Simulation based patient-specific optimal catheter selection for right coronary angiography

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ABSTRACT

Selecting the best catheter prior to coronary angiography significantly reduces the exposure time to radiation as well as the risk of artery punctures and internal bleeding. In this paper we describe a simulation based technique for selecting an optimal catheter for right coronary angiography using the *Simulation Open Framework Architecture* (SOFA). We simulate different catheters in a patient-specific arteries model, obtain final placement of different catheters and suggest an optimally placed catheter. The patient-specific arteries model is computed from the patient image data acquired prior to the intervention and the catheters are modeled using Finite Element Method (FEM).

Keywords: catheter simulation, optimal catheter, right coronary angiography, catheter selection

1. INTRODUCTION

Coronary angiography is an examination of the blood vessels of the heart. During this procedure, a small incision is made in the upper thigh and a catheter is inserted into the femoral artery and is threaded towards the aorta and coronary arteries. Then the contrast agent is injected through the catheter and is added to the blood in the small vessels. It renders the blood vessels more opaque and then clear images of the small vessels are obtained. Due to the anatomical variation of the aorta and coronary arteries in different humans, one common catheter cannot be used for all patients. It will be very helpful for the cardiologist to know in advance which one is an optimal catheter.

1.1 Related work

In the medical literature there exist approaches for the best catheter selection but these are rather experience based and not patient specific. There are discussions about the general concepts related to the shape of the aorta and the coronary arteries and catheter choices for particular anatomies. But it lacks discussion about patient specific catheter selection. For example, Schneider[1] and Kirks[2] discuss the very general cases and the recommended catheters. Kimbiris[3] focuses on the anomalous aortic origin of the coronary arteries. Brinkman[4] published results of a study about the variability of human coronary artery geometry. A general discussion about the guiding catheter selection for the right coronary artery angioplasty is given by Myler[5] and for the left coronary artery by Voda.[6] In some other studies, results related to best catheter selection after testing a series of catheters are given. Sarkar et al.[7] have tested 79 catheters on 24 patients which represents an average of three catheters per patient. We have done some preliminary work dealing with catheter recommendation based on patient specific image data.[8–10] In these works we compute some geometric parameters from the patient image data and parameters from the available catheters and suggest a suitable catheter based on these computations.

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There, we haven't considered the deformation of catheters inside the arteries. Such computation helps to restrict the catheter choices. But the deformable nature of catheters may affect their final placement. Therefore, we want to simulate the already restricted choices of catheters obtained from the geometric parameters' computation and find final placement of different catheters inside the arteries. Catheter simulation is an active research area and many training systems for catheter simulation are available. Although these training systems are not dealing with the problem of best catheter selection, these simulation strategies can be used for best catheter selection. One of the earliest training systems called Dawson-Kaufman simulator[11] is developed by HT Medical Inc. This system is used for catheter navigation in the abdominal aorta. The catheter movement requires longer time than the desired real-time response. A vascular catheterization simulator called daVinci[12] is a training system where a catheter has been modeled as a finite element system. Another such training system for medical students is ICard.[13] It is designed to enable medical students or physicians to familiarize themselves with the techniques of interventional catheterization procedures. The neuroradiology catheterization simulator called NeuroCath[14] is an FEM based physical model with haptic apparatus that gives the sense of touch during intervention planning and training. Lenoir et al.[15] present a training system for surgical thread simulation. It is a one dimensional dynamic spline model for thread simulation for surgery purposes. Another simulation system for training purposes is presented by Alderliesten et al.[16] The catheter is modeled as a set of joints and these joints are connected by straight, non bendable segments using spring forces. Duriez et al.[17] proposes a catheter model based on three dimensional beam theory. They try to improve the accuracy of the previously proposed models and handle geometric non linearities. A catheter-guidewire composite model is presented by Lenoir el al.[18] that avoids the problems of handling the numerous contacts between the catheter and guidwire due to the fact that both devices are co-axial. In the approach presented by Luboz et al.[19,20] a mass-spring model is used where the guidewire is modeled as a set of particles connected by stiff springs.

