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Original Research Article

Training of Surgical Skills by a 3D Augmented Liver Model Response During Instrument Interactions Simulation

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ABSTRACT

Background and Objective: In recent years, interest in surgical robotics simulation has grown significantly, particularly among trainee surgeons. This trend is driven by the demand for cost-effective training solutions, improved surgical outcomes, and reduced training times. Simulations also play a vital role in the design and testing of surgical instruments, enabling analysis of static and dynamic loads and optimization of tool–tissue interactions. However, because of the complex nature of soft tissue deformation during surgical procedures, developing realistic and effective simulations remains a challenge. This study focuses on modeling liver responses during tool–tissue interactions in laparoscopic surgery. Building on prior research in surgical robotics, the goal is to develop a personalized training platform that enhances the skills of surgical personnel without the need for live human or animal subjects.

Materials and Methods: The study begins by analyzing the motion of a tactile surgical instrument interacting with tissue. Direct kinematics is used to enable remote control of surgical robots by the lead surgeon. To improve control accuracy, systematic positional errors are introduced into the control links. A simulation program is developed to define the operational workspace and potential tool actions. Movement within this space is controlled by four motors connected to transmission mechanisms. Analytical models of these mechanisms are used to optimize performance under defined constraints. In addition, a training simulation program (TSP) is created to model liver responses during tool–tissue interactions. This program visualizes the 3D behavior of organs using physical material properties and simulates collisions between solids. The Unity Game Engine is used to generate animations compatible with both standard and VR/AR environments.

Results: Experimental data involving various laparoscopic instrument tips and biological tissues are stored in a MySQL database. These data can be accessed via local workstations, institutional servers, or cloud-based platforms. Users can also store their simulation data on mobile devices or processor cards.

Conclusion: This study presents a comprehensive approach to developing a surgical training system that simulates realistic tool–tissue interactions. The findings contribute to the advancement of minimally invasive surgical education by enabling personalized, data-driven training experiences. The proposed system offers a scalable and ethical alternative to traditional training methods, with potential applications in both academic and clinical settings. The simulation programs effectively transferred acquired skills to real-world scenarios, demonstrating the system's potential for enhancing surgical training.

Keywords—*Augmented reality, Training program simulation (TPS), Software applications, Surgical robotics, Surgical training.*

INTRODUCTION

Software applications offer innovative solutions in Medicine. In surgery, this progress allows the development of surgical simulators that reach the maximum level of realism and emulate complex procedures, taking into account the specificity and anatomical requirements of individual patients. Also, the simulation is a suitable method for training surgeons in complex movements and operations because it reduces the duration of the surgeon's training in minimally invasive surgery (MIS). The methodology for developing a web-based laparoscopy e-training system is particularly important.[1] Software applications can provide a surgical environment with its physical properties, texture, and complexity. Computer-based methods can be the main part of surgical tool design. To solve new problems that continue to arise in real surgical procedures, new tools are created every day. An important step in the creation of surgical instruments is the development and application of a virtual environment and near-real models to simulate the response of the organ when interacting with an instrument. Simulation methods can provide different scenarios for the operation to take into account different anatomies, pathologies, and working areas. Training modes include tabletop models, virtual reality (VR), augmented reality (AR), animals, and cadavers. There are claims that the haptic interface, along with the visual simulation, aids the student or young surgeon to get a virtual experience of the surgical procedure as in a real patient operation. However, a number of studies prove that a combination of models is more effective than model-based learning alone.

The main ways to accomplish the simulation task are: a model, a detailed description of the real-world application of the model, and the applied forces/moments. Different medical procedures require different organ models.

The basic approaches for model response during instrument interactions are Mass-Spring System (MSS)[2] and Finite-Element Method (FEM).[3] In the first approach, the geometric model of an organ is represented as particles with their own positions, velocities, and accelerations, which are connected by springs and dampers. The particles move under the influence of the forces of the surgical instruments. In FEM, each element of an organ model is calculated to obtain the deformation of the model under the applied forces.

Real-time surgical simulation requires computing the deformation of viscoelastic human tissue and generating both graphic and haptic feedback. Deformation simulation is based on a sequential calculation of the tissues' shape. The reaction forces result from the tool–tissue model interactions, where the virtual tools are controlled by the smart tools. Tissue models must look and behave realistically and be based on the physical laws related to human organ behavior.

Models used for simulation are mainly based on geometry or mechanics. Geometric models are not accurate enough because they only simulate relative visual displacements. Mechanical models are accurate, but for a VR simulation, they can change continuously until they reach an equilibrium state, which makes them difficult for the operator to manipulate.

Sorkine and Alexa4 propose a method for surface modelling, where the object changes the shape of a mesh while preserving the details. It is characteristic that the peaks of the original grid must be specified. Then, the boundary is determined for new positions, so that the rest of the mesh vertices adapt to the new shape. The original geometric size of the mesh should preserve as much of the deformation as possible.

