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Highly-Immersive Virtual Reality Laparoscopy Simulation: Development and Future Aspects

Pre-print version

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Abstract

Purpose Virtual Reality (VR) applications with head-mounted displays (HMDs) have had an impact on information and multimedia technologies. The current work aimed to describe the process of developing a highly-immersive VR simulation for laparoscopic surgery.

Methods We combined a VR laparoscopy simulator (LapSim) and a VR HMD to create a user-friendly VR simulation scenario. Continuous clinical feedback was an essential aspect of the development process. We created an artificial VR (AVR) scenario by integrating the simulator video output with VR game components of figures and equipment in an operating room. We also created a highly-immersive VR surrounding (IVR) by integrating the simulator video output with a 360° video of a standard laparoscopy scenario in the department's operating room.

Results Clinical feedback led to optimization of the visualization, synchronization, and resolution of the virtual operating rooms (in both the IVR and the AVR). Preliminary testing results revealed that individuals experienced a high degreee of exhilaration and presence, with rare events of motion sickness. The technical performance showed no significant difference compared to that achieved with the standard LapSim.

Conclusion Our results provided a proof-of-concept for the technical feasibility of an custom highly immersive VR-HMD setup. Future technical research is needed to improve the visualization, immersion, and capability of interacting within the virtual scenario.

Keywords: Surgical Training, Virtual Reality, Laparoscopic Surgery, Human-Computer-Interaction, Visualization

1 Introduction

Virtual Reality (VR) is currently used in surgical training to improve psychomotor skills that are important for laparoscopic surgery, such as hand-eye coordination, spatial orientation, and manipulations in the presence of a fulcrum effect[1]. Nonetheless, the use of VR simulators is limited in daily clinical routine, due to a lacking realism of tasks, abstract graphic design, and the awareness of participants to be in a training environment [2,3]. The variety of tasks has been enlarged since the development of VR laparoscopy simulations, and currently, abstract training tasks and procedural operations are available in VR. In addition, graphic design of simulation tasks and virtual tissue interaction in VR laparoscopy simulation have improved. However, users are continuously aware that they are in a training environment and not a real surgical situation. Realistic surroundings that increase the user's sense of presence during a VR simulation are only possible when performing team training sessions, which require more time, infrastructure, and human resources [4]. Recent advancements in information and multimedia technology have made it possible to develop VR applications in combination with head mounted displays (HMDs). These combined applications are currently used in the entertainment industry, in the military, and in aviation training. Medical applications include VR-HMD psychological interventions for posttraumatic stress disorders, phobias, cognitive rehabilitation and and pain treatment for burn victims [5-8]. Additionally, VR will enhance the validity of clinical, behavioural and affective and social neurosciences due to more realistic test scenarios [9]. The rise of commercially available VR-HMDs over the last year has led to the development of a virtual operating room environment to increase the attractiveness and the degree of presence during VR laparoscopy simulations. The present work aimed to describe the development process of an immersive VR laparoscopy simulation setup. The goal was to combine existing technologies to create a user-friendly simulation scenario with high immersion and presence. Continuous clinical evaluations and feedback from laparoscopic surgeons comprised an essential part of the development process.

2 Related Work

The current use of VR in medical fields is mainly due to the visual possibilities it offers, which are very helpful for processes such as education, simulation, planning, navigation, and even rehabilitation [10]. VR simulations in surgery are used to teach technical skills, behavioral skills, and entire procedures to trainees and practicing surgeons worldwide [11]. In VR laparoscopy trainers, users perform surgical tasks with standard laparoscopy instruments [12]. Studies on VR laparoscopy simulations have concluded that the skill acquisition is equivalent to that acquired with laparoscopy box trainer simulations, and these skills can be transferred to the operating room (OR) [13,14]. Also, a brief pre-surgical VR warm-up can improve performance in the OR[15].