The purpose of all these systems is to train young cardiologists by using virtual environment instead of real patients. These training systems help to familiarize them with the techniques of interventional catheterization procedure. However, these systems are still far from the real environment. Moreover, these systems do not handle the problem of patient-specific optimal catheter selection. We want to simulate the different catheters and find a patient-specific optimal catheter. The catheter models available in the literature are either FEM based or spring based models. The spring based approach of Luboz el al.[19,20] concentrate only on the guidewire which is easy as compared to modeling the whole catheter. Using an FEM based approach one can easily model the different properties like cross-sectional area, cross-section moment of inertia, polar moment of inertia, solid and hollow devices of various cross-sectional geometries and mechanical properties. Therefore, we use the FEM based modeling in our approach.

2. METHODS

We model the arteries from the patient's MR/CT data acquired prior to the intervention. The catheters are modeled as finite beam elements. We then simulate the different catheters, find final placement of the catheters and select the catheter placed along the optimal path.

2.1 Arteries modeling

For arteries modeling we need to segment the aorta and coronary arteries. We have described an automatic segmentation technique in our previous work.[8] However, the modeling algorithm is independent from segmentation schemes. Thus, any segmentation scheme that extracts the aorta and the coronary arteries can be used. A surface mesh is created from the segmented images using a series of VTK filters[21]*

2.2 Catheter modeling

We model the catheters as flexible beams that bend when they collide with the internal walls of the arteries. We need different parameters for the model for example diameter, mass and modulus of elasticity (Young's Modulus). We consider diameter and length of the catheters. We then discretize the catheters and find the mass of each point.

*http://www.vtk.org/

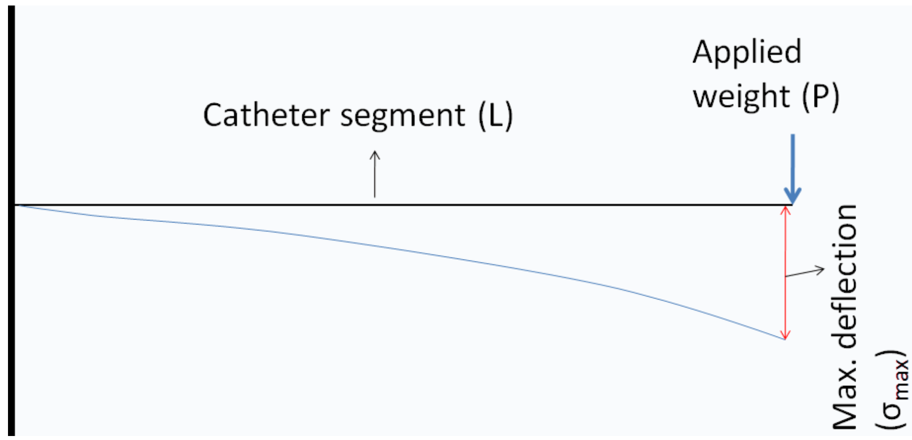

Figure 1. Measuring catheter's elasticity

For this, we measure the mass of the whole catheter and then divide it by the number of discrete points. The essential parameter for the simulation obtained by direct measurement is the modulus of elasticity. We use the following beam deflection formula to compute the elasticity.

$$\delta_{max} = P \cdot L^3/3 \cdot E \cdot I \tag{1}$$

Where δ_{max} is the maximum deflection, P is the applied force, L is the beam length, E is the modulus of elasticity and I is the second moment of inertia. For the second moment of inertia the following formula is used.

$$I = phi/64 \cdot ((OD)^4 - (ID)^4) \tag{2}$$

Where OD and ID is the outer and inner diameter of the catheter, respectively.

To compute δ_{max} in Eq. 1 we take each catheter and divide the whole catheter into different small segments. The length of each segment is taken as one centimeter. We fix one end of the segment and apply a force of one Newton at the other end of the segment and measure the maximum deflection (Fig. 1). To compute I in Eq. 2, OD and ID are read from the catheter manual.

