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Haptic Reproduction and Interactive Visualization of a Beating Heart Based on Cardiac Morphology

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Abstract

A goal of this work is proposal and construction of simulation methods of haptic reproduction and interactive visualization of a beating heart in cardiovascular surgical training and education. The data for the beating heart model was obtained from ECG-gated 3D MRI of a normal volunteer. The elastic information was assumed as a uniform value with clinically experienced elasticity. Using a real-time 3D graphics and a haptic device, a simulation environment of the beating heart was designed and implemented. After the construction, some cardiovascular surgeons evaluated the implemented system. Its visualization and haptic expression were scored excellent, but some details in haptic interface were remained to be improved. Finally, for more realistic cardiovascular surgical simulation, future development of the method is discussed.

Keywords:

Cardiac Simulation, Haptics, Interactive Visualization, Medical Education, Surgical Training

Introduction

In the medical field, various surgical procedures have been created and developed. Especially in recent days, minimally invasive surgery and robotic surgery also appeared. As a result of rapid advance in medical technologies, surgical education and training as a subset of graduate medical education has drawn increasing interest.

To satisfy above interest and requirements, virtual reality techniques have been focused. [1] The visual and interactive environment using VR technique has proven to be useful in understanding complex 3D structures and for training. [2][3] The manipulations such as navigation, palpation and surgical procedures are performed through haptic interfaces. [4][5] If constructed system generates realistic force like that of real tissues to the users, it also contributes to medical education as surgical simulators. [6] Haptic information during cardiovascular surgeries is very important for diagnosis and design of surgical strategies. As to surgical procedures in a surgery of cardiac tamponade, for example, it should be required that a surgeon inserts a thin pipe between myocardium and pericardium under the condition of the heart beating. This operation is a difficult example for surgeons, because delicate procedures are required to treat the heart directly. For these requirements, if a novel simulation environment to reproduce tactile sense of beating heart is constructed, safer operation can be realized by repeating rehearsal of the surgery. In addition, a system that simulates the motion of cardiac muscles and valves with haptics allows medical students and surgeons to learn palpation objectively.

On the other hand, it has been difficult to measure morphological information of entire cardiac cycle, because the heart is an active organ and has dynamic motion. Due to the complexity of cardiac dynamics including various variables such as myocardial motion, cardiac excitation, blood pressure and so on, it was difficult to describe and simulate its function faithfully. In addition, study of cardiac dynamics requires analysis of multi-dimensional variables and complex parameters. Therefore, in the field of computer-assisted simulation, few studies have ever tried to describe and simulate tactile sense of beating heart based on in vivo datasets. [7] On the contrary, this paper gives a cardiac force model and simulation methods for haptic reproduction and interactive visualization of beating heart based on cardiac morphology. And using a real-time 3D graphics and a haptic device, a simulation system of the beating heart is designed and implemented.

Materials and Methods

As heart dataset, time series of volumes of entire heart cycle are successfully acquired from a normal volunteer from ECG-gated 3D MRI. One research goal of this study is the proposal of dynamic force description of heartbeat for realistic tactile reproduction, from time series heart morphology. In addition, based on proposed force description, a visible and palpable simulation system is constructed for the purpose of interactive analysis, medical education and surgical training. The characteristics and functions of the system are summarized below.

- Four-dimensional (spatial and temporal) heart atlas
- Haptic reproduction based on cardiac morphology
- Interactive visualization and analysis

A constructed graphic and haptic simulation of a beating heart is named "ActiveHeart System". In this section, the methods of data preparation, data registration, force model, visualization and system implementation are described.

Heart datasets and Registration

The heart datasets are 15 time series chest formed volumetric data of a normal volunteer from ECG gated MRI technique, and one volume consists of 256*256*64 voxel. The resolution of the data is 1mm for horizontal direction and 3mm for vertical direction and 50 msec for time. One slice image is shown in the figure1.

