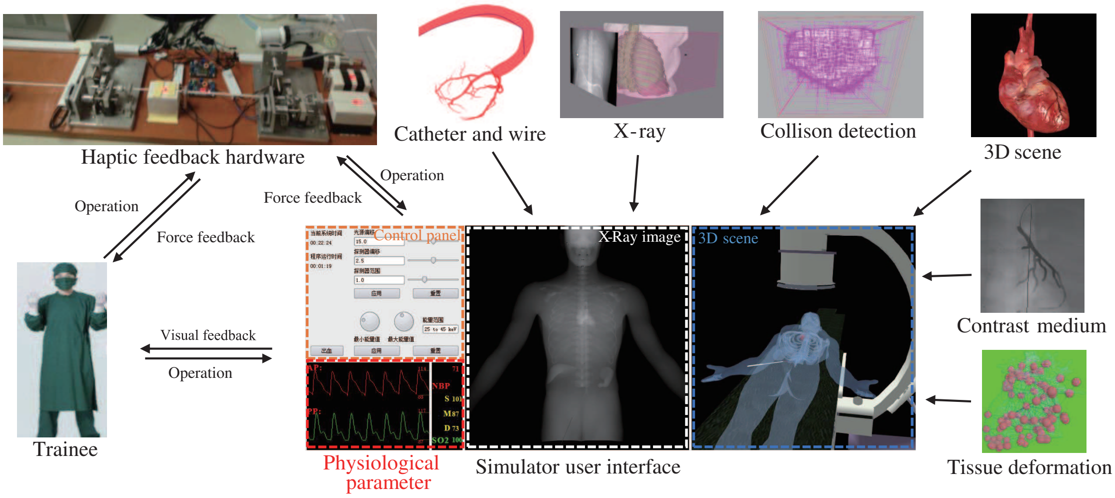


Figure 1 (Color online) The architecture overview of our patient-specific PCI surgery simulator.

medical simulators are for laparoscopic surgery. Even though there are some PCI simulators already, they can only deal with certain pre-settled data and scenarios, which cannot accommodate patient-specific surgery planning and rehearsing. Therefore, a functionally-completed PCI simulator supporting replacement of patients' clinical data is urgently needed, which will provide surgeons with more chances to be trained and lower down the possibility of mistakes in real surgery.

In this paper, we advocate a haptics-equiped interactive prototype system for PCI surgery training and rehearsing. Specially, the key technological innovations can be summarized as follows: (1) supporting personalized data, which is hard for existing medical simulators; (2) cardiovascular system physical simulation model based on the integration of position based dynamics (PBD) and spring system; (3) wire and catheter physical simulation based on Cosserat theory; (4) ray-casting based virtual X-ray imaging method; (5) the customized design of haptic feedback hardware supporting full PCI procedures; (6) CUDA-accelerated system implementation based on the organic integration of the aforementioned technical innovations.

2 System functionalities and technological innovations

As shown in Figure 1, our simulator's interface consists of a window showing virtual X-ray image, a window showing virtual 3D scene, a panel controlling different simulation parameters and a panel showing the patient's physiological data. The interface is connected to a haptic feedback hardware, which transforms the operations from trainees to the system, receives the response forces from the system, and feedbacks to the trainees through force sensing devices. Behind the interface, there are many other functional components, of which, the key technological innovations will be introduced one-by-one in the next.

3D reconstruction of patient-specific cardio-vascular model. Given patient-specific clinical dataset, to model the complex intravascular structures and the dynamics of the cardio-vascular system, we should first segment different tissues/organs apart and reconstruct corresponding surface meshes. The top row in Figure 2 shows the pipeline of reconstructing cardiovascular vessels from scanned CTA slices. Firstly, we employ 3D level set method used in [1] to segment vessels apart from other tissues. Secondly, we extract the centerline for the segmented volumetric vessels, and employ cubic B-splines to fit the vascular branches. Thirdly, we compute many cross sections of these center lines and estimate the radius of each branch at corresponding positions. Finally, a 3D vascular mesh is generated via lofting. As for the 3D reconstruction of patient-specific heart models, we resort to volumetric shape registration governed deformable model [2]. Given a generic heart tetrahedral model and the patient-specific CTA scans, we deform the generic template tetrahedral mesh towards the underlying geometry of the voxel-represented heart cells via global registration and elastic registration. The reconstruction process is semi-automatic,

