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HySim: towards development of a hybrid simulation framework with improved visual and tactile realism for minimally invasive surgeries

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Abstract

Simulation-based training is essential for developing minimally invasive surgical skills. While box trainers provide tactile feedback for practicing techniques like suturing and knot-tying, they lack visual realism. Virtual Reality (VR) simulators provide a visually realistic environment but often lack tactile feedback. This work integrates the strengths of both box trainers and VR simulators in a simulation framework. The proposed simulation framework, HySim, combines virtual and physical tissues into a unified operative view, thereby improving visual and tactile realism. HySim was assessed on: (a) simulation of surgical scenarios, (b) feedback from 10 participants specialized in robotic urology surgery on visual and tactile realism, and usefulness, and (c) the alignment of virtual and physical tissues during scope movements. HySim was successfully deployed for both laparoscopic (bowel anastomosis) and robotic (urethral dissection) scenarios. Compared to VR simulator, surgeons rated HySim higher for instrument motion and handling ($p=0.042$), tool-tissue interaction ($p=0.022$), tissue movement and behavior ($p=0.004$), and usefulness ($p=0.042$). It was also rated higher compared to box trainer for the operative view ($p=0.042$). However, all three simulation environments received similar scores for the likelihood of adoption. For a scope tilt/pan movement with speed less than 10 degrees per second, the physical and virtual tissues did not have noticeable misalignment. HySim can enhance the training environment by improving both visual realism and tactile feedback. Further user studies are required to assess HySim for simulating generic and patient-specific preoperative training scenarios.

Keywords Simulators · Virtual reality · Tactile feedback · Surgical training · Surgical skills

1 Introduction

Minimally invasive surgery, including traditional laparoscopy and robot-assisted procedures, is notably associated with improved patient outcomes (such as lower complications rate and recovery time) as opposed to highly invasive open approach (Peterson et al. 2014; Arnold et al. 2019; Niedermaier et al. 2025). Despite its well-known benefits, widespread adoption of minimally invasive surgery is hindered due to shortage of trained surgeons with the necessary proficiency and expertise (Lim et al. 2017). This is further exacerbated by the high cost and limited accessibility to standardized training programs for robot-assisted surgical training across different regions (Ticonosco et al. 2024). Similarly, training in laparoscopic skills is considerably demanding as it requires the acquisition of specialized skill sets before a trainee is considered proficient (Sparn et al. 2024). These skills include hand-eye coordination, ability to manipulate the laparoscopic tool on delicate tissues with precision and understanding of depth information using the two-dimensional operative view (Lahanas et al. 2015). Validated training curricula, following proficiency-based progression models, have been developed and implemented for minimally invasive surgical training. Such standardized programs include the Fundamentals of Laparoscopic Surgery (FLS) (Zendejas et al. 2016) and the Fundamentals

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of Robotic Surgery (FRS) (Satava et al. 2020). The FLS utilizes box trainers for 5 laparoscopic tasks consisting of peg transfer, precision cutting, ligating loop, suture with extracorporeal knot, and suture with intracorporeal knot. The FRS Dome was used for 7 robotic tasks including instrument docking, ring tower transfer, knot tying, suturing, fourth arm cutting, puzzle piece dissection, and vessel energy dissection. These programs are limited to teaching and assessing basic surgical skills with low fidelity visuals. Standardized curricula for advanced and complex minimally invasive surgical procedures remain scarce (Ticonosco et al. 2024). Such limited learning opportunities and ethical concerns about novices operating on patients prevent efficient training and skill acquisition (Gostlow et al. 2017). Due to the aforementioned reasons, integration of simulation training becomes imperative to meet the increasing demands for the development of minimallyinvasive surgical skills outside the operating room.

Surgical simulation involves the use of cadavers, animal models, Virtual Reality (VR) simulators, or box trainers to develop the necessary skills before a surgeon can perform a live surgery (Table 1) (Molzahn et al. 2024). However, practicing on human cadavers and animal models may be difficult due to limited availability and ethical concerns (Bergmeister et al. 2020). VR simulators can provide a visually realistic training environment though they might lack tactile feedback (Gani et al. 2022). Ongoing developments in VR trainers now incorporate the sense of touch and feel (Munawar et al. 2023). However, the tactile feedback simulated may be considered crude and inadequate for a truly realistic experience (Vaghela et al. 2021). On the other hand, box trainers using synthetic phantom tissue offer a cost-effective solution for minimally invasive surgical training. Though the tactile feedback is present in such trainers, they often lack in visual realism (Hull et al. 2010). Thus, an ideal platform for minimally invasive surgical training would be a hybrid simulator that combines the advantages of visual realism offered by VR simulators and tactile realism offered by box trainers. Working along this line, in this paper, we propose a hybrid surgical simulation framework, hereafter referred to as HySim, using: (a) synthetic phantom to maintain sense of touch and feel for a tissue, and (b) VR to simulate visually realistic operative view.

Table 1 Different types of minimally invasive surgical training platforms

Simulator type	Pros	Cons
Cadaver	Highly realistic, simulates actual procedure, accurate anatomical detail	Expensive, limited availability, controlled environment required, procedures not repeatable, ethical concerns
Animal model	Highly realistic	Limited availability, controlled environment required, procedures not repeatable, ethical concerns
Virtual reality	Visually realistic, computerized skill assessment	Limited sense of touch and feel, high cost
Box trainers	Sense of touch and feel, low cost	Not visually realistic

2 Related work

In recent years, efforts have been made to develop both VR based and hybrid simulators to generate training environments for minimally invasive surgical skill acquisition (Hong et al. 2021). Table 2 summarizes the related efforts and compares them across the following key features:

(i) *Scope movements*: Proper handling and movement of scope is a fundamental laparoscopic skill (Hong et al. 2021). Most of the hybrid simulators use an integrated static camera within box trainers. This limits the capability to learn scope maneuvering and navigation skills during training (Lahanas et al. 2015; Arts et al. 2019; Vörös et al.2023). Some simulators retain this feature by tracking the movements of the real camera scope used by the trainee (Javaux et al. 2018; Viglialoro et al. 2019).

(ii) *Visually realistic operative view*: A visually realistic operative view improves trainees' understanding, keeps them more engaged allowing for better skill retention (Toni et al. 2024). While box trainers are commonly used to train basic surgical skills, they do not simulate the visuals of a real laparoscopic procedure (Hong et al. 2021). VR based simulators offer a visually realistic operative experience using virtual tissues. However, portrayal of complex interactions such as cutting and needle piercing is still limited. The high computational cost required for simulating such interactions in a highly realistic manner restricts its usage for real-time settings (Shao et al. 2019).

