Tissue and Force Modelling on Multi-layered Needle Puncture for Percutaneous Surgery Training

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Abstract—**Percutaneous surgery is a typical minimally invasive surgery. Featuring minimization in trauma and infection rate as well as rapid recovery time to patients, percutaneous therapy has replaced various traditional open surgery approaches and has become an essential approach for a series of clinic operations over the past decades. However, the practice and training for such a vocational manual skill is both difficult and expensive, which imposes negative impacts on its further advances. In this paper, we conducted an immersive needle insertion simulator for percutaneous surgery through visuo-haptic rendering. Multi-layered deformable tissue model with human anatomic textures are simulated and rendered. Mass-spring based force model and algorithm are also employed for realistic trocar needle insertion. Last but not least, a highly immersive virtual training scenario, integrated with a desktop haptic device is implemented to facilitate perceptive and hands-on experiences. Medical professional and trainees have also been invited to practice on the training scenario and provide subjective opinions in refining our implementation.**

Keywords-percutaneous; haptic; simulation; deformable; trocar needle

I. INTRODUCTION

Percutaneous surgery refers to the insertion of surgical tubular apparatuses, such as needles, catheter, endoscopy and laser devices, into targeted lesion in human body with the guiding of intra-operative instruments (CT, X-ray and MRI) [1]. As one of the most typical minimally invasive surgery, percutaneous therapy decreases patient surgical injury and reduces post operation complications [2]. Nonetheless, the traditional training of percutaneous surgery is usually conducted through animals or cadavers, which can be unintuitive to trainees [3]. With the recent advances in virtual reality and computer graphics, training simulation of virtual surgery could be achieved on computers through anatomically correct 3D models, which clearly reflects the patient's anatomy and physiology condition, and provides interactive feedbacks for medical training and teaching [4]. In addition, the progress in the area of haptics have been influencing the way medical simulation and virtual training are conducted. Haptic devices boast a distinctive bi-directional sense that greatly augment the interaction and coordination between the hands (tactision) and eyes (vision), providing a higher fidelity and shorter learning curve for the training of percutaneous surgery. Fig.1 shows one of the traditional percutaneous surgery training methods implemented through animal specimen.

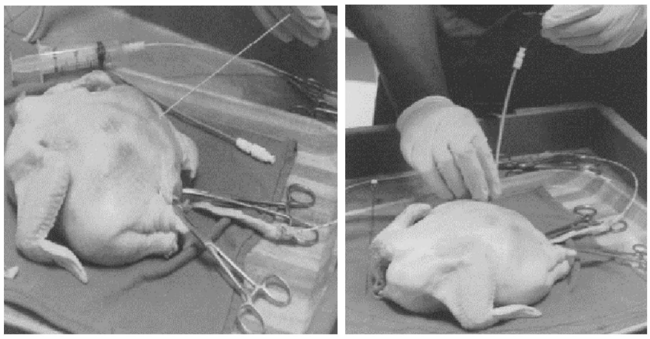


Figure 1. Traditional percutaneous surgery training procedures [3]

In this paper, we proposed the tissue and force modelling on multi-layered needle puncture for percutaneous surgery training, which facilitates trainees to virtually practice and accumulate hands on experience on the puncture procedure. The simulation implemented in this paper is unique for two reasons:

- Coupled trocar (includes tip and cannula) mechanical model with haptic device simulation during puncture procedure, which facilitates trocar-used minimally invasive surgical simulation being more accurate and realistic.
- Multi-layers deformable human tissue model (skin, fat and muscle) using specified human lower back data is reconstructed with accurate visual and haptic rendering.

The rest of this paper is structured as follows: In Section 2 we describe related works in the field. Section 3 focuses on the general design and force modelling involved in the proposed simulation system. In section 4 we discuss our implementation details on visuo-haptic integration. Simulation result analysis and corresponding discussion are presented in Section 5. Last but not least, we summaries the work done briefly and discuss future work in Section 6.

