CatAR: A Novel Stereoscopic Augmented Reality Cataract Surgery Training System with Dexterous Instrument Tracking Technology

Yu-Hsuan Huang[1, 3, *], **Hao-Yu Chang**[2], **Wan-ling Yang**[1], **Yu-Kai Chiu**[2],
Tzu-Chieh Yu[2], **Pei-Hsuan Tsai**[1], **Ming Ouhyoung**[1, 2, †]
[1]Graduate Institute of Networking and Multimedia,
[2]Department of Computer Science and Information Engineering
National Taiwan University, Taipei, Taiwan
[3]Department of Ophthalmology, National Taiwan University Hospital, Taipei, Taiwan
[*]yush.huang@gmail.com, [†]ming@csie.ntu.edu.tw

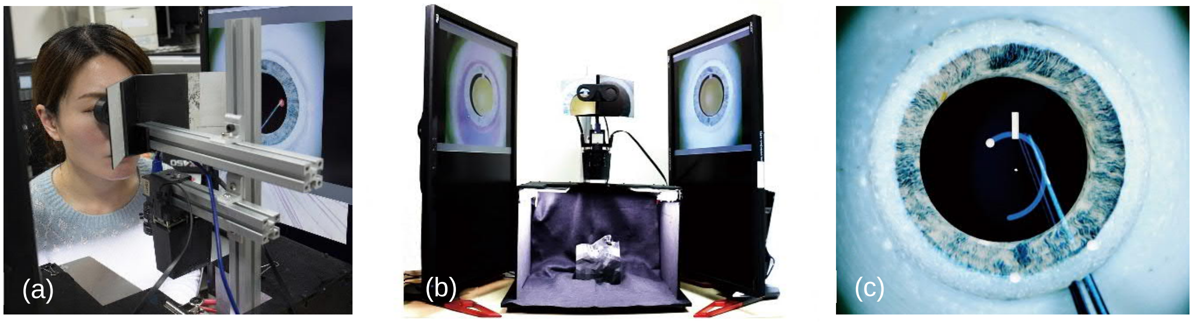

Figure 1. (a) A surgeon operating a CatAR system. (b) System overview: AR microscope platform, dual 4K displays, tracking area and surgical mannequin are shown. (c) A real surgical instrument interacting with the virtual object in a training module. The iris, blue guidance curve, and white rectangle are virtual objects overlaid on a real scene.

ABSTRACT

We propose CatAR, a novel stereoscopic augmented reality (AR) cataract surgery training system. It provides dexterous instrument tracking ability using a specially designed infrared optical system with 2 cameras and 1 reflective marker. The tracking accuracy on the instrument tip is 20 µm, much higher than previous simulators. Moreover, our system allows trainees to use and to see real surgical instruments while practicing. Five training modules with 31 parameters were designed and 28 participants were enrolled to conduct efficacy and validity tests. The results revealed significant differences between novice and experienced surgeons. Improvements in surgical skills after practicing with CatAR were also significant.

Author Keywords

Augmented reality; Microsurgery; Surgical simulator; Surgical training; Cataract; Instrument tracking; Dexterous input.

CHI 2018, April 21–26, 2018, Montreal, QC, Canada

ACM 978-1-4503-5620-6/18/04…$15.00
https://doi.org/10.1145/3173574.3174039

ACM Classification Keywords

H.5.2. Information interfaces and presentation (e.g., HCI): Multimedia Information Systems - *Artificial, augmented, and virtual realities*

BACKGROUND AND RELATED WORK

Cataract is a clouding of the lens in the eye that occludes vision. According to a recent assessment by the World Health Organization [26], cataract is responsible for 51% of blindness, representing 20 million people worldwide, which makes it the current leading cause of blindness. Although the opaque lens material can be removed through microsurgery procedures, it is very difficult for surgeons to master those skills because of following reasons:

1. Absence of force feedback

The lens is suspended behind the iris by a ring of fibrous strands called the zonule of Zinn. The diameter of the zonule is 1 to 2 micrometers, and it can be dehisced if the lens is pushed excessively during surgery. The lens capsule is only 2 to 28 micrometers thick and can be easily torn apart without any resistance. Due to these anatomical properties of the lens, cataract surgery mainly relies on visual feedback rather than the force feedback utilized in the other surgeries [7].

2. Difficult to reproduce subtle movements

The surgical field in cataract surgery is approximately 10 mm in both diameter and depth. Every movement is extremely delicate and the result can be significantly affected even if the difference is less than 1 mm. Young surgeons always learn the skills required by observing the actions performed by experienced surgeons through the assistant's eyepieces of the surgeon's microscope. In the microscopic field, only the instruments tips can be observed instead of the entire holding posture, which increases the difficulty for students to reproduce the subtle movements they have watched previously. This situation results in a major learning barrier for novice surgeons according to the interview results of cataract surgery trainees.

3. **Lack of realistic training tools**

   Before real surgeries are performed, surgeons can use cadaverous animal eyes or artificial eye models such as Kitaro DryLab kits [24] to practice. Pig or bull eyes are the most accessible choices [38] as they are similar in size to human eyes, but the thickness and tenacity of their lens capsules are different from those of human lens capsules. With artificial eye models, surgeons can obtain familiarity with the surgical steps, and practice the skills required to control the instruments, but the physical responses of their components are quite different from the real cases because of the synthetic membranes and simplified structures. Surgeons are always required to rebuild their hand-eye coordination and adjust the force output by practicing on real human eyes.

In the past 20 years, several systems have been proposed to not only solve the aforementioned problems, but also to provide a safer medical environment for patients. In 1995, Hunter and his colleagues [14] invented the first ophthalmic virtual reality simulation system that utilized mechanical robotic arms to receive subtle motion inputs. Researchers have adopted other technologies such as electromagnetic sensors [35], optical tracking cameras [32], Hall effect sensors [31], inertial sensors [8], and hybrid systems [20] to improve the accuracy and resolution of instrument localization. Specially designed, modified, or wired props instead of real instruments are required to interact with the sensors; the weights and tactile feedback patterns of these props differ from those of the real instruments.

In addition to the accuracy and resolution of an instrument's localization, familiarity with the required instruments is crucial for a cataract surgeon. For example, the capsule forceps may have curved or straight tips and a round or flat handle; each type requires different operation skills. Surgical techniques are highly related to the instrument type, especially in microsurgery, therefore the benefits of a training system will be limited if the real instruments are not accessible during practice. In a conventional optical tracking system, at least 3 reflection markers must be attached to the replicas for 6 degrees of freedom (DOF) tracking [6]. The weight and elasticity of the replicas will differ from those of real instruments. In an electromagnetic system, the accuracy might be influenced by the metal material of real instruments. In a mechanical articulated system, users usually manipulate with small robotic arms instead of surgical instruments [11]. These are the fundamental difficulties in utilizing real instruments in previous surgical training systems.

The works mentioned in this section are all built in virtual reality (VR). These systems track the instrument and then render the tool-eye interaction in a virtual environment, hence the real instruments cannot be observed. Furthermore, an eye model with a magnified scale is used, though it is unnoticed in a virtual environment, the movement will vary widely in real surgery. To overcome these limitations, we designed a novel infrared optical based dexterous instrument tracking method that is suitable for AR applications.

In this paper, we propose CatAR, a novel stereoscopic AR microsurgery training system to meet 3 critical user requirements in cataract surgery: realistic force feedback, subtle movement tracking, and real instrument practice. This system was designed according to the structures of a surgical microscope to improve trainees' hand-eye coordination. With a specially designed tracking system based on domain knowledge from cataract surgeons, users can utilize their pre-registered instruments under CatAR; thus, dexterous movements can be tracked. The improvements of their surgical skills could be transferred to real operations with a minimal transition period. In conclusion, the main contributions of this study are:

1. Proposing the first AR-based surgical training system using real instruments as the user interface.
2. Establishing a reliable and generalized microscopic tracking framework with ultra-high resolution (20 µm) for further HCI research at microscopic scale.

