HEART AND BLOOD FLOW SIMULATION USING POSITION BASED DYNAMICS

Thanandon Imaromkul[†] Makoto Fujisawa[†] Masahiko Mikawa[†]
[†]University of Tsukuba

ABSTRACT

Cardiovascular Disease (CVD) is considered to be the common cause of death in several counties while the necessity of experienced cardiologists is at its peak. The fate of the patients depends sorely on how well-equipped the personnel and the hospitals are to overcome the clinical issues. Still, it can take a substantial amount of time for the practitioners to perfect their skills, even more so for rookies who just entered this daunting field. Hence, an educational oriented tool will undoubtedly assist the newcomers in this critical profession. This paper aims to utilize a recent simulation technology namely "Position Based Dynamic" or PBD method to visualize the mechanism and phenomenon of the muscle and blood inside the human heart, including the heart muscle movement, the blood current and the interaction between them. Then an evaluation interview was conducted with a medical professor to review the simulated animation. As a result, the system had proven the concept of using PBD to create an educational oriented system for medical undergraduates has been proven plausible.

Keywords: Blood Flow Simulation, Fluid Simulation, Position Based Dynamics, Cardiovascular Disease

1. INTRODUCTION

Following the WHO definition, "Cardiovascular disease" refers to the group of disorders in heart and blood vessels [15, 1, 12]. These diseases can lead to a heart attack or stroke if left untreated. There are several common cases of CVDs. According to the report from World Health Organization or WHO, despite the growth of medical technology nowadays, CVDs are the number one cause of death globally, approximately 17.9 million people died in 2016 and 85% of the deaths were due to heart attacks and strokes [15]. Another recent statistic report form the American Heart Association had shown that in America, people die from CVDs roughly every 42 seconds [7]. Furthermore, [4] pointed out that CVDs are mainly caused by the malfunctions or defects discovered in the left ventricle chamber of the heart and it is vital for the practitioner to give it the highest inspection priority [4].

Recognizing the conditions requires an extensive amount of knowledge and experience from the doctors. Also, in the case of American, the need for the new generations of cardiologists is substantially high because of the growing demands and the geographic maldistribution of the services in the underserved area [9]. In the same manner with the rest of the world, it is crucial to rapidly train new medical trainees and students to become professionals as fast and as efficient as possible [14]. Heart muscle and blood flow analysis is vital for doctors and cardiologists. Even though there are tools for such analytical operations, most of those tools are aiming for advanced users which makes it challenging for early in-training students to access.

Therefore, the purpose of this research is to explore the possibility of developing this most desired tool. The system is required to be

- **Easy to use**: Medical students must be able to intuitively use the software with ease.
- **Interactive**: The software must respond to the students' configuration in real time.
- **Moderately accurate**: Since education is the aim of this system, the results must be realistic enough to not mislead the students.

The contribution of this research is to investigate the feasibility of using a modern simulation technology namely "Position Based Dynamic" or PBD to create an educational heart and blood simulation system for medical students. The rest of this paper is organized as follows. Related works and PBD are reviewed in section 2. The proposed method and the results are presented in sections 3 and 4. Finally, the evaluation and discussions will be shown in section 5 and 6.

2. RELATED WORKS

Heart and blood simulation is one of the active fields in Computer Graphics and continues to gain more popularity. Still, most of the researches are either focusing on the heart model simulation or the blood flow simulation, research that emphasis on combining the two are yet to be found.

Heart model simulation essentially falls under the domain of elastic simulation in the field of Computer Graphic

which there are numerous techniques for. [8] proposed an interactive method to construct a deformable heart model. The research offers a solution to simulate the model of a patient's heart based on an MRI scan. The constructed model represented the heart very accurately and the system allows the user to interact with the model, e.g., tissue cutting and pinning with ease. Another research [2] offers an alternative surgical cutting system for human muscle and tissue. The solution utilizes a contemporary graphic simulation technique called Position Based Dynamics or PBD in order to provide a fast and accurate simulation of electrosurgery. The solution in this paper offers not only the simulation of the deformable tissues but also the simulation of the surgical cutting in an interactive environment. However, these researches still haven't included the integration of blood flow simulation yet.