II. RELATE WORK

The mechanical models of needle puncture have been studied for various surgical procedures, most of which are focused on puncturing through a particular animal tissue (porcine or bovine) to obtain specific force data. In [5], Okamura et al. punctured an ex-vivo bovine liver and equipped load cell attached on needle to obtain related data. Their conclusion indicates that there are 3 forces during the puncture: stiffness, friction and cutting. They also experimented specific cases on bevel, needle diameter and type influencing the puncture results. Ng et al. inserted porcine sirloin and tenderloin specimen to study the relationship between insertion force and needle depth [6]. They have employed the acquired data into multi-layer gelation to simulate the surgery. The needle they used is triangular tip 18G with 15cm length. In [7], [8], the authors have conducted two experiments to simulate the robotic needle insertion into soft objects: bovine liver and rubber, CT fluoroscopic image were obtained to record the whole needle insertion process. In [9] , authors used sheep skin to simulate the resistance force feedback during the suture needle puncture into the skin. According to [10], there are two peaks during the puncture procedure. In [11], Abolhassani et al. summarized that the major factors influencing needle insertion simulations include: insertion force simulation, tissue deformation and needle deflection imitation, which implied that percutaneous surgery simulation can be further improved based on needle types. All the studies mentioned above are selected type of bevel needle as the research object, however trocar needle also widely utilized in laparoscopic and minimally invasive surgery which lack of specialized research. Rubber Silicone et al. mentioned about different kinds of needle tip during the puncture. They tested three types of needle (bevel, cone, triangular) tips and 6 diameters to record individual puncture force, yet they did not pay much attention to the cannula edge's study [12]. Gerwen et al. also took 18G trocar needle to puncture into porcine kidney, while setting up an ultrasound to monitor and record the insert procedure at every single step [10]. They tested trocar needle puncture force in artificial membrane and found there are typically two force peaks: one is the very tip of the needle cut into the material and another one is the cannula inserting into the tissue.

In the area of the physical simulation of deformable objects, there are two commonly adopted approaches: finite element method (FEM) and mass-spring system[13]. FEM has higher deformation fidelity, yet it is heavily depend on time-consuming calculations, which in many cases has become an obstacle for real time surgical simulations[14]. Mass-spring system, on the other hand, provides less accurate deformations but is more suitable for interactive rendering[15], [4]. In [16] Oleg Gerovichev proposed an experiment to evaluate the visual and haptic effect on needle insertion performance based on mass-spring models. They designed a simulator with four rough visual layers and tested the influence of the force feedback during the surgery in one-dimension simulation. In [17] Romano Joseph M. *et al*. reconstructed a three layers mesh and simulated the puncture and cutting with visual and haptics. Their force model is based on A. M. Okamura's model [16], two dimension simulation flat plane meshes were employed to simulate deformable tissues. In summary, most of the articles mentioned above simulated human multi-layers deformable tissues (such as skin, fat and muscle) as the same properties of force feedback and visual effect in each layer.

III. FORCE MODELING

For surgical simulation, the ultimate goal is to achieve real-time and realistic visuo-haptic rendering on soft bodies. This requires both visual and haptic pipelines asynchronously (mainly due to update rates) communicate regarding the instant physical state of deformable models, while represent the deformation both visually on the screen and haptically on the haptic device. Visual rendering pipeline is responsible for setting up visual collision detections and simulating object deformation. Then the force feedback models output the calculated results to the haptic device, which renders realistic reactions to the operator. In this paper, deformable simulation model is based on mass-spring system, which originates from Newton's laws of motion of particles. Compared to the FEM method, this method is suitable for less computational intensive models. Fig. 2 demonstrates the force features in different tissue layers during the needle puncture which is also the target we expect to simulate. Step I signifies the initial state before insertion, Step II–IV demonstrate the changes when the needle punctures through each layer's boundary, force transmissions occurs between adjacent tissues, and the magnitude of the deformation are related to permeation depth.