(iii) *Natural tooltip tactile feedback*: The feedback refers to the force felt by the user while interacting with the target tissue using surgical instruments (Gani et al. 2022). It assists in understanding tissue behavior (elasticity and resistance) during tool-tissue interaction. Virtual simulators either do not have any force feedback or employ inadequate artificial feedback generated by the software. On the other hand, synthetic phantoms that closely mimic the feel of the target tissue or organ can provide tactile feedback during simulation (Botden et al.2009). Training platforms incorporating natural tooltip tactile feedback are essential for trainees to learn

Table 2 Features of simulators for minimally invasive surgical training reported in the literature

Simulator type	References	Scope movements	Visually realistic operative field	Natural tactile feedback	Multiport laparoscopy
Virtual reality based	VBLaST (Maciel et al. 2008)	✗	✗	✗	✓
	LAP-X (Medical-X) (Kawaguchi et al. 2014)	✗	✓	✗	✓
	LapVR (Elevate Healthcare) (Iwata et al. 2011)	✓	✓	✗	✓
	LAP Mentor (Surgical Science) (Oussi et al. 2020)	✓	✓	✗	✓
	LapSim (Surgical Science) (Munz et al. 2004)	✓	✓	✗	✓
	CollaVRLap (Chheang et al. 2019)	✓	✓	✗	✓
	Huber et al. (2018)	✓	✓	✗	✓
Hybrid	Lahanas et al. (2015)	✗	✗	✗	✓
	eoSim SurgTrac (Arts et al. 2019)	✗	✗	✓	✓
	ProMIS (Haptica) (Gallagher et al. 2018)	✗	✗	✓	✓
	Vörös et al. (2023)	✗	✓	✗	✓
	LapAR (Inovus Medical) (Rawaf et al. 2022)	✗	✓	✓	✓
	Viglialoro et al. (2019)	✓	✗	✓	✓
	Javaux et al. (2018)	✓	✓	N/A	✗
	HySim (proposed in this work)	✓	✓	✓	✓

how to avoid applying excessive force that can lead to tissue damage (Abinaya et al. 2024).

(iv) *Multiport laparoscopy*: Minimally invasive procedures require multiple incisions on the abdominal wall to enable triangulation of the scope and surgical instruments (Arezzo et al. 2017). However, some hybrid simulators are limited to single incision procedures (Javaux et al. 2018). Such simulators cannot be generalized for practicing techniques specific to multiport surgeries.

A considerable amount of literature has been published related to VR based simulators for minimally invasive surgeries. The Virtual Basic Laparoscopic Skill Trainer (VBLaST) (Maciel et al. 2008) was a pioneering work in this field. However, in addition to providing low-quality tactile feedback (Sankaranarayanan et al. 2010; Arikatla et al. 2019), the VBLaST did not support scope movements and lacked a visually realistic operative view. While LAP-X (Medical-X) (Kawaguchi et al. 2014) simulated minimally invasive procedures beyond basic exercises, it lacked scope movements and natural tactile feedback. Furthermore, the immersive simulator using head mounted display (HMD) presented by (Huber et al. 2018) utilized a VR simulator without any haptic feedback. Other VR based simulators employed artificially generated haptic feedback to improve tactile realism. These include Lap VR (Elevate Healthcare) (Iwata et al. 2011), LAP Mentor (Surgical Science) (Oussi et al. 2020), LapSim (Surgical Science) (Munz et al. 2004), and CollaVRLap (Chheang et al. 2019, 2020). Nevertheless, the realism of tactile feedback was demonstrated to be insufficient in LAP Mentor (Pinzon et al. 2016) and LapSim (Hagelsteen et al. 2019). While these VR simulators enable scope movements, have a visually realistic operative view, and allow multiport laparoscopy, they lack natural tactile feedback.

With respect to hybrid simulators, an early contribution by (Lahanas et al. 2015) utilized real laparoscopic instruments fitted with electromagnetic (EM) sensors as an input device for simulating peg transfer and clipping tasks in a virtual space augmented on the camera view. Though, it demonstrated the potential of using Augmented Reality (AR) for surgical simulation, it lackedscope movements, visually realistic operative view, or natural tooltip tactile feedback. Similarly, the eoSim SurgTrac system consisted of a box trainer enhanced with instrument tracking to objectively assess the trainee's performance and provide feedback for tasks such as thread transfer, dissection, and tube ligation (Arts et al. 2019). Nevertheless, the system utilized low-fidelity physical models and did not provide a visually realistic operative view.

The ProMIS (Haptica) system, equipped with vision tracking, utilized real instruments on synthetic tissue (Lacey et al. 2007; Leblanc et al. 2010; Gallagher et al. 2018). In the hybrid setup, the operative view was augmented with visual effects such as bleeding, smoke, and irrigation. Though it improved visuals for tool-tissue interaction, it still lacked the visual realism of the operative field view. The system was also equipped with a pure VR simulation mode but lacked natural tactile feedback (Lacey et al. 2007). A simulator presented by (Vörös et al. 2023) used real instruments with EM tracking inside a box trainer with fixed camera view. A virtual rendering of gynecological procedure view was displayed on the screen to the trainee. While a visually realistic operative view was showcased, the simulator did not include scope movements or natural tactile feedback.

The LapAR (Inovus Medical) simulator is a commercially available hybrid simulator that can be used for general and gynecological procedures (Rawaf et al. 2022). It utilizes synthetic models with AR overlays to provide a visually realistic operative view while retaining tactile feedback. However, the simulator consists of an integrated camera and therefore does not allow for scope movements. In contrast, (Viglialoro et al. 2019) incorporated scope movements in a simulator for laparoscopic cholecystectomy training by tracking the laparoscope shaft. Synthetic organ models (liver and gallbladder) were utilized along with an AR software framework to display virtual tract overlays. Despite this, the simulator lacked overall visual realism of the operative view. A hybrid trainer specific to minimally invasive fetal laser surgery was introduced by (Javaux et al. 2018). The training platform consisted of a synthetic abdominal wall phantom and a VR component rendering the scope view of the uterine cavity. EM sensors were used to track the motion of the fetoscope used. Due to the nature of the procedure simulated (laser surgery), natural tooltip tactile feedback was not applicable, and the simulator was limited to single-port procedures.

The aforementioned studies have highlighted the need to successfully combine the benefits of both VR and box trainers together. To the best of our knowledge, none of existing minimally invasive simulators integrates scope movements, visually realistic operative field, and natural tactile feedback for multiport laparoscopy. To address this gap, this work presents a novel hybrid surgical simulation framework, HySim, that incorporates all the key features generating a training environment that seamlessly combines physical and virtual elements.

3 Materials and methods

3.1 HySim setup

The setup of HySim is shown in Fig. 1. A box simulator (to rehearse laparoscopic surgeries) is used and consists of multiple openings. These openings simulate the incisions for inserting surgical scope and surgical instruments during training sessions. The surgical scene to be simulated is constructed by classifying the tissues involved in the scene into two sets. The first set comprised of tissues that are operated using surgical instruments and undergoes deformation. The second set comprises of tissues in the vicinity of the scope view but are not operated using surgical instruments. These tissues do not require any interaction to complete the surgical step. The former set of tissues are fabricated using silicone and are placed inside the simulation box at a specific pose in front of a chroma background. For the latter set of