2.3 SOFA Framework

Having created the models for the arteries and catheters, the next step is the simulation. We use the *Simulation Open Framework Architecture* (SOFA)[22†] for simulation. SOFA is an open source framework used for real-time simulation. Based on an advanced software architecture, it allows creating complex and evolving simulations by combining new algorithms with algorithms already included in SOFA. It allows to modify most parameters of the simulation, i.e. deformation behavior, surface representation, solver, constraints and collision algorithms etc. It efficiently simulates the dynamics of interacting objects using abstract equation solvers. There are many collision models like *SphereModel, SphereTreeModel, CubeModel, TetrahedronModel, TriangleModel* etc. A number of ODE solvers are also available in SOFA.

2.4 Catheter's simulation

In our algorithm we have used different components of SOFA. The scene graph of our simulation is described as follows (Fig. 2). Different segments of a catheter have different elasticity levels. And therefore, we model a catheter as a combination of these segments. The segments are connected using the *AttachConstraint* component. All segments use *CGLinearSolver* component as linear solver and *CGImplicitSolver* component as ODE solver.

[†]http://www.sofa-framework.org/

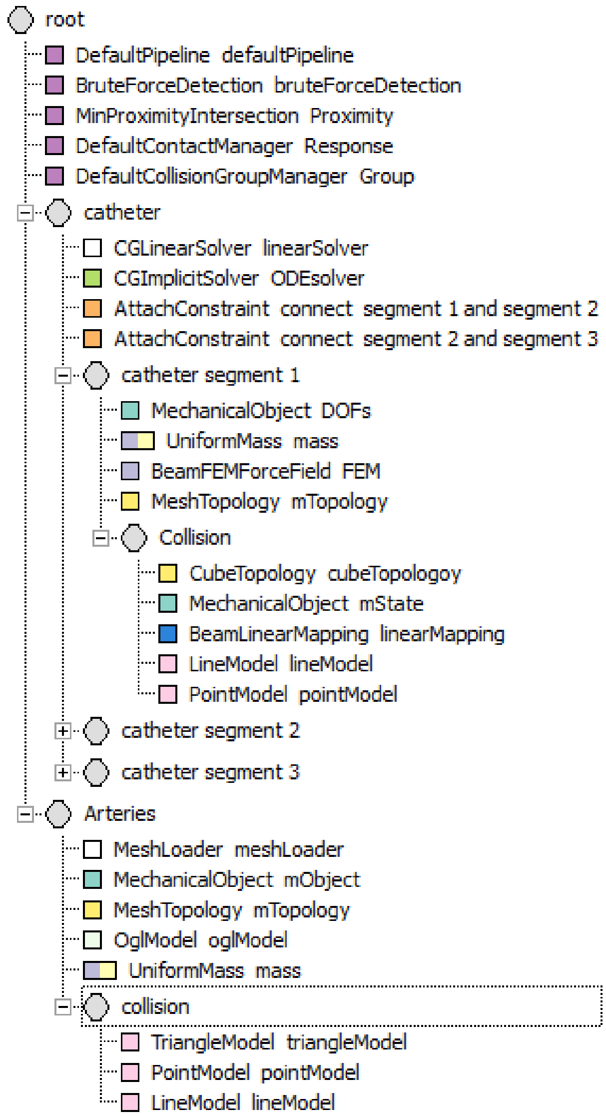

Figure 2. Scene graph

Every segment uses its own *MechanicalObject* component for representing position and velocity coordinates. Similarly, each segment uses its own *BeamFEMForceField* component for beam finite elements representation. For topology representation, each segment uses its own *MeshTopology* component. Each segment uses the *LineModel* and *PointModel* components for the collision detection. For the arteries representation, the *MeshLoader* component is used to load the mesh object file. *MechanicalObject* component is used for representing position and velocity coordinate. *OGLModel* component is used for visual representation. *TriangleModel*, *LineModel* and *PointModel* components are used for the collision detection. Velocity directions for the catheter are obtained from the centerline of the arteries. We simulate different catheters and find final position of the catheters. To compute the optimal catheter we use the clinical confirmation that in case of right coronary angiography a catheter placed along the arteries centerline (yellow line in Fig. 5) is an optimal catheter. We want to see how closely the different catheters are placed to the centerline. For this we divide the Arteries Center Line (ACL) into N equidistant points. Similarly, we consider the final placement of the catheters after simulation and every catheter k is divided into N equidistant points. Then we compute the distance between catheter k and ACL:

