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INTERDISCIPLINARY TOPICS

THE THREE-DIMENSIONAL AUGMENTED MODEL RESPONSE DURING INSTRUMENT INTERACTIONS SIMULATION

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ABSTRACT: In recent years, there has been considerable interest in simulations in surgical robotics, and in particular simulations in training surgeons. This is largely due to cost-effectiveness, the critical growing needs in surgical care and reduced training time for surgeons, improved outcomes during surgery. Simulation is a commonly required task in the design of surgical instruments also. With the help of simulation, it simulated a wide range of static and dynamic loads with linear and non-linear material properties, and optimized tool-tissue force interactions. Simulation in the surgical area is extremely challenging due to surface and anatomical soft tissues deformations and the nature of the interventions. The aim of the work is to create a suitable three-dimensional augment model to provide necessary information about the liver responses during tool-tissues interactions in the operating environment. To achieve this purpose, the following is done i) an investigation of the instrument motion is initially made to control the action under remote control ii) results from a simulating approach of liver model response during tactile instrument interactions are shown. The ultimate goal of the work is to use the accumulated results into simulators in the training of surgeons and young doctors. This work is a continuation of previous research in the field of surgical robotics, where a surgical instrument is designed, and its kinematics is considered here.

KEY WORDS: Advanced Intelligent Systems, Model, Simulating, Medical Education, Surgical Robotics, Augmented Reality.

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1 INTRODUCTION

Modern intelligent systems and technics offer different innovative solutions in medicine [1]. In surgery, this progress allows the development of surgical simulators that reach a maximum level of realism and emulate complex procedures. Also, simulation is a suitable method for training surgeons in complex movements and operations, as it reduces the duration of the surgeon's training. Advanced technology can provide an environment with its physical properties, texture and complexity, computer-based methods can be the main part of the design of the surgical instrument. An important step in the creation of surgical instruments is the development and implementation of virtual environments 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 work areas.

The model-based approaches for the response of the model during the interaction of the instruments are the mass-spring system (MSS) [2] and the finite element method (FEM) [3]. The simulation models are mainly based on geometry or mechanics. Sorkine and Alexa [4] propose a surface modeling method in which the object changes the shape of a mesh while preserving the details. The original geometric size of the mesh should be preserved as much as possible from the deformation.

Some authors show a virtual simulator for suturing pre-wound soft tissues without showing the knotting, which is a key point in suturing [2].

The student or young surgeon can practice their skills through visual simulation and haptic technology together. One such development is the EU PASSPORT for the simulation of laparoscopic liver resection, which uses many modern methods and the capabilities of GPUs to simulate various deformable organs in real time [6]. The work of [6], where the kinematics of the surrounding organs are also intended for simulation and training, and the access (geometry) to the liver is also presented for use in simulators for preoperative planning and training. Also, an advance in the field of organ modelling is the work of Villard [7], where the respiratory movements of the chest, the behavior of soft tissues of a group of patients, segmented by computed tomography. The liver biopsy simulator was modeled by Lister [8]. The accuracy of the model is assessed by probing simulation.

There has also been progress in the modeling of surgical procedures. A team of scientists [9] presented a virtual tool for real-time electrosurgical simulation, where the relationship between the heat generated in the tissue is established. Over the years, 3D organ models have moved from linear [10] to nonlinear [11], making them accessible and attractive for applications. Force feedback simulators are a more intuitive means of providing tactile information to the surgeon [12]. One of the first developments in palpation is a 3D visual and haptic liver diagnostic simulator with open source software [13].

The SimSuiteTM System from Medical Simulation Corporation is one of the representatives of haptic devices, with a realistic simulated clinical environment [14]. It offers haptic systems with real scenarios and images together. Force feedback is transmitted from an endoscope to give a real sensation.

VIRTUAL AND AUGMENTED REALITY SIMULATORS

One of the first virtual reality (VR) simulators was the Satava, introduced in 1993. It used a computerized 3D model of the abdominal cavity and a head-mounted display [15, 16]. This simulator pioneered virtual reality training in surgery for a wide range of procedures, from simple tasks to simulated surgical procedures. Virtual reality-based simulators allow for interactive exploration of 3D anatomical models and animations. Virtual reality allows for the exploration of surgical approaches using a smartphone or tablet through the use of mobile applications.

Disadvantages include high cost and lack of tactile feedback and realism [17–19]. VR simulators such as LapSimTM (Surgical Science, Gothenburg, Sweden) [20], for training basic skills, and LapMentorTM (Simbionix Corporation, Cleveland, OH, USA) [21] for comprehensive training are widely used that is evaluated by Wynn et al. [22].

Surgical simulation, combined with virtual, mixed and augmented reality, has become increasingly popular. AR is a technology in which 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].

Augmented reality simulators are useful for simulation immediately before performing complex surgical operations [24, 25]. The high accuracy of the simulator allows visualization of various tissues, tumors, arteries, and veins. One of the first medical AR systems was designed to display individual ultrasound slices of a fetus on a pregnant patient [26, 27]. AR overlays computer-generated images onto the actual view oriented to the surgeon's line of sight, who typically wears a suitable head-mounted display, HMD, or similar device. Recently, the MEDICAL Augmented Reality for Patient Workstation (MEDARPA) [28] has been developed, which uses AR without an HMD. The surgeon can see the exact location of the patient's injury while being observed without making a single incision.

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

Modern intelligent technologies offer innovative solutions in all spheres of human life [29–31], the most significant of which are in medicine. Artificial intelligence also has the potential to help in healthcare in various ways [32, 33]. Of course, there are still some general open questions that have no clear answer [34].

The aim of the work is to create a suitable three-dimensional augment model to provide necessary information about the liver responses during tool-tissues interactions in the operating environment. To achieve this purpose, the following is done i) an investigation of the instrument motion is initially made to control the action under remote control ii) results from a simulating approach of liver model response during tactile instrument interactions are shown . The ultimate goal of the work is to use the accumulated results into simulators in the training of surgeons and young doctors. This work is a continuation of previous research in the field of surgical robotics, where a surgical instrument is designed and its kinematics is considered here. This project may be upgraded using some ideas from [35], some calculating methods [36, 37] and animation projections [38] for identifying both tool tissue force and maximum local strength authors will try particularly to investigate in the future.

2 INVESTIGATION OF INSTRUMENT MOVING

The working space and the reachable area depend on the linear dimensions (l_2, l_3, l_4) and joint restrictions (permissible angles of rotation of the executive links: $q_{1\,\mathrm{min}} \leq q_1 \leq q_{1\,\mathrm{max}}$; $q_{2\,\mathrm{min}} \leq q_2 \leq q_{2\,\mathrm{max}}$; $q_{3\,\mathrm{min}} \leq q_3 \leq q_{3\,\mathrm{max}}$; $q_{4\,\mathrm{min}} \leq q_4 \leq q_{4\,\mathrm{max}}$). The value of and are determined by the type of activity (grasping, moving, cutting, clamping, etc.) which most it is often symmetrical for both jaws and therefore, the kinematic chains are the same but with autonomous drive [39]. The latter provides a differential approach to objects, meaning that the action is performed by controlled displacement of one jaw relative to the other during manipulation without moving the object. Uncontrolled movement occurs when the jaws are driven (open, close) by one motor and the object of action is not symmetrically located with respect to the two jaws. Figure 1 shows the instrument motions in workspace.

The direct kinematic task is used to control the action in telecontrol (by the leading physician of the operation). Moreover, to refine the action, the systematic positional error in the working position can be introduced into the control unit. Solving the straight kinematic problem of the studied scheme is a standard procedure. It is possible to develop a simulation program to outline the workspace and possible actions in it.

The movement in this space is obtained by four actively controlled motors and the corresponding transmission mechanisms corresponding between the motors and the executive links in its most general form, this relation can be written.

$$\dot{\varphi} = J\dot{q}\,, \tag{1}$$

where $\dot{\varphi} = [\dot{\varphi}_1,\, \dot{\varphi}_2,\, \dot{\varphi}_3]^{\mathrm{T}}$ is the vector of angular velocities of the executive link; J – the Jacobi matrix, which reflects the value of the transfer functions, including

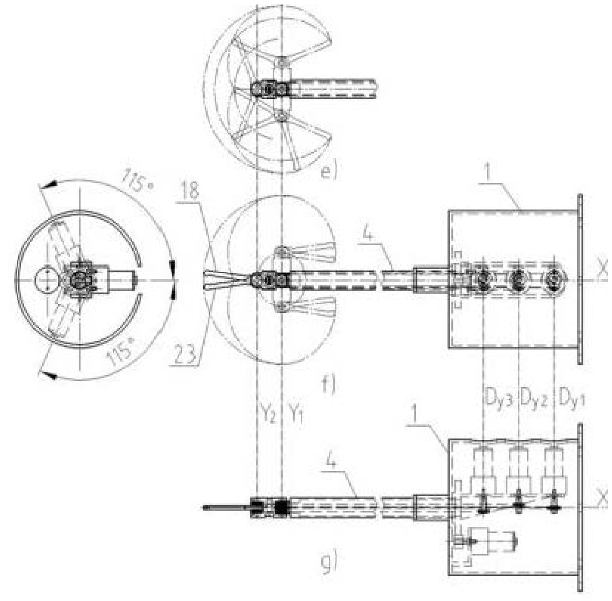

Fig. 1. Instrument motions in workspace.

dependent movements; $\dot{q} = [\dot{q}_1,\, \dot{q}_2,\, \dot{q}_3]^{\mathrm{T}}$ is the vector of angular velocities at the robot's joints.

The equation (1) can be written in more details as:

$$\begin{vmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \\ \dot{\varphi}_4 \end{vmatrix} = \begin{bmatrix} \dfrac{\partial \varphi_1}{\partial q_1} & 0 & 0 & 0 \\ 0 & \dfrac{\partial \varphi_2}{\partial q_2} & \dfrac{\partial \varphi_2}{\partial q_3} & \dfrac{\partial \varphi_2}{\partial q_4} \\ 0 & 0 & \dfrac{\partial \varphi_3}{\partial q_3} & 0 \\ 0 & 0 & 0 & \dfrac{\partial \varphi_4}{\partial q_4} \end{bmatrix} \begin{vmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{vmatrix} \tag{2}$$

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 Jacobi 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, i.e. 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:

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

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 i_{pi} $(i = 1, 2, 3, 4)$ are equal; i_{ini} $(i = 1, 2, 3, 4)$ are the value of the gear ratio of the wires. For determination of kinematic chains of links 2 and 3 are used, because of link 4 the kinematic chain of a link 4 is similar to link 3.

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

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

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_{ini} $(i = 1, 2, 3, 4)$ is the value of the gear transmission ratio of the wire.

For the determination of i_{pi} it has applied the following kinematic scheme of the proposed model of the laparoscopic robotized instrument, which is shown in Fig. 1.

The value of the components of (5) I_{pi} are received by

$$i_{pi} = \frac{\varphi_i}{\psi_i} = \alpha_i \qquad (i = 1, 2, 3, 4), . \tag{5}$$

The construction scheme and expression (2) showed that the controlled movement of link 2 causes dependent movement of links 3 and 4. To appropriately control this movement it is necessary to define the functions $\frac{\partial\varphi_2}{\partial q_3}$, respectively $\frac{\partial\varphi_2}{\partial q_4}$. Transmitting functions $\frac{\partial\varphi_2}{\partial q_3}$, respectively $\frac{\partial\varphi_2}{\partial q_4}$ are written in by

$$\frac{\partial\varphi_2}{\partial q_i} = i_{21}^{di} = \frac{1}{1 - \frac{d_i}{d'_1}} = \frac{d'_1}{d' - d_i} \qquad (i = 3, 4)\,. \tag{6}$$

Final for the angles q_i $(i = 1, 2, 3, 4)$ of rotation of the executive links when the rotation angles of the motors are set φ_i $(i = 1, 2, 3, 4)$.

Then it is obtained

$$\begin{aligned} q_1 &= \alpha_1 \frac{d_1}{d'_1}\varphi_1\,, \\ q_2 &= \alpha_2 \frac{d_2}{d'_2}\varphi_2\,, \\ q_3 &= \alpha_3 \frac{d_3}{d'_3}\frac{d'_3}{d''_3}\varphi_2 + \alpha_2 \frac{d_2}{d'_2}\left(\frac{d'_3}{d'_3 - d_3}\right)\varphi_2\,. \end{aligned} \tag{7}$$

Due to the specific nature of the construction and the requirements for symmetrical behaviours of executive links 3 and 4, the following is selected:

$$d_3 = d_4\,; \quad d'_3 = d'_4\,; \quad d''_3 = d''_4\,; \quad d'''_3 = d'''_4\,; \quad \alpha_3 = \alpha_4\,.$$

Then the last two expressions of equation (7) are identical, despite having two kinematic circuits and two controllable motors. If q_3, respectively q_4 has to adopt zero rotation values (to be stationary) when the link 2 is moving 2 ($\varphi_2 \neq 0$) for φ_3 and respectively φ_4 is received

$$\varphi_3 = \alpha_2 \frac{d_2}{d'_2}\left(\frac{d'_3}{d'_3 - d_3}\right)\frac{d'_3}{d_3}\frac{d''_3}{d'_3}\frac{\phi_2}{\alpha_3}\,. \tag{8}$$

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.

3 A Simulating Approach of Liver Model Response During Tactile Instrument Interactions

The actions involved in performing laparoscopy are extremely numerous and their priorities are determined and strictly implemented by the medical teams. Elementary actions such as touching and grasping are basic manipulations with instruments and are relatively easy to perform. Dissection, knotting and suturing are more complex and are also more difficult to simulate. A surgical task such as suturing involves a needle operating with one rotation and one displacement [40]. the needle to move in a circular path while the instrument rotates around its axis [41]. Some researchers have performed in vivo tests with different types of needles and tissues, showing that the required force range and resolution are 2.5 N and 0.01 N l, respectively [42, 43]. The study conducted shows the following results: For soft tissues, a force of 0.2 N is required, on average 0.5 N of gripping force is applied to soft tissues, and 0.9 N to hard tissues. The forces can vary in different ranges, between 1.5 and 3 N. In individual cases, the force varies between 6 and 12.5 N. The maximum cutting and spreading force vary between 3-6 N [44–46]. This information is useful for realizing a three-dimensional augmented model.

The three-dimensional augmented model response of a human organ due to impact with external objects is simulated. The behaviours of the model is represented by means of collision of two rigid objects with different physical characteristics. The physical characteristics of the rigid bodies are transposed to a "Physical Material" characteristics that enable the behaviours of the object in a simulation. The simulation is generated with the help of Unity Gaming Engine, which is used for development of graphic animations for conventional or VR/AR artificial representations.

Unity 3D modeming capabilities include libraries for surface manipulation, 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 normals may be used for deformation of an 3D object mesh grid. An example of usage of the Mesch class for deformation of a 3-dimensional object in Unity (see Fig. 2).

In Fig. 2 one can see an example of usage of Mesch class for deformation of a 3-dimensional object in Unity.

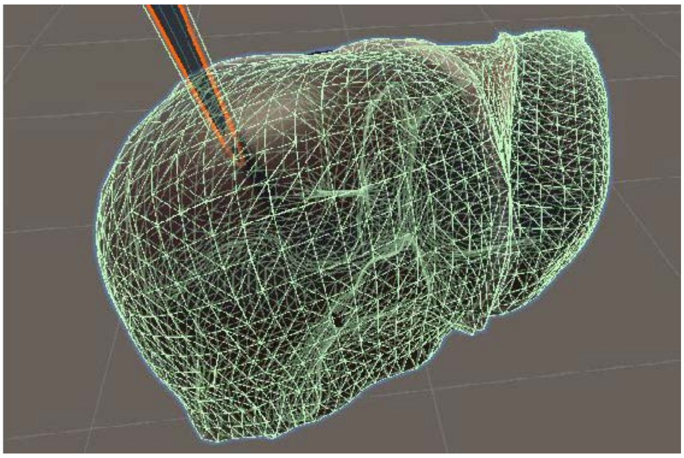

Fig. 2. A three-dimensional augmented model with Mesh Collider in Unity.

Unity's physics engine is used to simulate the behaviours of objects in the scene and create realistic interactions between them, through physics-based behaviours applied to GameObjects (Rigidbodies and Colliders). Each of the objects should contain a Rigidbody component in order to be affected by the physics engine. 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 AddForce() 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 realistic concept of the interaction pattern between the two objects which depends greatly of the level of detailing of the mesh [47].