Some authors show a virtual simulator for pre-rolled soft tissue suturing without showing the making of knots, which is a basic moment in suturing.[2]

Telesurgery is evolving thanks to AR and wireless technology. Lead surgeons can train students and young surgeons in complex surgical procedures. Surgery is also aided by 3D printing technology. Tumor data can be extracted from CT or MRI scans and converted into a digital 3D model, which can then be 3D printed. From this model, the surgeon can see the relationship between the tumors and the surrounding tissue, which aids in planning the surgery.

The student or young surgeon can virtually experience all the essential aspects of a procedure through visual simulation and haptic technology, which otherwise would involve invasive techniques on a real patient or a corpse.

Great computing power and accuracy of haptic devices are only part of the advantages characteristic of modern laparoscopic simulations, which create favorable conditions for the process of preoperative planning and the training of surgeons. One such development is the EU PASSPORT for the simulation of laparoscopic liver resection, which uses many modern methods and the capabilities of the GPU to simulate various deformable organs in real time."[5] The work of Acharya, where the kinematics of the surrounding organs are studied, is also intended for simulation training and access (geometry) to the liver.[6] In this research, diaphragm movement patterns are also presented for use in simulators for preoperative planning and training. An advancement in the field of organ modelling is also the work of Villard,[7] where respiratory movements of the chest and soft tissue behavior of organs of a group of patients segmented by computed tomography in a liver biopsy simulator are modelled. A nonlinear liver model to measure organ response to force, accounting for organ deformation and boundary conditions, is presented by Lister.[8] The accuracy of the model is assessed by drilling simulation.

There has also been progress in the modelling of surgical procedures. A team of scientists presented a real-time electrosurgical simulation virtual tool where the relationship between heat generated in the tissue and applied electrical potential was explored.[9] All this finds good application in virtual surgical ablation. Over the years, 3D organ models have moved from linear[10] to nonlinear,[11] Moreover, simulations are increasingly complex and realistic, making them accessible and attractive for applications.

Force feedback simulators are a more intuitive means of providing haptic information to the surgeon, while visual force feedback provides information about instrument contact with tissue under certain conditions. That is why haptic devices with touch simulation are increasingly being used. They are used in medicine for training and planning operations.[12] One of the first palpation developments is a 3D visual and haptic liver diagnostic simulator with open-source software.[13] SimSuiteTM System by Medical Simulation Corporation is one of the representatives of haptics devices, with a realistic simulated clinical environment.[14] It offers haptic systems with real scenarios and images together. The force feedback is transmitted by an endoscope to give the real feeling. The system includes personal or team training with varying levels of complexity. Its possibilities are the patient history, diagnosis, risk assessment, and intervention preparation.

The training program proposed in this publication, referred to as the training program simulating (TPS), facilitates the observation of three-dimensional (3D) augmented model responses during tactile instrument interactions within the context of surgical education. This program was developed to enhance the training of students and improve the qualifications of surgical personnel in the use of laparoscopic instruments. The application presented herein represents an advancement of an existing mechatronic system designed for laparoscopic surgical training, aimed at both student education and the professional development of surgeons. The system is constructed on a modular framework, reflecting the principles underlying the program's implementation. This training platform was developed so that students and surgeons can improve their qualifications without using living organisms—humans and animals.

VIRTUAL AND AR SIMULATORS AND THEIR PART IN SURGICAL EDUCATION

One of the first VR simulators is the Satava, proposed in 1993. It used a computerized 3D model of the abdominal cavity and a head-mounted display (HMD).[15] Satava is also targeting the military and aerospace industries, which rely on VR for training, to apply this training to teach skills in operating rooms.[16] This simulator sets the stage for VR training in surgery for many types of procedures, from elementary tasks such as suturing and knotting to mimicking entire surgical procedures.

Virtual-based simulators can use an application that allows interactive exploration of 3D anatomical models and animations. VR makes it possible, through developed mobile applications, to explore different surgical approaches using a smartphone or tablet. Each virtual study uses 3D anatomical models and animations. A learning system aimed at understanding the patient's positioning according to specific anatomy and specific purpose. The study of each approach in 3D mode can be divided into phases too.

VR simulators allow trainees to practice individual movements or entire procedures in a near-real environment. Modern VR simulators can reproduce complex MIS by measuring various parameters of the procedure, including movement efficiency and node reliability, time to perform the operation, and even remote performance evaluation. The price of simulators is quite high, and they do not have tactile feedback and lack realism.[17–19] Because of the lack of realism, the models of corpses and animals in VR simulators should be added to get optimal training. Despite these disadvantages, the number of VR training simulators is growing. VR simulators, such as LapSimTM (Surgical Science, Gothenburg, Sweden),[20] were used for training basic laparoscopic surgery skills, and LapMentorTM (Simbionix Corporation, Cleveland, OH, USA),[21] was used for comprehensive training in laparoscopic sigmoidoscopy. Wynn et al. evaluated the effectiveness of this training in terms of the completion time of the process, the number of right and left tool movements, and the total route length of the right and left tool movements.[22] The research indicates high efficiency. Surgical simulation combined with virtual, mixed, and AR has become increasingly popular in recent years. AR is a technology where digital information does not interact with the real environment but is superimposed on the user's view of the external environment as graphics, audio, or video information.[23]

Telesurgery is a good aid for experienced surgeons teaching young surgeons in complex operations. Thanks to AR and wireless devices, AR simulators take advantage of VR and physical materials, tools, and tactile feedback. The 3D virtual model is a static preoperative photo of a certain part of the body, where even respiratory movements and manipulation of the organ are taken into account. These kinds of simulators are useful for simulation immediately before performing complex surgical operations.[24,25] The high simulation accuracy of the simulator allows visualization of different tissues, tumors, arteries, and veins.

