Mixed Reality-Based Training Simulator for Learning Scope Maneuvering Skills in Hysteroscopy

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Abstract

Scope maneuvering skills are essential for performing hysteroscopy. Conventional methods using synthetic or animal models provide limited training value due to lack of realism, while virtual reality simulators can be prohibitively expensive. In this work we present a low-cost, portable, Mixed Reality (MR) based hysteroscopy simulator. The prototype was developed using a Head-Mounted Display (HMD) device (Meta Quest 3), and 3D printed components designed to simulate scope movements. When observed through using the pass-through feature of the HMD device, virtual elements (including the operating table, screen displaying a dynamic operative field, virtual patient, and surgical scope system) were spatially rendered around the operator. To evaluate the prototype, a user study was conducted using a real scope and the MR simulator. Subjects completed a training phase (10 trials) followed by a validation phase (2 trials), during which various outcomes were measured to assess the impact of the training environment. Training using the MR simulator was comparable to training using the real scope, resulting in similar completion times during validation trials. Perceived workload (measured using SURG-TLX scores) decreased over repeated trials, showing no significant variation between environments. Feeback survey indicated equivalent learning, confidence, and perceived usefulness in both training environments. We conclude that a low-cost simulator is feasible with MR technology. The simulator generates a realistic and immersive environment mimicking both the operating room and the operative field, enabling hands-on training to learn the hand-eye coordination skills required for maneuvering a scope during hysteroscopy.

Keywords: hysteroscopy, surgical simulation, training, mixed reality, head mounted display

1. Introduction

Despite being a routine and generally safe procedure, inadequate endoscopic skills can significantly increase the risk of complications during hysteroscopy (Munro et al. 2015; Haimovich et al. 2024). Hysteroscopy involves the insertion of an angulated rigid endoscope (Fig. 1a) into the uterine cavity to visualize the uterus for both diagnostic and therapeutic purposes (Fig. 1b). This involves the treatment of uterine fibroids, polyps, adhesions, or abnormal bleeding. The procedure demands a high level of proficiency in endoscope handling, navigation, and the ability to interpret real-time visual data of the operative field. If the procedure is not performed correctly, it may lead to complications such as uterine perforation, bleeding, or fluid overload (Munro et al. 2015). Thus, proper training is essential to develop these endoscope maneuvering skills and perform the procedure safely.

Unlike laparoscopic procedures where surgeons become proficient through a prolonged process of observing, assisting, performing under supervision, and operating independently, this transition is expected to be much more rapid for hysteroscopy (Gambadauro et al. 2018). Hysteroscopy can be challenging to master because the procedure requires quick adaptation to visualizing the uterine cavity in a confined space and manipulating instruments with a high degree of precision. However, adequate skill acquisition is challenged by the ethical and legal concerns surrounding surgical training on live patients, cadaveric models, and animals (Sanfilippo et al. 2025). Additionally, a low case volume also restricts training opportunities available for novice surgeons who need live procedural experience to gain the necessary skills (Gargan et al. 2023). These challenges can be overcome using simulation-based training methods developed for hysteroscopy (Neveu et al. 2017). Evidence from several studies has shown that simulation-based training methods can enhance the cognitive-motor skills required for hysteroscopy (Moulder et al. 2017). A systematic review conducted by Gambadauro et al. (2018) highlighted a significant reduction in the procedure duration, as well as improvement in performance scores, following simulation-based training. Another review (Moulder et al. 2017) showed the benefit of simulation-based training methods particularly in areas with a low surgical volume, where opportunities for hands-on practice are limited. Thus, simulation-based training methods offer a platform to learn and practice basic scope movements during hysteroscopy to visualize different areas of the uterus.

Simulation-based training methods can be broadly classified into three categories: (a) virtual reality (VR) based medical simulators, (b) synthetic phantoms, and (c) animal models (Bassil et al. 2017). VR is a desirable training tool because it is reusable and offers real-time performance metrics for assessment (Glazerman et al. 2009). Unlike synthetic phantoms, VR can render highly realistic scenarios with various pathologies. Additionally, unlike animal models, VR eliminates ethical concerns and the risks of infection (Davies et al. 2013). However, despite these advantages, the cost of commercially available VR based medical simulators can be prohibitive (Bernier et al. 2016). There is a need for a VR setup that facilitates hysteroscopy training with low-cost and high realism. Working along these lines, in this work, we propose a prototype of a novel low-cost portable hysteroscopy simulator. The proposed simulator uses Mixed Reality (MR) head mounted display (HMD) device along with three-dimensional (3D) printed components.

The use of MR has been extensively reported in the field of surgical education. The effect of MR use in improving surgical skills (Guha et al. 2023), procedural accuracy, reducing operating time (Toni et al. 2024), and flattening the learning curve (Magalhães et al. 2024) have been noted previously. Immersive technologies have also been found to be comparable with other modes of learning for reducing error rates and improving procedure-specific knowledge during surgical training (Gilliland et al. 2024). Based on these findings, we hypothesize that the training of hysteroscope maneuvering skills using the MR simulator can be comparable to training in a real environment. In this work, we present findings of a user study comparing the learning performances between the developed MR simulator and the real environment.

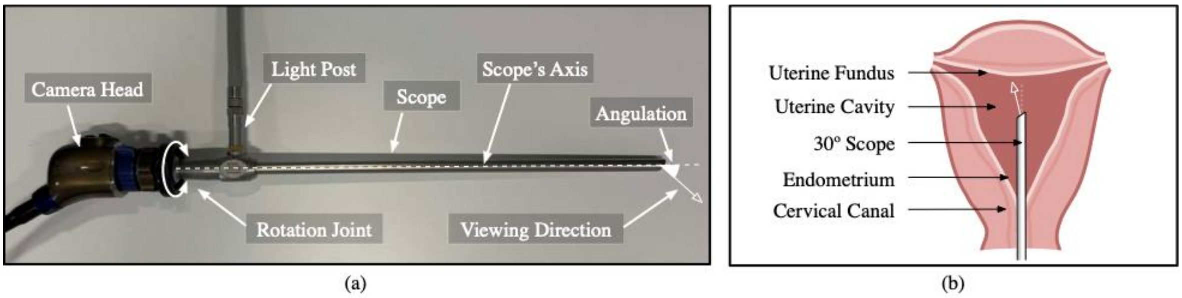

Fig. 1 (a) A 30° angulated scope with an attached camera head. The scope can rotate relative to the camera head along the axis of the scope's shaft. (b) Cross-sectional view of the uterus