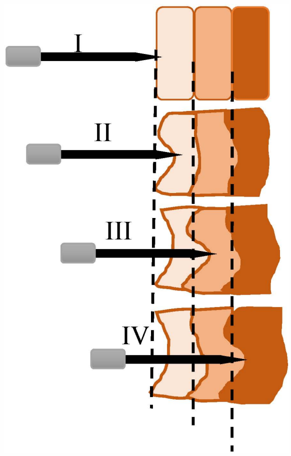


Figure 2. Multi-layers tissue deformation during needle insertion

A. *Human tissue modeling*

Human trunk's deformable anatomy structure normally consists of three typically layers: skin, fat and muscle. We simplify these layers as isotropous tissues, with each layer setting to different damping and stiffness parameters. According to the classifications in [16], we split the needle puncture process into two steps: before-puncture and after-puncture. Before-puncture refers to the period of time from when the needle contacts the tissue to the piercing extremum, while post-puncture refers to the period of time after puncturing through the previous layer surface and the needle tip moving through the tissue. Stiffness force is the only force feedback during the before-puncture step for skin layer and damping force feedback. Needle force feedback while the tip is within the fat and muscle layers are the combination of the stiffness and damping from the current layer and the previous layer. During the actual percutaneous surgery, as the needle penetrates deeper into the layers, user would feel the total damping force accumulated from the penetrated tissue layers. Below are a list of the commonly used coefficients for each tissue layer on human:

TABLE I. COEFFICIENTS OF HUAMN TISSUE IN NEEDLE INSERTION

Tissue Type	**Skin**		**Fat**		**Muscle**	
State	*Before-puncture*	*After-puncture*	*Before-puncture*	*After-puncture*	*Before-puncture*	*After-puncture*
Thickness (cm)	0.08		0.84		3.9	
Stiffness Coefficient(k) N/m	331		83		497	
Damping Coefficient(b) N*s/m^2	3		1		3	
Force model	$F = k_s y$	$F=b_s y v$	$F = k_f y + b_s y_s v$	$F = (b_f y + b_s y_s) v$	$F = k_m y + (b_s y_s + b_f y_f) v$	$F = (b_s y_s + b_f y_f + b_m y) v$

Tissue stiffness and damping response coefficient are adapted from [16], y is the needle insertion punctured by haptic device tip with respect to the current boundary; y_s and y_f represent the thickness of each layer, and v means the needle puncture velocity. k_s, k_f and k_m means stiffness coefficients and b_s, b_f and b_m means damping coefficients of each three tissue layers respectively. In this paper, we choose the human back as the percutaneous experiment, Petrofsky. J [18] outlined that the average thickness of human back is 0.08 ± 0.01cm, the average thickness of human fat and muscle are 0.84 ± 0.01 and 3.9 ± 0.01 cm, however the puncture spot human back skin and fat thickness is bit thin than the normal skin, the average thickness of 0.08cm, the fat and muscle thickness is 0.84cm and 3.9cm [19].

B. Trocar needle modelingas

Apart from deformable tissue force model simulation, trocar needle insertion model also needs to be represented in surgery. Different from the bevel tip needles, trocar needles consist of two parts, diamond shaped stylet and the outside cannula. When the trocar needle tip is cutting through the human tissue, corresponding puncture forces varies significantly, as shown in Fig. 3. Four distinct stages are recorded during the trocar needle puncture into the tissue. Stage I refers to the needle tip touching the tissue surface and begin to puncture, stage II refers to the tip cutting into the tissue and starting insertion, stage III refers to the needle cannula break into the tissue and stage IV refers to the stage when the whole needle stylet has been punctured into the tissue. Based on Fig.3, two force peaks have been identified during the trocar needle puncture I. The first ne is in stage II, while the other being in stage IV. Based on t [10], both force peaks are "popping" feedbacks during the actual percutaneous surgery. This force model was combined with the aforementioned mass-spring method to create the proposed implementation as well as experiments.

