A low-cost unity-based virtual training simulator for laparoscopic partial nephrectomy using HTC Vive

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ABSTRACT

Laparoscopic education and surgery assessment increase the success rate and lower the risks during actual surgeries. Hospital trainees require a safe and controlled environment, with affordable resources to practice and enhance their laparoscopic skills. Thus we have modeled and developed a surgical simulator to provide the initial training in Laparoscopic Partial Nephrectomy (LPN - a procedure to treat kidney cancer or renal masses). For this purpose, we have utilized an open-source game engine to develop a virtual simulator that can be accessed with a commercially available low-cost virtual reality (VR) device for visual and haptic feedback. The novel simulation with a soft body deformation based on simplex meshes can run efficiently on both CPU and GPU-based machines. This study shows the design of the proposed simulator, compares the cost, and evaluates the simulator performance using face and content validity measures. The controlled soft body effect, physics-based deformation, and haptic rendering using the HTC Vive provide the benefits of a good surgical simulator with a balanced trade-off between cost and performance. The experiments depict a positive feedback from the medical volunteers practicing initial LPN procedures for novice surgeons.

1 INTRODUCTION

Renal cancer is among the top ten cancers in both males and females, though males have a double chance of deveopling it than the females (1). Since the discovery of open radical nephrectomy (ORN) in the 1960s, the surgical removal of tumors from kidney using open radical nephrectomy has been the cornerstone of treatment for confined renal cell carcinoma (RCC) (2; 3). In 1991, the first report of a minor renal tumor treated with laparoscopic radical nephrectomy (LRN) was published after which it was widely-accepted as the new standard procedure for surgical recession of renal cancer (4). In laparoscopic Nephrectomy the surgeon makes a small incision on the patient's body and glides the laparoscopic instrument inside the body cavity. The extraction of renal tumor is performed inside the body cavity using a small camera to guide the surgeon of the surrounding organs. Laparsoscopic nephrectomy (LPN) is safer, quickly recoverable (as a result of the small cut), and produces better outcomes than the conventional open radical surgery. Laparoscopic nephrectomy also requires exceptional hand-eye coordination, a lot of surgical practice along with technical training, making it a more difficult surgical procedure with a steep learning curve as compared to open radical nephrctomy (5; 6). Owing to these reasons, laparoscopic nephrectomy is still harder to adapt as the standard practice in developing countries.

To solve these problems, virtual reality is used. Virtual reality not only enables distance learning and training in the medical field but also provides a suitable alternative to in-vivo surgeries (15). The virtual realistic laparoscopic simulator enables surgeons to rehearse various laparoscopic techniques, including clipping, cutting, suturing, knot tying, and camera handling (7; 8). By virtue of these laparoscopic

practices using advanced imaging and surgical techniques, the post surgery results in reduced hospital stays and a faster recovery rate. It also ensures a less painful surgery with little blood loss and improved cosmetic results.

There are various types of virtual reality simulators available in the market nowadays. Most simulators' ultimate goal is to present training systems that can prepare surgeons for complex operations in advance (9; 10). The field of laparoscopic training, skill assessment, and haptic feedback is well researched (11; 12; 13). However, there is still a need for improvement in low-cost hardware systems with trainees' evaluation for developing and underprivileged counties. These systems as shown to serve as an investment to enhance the surgical skills of doctors using game-based training (14; 16). It also increase the trainees self-confidence, skills, and experience in a controlled and repeatable environment tackling the moral issue of practicing on other living-beings (17; 18; 19). Some studies explicitly highlighted the importance and key benefits of using Unity for real-time applications and simulation purposes (20; 21). The HTC Vive VR device is getting attention as a low-cost simulation tool for its high accuracy and precision in position tracking. It is considered suitable for experiments that do not require self-motion, thus proving it a good option for surgery training (22; 23).

In this study, we present a low-cost surgical Unity-based Virtual Training Simulator for laparoscopic partial nephrectomy using HTC Vive. The main contributions of our research work are:

1. Creation of an anatomical model for the kidney with Renal Cell Carcinoma (RCC) and minimal mesh representation.
2. Proposing a stable and efficient solution for soft body deformation using Position Based Dynamics (PBD) combined with the force-based method.
3. Using a game engine when developing a specialized LPN training environment for surgeons.
4. Exploring the possible use of a low-cost HTC Vive VR device for training purposes and haptic feedback.
5. Determining the validity measures for our simulator and criterion-based approach for surgeons' evaluation.

Compared with other high fidelity expensive trainers, our proposed training system based on Unity follows a more straightforward deformation representation with less computing time but high solving speed. Compared to the previous methods, the flexibility of the proposed algorithm in tuning the parameters allows users to have great control over the simulation. The user can easily visualize and interact with the deforming body using the HTC Vive HMD and controllers.