IMPLEMENTATION

System overview

As an AR microsurgery training system, CatAR has 2 main parts: a stereoscopic AR microscope platform [13] and dexterous instrument tracking system (Figure 1b, 2) which helps meet user requirements for using real surgical instruments instead of fake props. Through 2 infrared (IR) cameras, the positions of instruments can be calculated in real time and the corresponding virtual animations can be generated [12]. The virtual images are overlaid on the real stereo videos captured by the microscope module, and finally users can view the AR results through binocular eyepieces.

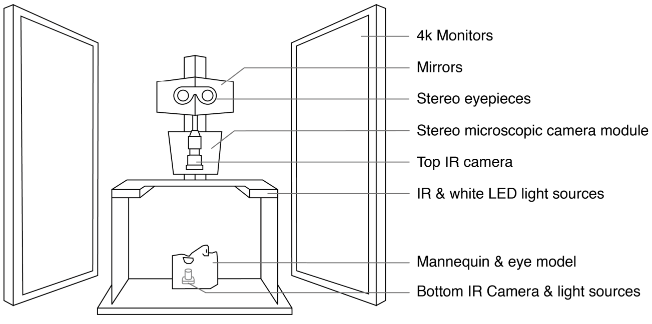

Figure 2. CatAR system structure diagram.

Stereoscopic Video See-Through AR microscope platform

Two mainstream AR technologies are optical see-through (OST) and video see-through (VST). Users of OST systems can observe real scenes directly with their eyes, and the augmented images will be projected into their eyes through a specially designed reflection interface. Users of VST devices look into displays that provide precomposed real and virtual images. Images of real scenes can be captured by a single camera or dual cameras set at a suitable distance to provide stereo vision. The latency between real and virtual images is the main challenge of AR systems in both methods, however, their visual results are quite different. The lag between real and virtual images is usually noticeable and sometimes bothersome due to the misalignment in OST systems. This situation worsens as the computational complexity increases. In VST systems, the latency of real and virtual images is always identical and will not cause misalignment, even if the computational complexity is high. Hence the visual results are more comfortable to view in a VST system and usually acceptable if the latency is below 33 ms. For this reason, we adopted VST technologies in the CatAR system.

Instrument tracking system

Several aspects must be considered when designing an instrument tracking system for microsurgery: movement characteristics, tracking errors, and instruments diversities. The surgical field is smaller than 1 cm^3 in cataract surgery therefore the movements during the entire operation are highly dexterous. Although the movements are subtle, the tracking errors are magnified through the microscope and can be easily noticed by the surgeons. The surgical instruments display a great diversity of size, tip shape, handling grip, and weight. An ideal tracking method should allow adaptation to different instruments with minimal modification. According to these principles, we designed an instrument tracking system supporting 6 DOF tracking with high precision and accuracy for the CatAR system.

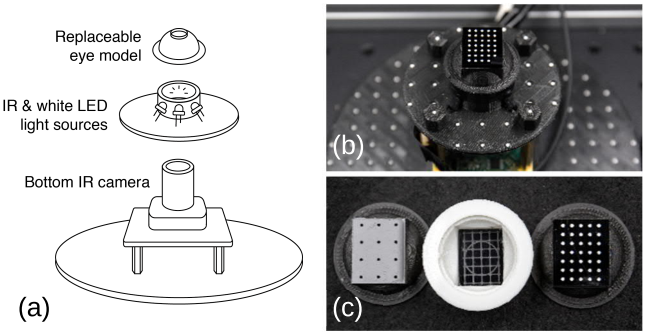

Figure 3. (a) Components and structure of the lower camera module. (b) Dot markers on 3 different plans. (c) Three different types of micro calibration boards.

The details of camera settings and tracking processes are described in the study of Huang et al. [12]. However, some modifications were made to enhance the visual performance and to support some instruments with an articulated structure such as forceps (Figure 5b). In real surgery, the retina reflects the light from the microscope to illuminate the tip of instruments. To imitate this phenomenon, we attached 4 adjustable white LEDs on the bottom of the model eye (Figure 3a), which helped users judge the depth of the tip with greater ease. Forceps have a symmetrical structure, and at least one of the proximal ends makes contact with the wound bottom during manipulation. This feature can be distinguished by utilizing the luminance difference of images from the bottom camera. Once the contacted part is recognized, the instrument position and its opening angle can be calculated using previous algorithms [12].

System Calibration

The CatAR system features 4 cameras, 2 for microscopic stereoptic VST AR vision and 2 for instrument tracking. The lens distortions must be corrected to restore normal stereo vision and obtain a precise tracking result. Furthermore, all cameras must be calibrated into identical coordinates to align the virtual and real environments. Unlike common camera calibration processes, the fields of view (FOVs) in the 2 camera sets are quite different (5 mm vs. 50 mm focal length), and the standard checkerboard method cannot be applied without modification. Three different types of micro calibration boards (Figure 3c) and dot markers on 3 different planes were designed for CatAR calibration (Figure 3b) to solve the extrinsic and intrinsic camera parameters.

Instrument Preparation

Before the CatAR system can be used, a tiny reflective ball must be attached to the distal ends of all instruments. This plastic ball is covered by 3M^{TM} Scotchlite^{TM} reflective tape to generate a uniform reflection regardless of the direction of the light source (Figure 5a, 5b). Trainees' performances are not affected while using the modified instruments because of its tiny diameter (6 mm) and light weight (0.8 g). The next step was to measure the instrument to determine the lengths between its tip, reflective ball, and its turning point. Users were required to wear black latex gloves while operating the instruments to minimize the interference from variant colors and reflected light (Figure 5c).

Resolution and stereopsis

Ophthalmologists are extremely concerned with the image quality in simulators because they use stereo microscopes frequently in their daily practice. Providing visual experiences similar to those from a real surgical microscope is a considerable challenge in the CatAR system. Theoretically, a display system with 60 pixels per degree (PPD) resolution, which equals 1 arc-minute resolution, can generate a 20/20 vision image according to the definition of [25]. We had previously tested different types of commercial head mounted displays (HMDs) but their resolutions were far below the acceptable level for microsurgery simulation (approximately 10–12 PPD for the Oculus CV1 and HTC Vive). The display panels in the EyeSi system are 800 × 640 pixels for each eye, providing approximately 13 PPD for a 50-degree viewing angle [23]. In the CatAR system, we used dual 28-inch 4K LCD monitors as image sources for a

Wheatstone stereoscope structure [45]. The distance between monitors and eyes was set at 32 cm to provide high PPD images (43 PPD) with a 50-degree viewing angle (Figure 4), which provided a realistic visual environment for microsurgery training.

The correlation between a user's stereoacuity and that user's simulator performance has been demonstrated in previous studies [3, 30, 34, 42], however, the stereopsis provided by simulators has seldom been discussed. The median stereoacuities of the surgeons in several studies has been 60 seconds of arc, evaluated by a TNO random dot stereogram (RDS) [39-41]. The CatAR system can provide 84 seconds of arc stereopsis under the definition of the RDS design [15], which defines 1 pixel width as the minimal disparity between 2 displays. However, while displaying natural images, the luminance distribution is continuous between pixels rather than binary in the RDS system. In this situation, the disparity can be phase-shifted and can become half of the pixel width [27], which is equal to 42 seconds of arc, and better than the median stereoacuities of the participants. With this feature, the CatAR system could be superior to other simulators in discriminating the fine performance difference between trainees.