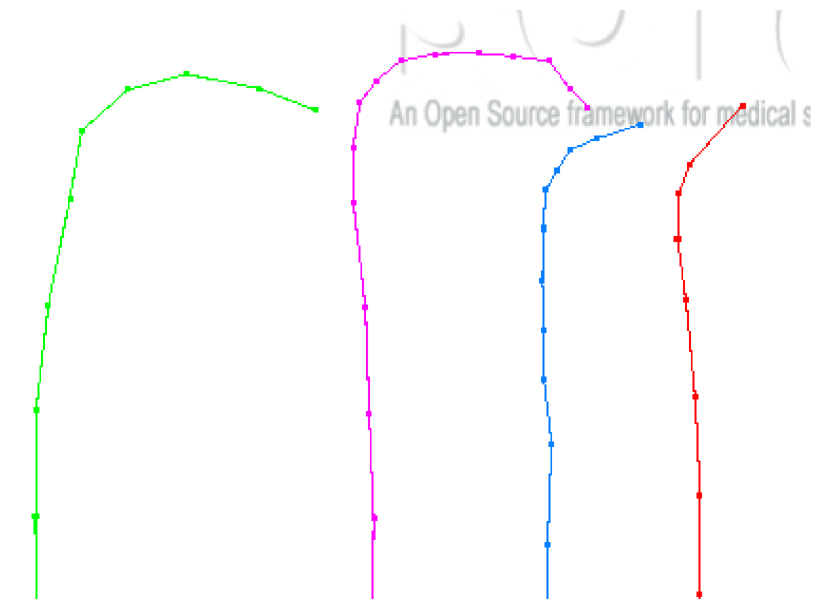

Figure 3. Four different catheters, from left: MB1 (green), JR35 (pink), JR10 (blue), SAR20 (red)

$$distanceCatheter_k = \sum_{i=1}^{N} \left(\sqrt{(Catheter_{ki} - ACL_i)^2} \right) \quad (3)$$

Where $Catheter_{ki}$ is the i^{th} point of catheter k and ACL_i is the i^{th} point of ACL. Since the points are in space so we can write this equation as

$$distanceCatheter_k = \sum_{i=1}^{N} \left(\sqrt{(X_{Catheter_{ki}} - X_{ACL_i})^2 + (Y_{Catheter_{ki}} - Y_{ACL_i})^2 + (Z_{Catheter_{ki}} - Z_{ACL_i})^2} \right) \quad (4)$$

Where $X_{Catheter_{ki}}$, $Y_{Catheter_{ki}}$ and $Z_{Catheter_{ki}}$ are the x, y and z coordinates, respectively, of the i^{th} point of k^{th} catheter. X_{ACL_i}, Y_{ACL_i} and Z_{ACL_i} are the x, y and z coordinates, respectively, of the i^{th} point of ACL. The optimal catheter will be selected as the one with the closeset distance to the centerline.

$$OptimalCatheter = \arg\min_k \{distanceCatheter_k\} \quad (5)$$

3. RESULTS

For this work, we have considered four different catheters (Fig. 3). They differ in shape, size and elasticity. An ideal test for our simulation would be the comparison of the final placement of a real catheter in a real artery and the final placement of this catheter in our simulation. But such an experimental set up was not possible. We restricted our evaluation to the elastic behavior of the beam model. We compared the real catheters to our virtual catheters with regard to their elasticity. Table 1 shows the four catheters we have used in our experiments. First, we considered the real catheters and computed the elasticity of each catheter using the procedure described in section 2. We checked the elasticity at different segments of each catheter. We found that catheters JR35 and JR10 had two different elasticity levels. The elasticity for SAR20 was same for the whole catheter every where. MB1 had three different elasticity levels. To compute the elasticity of the virtual catheters we followed the same procedure described in section 2 in our virtual environment. Figure 4 shows a segment of virtual catheter and the maximum deflection under the applied force of 1N. In the SOFA environment we fixed one end of the segment and applied force at the other end. Then we measured the deflection w_{max} and compared it to the deflection of the real catheters. Table 1 shows the deflection difference for real and virtual catheters. The average error is 9.52%.