Technical and visual improvements have influenced VR simulators. Three-dimensional displays with polarization or shutter technologies have been integrated and investigated with differing results [16,17]. On the other hand, recent developments in surgery, such as robotic operations, have led to the development of VR robotic surgery simulators [18]. Visualization for a VR robotic surgery simulation can be seen as a variant of an HMD simulation, performed on the robotic console; however, the OR surroundings have not yet been considered in this context. A recent study described a VR application that combined a VR laparoscopy simulation and a low-immersion HMD, with only a 45° field of view, to produce a virtual scenario, which consisted of a peg transfer task in a plain, computer-generated room [19].

The latest generation HMDs, which began shipping in 2016, feature several technological advancements realized in recent years. High pixel density displays from smartphones were used in early prototypes to reduce the 'screen-door' effect. These displays operate with a high refresh rate to reduce latency, which causes motion sickness. Novel methods and custom sensors were developed to improve positional tracking [20]. Asynchronous re-projection was introduced to reduce latency even further. This technique introduces small changes onto a previously rendered frame, according to the most recent positional tracking data, which lowers the computational requirements of the graphics processing unit (GPU) [21]. Other software solutions were required to correct for distortion and chromatic aberrations that arise from the lenses. These solutions were needed to map the HMD to a wider field of view and create a more comfortable point of focus.

Fig. 1: Custom IVR setup with LapSim Simulator with the 4D joysticks (Simball, G-coder Systems, Sweden); the goggles are the HTC Vive (HMD); and the headphones provide sound. A conventional monitor is not needed in this setup.

3 Materials and Methods

Virtual Reality Laparoscopy Simulation System

The basis of our custom setup was a VR laparoscopy simulator without haptic feedback (LapSim), purchased from Surgical Science AB, Goethenburg, Sweden. It consisted of a 27-inch LCD monitor (AOC International, Taiwan), a keyboard and mouse, a Windows 7 PC, and Simball™ 4D joysticks, with a double foot-switch (G-coder Systems). All hardware components were mounted on a rolling, height-adjustable array, and they were readily accessible, due to the open design of the chassis. For interactions with the VR environment, the simulator provided Simball 4D joysticks (**Fig. 1 and Fig. 2**). Their laser-marked ball joints, with three degrees of freedom, allowed real-time calculations of the exact 3D angular position. The input devices included a grasper instrument on the left and right sides, and a camera instrument in the center. During our tests, the camera was not used in any laparoscopic task. The computer featured proprietary software from Surgical Science AB, version 2015, which ran on Windows 7. This software allowed the user to perform basic training tasks, like peg transfer or pattern cutting, but also complex, more realistic scenarios, like a cholecystectomy or appendectomy simulation. The software logged the user's performance by recording a set of task-specific parameters. This allowed the assessment of execution quality for each performed task; thus, the individual's improvement in psychomotor skills could be monitored over time.

Custom Virtual Reality Head Mounted Display System

Two VR-HMD solutions from the consumer market were considered in our aim to extend the existing LapSim experience with additional hardware and content: The Oculus Rift CV1 and the HTC Vive. Compared to the conventional built-in monitor, HMDs provide a wider field of view. With the combined head tracking and stereoscopic depth effects, the user is immersed in an all-around visual experience that is much closer to real human vision than the 2D display of the LapSim. The high refresh rate and low latency of the OLED displays on the HMD were important in achieving minimum simulator sickness. We chose the HTC Vive HMD for this study, because compared to the Oculus Rift CV1, it featured a slightly larger field of view of 110° compared to 101° for the Oculus Rift CV1 and a large tracking area of 4.6 by 4.6 meters, which allowed highly-immersive, room-scale VR [22]. A separate computer was necessary to drive the HTC Vive HMD without interfering with the existing LapSim software and hardware (Fig. 2c). A VR-ready laptop (MSI GT72VR-6RE16H51) was chosen over a custom-built desktop PC for better mobility. The MSI laptop was equipped with an Intel Core i7 processor (6700HQ, 16GB RAM), a Nvidia GTX 1070 graphics card (8GB VRAM), and the ports necessary for connecting the HTC Vive link box.

