A visually guided spine biopsy simulator with force feedback

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ABSTRACT

A new surgical simulator is developed for spine needle biopsy, that provides realistic visual and force feedback to a trainee in the PC environment. This system is composed of four parts: a 3D human model, visual feedback tool, force feedback device, and an evaluation section. The 3D human model includes multi-slice XCT images, segmentation results, and force-feedback parameters. A block-based technique is adopted for efficient handling of large amounts of data and for easy control of rendering parameters such as opacity. For visual feedback, we implement a virtual CT console box and a 3D visualization tool providing MIP, MPR, summed voxel projection, and realistic 3D color volume rendering view. The visualization tool is for interactive 3D path planning. A haptic device is used to provide force feedback to the biopsy needle during simulation. The interactive force is generated in a voxel-based manner. After each simulation, the evaluation section provides a performance analysis to the trainee. We implemented the system by attaching a 3 DOF PHANTOMTM device to a PC with 600MHz Pentium III Dual CPUs and 512Mbyte RAM.

Keywords: Simulator, Spine biopsy, 3D human model, Visual feedback, Force feedback, Volume rendering, Segmentation, Haptic device

1. INTRODUCTION

Nowadays there are long strides in medical simulators that help the acquisition of medical skill and knowledge. Two major changes have taken place compared with previous simulators. One is use of 3D graphics in a user interface, and the other is force feedback during simulation. As typical examples of these changes, Yamashita et al. developed a navigation system for endoscopic paranasal sinus surgery, which uses a 3D head model for intuitive navigation [1]. And Reinig et al. implemented an algorithm to provide a realistic feeling of surgical cutting, for visually and haptically accurate surgical simulation [2]. Among various surgical operations, a spine needle biopsy is a useful non-invasive operation used to detect and verify a spine tumor. During this procedure, a tissue is to be extracted from the spine of a living body using a hollow needle. However, since there are many critical organs near the spine, the spine needle biopsy operation requires complicated and accurate procedures. Hence, a lot of training is essential for reliable operations and the need for a simulator is naturally stressed. Singh and Popa measured the force from the needle during a needle biopsy and tried to generate similar force-reflection in the needle biopsy simulation [3,4]. Cleary developed a 2D spine needle biopsy simulator using the PHANTOMTM device [5].

In this paper, we introduce an advanced surgical simulator for spine needle biopsy, that provides realistic visual and force feedback to a trainee in the PC environment. Contrary to a conventional spine biopsy simulator, the proposed simulator provides 3D visualization that helps a user to understand the 3D structure around a lesion, and an oblique section display that is convenient to plan a 3D path for inserting the needle. In addition, the system visualizes actual needle movement on the display screen in real-time, and also provides realistic force feedback using an advanced force model that is suitable for needle biopsy. We implement the system by attaching a 3 DOF PHANTOMTM device to a PC that has 600MHz Pentium III Dual CPUs and 512Mbyte RAM. The rest of the paper is organized as follows. First, we present the structure of the simulator in detail in Section 2. The 3D human model, visual feedback part, force feedback part, and evaluation part are described. In section 3, we present the simulation procedure and the corresponding simulation results. Finally, conclusions will be provided in Section 4.

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2. DESCRIPTION OF THE SYSTEM

The proposed spine biopsy simulator consists of four modules, namely, 3D human model, visual feedback, force feedback, and evaluation parts.

2.1 THREE-DIMENSIONAL HUMAN MODEL

A large number of 2D X-ray CT body images are prepared for constructing a 3D human model. Organs to provide visual and force feedback were selected through order of importance by several radiologists. In the thoracic vertebra region, bones, lungs, esophagus, arteries, skin, muscles, and fat are selected as meaningful organs. For the lumbar vertebra region, veins and kidneys are additionally chosen. Therefore, in total, nine organs are used for the 3D human model.