AR in medicine dates back to 1988. One of the first medical AR systems was designed to display individual ultrasound slices of a fetus on a pregnant patient.[26,27] AR aids MIS by enhancing reality in the operating room, expanding the internal view of the patient based on preoperative or intraoperative data, and presenting the surgeon with detailed information about the operative field. Integrating pictures of virtual objects into real scenes is a major tool used in AR systems in medicine. While the surgeon's working area is synthesized in the virtual environment, AR superimposes computer-generated images on the actual view oriented to the direction of vision of the surgeon, who usually wears a suitable HMD or similar instruments. MEDICAL AR for Patient Workstation (MEDARPA) has recently been developed[28] which uses AR without HMD. The surgeon can see the exact location of the damage on the patient while being observed without making a single incision. It is possible to design invisible blood vessels, reducing the risk of accidental damage. The improved visualization from this technology can benefit a variety of clinical procedures. AR serves as a guide for planning practical surgical actions. The patient is positioned in AR: with the help of AR, it is possible to view the entire anatomy and change the position of the body along the three axes. AR visualizes the target of the operation before it is visualized on the simulator. Some of their weaknesses are related to the correct alignment of the position and orientation of the surgeon's eyes with a virtual coordinate system of the augmented images, the spatial tracking systems, and the virtual environment peripherals used.

Simulators combining haptic interfaces with AR tools can be used to detect deviations between the real position and the preoperative plan and to generate guiding forces for the surgeon. Robot-guided instruments follow the movement of the surgeon, who senses forces interacting with the tissue through the haptic device. The haptic device includes preoperative planning based on medical images and AR to guide the surgeon's movements; AR models also provide visual feedback to the surgeon.

The advantage given by the simulation is that different parameters can be optimized, which gives good results in different areas of application.[29]

From the foregoing, it is clear that the high level of technical complexity of advanced laparoscopic procedures and the lengthy training pose many challenges to surgeons. This makes simulation an important tool in the training of complex laparoscopic surgery. That is why our efforts are directed in this direction.

This paper is organized into the following sections: Section 2 is referred to as the Investigation of Instrument Moving. Section 3 marks Architectures of Control Program Algorithms. Section 4 refers to A Simulating Approach of Liver Model Response during Tactile Instrument Interactions and Its Results. At the end, there are sections on Future Challenges and Conclusions.

Software applications offer innovative solutions in all spheres of human life,[30,31] the most significant of which are in medicine. For this work, some calculating methods[32] for identifying both tool tissue force and maximum local strength are touched upon. Authors will specifically try to investigate these in the future.

A contemporary strategy yielding favorable outcomes involves the enhancement of existing systems across various domains and purposes, thereby conserving both financial and temporal resources in the research and development of new systems. An illustrative example is provided in reference,[33] which outlines the primary procedures for upgrading existing systems for the automation and control of industrial and manufacturing processes. In alignment with this approach, it proposes to upgrade a laparoscopic execution tool system for robotic applications, incorporating functionalities that leverage AR and simulation technologies to facilitate the training of surgeons.

INVESTIGATION OF INSTRUMENT MOVING

The action control in telecontrol (by the leading physician of the operation) is realized by the direct kinematic task. Moreover, to refine the action, the systematic positional error in the working position can be introduced into the control links. Solving the straight kinematic problem is a standard procedure.[34] It is possible to develop a simulation program to outline the workspace and possible actions in it. For an instrument with four independent movements, these movements are obtained by four motors and the corresponding transmission mechanisms between the motors and the executive links in this space. Figure 1 shows the possible instrument workspace and the instrument motions in this workspace. The relation can be written in Equation 1:

$$\begin{vmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \\ \dot{\varphi}_4 \end{vmatrix} = \begin{bmatrix} \frac{\partial \varphi_1}{\partial q_1} & 0 & 0 & 0 \\ 0 & \frac{\partial \varphi_2}{\partial q_2} & \frac{\partial \varphi_2}{\partial q_3} & \frac{\partial \varphi_2}{\partial q_4} \\ 0 & 0 & \frac{\partial \varphi_3}{\partial q_3} & 0 \\ 0 & 0 & 0 & \frac{\partial \varphi_4}{\partial q_4} \end{bmatrix} * \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix} \quad (1)$$

where $\varphi = [\varphi_1, \varphi_2, \varphi_3]^T$ is a vector of angular velocities of the executive link