Blood flow simulation falls under fluid simulation in Computer Graphics. In this area, Computational Fluid Dynamics (CFD) seems to be the most respected method. A review paper [4] clearly addressed the state of art of heart blood flow simulation. The paper reviewed over 31 highly accurate blood flow simulation techniques that centered around CFD. Almost all of them use an MRI scan while the rest use CT-scan. Despite that, the paper informed that the methods are still not clinically applicable due to the limitations on computational time and the fact that some important phenomenon cannot be integrated into the simulation still.

In CFD, Smoothed Particle Hydrodynamics or SPH offers a much faster solution [6]. [10] reviewed the application of SPH in simulating the mechanism of biological tissue. It is also notable that all of the mentioned researches not interactive and presented their result in blood current and blood velocity chart rather than in fluid particles.

3. PROPOSED METHOD

In our method, there are 4 main components to be considered; (3.1) Heart model simulation, (3.2) Blood simulation, (3.3) Cardiac cycle simulation and (3.4) Heart and blood penetration detection, which will all be discussed in this section.

Initially, the system will try to predict the new position $\mathbf{x}^*$ based on the new velocity $\mathbf{v}^*$ which computed by adding the previous velocity $\mathbf{v}^t$ with the multiplication of the timestep Δt and external force f. Then, the movement of the cardiac cycle will be simulated. The heart model will deform according to the cardiac rhythm. If $\mathbf{x}^*$ of any particle penetrates the model, it will be corrected during the heart and blood penetration detection step. Next, all collisions and constraints will be managed, $\mathbf{x}^*$ and $\mathbf{v}^*$ will again be updated accordingly. Finally, the system stores the $\mathbf{x}^*$ and $\mathbf{v}^*$ as the current position $\mathbf{x}^{t+1}$ and velocity $\mathbf{v}^{t+1}$ of the timestep $t+1$.

These steps will be repeated for the whole simulation. In PBD, the animation properties of the models are controlled by employing constraints. Thus, designing them is a very crucial element of this research. The constraints are classified and explained in the next section.

3.1. HEART MODEL SIMULATION CONSTRAINTS

The deformable constraints will be applied to the heart model to achieve the soft and non-rigid property of the heart tissue.

3.1.1. Tetrahedron volume conservation constraint

The heart model in this research will be comprised of tetrahedron meshes. This constraint aims to conserve and maintain the volume of the mesh in the heart model to hold their structure. The equation is listed below;

$$C(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4) = \frac{1}{6}(\mathbf{x}_{2,1} \times \mathbf{x}_{3,1}) \cdot \mathbf{x}_{4,1} - V_0 \quad (1)$$

$$V_0 = \frac{1}{6}(\mathbf{x}_{rest_{2,1}} \times \mathbf{x}_{rest_{3,1}}) \cdot \mathbf{x}_{rest_{4,1}} \quad (2)$$

where $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4$ are the four vertices or corners of the tetrahedron and $\mathbf{x}_{i,j}$ represent the edge vector for the vertex i and j (ex, $\mathbf{x}_{2,1} = \mathbf{x}_2 - \mathbf{x}_1$). V_0 is the volume of the mesh at rest state which can be calculated by using equation (2) where $\mathbf{x}_{rest_1}, \mathbf{x}_{rest_2}, \mathbf{x}_{rest_3}, \mathbf{x}_{rest_4}$ are the four vertices of the tetrahedron at rest state [5].

3.1.2. Triangle face area conservation constraints

Besides the mesh volume, the surface area of the triangles that are representing the mesh has to also be maintained. The constraint is listed below.

$$C(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) = \frac{1}{2}|\mathbf{x}_{2,1} \times \mathbf{x}_{3,1}| - A_0 \quad (3)$$

$$A_0 = \frac{1}{2}|\mathbf{x}_{rest_{2,1}} \times \mathbf{x}_{rest_{3,1}}| \quad (4)$$

where $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3$ are the three vertices of the triangle and A_0 is the area of the triangle at rest state which can be calculate by using equation (4).

3.2. BLOOD SIMULATION CONSTRAINTS

This research uses particles to represent the blood fluid and adopts 3 main constraints consisting of collision with environment, collision with particles, and density constraints. However, only density constraints will be explained in this paper since it is the most prominent constraint for simulating blood. Besides, this research also utilizes XSPH with an implicit solver to introduce the viscosity effect or the stickiness of the blood [13].