2. Related Work

Augmented reality (AR) and VR systems have been implemented in multiple surgical domains including minimally invasive surgeries. Literature reviews have highlighted the benefits of using AR devices for training in laparoscopic surgeries (Celdrán et al. 2025) as well as spinal surgeries (Pierzchajlo et al. 2023). However, it was also noted that most implementations involved simple AR enhancements of the training setup with visual information, while only few studies enabled users to interact with the virtual objects (Celdrán et al. 2025). As for gynecological procedures, an early study (which included salpingectomy) underscored the value of VR training for improving surgical skills especially among novice surgeons (Hart et al. 2006). Current literature on hysteroscopy simulations focuses extensively on the use of VR based medical simulators (Gambadauro et al. 2018). Another study utilized a 3D printed hysteroscope model and a virtual scene on an external screen (Ferreira et al. 2020). In this setup, a tracking device (Leap Motion) is used to detect the trainee's hand and fingers interacting with the 3D printed hysteroscope model, and the virtual hysteroscope is manipulated accordingly. While it provides a low-cost solution for scope training, the setup presented does not simulate an operating room setting realistically. Depiction of realism in simulator based surgical training is crucial for effective skill transfer (Akhtar et al. 2014; Radhakrishnan et al. 2025). Incorporating virtual patient models and surgical drapes provides a more contextualized training approach contributing to a deeper learning experience (Agha et al. 2015). In the prototype proposed in this work, the virtual hysteroscope model is overlayed on the trainee's view of the replicated scope, thereby providing a true-to-life operating room experience. In addition, it does not require external tracking devices. Instead, it uses the device controllers to detect scope movements. In recent years, there has been a growing interest in simulators which can merge the physical world (such as a synthetic training phantom) with a highly realistic virtual rendering of the endoscopic view. One such setup is the EndoTrainer platform (Hernansanz et al. 2023) that utilizes a synthetic anatomy while further enhancing the operative view using augmented reality. However, the platform requires the use of a real endoscopic camera which is not easily accessible and can be expensive. On the other hand, our proposed prototype utilizes low-cost MR device controllers with 3D printed elements to simulate the endoscope. Furthermore, a compact and portable training setup is ensured by eliminating the need for an external display screen or a bulky synthetic training module.

An MR based simulation tool that superimposes a virtual 3D scene onto the real environment to replicate functional endoscopic sinus surgery has also been reported (Barber et al. 2018; Richards et al. 2020). This simulation tool combines the use of head mounted display VR device (HTC Vive) with 3D printed anatomy models. However, the setup utilizes only one tracker for the simulated endoscope, making it difficult to detect the rotation of the camera head with respect to the scope shaft (and vice versa). Since our prototype utilized two device controllers in the simulated endoscope, the rotation of the camera head and the scope shaft can be detected independently. Compared to VR based medical simulators and other developed systems (Barber et al. 2018; Richards et al. 2020; Hernansanz et al. 2023), the prototype presented in this work provides a low-cost and portable solution by eliminating the need for external hardware like a real rigid endoscope, a camera head, screens, synthetic phantoms, and external tracking systems. Compared to low-cost system already presented in the literature (Ferreira et al. 2020), our work provides a realistic hysteroscopy simulation that accurately replicates all the basic movements of the scope.

3. Methods

3.1 Development of an MR Simulator

Hysteroscopy is usually performed for the diagnosis of uterine pathology. During the procedure, a rigid hysteroscope is inserted into the uterine cavity using a transcervical approach without incisions (Khoiwal et al. 2024). While forward facing 0° scopes are sometimes used, angulated scopes (such as 30°) are often preferred as they offer a wider range of views, enabling the surgeons to view forward and sideways at the same time. However, the motions required to view different parts of the endometrial cavity using a 30° scope can feel counterintuitive. To visualize the sides of the cavity, a 0° scope must be panned and tilted (moved side to side), while a 30° scope must be rotated on its axis. Rotation of the scope shaft and rotation of the camera are two distinct movements used during hysteroscopy (as depicted in Fig. 2). Rotation of the scope shaft, which is done by turning the light post, allows the user to rotate the line of sight and view various regions of the uterine cavity along a circular periphery. In contrast, rotation of the camera head changes the orientation of the field of view displayed on the screen, causing it to tilt accordingly. In this work, we developed a prototype to enable training of such angled scope maneuvering techniques during hysteroscopy. The prototype consisted of Meta Quest 3 (Meta, USA) HMD device and 3D printed components. The two controllers of an MR HMD device were connected via a frame to simulate a surgical scope with a camera head (Fig.

3a). The frame consists of lightweight rod that mimic the scope's shaft. One controller (Controller 1) served as the scope's camera head and was attached to the rear end of the frame, while the other controller (Controller 2) was positioned at the distal end. The arrangement of the controllers can be switched based on whether the operator is right- or left-handed. At the rear end of the frame, an orthogonal extension replicated the light post and connected to controller 1 via a rotational joint. The relative rotation between the two controllers along the frame shaft was detected by the MR HMD device and simulated the rotation of the camera head relative to the surgical scope, or vice versa.

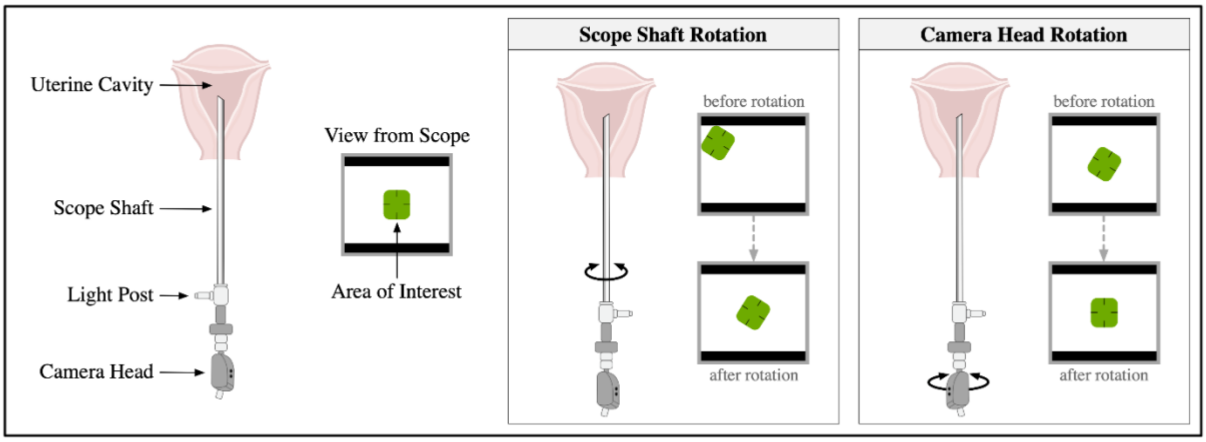

Fig. 2 Pictorial representation on the effect of scope shaft rotation versus camera head rotation on the displayed image. Rotation of an angulated scope shaft allows the user to see different parts of the uterine cavity, whereas rotation of the camera head causes the image to rotate on the display screen.