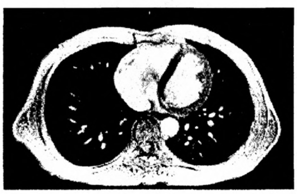

Figure1. One slice MRI image

After semi-automatic region extraction using a region-growing technique from surrounded tissues, time series heart formed volumes were acquired. Figure2 is the slice image after segmentation.

Figure2. After region extraction

To describe cardiac dynamics from volumetric heart data, a volume registration method using space digitizing approach was taken. In this case, 1.0mm*1.0mm*3.0.mm space was applied to one voxel based on space resolution of heart data. Then, considering the spatial size of heart data, a definite space in the real world was assigned to one volume. As a result of this registration method, 25.6cm*25.6cm*19.2cm area was defined as a virtual workspace to reproduce a four-dimensional heart object.

Force Models

The main subject of this study is how to reproduce realistic tactile sense of a heartbeat from time series heart dataset. Since conventional computer-assisted simulation dealt with static organs like the liver or leg, it was important to consider how to reproduce passive stress only against the movement of the user's hand interactively. [8][9] In this study, however, another description must be given for tactile reproduction because the in-vivo beating heart is an active organ.

In this paper, cardiac dynamics is described using two – step force model: one model is static for passive stress by pushing cardiac muscle, and another model is dynamic for active pressure by cardiac autonomous diastole. In other words, static model simulates stiffness of myocardium of a static heart, and dynamic model simulates active force feedback of a beating heart.

Static Model

The registration method makes the collision detection algorithm more precise and attains realistic force feedback time rate. Figure3 illustrates static force description.

Figure3. Static Force Model

[STEP1] A position of user's hand (user point) in the real space that means a position of stylus point of the haptic device is mapped onto absolute coordinate of the workspace.

[STEP2] If the user point is mapped on the part of heart data, this situation means "contact." Like this, accurate and simple collision detection can be realized, because it doesn't need to calculate a distance between user's hand and the object.

[STEP3] After collision detection, if a user moves his or her hand into the heart object, passive stress is generated in proportion to the distance from the contact point. As for force calculation, elastic coefficient was assumed as a uniform value with clinically experienced elasticity.

Dynamic Model

Constructed virtual space using the space digitizing method can be applied to active pressure description. Figure4 illustrates active force description for dynamic myocardial motion.

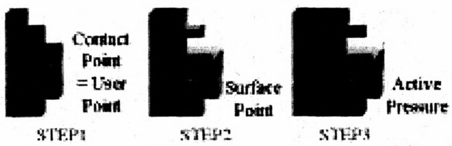

Figure4. Dynamic Force Model

[STEP1] It supposes that a user is touching the heart, that is, a user point is on the surface of virtual heart object.

[STEP2] In this case, it is not a user point but a heart object that moves in this virtual space. If heart surface moves to the user point, the user point is temporally inside the beating heart object.

[STEP3] Then, by the same way as static model, active pressure is generated in proportion to the distance from the user point to the scanned surface point.

Based on the force description using two-step model, active force is generated at cardiac diastole. However, there is still one definite problem, that is, time resolution of generated time series force. If generated 15-frames/second dynamic forces were presented, a user feels it is an awkward force expression. To solve this problem, the time series force value was complemented linearly, and generated 1000-frames/second dynamic forces. [10] Figure5 shows one example of time series force values of the left ventricle after smoothing.

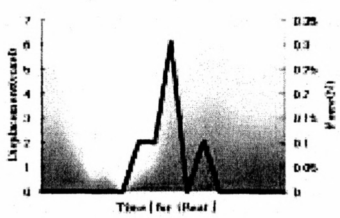

Figure5. Time series of force value of the left ventricle

Visualization

There was still another subject, that is, how to generate real-time and interactive images or animations of a beating heart. To achieve interactive functions such as rotation, scale change and cutting, time series volume dataset need large calculation time for volume rendering. This work solved these problems and achieved refresh time rate for real-time rendering, using rendering hardware, parallel computing and synchronized process mechanism. And various interactive operations came to be realized by providing graphical user interface.

