Integrating Virtual Reality and Haptics for Renal Puncture Surgical Simulator

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Abstract—**Percutaneous nephrolithotomy is one of the most effective and invasive surgeries in renal calculi therapies. Traditional puncture training simulation is conducted by animals' organs or bench models which does not represent neither visual nor tactile clues through the actual procedure. In addition, the accuracy of the training results is also debatable due to the artificial setup. In this paper, we propose a haptically-enabled virtual reality (VR) renal puncture simulation system, which utilises a novel force model specifically for trocar needle puncture on multi-layered kidney (capsule, cortex and pyramid) simulation. The system is applied to substitute the conventional renal puncture vocational training for novice urologists. 18G trocar needle with 20 cm length punctured force feedback model is employed to evaluate the haptic rendering, where both damping force and dynamic friction force model are accurately simulated. A detailed human kidney anatomical structure reconstructed from CT images is also implemented for realistic visual and haptic rendering. The proposed virtual training simulation environment can also be implemented to simulate other kidney-related puncture training and evaluation.**

Keywords-PCNL; haptic; renal puncture; trocar needle; simulation; force model

I. INTRODUCTION

Nephrolithiasis morbidity happens to 10%-15% of world population. Among those, the relapse rate with various complications to human urinary system is also significantly high (50%) [1]–[3]. To substitute the conventional open surgery approach which brings enormous trauma and prolonged recovery time to patients, three new medical approaches have been implemented: Extracorporeal Shockwave Lithotripsy (ESWL), Ureterorenoscopy (URS), and Percutaneous Nephrolithotomy (PCNL). Among these, PCNL is recognized as the most effective procedure to stone removal (>90% stone free rate) [4], and is suitable for most sizes of renal stones, even the staghorn stones and renal stones in children and obesity people. Nonetheless the precise and accurate technical requirement for performing PCNL is extremely high, and is a major challenge for many urologists. During PCNL, fluoroscopy is used to monitor the procedure, and an 18-gauge diamond-tripped trocar needles medial to posterior axillary line is penetrated into the human trunk and broke into renal capsule, across the renal cortex and pyramid, and eventually reach the target calyx [5]. Figure 1 shows the structure of human kidney, it is clearly demonstrate that kidney is a rich blood supplying organ. (20%-25% of total cardiac total blood output) [6]. Therefore, most common complications in PCNL are related to bleeding and infection [7]. Internal anatomic diversity, important neighboring organs, as well as structural complexity of renal stones leads even in minimally invasive surgery, there are still exist many unpredictability. For the reasons listed above, needle trajectory needs to avoid vessels and viscera with high accuracy on puncture point and inserted depth. At present, only 11% of urologists have the ability to the PCNL surgery [8]. Such a low percentage is mainly due to the lack of high fidelity training. Traditional puncture training approach used by urologists is placed porcine kidney within chicken carcass to simulate the puncture process [9]. However this rough simulation is huge different with real surgery in accuracy and coincidence.

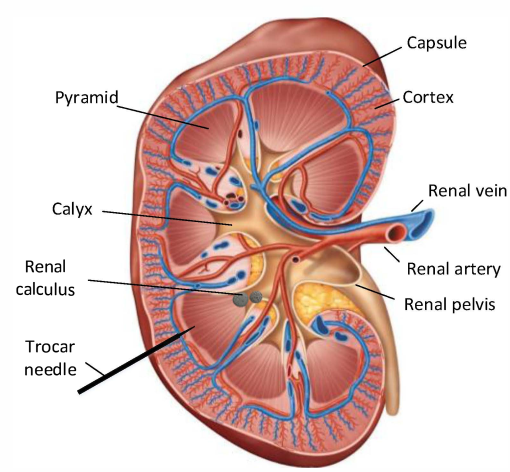

Figure 1. PCNL surgery trajectory in kideny [5]