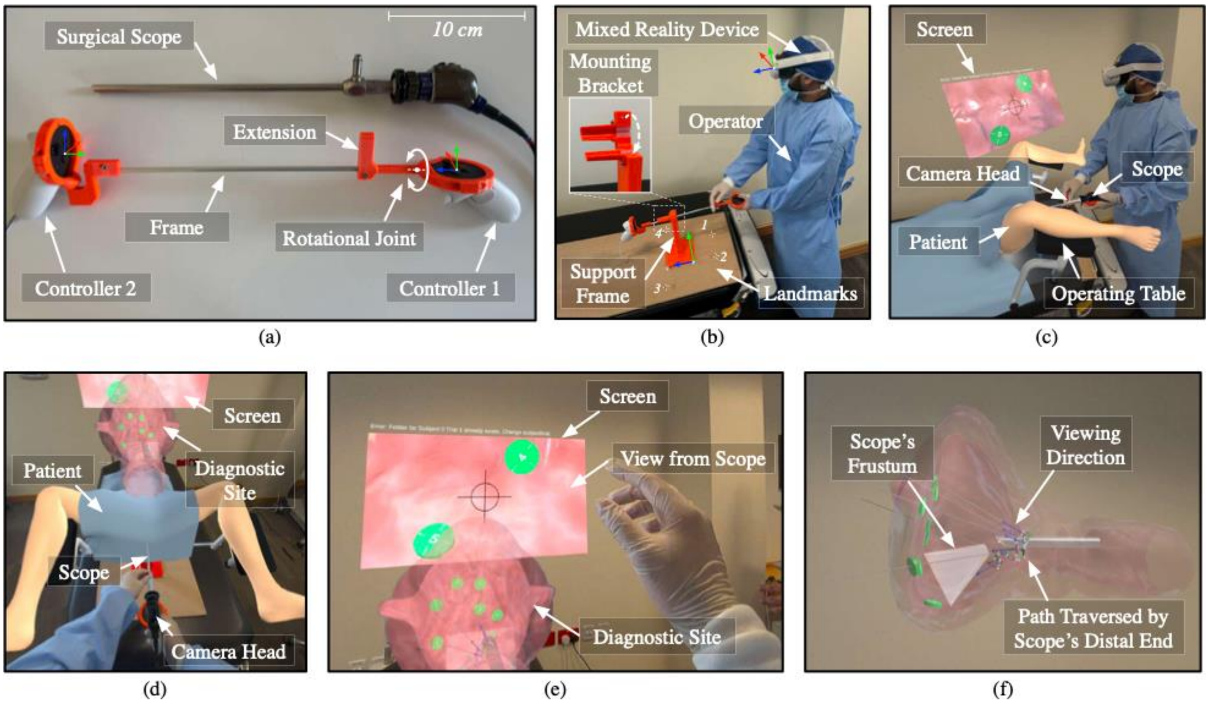

Fig. 3 (a) Frame with controllers of the MR device replicating the functioning of a surgical scope and camera. (b) Support frame with a mounting bracket to host the frame with controllers. (c) The MR environment with virtual elements (patient, operating table, screen, surgical scope, and camera head) rendered in the 3D space. (d) The MR view seen by the operator of the virtual diagnostic site rendered along with the screen in the 3D space. (e) Close-up view of the virtual diagnostic site. (f) Dynamic virtual elements (scope, scope's frustum, path traversed by scope distal end) rendered inside the virtual diagnostic site in real-time

The software was developed in Unity using the Meta All-in-One XR SDK for deployment on the Meta Quest 3 headset. Development and implementation were carried out on a Windows PC, with C# serving as the primary programming language. The application was compiled as an Android APK and deployed to the headset. A support is used to mount the frame on a mounting bracket (Fig. 3b), allowing for controlled movements. To register the platform's pose relative to the MR device, numbered landmarks are drawn on the base of the support platform. During registration, the user is presented with a virtual marker attached to his/her right controller. The user sequentially positions the virtual marker on each of the four numbered landmarks and presses a button on the controller for confirmation, linking physical landmarks to their virtual counterparts. The mounting bracket functions as the opening of a natural orifice and enables the user to perform insertion/retraction and tilting/panning motions of the frame. We also incorporated a silicone coating in the form of a cylindrical sleeve within the simulated opening for scope insertion. This provides tactile feedback to the user. To restrict the tilting/panning motion, a hollow tubular structure is used in conjunction with the mounting bracket mimicking the restriction faced while using a real scope through a dilated cervical canal.

The MR environment with virtual elements rendered by the HMD device using the pass-through feature is shown in Fig. 3c and Fig. 3d. The view consisted of virtual structures overlaid onto top of the real-world space around the operator. This gave the operators the sensation of being in an actual operating room, while still maintaining awareness of their physical surroundings. The developed simulation software retrieved the positions and orientations (poses) of the controllers relative to the MR headset using the Meta XR Toolkit. A virtual camera head was rendered onto the pose of controller 1, and a virtual scope was rendered such that its shaft overlays and aligns with the frame. The difference in the X-axis orientation between the poses of controller 1 and controller 2 was used to compute a rotation angle. The virtual scope was then rotated according to this angle with respect to the virtual camera head. The operator used one hand to hold the right controller mimicking the camera head, whereas the other hand was used to hold the extension replicating the light post. When the operator turned the extension, the light post of the virtual scope turned, and aligned with the extension on the frame. The movement of controller 1 replicated the insertion/retraction and tilting/panning motions of the scope.

Landmarks on the base of the support platform were used to register its pose relative to the MR HMD device. A virtual operating table and a virtual patient were rendered according to the pose of the support platform, with the mounting bracket coinciding with the opening of the cervical canal. The view of the virtual diagnostic site (which refers to the uterine cavity where the distal end of the scope is placed during the procedure) was displayed on a virtual screen. The operator maneuvered the virtual scope to visualize and explore different regions of the inner uterine lining. Movements available to the operator included scope insertion, retraction, rotation of the angled scope, rotation of the camera head, and slight tilting or panning of the scope. The operator was also allowed to move and position the virtual screen within the real environment through zooming, rotation, and translation. A video demonstration of the MR simulator is provided in Supplementary Material 1.