$$J = \begin{bmatrix} \frac{\partial \varphi_1}{\partial q_1} & 0 & 0 & 0 \\ 0 & \frac{\partial \varphi_2}{\partial q_2} & \frac{\partial \varphi_2}{\partial q_3} & \frac{\partial \varphi_2}{\partial q_4} \\ 0 & 0 & \frac{\partial \varphi_3}{\partial q_3} & 0 \\ 0 & 0 & 0 & \frac{\partial \varphi_4}{\partial q_4} \end{bmatrix}$$

where J is the Jacobian matrix, which reflects the value of the transfer functions, including dependent movements; $q = [q_1, q_2, q_3]^T$ is the vector of angular velocities at the robot's joints.

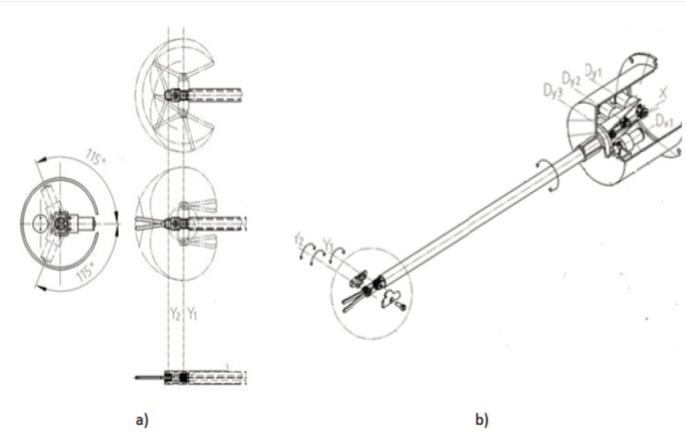

FIGURE 1. Possible instrument workspace and instrument monuments.

There is a need to determine the optimal area for the movement of the tool, using qualitative indicators. These indicators are based precisely on the Jacobian matrix. As a result, the geometry of the tool is optimized so that in a certain area, the configurations will provide optimal movement from the point of view of kinematics. This is important when scaling movements, that is, with a larger "size" of movement by the operator (master), minimal movements of the robotic tool are ensured. In an optimal configuration (a good quality indicator), these optimal configurations facilitate the control system.

The transmission functions $\frac{\partial \varphi_i}{\partial q_i}$ (i = 1, 2, 3, 4) along the main diagonal have the same structure:

$$\frac{\partial \phi_i}{\partial q_i} = i_{pi} \times i_{ni}, (i = 1,2,3,4) \tag{2}$$

where $i_{pi}\,(i = 1,2,3,4)$ is the value of the gear ratio of the reducer of the corresponding circuit (most often and in this case are equal); $i_{ni}\,(i = 1,2,3,4)$ is the value of the gear ratio of the wires. For the determination of i_{ni}, kinematic chains of links 2 and 3 are used, as the kinematic chain of link 4 is similar to link 3.

Transmitting functions at the major diagonal $\frac{\partial \varphi_i}{\partial q_i}$, where $i_{pi}\,(i = 1,2,3,4)$ possesses a similar structure.

$$\frac{\partial \phi_i}{\partial q_i} = i_{pi} \times i_{ini}, (i = 1,2,3,4) \tag{3}$$

where $i_{pi}\,(i = 1,2,3,4)$ is the value of the gear reduction ratio of the respective chain (often and in this case they are identical) and $i_{ni}\,(i = 1,2,3,4)$ is the value of the gear transmission ratio of the wire.

The derived analytical dependencies of the transmission functions make it possible to carry out calculation procedures for the optimization of dimensions under the existing limiting conditions and also to be implemented in the software for controlling the movement of the tool, which is explained in the next section.

A SIMULATIING APPROACH OF LIVER MODEL RESPONSE DURING INSTRUMENT INTERACTIONS

Tasks and Motions in Surgical Operation

The actions that are referred to in the performance of laparoscopic operations are numerous, and their priorities are defined and strictly performed by the medical teams. In this case, when they are referring to actions that require manipulative movements through specialized tools, they include:

Visualization (illumination and movement of a mini video camera into the body of patients) of the manipulated objects at the place where the controlled action is performed:

- Gripping with positional fixation of the object in order to be manipulated, without being uncontrolled;
- Gripping (clamping) in order to isolate and temporarily disconnect the object during manipulation with it;
- Clamping blood vessels to hold up bleeding damage.

Elementary actions such as touching and grasping are basic tool manipulations and are relatively easy to perform. More complicated actions are (1) dissections and (2) working with robotic suturing instruments, which require a lot of knowledge and skills from the surgeons, and they are more difficult to simulate too. However, some of them, such as robotic needle driving and grasping, which are easy in open surgery, are found to be more difficult to perform during laparoscopy.