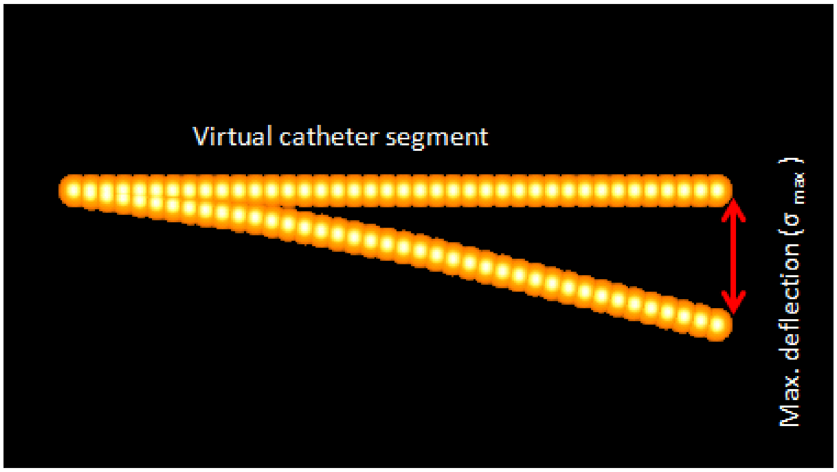

Figure 4. Measuring virtual catheter's elasticity in SOFA

Catheter Type	Catheter Segment	w_{max} real catheter	w_{max} virtual catheter	error in %
JR35	1	0.001	0.00107584	3.792
	2	0.003	0.0032275	11.375
JR10	1	0.002	0.0022175	13.588
	2	0.004	0.00454356	13.589
SAR20	1	0.002	0.00215167	7.584
MB1	1	0.002	0.00182501	8.75
	2	0.001	0.00091252	8.748
	3	0.003	0.00273752	8.749

Table 1. Deflection measurements of the virtual catheters compared to the deflection of the real catheters

3.1 Catheter simulation:

We used the SOFA framework for catheter simulation. We restricted our experiments to the right coronary angiography (the same simulation algorithm can be applied to the left coronary angiography by directing the catheter tip towards left coronary artery). The catheter was inserted following the centerline of the arteries using the *LinearMovementConstraint* component of SOFA. The simulation was manually stopped when the catheter's tip reached the ostium. In Fig. 5 positions of different catheters are shown after simulation. Using Eqs (4) and (5) the catheter placed closeset to the centerline is selected as the optimal catheter. This new simulation based technique is expected to give more accurate results because both, the arteries and catheter models are deformable and the catheters diameter is also included. A more extensive quantitative evaluation is in progress and we are considering more patient data and more catheters. In the next section we compare this approach with the geometric parameter based approach for catheter selection.

3.2 Comparison with the geometric parameters based catheter selection

In our previous work[8,9] we have developed techniques for optimal catheter selection which is based on some geometric parameters (curve angle, curve length etc). There, we assumed catheters and arteries to be rigid objects. We also did not consider the catheter's diameter. Using the geometric parameters based approach the best catheter selection depends on the proper selection of the weights for parameters (curve angle, curve length) but in the simulation based approach we do not have to take care for such adjustments. Since the geometric parameters based approach do not consider the flexible nature of the catheters sometimes it exclude a catheter that can be used after angle adjustment. For example in Fig. 5 the RCB catheter (light blue) was excluded by the geometric parameter based approach but our current approach shows it as a second best catheter. As an advantage, the geometric parameter based algorithm is fast and the whole catheter selection decision takes one minute. But the simuation based appraoch is expected to give more accurate results.