The selected organs are segmented for their modeling so that they can provide information for visual and force feedback, and miscellaneous medical information needed for simulation. We adopt three different methods for effective segmentation. First, an automatic approach is used for segmenting organs that have a definite border from surrounding environments in CT images. It shows good results in segmenting bones, lungs, skin, muscles, and fat by using the hierarchical watershed algorithm [6]. Second, a semi-automatic approach is adopted for segmenting organs that have a definite boundary in some slices and have an ambiguous boundary in others. To clarify the ambiguous boundaries, an object-tracking method is adopted which is similar to that in video coding. This method can find a plausible segmentation result even on slices that have ambiguous borders. It shows good results in kidney segmentation [7]. Finally, for organs having ambiguous borders from surrounding environments, such as the esophagus, arteries, and veins, the manual approach is adopted. For this approach, the system provides an interactive tool for efficient manual segmentation. Contrary to the conventional manual segmentation tool, the tool provides over-segmentation results for a given slice and helps the user to simply merge the over-segmented results. After the merging procedure, its user interface enables the doctor to manually refine the border of the target organ. The merging-and-refining approach increases work efficiency and improves the precision of segmentation results [8].

The 3D human model consists of two types of data, namely, common data and individual data. All voxels have common data such as CT density, normal vector, gradient, and segmentation results. These common data are mainly used in the visual feedback part, while the segmentation data are also used for the force feedback part. And individual data are assigned to organs rather than voxels. Each organ is represented by data such as rendering parameters (color, opacity), force parameters (spring constant), etc. In the proposed 3D human model, we use 335 XCT slices having an intra-slice resolution of 0.7mm and an inter-slice resolution of 1mm.

2.2 VISUAL FEEDBACK PART

Visual feedback includes all the GUI (graphic user interface) of the simulation system. A trainee can visually monitor the whole procedure from this module. The system provides two types of visual feedback, i.e., a 2D virtual CT console and a 3D view.

We implement a 2D virtual CT console box that mimics the GUI and functions of a real CT system. A trainee can simulate the scanning of CT images around spine tumor candidates (Figure 1a). After scanning, obtained axial images are displayed as in a conventional CT console box, in order to inspect tumor candidate areas in detail. The trainee can display images by either 1x1, 2x2 or 4x4 (Figure 1b). Various kinds of analysis tools are provided for finding the distance between two points, measuring the angle between two lines, zooming a specific region of a CT image, etc.

In the 3D view, a 3D path planning tool and a virtual experiment tool are provided. As shown in Figure 2, the 3D view consists of MPB images (axial, sagittal, coronal), an oblique section image, and a 3D visualization image. Especially for 3D visualization, a trainee can select one image among the color volume rendering image, gray volume rendering image, maximum intensity projection (MIP) image, and summed voxel projection (SVP) image. Unlike previous simulators, it supports a realistic 3D volume rendering view interactively as the user moves the needle, and also provides the oblique section image for easy 3D path planning.

2.2.1 MPB

Multi-Planar Reformatting (MPR) can help a user to understand CT volume information by providing the axial image orthogonal to the z-axis of the patient coordinate system, the sagittal image orthogonal to the x-axis, and the coronal image orthogonal to the y-axis. It has been a fundamental tool for presenting 3D information indirectly in the conventional 2D simulator. Especially, our MPR view can be interpreted as a kind of navigation tool, because when the user moves the needle, the MPR images including the needle tip are interactively displayed. In addition, the virtual needle is overlaid on the MPR images and its relative location is provided. Therefore, we can continuously monitor the current needle position based on a planned 3D path, which is represented by the projected line. Using this overlaying information, we can acquire visual feedback during the simulation, regarding the current needle position compared to the planned needle path.

2.2.2 Oblique section display

In the current 2D biopsy treatment, the path of the needle is usually determined only on the axial plane, which coincides with the CT scanning direction. Hence, the path can be easily planned in advance of the procedure and checked by CT in the middle of the procedure. However, in the 2D case, doctors have to confine the needle proceeding direction within a 2D axial plane because the operation should mostly be performed on an axial plane. So doctors cannot help but find a local 2D solution for the needle path problem instead of the 3D global solution. Therefore, the planned path would be longer than the optimal path, or the patient might be burdened.