Virtual surgery training simulation, combined realistic visualization and haptic feedback, could provide repetitive, hygiene and immersive simulation experiences for various surgical procedure training, increasing surgical skills and reduce the risks associated with complicated procedures. There have been a number of previous works on this in the literatures. Watterson reconstructed renal stones patients' 3D collection system before PCNL surgery, aims to fully understand forms and spatial distribution of the calculus [10]. S. Chan combined computer visualization with anthropometric model, designed a 3D human collecting system surgery simulator to guide the puncture training [11]. Jens J. Rassweilera employed the rear camera of iPad to capture real-time images from surgery, then fused it immediately with preoperative renal stones structure for intraoperative puncture guidance. However, most of the research is focusing on reconstruction of the kidney and renal stone to simulate 3D anatomical structure visualization without force feedback [12]. Some researchers investigated the force data when needle insert into kidney, Zhai et al. and Maurin et al. [13], [14] punctured trocar 18 G trocar needle into porcine kidney with different speeds to study force characteristics during percutaneous surgery. Gerwen D. J. [15] designed sixty times of puncture on porcine kidney recorded by ultrasound probe to capture different force feedback features in different stages. However, none of these studies mentioned how to combine graphic and force feedback model together to evaluate an immersive PCNL surgical simulation system.

In this paper, we integrated VR-based training simulation with haptics and renal force feedback model to improve the effectiveness and accuracy for PCNL therapy. CT images based 3D kidney model with detailed anatomical structures such as vessels, calyxes and calculus etc. are reconstructed in this paper. Section II focus on the general architecture of renal puncture procedure, in Section III and Section IV we present hardware and software components design respectively. Section V demonstrates our simulation experiment results and we summaries our research in Section VI.

II. System Architecture

We propose to design a PCNL simulation system aims at facilitate urologist to overcome the existing issues in open surgery training. The major components and their respective functionalities are listed below:

- Surgery environment needs to be reconstructed with details.
- The renal model should be reconstructed accurately in both graphic and haptic, which means three dimension deformable anatomical structures and puncture force model should be considered in scenario.
- Operation model should provide interactive viewing including zoom, rotation, and various transparency settings on different parts of the kidney model to facilitate urologists to analysis puncture position, percutaneous points, routes and depth.
- System integrated seamlessly which could let haptic and visual rending in surgical simulation be manipulated in real time.

Based on these requirements, we designed a framework for renal puncture training simulation, as shown in Fig. 2.

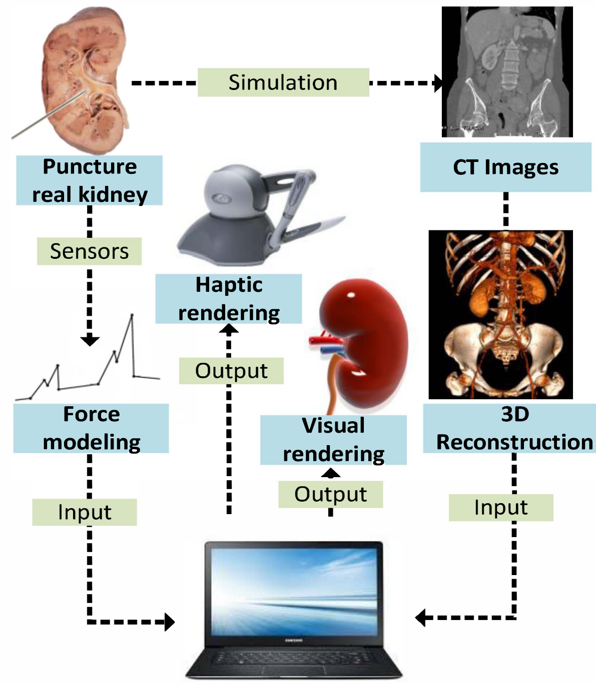

Figure 2. Architecture of Renal Puncture Procedure simulation

Both visual and haptic pipelines have been proposed. The haptic rendering pipeline includes the reconstruction of puncture force model and haptic package setting. Based on the deformable force models described in [16], we proposed a novel trocar needle puncture force model specifically for PCNL surgery. Real time force feedback of trocar needle insertion with a modified mass-spring force model is constructed for haptic rendering. Three basic layers of renal tissues (capsule, cortex and pyramid) with their respective stiffness and damping coefficients are provided.

The visual pipeline includes graphic rendering and renal deformation modeling. Detailed polygonal mesh model has been constructed to represent realistic deformable tissues.