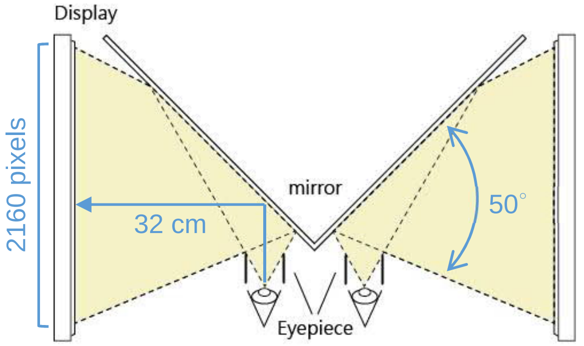

Figure 4. Stereoscopic display system in CatAR. The distance between the eye and screen is 32 cm, the viewing angle is 50 degrees and has 2160 pixels in this field (43 PPD).

Passive haptic feedback mannequin and eye model

Passive haptic devices can be defined in 2 ways: "Replicas of virtual objects that provide feedback through their shape" and "Interfaces that use energetically passive actuators which may in general only remove, store, or redirect kinetic energy within the system"[1]. For a novice surgeon, finding an area on a patient's face on which to place the hands and learning how to keep a stable posture are the initial challenges that must be conquered before commencing an operation (Figure 5c). Most related studies had either no mannequin with an active force feedback controller instead [2, 4, 9, 17], or a simplified rounded head model [11, 18]. To provide a more immersive environment and passive haptic feedback, we used a realistic mannequin modified from a three-dimensional (3D) scanned human model with a prominent orbital rim and a frontal bone in its actual dimensions.

The eyeball is relatively soft, and can be easily distorted or depressed by instruments through the cornea wound during cataract surgery. Although this physical property is important to reflect the quality of surgical skills, there is only one prototype proposed with a nonrigid eyeball model for intraocular surgery simulation [16] because of its difficulties. On the contrary, the only cataract surgery simulator in the market is equipped with a rigid eye model [43] with fixed holes to represent the cornea wound. Its controller tip can be freely rotated inside the holes but horizontal sliding is not possible. These limitations can be partially solved by 3D-printing technology. We utilized a 0.2 mm nozzle with an ethylene vinyl acetate (EVA) filament to print the delicate elastic cornea part on top of the rigid bottom (Figure 5d). The wound width was 2.4 mm, identical to the standard cornea incision in microincision cataract surgery. The height of the wound was adjusted iteratively and checked by 2 expert surgeons to obtain realistic deformation properties to constrain the forceps opening while tilting laterally (Figure 7e, 7f). By combining this eye model with the realistic mannequin, the requirements of physical feedback in cataract surgery training can be met.

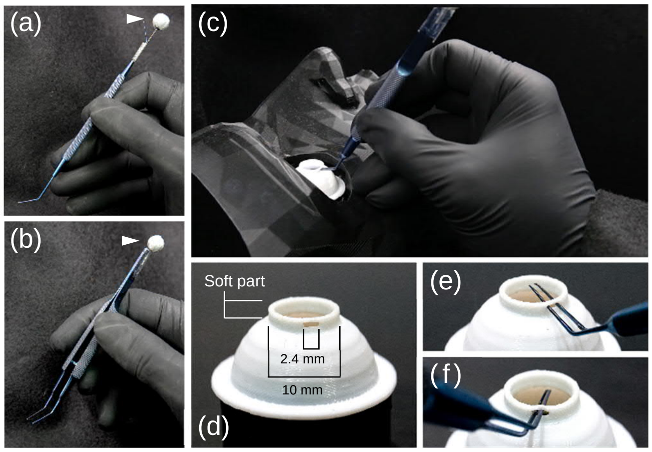

Figure 5. (a) Spatula and (b) Capsule forceps used in cataract surgery. Arrow: reflective tracker. (c) Standard hand posture on the face model while holding forceps. (d) Dimensions of eye model, the soft part is made using EVA material. (e) The soft part allows the forceps to be tilted in the small artificial wound. (f) The elasticity will constrain the opening distance of forceps while tilting laterally.

SYSTEM EVALUATION

One three-axis linear translation stage with micrometer drives providing 10 μm travel per division was utilized for system evaluation (Figure 6). After fixing the instrument on the stage using an extended holder, we adjusted the micrometers to place the spatula tip on 25 different positions that were evenly distributed in the eye model through the artificial wound. The 3D coordinates of the spatula's tip, corner, and optical marker were recorded repeatedly 60 times on every position. The standard deviation (SD) and root-mean-square error (RMSE) for each point were calculated, representing the system precision. The mean SD was within 1.50 μm of the tip and 16.0 μm of the marker end. The mean RMSE values were below 0.2 μm for the tip and 2.0 μm for the marker end (Table 1).

To evaluate the accuracy, we placed the spatula tip on 25 different starting points in the eye model and moved the instrument in a single direction (13 in X and 12 in Y direction) through micrometer drives. The 3D coordinates of 3 spatula landmarks were recorded every 50 µm for 20 iterations of each starting point. The vector differences between the tracking system and the ground truth from the translation stage were calculated. The system accuracies of tip, corner, and marker were 19.97, 28.52, and 58.53 µm, respectively (Table 1).

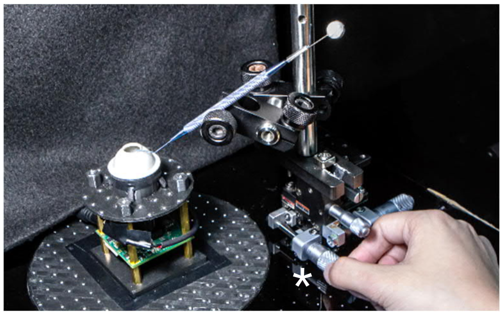

Figure 6. This spatula is fixed on the linear translation stage and its tip is placed inside the eye model through the wound. * Micrometer drive.

	Precision				Accuracy	
	SD		RMSE		Vector error	
(µm)	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Tip					19.97	10.16
X	1.50	2.26	0.19	0.29		
Y	0.79	0.60	0.10	0.08		
Z	0.13	0.11	0.02	0.01		
Corner					28.52	17.86
X	3.91	6.91	0.50	0.89		
Y	1.24	0.74	0.16	0.10		
Z	0.30	0.27	0.04	0.03		
End					58.53	24.21
X	8.42	6.56	1.09	0.85		
Y	15.24	10.08	1.97	1.30		
Z	15.06	10.14	1.94	1.31		

Table 1. Precision and accuracy of the tracking system

TRAINING MODULE DESIGN

Four abstract training modules (antitremor, anterior chamber navigation, circular tracing, and forceps training) and 1 procedural module (capsulorhexis) were designed according to clinical experience and previous validity studies of VR simulators [21, 22, 29, 33, 37].

Wound touch detection

The cornea structure can be irreversibly damaged if a surgeon manipulates instruments forcefully on the edges of the cornea wound [44]. These complications can be avoided if surgeons utilize the pivot concept [19]. However, it is difficult to take care of the wound condition while the trainees are intensively focused on the instrument tip. In the CatAR system, warning indicators are set on the right and left edges of the artificial wound and will turn red if a collision with the instruments is detected (Figure 7d). The measurements of wound touch, total wound touch time, and maximum wound touch time are recorded and analyzed in all but the antitremor modules.

Antitremor module

Six blue balls are distributed evenly along the virtual pupil margin with the same height (Figure 7a). The balls will turn red when contacted by the spatula tip and will disappear after continuous touching for 5 seconds. Trainees can touch the balls in arbitrary order and the tip position will be recorded 5 times per second while the tip is touching the ball. The motion ranges in the X, Y, and Z axes and the cubic space of motion are calculated and analyzed.

Anterior chamber navigation module

Two sets of blue balls the same as in the antitremor module are placed at 2 different heights. One white ball is set in the pupil center as a starting point. The trainee has to touch the white ball first and 1 randomly selected blue ball will appear after that. After the blue ball has been touched and has disappeared, the white ball will show up again until 12 blue balls have all been touched (Figure 7b). The time the trainee takes to manipulate the spatula tip from the white ball to the next blue ball is defined as the search time. The total and maximum search time and total task time are recorded and analyzed.