Video and Audio Signal Transfer

To integrate the video output previously displayed on the 2D LapSim monitor (Fig. 2a) into a virtual environment created with the separate HTC Vive HMD system, a frame grabber was used (Fig. 2d). This USB 3.0 HD video capture device (Startech USB3HDCAP; Startech, Northampton, UK) received the HDMI output from the LapSim PC at 1080p resolution and 60 fps, and sent it over the USB to the laptop via the HTTP live-streaming protocol, HLS. An HDMI splitter (Fig. 2e) was inserted upstream to allow the video signal to be routed back to the LapSim system for simultaneous display on the built-in monitor. The simultaneous display allowed other developers to follow the laparoscopy simulation, as usual, on the 2D monitor. Thus, the other developers could provide technical administration and control the LapSim software with the keyboard and mouse, while the user was wearing the HMD. Audio feedback generated by the LapSim software (e.g., when working with a virtual electronic device) was transferred via an analog cable from the LapSim PC headphone jack to the MSI laptop microphone jack (Fig. 2f). The final audio mix-down was performed on the laptop. The user wearing the HMD listened to the audio output with stereo headphones connected to the HTC Vive HMD.

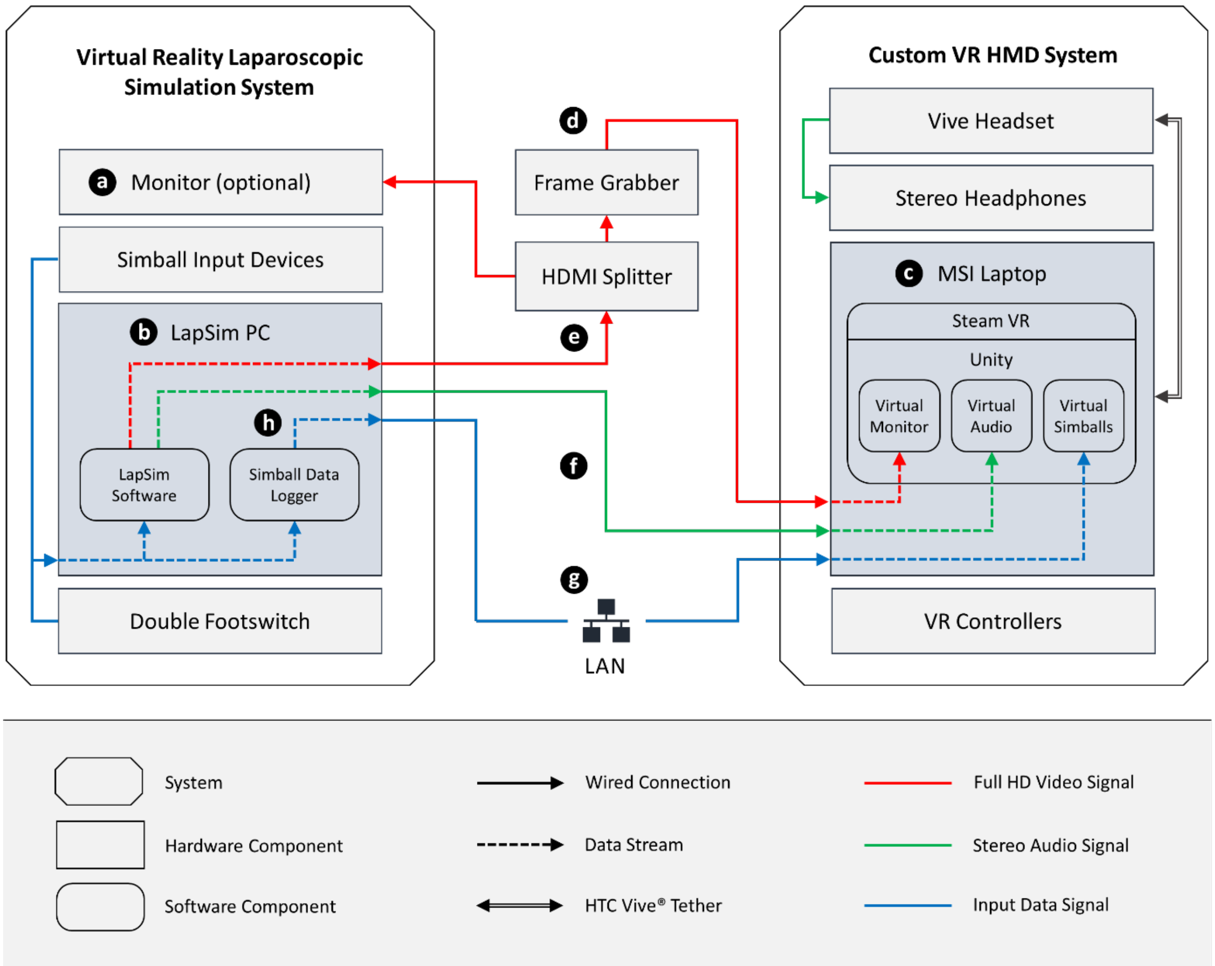

Fig. 2: Component diagram of the VR laparoscopy simulation system and our customized VR HMD system. a: conventional 2D screen, b: surgical simulator, c: VR-ready MSI laptop, d: HDMI to USB frame grabber, e: HDMI signal splitter, f: stereo audio cable, g: local network connection (LAN), h: Simball data logger auxiliary program.

Creation of Virtual Reality Surroundings

The cross-platform game engine, Unity™ (Version 5.4.2), was used to create the virtual surroundings by integrating the virtual monitor with the Simball joystick movements. The live video stream from the screen grabber was displayed on a plane, which served as a virtual monitor, with the Unity engine, "WebCamTexture class". The original stream was rendered at the standard resolution of 1920×1080 pixels. To optimize performance, the texture was down-sampled to 960×540 pixels prior to rendering. Sound from the LapSim system was integrated by placing an AudioSource object in the scene that captured the input from the laptop's microphone jack. The remaining virtual space was filled, via drag and drop, with models of medical devices, furniture, props, and animated character models of medical personnel and the patient. The models could be moved around to create a setting that mimicked the appearance of an OR during laparoscopic surgery.