3.2.1. Density Constraints

In order to accomplish realistic fluid behavior, density conversation is also a notable aspect to consider. Assuming that the mass of each particle m_i is constant and a constant density ρ represents the volume conservation. Hence, a constraint for the fluid density ρ can be introduced as;

$$C(\mathbf{x}_1, \ldots, \mathbf{x}_n) = \frac{\rho_i}{\rho_0} - 1 \tag{5}$$

where ρ_0 is the density of the fluid at rest state and ρ_i is the volume at the particle i which defined as the sum of smooth kernels of the surrounded neighbor particles [6].

$$\rho_i = \sum_j m_j W(\mathbf{x}_i - \mathbf{x}_j, h) \tag{6}$$

3.3. SIMULATE CARDIAC CYCLE MOTION

There are two phases in human cardiac cycle [3]. The contraction phase where the heart shoots the blood throughout the body is called "Systole" and the relaxation phase which suggests to the moment when the muscle relaxes to allow the blood to fill the chambers is called "Diastole".

3.3.1. Ventricular Systole

In systole, the ventricular muscles contract, starting to increase the blood pressure inside the ventricle chambers and finally the pressure forces the blood to begins opening the valves which direct the blood to the atriums [3].

In order to imitate the muscle contraction, the surface particles of the heart must be explicitly shifted toward a certain point which is known as the center of the contraction. Then the accurate number of animation step should be calculated based on the actual cardiac cycle to best embody the motion.

3.3.2. Ventricular Diastole

In diastole, the ventricular muscle relaxes causes the pressure of the blood inside the ventricles to drop. When the blood pressure inside the ventricles is dropped below the blood pressure inside in the atriums, the blood from the atriums will flow passes through the valves into the ventricles [3]. This can be archived by stop applying position changes to the particles and let the programmed constraints to reset the position of the particles into their resting stage.

Fig.1 shows the result of the described algorithms. Fig.1(a) and Fig.1(b) demonstrating the end result of simulating the systole and diastole phase repectively. Note that the red circles refer to the selected beating particles that the user have selected.

(a) The heart model at the end of systole phase

(b) The heart model at the end of diastole phase

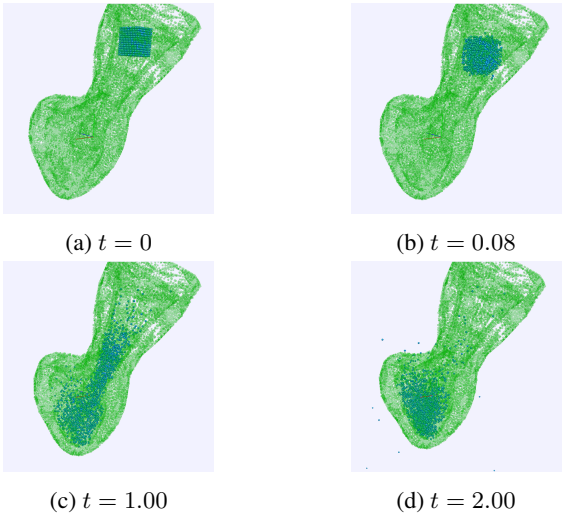
Figure 1: Simulation results

3.4. HEART AND BLOOD PENETRATION DETECTION

In order to test the penetration of a particle against a tetrahedron, the system use Plücker coordinates to calculate the face that the particle enters the tetrahedron and the intersection point [11] for correction.

4. RESULTS

The simulation will be presented in four different timestep $t = \{0, 0.08, 1.0, 2.0\}$ as shown in Fig. 2.



(a) $t = 0$ (b) $t = 0.08$

(c) $t = 1.00$ (d) $t = 2.00$

Figure 2: Result of the heart and blood simulation

5. EVALUATION

After implementing the proposed method, another 40 minutes interview was conducted. The interviewee was the same medical professor who provided the consultation about this educational tool in the preliminary section. Conclusively, the interviewee agrees that the platform got potentials and the simulation was quite genuine, though he suggested that it would be more promising to observe real pa-

tient's heart models from CT or MRI scans and simulating multiple cardiac cases, normal and abnormal.