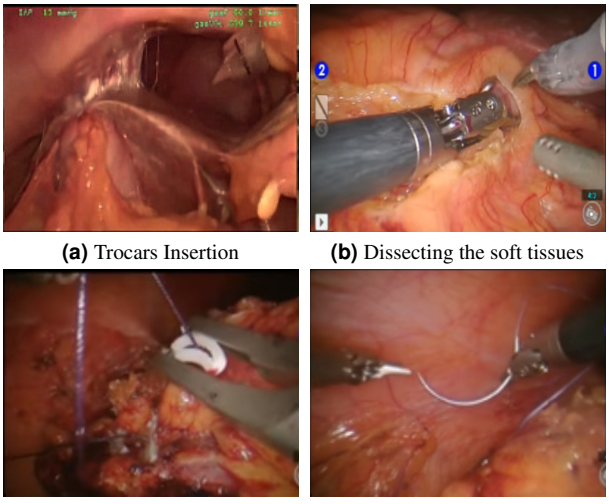
1.1 Details and Challenges in LPN

LPN has emerged as a viable alternative to open nephrectomy while minimizing patient morbidity. The advancements in laparoscopic experience have helped treat exophytic renal tumors, which is the main focus of this study.

The Da Vinci Surgical System is usually used for surgical practices as it is safe and very accurate. However the machine is very costly. Fig. 1 is added here to show the typical surgical procedure of Da Vinci surgical system. This procedure usually requires four primary steps: a) position the patient in the right place and insert the camera and other instrumentation through the trocars; b) dissect the tissues to find the exact location of the tumor, vessels, and the ureter; c) clip and ligate the kidney structure; d) tease away adhesions between the kidney and tumor part and suture the saved part of the kidney. Our team has simulated some of the same steps with a simple mesh representation and rendered them over the HTC Vive, which is much cheaper than the Da Vinci machines. Our system can be made available to surgeons in developing countries for an initial LPN practice at a very affordable rate. We have focused on the essential steps b) and d) of Fig. 1, as others can be practiced in separate training sessions.

The main difficulties during the operating process that require practice are:

1. Identifying the exact tumor location is necessary to save the kidney and surrounding parts from unnecessary damage.
2. Clipping the renal artery, renal vein, and ureter helps prevent uncontrollable bleeding.



(a) Trocars Insertion **(b)** Dissecting the soft tissues

(c) Ligating and clipping **(d)** Suturing after teasing away the cancerous mass

Figure 1. Core steps of a surgical procedure. Reprinted from (24).

3. Correctly separating adhesions among the kidneys can prevent procedure failure.
4. The laparoscopic instrument insertion should be performed carefully as unskilled manipulation can damage the main blood vessels and intestines.

The ability to handle this wide range of indications will allow the surgeon to efficiently practice and perform a wide range of partial nephrectomies.

2 RELATED WORK

Yu et al. (25) have analyzed the literature on partial nephrectomy to put the diagnosis and treatment of renal cancer in a modern context. This procedure has the main advantage of preventing complete kidney loss, but the drawbacks include the potential for regional infection and other complications. In their research, Verhoest et al. (26) have discussed some of the effects of laparoscopic nephrectomy compared to open nephrectomy for the disease of Autosomal Dominant Polycystic Kidney Disease (ADPKD). They identified that the incisional hernias occurred in two patients who had open cyst removal. In contrast, there was minimal blood loss, less postoperative pain, and rapid recovery with laparoscopic nephrectomy.

Christan at el. (27) have discussed some of the algorithms and techniques for surgical modelling of tissues and blood vessels so that these models can be effectively used while training. Another exciting research work of Qian et al. (28) has focused on the efficient methods of computation and simulation frameworks instead of individual issues of deformation, force direction, and feedback. The techniques offered have many intuitive parameters for realistic rendering. The tailored algorithms in these works (29; 30) based on the finite element method (FEM) and extended finite element method (XFEM) suggest improvements for the efficiency of simulation and accuracy of the designed procedure. However, the FEM method usually requires a longer execution time and a more extensive data set for mapping nodal connectivity. The position-based dynamics (PBD) method is more convenient and stable due to nonlinear constraint handling, and a fast convergence rate (31; 32). It directly manipulates the vertex positions, omitting the velocity layer as opposed to the FEM method. Another helpful approach is extended position-based dynamics (XPBD), which implicitly provides force estimates, making simulations visually look realistic but requiring high processing power (33).

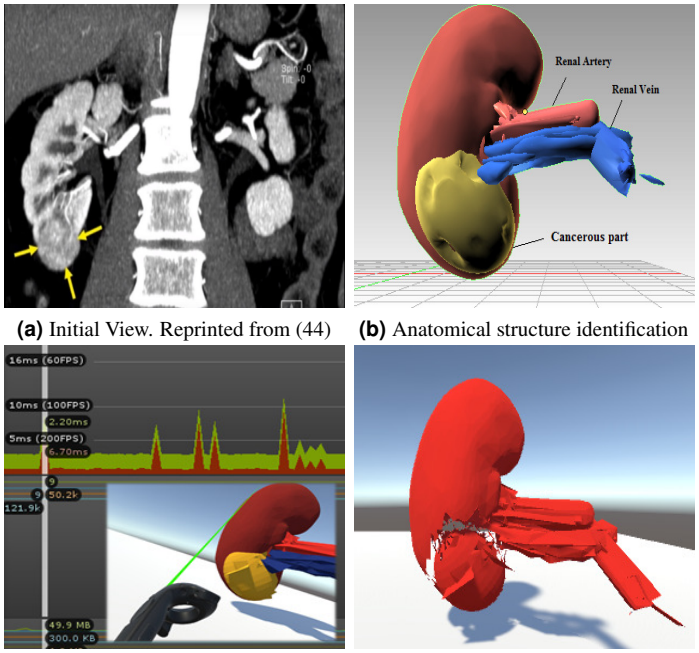
Witt et al. (34) have highlighted the three soft tissue deformation techniques: linear elasticity theory, tensor-mass model, and spring-mass model. The computational complexity of all models depends on the number of edges involved. They developed a new hybrid technique featuring the benefits of previous tissue cutting and tear modelling methods. Many state-of-the-art works use the SOFA architecture for simulations. It incorporates hyperelasticity with realistic object physics, which is computationally more

intensive. It works well with haptic devices like Geomagic, ARTTrack, Novint, Falcon, etc. (35). The advancements and growing requirements in the simulation of virtual healthcare environments require a change in the development process. The development process must decrease the method's complexity and trainer expenses.