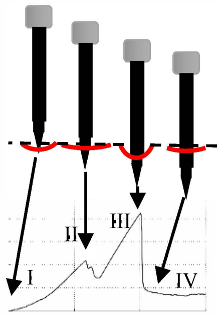


Figure 3. Architecture of Needle Insertion Simulation

Force model implemented in this paper is integrated multi-layers human tissue model and trocar needle modeling which are aforementioned into percutaneous surgery training. Moreover, we improved the human tissue model with visual deformable properties which synchronal displayed with each trocar needle insertion step. This force model facilitates trainees could feel twice "popping" force feedbacks effects when needle tip break through the tissue boundary as well as the stiffness and damping force during the needle piercing into the tissues.

IV. IMPLEMENT DETAILS

Fig. 4 shows the architecture of the Needle Insertion Simulation system which is comprise of three mainly components. Real time force feedback of trocar needle insertion with a modified mass spring force model is constructed for haptic rendering. Skin, fat and muscle, three basic layers of human tissues with their respective stiffness and damping coefficients are provided in our system.

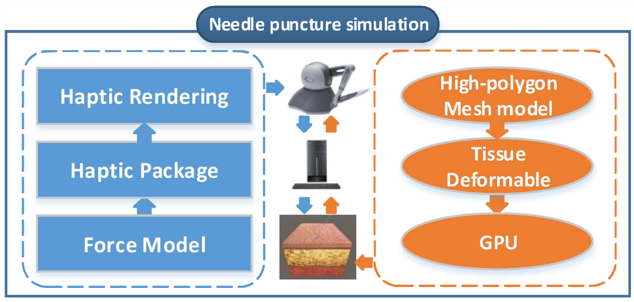


Figure 4. Architecture of Needle Insertion Simulation

The first component is the haptic rendering pipeline, which includes the reconstruction of puncture force model and haptic package setup. Based on the force models mentioned in [10] and [20], we proposed a more detailed force model for trocar needle puncture.

The second component is the visualization pipeline which includes the visual rendering and the deformable tissue deforming simulation. High-polygon mesh model with fine visual rendering details have been constructed to represent realistic visual effect of deformable tissues.

The third component is the system operation framework, which also serves as the communication connector between the visual and the haptic rendering pipelines. Table II describes multi-layer needle puncture algorithm as pseudo code.

TABLE II. PSEUDO CODE OF FORCE RENDERING DURING NEEDLE PUNCTURE

Algorithm: Multilayers Haptically Needle Puncture Simulation

Input: init_HIP, init_Direction, current_HIP, current_Direction, puncture_start, puncture_start, disable_HIP, release_Device

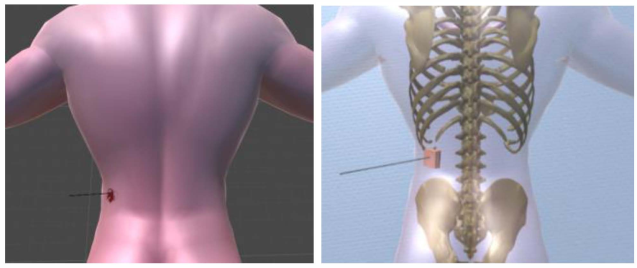
Output: force_Pop, force_Stiffnes, force_Damping,

```
if    puncture_State = = TRUE then
      init_HIP = current_HIP
      init_Direction = current_Direction
      puncture_start = FALSE
      disable_HIP = TRUE

else
      translation_diff = current_HIP - init_HIP
      init_Direction = current_Direction - init_Direction
      disable_Rotation = TRUE
      force_Pop =   Popthrough_coeff
      force_Stiffnes = translation_Depth*Stiffness_coeff
      force_Damping = translation_Depth*Damping_coeff
end if
release_Device
```