III. Hardware Component

The hardware we adopted to implement multi-layered needle puncture is the Phantom Omni, by Geomagic. Phantom Omni has 6DOF positional input sensing and 3DOF output force feedback which enabling it to move around object in virtual space, consequently allowing the operator to adjust needle in X-axis, Y-axis and Z-axis to find optimum puncture position. When needle punctures into kidney tissue, the actual force feedback exerted on the needle is calculated based on the actual one dimension trajectory which means force feedback can be accurate providing with a high fidelity sensation. Omni also can be integrated in multi-instrument operation, for example, two Omni devices can be operated in both left and right handed to optimize the surgery simulate immersion. API of this device support providing accurate distance measurement between the needle tip and the position of the kidney surface which facilitate the software calibrated. This hardware meet the requirements in our simulation system, that can be sent information from the environment and apply force feedback based on operator manipulation in virtual environment.

IV. MODELING AND SOFTWARE DESIGN

The whole system needs to achieve two essential performances, graphic rendering and force feedback rendering. To achieve this immersive and realistic simulation, we employ a game engine as the skeleton frame to develop virtual objects with real physical property and collision detection. For visual and haptic rendering for PCNL surgery training procedures we designed a complex software to implementation. Various parameters during the PCNL surgery can also be dynamically adjusted and simulated. Not only immersive graphical rendering, but also accurate deformation when external forces are being exerted. Here are the coefficients identified in our simulation:

- Deformation degree. This coefficient is used to adjust the needle deformable range when needle puncture the deme. We also designed the bleeding effect during the puncture moment;
- Stiffness and damping force. This coefficient is used to adjust set the range of force feedback during the puncture;
- Puncture point. Puncture point can also be chose to let the urologist to find the best puncture route for different kinds of renal stone.

System software flow diagram is demonstrate in Fig.3. After the system initialization, System starts to running the scripts in Awake () script, which is preset parameters of deformable and force feedback. Then software system is ready to running the surgical simulation in visual and haptic loop, we also set the exit controller to let the operator interact simulation in anytime.

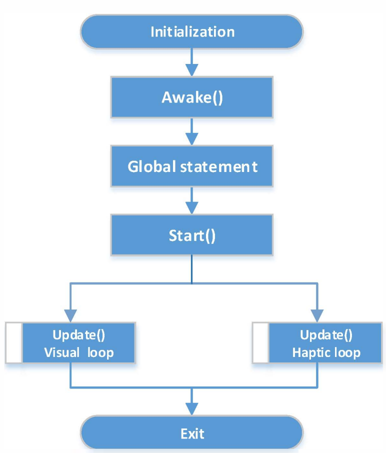

Figure 3. Software flow diagram of simulation system

For the visualization components of simulation system, we employed a game engine names Unity3D as the visuo-haptic connection interface. Unity3D is a software game engine available in both game designing and scientific research. It provides a cross-platform game creation system and integrated development environment (IDE), which facilitates realistic real-time simulations. However the Unity engine does not support Phantom Omni API directly, so we created a plug-in for our simulation. We executing code from HDAPI (Haptic Device Application Programming Interface), which utilized for motion control and force rendering of haptic device, and HLAPI (Haptic Library Application Programming Interface) assist to setting force effects and haptic environment, convert into Unity. A dynamic link library in which individual methods can be executed individually for Unity3D scripts.

After force feedback integration through plug-in between different working platforms, we also needs to consider the visualization component performance, which shows in Fig.4. Firstly, renal calculus patients' CT images (DICOM format) were imported to reconstruct surgical simulation demo, we designed the direct lighting and a main camera to set the basic environment for surgery operation. Secondly, zoning and threshold limitation algorithm are utilized to keep the necessary part in PCNL surgery, which are ribs, dual renal, artery and vein. To demonstrate realistic visual effect, different parts of kidney with their own texture also be designed in our simulation. Considering the demo need to be deformable during the puncture, we used the shader programing to put the vertex color on. Distance between needle and mesh vertex were be calculated to set demo visual deformation and scripts employed to control the needle and demo transform in the reconstructed surgicla environment[17]. Finally we converted the visualization demo into mesh modeling which is includes collider components, collider mesh for each layers was also created in collision detection system. The virtual kidney was rendered with the optional transparency with size variable, enabling the user to visually review their accuracy in insert the needle. Number of triggers are implemented to respond to needle tip touch different layer of renal demo that also is used to determine which costa will be hit as the tip of the needle inserting current trajectory. If the needle hits the wrong organ, a message is sent to the user telling them that they choose the wrong puncture route, which such errors can cause a serious injury or harm in real surgery.