In our developed system, 3D needle path planning is made possible by introducing an oblique image to the user interface. 3D planning starts from taking multi-slice axial CT images around the lesion. From this CT volume information, oblique images with a tilting angle of $-15^{\circ} \sim 15^{\circ}$, are provided to the user. Hence, the user examines each oblique image to find the best path, which is short, safe, and easily accessible. It is shown in Figure 3 that a better needle path is found in the oblique image with an angle of 13.2° than in the axial image. Since oblique CT images can be directly scanned with a tilted angle of $-15^{\circ} \sim 15^{\circ}$ by most CT systems, the selected path can be checked during the procedure through simple 2D CT scanning.

2.2.3 Volume rendering image

In the proposed system, a volume-rendering image is also provided for effective path planning and examining. During the spine biopsy operation, the needle should not touch any important organs near the spine, such as lungs, kidneys, vessels, etc. Therefore, to effectively examine relative locations of organs in the rendered image, a volume rendering algorithm should separately handle the spine and organs around it. In order to provide the best visualization for 3D planning or tracking of a needle path, the algorithm should also produce an image easily in spite of the user changing rendering parameters (such as opacity and color) of organs during the simulation.

For this purpose, we have developed a volume rendering algorithm providing high quality images without any specific hardware accelerator. The algorithm uses block-based shear-warp factorization and utilizes segmentation information to handle each organ separately [9]. In addition, it drastically reduces the rendering time by ignoring blocks of no interest based organ segmentation information. Hence, the algorithm can change the viewing angle and needle location interactively. Unlike previous volume rendering methods that suffer from a heavy computational burden for changing an opacity mapping function, the proposed algorithm can easily change opacity by dividing volume data into small blocks without run-length encoding.

2.2.4 MIP and SVP image

Among various 3D visualization methods, maximum intensity projection (MIP) displays the maximum value encountered along each ray through the volume. MIP provides more detailed texture than the volume rendering or surface rendering image. Especially, MIP has an advantage in visualizing the bone structure in CT and blood vessels in CT angiography without obstruction of fore organs. Summed voxel projection (SVP) acquires the average value corresponding to each ray. This function gives accumulated projection as in the conventional X-ray film that is familiar to medical doctors. The 3D volume rendering image can be replaced with one of these images if the user wants.

2.2.5 Needle rendering

A needle used in biopsy is made of stainless steel with a light gray color, and it has a cylindrical shape with about 15 cm in length and 1 mm in radius. We display it as a simple cylinder on the screen. Since the needle is used throughout the simulation, it has to be updated quickly enough in the rendered image. Therefore, we need a real-time rendering algorithm

for the needle. Since the needle surface is relatively simple, surface rendering with the Z-buffer having depth information is selected for visualizing the needle.

Now, fast and proper combining of the surface-rendered image of the needle and the volume-rendered image of the 3D human model is important in order to render the scene when a needle is penetrating into the body. In this system, we adopt the algorithm proposed in [10]. As mentioned above, the needle is to be rendered frequently, whereas the 3D human model does not have to be rendered that frequently since the viewing direction is usually not changed during biopsy simulation. Hence we use a masking region, where the image can be updated frequently according to needle motion. Therefore, only the masking region needs to be updated when the needle moves for a fixed viewing direction.