To increase the surgical ability among surgeons, low-cost virtual devices are being implemented, thus increasing market competition. To find a cost-effective solution and limit the problems related to the controlled training environment, Zhong et al. (36) and Wheeler et al. (37) have developed plausible virtual environments using Unity3D. The game engines help with fast prototyping and response collection. Nowadays, different commercially available head-mounted displays are used in specific scenarios, and their performance is evaluated based on the type of functionality they provide (38; 39). In their study, Vamadevan et al. (40) have discussed the use of haptic and non-haptic responsive devices as the most effective means to acquire surgical training with a sense of realism in comparison to old-school methods. This study compared different simulators based on their working technology, response to external forces, degree of freedom, authenticity, and immersive experience. In this study (41), Nemani et al. used the task performance scores as assessment metrics for the Fundamentals of Laparoscopic Surgery (FLS) trainers and the Virtual Basic Laparoscopic Skill Trainer (VBLaST) trainers of a pattern cutting simulator.

There is an enormous gap to close for improvements in accurate functioning, effective organ modeling, less computational time, and standardization of metrics used for surgeons' evaluation. The critical point is the ongoing evaluation of existing systems and the establishment of specific practise tasks, scores, and training time as directed by these works (42; 43).

This study focuses on the efficient method of soft body modeling, position-based mesh deformation, performance evaluation in terms of stability and quick solving time, and haptic feedback from the system using a less expensive VR device. Similarly, by simulating the virtual environment through Unity, we have studied this game engine's capacities and limitations, focusing on the training purpose. Other works mentioned do not consider using the HTC Vive as a surgical trainer.



(a) Initial View. Reprinted from (44)

(b) Anatomical structure identification

(c) Laser cut across the cancerous part with profiler view

(d) Teasing away the cancerous part

Figure 2. Modular views of laparoscopic partial nephrectomy simulated procedure.

3 SYSTEM INFRASTRUCTURE

Usually, a training simulator consists of a rendering component for viewing 3D elements, the user interfaces for interaction, a physical element for practicing the procedure, and an event management

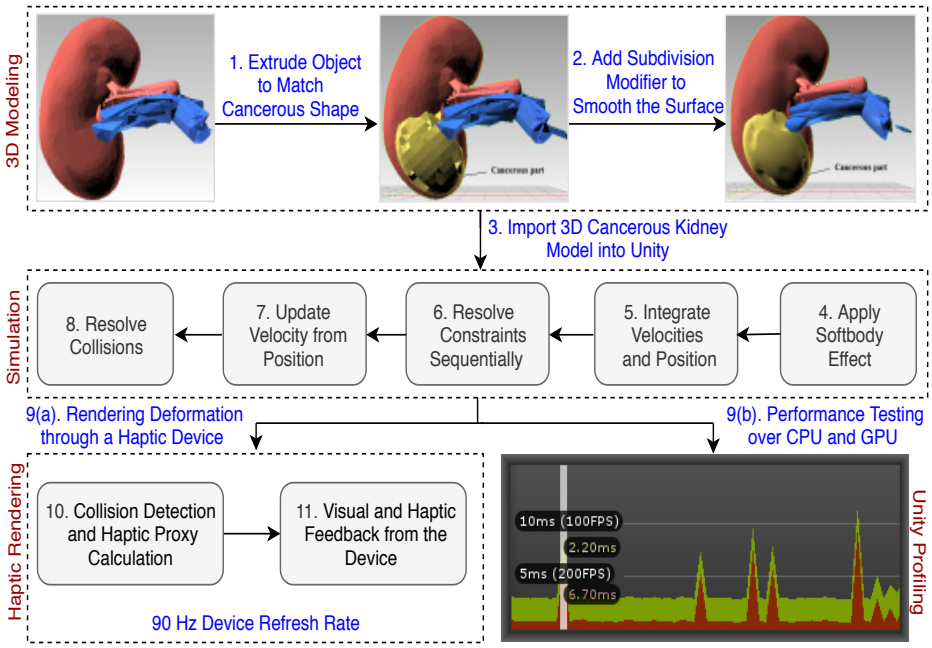


Figure 3. Laparoscopic partial nephrectomy system architecture.

module for input/output. Our simulator is based on the same hierarchy.

In our design component, we prototype a small renal cell carcinoma case with a peripheral mass of almost 3-5 cm. In practical terms, we construct the game module as below (Fig. 2 shows four primary steps):

1. A video (45) shows the process by which the insertion points are labeled and trocars inserted through the abdomen. The user can adjust the camera position to get the optimal viewpoint for his convenience.

2. The trainees are then required to identify cancerous tissues and other relevant structures.

3. With the help of two laser emitting controllers, trainees can easily mark and precisely cut along the cancerous structure, avoiding damage to the nearest tissues. The Unity profiler will record the task's performance time.