A surgical task such as suturing includes a needle acting with one rotation and one translation.[35] The surgeon's hand is close to the surface being sutured while rotating the needle so that the needle moves in a circular path without damaging the tissue. In robotic surgery, it can be reduced to one movement—rotating around the axis of the instrument, bending the short part of the needle near the blunt end, and just in front of where it is held by the slave instrument, so that the needle moves in a circular arc, while the tool rotates about its axis.[36] Some authors have been focusing on knitting manipulation by robots. Some researchers have performed in vivo tests with different types of needles and tissues, showing that the required range of force and resolution is 2.5 N and 0.01 N, respectively.[37,38] The results in Table 1 are obtained with the designed laparoscopic executive instrument for robots (Figure 2).

TABLE 1. Description of usability attributes.

Samples	Min. force (N)	Max. force (N)	Average value (N)	Amplitude (N)
Styrofoam sample	0.1	1.67	0.83	1.57
Styrofoam rubber sample	0.785	2.26	1.13	1.47
Muscle tissue sample	0.45	2.4	1.21	1.94
Sample liver, pork	0.05	1.96	0.93	1.9

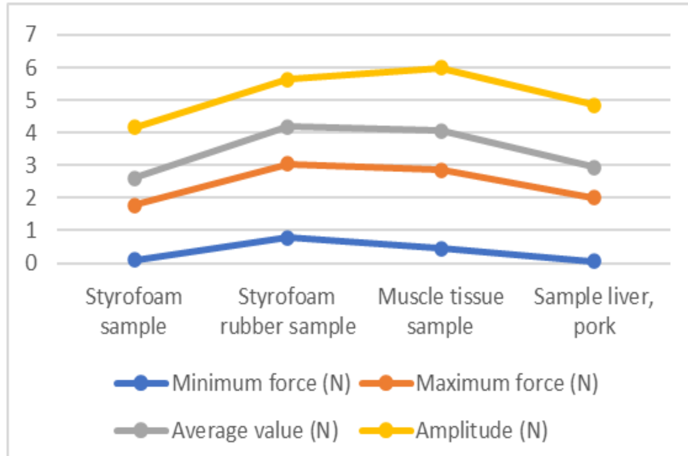

FIGURE 2. Force measurements for different samples.

The research shows the following results. The required force for soft tissues is about 0.2 N, the applied gripping force for soft tissues is 0.5 N, and it is 0.9 N for hard tissues. The required force is different for different cases. It depends on the patient's age, health, gender, and other factors. In general, the maximum force is from 1.5 to 3 N. In isolated cases, the required force is from 6 to 12.5 N. These cases occur when the instrument is used for tissue lifting. So, the instrument force is combined with the forces because of the properties of the fabric and those of gravity. However, the simulation program does not take gravity into account. The maximum cutting and spreading force is from 3 N to 6 N. Suture tasks force measurements show liver puncture up to 5 N, and the required gripping force is 3.45 N. [39–41]

This information is useful for realizing a 3D augmented model.

A SIMULATING APPROACH OF LIVER MODEL RESPONSE DURING INSTRUMENT INTERACTIONS AND ITS RESULT

A training simulation program (TSP) has been developed wherein the 3D extended model response of a human organ upon impact with external objects. The behavior of the model is represented by the collision of two solid objects with different physical characteristics. The physical properties of the solids are transposed to "physical material" properties that enable the behavior of the object in the TSP. The Unity Game Engine is used for the TSP, which is intended for developing graphical animations for conventional or VR/AR artificial representations.

TSP includes surface manipulation libraries such as the mesh class. Meshes contain vertices and multiple triangle arrays with corresponding vertices. All vertex information is stored in separate arrays of the same size. The mesh class, along with its vertices, vectors, triangles, and normal, can be used to deform a mesh grid on a 3D object. An example of using the mesh class to deform a 3D object in Unity (see Figure 3) is given with the script below:

```
using UnityEngine;

public class Example: MonoBehaviour

{

    void Update()

    {

Mesh = GetComponent<MeshFilter>().mesh;

Vector3[] vertices = mesh.vertices;

for (int i = 0; i < vertices.Length; i++)

{

//Some conditional transformation for example

                vertices[i] += Vector3.up * Time.deltaTime;

}

mesh.vertices = vertices;

mesh.RecalculateNormals();

mesh.UploadMeshData(false);

}

}
```

If the mesh surface deformation has to be executed on some event, the void method Start() should be invoked.

```
void Start()

{

Mesh = GetComponent<MeshFilter>().mesh;

mesh.Clear(); //preserves the existing mesh vertex positions

    //Do some calculations with the mesh.vertices and mesh triangles

}
```

Figure 3 shows an example of the usage of the mesh class for deformation of a 3D object in Unity.