The simulator also included enhanced features that enable another mode of visualization with additional virtual structures, such as the virtual diagnostic site outside the virtual patient (Fig. 3d and Fig. 3e). In this mode, an enlarged version of the uterus appears to the trainee, helping them understand how the viewing direction of the angulated scope changes within the uterine cavity as the scope tip moves. Within the transparent virtual diagnostic site, virtual elements like the scope, the scope's frustum, and the path traversed by the camera of virtual scope were displayed dynamically in real-time (Fig. 3f). The real-time feedback enabled the operator to understand the spatial relationships and positioning of the scope within the diagnostic site (uterine cavity).

3.2 Experimental Setup

3.2.1 Subjects

A total of 14 subjects (right-handed with age from 25 to 40) from the Department of Surgery, Hamad General Hospital, Doha, Qatar participated in the user study. The subjects were researchers (non-surgeons) with no prior experience in maneuvering the scope. The study was approved by the institutional review board comprising of the ethical committee (Medical Research Center, Doha, Qatar, approval number MRC-03-23-786). Before the study, the subjects participated in a 10-minute preparatory session, which included watching videos to understand the movements of the scope and how these movements influence the views obtained through the scope. The subjects were distributed into two groups. A parallel group design was followed with an equal 1:1 allocation ratio. Random allocation sequence, using block sizes of 4 and 2, was concealed in opaque envelopes (Doig et al. 2005). This was done to ensure that an equal number of subjects will be allocated in each group, and to prevent the researcher from unconsciously influencing which group a subject will be assigned to. Due to the nature of the study, subjects blinding was not possible. The user study was reported according to the Consolidated Standards of Reporting Trials (CONSORT) statement (Schulz et al. 2010).

3.2.2 Study Design

The details of the study design are depicted in Fig. 4. The subjects (n = 14) enrolled in the study were randomly assigned to either of the two scenarios simulated: (a) using a real scope, where a rigid angulated endoscope was used with a 3D printed uterus phantom (Fig. 5a) and (b) using the MR simulator, where the MR controllers were used (to mimic the scope) with a virtual uterus phantom. Each group (n = 7) participated in only one scenario. Each training scenario consisted of two phases: a training phase followed by a validation phase. After completing 10 trials in the respective environments during training phase, the subjects (n = 14) moved to the validation phase where they completed two assessment trials: one in the real scope scenario and the other in the MR scenario. The task completion time was recorded for each trial.

In the real scope scenarios, a rigid scope (Karl Storz 30° angulated), a camera head (Karl Storz's Image 1 HD), a light source (Model # 201331 20), a video processor (Model #222010 20) and a 3D printed uterus phantom were utilized (Fig. 5b and Fig. 6a). Circular markers, numbered from 1 to 8, were placed in a clockwise order along the inner uterine lining of the phantom (Fig. 6b and Fig. 6c).

In the MR environment, the developed prototype was employed with a virtual uterus model (Fig. 6d). To create the uterus model, a 3D mesh model of the uterus was downloaded from free3d.com and was then modified using Blender software. The modifications were done based on the input provided by a clinician, which included (a) expanding the uterine cavity (b) broadening the cervical canal to allow passage of the scope, and (c) removing extra tissue structures (such as the fallopian tubes and ovaries). Both the 3D printed, and virtual uterus models had identical dimensions and marker arrangements within the uterine cavity. A crosshair was rendered at the center of the operative field view in both scenarios to assist in visualizing the alignment of the focus (Fig. 3e and Fig. 5a). Each marker was also outlined with a crosshair (four lines spaced 90 degrees apart). This provided a visual guide to maintain the scope's horizon. In each trial, a random sequence of five numbers (ranging from 1 to 8) was generated. For each number in the sequence, the subject was tasked with maneuvering the scope to align its focus with the corresponding numbered marker. After aligning a marker, the subject was provided with the next number in the sequence to continue the alignment process. Once all the markers in the sequence were correctly aligned by the subject, the task was considered successful.