4. The final step is to tease away the cancerous part from the kidney.

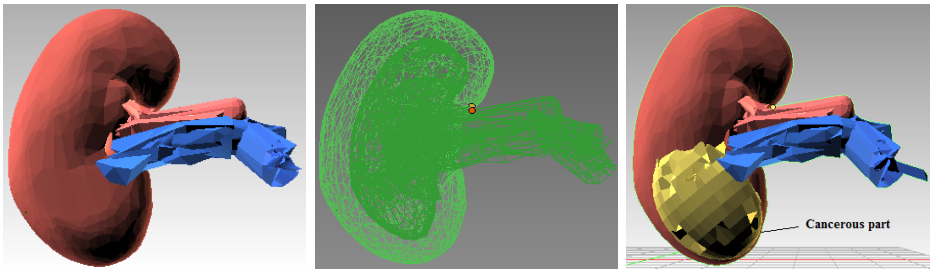
4 SYSTEM DESIGN AND PHYSICAL SIMULATION

The soft body for kidney organs has been designed using Blender (46), and the physics behavior is interpreted through the Unity physics engine. The rendering process features the physical appearance of the object while cutting triangular meshes with a specific force in a particular direction. Fig. 3 represents an abstract view of the complete system architecture.

4.1 3D Modeling

We have modelled the kidney and cancerous part with simplex meshes, which are topologically dual triangulations. These meshes are more adaptive, depending on the local energy. This technique is widely used for efficient physics-based modeling. It permits efficient and robust object deformation.

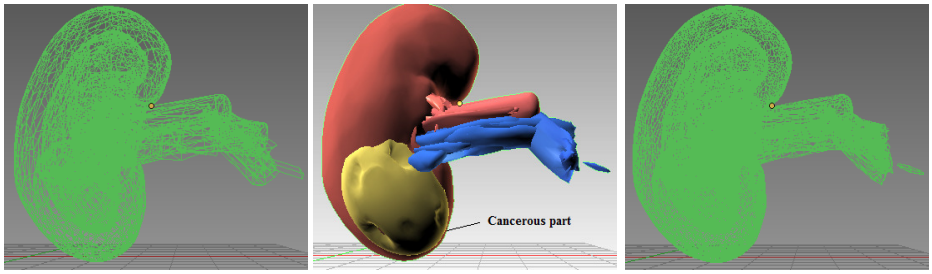
Joining Components: Fig. 4 shows the kidney model consisting of different 3D components (renal artery, vein, and cancerous part) extruded and then joined together using Blender's Join operation. A subfigure (a) and (b) of Fig. 4 present the 3D structure of a healthy kidney with a solid and wireframe view, respectively. Relevant materials have been applied to match the organ color scheme and gain a better understanding. After incorporating the cancerous part on the mesh surface, a solid view in subfigure (c)



(a) 3D healthy kidney model solid view

(b) 3D healthy kidney model wireframe view

(c) 3D kidney model solid view



(d) 3D kidney model wireframe view

(e) 3D kidney model solid view after subdivision modifier

(f) 3D kidney model wireframe view after subdivision modifier

Figure 4. Step-wise 3D modeling of kidney organ and cancerous structure.

and a wireframe view in (d) of Fig. 4 can be seen. The rocky mesh surface in (c) is not plausible as the mesh triangles are sparse enough.

Subdivision Modifier: A subdivision surface modifier has been applied to the mesh surface to make it look smooth, which works by dividing the mesh triangles into subsurfaces. The basic topology of the mesh remained the same; just some of the properties were adjusted. The subfigure (e) and (f) of Fig. 4 show the models after applying the modifier. Now the same surface area covers more triangles, which appear to be more delicate and smooth. This smooth structure is computationally heavy on the system as the CPU or GPU has to process more triangles than the model (c). We selected the model in (c) for simulation purposes as it's a trade-off between the computational cost and the visually realistic model.

4.2 Force based Soft Body Simulation

For this specific technique, a triangular mesh defines the structure of the soft body, and the constraints apply the necessary force to present the volumetric effect. Each surface point is modelled on account of forces like spring force, damping force, pressure force, and offset directional force. These forces exhibit the pressure on a particular region while the total number of vertices remains the same. The combined effect of these forces gives a subtle soft body effect, as the whole object would shift without changing its native structure.

We define the 3D soft body, SB3D, as
SB3D = ¡ S, F, V, N, C ¿
whereas S here defines the soft body,

- F = { F_j — j = 0 ,.., m - 1 } represents the set of forces for each point j.
- V = { V_j — j = 0 ,.., m - 1 } represents the set of velocities for each point j.
- N represents the count of total edges.
- C represents a constraints set being observed for object deformation.

Combined Force Effect: The composite force, F_j is centered on elasticity control force, pressure control force, damping control force, and a direction offset component from the point j on the body. The composite force F_i is defined by the Equation (1) as:

$$F_{\mathrm{j}} = F_{\mathrm{sj}} + F_{\mathrm{dj}} + F_{\mathrm{pj}} + F_{\mathrm{oj}} \tag{1}$$

where

- F_{sj} represents the spring force at point j,
- F_{dj} represents the damping force at point j,
- F_{pj} represents the pressure force at point j, and
- F_{oj} represents the offset force at point j.