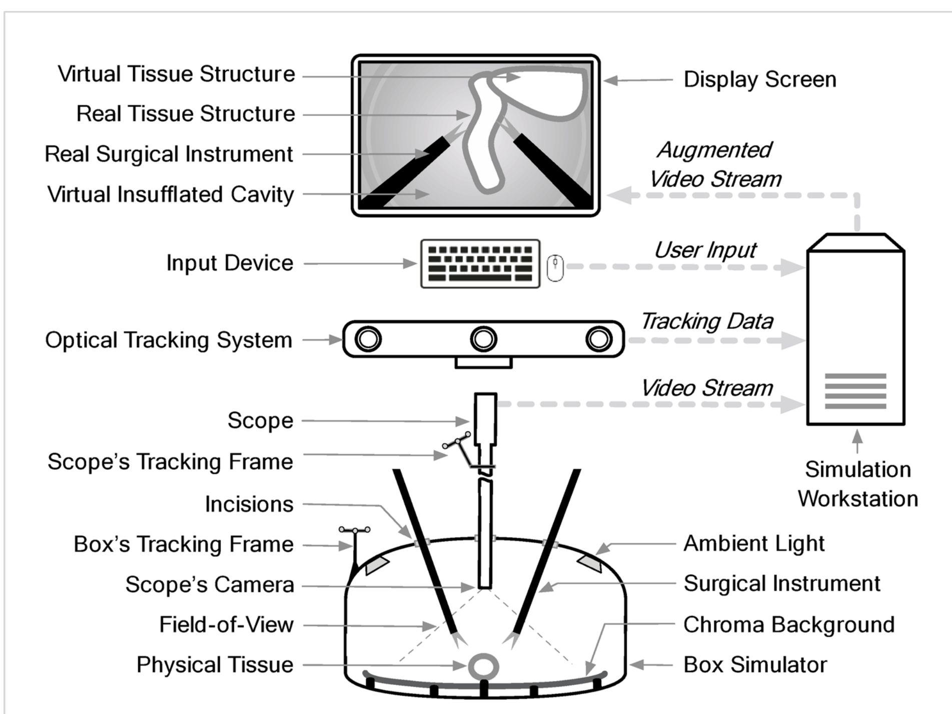

Fig. 1 Setup of HySim illustrating hardware components

tissues, virtual mesh models are used and primarily consist of tissues around the insufflated cavity.

The poses of the box simulator and the scope are tracked using an optical tracking system and assist in registering the physical tissues with virtual tissues during the simulation. Tracking frames, each with a unique arrangement of retroreflective markers, are attached to the box simulator and the scope. The video stream acquired from the scope and the tracking data collected from the optical tracking system are fed to a simulation workstation. The simulation workstation processes the information and renders the view of the simulated operative field onto a display screen. An input device was used to configure the setting on the simulation workstation.

3.2 HySim architecture

The simulation workstation runs six software modules that interface with the hardware units (an optical tracking system, a surgical scope, input devices and a visualization screen) and processes the data (Fig. 2). The working of each software module is as followed:

(i) *Video Module*: The *video module* receives video stream of the simulated surgical view inside the box simulator from the surgical scope, processes it frame by frame, and sends the video frames to the *core processing module*. A video frame at time instant 't' is denoted by $F_{SurgicalView}(t)$ and consists of a chroma background, surgical instruments, and physical tissue.

(ii) *Tracking Module*: The module continuously fetches the tracking data from the optical tracking system, converts it into poses, and sends these poses to the *core processing module*. The pose of the distal end of the scope and the simulation box at time instant 't' is represented by a 4×4 homogenous transformation matrix $M_{Scope}(t)$ and $M_{Box}(t)$, respectively. These poses are measured with respect to the optical tracking system as the world coordinate.

(iii) *User Interfacing Module*: The module enables users to provide input for configuring the parameters of HySim and renders a Graphical User Interface (GUI) on the visualization screen.

(iv) *Tissue Module*: Depending upon the surgical scenario to be simulated, the module retrieves the 3D meshes of the virtual tissue and their poses $M_{Tissue}[i]$, where 'i' denotes the virtual tissue to be used in surgical scenario, from a database and sends it to the *core processing module*. These poses are measured with respect to the simulation box tracking frame.

(v) *Core Processing Module*: The module acts as a central core for processing data received from different modules. It first applies a chroma key filter to the video frame $F_{SurgicalView}(t)$ to segment and extract physical tissues and surgical instruments. The chroma key filtering removes the background chroma color and makes it transparent by introducing an alpha channel. A virtual camera frustum is rendered at $M_{Scope}(t)$ and is calibrated based on the scope's camera intrinsic parameters. The video frame $F_{SurgicalView}(t)$ is rendered onto a plane

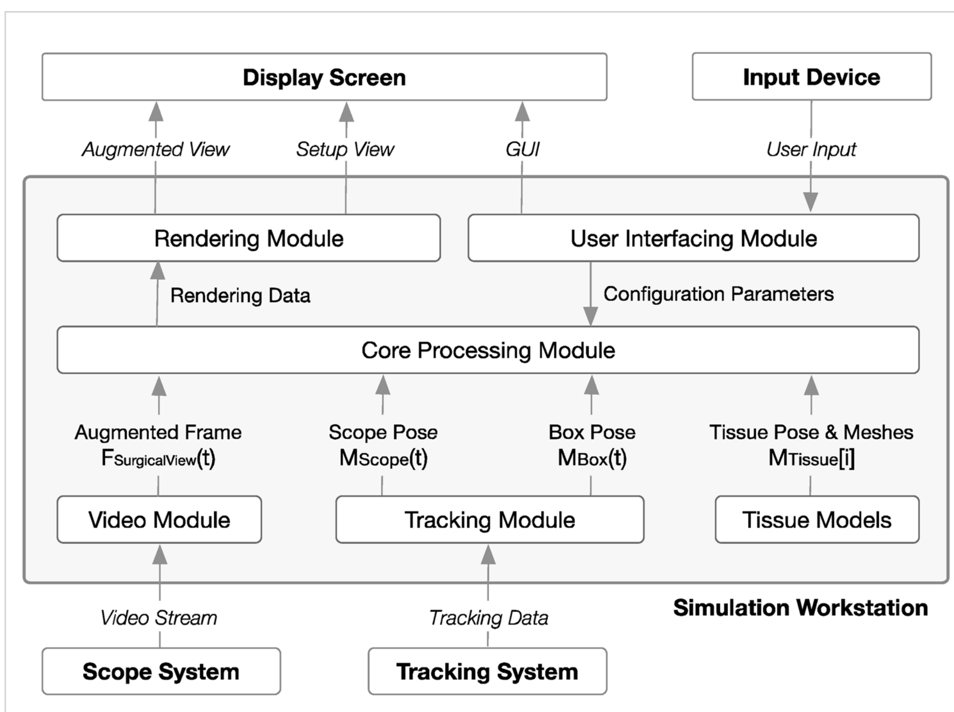

Fig. 2 Architecture of HySim illustrating software modules operating on the simulation workstation and interfacing with various hardware components

orthogonal to the scope viewing direction at a distance Z_{Far} (Fig. 3a). The distance Z_{Far} is adjusted such that the tissues representing the insufflated cavity are in the back side of the plane, whereas tissues overlaying the surgical scene are in front side of the plane. The illustration in Fig. 3b shows the surgical view frame Z_{Far} is adjusted such that 'Tissue 1' is in front of the surgical view whereas 'Tissue 2' is rendered behind. When the operator observes the surgical scene from a virtual camera placed at $M_{Scope}(t)$, it appears as if 'Tissue 1', 'Tissue 2', and the surgical view are merged into one operative field. As video frame $F_{SurgicalView}(t)$ is rendered with respect to $M_{Scope}(t)$ and all the tissue poses $M_{Tissue}[i]$ are rendered with respect to $M_{Box}(t)$, it enables the segmented video frame to be registered with respect to the surrounding 3D meshes of the virtual tissues.

(vi) *Rendering Module*: The view of the surgical scene seen from $M_{Scope}(t)$ perspective is rendered by the rendering module on a visualization screen, creating a hybrid surgical scene comprising of both virtual and physical elements. The *rendering module* also renders a setup view from a third person perspective and allows user to manipulate the poses $M_{Tissue}[i]$ of virtual tissue models. The setup view can be rotated, panned, and scaled.