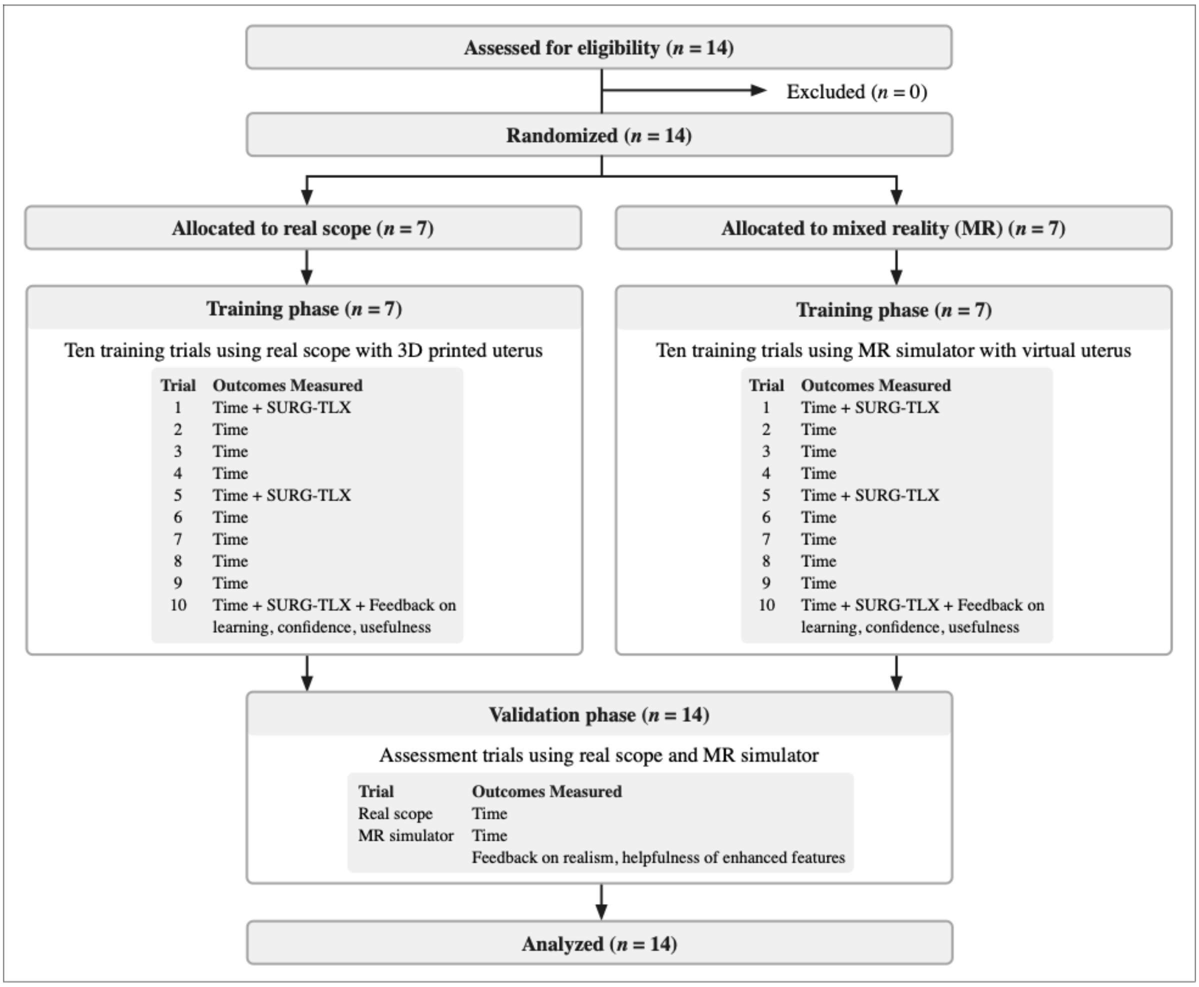

Fig. 4 Depiction of the study design

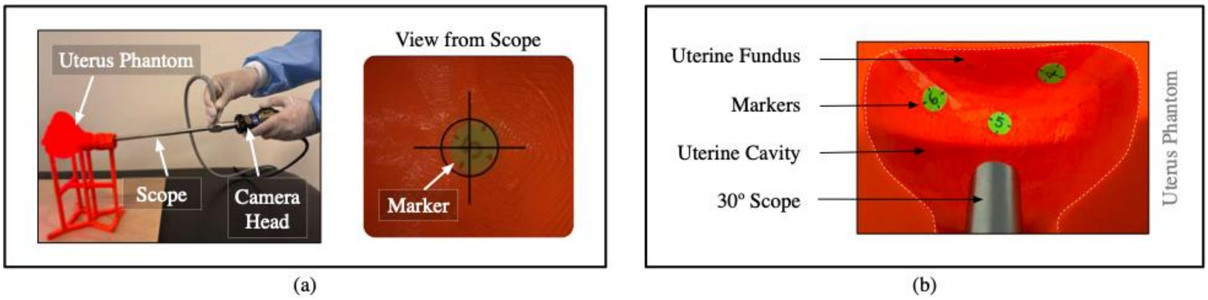

Fig. 5 (a) Training scenario with a real scope and 3D printed uterus phantom; (b) A cross-sectional view of the uterus phantom

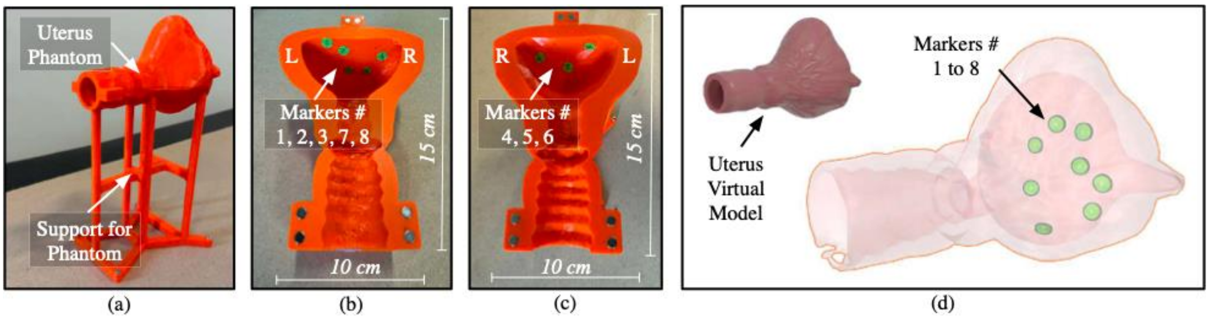

Fig. 6 (a) The 3D printed uterus phantom used for training using a real scope. (b) and (c) are cross-sectional views of the uterus phantom. (d) The virtual uterus model employed for training in the MR environment

3.2.3 Outcomes Measured

The primary outcome measured was the task completion time (seconds) for each trial. This was extracted from the video recordings of the operative field acquired in both the scenarios. The secondary outcome included the change in perceived workload throughout the training phase using the Surgery Task Load Index (SURG-TLX) instrument (Wilson et al. 2011). The SURG-TLX was previously adapted from the National Aeronautics and Space Administration Task Load Index (NASA-TLX) specifically for surgical applications. In addition to the domains of mental, physical, and temporal demands assessed in NASA-TLX, the SURG-TLX also includes assessment of task complexity, situational stress, and distractions (Nagyné Elek et al. 2021). The original TLX includes user assignment of weights for pairwise comparisons of the domains, followed by 20-point scales measuring workload. Since a high correlation has been observed between weighted and unweighted workload scores (Dickinson et al. 1993), we adopted a simple and easy-to-use 10-point scale ranging from very low (1) to very high (10) (Henderickx et al. 2023). The main purpose of using the SURG-TLX was to assess the difference in perceived workload over the course of the training phase (Abe et al. 2019). Hence, the subjects were required to complete the SURG-TLX after the 1st, 5th, and 10th trials to identify patterns in the reduction of workload with repetition of trials.

Additionally, after the completion of the training phase, the subjects were asked to complete a feedback form to assess learning, confidence, and perceived usefulness of respective training environments using a 5-point scale ranging from strongly disagree (1) to strongly agree (5). The development of the feedback form was guided by previously published assessments of endoscope simulators (Bajka et al. 2009; Janse et al. 2014; Abe et al. 2019) from which items were adapted for scope navigation tasks performed by novices.

After the validation phase, each subject was shown the enhanced features, such as hysteroscope path summary and transparent uterus mode (as shown in Fig. 3d, Fig. 3e, and Fig. 3f) available on the MR simulator. After the subjects completed the validation trials in both the environments, they were asked to rate the realism of the MR environment as compared to the real scope with 3D printed uterus phantom on a 5-point scale from very unrealistic (1) to very realistic (5). Feedback on the helpfulness of the enhanced features was also obtained from all the subjects using a 5-point scale. Since the enhanced features are exclusive to the MR environment and are absent while training using the real scope, they were demonstrated only after the validation phase to prevent any bias during the learning and validation phases.

3.2.4 Statistical Analysis

For the training phase, mixed model analysis of variance (ANOVA) (Brauer 2018; Murrar et al. 2018) was used to compare the effect of repeated trials on the task completion time among the two groups. The dependent variables were approximately normally distributed, and the randomized groups had equal sample sizes. Where sphericity was not assumed, the Greenhouse-Geisser correction was used. For the validation phase, an independent samples *t*-test was used to check for statistically significant difference between the two independent groups where the data met the assumptions for parametric tests (Ploeger-Lyons 2017). The Mann–Whitney *U* test was used where the data failed the test for normality (Hinton 2010). For the SURG-TLX scores, mixed model ANOVA was used to compare the change in scores within the 6 subscales over the repeated trials among the two groups. The level of significance was set at $p < 0.05$. The statistical analyses were conducted using IBM SPSS Statistics version 29.0.