Consider this simulation system with the numerical integration of Hooke's spring force described through Equation (2).

$$F_{\mathrm{j}} = m_{\mathrm{j}}.\frac{\partial^2 \overrightarrow{r_{\mathrm{j}}}}{\partial t^2} \tag{2}$$

The pressure force applied will deform the body shape acting in the direction of normal vector $\hat{n}$ as described in the Equation (3).

$$P = \overrightarrow{P}.\hat{n}[\frac{N}{m^2}] \tag{3}$$

Where P is a pressure value and $\hat{n}$, is a normal vector to the surface on which pressure force is acting. For calculating specific pressure forces, we multiplied pressure by the surface area, giving us Equation (4).

$$\overrightarrow{F_{\mathrm{P}}} = \overrightarrow{P}.\triangle A[N] \tag{4}$$

The algorithmic part 1 represents the soft body functioning of this model.

Result: Soft body effect

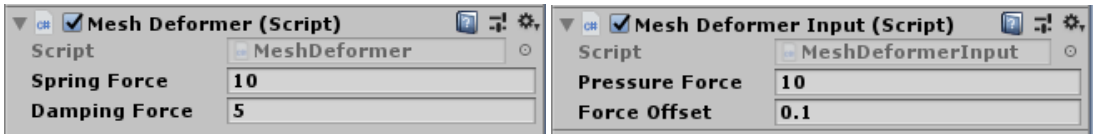
1. *Initialization*
2. *Loop over all particles:*
   UpdateVertex(int)
3. *Loop over all faces:*
   (a) UpdateVertexVelocity(vertex velocity)
   (b) AddPressureForce(3D vertices, force)
   (c) AddDeformingForce(3D vertices, force)
   (d) AddForceToVertex(int, 3D vertices, force)

Algorithm 1: Force Based Soft Body Algorithm

Detecting User Input: A ray is tossed into the scene from the camera location. The physics engine of Unity processes the location information of the object it hits. After clicking the controller trigger buttons, we move over the mesh surface to place a cut along the triangles, capturing the location of points. Adding the combined force at the contact points gives an elastic effect. Each surface point experiences a drag force until it returns to its original position, as expressed by Equation (5).

$$v_{\mathrm{d}} = v(1 - d\Delta t) \tag{5}$$

For a high value of damping force, the mesh becomes less bouncy. Spring and damping force scripted variables have been shown in part (a) of Fig. 5. The values for these variables can be easily changed, so the user may have complete control over how firm the generated soft body effect will be.



(a) Spring force and damping force variables **(b)** Pressure force and offset force variables

Figure 5. Mesh deformer input attached to scene camera.

Moving Vertices Under the Pressure Force: The function AddPressureForce() loops through all newly located points and adds the necessary pressure force separately. We can add a small direction offset in this loop so that the vertices are always driven into the surface, following the normal to the contact points. Pressure and offset force variables are shown in part (b) of Fig. 5.

Through Equation (6), we can find the exact distance between vertices and the direction in which force is applied.

$$F_{\mathrm{v}} = \frac{F}{1 + d^2} \tag{6}$$

One plus the squared distance ensures the full-force strength even if the distance is zero. Once we know the force, we can use the relation $F = \frac{m}{a}$ and $a = \frac{\Delta v}{\Delta t}$ to calculate the approximate change in velocity. Considering the mass m = 1 for each vertex, we finally have the Equation (7).

$$\Delta v = F\Delta t \tag{7}$$

The vertices can now be shifted with an absolute velocity, updated with each frame. After that, the relocated vertices are added to the mesh to change its shape. We need to recalculate the normals for the newly located vertices. Each vertex position is adjusted by the Equation (8)

$$\Delta p = v\Delta t \tag{8}$$

Dealing with Mesh Transformation: We only have a set of vertices representing an elastic surface, but it does not have a real volume like solid real-world objects. While cutting, vertices begin to move as soon as we apply pressure on them with the specified spring and damping effect, which is further handled through collision and bending constraints in PBD. The mesh colliders for the kidney model do not get affected by these forces; that's why the natural shape of the object never changes while simulating.

4.3 Constraint Based Physics Approach

In PBD, model points are linked by the triangular edges of the mesh with common connection points. While simulating, the positions of the points and the direction of the force (velocity is always tangent, constraint force is still normal) are calculated directly. This is why the instability issues can be handled easily through PBD (30; 31). Equation (9) and Equation (10) provide the central idea of sequentially resolving the system with constraints of equality and inequality in different time steps.

$$C_{\mathrm{j}}(x_{\mathrm{ij}}, ..., x_{\mathrm{in_j}}) = 0 \tag{9}$$

$$C_j(x_{ij},...,x_{in_j}) \geq 0 \tag{10}$$

While simulating, if one mesh triangle responds to the stretch amount in the direction normal to the force, the neighboring triangles will behave in response to bending constraints under the same stretching influence. The stretching constraint function is described for each connecting edge through Equation (11).

$$C_{str}(x_1,x_2) = |x_1 - x_2| - d_{12} \tag{11}$$

Where d_{12} is the length of the edge at rest position, the bending constraint generated for any two triangles is described through Equation (12).

$$C_{bend}(x_1,x_2,x_3,x_4) = arccos(n_1.n_2) - \varphi_{12} \tag{12}$$

where n_1 and n_2 represent the normal vectors in the rest position and φ_{12} is the dihedral angle between the triangle 1 and 2. The Equation (13) for minimizing the total energy defined as:

$$E_{tot} = \sum (k_{str} C^2{}_{str} + k_{bend} C^2{}_{bend}) \tag{13}$$

where k_{str} and k_{bend} are global stiffness parameters.