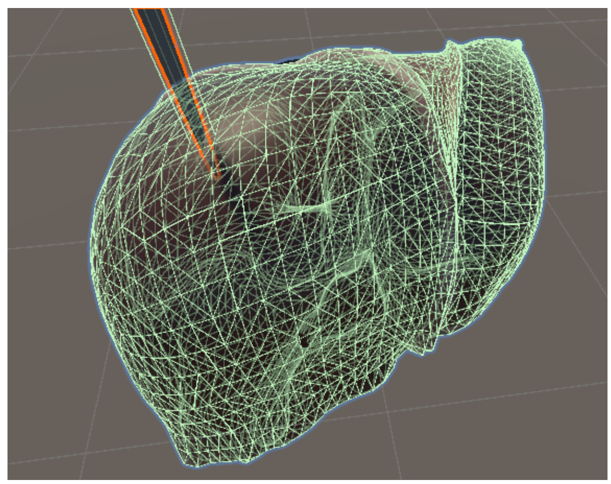

FIGURE 3. A 3D augmented model with mesh collider in Unity.

SOFTWARE ARCHITECTURE

The information from the experiments performed with different tips of the laparoscopic instrument and different biological tissues is recorded in a database that has a connection with the database of the application (developed on the basis of MySQL). The databases are structured as a collection of directories, one for each student (surgeon), with each directory carrying its own ID number (for students, this may be a faculty number). Each of the directories is a collection of subdirectories as follows:

• Personal data for the student/surgeon (three names, social security number, etc.). Only the learner and the teacher can access this subdirectory;

• Subdirectory with information about conducted experiments and their results in text and graphic forms;

• Evaluation of the achieved results and attestation of the student/surgeon;

• Other information required by the relevant university or medical facility.

At the discretion of the institution/clinic concerned, subdirectories of experimental results may be made publicly available to allow for comparisons and solutions for further simulations.

It is planned that the information accumulated in the relevant databases will be stored on a local operator station, a server of the relevant university/clinic, or a cloud medical server, on which more important results of conducted experiments will be published.

Each student/surgeon can save their information on their mobile phone or on a processor card. By their nature, processor cards have the same appearance as telephone cards. However, phone cards only have memory, while electronic chip cards contain a processor. The reprogrammable memory acts as a hard disk for the card—the data stored in this memory retains its values after the supply voltage is turned off.[42] The introduction of processor cards in the educational system in Bulgaria will allow the replacement of existing paper student books with electronic ones, which will guarantee greater reliability, security of information, and access to student data at all levels of educational institutions. Data change is associated with different priority levels. Each teacher will have a unique number/password to change the data in the cards of students/surgeons.

The solution assumes that each classroom is equipped with a personal computer with a minimum configuration that allows work in the Windows operating system. The database will be installed on the teacher's personal computer, as well as the terminal program allowing working with the processor cards. Each student/surgeon must be provided with a Basic Card ZC2.3 processor card (or similar) upon commencement of training by the instructor. The teacher or another person authorized for this activity personalizes the card using the personal computer and the included reading device.[42]

Various means of controlling access to the information are provided, such as the use of passwords, QR codes (for mobile phones),[43] ECG,[44] or an identification chip of the company Dallas Semiconductor/Maxim-DS9490B45 (for access to the software installed on the teacher's personal computer/laptop). The ECG device as a means of access control is proposed because one has already been developed for the modular laparoscopic system described above. At this stage, access control and information protection tools are based on the team's accumulated experience in this area. Information encryption tools are an important element in building a medical security system. This fact is a consequence of the requirements that personal data be protected, both at the local operator stations and on the way to another destination. As a means of access control, the wireless ECG device developed for the mechatronic system can be used.

As the system is built on a modular principle, it will be further updated in the future, both in terms of hardware and in terms of developing new applications based on VR and AR, with the aim of improving the quality of training of medical students and improving the qualification of surgical personnel, which allows various skills and capabilities of the instruments to be acquired and tested before their application in real laparoscopic operations. In the area of information protection and access control means, the possibilities of using other means will be explored, which will be applied at all levels of usability of the accumulated information, which will be effectively used in improving the work with laparoscopic instruments. The possibilities and combinations of means of access control and protection of information in the developed mechatronic training laparoscopic system and the applications developed for it will be studied, as discussed in the present publication. A secure transfer of the information to central servers (of the educational or medical institution) or to specialized cloud medical servers is also planned.

Unity's physics engine is used to simulate the behaviors of objects in the scene and create realistic interactions between them, through physics-based behaviors applied to GameObjects (Rigidbodies and Colliders). Each of the objects should contain a Rigidbody component in order to be affected by the physics engine. The configuration of the Rigidbody component is made by adjusting the properties in the Rigidbody component's inspector. Some of the properties include:

- Mass: The mass of the object, which affects how it will be affected by forces;
- Drag: The amount of air resistance the object will experience;
- Angular Drag: The amount of resistance the object will experience when rotating;
- Use Gravity: Enables or disables the effect of gravity on the object;
- Is Kinematic: This checkbox makes the object not affected by forces, but it will be affected by collisions;
- Forces can be applied to objects by using the "Add-Force() function" of the Rigidbody component.

Using Unity's physics engine enables tool–tissue model interactions to be reduced to setting parameter values, without the need to write complex programs with physics dependencies. The correct settings give a realistic concept of the interaction pattern between the two objects, which depends greatly on the level of detailing of the mesh.[46] The coding is reduced to a basic script that initiates the interaction between collider objects and the deformation of the rigid bodies. The script has to be attached to the corresponding object. The result from a 3D augmented model response because of the impact with external objects is shown in Figure 4.