An alternative way to create a virtual surrounding was to integrate the playback from a 360° video. To create this effect, the video clip could be mapped onto a sphere with the MovieTexture feature in Unity. The SteamVR camera rig was then placed in the center of the sphere and scaled down to a very small size to adjust for the fixed perspective of the 360° video recording.

Clinician Feedback

Four members of the surgical department were continuously involved in the development process. All four members had previous experience with the VR laparoscopy simulator.

Testing Phase

As part of the first clinical pilot investigations, other members of the surgical department performed laparoscopic tasks on the simulator. Hypothetically, a difference in performance due to distractions in the immersive setup may be possible. Furthermore, the degree of immersion into a virtual world, the attention to the environment and exhilaration of the participant are important aspects to optimize the surrounding. We thus used the validated questionnaire by Nichols et al. to quantify these aspects [23]. Furthermore, negative psychopathological aspects and vegetative side effects have been described in VR and have lead to the description of a "code of conduct" regard VR research [24]. Thus we investgated participants' heart rate (stress level) and motion sickness with the validated motion sickness scale by Keshavarz et al. [25].

The presented technical data is a comparison of immersive and regular VR simulation. This was investigated with the consectuvie performance of three tasks (peg transfer, fine dissection, and cholecystectomy) after an initial warm-up phase in regular VR mode. The selected tasks represent different aspects of laparoscopic surgery, navigational maneuver, fine preparation and procedural aspects. Tasks were always performed in regular mode first and AVR second and in the above mentioned order. Simulator metrics have been analysed using the total z-score of each task. Additionally, metrics have been grouped into categories time, handling economics and errors as previously described [15].