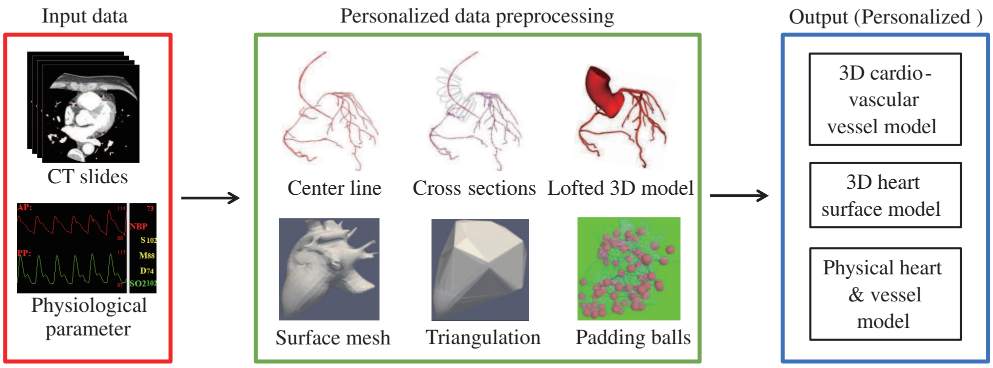


Figure 2 (Color online) Illustration of data preprocessing. The input consists of personalized CT slides and the clinic physiological parameter. The output contains a 3D vessel model, a 3D heart surface model and a physical model for both of them.

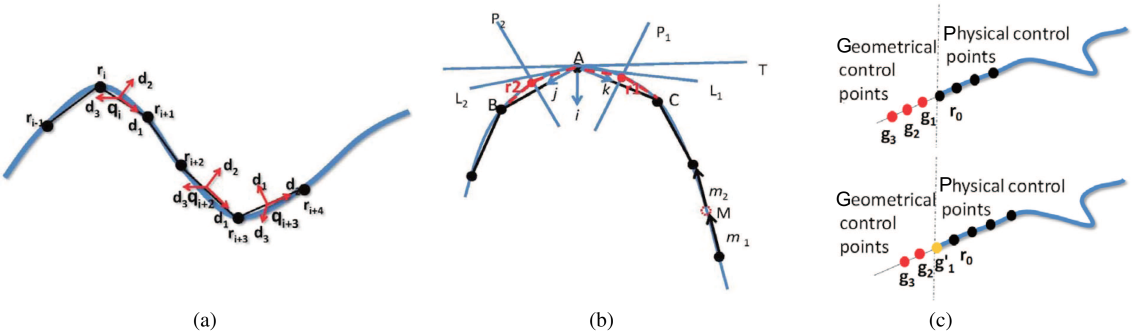


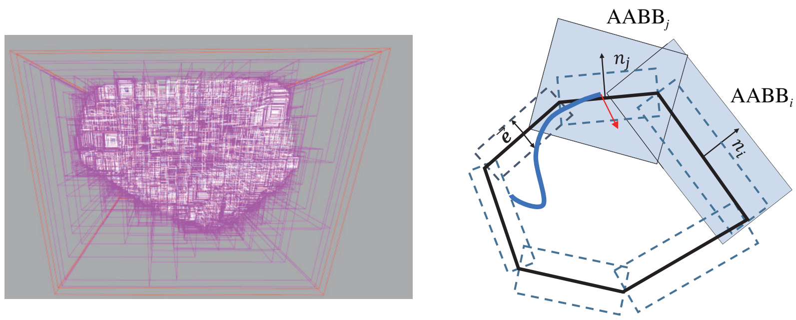
Figure 3 (Color online) Illustration of wire/catheter simulation model. (a) The wire is discretized into N spatial control points r_i, where the orientation of each element is represented by a quaternion q_j; (b) the adaptive sampling, where r_1 and r_2 are the two additional points and M is the deleted points; (c) two different states of the hybrid model.

and thus our system is applicable to different personalized data, which is very helpful for surgeons when planning certain patient's personalized surgery.

Physically-plausible deformation model. Actually, during PCI surgery, we need to simulate the dynamics of heart and cardiovascular system, which is modeled by integrating position based dynamics (PBD) [3] and mass-spring models, so that the computation of contact force can be decoupled from the deformation model, which guarantees the system's stability. As shown in the bottom row of Figure 2, given the reconstructed 3D cardio-vascular model, to character the volumetric properties, we place a padding ball at the vertex of each tetrahedron, each pair of padding balls on the same tetrahedron are connected with 3 different types of springs governing 3 kinds of deformations, such as twisting, bending and tensiling. Finally, a mapping is constructed between padding balls and surface vertexes. The deformation of padding balls is computed using PBD with springs' constraints, and the deformation of a surface point is a weighted combination of its corresponding padding balls.