3.3 Implementation details

The software modules were developed in C++ with different libraries integrated based on requirements. For 3D visualization and scene interaction, we used VTK (version 9.2), which allows rendering 3D models such as anatomical models and virtual instruments in real-time. A processed video frame was overlaid with alpha blending onto a 3D plane in the VTK scene to facilitate mixed reality rendering. Chroma keying and related image processing were done using OpenCV (version 4.x). The GUI was developed using Qt5 (version 5.12.1), which consisted of standard controls such as buttons, dropdowns, and sliders for scene setup, calibration, and user interaction. The VTK render window was embedded within the Qt5 window in a QWidget. CPU multi-threading was used for modules such as video capture, 3D visualization and image processing running in their own threads. Multi-threading was implemented using the Boost library (version 1.68.0). Eigen3 (version 3.4.0) and GLM (version 0.9.9.8) were used for mathematical computations such as registering the virtual and real environment based on optically tracked markers. The simulation workstation was realized on an off-the-shelf PC (Intel i9 14th generation with 32 GB RAM). For optical tracking, we used a V120:Trio system from NaturalPoint with passive retroreflective markers. The tracking data was streamed over loopback on the same machine using Motive software (version 2.3.7) which captures tracking data at 120 Hz refresh rate. This data is received and parsed in the simulation software using the NatNet SDK (version 4.0), which allowed us to synchronize the physical environment, scope to the virtual environment and virtual camera in real-time.

3.4 Experimental setup

3.4.1 Assessing training scenario generation

HySim was assessed for generating training scenarios in robotic and laparoscopic surgeries. HySim was integrated with da Vinci Xi surgical system - Intuitive Surgical Inc. (Fig. 4a). Video frames acquired by the scope were fetched by the simulation workstation from the da Vinci Xi's Vision Cart using a video adapter (Magewell USB Capture HDMI 4 K Plus). A scope tracking frame was attached to the zero-degree rigid scope. EndoWrist's curved scissors and needle driver were used as surgical instruments. Urethral dissection during Robot Assisted Radical Prostatectomy (RARP) was selected as a surgical step to be simulated. The surgical step involved dissecting the urethra using curved scissors. The surgical scene comprised of bladder, prostate, urethra, and background tissues. While bladder, prostate, and background tissues were simulated using virtual tissue models, an elastic tube was used to simulate physical tissue

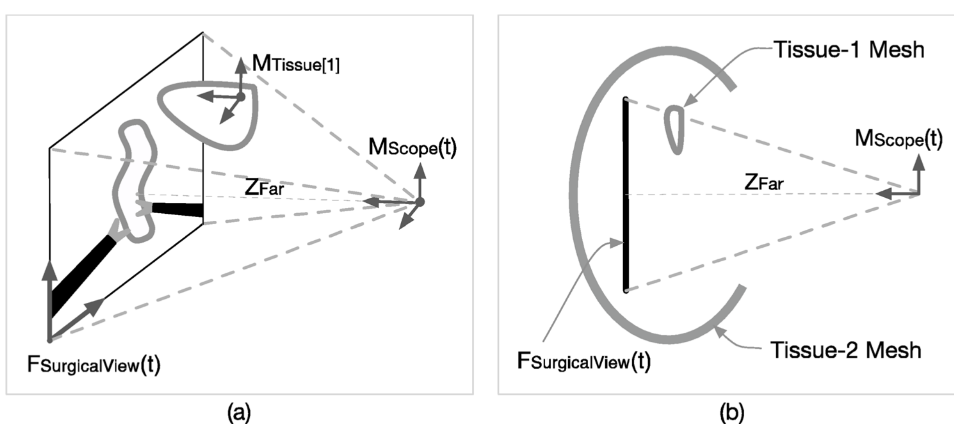

Fig. 3 **a** Surgical view rendered as a frame aligned with the scope's viewing direction, depicting the interaction between the physical tissue and the surgical instrument. **b** Schematic representation showing the adjustment of z-Far to position virtual tissue-1 and tissue-2 in the foreground and background of the surgical view

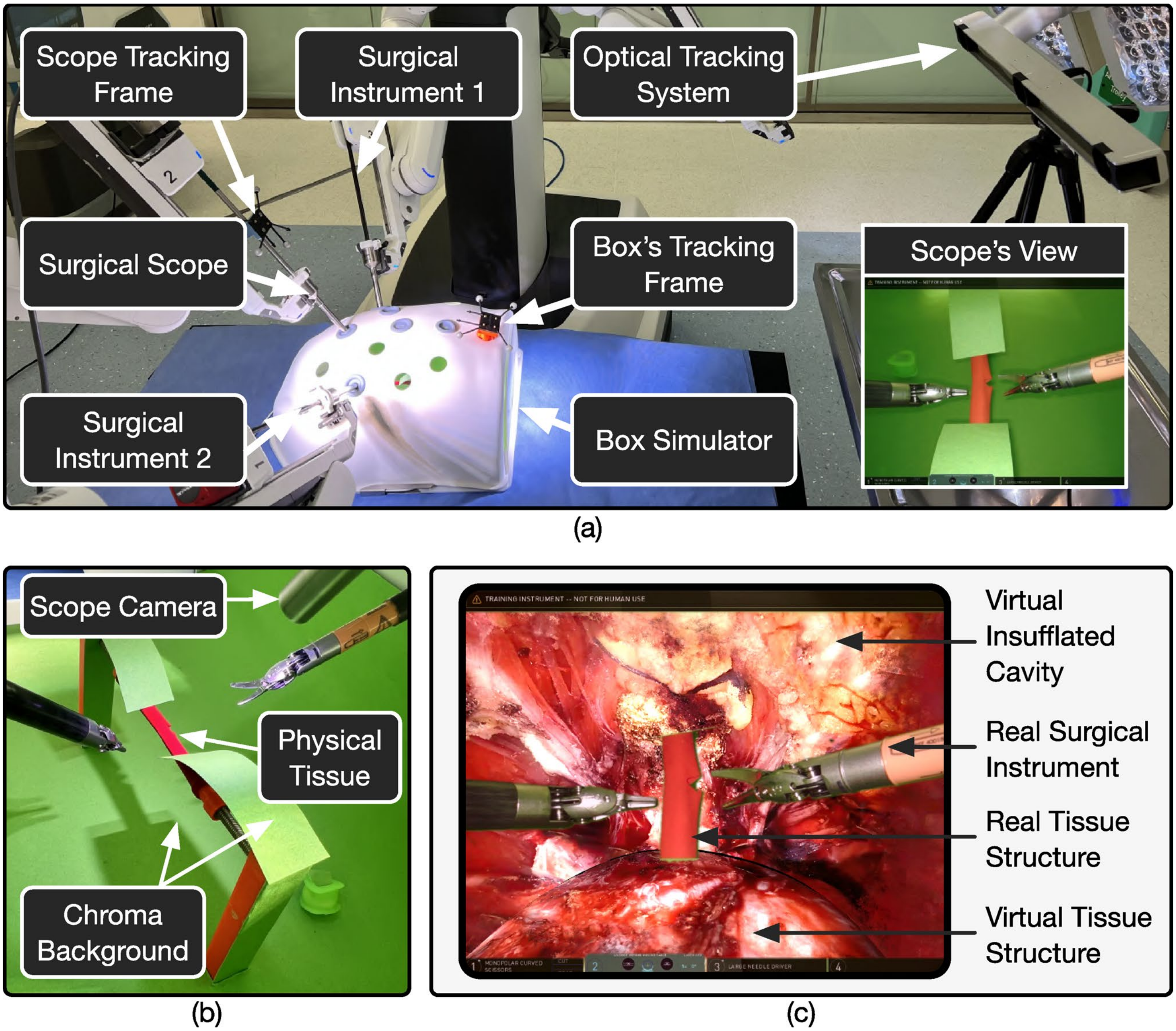

Fig. 4 **a** Integration of HySim with a robotic surgical system simulating urethral dissection during robot assisted radical prostatectomy. **b** Physical tissue placed inside the simulation box. **c** View seen be the operator on the console of da Vinci Xi surgical system