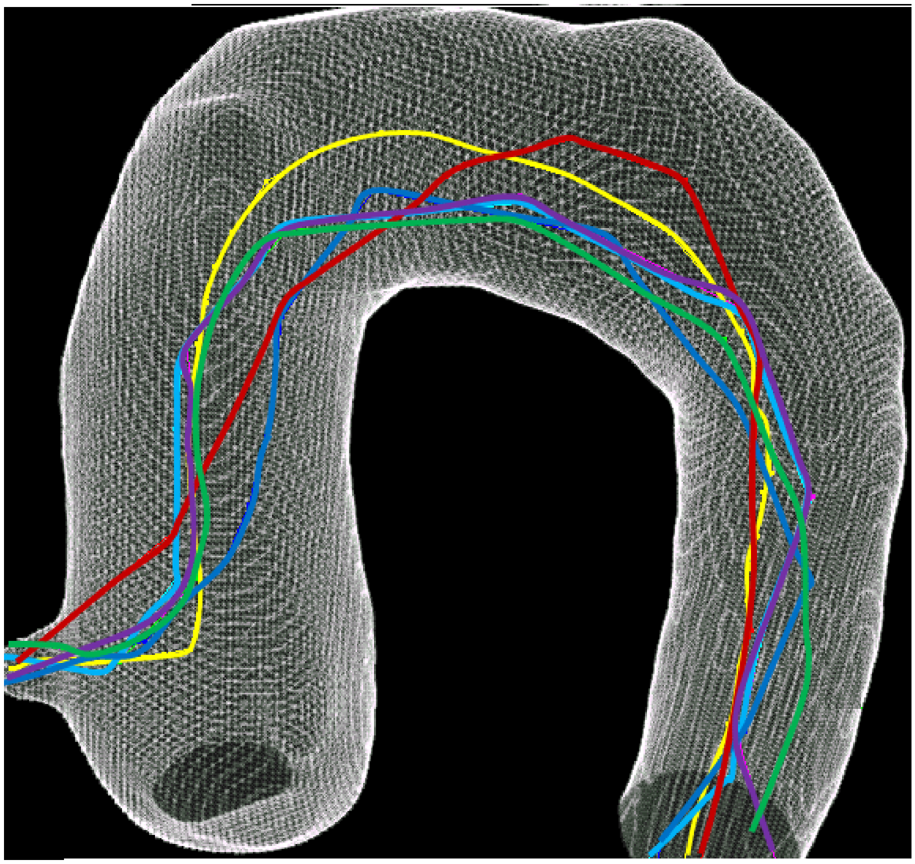

Figure 5. Catheters' position inside the arteries. The yellow line is the arteries' centerline and green line shows the optimal catheter.

4. DISCUSSION AND CONCLUSION

In this paper we presented a simulation based technique for patient-specific optimal catheter selection for right coronary angiography. This work is an extension of our previous work where we suggest a technique for patient-specific optimal catheter selection based on geometric parameters computation. In our previous work we did not consider the deformable nature of catheters and also considered the arteries as rigid bodies. In this work we simulate the catheters inside the arteries and consider its shape after deformation. We can also change stiffness of the arteries which helps to get more realistic final position of the catheters. The simulation takes more time as compared to simple parameters computation but it considers the deformable nature of catheters as well as arteries. The work is in progress and a clinical evaluation is yet to be done. We will also extend the current algorithm to handle left coronary angiography as well as abnormal arteries. This work will help (especially) inexperienced cardiologist who try six to seven catheters per patient.

5. ACKNOWLEDGMENTS

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REFERENCES

[1] P. Schneider, *Endovascular Skills: Guidewire and Catheter Skills for Endovascular Surgery*. Marcel Dekkar Inc., "second edition" ed., 2003.

[2] D. R. Kirks, C. R. Fitz, and D. C. Harwood-Nash, "Pediatric abdominal angiography: Practical guide to catheter selection, flow rates, and contrast dosage," *Pediatric Radiology* **5**, pp. 19–23, 1976. 10.1007/BF00988657.

[3] D. Kimbiris, A. Iskandrian, B. Segal, and C. Bemis, "Anomalous Aortic Origin of Coronary Arteries," *Circulation* **58**(4), pp. 606–615, 1978.

[4] A. Brinkman, P. Baker, W. Newman, R. Vigorito, and M. Friedman, "Variability of human coronary artery geometry: An angiographic study of the left anterior descending arteries of 30 autopsy hearts," *Annals of Biomedical Engineering* **22**, pp. 34–44, 1994. 10.1007/BF02368220.

[5] R. Myler, R. Boucher, D. Cumberland, and S. Stertzer, "Guiding catheter selection for right coronary artery angioplasty," *Catheterization and Cardiovascular Diagnosis* **19**, 1990.