4. Results

The means and standard deviations of the task completion time (in seconds) are provided in Table 1. During the training phase, a reduction in task completion time was observed over the ten trials for both groups that were trained using a real scope and the MR simulator (Fig. 7a). The result of the mixed model ANOVA showed that the task completion time significantly changed for both the groups with a significant main effect of repeated trials ($p < 0.001$). This indicated that the task completion time significantly decreased with repeated trials ~~for all subjects~~. In the group trained using the real scope, the task completion time reduced from 247 ± 137.9 s to 82 ± 42.8 s from trial 1 to trial 10, respectively. Similarly, in the MR simulator group, the task completion time significantly reduced from 176.4 ± 105.5 s to 55 ± 22.8 s. However, the training environment did not have a significant effect ($p = 0.063$) implying that task completion time did not differ significantly between real and MR environment groups. Furthermore, the interaction effect of the repeated trials with training environments was also not significant ($p = 0.425$). This revealed that the changes in task completion time over the repeated trials did not significantly differ between those who trained using either the real scope or the MR simulator.

During the validation phase, all the subjects completed one validation trial in each environment (Fig. 7a). When the subjects were assessed using the real scope, both the groups (those who were previously trained using the real scope and those who were trained using the MR simulator) showed no significant difference in task completion times ($p = 0.620$). Similarly, no significant difference in task completion time was observed between the groups for the validation trial in the MR simulator environment ($p = 0.060$). This suggests that exclusively training the subjects using the real scope or the MR simulator resulted in similar performances while assessing them in either of the environments.

Table 1 Mean and standard deviation of the task completion time in seconds

Phase	**Trial**	**Trained Using**	
		Real Scope ($n = 7$)	**MR[a] Simulator** ($n = 7$)
Training	1	247 ± 137.9	176.4 ± 105.5
	2	189.4 ± 102.4	102.6 ± 61.7
	3	137.9 ± 71.4	71.9 ± 27.9
	4	113.4 ± 45.1	62.9 ± 24.2
	5	91 ± 25.9	63.7 ± 38.1
	6	117.3 ± 49.6	70.9 ± 34.8
	7	115 ± 80.4	61.7 ± 37.7
	8	85 ± 37	61.6 ± 33.2
	9	83.7 ± 30.3	64.3 ± 26.8
	10	82 ± 42.8	55 ± 22.8
Validation	Real Scope	100.4 ± 52.8	85.4 ± 45.5
	MR Simulator	106.7 ± 55.3	64.3 ± 37.8

The analysis of average SURG-TLX scores (Fig. 7b) obtained during the training phase for both the real scope and the MR simulator groups (after 1st, 5th, and 10th trials) showed that there was an overall significant reduction in task load scores over the repeated trials ($p = 0.036$). However, there was no significant main effect of the training environment ($p = 0.276$) implying that the overall task load scores did not significantly differ between the two groups. Additionally, the interaction effect between the training environment, SURG-TLX scores, and repeated trials was not statistically significant ($p = 0.761$). This suggests that the assigned training environment did not significantly influence the change in task load scores over the repeated trials.

As depicted in Fig. 8, responses to the questionnaire on learning, confidence and usefulness conducted after the training phase slightly varied between the groups trained using the real

[a] MR stands for Mixed Reality

scope or the MR simulator. However, the difference was not statistically significant ($p > 0.05$) for all the questions. While some movements, such as the control of angulated lens view, perceived challenge, the subjects felt that it was easier to navigate once they were used to it. Certain markers were initially difficult to locate and align, however, this was less challenging in the subsequent trials. At the end of the validation trials, all subjects ($n = 14$) had experienced performing the tasks in both MR and real environments. Fig. 9 depicts the responses to questions on realism and helpfulness. While they were not expert surgeons, when asked how realistic the MR simulator was in comparison to the real scope (Fig. 9a), 11 (79%) responded that it was realistic, 2 (14%) rate it as very realistic, while 1 (7%) responded neutral. The subjects noted that the rotational movements of the controllers and replicated scope shaft were too smooth in the MR simulator as compared to the slight resistance felt while rotating the camera head and the real scope shaft. Regardless, some others reported that the textured uterine cavity in the MR simulator provided a much more realistic view, compared to the real scope view inside the 3D printed uterus model. When asked to rate the helpfulness of the enhanced features that could be implemented in the MR simulator (Fig. 9b), 7 (50%) felt the path traversed by the camera of virtual scope was very helpful, 4 (29%) felt it was helpful, and 3 (21%) responded neutral. Higher ratings of helpfulness were noted for the dynamic virtual diagnostic site, with 8 (57%) felt it was very helpful, 5 (36%) helpful, and 1 (7%) neutral.