structure of urethra. It was suspended in front of the scope camera (Fig. 4b). The virtual tissues were registered, and the augmented view after removing chroma background generated by the simulation workstation (shown in Fig. 4c) was streamed to the console of da Vinci Xi surgical system. Similarly, HySim was also accessed for generating training scenarios in laparoscopic surgery (Fig. 5). HySim was integrated with a box trainer (Fig. 5a) and a physical tissue for rehearsing suturing step during bowel anastomosis was used (Fig. 5b). A virtual background with intestinal tissues was added.

3.4.2 Evaluating hysim with end users

A user study was conducted to evaluate the training environment generated by HySim (illustrated in Figs. 4 and 5) against those generated by a VR simulator and a box trainer. The participants were asked to rate the three training environments using a 5-point Likert scale ranging from strongly disagree (1) to strongly agree (5). The evaluation was focused on subjective criteria, including the visual and tactile realism, perceived usefulness, and the likelihood of adoption. The questionnaire was designed based on previously published validation studies of surgical simulators. The questions are illustrated in Fig. 8 and presented in Sect. 4.2 below. Specifically, the participants were asked to provide their opinion on the realistic portrayal of the

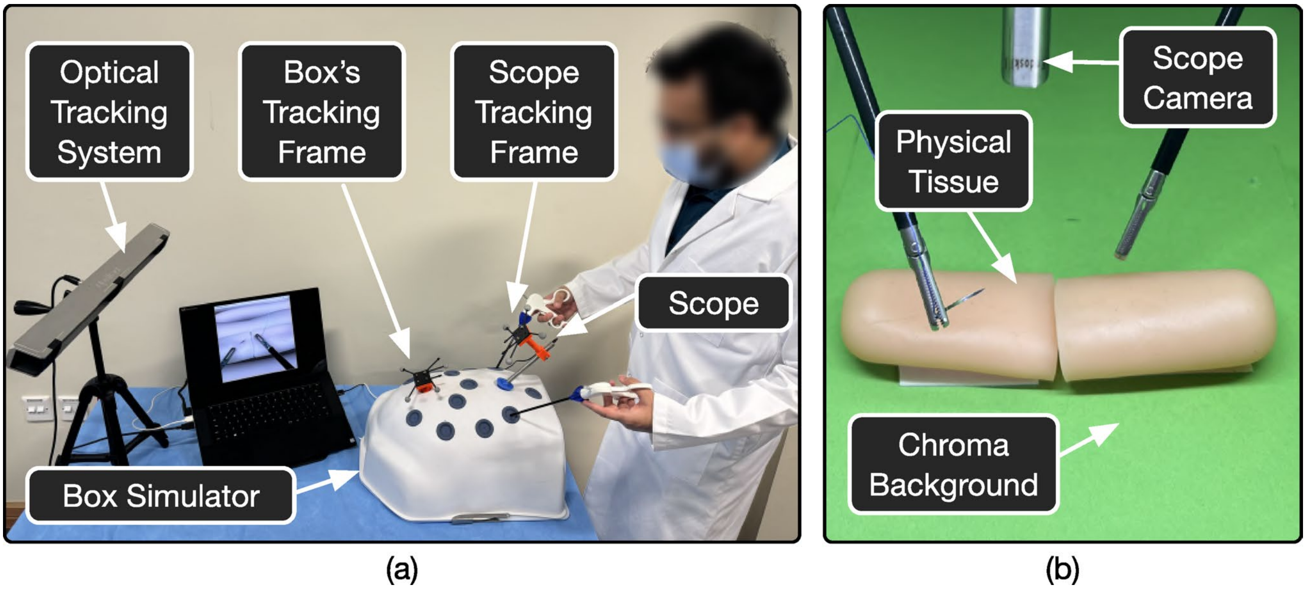

Fig. 5 **a** Integration of HySim with a laparoscopic surgical setup simulating bowel anastomosis. **b** Physical tissue placed inside the simulation box with chroma background

operative field view (Lahanas et al. 2015; Lang et al. 2023), change in the operative view relative to scope motion, size and color of the anatomy (Shen et al. 2023; Shibuya et al. 2024), movement and behavior of the target tissue (Shen et al. 2023), instrument motion and handling (Shibuya et al. 2024), instrument-tissue interaction (Lahanas et al. 2015), and force sensation (Shen et al. 2023). The participants were also asked to rate the usefulness of each training environment for learning camera navigation, instrument control (Brinkmann et al. 2017), improving laparoscopic skills (Ulrich et al. 2020; Asfaw et al. 2023), and assessing performance (Ulrich et al. 2020). Additionally, they were asked to evaluate the likelihood of utilizing the training environment (Ulrich et al. 2020; Kuemmerli et al. 2024), recommending it to others (Lang et al. 2023), and using it for teaching purposes (Shibuya et al. 2024). The user study was conducted at the Hamad General Hospital, Hamad Medical Corporation, Doha, Qatar and was approved by the institutional review board comprising of the ethical committee (Medical Research Center, Doha, Qatar, approval number MRC-03-23-786). To obtain expert opinion on HySim, we included participants who were robotic surgeons in the urology specialty, experienced with the da Vinci skills simulator and RARP. Ten participants participated in the study, including nine urology surgeons with varying levels of experience and one simulation expert. Among the surgeons, there were two senior consultants, three consultants, two associate consultants, one clinical fellow, and one resident, listed in a decreasing order of experience. The responses were analyzed using Friedman test to assess the distribution of ratings between the three simulators. When a statistically significant difference was found, a post-hoc test with Bonferroni correction for pairwise comparisons was utilized.

3.4.3 Evaluating alignment of virtual and physical tissues

HySim relies on real-time tracking of the surgical scope- and box simulator to register the virtual and physical tissues together in the scene. The motion of the surgical scope causes the pose of the camera frustrum $M_{Scope}(t)$ to change. This alters the pose of the video frame $F_{SurgicalView}(t)$. The processed video frame $F_{SurgicalView}(t)$ depicting the physical tissues with removed chroma background should appear in synchronization with the poses $M_{Tissue}[i]$ of virtual tissues models. If the synchronization is not perfect, it appears as if the physical tissues move with respect to the virtual tissue during scope movement.