6. CONCLUSION AND FUTURE WORKS

As a result, the 3D human heart and blood simulation proof-of-concept engine proposed in this research has shown a considerable amount of potentials. The platform can simulate the deformable heart model, blood flow and the interaction between the two in an interactive environment, additionally, with a feature to manipulate how the heart should behave in the cardiac cycle. With all of these in mind, the concept of using PBD to create an educational oriented system has been proven plausible. Thus, with time and effort, such an innovative tool is absolutely possible.

There are still a number of limitations in this research. Further study has to be done to elevate the result to be even more realistic and educative, e.g., utilizing the CT or MRI scan of the patient's heart for a more detailed and precise model, and simulating abnormal cases in comparison with the normal ones as stated in the previous section. More noticeably, the interaction between the heart model and blood flow is still one-sided. The interaction presented in this research only considers the forces that the deformable object applies to the fluid particles, but the forces that the fluid particles apply to the object is still overlooked. This fluid and deformable object interaction issue is still ongoing in the field of PBD.

7. ACKNOWLEDGMENT

I would also like to express my gratitude to Professor Thanongchai Siriapisith, Medical Professor, Department of Radiology, Faculty of Medicine, for all of his precious opinions and suggestions he gave in both of the interviews conducted in this research.

REFERENCES

[1] American Heart Association. *What is Cardiovascular Disease?* May 2018. URL: https://www.heart.org/en/health-topics/consumer-healthcare/what-is-cardiovascular-disease.

[2] Jan Bender, Matthias Müller, and Miles Macklin. "Position-Based Simulation Methods in Computer Graphics." In: *Proceeding of Eurographics 2015 - Tutorials*. 2015.

[3] J.G. Betts. *Anatomy & Physiology*. OpenStax College, Rice University, 2013. URL: https://books.google.co.jp/books?id=st7ZvAEACAAJ.

[4] Siamak N. Doost et al. "Heart blood flow simulation: a perspective review". In: *BioMedical Engineering OnLine* 15.1 (Aug. 2016), pp. 101:1–101:28. ISSN: 1475-925X. DOI: 10.1186/s12938-016-0224-8. URL: https://doi.org/10.1186/s12938-016-0224-8.

[5] Miles Macklin et al. "Unified particle physics for real-time applications". In: *ACM Transactions on Graphics (TOG)* 33.4 (2014), pp. 153:1–153:12.

[6] Joe J Monaghan. "Smoothed particle hydrodynamics". In: *Annual review of astronomy and astrophysics* 30.1 (1992), pp. 543–574.

[7] Dariush Mozaffarian et al. "Heart disease and stroke statistics-2016 update a report from the American Heart Association". In: *Circulation* 133.4 (2016), pp. e38–e48.

[8] Kazutaka Nakashima et al. "Interactive deformation of structurally complex heart models constructed from medical images". In: *Proceedings of Eurographics 2016*. 2016, pp. 49–52.

[9] Akhil Narang et al. "The supply and demand of the cardiovascular workforce: striking the right balance". In: *Journal of the American College of Cardiology* 68.15 (2016), pp. 1680–1689.

[10] Andrey Palyanov, Sergey Khayrulin, and Stephen D Larson. "Application of smoothed particle hydrodynamics to modeling mechanisms of biological tissue". In: *Advances in Engineering Software* 98 (2016), pp. 1–11.

[11] Nikos Platis and Theoharis Theoharis. "Fast ray-tetrahedron intersection using plucker coordinates". In: *Journal of graphics tools* 8.4 (2003), pp. 37–48.

[12] Sandhya Pruthi. *Heart disease*. 2018. URL: https://www.mayoclinic.org/diseases-conditions/heart-disease/symptoms-causes/syc-20353118 (visited on 03/22/2018).

[13] Volker Springel. "Smoothed particle hydrodynamics in astrophysics". In: *Annual Review of Astronomy and Astrophysics* 48 (2010), pp. 391–430.

[14] Nick Townsend et al. "Cardiovascular disease in Europe: epidemiological update 2016". In: *European heart journal* 37.42 (2016), pp. 3232–3245.

[15] World Health Organization. *Cardiovascular diseases (CVDs)*. May 2017. URL: https://www.who.int/en/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds).