Implementation and assessment of Assistance-as-Needed Virtual Fixtures for VR Surgical Training with a *daVinci* surgical robot: an experimental study

Politecnico di Milano - Master of Science in Biomedical Engineering

Academic year 2022/2023

Candidate: ***Alberto Rota***
Supervisor: ***prof. Elena de Momi***

Abstract

This is the abstract of the essay

1 Introduction

Since its advent in the middle of the 1980s, robotic surgery has revolutionized the healthcare industry introducing safer and more efficient solutions to the challenges of surgical practices. By embracing robotic devices in a collaborative effort, surgeons and medical practitioners have been empowered with tools engineered to enhance their skills and optimize patient outcomes. From dental to orthopedic to neurosurgery, almost every area of the medical panorama has now been reached by robotics, with regulatory organizations approving novel procedures with increasing frequency.

Formally, *robot-assisted surgeries* are operations where the medical team works with a robotic device that actively interacts with the patient's body, manipulating tissues with precision instruments that are mounted on the machine itself. However, there is a major distinction between two methodologies of deploying robotic assistance [**?**]:

- **Teleoperated systems** involve a user who directly and continuously interacts with the robot, controlling its motion mainly by hand-held manipulators which replicate the surgeon's movement to the robotic actuation
- **Image-guided systems** rely on the acquisition of medical imaging data (in the form of CT scans, MRIs, *etc.*), later used for planning the motion of the robotic tools, without a direct and real-time interface with the surgeon

Mixed approaches are also possible, where teleoperation is accompanied by fully automated sub-tasks or where image guidance is updated in real-time by information gathered from sensors. In all cases, controlling the position, orientation and motion of the robotic system is, however, a responsibility of the surgeon himself, that takes advantage of the high precision potentiality of the mechanical system for achieving a less invasive, less error-prone and safer procedure. These systems are not meant to replace the physician, but rather to augment its capabilities [**?**]. Such a synergistic perspective highlights the role of the Human-Robot Interaction (HRI) paradigm, which involves all aspects of understanding, designing, and evaluating robotic systems for use by or with humans [**?**]: in the context of teleoperated surgical robots, HRI includes all the hardware and software features that enhance the surgeon's experience, improve his performance, grant a higher level of safety for the patient and achieve better surgical outcomes.

Modern surgical robotic systems like the *daVinci*® (Intuitive Surgical, Inc.) are extremely complex devices and, as such, demand long and extensive training programs to medical facilities and surgeons who want to operate them. In the past, surgical training was conducted on semi-realistic plastic phantoms, animals or cadavers, which other than not being a reusable resource in a lot of cases came out to be non-cost-effective solutions. More modern approaches consist, instead, of virtual environments where a simulated surgical scenario is re-constructed with a discrete level of realism, and where physics engines emulate the interaction between the virtual objects. A Virtual Reality (VR) environment has multiple advantages compared to the dated approaches above: infinite customizability and repeatability, non-destructiveness, easy setup, reduced costs, accurate progress monitoring, *etc.* Virtual environments, also, allow an easier developing and deploying of assistive algorithms that, by running "in parallel" to the surgeon's teleoperation, contribute to the HRI paradigm in terms of performance and safety.

Figure 1: A *daVinci*® surgical robot in the operating room

Surgical assistance has become an impactful element in the most recent surgical robotic solutions on the market, for the most part concerning visual cues super-imposed to the camera feed. For example, such visual cues may consist of the detection and localization, on the screen, of delicate surgical structures that should remain untouched by the instrumentation. Deep Learning and other modern AI-based computer vision techniques are the most useful in this context, and a few commercialized surgical robots already employ such assistive strategies.

Most of the surgical robotics solutions on the market consist of a teleoperation console that interfaces with the practitioner and, separate from it, the surgical robot itself, which mimics the movements of the surgeon in real-time. This setup allows for higher motion accuracy, tremor filtration and magnified viewing of the surgical area; nonetheless tactile forces, friction and texture perception are excluded from the so crucial visuo-haptic feedback loop that would guide the surgeon in a standard "non-robotic" procedure. This work, specifically, investigates the role of haptic assistance in the context of HRI, and analyses the role of mechanical forces when employed as a guidance medium.

1.1 Context

Surgical robotics training is a crucial aspect of the medical education process: aspiring robotic surgeons should develop a highly-specific skillset that includes cognitive, motor, and perceptual abilities that are not typical of any other medical field. Usually, medical facilities collaborate with the company commercializing the robot with the aim of defining a correct, extensive and effective training program that will yield skilled surgeons who will make the most out of the robot utilization in the Operatory Room (OR). If in the past these training programs were targeted only to experienced surgeons with established surgical skillsets, more recently they have been extended to medical students and residents, who conduct this phase in parallel to the standard medical education program: this attests how the surgical robotics field is becoming more and more mainstream, and how the medical community is embracing this new technology.

Assistance strategies are usually featured in the training programs, and they are meant to guide the trainee toward the optimal execution of a surgical task or to help him overcome a specific difficulty. This role is also covered by an expert supervisor, who is usually present alongside the trainee and provides suggestions and corrections regarding the execution of the procedure. With simulated environments and VR, a supervision of this kind can be implemented in the software and delivered autonomously, for example showing the trainee the correct way to perform a specific maneuver or highlighting the presence of an error.

Haptic assistance however is not yet a common feature in surgical robotics training programs. In a few cases, this is due to the lack of a haptic interface in the training setup (the manipulators may not be equipped with motors able to generate a force), but in most cases it is due to the lack of a clear understanding of the role of haptic feedback in the training process. Purpose of this work is, therefore, to investigate if the introduction of a haptic interface in the training setup can be beneficial for the trainee and which aspects of the learning process can be improved by such a feature.

1.2 Motivation

A single surgical robot on the market, the *Senhance*® (Asensus Surgical Inc.), is equipped with a force-torque sensor exploited for providing haptic feedback to the surgeon at the console: the sensor measures the forces and torques received by the end-effector when it comes in contact with the tissues and organs in the operatory space, which are then re-created in real-time by actuators integrated to the manipulators at the teleopereation station. As beneficial and effective as it is, it is not an assistance strategy since it cannot be used to re-direct the surgeon's movement towards targets or away from obstacles.

Moreover, none of the surgical simulators on the market include haptics as a tool for error correction and enhanced learning. A few research projects have developed highly specific applications where mechanical feedback was applied for training purposes, but none of them evaluates haptic assistance in the context of a generic surgical training program. The lack of a clear understanding of this concept is what motivates this project toward the implementation and assessment of a haptic interface in a surgical training setup where a VR simulator is built *ad-hoc* and from scratch.

2 State of the Art

2.1 The *daVinci*® Surgical System

Since the FDA approval recieved by Intuitive Surgical Inc. (Sunnyvale, CA, USA) in 2000, the surgical robotics market has been dominated by the *daVinci*® surgical system and its multiple evolutions (*daVinci X*, *daVinci Xi*, *daVinci Si* and most recently the *daVinci SP*). In 2021 there were more than 6,500 *da Vinci* surgical systems installed in 67 countries, and more than 55000 surgeons worldwide have trained on the use of *da Vinci* systems [**?**]. The numerous advantages in safety, non-invasiveness, precision and dexterity were the key factors that made this technology so disruptive, as well as the role that this surgical robot was designed to undertake in the OR: it is, as a matter of fact, a tool for the surgeon to exploit to enhance his performance, and not a replacement for the surgeon himself.

Three distinct componets make up a *daVinci* surgical system:

- The **Surgeon Console** accomodates the practictioner and acts as the primary interface between him and the robot. Seated at the console the surgeon grips the Master Tool Manipulators (MTMs) to control the motion of the robot arms, sees in 3D the surgical scene by looking into the High-Resolution Stereo Viewer (HRSV) and presses foot-switches to change specific settings.

- The **Patient Cart** is positioned next to the patient, and it mounts the Patient-Side Manipulators (PSMs) and the Endoscope Camera Manipulator (ECM). The PSMs are the robot arms that are used to manipulate the surgical instruments, while the ECM is used to control the stero endoscope camera.

- The **Vision Cart** handles the communication between all the hardware components, and it is responsible for the image processing and the motion planning of the robot arms.

Figure 2: The macro consituents of a *daVinci*® surgical system in the operatory room: the Surgeon Console (left), the Vision Cart (middle) and the Patient Cart (right).

2.1.1 The Surgeon Console

The console is the main input-output interface between the surgeon and the robotic arms. The surgeon, in fact, holds the grippers of the MTMs (one for the right hand and one for the left hand) and moves his hands, wrists and fingers. Each MTM is a 8 degrees-of-freedom serial kinematic chain: by knowing the coordinate of each rotational joint in the chain, the position and orientation of the gripper in the cart reference frame is know through forward kinematics. A detailed kinematics analysis of the *daVinci*® was conducted in [**?**], and the Denavit-Hartenberg (DH) parameter for FK and IK are determined asweel.

The pose of the MTMs grippers with respect to the console reference frame will then be used to compute the desired position of the end-effector of the PSMs, and inherently the joint coordinates through an inverse kinematics algorithm.

Seated at the console, the practitioner feels immersed into the surgical scene thanks to the 3D viewing capability of the HRSV. This pair of oculars is directly connected to the pair of cameras situated on the ECM: the disparity between the images displayed in the left and right lenses gives the surgeon the perception of depth, ultimately rendering the surgical scene three-dimensional.

Finally, the operator has also available a set of four foot switches that may be pressed without removing the hands from the manipulators. The switches clutch the system (for repositioning purposes), change the control from the PSMs to the ECM (to achieve a different viewing point of the surgical scene) and energize the mono-polar or bi-polar electrosutgical elements wether they are mounted.

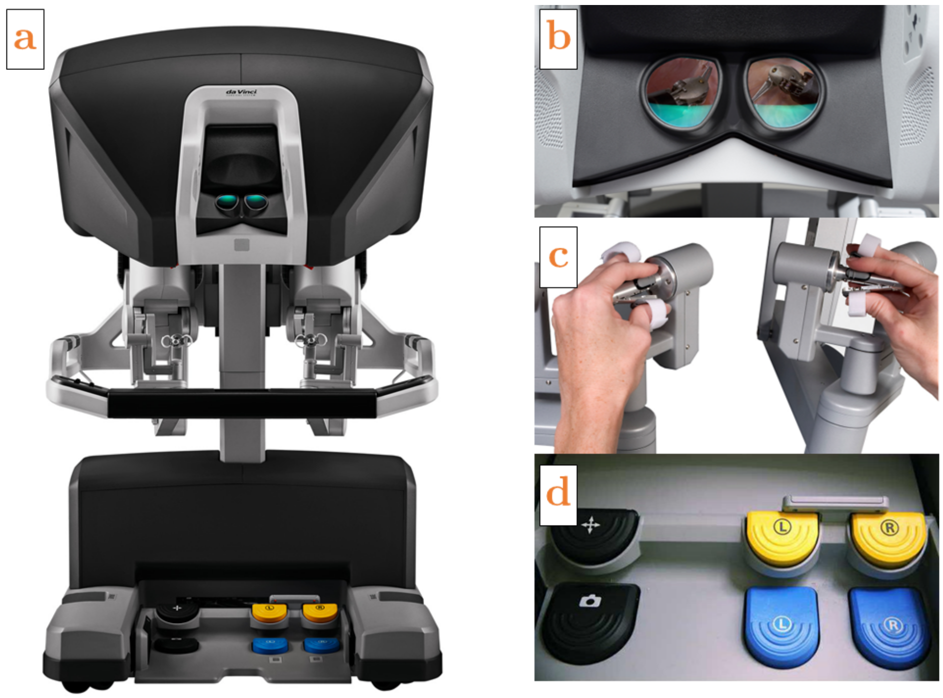

Figure 3: a. The *daVinci*® surgeon console; b. The HRSV oculars; c. The MTMs; d. The foot switches

2.1.2 The Patient Cart

A robot-assisted surgery with the *daVinci*® is set up by positioning the patient cart in proximity of the surgical table: the relative position of the two depends on the type of operation to be executed. The cart is the frame of allocation for the PSMs and the ECM: the ECM is the kinematic structure that controls the pose of the stereo endoscope camera, while the PSMs are the robot arms that are used to position and rotate the surgical instruments. A standard *daVinci*® robot mounts four PSMs, controllable by two surgeons independently seated at two different consoles; however, a single surgeon can teleoperate a two-PSMs-robot by himself as it's the case for this study. The position of both PSMs and the ECM relative to the frame of the patient cart can be further adjusted to optimize their pose with respect to the surgical site and the type of operation to be performed: a set of 4 Set-Up Joints (SUJs) can be used to position in space the base of each of the PSMs and ECM. The SUJ kinematic chain consists of 1 prismatic joint and 3 revolute joints moved manually by the surgeon or the OR nurse during the pre-operative phase.

Patient-Side Manipulators Each PSM is a 7-DOF actuated arm (5 revolute joints, 1 prismatic joint, and the gripper angle of opening), which moves a surgical instrument about a Remote Center of Motion (RCM), *i.e.* a fixed fulcrum point that is invariant to the configuration of the PSM joints and the position of which is dependent only on the base link reference frame of the arm. When the surgeon or the OR nurse manually positions the SUJs, ultimately he is positioning the RCM in space: because the RCM is a fixed fulcrum point, its position will not change while the PSM is moving. This feature is what makes the *daVinci*® a truly minimally invasive technology, since if the RCM is positioned exactly at the surgical incision on the patient's body the surgeon has a wide range of motion that will still not require a larger opening on the patient's skin.

Figure 4: A visual representation of the concept of Remote Center of Motion (RCM). Indepenently by the configuartion of the PSM, the RCM is always located at the same point in space.

Intuitive Surgical makes available a variety of surgical instruments that can be mounted on the PSMs and that cover a vast range of use cases, from tissue manipulation to suturing to cauterization. An attachment mechanism unique for all instruments allows one to quickly swap them even during the procedure.

Each of the available instruments designed by Intuitive Surgical exploits the *EndoWrist*® technology: a set of minuscule pulleys and cable allows the instruments' tooltips to achieve greater dexterity and range-of-motion when compared to the human wrist. This factor highly contributes to the minimally invasive nature of this surgical robot, as it permits achieving articulate and complex orientations that would require a larger incision if performed in a conventional approach.

Endoscope Camera Manipulator One of the robotic arms mounted on the patient cart holds the stereo endoscope camera and determines its pose in space. Contrary to a standard laparoscopic approach where the endoscope placement is a responsibility of the assistant surgeon, with a *da Vinci*® robot it's the operating surgeon himself that controls the position of the camera. As a matter of fact, when the operator at the console desires to change the viewing point of the surgical scene, he switches the control from the PSMs to the ECM by pressing one of the foot pedals. While that pedal is held down, the control signal from the MTMs is sent to the ECM instead of the PSMs, which moves accordingly.

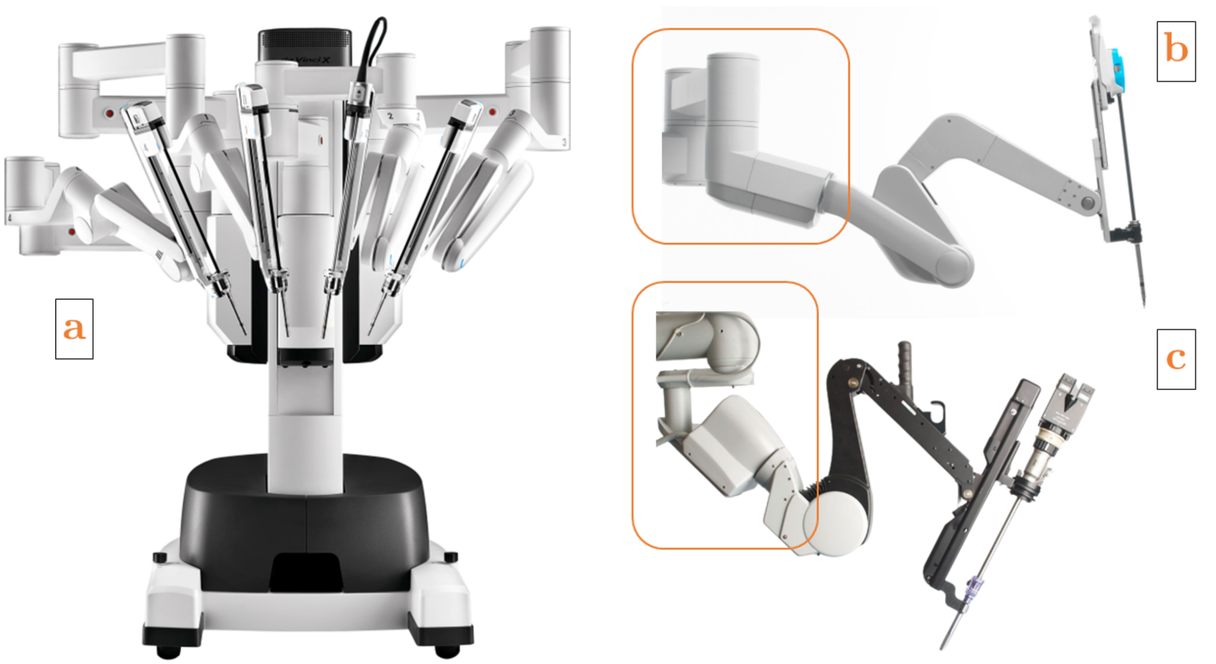

Figure 5: a. The patient cart of the *da Vinci*® robot; b. A PSM; c. The ECM; The SUJs of the PSM and ECM are in the orange boxes

2.1.3 The Vision Cart

The computational, control and communication hardware are hosted on the vision cart, which acts as the main interface between the components. It is also responsible for computing FK and IK and for powering the motors, sensors and endoscope camera.

2.2 VR Surgical Simulators

Aghazadeh A. *et al.* [?] demonstrated a statistical correlation between robotic performance in a simulated environment and robotic clinical performance, effectively showcasing the potential of VR simulators for surgical training and their comparability to the standard dry-lab phantom training. Most of the surgical robotics companies on the market have developed and marketed their own general-purpose VR simulator, and a lot of research projects have been conducted to develop simulators for specific robotic platforms or for testing specialized applications.

Intuitive Surgical commercializes the *daVinci SimNow* virtual surgical simulator (previously *dVSS, daVinci Skill Simulator*) as a skill-building framework for learning how to safely and successfully operate its surgical robot. It offers a realistic simulated environment comprising 47 skill exercises and 33 virtual surgical procedures, with performance tracking and procedure-specific feedback.

Other relevant simulators on the market [?] [?] are the *Mimic dV-Trainer* (dV-Trainer; Mimic Technologies, Inc, Seattle, WA, USA), the *Robotic Surgical Simulator* (RoSS; Simulated Surgical Systems, Buffalo, NY, USA), the *Sim-Surgery Educational Platform* (SEP, SimSurgery, Norway), and the *ProMIS* hybrid simulator (*Canadian Aviation Electronics Healthcare, Canada*). Visual assistance algorithms are present in most of the listed simulators, but haptic guidance is missing in all cases.

An anticipation of the role of virtual reality environments in surgery was published in the literature as early as 2001 [?], while the very first research work on the topic developing and validating a VR simulator interfaceable with the *daVinci*® appeared in 2008 [?]. From there, several studies and advancements have been published in literature [?]: initially, most of the work was focused on validating and comparing the simulators on the market, assessing their role in the acquisition of surgical skills in general [?] or for specific surgical fields [?]. Later, the focus shifted towards the development of new simulators and the improvement of existing ones, with the goal of making them more realistic, effective and affordable [?].

2.3 Virtual Fixtures

3 Materials and Methods

3.1 Equipment

This research has been conducted on a first-generation *daVinci*® surgical system decommissioned in 2016 and equipped with the dVRK (*daVinci*® Research Kit) framework. The dVRK [?] is an open-source mechatronics system, consisting of electronics, firmware, and software, that is being used to control research systems based on the first-generation *daVinci*® systems. Based on a ROS [?] framework, the dVRK implements high-level accessibility to the sensors, actuators and control algorithms of the *daVinci*® robot, making it more easily interfaceable with advanced strategies and algorithms developed in the most diverse software environments.

The simulator developed for this project renders necessary only the surgeon console, as the ROS messages are sent solely to the virtual surgical scene and not to the physical robot. However, all features of the PSMs and of the ECM are implemented: the HRSV shows the 3D virtual surgical scene, the MTMs correctly controls the virtual surgical tools, and the clutch foot-switch allows proper repositioning maneuvers.

3.2 Surgical Simulator

The objective of investigating a high-specificity aspect regarding the impact of Virtual Fixtures (VFs) introduced the necessity of developing an *ad-hoc* surgical simulator with specialized surgical tasks and training exercises: this would allow quantifying surgical performance and monitor training over the key surgical skills as indicated by Smith *et al.* in [**?**].

The simulator is based on the *Unity* game engine, which is a cross-platform game engine that allows the development of 3D applications and games. The Unity engine is a powerful tool for the development of virtual environments, as it allows the creation of complex 3D scenes with a high level of realism, and the implementation of complex interactions between the virtual objects and the user. Specifically, the simulator implements gravity, object collisions and manipulation. A 3D model of the *daVinci*® patient cart is present in the simulator and responds in real-time to the ROS messages received from the console, therefore the virtual PSMs replicate the motion of the real ones.

Two virtual cameras are positioned in the Unity scene on the tip of the endoscope mounted on the ECM: the horizontal distance between the two virtual cameras (5.3mm) matches the one of the real endoscope, as does the Field-of-View (80deg^2). The feeds of the virtual cameras, rendering the 3D scene in real-time, are sent separately to the two oculars of the HRSV. The slightly different images from the left and right eye yield the sensation of depth perception and allow the user to perceive the virtual scene in three dimensions, as it happens when teleoperating with the real robot.

The simulator comprises eight surgical tasks, four of which (*Path, Rings, Pillars* and *Exchange*) are simplistic training tasks built with objects of simple geometry, while the remaining four (*Liver Resection, Nephrectomy, Thymectomy* and *Suturing*) emulate *in-vivo* surgical procedures and are therefore more realistic. Fig.6 collects snapshots of the tasks. All of these are constructed and set up in order to be as challenging as possible in relation to a specific surgical skill. Specifically:

- *Path* and *Liver Resection* require articulate wrist motion and stability
- *Rings* and *Nephrectomy* survey the depth perception skills

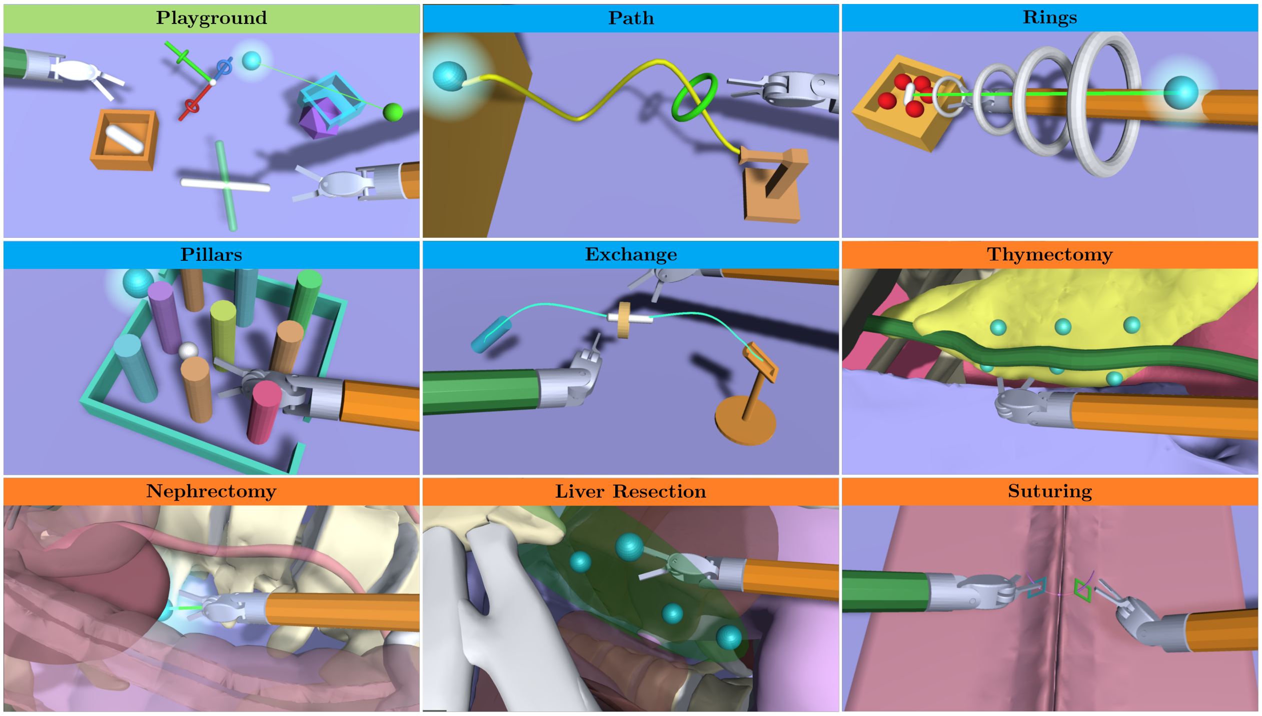

Figure 6: Snapshot of the simulated surgical tasks, with the respective denomination. Training tasks have blue headlines, while realistic evaluation tasks have orange headlines. *Playground* is a propaedeutic task and isn't featured in the experimental study

- *Pillars* and *Thymectomy* are hand-eye coordination tasks
- *Exchange* and *Suturing*, both bi-manual tasks, challenge the capabilities in terms of instrument exchange

The simulator implements

3.3 Virtual Fixtures

3.4 Clinical Validation

3.5 Experimental Protocol

3.6 Performance Metrics

4 Results

5 Discussion

6 Conclusion