Fig. 3: Screenshot of the artificial virtual reality (AVR) operating room. The virtual environment was modeled, based on a 3D model kit from Vertigo Games, Rotterdam. A virtual instrument allows interaction with the LapSim simulator. A virtual monitor (center) shows the laparoscopy simulator's graphic output.

4 Results

A general overview of the custom VR setup we developed is shown in **Fig. 2**. All software and hardware components and connections proved to be generally technically feasible. The setup was user friendly, easy to assemble, and highly mobile.

Artificial Virtual Operating Room

We first developed an artificial virtual reality (AVR) OR. Our AVR was based on a commercially available modular 3D asset kit, which contained a fully equipped surgical OR (Vertigo Games, Rotterdam, Netherlands). It featured animated 3D characters and several models of surgical devices, props, and furniture. The feedback from the clinical development team led to repositioning certain components in the virtual environment. The position of the virtual display was adapted to correspond to the setting in our clinic. The positions of the trocars, sterile equipment, and surrounding team members in the AVR were changed to ensure the position was comfortable for the user and reflected the clinical setting (Fig. 3). Additionally, the size of the virtual monitor was increased to improve visibility of fine details, but at the same time, it remained realistic. A very small delay between the joystick movements and the corresponding movements in the VR surgical monitor was achieved on the virtual display. Even after the AVR was optimized, clinical feedback from the development team revealed that they remained aware of the fact that they were in an artificial environment the entire time, which led to a low degree of presence. This limitation stimulated the initiative to improve the surroundings and create a more realistic simulation.

Integration of Laparoscopy Instruments

At first, the four developers remarked that the instruments in front of them were missing during the AVR simulation. The Simball input devices provided a haptic sensation to the user, which was similar to the sensation of holding real surgical instruments. These instruments were the only means by which the user could physically interact with the virtual world. Therefore, it was important that virtual representations of these instruments could be seen when wearing the HMD. This visualization of the instruments in VR enabled the user to locate and grab the devices while wearing the HMD. To achieve this effect, the input data from the Simballs had to be translated into movements that were then applied to the virtual objects represented by the shapes of the simulated instruments. Because the virtual environment was generated in the VR system, and not the LapSim system, the Simballs input data had to be intercepted and sent from one computer to the other. An auxiliary program, the Simball Data Logger (Fig. 2h), which ran in the background on the LapSim PC, recorded the data without interfering with the LapSim software. Ee routed the data stream to pass through a local area network, which sent it to the laptop that ran the VR system (**Fig. 3**). The movements of the virtual instruments were very accurate, according to the users. The double foot-switch was not visualized within the virtual environment. However, this did not seem to be a problem for the clinicians since the footswitch is often not visible in the real operating room as well due to the surgical covers.

Highly-Immersive Virtual Operating Room

An alternative VR environment, the highly immersive VR (IVR) OR, was created with a 360° camera (Samsung Gear 360, Samsung AG, Seoul, Korea). Spherical video sequences were recorded inside a real surgical OR at the University Hospital Mainz, Germany. For the video, a surgical staff re-enacted the situation of a real laparoscopic surgery. Actual members of the departments acted as the patient, scrub nurses, laparoscopy assistant, and anesthesiologist (**Fig. 4**). The OR was first recorded without a scripted dialogue. Later, a second scenario was created with interactions between the fictional characters (e.g., the scrub nurses). The second scenario included sounds, actions, and conversations that were typical during a standard laparoscopic procedure.

The testing clinicians were highly exhilarated in response to the presence they felt in the OR, particularly during the second scenario. The sensation of presence was even more exhilarating when performing procedural simulation settings, such as a cholecystectomy, on the LapSim. Nonetheless, the display resolution was limited in the AVR and the IVR, particularly in tasks like fine dissection, where blood vessels must be differentiated. Despite many changes of settings, this limitation was mentioned by all participants. That finding led to the conclusion that the resolution was lacking with the HMD. Down-sizing the input signal to 960×540 in Unity did not impact the visual quality of the image significantly, because the virtual monitor only covered part of the user's field of view. The native resolution of the HTC Vive HMD was insufficient to display the original image in full HD resolution at that size.