Figure 5 shows screenshots of the MySQL-based database in the developed application. Figure 6 shows the 3D augmented model response during tactile instrument interactions simulating in surgical education.

Figure 7 shows a photograph of the laparoscopic instrument included in the system (Figure 6). The tool

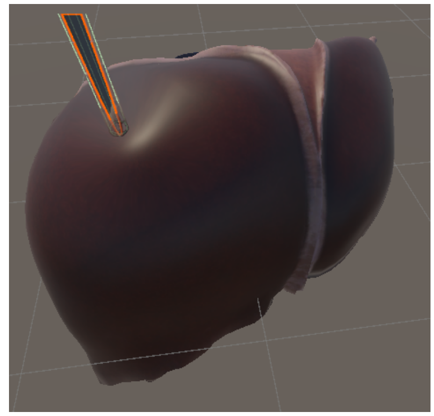

FIGURE 4. A 3D augmented model responds because of the impact with external objects.

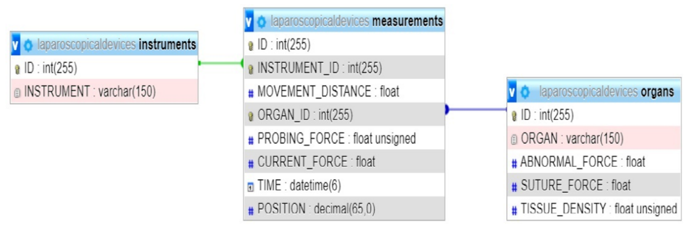

FIGURE 5. MySQL database.

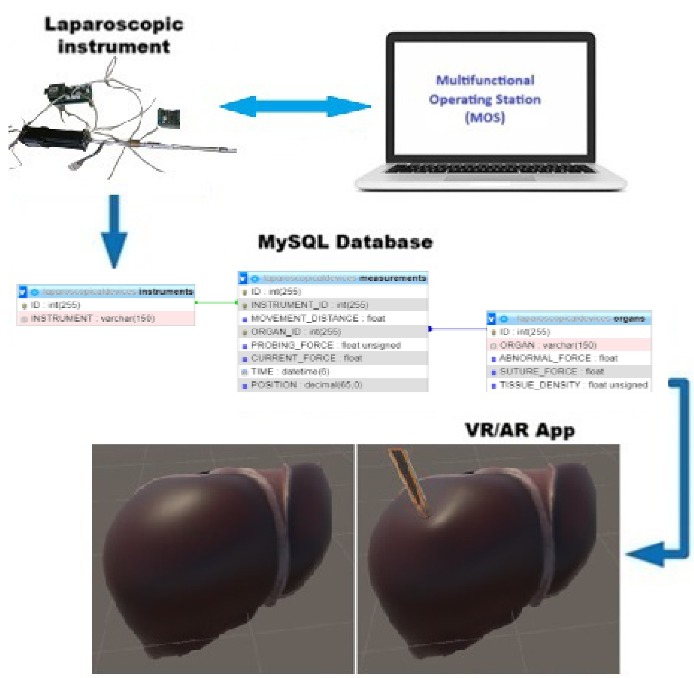

FIGURE 6. The 3D augmented model response during tactile instrument interactions simulation in surgical training.

was developed as part of the "System for analysis and control of mechanical properties of biological tissues," and is protected by a utility model.

Figure 8 shows four tips, called end effectors, that were designed for contact of the tool with a given surface.

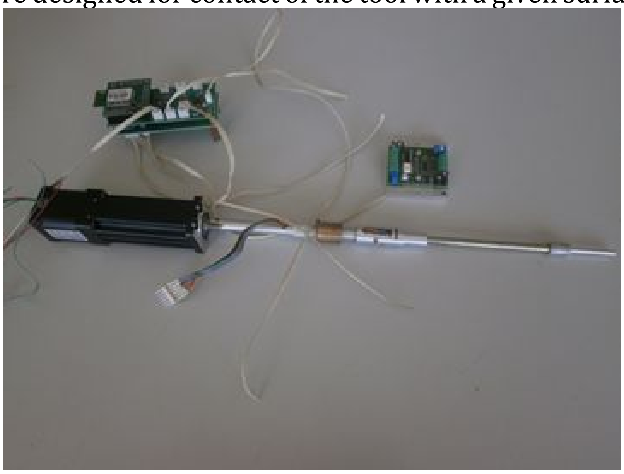

FIGURE 7. An experimental module with force capabilities.

Several experiments were performed with the developed experimental model of a laparoscopic executive instrument.

Figure 9 shows the frame of the AR video stream. The program could be installed on smart devices such as smartphones or smart glasses and exploit built-in microelectromechanical system (MEMS) sensors (accelerometer, gyroscope, camera, solid state compass, GPS, etc.) to evaluate objects and positions situated in the surrounding world.