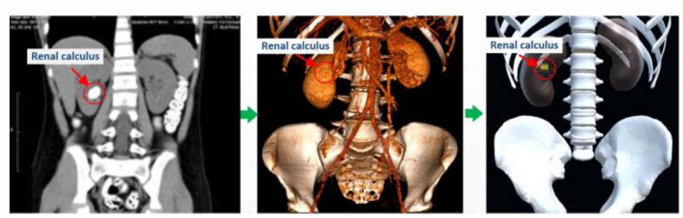

Figure 4. Visual rendering procedure in our simulation system

The renal internal structure consists of three typically layers as we mentioned in part I. Renal capsule, cortex and pyramid has different physical properties. During the punctured, with needle break through each layer's surface, there should be a ''popping'' tactile sensation for operator. Forces associated with "popping" feedback should be need to output to the operator in our simulation. Apart from that, trocar needle insertion model also need to be represented during the puncture simulate, which means two force peak are could be feel like a "popping" tactile sense during the associated with break into moment. To achieve these requirements, haptic rendering software we design is based on the Phantom toolkit OpenHaptics. To achieve realistic haptic rendering, we incorporated multiple physical properties, such as stiffness and damping, for different renal layers. Damping and stiffness force formula are represented using different kinds of sources in OpenHaptics surgical tools such as trocar needle and dilation have also been implemented with corresponding properties[18], [19]. Different tools also support distinct available operations. Followed by a sudden decrease in force as the tissue fails. Finally, we write a custom wrapper by using of scripts to callback the HD and HL in plugin to implement real-time communication between Phantom Omni and our surgical scenario.

V. RESULT AND DISCUSSION

Our experiment constructed on a platform consist of Intel i7 CPU with 3.5GHz, 4 GB memory of NVIDIA Quadro 5000 Graphic and 16 GB system memory, Phantom Omni, produced by Geomagic Company with 6DOF input and 3DOF output as the force feedback device in our simulation. Unity 3D, as the visuo-haptic interface is facilitated to construct the surgery scenario which is controlled by scripts. Visual update rate is around 60Hz and haptic rendering refresh frequency approximate 1 KHz.

Fig. 5 demonstrates the operation platform of our surgical simulation system, kidney model reconstructed by CT images is a high polygonal mesh model, and each layer component (capsule, cortex and pyramid) is set with respective texture and physical property. Haptic force feedback in our system include stiffness feature which assigned to reflect renal densities differences, and damping feature which is assigned to express the friction force between renal tissue and the needle shaft. Deformable visual performance of kidney puncture with accurate graphic rendering is also displayed in Fig. 5, which based on the mass-spring algorithm to implement visuo-haptic rendering synchronization.

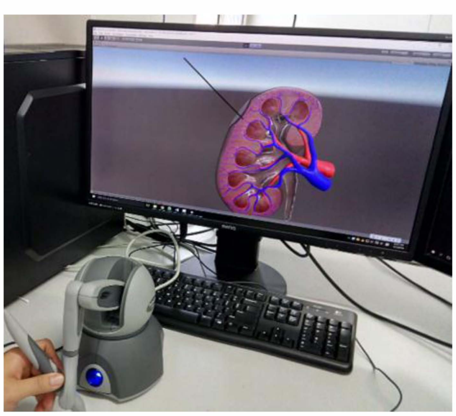

Figure 5. Actual renal puncture procedure simulation system

Except deformable renal structure demo is reconstructed in our study, we also create a VR-based scenario for PCNL surgical simulation. Fig. 6 (a) demonstrates the final reconstruction visual model we built for the surgery simulation. We created clearly discernible three dimensional model with kidney internal structure distribution and the space relationship among kidney stones, renal blood vessels, collection systems and costa position. The specification of each object in the surgical scenario is demonstrated in Table 1, which includes the vertex and triangles numbers, as well as each file size.