Circular tracing module

A virtual reference circle is defined at the pupil center to represent the capsulorhexis area. The trainee has to trace this circle with the spatula tip starting from the side opposite to the wound (Figure 7c). This task can be performed in a clockwise or counterclockwise direction based on the trainee’s preference. For each sampling point on the tracing curve, a corresponding point can be determined with the same central angle on the reference circle. The average distance of each point’s pair is calculated. The Frechet distance [6] and the lengths difference between the tracing curve and reference circle are also calculated. The task time is recorded and normalized according to the central angle.

Forceps training module

Six blue balls are set on the same positions as in the antitremor module. The trainee has to grasp one blue ball with the capsule forceps first, and then bring it carefully to the white ball in the pupil center to make it disappear (Figure 7d). The blue balls are approached in counterclockwise order. The time the trainee takes to grasp the next blue ball is defined as the search time, and the time required to bring the blue ball to the white ball is defined as the grab time. All the moving path lengths are accumulated as the value of the odometer.

Capsulorhexis module

After an initial flap has been created on the anterior capsule, the surgeon should grasp the proximal end of the flap using capsule forceps, and drag it to create a round tear (Figure 7f). The flap should be released after a quarter tear has been completed, and the surgeon must move the forceps tips to the new proximal end. These steps are repeated until a continuous circular capsulorhexis has been completed. In this module, a thin box is placed on the ideal capsulorhexis margin representing the proximal end of the flap. The trainee has to grasp the box and drag it along a virtual guidance curve to the releasing point (Figure 1c, 7e). This task should be repeated in 4 quarter directions to practice the movements in a standard capsulorhexis. The time the trainee requires to grasp the box is defined as the search time and the time required to bring it to the release point is defined as grab time. All the moving path lengths are accumulated as the values of the odometer.

USER STUDY

Participants

From March to April 2017, 28 participants consisting of 1 ophthalmic surgical physician assistant (PA), 1 intern and 2 postgraduate year 1 (PGY 1) residents in an ophthalmology training course, 18 ophthalmology residents and 6 cataract surgeons were included in this study (Table 2). Of the participants, 26 were trained or had completed their residency training in one single medical center, and only one first year (R1) and one third year (R3) resident were from 2 other different medical centers in the same city. We intended to include cataract trainees and surgeons of all experience levels but with similar training background to ensure the influence of different training curriculums were minimized. Participants were divided into 3 groups according to their levels of training: (1) Novices, the group of trainees who were in or before their second year of residency (R2). All of them had experience in watching or assisting cataract surgery but only a few had limited experience in performing surgical steps on humans. (2) Intermediate trainees, defined as residents who had performed steps of cataract surgical procedures under supervision regularly but had yet to operate independently (zero independent operations at time of enrollment in the study). (3) Experienced surgeons were those able to complete cataract surgery independently. All participants provided oral consent before inclusion and completed a questionnaire regarding demographic data, training and surgical experience, surgery preferences, and their opinions about the role of haptic feedback during surgery (Table 2). There were no differences between groups in gender, age, and hand dominance, but training and surgical experience were significantly abundant in experience surgeons compared with novices. None of the participants were exposed to any type of VR surgical simulator before. Most of the participants recognized visual feedback is much more important than haptic feedback in cataract surgery, confirming the statements provided by Doyle et al. [7].

Intervention

All the participants were first instructed in a standardized manner on the function and operation methods of the CatAR system (5 min). After adequately adjusting the interpupillary distance, one short warm-up section (5 min) followed to familiarize them with the CatAR system. The pre-intervention section was started after that, and 5 training modules were required to be completed once in the following sequence: Antitremor training, anterior chamber navigation, circular tracing training, forceps training, and capsulorhexis training. The results were recorded and their performances were monitored by one single senior instructor.

The practice section followed, consisting of 5 iterations of the antitremor and anterior chamber navigation modules and 10 iterations of the other 3 modules. Approximately 1 hour was required to practice these modules, and participants could ask for short breaks if needed. All modules were performed once again in the same order in the post-intervention section after practice. The results were recorded and compared with the corresponding results in the pre-intervention section (Table 3).

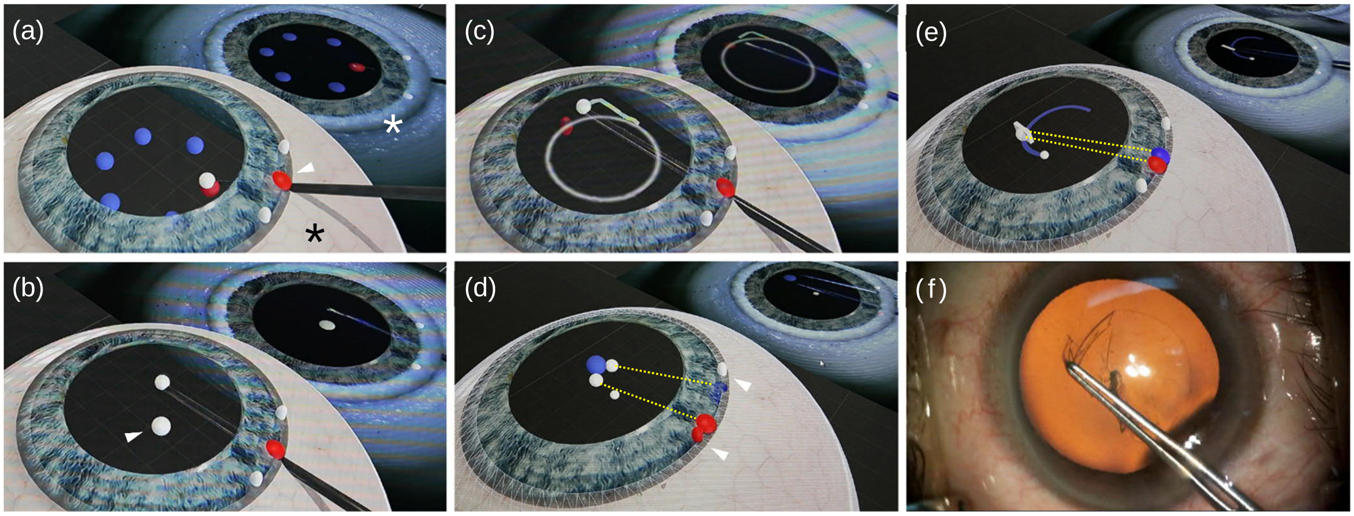

Figure 7. Instructor's 3D view (black star) and user's AR view (white star) of 5 modules. (a) Antitremor module, 6 blue virtual balls are placed in the pupil area, and turn to red when touched. Arrow: insertion point of the instrument. (b) Anterior chamber navigation module. Arrow: starting point in the pupil center. (c) Circular tracing module, green line represents the curve drawn by the user along the white reference circle. (d) Forceps training module: six blue balls are dragged to the small white point in the pupil center. Two white balls beside the blue ball represent the forceps tips. Arrow: wound touch warning indicators, the lower one is touched and turned to red. (e) Capsulorhexis module: white thin box represents the proximal end of the capsule flap. The box is dragged along the blue curve to the white point. (f) Capsulorhexis in the human eye.