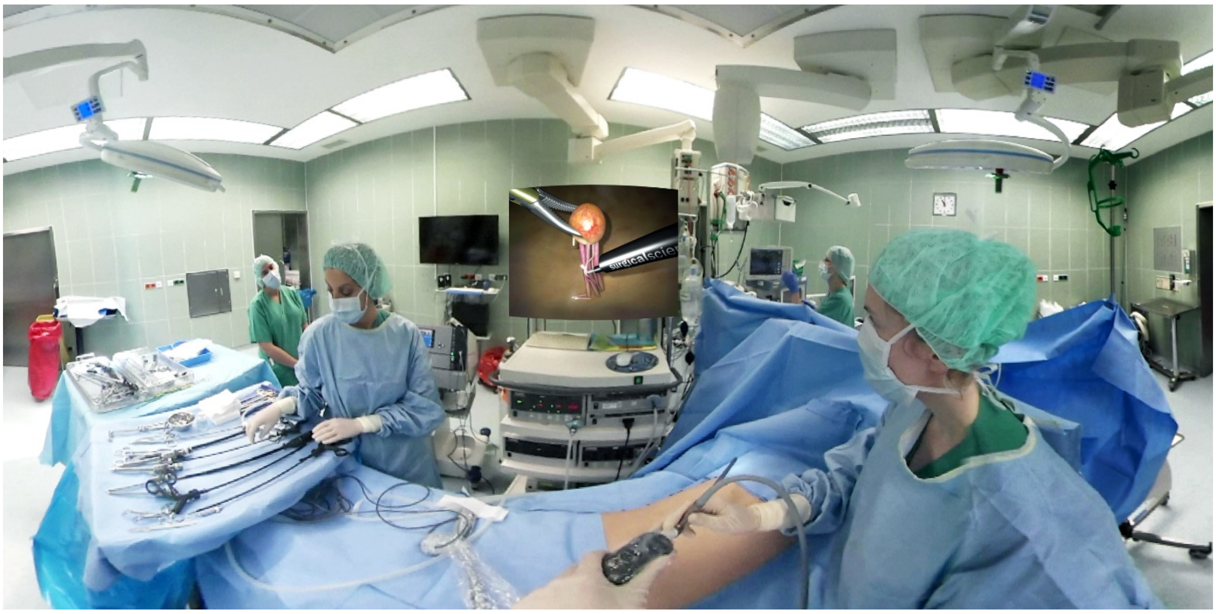

Fig. 4: Screenshot of the 360° highly immersive virtual reality (IVR) operating room (OR). A spherical video was generated with a Samsung Gear 360° camera in the OR at the University Hospital Mainz, Germany. The virtual monitor in the center shows the graphic output from the laparoscopy simulator (LapSim).

Testing Phase

In a previously published pilot study, we found no significant difference in performance between the regular VR laparoscopy and IVR. The participating surgical staff was highly exhilarated and indicated a high level of presence [26]. In a different approach, we previously investigated potential vegetative side effects. Nausea was present in this previous investigation in 10% of participants (2/20). These two female surgeons had a history of motion sickness. Although heart rates were elevated during IVR simulations, the elevations were not statistically significant [27].

The current analysis of technical performance compared regular VR laparoscopy and AVR of 16 participants. We observed no statistical differences in the total z-scores or in the categorized z-scores for handling economics, errors, and time. These technical results are displayed in **Table 1**.