2.3 FORCE FEEDBACK PART

Force feedback increases reality in a simulation situation. A haptic device is used to provide force feedback through the biopsy needle to a trainee during simulation. We use a PHANToMTM haptic device and replace its stylus pen with a biopsy needle in order to implement directional and rotational forces without any additional calculation. For proper force feedback generation, we use 3D human model data that contain force feedback parameters of organs near the spine and keep the haptic device operating at 1kHz. We made a mock operation table that has the same height of a real table of a CT system and laid down a dummy on the table. Then, a trainee inserts the spine biopsy needle into the hollow dummy on the table to feel the force of the realistic environment. Figure 4 shows the physical interface of the developed system. And Figure 5 illustrates a force reflection mechanism for the needle biopsy simulator [11]. The total force (F) consists of three components: 1) the force required to penetrate tissue (F_R); 2) a correction force to keep the needle along the direction of movement (F_C); and 3) an ambient force to compensate for gravity (F_G).

$$F = F_R + F_C + F_G \quad (1)$$

2.3.1 Resistive force to tissue penetration

This force is simulated from the initial skin puncture to the touching of bone. Since the maximum force that PHANToMTM can generate is 8.5N, the device has limited ability to simulate a stiff bone [3]. In addition, since soft tissue, muscle, and fat have nonlinear properties, many experiments and analyses of their results are required for accurate modeling. In this system we adopt the Singh's tissue model and adjusted it by using our experimental data with a dead pig. Singh's experimental data were collected by needle insertion with a constant velocity of 1cm/sec [12]. The upper limit of this kind of force must be set to 6N, since PHANToMTM can only generate 8.5N as a peak value. Each tissue is modeled as a spring without damping, since the position resolution at the needle tip is low and there is limitation in simulating high damping of the haptic device [13]. To simulate a realistic force profile, stiffness is changed according to the depth of the inserted needle and the image segmentation value.

Although image segmentation classifies tissues as air, skin, muscle, lung, vein, artery, kidney, and bone, the simulated force is derived only from air, skin, fat, and bone, since these are the typical tissues penetrated by a needle in most spine biopsies. If the biopsy path touches a lung or a kidney, the force falls to zero and a red warning sign will appear on the screen. Figure 7 shows simulation results of the resistive force.

2.3.2 Correction force to simulate tissue constraint

In real needle biopsy, the motion of the needle is constrained after it is inserted to the internal tissue. Pushing the needle along its direction is relatively easy, while it is very difficult to move perpendicular to the needle direction. Since PHANToM (version 1.5) can only generate translational haptic forces (and not torques), an additional force is required to constrain the needle once it is inserted into the hollow dummy. To solve this problem, we make a hole at the surface of the dummy and use it as a pivot point to create rotational forces to constrain the needle along the inserted direction. First, the direction vector of the needle is computed after skin puncture. To calculate the correction force, we assume the following:

- The needle is touching only muscle or fat.
- The punctured skin position is a point and does not move.
- The rotation angle is much smaller than 1 radian.

Using these assumptions, the correction force is calculated by using the torque derived from the force at the needle tip. From experimental results, we verified that this correction force helps to keep the needle along the initial inserted direction. Figure 6 shows the simulated force that must be applied by the haptic device. Here, F_{c_sim} is derived as follows:

$$F_{c_sim} = -\frac{l_1}{l_2} F_c \quad (2)$$

2.4 EVALUATION PART

The evaluation part provides a full performance analysis to the trainee after simulation. It is designed so that a trainer can check the trainee's completion level of the simulation and the trainee can understand and overcome his/her mistakes by himself/herself. We selected possible objective evaluation items, with help from medical experts. The evaluation items are the final position of the needle tip, a list of critical organs punctured, maximum deviation from the planned path, number of trials, and the total time spent for operation. Each item is described in detail in the following.

Final position of the needle tip: This item represents the name of the final organ where the needle tip is located at the end of the simulation. If it is the target lesion, the mission is considered successful.

List of critical organs punctured: This item provides the names of critical organs the needle tip touched, with the information of contact time. Lungs, kidneys, and vessels are considered critical organs. Even if the needle tip touches a critical organ only once, the mission is considered a failure, because it implies that the trainee hurt the virtual patient seriously.

Maximum deviation from the planned path: This represents the maximum Euclidean distance from the needle tip to the planned path during simulation. If this value is large, the trainee is yet considered maladroit.