	Novice	Intermediate Trainee	Experienced Surgeon
Number	12	5	11
Gender, n (%)			
Male	6 (50%)	3 (60%)	5 (45%)
Female	6 (50%)	2 (40%)	6 (55%)
Age (year)			
Mean	27.8	29.6	33.3
Range	26-35	29-30	30-38
Hand Dominance, n (%)			
Right-handed	12 (100%)	5 (100%)	11 (100%)
Training Level			
Surgical PA	1	-	-
Intern	1	-	-
PGY 1	2	-	-
R 1	4	-	-
R 2	4	-	-
R 3	-	5	-
R 4	-	-	3
Fellow	-	-	2
Attending	-	-	6
Training Experience (median)†			
Pig eye	0*	1~5	1~5*
Silicon eye	0*	1~5	1~5*
VR simulator	0	0	0
Human‡	0*	11~15	21~50*
Surgical Experience (months, mean ± SD)			
Assistant	5.3 ± 7.1*	27.4 ± 5.6	28.4 ± 10.3*
Operator	0*	0	40.5 ± 31.2*
Eyes †	0	0	>51
Location of Cornea Incision			
Temporal	-	-	5
Superior	-	-	2**
Both	-	-	4
Visual vs. Haptic feedback			
100 % : 0 %	-	3	2
80 % : 20 %	1	-	6
60 % : 40 %	-	-	3

PA = physician assistants, PGY = postgraduate year, R = resident

† Category: 0 / 1~5 / 6~10 / 11~15 / 16~20 / 21~50 / >50 eyes

‡ Under the supervision of the instructors

* P < 0.05 between novices and experienced surgeons

** They are excluded in the validity analysis due to unfamiliar position

Table 2. Demographic characteristics on study participant

After the intervention finished, a questionnaire regarding subjective efficacy evaluation and system performance was completed by the participants. A 10-minute individual interview with each participant was conducted to collect feedback. Subjective improvements in real operations related to this intervention were investigated 1 month later.

Validation of the CatAR system

A beneficial training system must have the ability to discriminate different skill levels by its scoring parameters. Comparing the pre-intervention scores of novice and experienced groups has been a standard method of "construct validity" [5] in previous VR cataract surgery simulator studies [21, 22, 29, 33, 37]. Although the training modules in the CatAR system were designed with proficiency-based concepts similar to VR systems, the validity of AR technology in surgical simulator has not been explored before. In this study, we conducted a construct validity analysis of all 5 modules proposed in our system by comparing the pre-intervention results of the novice group (n = 12) with the experienced surgeon group (n = 9).

Unlike other participants, 2 of the attending physicians had performed cornea incision from the superior side of a patient's head (superior approach) for many years. When they practiced on the mannequin designed for a temporal approach in this study, their hands' supporting postures and manipulation techniques through different directions of the cornea wound severely affected their baseline performance. Therefore, they were excluded from the experienced surgeon group in the construct validity analysis.

RESULT

Statistical analysis

MedCalc software version 17.5.5 (MedCalc software BVBA, Ostend, Belgium) was employed for the statistical analysis. Differences in performance parameters between groups and in the subjective efficacy evaluation between training methods were tested for statistical significance using a two-tailed Mann-Whitney U test. Pre- and post-intervention performances were compared using the two-tailed Wilcoxon signed-rank test set at a significance level of .05. The Spearman's rank correlation coefficient was calculated to analyze the relationship between surgical experience (month) and hand-eye coordination ability, quantified by search time in the anterior chamber navigation module (Figure 9).

Construct validity analysis

The experienced surgeons significantly outperformed novices by at least one parameter in all training modules (Table 3): motion range in Y direction (P = .047) in the antitremor module; total task time (P = .016) and search time (P = .016) in the anterior chamber navigation module; difference of travel path (P = .049), average distance difference (P = .042) and Frechet distance (P = .010) in the circular tracing module; search time (P = .043), grab time (P = .019), total task time (P = .018), odometer (P = .019) and wound touch time (P = .037) in the forceps training module; grab time (P = .047), total task time (P = .023), odometer (P = .001) wound touch time (P = .047) and maximum wound touch time (P = .039) in the capsulorhexis module. Sixteen out of the 31 parameters successfully passed the construct validity test.

Objective efficacy analysis

Participants gained statistically significant improvements (P < .05) after a 1-hour intervention in all parameters except motion range in the X direction in the antitremor module (P = .2275) (Table 3). Furthermore, the differences were highly significant (P < .01) in most of the parameters (27/ 31) except the motion range in the Z direction in the antitremor module (P = .024), quantity of wound touch in the circular tracing module (P = .027) and search time in the capsulorhexis module (P = .032).

Subjective efficacy analysis

Participants were asked to compare the efficacy of 3 traditional training methods (pig eye, silicone eye, and human eye under supervision) to the CatAR system through 10 training goals according to their previous experiences Table 4). The CatAR system was evaluated to have better efficacies in all training goals than the pig eye and silicone eye. Not surprisingly, practice on a real human eye under supervision almost achieved full scores in every question. However, participants perceived that the CatAR system could provide training effects similar to human eyes in practicing the pivoting technique (P = .155). Instructions can be received instantly and then practiced repeatedly during the training course as in a real operation (P = .862)

System performance evaluation

Satisfaction related to display resolution, stereoscopic perception, dizziness, motion-to-photon latency, tracking accuracy, and wound tenacity in the CatAR system were investigated (Table 5). Participants stated the resolution was excellent (mean = 9.0), and perceived no significant dizziness (mean = 8.6) and latency (mean = 8.4) during and after training. Tracking accuracy (mean = 7.8), stereoscopic perception (mean = 7.5), and wound tenacity (mean = 7.4) were acceptable. The overall efficacy was excellent (mean = 9.1) and they stated that they would like to use CatAR as a standard training method (mean = 7.7).

Subjective skill transfer after intervention

We contacted the participants again 1 month after the intervention and asked them about the subjective feeling of skills improvement in real surgery related to CatAR training (Table 5). Fifteen participants reported a noticeable improvement after using the CatAR system (mean = 9.1) in the following aspects: pivoting technique (n = 4), instrument handling posture (n = 3), navigation technique (n = 2), and minimized wound damage (n = 1).

	Novice Baseline n = 12	**Experienced Surgeon Baseline n = 9¶**		**Pre-intervention n = 28**		**Post-intervention n = 28**		
	Median	*Median*	p-value†	*Mean*	*SD*	*Mean*	*SD*	p-value‡
Antitremor Module								
Motion range in X (mm)	0.82	0.64	0.1179	1.08	0.76	0.81	0.22	0.2275
Motion range in Y (mm)	0.88	0.68	0.0466*	0.41	0.21	0.70	0.20	0.0088*
Motion range in Z (mm)	0.36	0.29	0.8870	1.06	0.87	0.32	0.19	0.0242*
Cubic space of motion (mm^3)	0.25	0.11	0.1769	0.82	1.46	0.18	0.14	0.0067*
Anterior Chamber Navigation Module								
Total task time (sec)	107.42	78.04	0.0157*	99.43	28.44	72.90	12.03	< 0.0001*
Search time (sec)	73.93	49.24	0.0157*	66.72	23.85	45.70	9.90	< 0.0001*
Max search time (sec)	13.90	9.22	0.0646	15.14	12.69	7.35	2.41	0.0001*
Wound touch (n)	13.50	7.00	0.2196	9.50	6.17	4.69	4.13	0.0016*
Wound touch Time (sec)	7.44	2.78	0.3525	9.05	11.92	1.83	1.81	0.0013*
Max wound touch Time (sec)	2.25	0.94	0.8658	3.20	4.55	0.66	0.55	0.0003*
Circular Tracing Module								
Normalized task time (sec)	15.11	19.09	0.2679	18.22	6.52	13.66	3.98	0.0004*
Difference of travel path (%)	0.40	0.23	0.0489*	0.54	0.66	0.20	0.14	0.0001*
Average distance diff. (mm)	0.64	0.45	0.0423*	0.80	0.59	0.50	0.39	< 0.0001*
Frechet distance (mm)	1.17	0.90	0.0097*	1.71	2.14	0.84	0.28	< 0.0001*
Wound touch (n)	2.00	2.00	0.8262	3.04	2.29	1.88	1.34	0.0266*
Wound touch Time (sec)	4.73	3.58	0.7762	4.13	2.72	2.01	1.78	0.0024*
Max wound touch Time (sec)	2.74	3.30	0.8870	3.04	2.32	1.30	1.04	0.0018*
Forceps Training Module								
Search time (sec)	69.34	31.16	0.0425*	61.69	54.17	26.76	13.67	< 0.0001*
Grab time (sec)	27.74	11.84	0.0190*	24.45	17.48	11.69	6.98	0.0001*
Total task time (sec)	105.05	45.42	0.0180*	84.42	67.35	38.78	19.97	< 0.0001*
Odometer (mm)	234.20	100.88	0.0190*	212.77	163.38	121.42	75.19	< 0.0001*
Wound touch (n)	26.50	11.00	0.0892	22.85	21.72	12.07	10.62	0.0002*
Wound touch Time (sec)	20.66	4.91	0.0372*	18.53	20.15	7.69	8.52	0.0001*
Max wound touch Time (sec)	2.61	1.27	0.1052	2.32	1.56	1.38	1.43	0.0012*
Capsulorhexis Module								
Search time (sec)	11.66	9.68	0.1356	14.10	6.10	11.90	6.57	0.0325*
Grab time (sec)	27.85	18.78	0.0466*	31.88	19.91	19.49	8.13	0.0001*
Total task time (sec)	41.45	27.88	0.0230*	45.98	23.01	31.38	13.32	< 0.0001*
Odometer (mm)	128.41	93.55	0.0011*	127.29	43.59	100.88	34.75	< 0.0001*
Wound touch (n)	14.50	7.00	0.0549	13.48	6.92	8.48	5.25	0.0004*
Wound touch Time (sec)	13.86	7.80	0.0466*	12.58	8.88	7.26	6.43	0.0003*
Max wound touch Time (sec)	2.80	1.76	0.0393*	2.62	1.99	1.62	0.85	0.0012*

