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A Hybrid Virtual Reality-Haptic Simulation Framework for Layer-aware Needle Insertion in Extended Reality

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I. Introduction

Incorporating haptic rendering into Virtual Reality (VR) is essential for improving the realism and effectiveness of simulations, particularly in procedures where tactile cues are vital, such as needle insertion, a common and sensitive clinical task. Accurate haptic feedback is especially important in these scenarios, as over-puncturing can lead to serious complications, and the sensation of resistance during penetration provides key information about tissue boundaries.

Since the human body consists of multiple distinct layers, considering multi-layer structures during puncture is crucial for both realism and safety. However, the majority of existing haptic rendering approaches have focused only on single-layer puncture models [2–3]. One previous study attempted to account for two layers [4], utilizing a spring-mass model with friction guided along a predetermined path. While this approach allowed some level of force rendering, it lacked the ability to simulate tissue rupture—a key component of realistic puncture feedback. As a result, the generated force profile significantly deviated from real-world tactile responses. To date, there remains no haptic rendering method capable of simulating the tearing of tissue while accounting for multi-layer anatomical structures during puncture tasks.

Here, we present a realistic VR simulation framework that renders appropriate haptic feedback during needle insertion into multi-layered tissue, while incorporating tissue rupture. For visual cues, we used Position-Based Dynamics (PBD) to model the inter-layer interactions as shown in Figure 1(a), allowing for real-time visual deformation and more stable collision and contact handling compared to conventional mass-spring systems (MSSs) [5]. For realistic force rendering, we collected a dataset from experiments puncturing a phantom, obtaining force data with respect to the depth, velocity, and angle of insertion as shown in Figure 1(b). By tightly coupling force and visualization models—while separating visual modeling (PBD) from force calculation (via a custom nonlinear function)—our system generates haptic feedback that closely replicates real tactile responses, thereby improving the fidelity and training value of VR-based needle insertion simulations.

II. System Design

While Finite Element Method (FEM) and complex nonlinear models offer high physical realism and enable direct force computation, they are computationally expensive and unsuitable for real-time simulation—especially for multi-layered biological tissues. PBD, on the other hand, allows for real-time performance but does not directly compute reaction forces from object interactions. In contrast, while MSSs compute forces directly, they fall short in terms of real-time performance and robust contact handling as previously discussed. To leverage the computation advantages of PBD while enabling force computation, we additionally incorporated a custom function that computes interaction forces between objects into the needle model. In this framework, we adopt a PBD-based model to focus on real-time visual deformation per layer.

To demonstrate vessel puncturing, we constructed a multi-layered arm model using PBD. Each layer was assigned distinct material properties via constraint settings, with additional inter-layer constraints ensuring continuous response. While PBD does not directly compute forces, it governs the position and velocity of interacting objects, which are then used as inputs to a custom force estimation function. Furthermore, by incorporating the insertion angle as an additional input and modeling the needle as a rigid body, we introduce a custom force model that estimates the reaction force based on the needle's position, speed, and angle relative to the tissue layers.

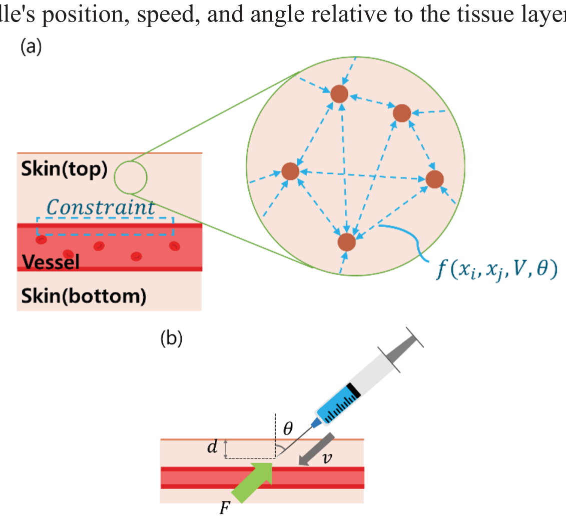

Figure 1. Overview of the proposed framework

A. . Multi-Layer Design

The tissue is designed as a simple three-layer model: top skin, vessel, and bottom skin. Each layer incorporates the following PBD constraints:

Distance constraint: $C_{dist}(x_i, x_j) = \|x_i - x_j\| - L_0$

Volume constraint: $C_{vol}(V) = V - V_0$

Bending constraint: $C_{bend}(\theta) = \theta - \theta_0$

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x_i and x_j represent the positions of particles, V is the volume of the object, θ is the bending angle between planes composing the object, L_0 is the distance constraint constant, V_0 is the volume constraint constant, and θ_0 is the bending angle constraint constant.