System Overview

The ActiveHeart system was constructed using a PHANToM haptic device, Windows NT PC, graphic user interface and rendering hardware. As shown in Figure6, the ActiveHeart system has a graphic part and a haptic part. In the haptic part, movement of the user's hand is transmitted though the PHANToM haptic device. And this system calculates force by the user's position information and returns force value to PHANToM. In the graphic part, the user's operative information, such as rotation, is transmitted to the rendering hardware. On the rendering board, real time rendering is done and the time series rendered images are displayed as heart animation through the graphic user interface.

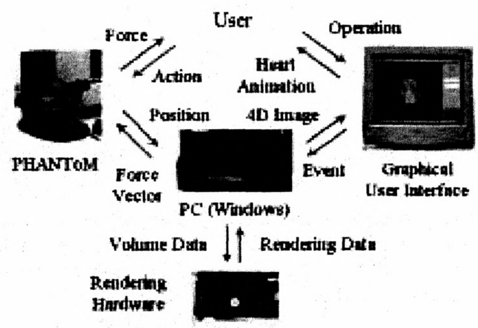

Figure6. The overview of the ActiveHeart System

Results

Figure7 shows a graphical user interface of the implemented simulation system. Figure 8 shows the results of haptic reproduction and interactive visualization of a beating heart. Upper images illustrate haptic expression of the left ventricle. User point is described as a sphere image and line images show generated dynamic force vector. Lower images illustrate real time visualization of inner organs and blood flow.

Some cardiovascular surgeons evaluated the system. By the surgeons, generated tactile sense is the same as that of experienced elasticity in cardiac palpation. Consequently, both beating expression and visualization scored excellent, but some details in haptic expression were remained to be improved.

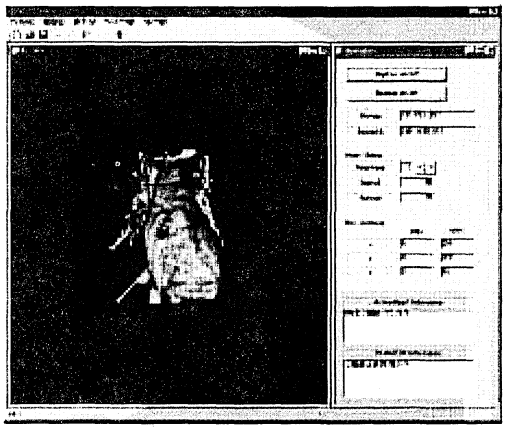

Figure 7. Graphical user interface

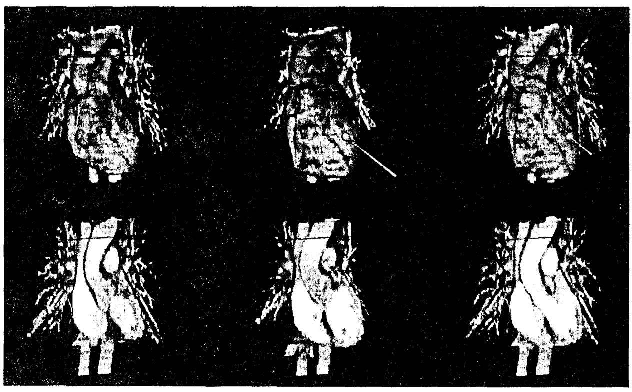

Figure 8. Haptic reproduction and interactive visualization of a beating heart

Discussion

For visible and palpable educational system including various heart diseases, we are now developing the interface and adding heart pressure to this system. And, for more realistic cardiovascular surgical simulation, the system should support other functions like stereoscopy, multiple haptic interfaces, and adding other clinical parameters. In the near future, however, we believe this system will be available for medical education for palpation and basic surgical training in procedures such as intra-cardiac catheter ablation.

Conclusion

This work provided dynamic force description about active force and passive stress based on cardiac morphology. Based on above two-step methodology, force feedback algorithm was described and implemented as ActiveHeart system using rendering hardware and haptic interface. System processes by parallel computing were also developed to optimise and synchronize graphics and haptics. Consequently, constructed simulation environment performed realistic haptic reproduction and real time visualization of a beating heart.

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