Number of trials: This value is the number of attempts and is increased by 1 when the needle tip moves backward from the lesion and then moves forward. It represents a tendency inversely proportional to the level of skill. High value signifies poor skill in simulation.

Total time spent: This represents the total time expended to perform the mission. It is also one of the important factors in evaluating the performance of a trainee.

3. SIMULATION PROCEDURE

We have implemented the system by attaching a 3 DOF PHANTOMTM device to a PC that has 600MHz Pentium III Dual CPUs and 512Mbyte RAM (Figure 8). In our system, the simulation starts with opening the 3D human model data file of a target patient, which has a size of 512 x 512 x 335. A trainee simulates CT image scanning of the patient, and selects a candidate lesion for spine tumor out of the many CT images in the 2D virtual CT console. In the 3D view, the 256 x 256 x 256 volume centered on the lesion is rendered so that the trainee can find an appropriate needle path from the skin to lesion in an oblique image without touching any critical organs as described in Section 2.

After planning, a trainee can virtually operate a needle biopsy procedure. When he or she moves a needle, the haptic device captures its movements. These captured movements are displayed in MPR images, and are surface-rendered and displayed in the volume rendering image (Figure 2). In addition, the captured movement information is used to generate force feedback via the PHANTOMTM device. According to the position of needle, the trainee can feel different force reflection. Thereby the trainee gets to become familiar with the 3D structure of the body by visual feedback and tactile feelings through the fingers by force feedback. When the needle touches the lesion with its tip, the simulation is over. During this process, the trainee naturally studies the relationship between visual and force feedback. Therefore, by training with this simulator, the trainee will be able to reconstruct the 3D structure of the body only relying on force feedback. This experience will prove to be very useful in real medical operations.

For an XCT abdomen volume data set of 256x256x256, if only the biopsy needle is moved, an update-rate is over 25 Hz. Meanwhile, if the viewpoint is also changed, an update-rate becomes about 5 Hz for visual-feedback and 1kHz for force-feedback.

4. CONCLUSIONS

A spine needle biopsy simulator with force and visual feedback has been developed. The developed system consists of 4 modules: 3D human model, visual feedback part, force feedback part, and evaluation part. Supplanting 2D needle path planning, our system provides a 3D needle path planning method by using oblique section images. As a needle penetrates through the planned path into the body, the biopsy simulator provides an intuitive and realistic way of recognizing the position of the needle. This can be done by using a 3D volume rendering tool with interactive speed and generating more realistic force reflection with advanced force models. Thereby it helps trainees to naturally understand the relationship between the two types of feedback. However, the force feedback part still has some unstability problem, which is minor but cannot be overlooked. To stabilize this problem, we may need to employ a new haptic device and controller that can generate high stiffness and large damping force, or develop a well-designed digital filter. Finally, the system provides objective evaluation items for the performed simulation so that trainees can improve their skill in the next simulation or real operation. The developed system will be useful as an educational tool for beginners in spine needle biopsy operation, and can be used as a test bed to invent new procedures or practice existing ones to obtain expertise.

ACKNOWLEDGEMENTS

This research was supported by the Korean Ministry of Information and Communication.

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Figure 1. 2D virtual CT console of the simulator.

Figure 2. 3D view of the simulator.

(a) An axial CT image and its corresponding sagittal image.

(b) An oblique CT image taken with an angle of 13.2° and its corresponding sagittal image.

Figure 3. 3D path planning by using oblique section display.

Figure 4. The developed spine needle biopsy simulator

k	Force scale, inserted length/needle length
F_P	PHANTOM generating force, $F_P = -k * F_T$
F_T	Total resistive force, $F_T = F_R + F_C$
V_i	Initial needle inserted direction vector
V_C	Current needle direction vector
C	Correction vector, $C = V_i - V_C$
F_C	Correction force for needle direction, $F_C = C * const$
F_R	Puncturing resistive force

Figure 5. Force reflection mechanism

Figure 6. Conversion of correction force

Figure 7. Simulated resistive force

Figure 8. Simulation scene.