[6] J. Voda, "Long-tip guiding catheter: Successful and safe for left coronary artery angioplasty," *Catheterization and Cardiovascular Diagnosis* **27**(3), pp. 234 – 242, 1992.

[7] K. Sarkar, S. Sharma, and A. Kini, "Catheter Selection for Coronary Angiography and Intervention in Anomalous Right Coronary Arteries," *Journal of Interventional Cardiology* **22**, pp. 234–239, 2009.

[8] E. Flehmann, S. Rahman, S. Wesarg, and W. Völker, "Towards Patient Specific Catheter Selection: Computation of Aortic Geometry Based on Fused MRI Data," in *Functional Imaging and Modeling of the Heart*, D. Metaxas and L. Axel, eds., *Lecture Notes in Computer Science* **6666**, pp. 145–152, Springer Berlin / Heidelberg, 2011.

[9] S. U. Rahman, W. Wesarg, and W. Völker, "Patient specific optimal catheter selection for right coronary artery," Proc. SPIE 7964, 796412 ; doi: 10.1117/12.878111, 2011.

[10] S. U. Rahman, W. Wesarg, and W. Völker, "Patient specific optimal catheter selection for the left coronary artery," Workshop: Emerging Technologies for Medical Diagnosis and Therapy, Informatik 2011.

[11] D. Meglan, "Making surgical simulation real," *SIGGRAPH Comput. Graph.* **30**, pp. 37–39, November 1996.

[12] J. Anderson and R. Raghavan, "A vascular catheterization simulator for training and treatment planning," *Journal of Digital Imaging* **11**, pp. 120–123, 1998. 10.1007/BF03168278.

[13] Y. Wang, C. Chui, H. Lim, Y. Cai, and K. Mak, "Real-time interactive simulator for percutaneous coronary revascularization procedures," *Computer Aided Surgery* **3**(5), pp. 211–227, 1998.

[14] W. L. Nowinski and C.-K. Chui, "Simulation of interventional neuroradiology procedures," in *Proceedings of the International Workshop on Medical Imaging and Augmented Reality (MIAR '01)*, *MIAR '01*, pp. 87–, IEEE Computer Society, (Washington, DC, USA), 2001.

[15] J. Lenoir, P. Meseure, L. Grisoni, C. Chaillou, and Christophe, "Surgical thread simulation," 2002.

[16] T. Alderliesten, M. K. Konings, and W. Niessen, "Simulation of minimally invasive vascular interventions for training purposes," *Computer Aided Surgery* **9**(1-2), pp. 3–15, 2004.

[17] S. Cotin, C. Duriez, J. Lenoir, P. Neumann, and S. Dawson, "New approaches to catheter navigation for interventional radiology simulation," in *In: Proceedings of medical image computing and computer assisted intervention (MICCAI), Palm*, pp. 300–308, 2005.

[18] J. Lenoir and S. Cotin and C. Duriez and P. Neumann, "Interactive physically-based simulation of catheter and guidewire," *Computers and Graphics* **30**(3), pp. 416 – 422, 2006.

[19] V. Luboz, R. Blazewski, D. Gould, and F. Bello, "Real-time guidewire simulation in complex vascular models," *The Visual Computer* **25**, pp. 827–834, 2009. 10.1007/s00371-009-0312-x.

[20] V. Luboz, J. Zhai, P. Littler, T. Odetoyinbo, D. Gould, T. How, and F. Bello, "Endovascular guidewire flexibility simulation," in *Biomedical Simulation*, F. Bello and S. Cotin, eds., *Lecture Notes in Computer Science* **5958**, pp. 171–180, Springer Berlin / Heidelberg, 2010. 10.1007/978-3-642-11615-5-18.

[21] W. J. Schroeder, K. Martin, and W. Lorensen, "The visualization toolkit: An object-oriented approach to 3d graphics, third edition," 01 2003.

[22] J. Allard, S. Cotin, F. Faure, P.-J. Bensoussan, F. Poyer, C. Duriez, H. Delingette, and L. Grisoni, "SOFA an Open Source Framework for Medical Simulation," in *Medicine Meets Virtual Reality (MMVR'15)*, (Long Beach, USA), February 2007.