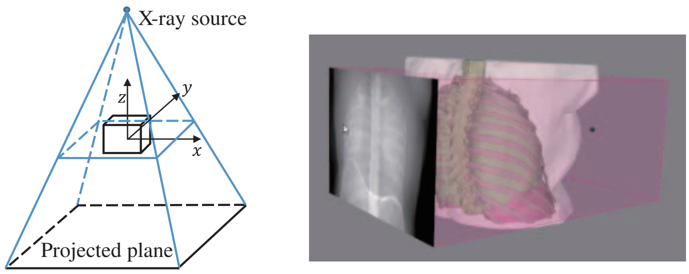
Wire and catheter simulation model. Another important physical model is for the wire and catheter simulation. In a PCI surgery, the wire is used to traverse the path along vessels to the target lesion region and guide the entrance of catheter, and the catheter is used as a tunnel to transmitting balloon/stents or medicines. In our system, we adopt Cosserat based method [4] to model their physical behaviors. Of which, the wire is discretized as a set of N control points, for each element, a local frame is defined to control its orientation, as shown in Figure 3 (a). The wire/catheter consists of two main parts: rigid slender body and soft tip. The movement of each control point is governed by its potential, kinetic, and dissipation energy. The variational formulation will result in a Lagrangian equation, and we apply an implicit Euler solver to update the position of each control points, which guarantees the robustness and stability of the simulation.

Collision detection and response handling. When the wire is pushed inside a blood vessel, they



(a) (b)

Figure 4 (Color online) Illustration of collision detection and response. (a) Hierarchical axis-aligned bounding box; (b) the curved wire dragged back along the normal of contact point.



(a) (b)

Figure 5 (Color online) Illustration of X-ray simulation. (a) The schematic of ray-casting based method; (b) the generated X-ray image of a human chest reconstructed from scanned CT slices.

will contact with each other and produce force feedback to the surgeons. Firstly, we employ a top-down algorithm to construct a hierarchical structure of axis-aligned bounding box (AABB), as shown in Figure 4 (a). The bounding boxes split the space into many small cuboids, which can greatly improve the triangle-accessing efficiency when collision happens. As shown in Figure 4 (b), when the wire comes into a bounding box, the system will immediately find all the triangles in this box, and judge whether it goes through these triangles or not. In our system, we adopt constraint projection method to deal with the collision response, in which the object that passes through the boundary will be moved along the normal of contact point to make sure it just lies outside of the collision surface. This approach directly modifies the wire's position, avoiding the explicit computation of velocity, and guarantee the high efficiency of our system. Moreover, when the collision happens, we compute a force based on the penetration depth and collision angle, this virtual force will be sent to the haptic devices and feedback to the surgeons.

Virtual X-ray image generation. In a real PCI surgery, surgeons should continually adjust the marching direction of the wire, the only thing they can use as guidance is the X-ray image. In our system, we use a ray-casting based method to generate virtual X-ray image. As shown in Figure 5 (a), an X-ray starts from the source, passes through the target object and finally reaches the projected plane. The intensity of X-ray will decrease after getting through certain object, and the influence is different for objects with different materials. Therefore, we can record the intensity of all lights that finally reach the projected plane to mimic X-ray imaging. In the X-ray generator, we also design a data structure storing the uniformity of CT data. When computing the light path, we can sample with different intervals according to the uniformity, so that it can ensure the real-time performance of our X-ray generator.

Contrast medium releasing simulation. Because of the complex anatomical structure of heart, it is still very hard to distinguish different cardiovascular branches solely based on X-ray image, surgeons usually inject contrast medium into the patient's heart vessels. In our system, we model the contrast medium as a particle system, which has been widely used in fluid simulation [5]. As these particles move following the blood and change the uniformity of vessels, the cardiovascular branches will be much more clear on the generated X-ray image. Figure 6 shows 3 snapshots of injecting contrast medium in

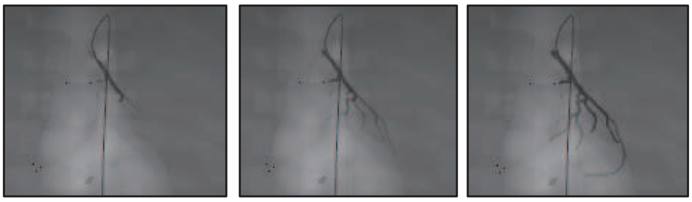


Figure 6 (Color online) Injecting contrast medium during virtual surgery.

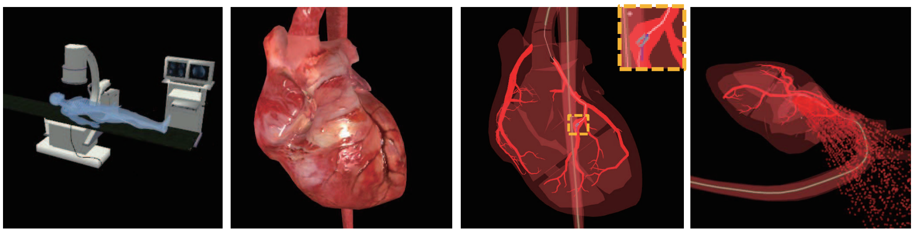


Figure 7 (Color online) Realistic rendering of 3D virtual surgery scene.