Result: Constraints handling with collision detection

1: **forall** vertices i **do** GenerateCollisionConstraints $(x_i \rightarrow p_i)$
2: **loop** SolverIterations **times**
3: ProjectConstraints(C_1 ,.....,C_n, P_1 ,.....,P_m)
4: **end loop**

Algorithm 2: Position Based Dynamics

The primary functioning of algorithm 2 is presented here: the solver iterations compute and project the position constraints. The calculated points are moved to their estimated locations, along with updating the point velocities. Distance constraints represent the connective part of the cancerous mass in the kidney. Each connection is breakable depending on the stiffness parameter and rest length. The marked points are torn apart by algorithms at a given break threshold. However, in our method, there is no simulation of fascia tissues, so the deformation is not visually plausible as it is just a single layer of a soft structure. When the cancerous component is separated from the kidney, the fascia looks like a broken piece of paper. Still, another considerable advantage is the reduced solving time due to the fewer mesh triangles.

4.4 Tactile Rendering and Force Feedback

The HTC Vive haptic device immerses the user with a strong sense of presence. The responsive haptic feedback improves cognition by providing consistent visual and sensory movement. The headset has a resolution of 1080×1200 per-eye, with a refresh rate of 90 Hz and a 110 degree field of view. The refresh rate is similar to most sensory devices, as shown in Fig. 6. However, we are enjoying a cost benefit here with the HTC Vive Pro VR device.

VR Devices	*Oculus Rift S*	*HTC Vive Cosmos*	*Valve Index*	*Samsung HMD Odyssey+*	*Razer OSVR HDK*	*StarVR One*
Refresh Rate	80 Hz	90 Hz	80 – 144 Hz	90 Hz	90 Hz	90 Hz

Figure 6. Refresh rate comparison of sensory devices (47).

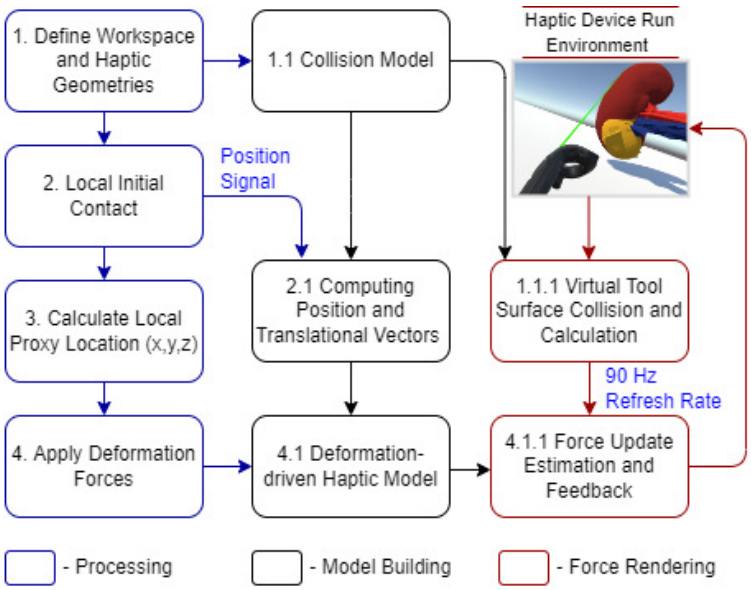


Figure 7. HTC Vive haptic device integrated workflow.

The SteamVR plugins in Unity allow us to manipulate haptic sensors in communication with organ tissues. Fig. 7 demonstrates the haptic device integrated workflow.

At first, the geometry track and initial contact information are processed. Then the haptic proxy continues to change along with the controller location. The fast refresh rate provides a plausible visual display of soft tissue deformation of a cancerous part. The PBD based collision model ensures stability while removing the triangular meshes from certain positions. This deformation gives visual feedback and an instant vibrational effect, which we have considered the haptic force feedback of the system. In this simulation scenario, the sensory device performance has been satisfactory while deforming the soft structure.

5 SYSTEM EVALUATION AND FEEDBACK

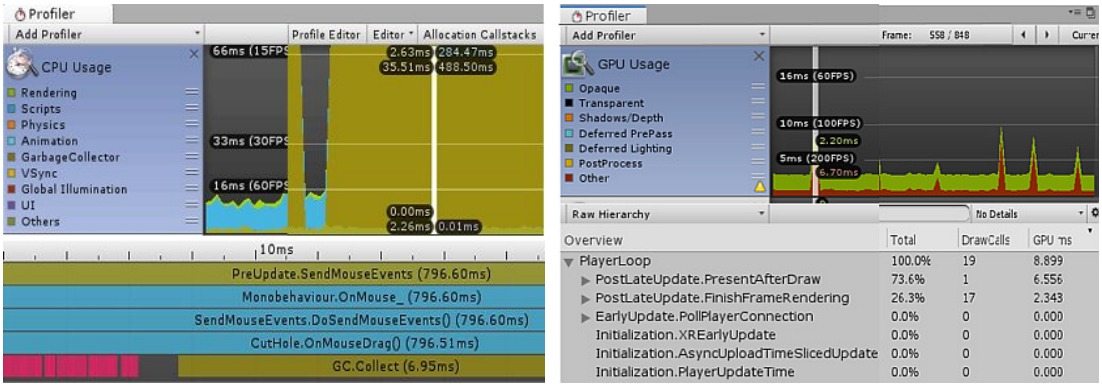
The Unity profiler has been used for evaluating system performance and usability. The Unity editor is good for fast profiling, as we do not have to release the application on the targeted platform for just testing purposes. This part discusses the experimentation and performance results obtained from the testing of the simulator on two different machines with different configurations.