To assess the distortion during scope movements, a scope camera along with a tracking frame (#1) was mounted on a UR5e robotic manipulator. A marker in the form of a rectangular block (20 mm × 23 mm) with a tracking frame (#2), representing the physical tissue, was placed on a table in front of the scope (Fig. 6a). The robotic manipulator was actuated to generate the scope movements: tilt, pan, and insertion/retraction at three different speeds. The marker tracked using the optical tracking system was projected onto the surgical view frame in the virtual space (Fig. 6b). The video acquired from the scope was processed to extract the marker within the surgical view frame. For accurate alignment, the projection of the tracked marker (representing physical tissues) and the marker in the surgical view frame (representing virtual tissue) were expected to overlap with

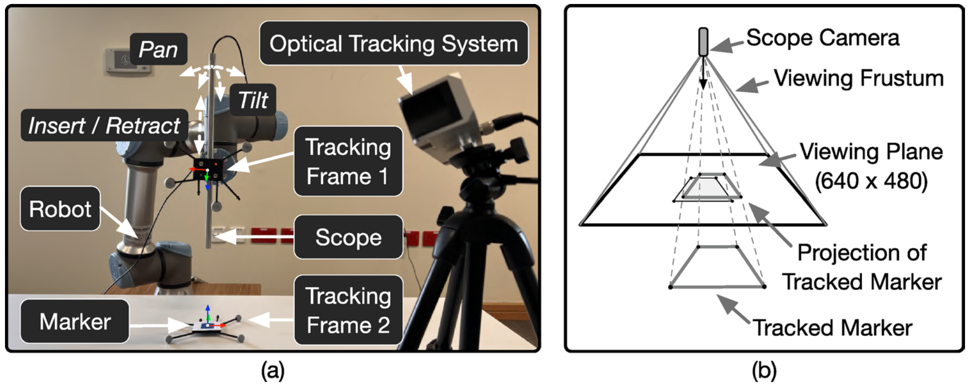

Fig. 6 **a** Experimental setup to assess distortion caused by movement of physical tissues with respect to the virtual tissue during scope maneuvering. **b** Schematic representation of projection of the tracked marker onto the viewing plane of the scope camera

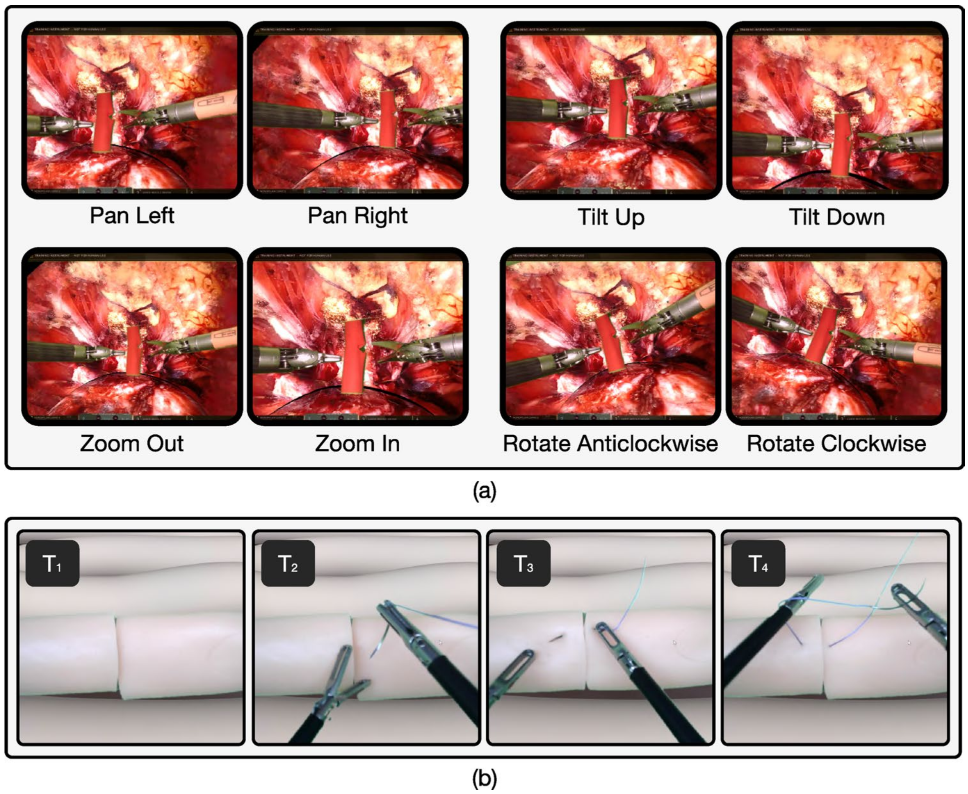

Fig. 7 Training scenario generated using HySim. **a** Urethral dissection during robot-assisted radical prostatectomy. The sequence illustrates changes in the view of the surgical field as the operator manipulates the surgical scope through panning, tilting, zooming, and rotation. **b** Bowel anastomosis during laparoscopic surgery. The sequence presents a time series of images depicting suturing performed with laparoscopic instruments on physical tissue, with virtual tissue structures rendered in the background

each other. Alignment errors were quantified by measuring pixel misalignment along the vertical and horizontal axes of the video frame for various scope movements. Each scope movement at a specific speed was repeated over 5 trials.

4 Results

4.1 Simulated training scenarios

HySim successfully generated training scenarios for both robotic and laparoscopic (manual) minimally invasive surgeries. In the case of robotic surgery, when the scope was maneuvered (panned, tilted, rotated, and zoomed) by the operator using the console, the registration enabled both virtual and physical tissues to appear as interconnected with each other (Fig. 7a). It assisted the operator to understand the spatial relationships and anatomical structures inside the insufflated cavity. In the case of laparoscopic surgery, the physical tissue replicated the dynamics of needle-tissue interaction during the surgical step and assisted the operator to develop an understanding of the forces required to pierce, pass through, and pull the needle through tissue during suturing. On the other hand, the virtual tissue enhanced the visual fidelity of the simulation environment (Fig. 7b).

4.2 End user evaluations

The end user study evaluated the training environment generated by HySim against those generated by a VR simulator and a box trainer (Fig. 8). While comparing the environments, the following observations were made:

(i) *Visuals*: For the statements on the realistic portrayal of visuals, the responses were clustered around “strongly disagree” for the physical simulator, and “neutral” for the VR simulator. The responses for HySim, which were mostly “agree” and “strongly agree”, was significantly different as compared to the physical simulator in terms of the view of the operative field ($p = 0.042$) and as compared to the VR simulator in terms of the movement and behavior of target tissues ($p = 0.004$).

(ii) *Tactile Feeback*: Both the box trainer and HySim were rated considerably positive with respect to the realistic portrayal of tactile feedback, while the responses for the VR simulator heavily leaned towards “strongly disagree”. The responses for HySim were significantly better than the VR simulator with respect to the instrument motion and handling ($p = 0.042$) and interaction between the instrument and tissue ($p = 0.022$).

(iii) *Usefulness*: For the statements related to usefulness, HySim received largely positive responses, while the physical and VR simulators had varied responses indicating a level of uncertainty. When compared to the VR simulator, HySim was rated more useful for improving laparoscopic skills ($p = 0.042$).

(iv) All the three simulators were rated favorably when asked if the participants feel motivated to use them, would recommend them to others, or use them for teaching purposes. While HySim had more “strongly agree” responses for these statements, the difference in responses was not statistically significant.