† Mann-Whitney U test ‡ Wilcoxon Signed-Rank test * Statistical significance ¶ Two attending physicians are excluded

Table 3. Validity analysis and pre- / post-intervention comparison

		CatAR	Pig eye	Silicone eye	Human	
	Training Goals	*Median* ‡			*Median*	p-value ‡
1	Holding posture of instruments (spatula, forceps)	8.5	7.0†	7.0†	10.0	0.0017†
2	Bimanual hands positions for good support on patient's face	8.0	3.0†	3.5†	10.0	0.0001†
3	Improve instruments stability in anterior chamber	9.0	6.0†	6.0†	10.0	0.0160*
4	Improve microscopic stereopsis and hand-eye coordination	8.0	7.0*	7.0†	10.0	0.0003†
5	Pivoting technique for instruments navigation in anterior chamber	9.0	6.0†	5.5†	9.0	**0.1552**
6	Basic manipulation skills of capsule forceps (hold, rotation, and grasp)	8.0	5.5*	6.5†	10.0	0.0001†
7	Fundamental steps to perform a capsulorhexis (grasp, tear, and release)	8.0	5.0†	6.5†	10.0	0.0001†
8	Minimize corneal wound injuries during manipulation	8.0	5.0†	3.5†	9.0	0.0244*
9	Instant instruction and repeated practice during training course	9.0	5.5†	6.0†	9.0	**0.8622**
10	The possibility to transfer the training experience to real operation	8.0	4.5†	5.0†	10.0	< 0.0001†

10-point Likert Scale to evaluate the effectiveness of training tools, 1: Very poor 10: Excellent
† P < 0.01 * P < 0.05 ‡ Mann-Whitney U test

Table 4. Subjective evaluation of the training methods

	Question	*Mean*	*SD*	n
1	Display resolution compare with optical microscope	9.0	0.9	28
2	Stereoscopic perception compare with optical microscope	7.5	1.4	28
3	No dizziness sensation after complete training course	8.6	1.6	28
4	No Sensible Motion-to-Photon latency	8.4	1.5	28
5	Motion tracking accuracy	7.8	1.5	28
6	Tenacity of artificial wound compare with real cornea wound	7.4	1.1	17
7	Overall effectiveness of the CatAR training system	9.1	1.0	28
8	Motivation to use the CatAR system as training facility	7.7	1.5	28
9	Subjective improvement of surgical skills in real surgery	9.1	1.0	15

10-point Likert Scale to evaluate the effectiveness of training tools, 1: Very poor / Strongly disagree 10: Excellent / Strongly agree

Table 5. Performance evaluation of the CatAR training system

DISCUSSION

Wound condition during and after the cataract surgery is a crucial indicator for assessing a surgeon's competency. An expert surgeon can keep the wound intact to allow it to become self-sealed without suture at the end of surgery. On the contrary, a novice can overmanipulate or burn the cornea wound with a poor pivoting technique, leading to a leakage and poor post-operation vision. Through the post-intervention interview, not only novices but also experienced surgeons reported the difficulty in maintaining attention on the instrument tip and wound at the same time. Most of them did not realize how they treated the wound until seeing the CatAR warning indicators turning to red during practice. This might be the reason that most of the wound-related parameters could not pass the construct validity test and significant improvements can be observed even in the experienced group (Figure 8) in our study.

In the preliminary stage, we invited 2 expert surgeons to help us adjust the system's stereopsis settings. Although they did not perform a warm-up section, both of them reached the virtual targets precisely without any hesitation. This test proved that the depth perception in the CatAR system is quite similar to that in real surgical microscopes and does not require users to adapt their hand-eye coordination to a different scale. Interestingly, some of the novice participants informed us that they did not feel any depth sensation in the beginning of the intervention under the same stereopsis settings. They had to perform many attempts and even relied on trial and error methods to reach the virtual balls.

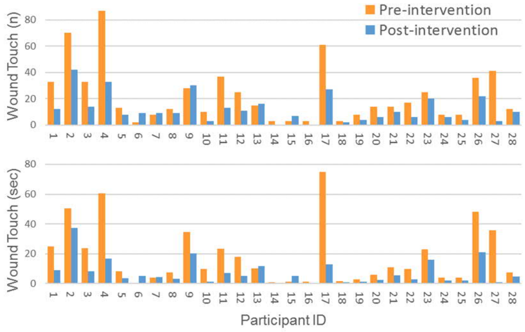

Figure 8. Wound touch counts and accumulated time of every participants' pre- and post-intervention in the forceps training module. The IDs are sorted in ascending order by their total training experience.

We calculated the Spearman's rank correlation coefficient between the total training experience (training plus surgery experiences in the month) and the search time in the anterior chamber navigation module, and the results revealed a moderately negative correlation in both pre- ($r = -.5923$, $P = .0009$) and post-intervention ($r = -.57851$, $P = .00126$) (Figure 9). This confirms that stereopsis plays an important role in a microsurgery simulator and the CatAR system is sufficient to build trainees' hand-eye coordination which can be used in the real environment.

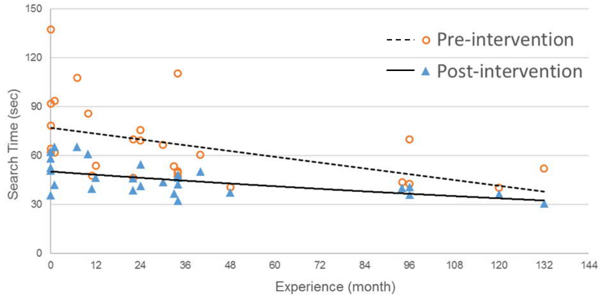

Figure 9. Correlation between experience and search time in the anterior chamber navigation module. Linear regression lines are presented.

In our study, although a trend could be observed in which experienced surgeons exhibited a lower tremor amplitude than novices before intervention (Figure 11a), the difference was not statistically significant. Physiological tremors arises from both mechanical and neuromuscular sources [10] and can be aggravated by a number of factors such as stress, fatigue, and caffeine [28]. It is difficult to control, and affects performance especially in microsurgeries, therefore some surgeons take β-blockers before an operation to eliminate anxiety and decrease the severity of tremors [36]. With the CatAR system, users can determine a proper hand posture to relax their muscles and stabilize the instruments, which leads to a significant decrease in tremor amplitude after practice.