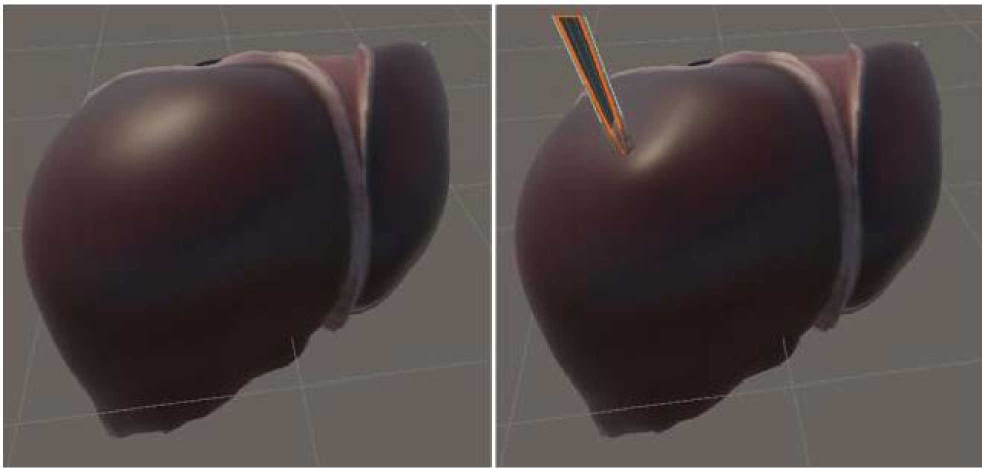

Fig. 3. A three-dimensional augmented model response of due to impact with external objects.

The coding is reduced to a basic script which initiates the interaction between collider objects and the deformation of the rigid bodies. The script has to be attached to the corresponding object. An example script is presented below:

```
using UnityEngine;
public class CollisionDeformation :  MonoBehaviour
{
   private Rigidbody rigid;

   private void Start()
{
       rigid = GetComponent<Rigidbody>();
   }
private void OnCollisionEnter(Collision collision)
{
// Apply force to the rigidbody of Liver in the direction of
the collision normal rigid.AddForceAtPosition (collision.impulse /
Time.fixedDeltaTime, collision.contacts[0].point, ForceMode.Impulse);
   }
}
```

The result from a three-dimensional augmented model response of due to impact with external objects is shown in Fig. 3.

Another C# script is needed for database communication management which is described in [48]. Its function is to connect to the MySQL database and to retrieve the data from the laparoscopic instrument.

```
using UnityEngine;
using UnityEngine.UI;
using System.Data;
using MySql.Data.MySqlClient;

public class DatabaseConnection :  MonoBehaviour
{
  private string serverAddress = "server=localhost;";’’   private string
databaseName = "database=LaparoscopicDevice;";
  private string username = "uid=***********;";
  private string password = "pwd=***********;";
  private IDbConnection dbConnection;
  private IDbCommand dbCommand;
  private IDataReader reader;
  private Text coordinatesText;

  void Start()
  {
   organText = GetComponent<Text>();
   string connectionString = serverAddress + databaseName + username +
password;
```

```
    dbConnection = new MySqlConnection(connectionString);
    dbConnection.Open();

    string selectQuery = "SELECT organ, suture_force, tissue_density FROM
organs";
    dbCommand = dbConnection.CreateCommand();
    dbCommand.CommandText = selectQuery;
  }
  void Update()
  {
    reader = dbCommand.ExecuteReader();

    if (reader.Read())
    string organ = reader.GetString(0, bytes.length);
    float sutureForce = reader.GetFloat(1);
    float tissueDensity = reader.GetFloat(2);
    organText.text = " organ:  " + organ + " Suture Force:  " + sutureForce
+ " Tissue Density:  " + tissueDensity;
  }   reader.Close();
  reader = null;

  void OnDestroy()
  {
    dbCommand.Dispose();
    dbCommand = null;
    dbConnection.Close();
    dbConnection = null;
  }
}
```

In Fig. 4 it is shown the three-dimensional augmented model response during tactile instrument interactions simulating.

4 FUTURE CHALLENGES AND CONCLUSIONS

Simulating realism is already reality, despite challenges such as realistic behaviour encountered when interacting with them, fluid flow, force feedback modelling. Medical applications with computer graphics techniques are becoming commonplace. However, many other research challenges remain including: improved realism, more variety of solutions and calculations methods of applications, training simulators and computer graphical methods should be displayed and used to their best advantages.