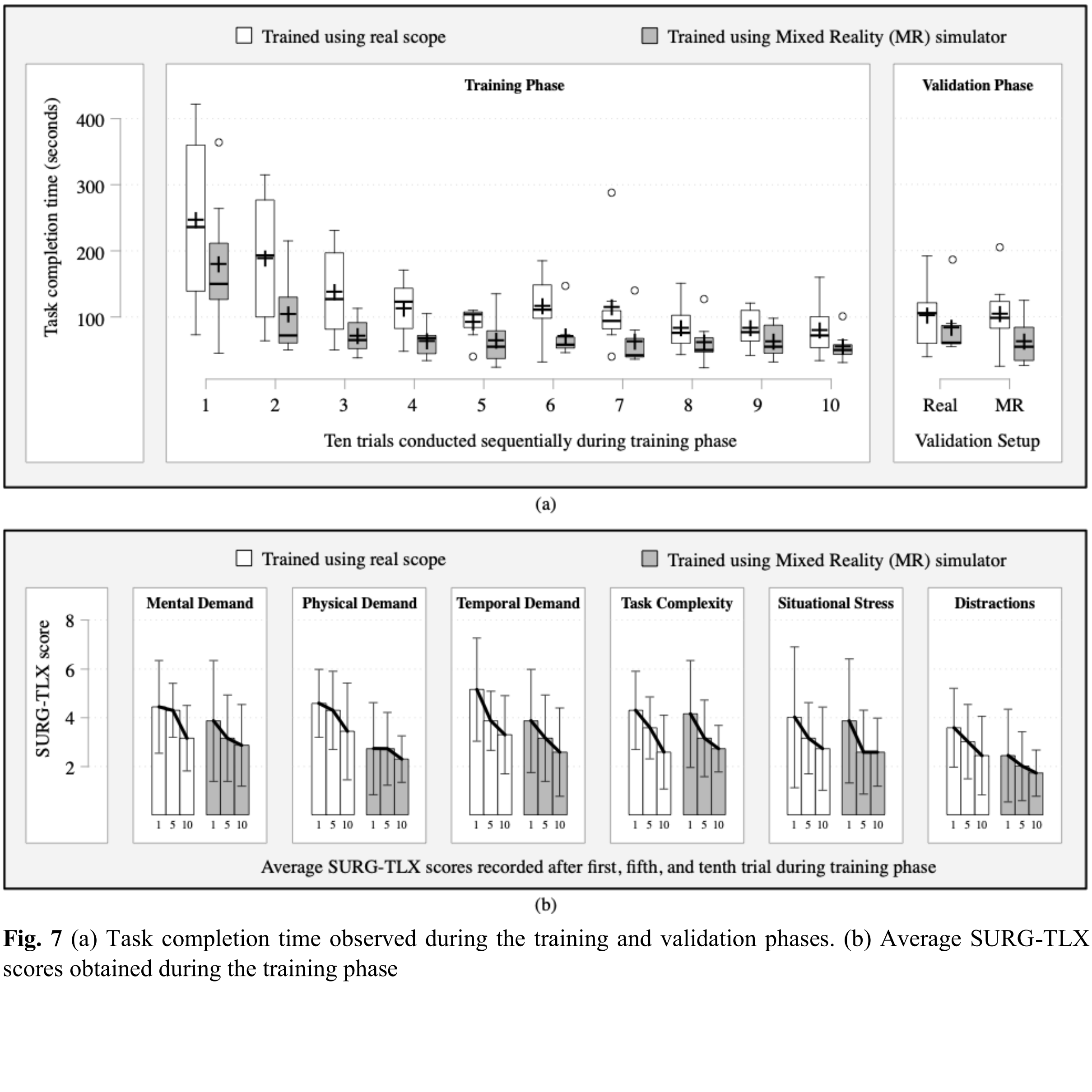

Fig. 7 (a) Task completion time observed during the training and validation phases. (b) Average SURG-TLX scores obtained during the training phase

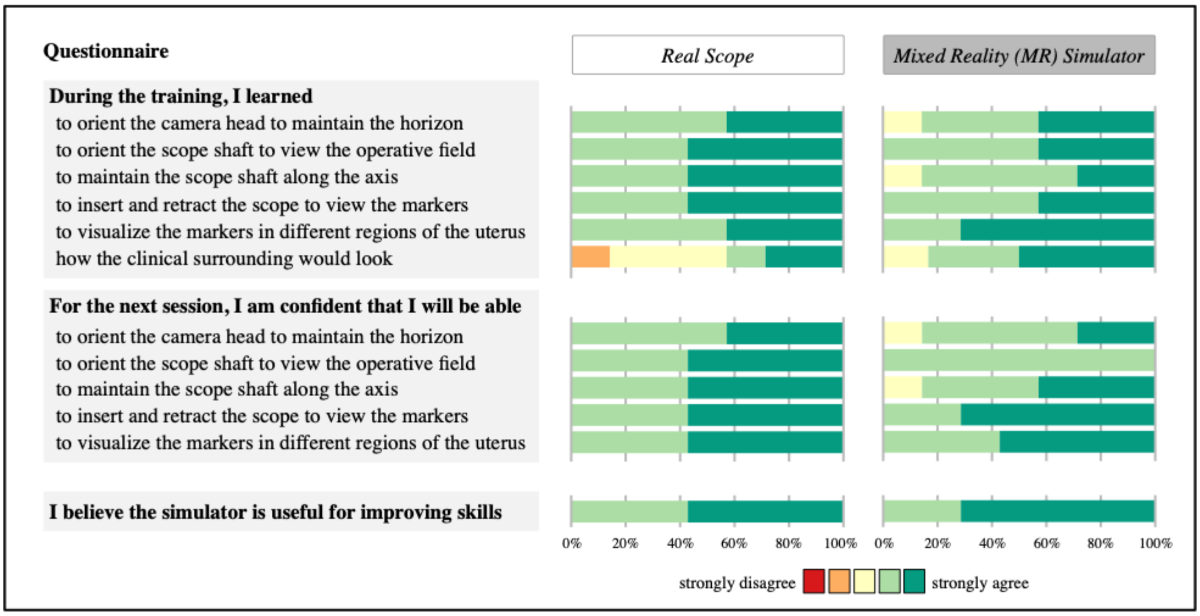

Fig. 8 Responses to the questionnaire assessing learning, confidence, and usefulness administered after the training phase

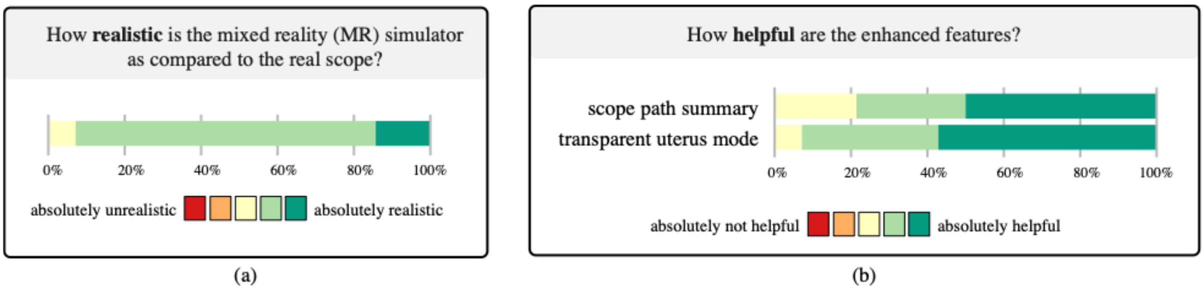

Fig. 9 Responses to the questionnaire assessing (a) realism and (b) helpfulness administered after the validation phase

5. Discussion

The primary aim of the user study was to validate the effectiveness of training using a low-cost in-house developed MR simulator. While using the simulator, the trainees visualize a virtual patient and the operating bed within the environment which acts as spatial anchors, helping them understand how the scope is manipulated relative to the patient and bed orientation. The use of pass-through feature in MR (instead of VR) allows the trainees to retain spatial awareness of the 3D printed attachments. This helps reduce the mismatch between virtual and physical cues, minimizing disorientations, and ensuring correct hand-eye coordination during training which focuses on scope orientation and manipulation. A significant reduction in task completion time was observed through the repeated trials, which is consistent with the observations of previous reports of hysteroscopy training platforms (Gambadauro et al. 2018; Hernansanz et al. 2023). Our study introduced a unique MR environment for training in hysteroscopy. The main finding of the study confirms our hypothesis that training in MR environment is comparable to training using a real scope. This is evident through a similar reduction in task completion times during the training phase. In addition, there was no statistically significant difference in completion time during the validation phase. It can be inferred that subjects performed similarly regardless of the training environment to which they were assigned. Nevertheless, it should be noted that since the sample size was small (n = 7 in each group), the findings of the mixed model ANOVA will have to be interpreted with caution. Future validation studies featuring larger sample sizes in each group are needed to ensure the generalizability of our findings. Similarly, while there was a significant reduction in SURG-TLX scores over the course of the trials, the overall task load scores did not significantly differ between the training environments. The current study included novices who used the training environments and performed hysteroscope maneuvering tasks for the first time. While the training environment differed visually, both groups had to perform the same task of manipulating the scope. This might have led to the lack of variations in task load perception.