Aside from the quantitative description, the differences between novice and experienced surgeons can be clearly observed through the tracking plot. Novices achieved a better circle after practice, but still worse than the baseline of an attending physician (Figure 10). Novices could reach some of the virtual balls precisely and quickly, but failed many times in the others (Figure 11b). After a short practice session with the CatAR system, novice could build better hand-eye coordination and acquire forceps control skills. The shorter and smoother trajectories in the capsulorhexis module confirm these improvements (Figure 11c).

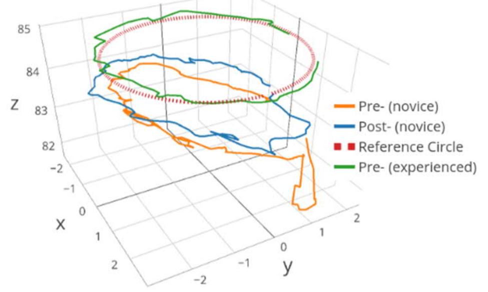

Figure 10. 3D presentation of the results in circular tracing module. Novice: R2, Experienced: Attending physician

CONCLUSION AND FUTURE WORK

To our knowledge, CatAR is the first AR microsurgery simulator and also the first system using real instruments as the user interface. This system not only provides high spatial resolution stereoscopic AR images with realistic haptic feedback, but also tracks the surgical instruments with ultra-high accuracy (20 μm) in real time. CatAR can discriminate surgical performance between different experience levels and can become a new assessment tool for surgical proficiency. The 3D motions during practice are recorded, and could be crucial training data sets for AI surgery in the future. The next step of this study is to investigate the capability of skill transfer using AR technology. Feedback from the participants will enable a physics simulation of the capsule and lens material, more realistic rendering effects, and more advanced modules to practice.

ACKNOWLEDGMENTS

The authors thank all the residents and staff in the Department of Ophthalmology at the National Taiwan University Hospital for their time and assistance. This study is partially supported by MOST 105-2622-8-002-002, 105-2221-E-002-128-MY2, 103-2218-E-002-025-MY3, and 106-3114-E-002-012.

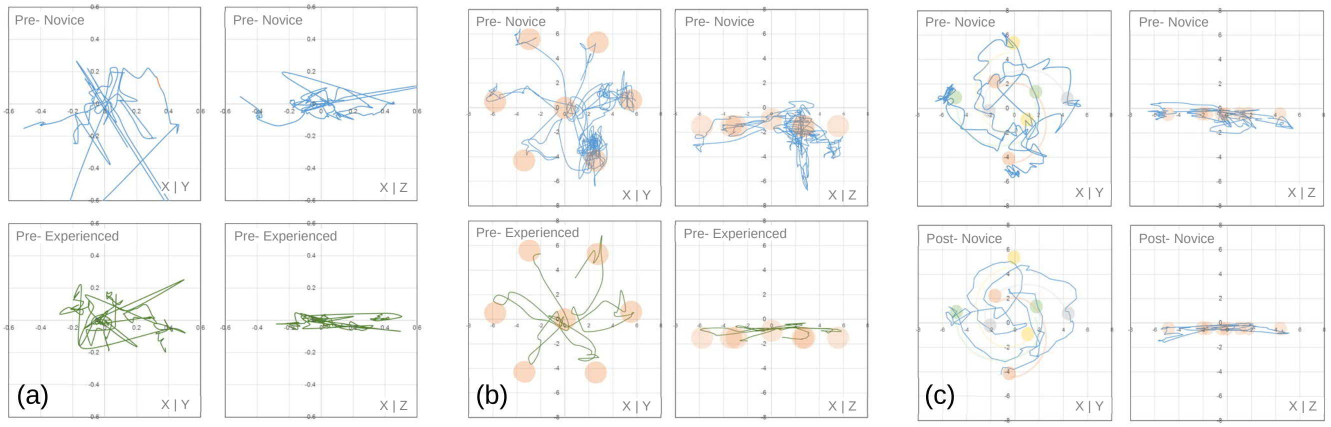

Figure 11. Tracking plots on the XY and XZ planes in 3 different modules (unit of axes: mm). (a) Pre-intervention results of novice (R2) and experienced surgeons (R4) in the antitremor module. (b) Pre-intervention results of novice (R2) and experienced surgeons (Fellow) in the forceps training module. The pink circles represent the position of virtual balls. (c) Pre- and post-intervention results of the same novice participant (R2). The circles in 4 different colors represent the starting and releasing point of 4 tears. The curves connecting 2 circles are the guidance tracts for the trainee to follow.

REFERENCES

1. M. Achibet, A. Girard, A. Talvas, M. Marchal and A. Lécuyer. 2015. Elastic-Arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments. in *2015 IEEE Virtual Reality (VR)*, 63-68. 10.1109/VR.2015.7223325
2. P. P. Banerjee, D. P. Edward, S. Liang, C. S. Bouchard, P. J. Bryar, R. Ahuja, P. Dray and D. P. Bailey. 2012. Concurrent and face validity of a capsulorhexis simulation with respect to human patients. *Stud Health Technol Inform*, 173. 35-41.
3. E. Bloch, N. Uddin, L. Gannon, K. Rantell and S. Jain. 2015. The effects of absence of stereopsis on performance of a simulated surgical task in two-dimensional and three-dimensional viewing conditions. *Br J Ophthalmol*, 99 (2). 240-245. 10.1136/bjophthalmol-2013-304517
4. K. S. Choi, S. Soo and F. L. Chung. 2009. A virtual training simulator for learning cataract surgery with phacoemulsification. *Comput Biol Med*, 39 (11). 1020-1031. 10.1016/j.compbiomed.2009.08.003
5. D. A. Cook, R. Brydges, B. Zendejas, S. J. Hamstra and R. Hatala. 2013. Technology-enhanced simulation to assess health professionals: a systematic review of validity evidence, research methods, and reporting quality. *Acad Med*, 88 (6). 872-883. 10.1097/ACM.0b013e31828ffdcf
6. J. Dequidt, H. Courtecuisse, O. Comas, J. Allard, C. Duriez, S. Cotin, E. Dumortier, O. Wavreille and J. F. Rouland. 2013. Computer-based training system for cataract surgery. *Simulation*, 89 (12). 1421-1435. 10.1177/0037549713495753
7. L. Doyle, N. Gauthier, S. Ramanathan and A. Okamura. 2008. A simulator to explore the role of haptic feedback in cataract surgery training. *Stud Health Technol Inform*, 132. 106-111.
8. Mario Gomez-Blanco, Cameron N. Riviere and Pradeep K. Khosla. 1999. Sensing Hand Tremor in a Vitreoretinal Microsurgical Instrument. in.
9. A. Hamam, S. Nourian, N. R. El-far, F. Malric, X. Shen and N. D. Georganas. 2006. A distributed, collaborative and haptic-enabled eye cataract surgery application with a user interface on desktop, stereo desktop and immersive displays. in *2006 IEEE International Workshop on Haptic Audio Visual Environments and their Applications (HAVE 2006)*, 105-110. 10.1109/HAVE.2006.283773
10. R. C. Harwell and R. L. Ferguson. 1983. Physiologic tremor and microsurgery. *Microsurgery*, 4 (3). 187-192.
11. HelpMeSee. 2013. Simulation-Based Training Program, http://helpmesee.org/Our-Technology.
12. Yu-Hsuan Huang, Wan-Ling Yang, Yi-Lung Kao, Yu-Kai Chiu, Ya-Bo Huang, Hao-Yu Chang and Ming Ouhyoung. 2016. A novel dexterous instrument tracking system for augmented reality cataract surgery training system *SIGGRAPH ASIA 2016 VR Showcase*, ACM, Macau, 1-2.
13. Yu-Hsuan Huang, Tzu-Chieh Yu, Pei-Hsuan Tsai, Yu-Xiang Wang, Wan-Ling Yang and Ming Ouhyoung. 2015. Scope+: a stereoscopic video see-through augmented reality microscope *SIGGRAPH Asia 2015 Emerging Technologies*, ACM, Kobe, Japan, 1-3.
14. Ian W. Hunter, Lynette Jones, Tilemachos Doukoglou, Serge Lafontaine, Peter J. Hunter and Mark Sagar. 1995. Ophthalmic microsurgical robot and surgical simulator. in, 184-190.
15. B. Julesz. 1960. Binocular Depth Perception of Computer-Generated Patterns. *Bell System Technical Journal*, 39 (5). 1125-1162.
16. A. Kopfle, F. Beier, C. Wagner and R. Manner. 2007. Real-time Marker-based Tracking of a Non-rigid Object. *Stud Health Technol Inform*, 125. 232-234.
17. Chee Kiang Lam, Kenneth Sundaraj and M. Nazri Sulaiman. 2013. Virtual Reality Simulator for Phacoemulsification Cataract Surgery Education and Training. *Procedia Computer Science*, 18. 742-748. 10.1016/j.procs.2013.05.238
18. C. G. Laurell, P. Soderberg, L. Nordh, E. Skarman and P. Nordqvist. 2004. Computer-simulated phacoemulsification. *Ophthalmology*, 111 (4). 693-698. 10.1016/j.ophtha.2003.06.023
19. H. Y. Lin, Y. J. Chuang, X. Tang, C. C. Lin, H. Y. Chen and P. J. Lin. 2017. Pivot concept: achieving a good-quality capsulorrhexis through a 2.2 mm or less clear corneal incision by using standard capsulorhexis forceps. *Int J Ophthalmol*, 10 (7). 1175-1177. 10.18240/ijo.2017.07.25
20. Bing Liu, Dennis Maier, Markus Schill and Reinhard Maenner. ROBUST REAL-TIME LOCALIZATION OF SURGICAL INSTRUMENTS IN THE EYE SUGERY SIMULATOR (EYESI).
21. M. A. Mahr and D. O. Hodge. 2008. Construct validity of anterior segment anti-tremor and forceps surgical simulator training modules: attending versus resident surgeon performance. *J Cataract Refract Surg*, 34 (6). 980-985. 10.1016/j.jcrs.2008.02.015
22. C. A. McCannel, D. C. Reed and D. R. Goldman. 2013. Ophthalmic surgery simulator training improves resident performance of capsulorhexis in the operating room. *Ophthalmology*, 120 (12). 2456-2461. 10.1016/j.ophtha.2013.05.003
23. NVIDIA. 2014. Automotive Screen Density Calculator, http://phrogz.net/tmp/ScreenDens2In.html.
24. FCI ophthalmics. 2011. KITARO Kits: A Superior Way to Practice Cataract Surgery, http://www.fci-ophthalmics.com/blog/kitaro-kits-a-superior-way-to-practice-cataract-surgery/.
25. American Academy of Ophthalmology. 2007. Optics of the Human Eye. in *Clinical Optics*, American Academy of Ophthalmology, USA, 105-123.
26. World Health Organization. 2010. Gobal data on visual impairment 2010, World Health Organization, http://www.who.int/blindness/publications/globaldata/en/.