Table 1: Calculated *z*-scores for tasks performed by participants (n=16)

Task parameters	VRL Session Median (IQR)	AVR Session Median (IQR)	*P**
Cholecystectomy			
Total	2.76 (-1.18; 5.40)	1.07 (-2.18; 6.14)	0.918
Time	0.39 (-0.60; 0.74)	0.28 (-0.86; 0.85)	0.836
Economics	2.47 (-3.00; 4.45)	0.93 (-0.74; 4.72)	0.836
Errors	0.80 (-1.48; 2.33)	0.97 (-1.77; 2.03)	0.756
Fine Dissection			
Total	0.35 (-1.58; 3.10)	0.39 (-3.53; 3.35)	0.918
Time	0.12 (-0.71; 0.57)	-0.12 (-0.59; 0.86)	0.959
Economics	1.22 (-1.19; 2.16)	0.12 (-1.43; 1.63)	1.000
Errors	-0.19 (-1.57; 1.64)	-0.18 (-1.23; 1.49)	0.756
Peg Transfer			
Total	0.59 (-1.73; 2.06)	1.39 (-1.33; 2.67)	0.756
Time	0.19 (-0.62; 0.60)	0.28 (-0.22; 0.72)	0.796
Economics	0.23 (-0.24; 0.79)	0.78 (-1.29; 1.24)	0.756
Errors	-0.61 (-0.61; 1.01)	0.27 (-0.60; 0.71)	0.679

IQR: interquartile range; VRL: virtual reality laparoscopy simulation;
AVR: artificial virtual reality operating room *Wilcoxon-Signed-Rank-Test

5 Discussion

Previously, Bowman et al. [28] discussed the important aspects of immersion, and the sensation of presence in VR. These aspects require hardware components that provide optimal refresh rates, frame rates, display sizes, and display resolutions. In the current study, our VR setup included an HMD with potentially the best hardware components commercially available. Nevertheless, the resolution in the HMD was limited for very fine preparations, and it must be optimized to determine the sweet spot with the best combination of a smooth frame rate and video playback, an acceptable virtual monitor size, and good image resolution. According to the "reality-virtuality continuum" [29], the combination of the VR laparoscopy simulation and a virtual OR in the current setup represented a combination of two virtually generated worlds. The VR laparoscopy simulator is usually perceived as closer to reality than the newly developed setup, because the simulation is presented on a two-dimensional monitor in an out-of-context environment. The only connection left to reality is the haptic user interface (Simball joysticks) which makes the virtual display of the instruments even more important. However, interaction in AVR and IVR is currently not possible and should be improved by further technical advances. An overview of the limitations in the setup we developed is given in **Table 2,** with corresponding technical solutions and ratings of clinical importance and technical viability. Hand tracking (e.g., via stereo cameras) may increase spatial awareness and proprioception, and this feature may function as an interface for changing the simulator settings in VR. Furthermore, several issues remain with HMD technology that are disadvantages to enhancing the immersion, and in these aspects, the traditional monitor outshines the new HMDs. For example, although the selected HMD possessed high pixel density (above 450 ppi), at close viewing distances, the so-called screen-door effect which is defined as the visibility of inter-pixel spaces was quite noticeable [30]. In addition, from an ergonomic standpoint, the roughly half a kilogram weight of the HMD can become uncomfortable with prolonged use, and this weight also hinders immersion. However, new advancements may give rise to higher-resolution, lighter-weight, and possibly wireless HMDs; thus, both the image quality and weight might be reduced in future applications to increase user-friendliness. Furthermore, the cost and complexity could be reduced by combining the two computer setups into a single computer system. We demonstrated the technical feasibilities of both the AVR, produced with a computer-generated OR, and the IVR, produced with the 360° spherical video sequence.