This article describes a simulation approach of liver model response during tactile instrument interactions. For these reasons at the beginning investigation of instrument moving is done. The direct kinematic task is used to control the action in telecontrol. The derived analytical dependencies of the transmission functions make it possible to carry out calculation procedures for the optimization of dimensions under the existing

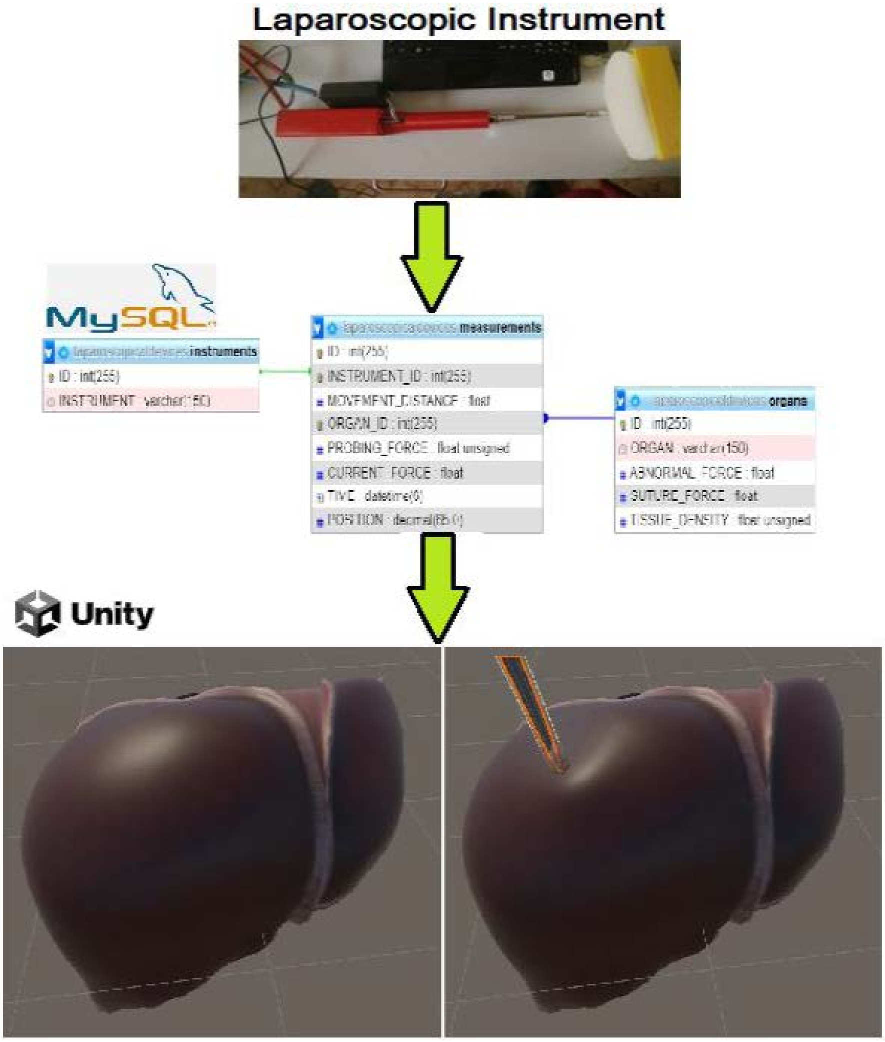

Fig. 4. The three-dimensional augmented model response during tactile instrument interactions simulation.

limiting conditions, and also to be implemented in the software for controlling the movement of the tool. After that a three-dimensional augmented model response of a human organ due to impact with external objects is simulated with Unity 3D modelling capabilities.

The behaviours of the model is represented by means of collision of two rigid objects with different physical characteristics. Application of Mesch class to deform a

3D object in Unity is provided with script. The results from a three-dimensional augmented model response due to impact with external objects are shown. The coding is reduced to a basic script which initiates the interaction between collider objects and the deformation of the rigid bodies. The script has to be attached to the corresponding object. An example script is presented using UnityEngine;

For this work some calculating methods and animation projections for identifying both tool tissue force and maximum local strength authors will try particularly to investigate in the future.

Received results from this work are suitable for surgical education. Training tasks can be developed that aim at acquiring skills for minimally invasive surgery.

From the viewpoint of mechanics, kinematics simulations will be performed to obtain information about the speed and velocities of the linkages and the end effector of the tool.

Also in the future, the mechanical properties of the liver and its force response on the instrument will be modeled, as well as kinematic simulations of the instrument's rotational speeds at the joints and its end-effector.

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