V. RESULT AND DISCUSSION

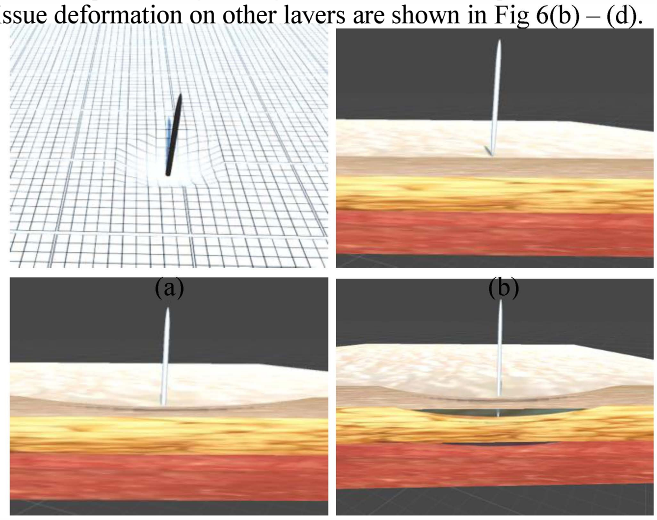
We conducted our experiments on a workstation using Intel i7 6700(3.4GHz), 16 GB memory, NVIDIA Quadro 5000 Graphics (4 GB) and Windows 10(64bit) OS. The haptic device we used in this work is Phantom Omni from Geomagic Company with 6DOF input and 3DOF output. Haptic rendering update rate approximate 1 KHz and the visual refreshment frequency is 60Hz.The modified mass-spring force model apply to the deformable tissue generate a real-time feedback with the visualization. Lighting, medical toolkits and cameras have also been reconstructed to provide better immersion for simulating the surgical environment a. Fig. 5 (a), demonstrated the dummy bleeding when the needle insertion started and with the needle puncture deeper into the skin, human body could become transparent and internal anatomy structure are then shown as in Fig. 5 (b).



(a) (b)

Figure 5. Visual environment and human body reconstrction

Combined with the Phantom Omni device, the simulation of soft tissue deformation is implemented through grasping the polygon vertices to control the deformation of each layers, Fig. 6 (a) shows the real-time deformation of the vertices when the needle is puncturing through the mesh. Visual performance of tissue deformation on other layers are shown in Fig 6(b) – (d).



(a) (b) (c) (d)

Figure 6. Deformation of different tissue layers

The actual force feedback outputs diagram during the trocar needle insertion are shown in Fig.7. The speed we set during the experiment is 2mm/s, force output diagram of Phantom Omni of needle cutting through three different tissues are fidelity simulated. The "Popping" effect of each tissue boundary is obviously demonstrated in simulation. Skin, fat and muscle layers are display different kinds of stiffness and damping force feedback during the simulation.

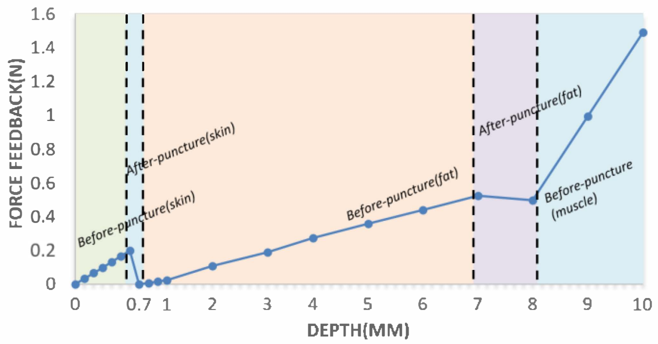


Figure 7. Force feedback diagram during the simulation

VI. CONCLUSION AND FUTURE WORKS

In this paper we proposed a multi-layered trocar needle insertion simulation system for percutaneous surgery with real-time visuo-haptic rendering. Reliable force mode for trocar needle is verified with specially speed of puncture which demonstrate with pleasing effects. This work may potentially facilitate the trainees to learn and practice various conditions and complication during percutaneous surgery, Due to the timeframe we have put on this work, there are a few other parameters that have not been taken into consideration, which may adversely influence the results of the simulation. These parameters include diameters of needle, tissue density, as well as the mechanical properties of the conjunctive tissue. These detailed aspects will be further studied in our future work.

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