TABLE I. SPECIFICATIONS OF DEMO SIZES IN EXPERIMENT

Demo name	Vertex Number	Triangles Number	File Size
Kidney	5242	10336	13.67M
Ribs	3641	6527	844K
Trunk	3383	6368	768K

Fig. 6 (b) puncture model provides how to targeted physiological anatomical site, which could simulate not only the correct site puncture into the collection system, but designed to measure the shortest puncture route from the skin to the target renal stone, transparency and coordinate axis could be also set which demonstrated. To evaluate reliability of our simulation system, we conducted an academic urologist teacher and 3 novices to complete the visual PCNL simulation. We arranged all novices to practice 4 times (each time cost about 20 minutes) on the simulator, then novices asked to operate the same surgical task as the professional urologist respectively. Fig. 6 (c) and (d) diagrams demonstrates the experimental results by comparison of needle trajectories and puncture force. After training by our simulator, novices' needle trajectory in space are nearly coincide with professor's, each force record shows dual force peaks during the puncture which are the moment needle break through skin and renal capsule. However the force magnitude of novices are still not demonstrated a convergent improvement after training, which we will conducted more validation of trainees and data analysis.

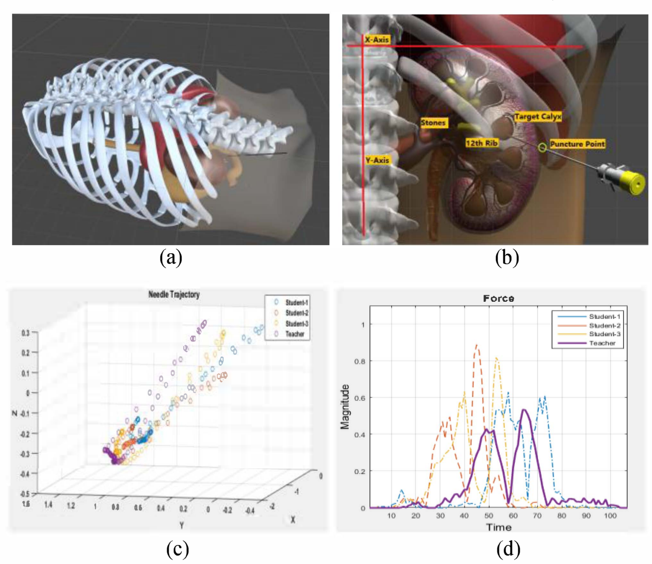

Figure 6. Renal puncture procedure simulation

In order to build a more realistic visual surgical scenario, deformable simulation of renal tissue during the needle puncturing is also be testified in our virtual environment. Utilizing the haptic device of Phantom Omni, customers could control the needle to deform the different layers of renal. Fig. 7 demonstrates surface deformation when the needle puncture into the renal capsule. We also reconstructed three layers kidney combined with renal capsule, renal cortex and pyramid with different damping coefficients respectively.

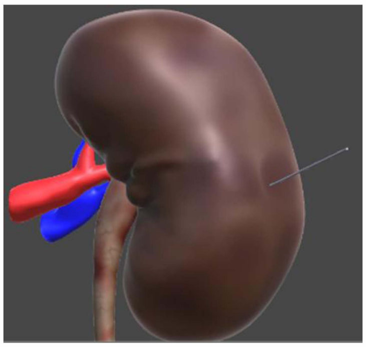

Figure 7. Renal capsule deformation simulation of needle puncture

VI. CONCLUSION

Detailed and accurate anatomical kidney structure and blood vessel distribution are reconstructed from the patient original CT images during the simulation. The final reconstructed training model can be zoomed, rotated as well as transparency, which aims to orientate puncture position and comprehensive percutaneous trajectory planning. Furthermore, real time 18G, 20 cm length trocar needle puncture force model was produced by haptic device with deformable visualization can facilitate manipulator to label accurate puncture points, routes and depth. This work of virtual renal puncture surgical simulation may potentially assist urologist to formulate pre-operation surgery plan conveniently, reduce kidney vascular complications and operational mistakes in real surgery, as well as decrease organ damage around the neighborhood, finally achieve a satisfying surgical result. Although the most critical and difficult procedure in PCNL surgery is the puncture channel establishment which we focused on, there are also some other surgical details need to extend, in the future, we will focus more attention on the research of dilation and stone fragment process simulation.

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