5.1 Simulator Performance Comparison using Unity Profiler

The first simulation experiment was carried out on a system equipped with an Intel(R) Core(TM) i7-7700 CPU running at 3.60 GHz, an x64-based processor, and 8.00 GB of installed memory. The second testing experiment has been performed using a high-end graphics system, the GeForce GTX 1060 with Max-Q Design 6.00 GB GDDR5 memory on the card, 1280 shading units, and 80 texture mapping units. This Max-Q design has the advantage of less power consumption as compared to other graphics cards.

Unity's "CPU/GPU Usage Profiler" displays data such as the time taken by different functions and events to get run, such as rendering, physics, animations, and scripts. This describes all the key areas where our system spends most of its time. The CPU usage for rendering the simulation has been shown at a specific timestamp in part (a) of Fig. 8 while part (b) of Fig. 8 shows the same simulating system rendering on the GPU, and we can see that most of the time is allocated to the "Game Player Loop" and its hierarchy.

Table 1 and Table 2 show the complete component details for Unity's renderer and memory profilers.



(a) CPU rendering profiler **(b)** GPU rendering profiler

Figure 8. Screenshots from Unity Profiler rendering LPN simulation.

Rendering Parameters	CPU	GPU
Total Batches	19	9
Draw Calls	19	9
SetPass Calls	20	9
Triangles	50.2k	50.2k
Vertices	123.9k	121.9k
VRAM Usage	9.2MB	9.1MB

Table 1. CPU and GPU rendering profiler comparison.

Table 2. CPU and GPU memory profiler comparison.

Memory Parameters	CPU	GPU
Total Memory	38.9MB	49.9MB
Memory used by Unity	29.9MB	40.2MB
Textures	29/299KB	31/300KB
Meshes	11/6.8MB	6/6.8MB
Materials	24/79KB	26/87KB
Game Objects in a scene	14	16

GPU requires a high processing unit with a large amount of memory, which is quite expensive and hard to arrange by the hospital authorities when there will be a need for a large number of trainers. The computation time over the CPU was quite good with a short time step, but we had to compromise on the deformation performance, which was not plausible. The experience was much better with the GPU as it provides a parallel processing facility. Our simulation's overall computation time also decreased with a fast convergence rate.

5.2 Face and Content Validity for Simulator Performance Evaluation

To evaluate the overall performance and usability of the simulator, we have defined some face and content validity measures, as presented in Table 3 and Table 4. Each measure has a score range [0 - 9] (0 indicates a poor score, and 9 indicates an excellent score).

Table 3. Face validity measures for simulator performance evaluation.

Face Validity Measures
1. Realistic graphics
2. Precision of the platform
3. Instrument mapping
4. Anatomy representation
5. Interactivity of procedure

Table 4. Content validity measures for simulator performance evaluation.

Content Validity Measures
1. Useful for training novice surgeons
2. Useful for training expert surgeons
3. Useful for assessing cutting skills
4. Useful for assessing skill progression
5. Useful for assessing instrument handling

Seven final-year students and five interns from the department of nephrology at Shaikh Zayed Medical Complex Lahore voluntarily participated in this experiment. Subjects were given a brief explanation of the study's purpose and how to use the simulator. We are very thankful for their support here. A scoring system was assigned to each evaluation measure. The mean score values from both student and intern groups representing face and content validity measures are plotted in Fig. 9.

All participants found the simulated environment user-friendly and the HTC Vive haptic device helpful for increasing skill progression. We received positive feedback regarding the procedure interactivity and precision of the platform from both groups, as these measures reached the highest scores. The student group mentioned that realistic graphics should be improved. While performing the procedure, the intern group found instrument mapping to be ineffective. For simulation purposes, we have considered the laser pointer as the laparoscopic instrument.

Both groups agreed that the simulator is not in a position to train any expert surgeons yet. However, it possesses the ability to improve the tissue cutting skills of novice surgeons. More advanced testing techniques and measures will be used in the future to get more precise results. We intend to enhance the anatomy, force feedback, and simulator design and stability under the guidance of medical experts.

5.3 Game based System Advantages and Limitations

Using a constraint-based approach like PBD in combination with Unity has given us considerable advantages, along with some limitations.

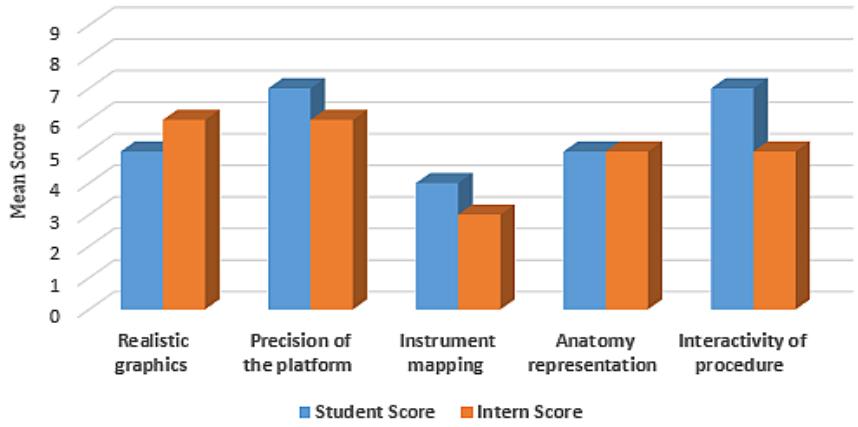
5.3.1 Advantages

1. The constraint-based approach provides the solution to the instability problem. This method provides control and supports physical-based effects.