27. S. S. Patel, M. T. Ukwade, H. E. Bedell and V. Sampath. 2003. Near stereothresholds measured with random-dot stereograms using phase disparities. *Optometry*, 74 (7). 453-462.
28. R. Pointdujour, H. Ahmad, M. Liu, E. Smith and D. Lazzaro. 2011. beta-Blockade Affects Simulator Scores. *Ophthalmology*, 118 (9). 1893-U1237.
29. B. Privett, E. Greenlee, G. Rogers and T. A. Oetting. 2010. Construct validity of a surgical simulator as a valid model for capsulorhexis training. *J Cataract Refract Surg*, 36 (11). 1835-1838. 10.1016/j.jcrs.2010.05.020
30. R. Sachdeva and E. I. Traboulsi. 2011. Performance of patients with deficient stereoacuity on the EYESi microsurgical simulator. *Am J Ophthalmol*, 151 (3). 427-433 e421. 10.1016/j.ajo.2010.09.011
31. Markus A. Schill, Clemens Wagner, Marc Hennen, Hans-Joachim Bender and Reinhard Männer. 1999. EyeSi – A Simulator for Intra-ocular Surgery. in Taylor, C. and Colchester, A. eds. *Medical Image Computing and Computer-Assisted Intervention – MICCAI'99: Second International Conference, Cambridge, UK, September 19-22, 1999. Proceedings*, Springer Berlin Heidelberg, Berlin, Heidelberg, 1166-1174.
32. O. Schuppe. 2012. An optical tracking system for a microsurgical training simulator. *Stud Health Technol Inform*, 173. 445-449. 10.3233/978-1-61499-022-2-445
33. M. Selvander and P. Asman. 2013. Cataract surgeons outperform medical students in Eyesi virtual reality cataract surgery: evidence for construct validity. *Acta Ophthalmol*, 91 (5). 469-474. 10.1111/j.1755-3768.2012.02440.x
34. M. Selvander and P. Asman. 2011. Stereoacuity and intraocular surgical skill: effect of stereoacuity level on virtual reality intraocular surgical performance. *J Cataract Refract Surg*, 37 (12). 2188-2193. 10.1016/j.jcrs.2011.05.048
35. Michael J. Sinclair, John W. Peifer, Ray Haleblian, Malcolm N. Luxenberg, Keith Green and David S. Hull. 1995. Computer-simulated Eye Surgery. *Ophthalmology*, 102 (3). 517-521. 10.1016/s0161-6420(95)30992-x
36. Jacquelyn Slomka. 1992. Playing with Propranolol. *Hastings Center Report*, 22 (4). 13-17. 10.2307/3563017
37. D. J. Solverson, R. A. Mazzoli, W. R. Raymond, M. L. Nelson, E. A. Hansen, M. F. Torres, A. Bhandari and C. D. Hartranft. 2009. Virtual reality simulation in acquiring and differentiating basic ophthalmic microsurgical skills. *Simul Healthc*, 4 (2). 98-103. 10.1097/SIH.0b013e318195419e
38. R. Sudan, J. S. Titiyal, H. S. Sethi and H. K. Rai. 2002. Animal model for teaching phacoemulsification. *J Cataract Refract Surg*, 28 (1). 4-5.
39. A. S. Thomsen, J. F. Kiilgaard, H. Kjaerbo, M. la Cour and L. Konge. 2015. Simulation-based certification for cataract surgery. *Acta Ophthalmol*, 93 (5). 416-421. 10.1111/aos.12691
40. A. S. Thomsen, J. F. Kiilgaard, M. la Cour, R. Brydges and L. Konge. 2017. Is there inter-procedural transfer of skills in intraocular surgery? A randomized controlled trial. *Acta Ophthalmol*. 10.1111/aos.13434
41. A. S. Vergmann, A. H. Vestergaard and J. Grauslund. 2017. Virtual vitreoretinal surgery: validation of a training programme. *Acta Ophthalmol*, 95 (1). 60-65. 10.1111/aos.13209
42. S. Waqar, O. Williams, J. Park, N. Modi, T. Kersey and T. Sleep. 2012. Can virtual reality simulation help to determine the importance of stereopsis in intraocular surgery? *Br J Ophthalmol*, 96 (5). 742-746. 10.1136/bjophthalmol-2011-301150
43. R. Webster, J. Sassani, R. Shenk, M. Harris, J. Gerber, A. Benson, J. Blumenstock, C. Billman and R. Haluck. 2005. Simulating the continuous curvilinear capsulorhexis procedure during cataract surgery on the EYESI system. *Stud Health Technol Inform*, 111. 592-595.
44. M. P. Weikert, L. Wang, J. Barrish, R. Dimalanta and D. D. Koch. 2012. Quantitative measurement of wound architecture in microincision cataract surgery. *J Cataract Refract Surg*, 38 (8). 1460-1466. 10.1016/j.jcrs.2012.03.036
45. L. M. Wilcox and J. M. Harris. 2010. *Fundamentals of Stereopsis*.