Layer	Distance (L_0)	Volume (V_0)	Bending (θ_0)
Skin(top)	0.01	1.0	180°
Vessel	0.015	0.8	0°
Skin(bottom)	0.012	1.0	180°

Table 1. Constraint hyperparameter settings for each tissue layer.

Table 1 Summarizes the constraint hyperparameters for each tissue layer, chosen to replicate realistic tissue deformation and low-stiffness vascular response. Distance constraints between layers were applied to prevent separation and preserve structural continuity.

B. . Experiment for Hyperparameter Tuning

To determine the physical and force model parameters, we conducted experiments using gelatin-based phantoms that mimic skin properties such as stiffness and elasticity. Each phantom was composed of uniformly thick, multi-layered segments. By inserting a needle and measuring the resulting force profiles, we tuned the custom force model. A subset of the results is presented in Figure 2.

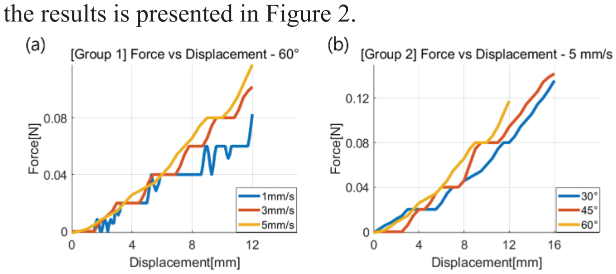

Figure 2. Experimental Results

Figure 2. (a) Measured insertion forces when a needle was inserted into the phantom at a 60° angle with speeds of 1 mm/s, 3 mm/s, and 5 mm/s. (b) Measured forces at an insertion speed of 5 mm/s for angles of 30°, 45°, and 60°.

C. Unity Setup

The needle is implemented as a rigid body in Unity. A C# script is used to calculate insertion depth, velocity, and angle between the needle and the soft tissue model in real time. These parameters are passed to the previously generated force function to produce responsive force feedback.

Figure 3 shows a Unity simulation where a 3D needle is inserted into a 3D arm model with a vessel (as shown in the supplementary video). During injection, insertion depth, speed, and angle are calculated and visualized in real time. The simulation also detects and displays whether the needle intersects the vessel.

Figure 4 presents the force–depth profile generated using the custom force function described in Figure 3. While the trend resembles that of Figure 2, the absolute values are not yet precise due to ongoing hyperparameter tuning. Nevertheless, this generated force profile serves as interaction data that can provide haptic feedback closely resembling the reactive force experienced during actual needle insertion, making it suitable for use with haptic devices.

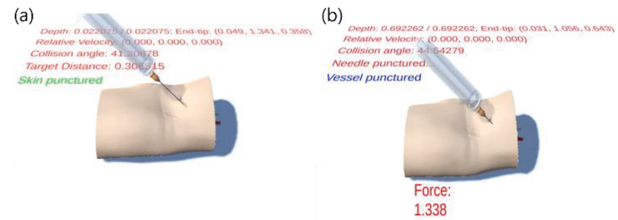

Figure 3. Unity simulation setup

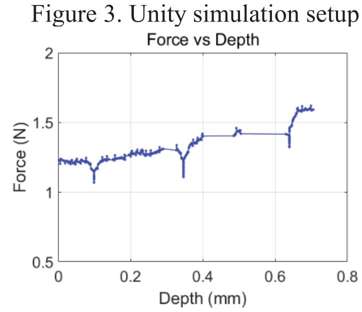

Figure 4. Force Calculation

III. Conclusion

Unlike conventional simulations that tightly couple force and visualization models, our framework separates visual modeling (PBD) from force calculation (custom nonlinear function). This enables both real-time computability and physically realistic haptic feedback. The ability to model and detect layer transitions also provides haptic cues that help guide users during needle insertion. This framework can be expanded for various layered-object interaction scenarios and serve as a foundation for XR-based real-time surgical training or simulation systems. Furthermore, it is expected that the performance can be further improved through machine learning-based regression, provided that sufficient data is obtained using FEM tools such as COMSOL during the hyperparameter tuning process.

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