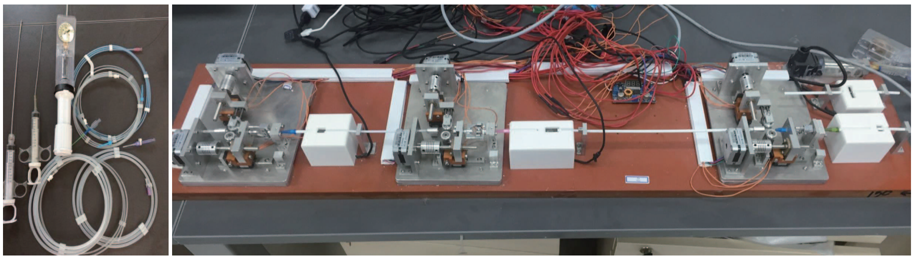


Figure 8 (Color online) The hardware in our system. The left picture shows real tools related to PCI surgery, the right picture shows the signal acquisition and force feedback devices.

Table 1 Time statistics (in millisecond) of each step in our system. From left to right, time for: 3D reconstruction of heart and vessels (in initial stage), heart deformation, wire and catheter simulation, collision detection and response, X-ray imaging, contrast medium simulation, 3D scene rendering, and the total time of one simulation circle

3D Rec (min)	Heart def	Wire	Collision	X-ray	Contrast	3D scene	Period
10	28	8	17	20	6	15	74

our virtual surgery, wherein the contrast medium finally vanish after a few seconds just as that in real surgery.

Realistic 3D rendering. We also provide a window in our interface to show the 3D scene during the surgery simulation process. However, it is not included in real surgery, which is only for trainees to better know the situations. As shown in Figure 7, this window can show the whole settings of the surgery, users can roam in this virtual world simply using mouse and keyboard, or zoom in to see the details of the heart and the things inside it. The region marked with a dashed rectangle in the 3rd picture shows an implanted heart stent, and the 4th picture shows an example of bleeding when the wire impales a vessel.

Haptic feedback hardware. All tools involved in our system, such as wire, catheter, injector, pneumatic pump and so on, are the same with those used in real surgery. Besides, we also integrate a specially-designed haptic feedback hardware into our simulation system. We use a few optical sensors to measure the displacements and rotations of wire/catheter, as the white box shown in Figure 8, and a few driving motor to simulate force feedback, as the 3 metal devices shown in Figure 8.

Perfomance. We have implemented all techniques mentioned above on a desktop with NVIDIA GTX 780 using CUDA, which guarantees the interactive performance of our system. A detailed time statistics of each step is given in Table 1, benefited from the GPU acceleration, our system only need a few tens of milliseconds to finish an entire simulation circle. It should be noted that, the computation of X-ray is executed on another separate thread synchronously, thus not included in the period.

3 Conclusion

We have briefly introduced a patient-specific PCI simulation system. At technical fronts, our system covers personalized data based modeling, physically-based simulation, and PCI-specific haptic instrument design. The key technical innovations include hybrid model based tissue deformation, catheter and wire simulation, collision detection and haptic response, virtual X-Ray generation, fluid-based contrast medium and 3D realistic rendering. Besides, our system has been tested and used for training and teaching in Peking Union Medical College Hospital and some other hospitals or medical institutes. The illustrated high-fidelity and comprehensive functions encourage us to propel it for clinical applications in near future. For more vivid details and results, please refer to our supplementary videos.

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Conflict of interest The authors declare that they have no conflict of interest.

Supporting information The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Li S, Zhao Q P, Wang S F, et al. Interactive deformation and cutting simulation directly using patient-specific volumetric images. Comput Animat Virt Worlds, 2014, 25: 155–169

2 Sahilloglu Y, Kavan L. Skuller: a volumetric shape registration algorithm for modeling skull deformities. Med Image Anal, 2015, 23: 15–27

3 Camara M, Mayer E, Darzi A, et al. Soft tissue deformation for surgical simulation: a position-based dynamics approach. Int J Comput Assist Radiol Surg, 2016, 11: 919–928

4 Mao Y R, Hou F, Li S, et al. Robust and high-fidelity guidewire simulation with applications in percutaneous coronary intervention system. In: Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology. New York: ACM, 2013. 27–30

5 Yang L P, Li S, Hao A, et al. Realtime two-way coupling of meshless fluids and nonlinear FEM. Comput Graph Forum, 2012, 31: 2037–2046