4.3 Alignment accuracy

The experiments allowed quantifying the distortion as alignment errors during the scope movements. Pixel misalignments were measured along the vertical and horizontal axes of the video frame for the three scope movements: tilt, pan, and insert/retract. When the scope was tilted or panned at a speed of 15 degrees per second, misalignment became

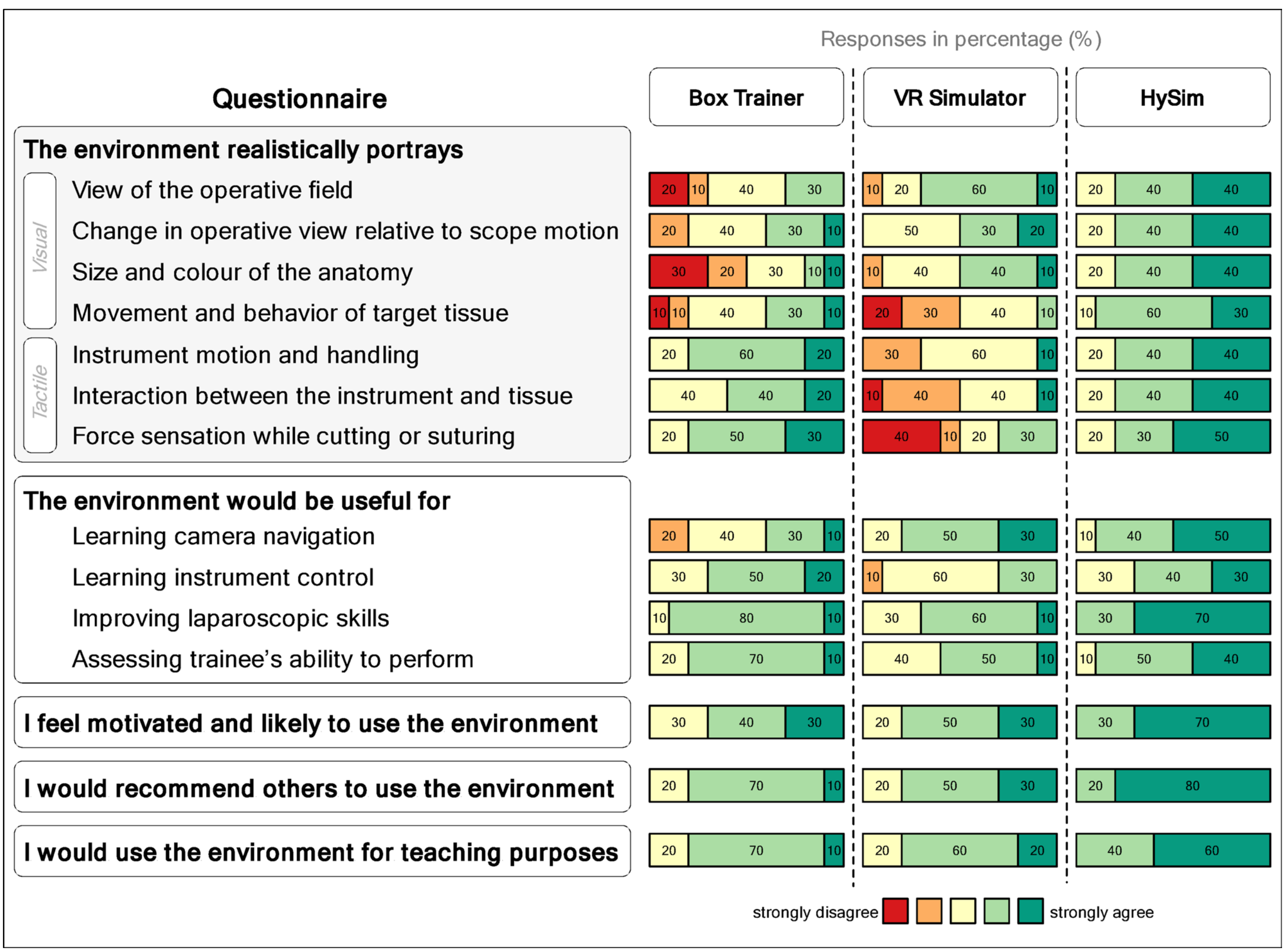

Fig. 8 Summary of clinician perceptions on a Likert scale for the environments generated by box trainer, VR simulator, and the proposed HySim

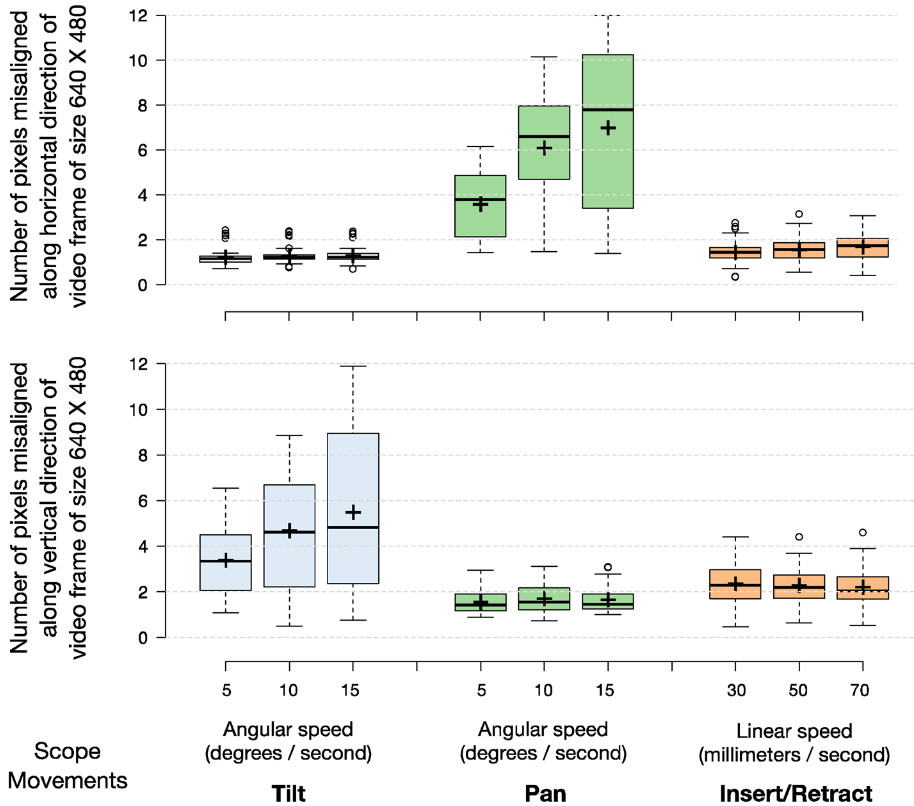

Fig. 9 Pixel misalignment measured along the vertical and horizontal axes of the video frame for the three scope movements: tilt, pan, and insert/retract

visually noticeable (Fig. 9). However, at speeds between 5 and 10 degrees per second, the physical and virtual tissues remained aligned without any noticeable misalignment. For insertion and retraction movements, no alignment error was observed.

5 Discussion

The present study introduced a hybrid surgical simulation framework, HySim, for minimally invasive surgeries. HySim is compatible with both robotic and laparoscopic procedures. While box trainers are useful tools to introduce basic surgical skills to trainees and develop muscle memory (Papanikolaou et al. 2019), VR/AR based simulators can provide a comprehensive experience related to the surrounding anatomy inside the insufflated cavity (Feifer et al. 2011). These technologies, meanwhile, fall short when employed separately in terms of preparing trainees for actual surgical procedures (Cumin et al. 2013). Thus, a framework that combines the benefit of both box trainers (realistic tool tissue interaction, and scope navigation) and VR/AR simulators (true-to-life operative field), can bridge the gap for surgeons trained on box trainers and VR/AR simulators, to operating for the first time on a patient.