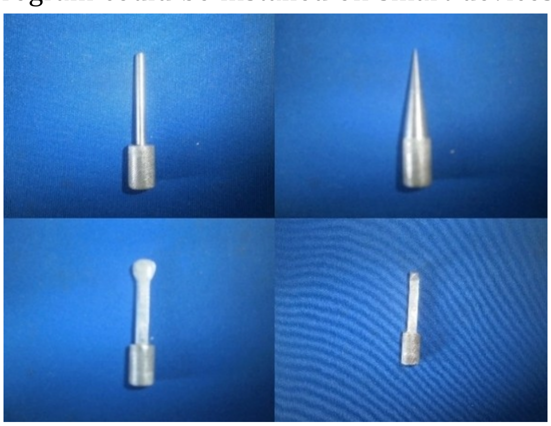

FIGURE 8. End effectors for an experimental module.

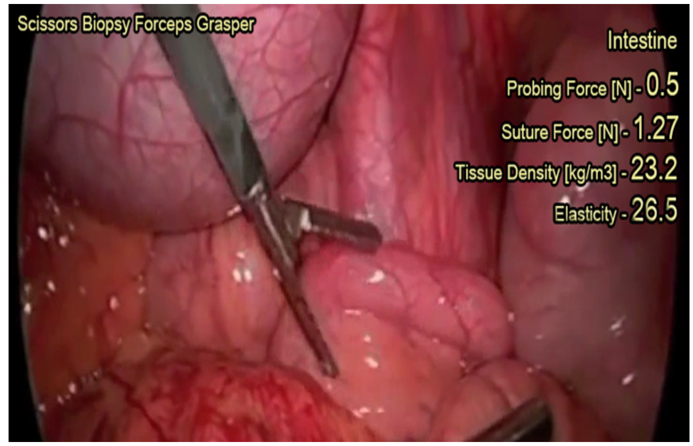

FIGURE 9. The frame of the AR video stream. The visual interface contains only essential information in order to allow the surgeon to concentrate on the medical task.

EVALUATION OF ACQUIRED SKILLS

The review of the literature revealed two approaches to evaluate the skills of medical students and staff: (1) the objective structured assessment of technical skills checklists and (2) the GOALS.[47,48] Methods using AR have been developed to overcome some of the shortcomings of working with laparoscopic instruments, and basic assessment methods have been identified. More information on the topic is given by Roberto et al.[49] These approaches help with the objective assessment of surgical competencies before performing an MIS.[50]

CONCLUSION

The simulation of realistic interactions has become a tangible reality, despite existing challenges such as modeling realistic behavior during user interactions, fluid dynamics, and force feedback mechanisms. The application of computer graphics techniques in medical contexts is increasingly prevalent; however, numerous research challenges persist. These include the need for enhanced realism, a broader array of solution approaches, and improved computational methods for applications. The optimization of training simulators and the effective utilization of computer graphics methods remain critical areas for development.

This article presents a simulation approach that examines the response of a liver model during tactile interactions with surgical instruments. Initially, the investigation focuses on the movement of instruments, utilizing a direct kinematic task to control actions in teleoperated environments. The derived analytical dependencies of the transmission functions enable the execution of computational procedures aimed at optimizing dimensions within specified constraints, which can subsequently be integrated into software for controlling tool movements. The architecture of the control program algorithms is reviewed, highlighting the simulation module's relevance to this research. This training platform was developed so that students and surgeons can improve their qualifications without using living organisms— humans and animals

Subsequently, a 3D augmented model simulating a human organ's response to external impacts is developed using Unity 3D modeling capabilities. The model's behavior is illustrated through the collision of two rigid objects exhibiting different physical properties. The application of the mesh class for deforming a 3D object within Unity is implemented via scripting. Results depicting the 3D augmented model's response to external impacts are presented, with the coding distilled into a fundamental script that initiates interactions between collider objects and the deformation of rigid bodies. This script must be attached to the corresponding object, with an example provided utilizing the Unity Engine.

Future investigations will specifically focus on computational methods and animation projections to quantify both tool–tissue forces and maximum local strength. The outcomes of this research are deemed applicable to surgical education, allowing for the development of training tasks aimed at cultivating skills necessary for minimally invasive surgical procedures.

AUTHOR CONTRIBUTIONS

Conceptualization, V.I., P.V.V. and A.T.B.; Methodology, V.I., P.V.V. and A.T.B.; Software, P.V.V. and A.T.B.; Hardware, V.I.; Validation, V.I, P.V.V. and A.T.B.; Formal Analysis, V.I and P.V.V.; Investigation V.I., P.V.V., and A.T.B.; Re-sources, V.I. and P.V.V.; Data Curation, V.I.; Writing–Original Draft Preparation, V.I., P.V.V. and A.T.B.; Writing–Review & Editing, V.I., P.V.V. and A.T.B.; Visualization, P.V.V. and A.T.B.; Supervision, V.I. and P.V.V.; Project Administration, V.I.

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The authors declare no conflict of interest.

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