The responses for the self-reported perceptions on learning, confidence, and usefulness offered some valuable insights. In general, the subjects felt that their performance and confidence improved with the repeated training trials. There were some challenges in navigating and locating the markers in the initial trials, which became easier with repeated trials. Overall, the subjects were able to become familiar with the required movements and the operating scene. While there were some reservations regarding the realism of the rotational movements of the simulated camera head and the scope shaft in the MR simulator environment, the subjects preferred the virtual uterine cavity with textures as compared to the 3D printed uterus model. Furthermore, none of the subjects felt the MR simulator was unrealistic. Subjective responses must be interpreted with caution as gynecological surgeons were not a part of the current study. Given that the subjects were not expert surgeons, they were not asked to compare realism of the MR environment with live surgery. Instead, they were asked to compare the MR environment with training on the 3D printed uterus phantom using a real scope. Future work incorporating expert evaluation of face validity is needed.

With respect to the enhanced features that can be implemented in the MR environment, some subjects felt that the summary of the traversed path would be better than verbal commands enabling them to understand and follow the movements required (Fig. 3f). Most subjects rated the transparent uterus model (Fig. 3d and Fig. 3e) as very helpful. They reported that the transparent uterus can act as a navigation map providing them with a clear understanding of how angulated scope movements and orientations result in different views of the uterine lining. Some others reported that the transparent uterus view can help them be cautious about hitting the uterine lining with the scope.

The overall direction of the results suggests that the low-cost MR simulator can be integrated into hysteroscopy training curricula. Typically, commercially available VR based medical simulators are incorporated into such training curricula. VR simulators for hysteroscopy training usually consist of a synthetic cervix model with hysteroscope handles, along with a screen displaying the simulated virtual environment. During training, the user manipulates the hysteroscope handles, which are equipped with sensors, to interact with the virtual environment. While VR simulators are often used for training in diagnostic hysteroscopy, some incorporate complex operative hysteroscopy procedures as well (Vitale et al. 2020). The Apex VR (LAPARO, Poland) provides virtual training modules for adnexectomy, hysterectomy, and ovarian procedures. Previous studies have shown that training on HystSim (VirtaMed, Switzerland), which was later incorporated into the GynoS platform (Bourdon et al. 2023), resulted in improvement of psychomotor skills (Neis et al. 2016). Regardless of these benefits, the cost of commercially available medical simulators can be very high owing to the use of specialized sensors for tracking scope handle movements, haptic devices that simulate tactile feedback, and high performance computing systems incorporated (Sutherland et al. 2006). Commercially available medical simulators with virtual environments can cost about $75,000 for basic skills training, and up to $200,000 when including procedure specific modules (Bernier et al. 2016). In contrast, the MR HMD device used in the presented prototype costs about $500. However, this does not consider the software development process, commercialization, and maintenance, which will contribute to the overall cost of the MR based hysteroscopy simulator. Additionally, to the best of our knowledge, more recent pricing information of VR based surgical simulators was not readily available in the scientific literature. Nevertheless, the large difference in hardware costs suggests that the MR HMD holds a potential in being a low-cost solution for surgical training. Unlike the VR based medical simulators, the proposed work does not incorporate complex operative hysteroscopic procedures. Instead, at the current stage, it provides a low-cost, compact, and immersive platform for scope maneuver training required for diagnostic hysteroscopy.

The findings of this study demonstrate some of the key factors influencing the acceptance and use of the MR simulator as explained by the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al. 2003). The UTAUT model has been utilized to assess the acceptance of surgical technologies (Toni et al. 2024; Verhellen et al. 2024) and consists of four key factors. They include performance expectancy (improvement of performance with the use of the simulator), effort expectancy (ease of use), social influence (virtual instructors), and facilitating conditions (resources). The in-house developed MR simulator demonstrates performance expectancy through reduced task completion time, effort expectancy through low SURG-TLX scores, and facilitating conditions by providing a training platform using a low-cost MR device, as opposed to expensive platforms such as real endoscope or commercial VR simulators. Future works may incorporate the use of virtual instructors and validation of the training platform by expert surgeons.

The current proposed MR simulator was limited to the training of basic camera navigation skills required for hysteroscopy. Further developments incorporating external trackers can enhance its application for other essential skills such as fluid distension, biopsy, and polyp removal. Complex hysteroscopic scenarios such as endometrium ablation, polypectomy, and myomectomy may also be incorporated. Apart from gynecological procedures, the concept of MR simulators can be expanded to other surgical specialties and procedures, including rhinoscopy, cystoscopy, and laparoscopy (Toni et al. 2024). Additionally, the MR simulator can be improved through the integration of automated skills assessment which can provide instant feedback to the trainee. Furthermore, face and content validity of the simulator must be conducted with expert surgeons. Likewise, to understand the learning effect of the simulator across varying surgical expertise, the sample size should include different groups such as novices with no experience as well as those with intermediate expertise (McConnell et al. 2019). A multi-institutional study design would be required to obtain a larger sample size. In addition, a future study comparing the MR simulator with current training practices for hysteroscopy using VR based medical simulators would be valuable.

6. Conclusion

This work introduces a prototype of a low-cost, portable, MR-based hysteroscopy simulator designed for learning scope maneuvering skills. The findings of the user study showed that hands-on training using the MR simulator is comparable to training using a real scope. Apart from providing an immersive training environment, the MR environment would be useful to learn hand-eye coordination skills during hysteroscopy. In a broader sense, the MR device and controllers present a viable platform for mimicking the movements of objects in the real world to learn essential psychomotor skills. With further developments, the simulator may also be adapted for other diagnostic procedures that utilize rigid angled endoscopes including cystoscopy, rhinoscopy, and laparoscopy. Future research incorporating expert surgeon evaluation and a multi-institutional validation study would be beneficial.

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Competing Interests

The authors of this submission have no conflict of interest or financial ties to disclose.

Compliance with Ethical Standards

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 subjects of the user study.

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