Despite the mentioned technical limitations, the current pilot study, which compared the AVR to regular VR laparoscopy, showed that participants technical performance was not different to regular VR. Still, a non-randomized study design is a limitation regarding the interpretation of the current results. Cochrane reviews comparing regular boxtrainers to VR laparoscopy showed equivalence in those training methods [14]. The current results show no significant difference in performance compared to regular VR surgical simulation techniques. This was consistent with our previous investigation, where we compared regular VR laparoscopy and IVR. In that study, although we found no difference in technical performance, the questionnaires revealed that the users experienced a high degree of presence and exhilaration and a rather low rate of motion sickness with the IVR [26,27]. The exhilaration experienced in VR laparoscopy combined with the HMD scenarios was a key aim of the current approach, and it is likely to increase the attractiveness of VR laparoscopy simulation. Further studies with a larger cohort must be performed to evaluate the general influence of AVR and IVR on laparoscopy simulations.

However, future research should place the greatest emphasis on interactions within the VR environment, according to the user's performance on the LapSim. Here, it may be possible to use technical data from the simulator or a speech recognition feature to trigger different environmental scenarios, depending on the situation. Immersion may be improved by replacing static video parts with high resolution 360° images or by constructing virtual environments with multiple 360° videos. Currently, these improvements might be technically demanding; however, it would not be difficult to implement binaural recordings of OR sounds to increase presence in the generated world. The degree of immersion may generally be higher in the computer-generated AVR than in the IVR, because AVR allows movements about the virtual room (roomscale VR). However, the fact that the OR surroundings and the acting individuals were familiar to all participants may have increased the degree of presence in the IVR. On the other hand, in IVR, movement in the virtual room is currently impossible, due to the static video recording. Movement in IVR might be achieved by fusing multiple 360° camera recordings of a virtual environment to create a photorealistic type of AVR. The low degree of motion sickness achieved might be explained by the fact that all movements were controlled by the participants, and not by the VR environment. The ability to simulate camera navigation was not used in this first VR setup. A potential goal of future developments might be to integrate an assistant that performs camera navigation; however, this integration might also affect motion sickness. Another promising improvement due to highly-immersive VR application could be the simulation of stress training in the OR as part of the surgeon's learning curve. Further research additionally needs to focus on the simulation of interactive scenarios. IVR may be a useful tool to support this and interfaces should be developed for surgical simulation software that trigger aspects in a virtual surrounding.

In conclusion, we have presented the technical and clinical development of a highly immersive VR laparoscopy simulation setup. This new generation of simulation will enable clinical studies to evaluate the impact of VR for surgical training. Further technical advances are needed to improve visualization and interactivity. Clinical analyses should focus on the influence of AVR and IVR on laparoscopy training.

Table 2: Overview of current limitations of the custom immersive Virtual Reality Simulation and possible solutions for future research, including ratings of their clinical importance and technical viability

Current limitation	Possible solution	Clinical importance	Technical viability
Mono audio recording of 360° camera	Binaural recording of intraoperative sounds	3	3
Missing visibility of user's hand motion	Hand tracking with data gloves	1	2
Missing haptic/tactile feedback from objects (patient, table, sterile drapes, other persons…)	Use of appropriate haptic feedback device	3	1
Flat sphere with missing depth of field	Three-dimensional 360° camera video	3	2
Static 360° video of surroundings (no room-scale VR in IVR)	Multiple 360° videos to create a photo realistic VR operating room to enable room-scale VR	2	2
No reaction of surroundings to VR simulator data (e.g., mistakes)	Recording of simulator data that can be used to trigger different scenarios Text recognition of simulator commands	1	3
Interaction with VR simulator (administrative)	Connect data gloves to steer simulation software	1	2
Camera navigation not included	Perform virtual surgeries as a team of surgeons, and include a camera navigator, with two VR headsets	2	1
Simple operating room scenario	Record different scenarios (e.g., stress training)	1	3
Surroundings familiar to the participants	Record different operating rooms	2	3

Range of clinical importance ratings: 1 = high importance, 3 = low importance
Range of technical viability ratings: 1 = difficult, 3 = feasible

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Ethical Approval

For this type of study, formal consent was not required. This study did not include patients or animals.

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Conflict of Interest

The authors TH, TW, MP, HL, WK and CH declare no conflicts of interest or financial ties related to this study.

Informed consent

This article does not contain patient data.

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