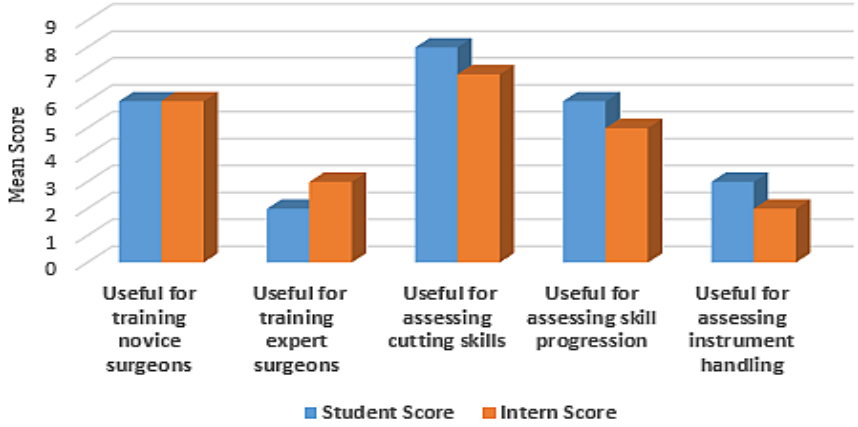
2. The point's positions and velocities are updated through a time-step method, so the overall computational time gets decreased.

3. Game-based simulators are less expensive and help in fast prototyping, with a bit of compromise in functionality.

4. Modern game engines like Unity provide a user-friendly environment for simulating medical procedures, collaborative tasks, and emergencies.



(a) Mean score from student and intern group for face validity measures (0-Poor, 9-Excellent)



(b) Mean score from student and intern group for content validity measures (0-Poor, 9-Excellent)

Figure 9. Simulator performance evaluation

5.3.2 Limitations

1. The overall computational time for simulation gets increased for a more complex system (multilayer tissue models).

2. The primary function of a game engine is to develop games. The human anatomy is too complex to precisely be simulated by a game or physics-based engine.

5.4 HTC Vive as a Surgical Trainer

Many studies have shown that virtual simulators are not very accurate and consistent and even do not provide realistic force or haptic feedback. These high-fidelity VR simulators also have a significant drawback: their high cost. In addition, hardware and software maintenance costs significantly more per year. Although these devices substantially affect overall surgical training, their high price can make them an unwanted choice in the presence of other comparatively low-cost resources. The HTC Vive head-mounted display is an affordable option that provides the vibration effect for tactile movement. For our scenario, we have considered that effect as haptic feedback from the system. We have compared our proposed system in terms of price and function with some of the standard commercially available virtual simulators. A comparative cost analysis has been shown in Table 5. Our study has shown that the HTC Vive can act as the most affordable VR-based surgical trainer combined with an open-source game engine with a bit of compromise in performance and feedback functionality.

Table 5. Comparative cost analysis of various virtual simulators

Device	Description / Characteristics	Cost
MIST VR	Advance technology based on surgical practices curriculum	$16000 - $25000
	An expanding library of modules	
	Used in suturing, knot-tying, needle passing and stitching	
LAPSIM Essence	Camera and instrument navigation	$5900
	Coordination	
	Lifting & grasping	
	Fine dissection	
LAP Mentor III	Portable	$500
	Cost-effective	
	Height adjustable tower	
	Non-haptic	
	Ideal for team training	
Oculus Rift S	Improved optics with vivid colors	$770
	Peed and comfort	
	Intuitive, realistic precision	
Samsung Odyssey	Inside-Out Tracking	$500
	High resolution	
	High-end integrated audio	
	Wider field of view	
HTC Vive	Fully immersive	$399
	Intuitive controls and gestures	
	Realistic haptic feedback	
	Eye relief adjustments	

6 CONCLUSION AND FUTURE IMPROVEMENTS

This research must be seen as a first step toward developing a functional LPN training simulator. In this study we have shown that a soft body of simplex meshes can be efficiently deformed with a low computational cost and high solving speed. A virtual, realistic LPN simulator based on Unity3D is an efficient and cost-effective solution for surgical training. The experiments resulted in a positive feedback from the medical users, who showed more control over the elasticity and force applied during laparoscopic procedure, thus enhancing their personal training experience. Another novelty of this study is using HTC Vive in LPN training, which has not been explored in this field yet.

We propose the following future improvements:

1. To allow a more realistic behavior, further requirements such as boundary limits, constraints, and force feedback for the system must be determined.
2. The organ and related anatomical structures (adhesive constraints, fascia tissues, and ureter) can be mapped from a large set of data using image analysis and segmentation for better anatomical representation.
3. For evaluation purposes, the simulator's proficiency goals can be determined, and proficiency scores can also be calculated for simulated procedures.

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