HySim builds on previous research focusing on surgical simulators incorporating AR-based elements. Several AR-based trainers facilitate basic surgical skillacquisition (such as peg transfer, clipping etc.) without a visually realistic operative view (Loukas et al. 2013; Lahanas et al. 2015; Arts et al. 2019; Viglialoro et al. 2019). However, HySim allows the rendering of realistic virtual surgical scenes onto the trainee's view. The enhanced realistic operative view provides trainees with an opportunity to practice their skills through a platform closely mimicking a surgical procedure outside of the operating room. A realistic visual environment assists trainees in understanding what they would see during a real surgery. This has the potential to improve their situational awareness and decision-making skills (Herur-Raman et al. 2021). Additionally, a high-fidelity environment keeps the trainees more engaged and focused, allowing for better skill retention (Toni et al. 2024).

HySim also facilitated natural tactile feedback during laparoscopic procedures. This is a significant improvement from other purely virtual simulators that lack tactile realism (Vörös et al. 2023). The integration of physical and virtual tissues together in the same environment bridges the gap between simulation and reality, improving the transfer of skills to real surgical scenarios (Hong et al. 2021). HySim replicates the physical sensations of handling real tissue and provides trainees with a hands-on experience. The trainee could feel the resistance and texture of tissues during tool-tissue interaction, learning how much forces need to be applied. This reduces the risk of overhandling or causing unintended damage during surgery. This is crucial during delicate surgical procedures, where fine precise movements are required with accuracy (Vaghela et al. 2021).

In addition to visual and tactile realism, HySim can be used for acquisition of scope maneuvering and navigation skills. Existing AR-based simulators often utilize views from fixed cameras during the simulation session (Leblanc et al. 2010; Rawaf et al. 2022). This significantly limits the trainees' ability to train in scope handling and navigation skills. In HySim, the rendered virtual surgical scene changes corresponding to the movements of the scope, providing an interactive and engaging platform for trainees. It assists trainees to develop a better understanding of spatial anatomical relationships within the operative field and adjust the scope pose for the optimal visualization of the operative field. This is especially significant as minimally invasive surgeons are completely dependent on the camera scope view while performing the procedures. During laparoscopic surgeries, the camera scope movements are handled by an assistant surgeon (Ohmura et al. 2019), whereas during robot-assisted surgery it can be manipulated by the operating surgeon using the robotic console (Pandya et al. 2014). Efficient scope movements are essential for viewing the anatomy from different perspectives, and to avoid misidentifying critical structures or incision lines (Zhu et al. 2013). A scope movement can be discretized into basic movements comprising of tilt, pan, and insert/retract. Since quick maneuvers can cause vision fatigue or risk of collision (Zheng et al. 2017), scope movements generally do not occur at a speed of 15 degrees per second or more. Our study found that at a lower speed, the misalignment between physical and virtual tissue was negligible (Fig. 9). This was further supported by the surgeons' responses to the questionnaire (Fig. 8). HySim was rated favorably by the surgeons in terms of realistic portrayal of "change in operative view relative to scope motion" (40% responded strongly agree), and usefulness of the framework for "learning camera navigation" (50% responded strongly agree).

Several limitations exist in the current study. First, a limitation of this study is the small sample size, which poses concerns about generalizability of the findings. We focused on robotic surgeons in the urology specialty who were well-versed in RARP in real surgical settings as well as the training modules of the da Vinci skills simulator. The resident included in the study was also undergoing robotic training. Due to the selective inclusion criteria, many participants had to be excluded from the study. This was a limiting factor for the sample size. As a result, we were also unable to meaningfully compare feedback between consultants ($n=8$) and the resident ($n=1$). Despite this limitation, the positive findings suggest a promising direction for future efforts in conducting multi-institutional studies with larger and more diverse participant groups. Second, we also did not assess the effectiveness of HySim in improving surgical performance. Instead, we gathered expert surgeons' perceptions on realism, usefulness, and likelihood of using HySim as a teaching tool. With a future study involving a larger sample size, a correlation analysis can be conducted to make effective comparisons between residents, fellows, and consultants. Furthermore, objective measurements such as knowledge and skills of the participants can be included. By measuring the extent to which skills acquired during training are transferred into the operating room, the predictive validity of HySim can also be assessed in a randomized controlled trial.

HySim can be improved in three aspects. First, to improve visual realism, better textures need to be applied to virtual tissues. In the current approach, the operative field for urethral dissection (shown in Fig. 4) was generated by processing MRI images of a prostate phantom to create meshes of the tissues. These meshes were then placed within a hollow mesh that represented an insufflated cavity. Textures extracted from intraoperative video frames were applied onto these meshes. However, for a more accurate representation, it is crucial to use textures derived from real surgical video footage that excludes cauterized tissue, blood, smoke, or other instruments in the vicinity. Furthermore, at the current stage, users can perceive differences between real and virtual 3D structures due to sharp visual boundaries between real and virtual elements, color/lighting differences, and texture continuity. To improve this, we plan to apply additional image processing to soften the edges, so it gradually fades from virtual elements to real and vice versa. Additionally, a virtual overlay can be added onto the real structures by tracking the tissue with optical markers attached to the edges of the real tissues. The markers will facilitate tracking the relative position of different areas of the real tissue, allowing for real-time deformation of virtual 3D elements while aligned to the physical tissues. With the same markers, we can also support applying virtual textures for visually blending the real and virtual elements into an immersive mixed-reality environment. This would help improve the details by providing cleaner, more representative visuals of the surgical environment. Second, the surgical view frame, which includes both the physical tissue and the tool, can be separated into two distinct frames: one containing the physical tissue and the other containing the tool. This layered separation would enable the placement of virtual tissue structures between the physical tissue and the tool. To achieve this, integration of surgical instrument mask detection methods would be required for processing the frames. Lastly, silicone-based tissues can be casted in 3D-printed molds based on the patient's real anatomy from preoperative images. This would enable the simulator to be used for hands-on preoperative planning and rehearsal of patient-specific aspects of the surgical procedure. Further user studies are needed to assess HySim's effectiveness in patient-specific preoperative training scenarios and surgeon's ability to plan and perform procedures.

6 Conclusion

In this paper, we present a hybrid surgical simulation framework by combining synthetic phantom and VR elements together. It was successfully implemented for both laparoscopic and robot-assisted surgical scenarios. A high alignment accuracy between physical and virtual tissues during scope tilt/pan movement (less than 10 degrees per second) was observed. These findings can be utilized for the development of hybrid simulators for various minimally invasive surgical procedures. Overall, HySim received superior ratings for visual realism as compared to box trainers, and tactile realism as compared to VR simulators. Better scores in terms of instrument motion, tool-tissue interaction, and realistic view of the operative field suggest that it could be a desirable tool for training novice surgeons. However, further studies are required to objectively assess performance improvement and surgical skills acquisition. Future work on improvement of virtual tissue realism and incorporation of patient-specific silicone models is also needed.

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Author contributions W.P. and S.P. prototyped the system. A.B. and H.H. assisted in conducting user study. A.A and O.A provided input from surgical perspective. Z.D. and N.N. were responsible for the conception, and design of the study.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval The study was approved by institutional review board ethical committee (Medical Research Center, Doha, Qatar, approval number MRC-03-23-786). Informed consent was obtained from the participants of the user study.

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