tvst https://doi.org/10.1167/tvst.8.4.2
Article

The Effect of Haptic Feedback on Efficiency and Safety During Preretinal Membrane Peeling Simulation

Anibal Francone[1,*], Jason Mingyi Huang[1,*], Ji Ma[2], Tsu-Chin Tsao[2], Jacob Rosen[2], and Jean-Pierre Hubschman[1,3,4]

[1] University of California Los Angeles Stein Eye Institute, Los Angeles, CA, USA
[2] University of California Los Angeles Department of Mechanical and Aerospace Engineering, Los Angeles, CA, USA
[3] Center for Advanced Surgical and Interventional Technology (CASIT) at UCLA, Los Angeles, CA, USA
[4] Advanced Robotic Eye Surgery Laboratories, Stein Eye Institute, University of California Los Angeles, Los Angeles, CA, USA

Correspondence: Jean-Pierre Hubschman, 200 Stein Plaza, Los Angeles, CA 90095, USA. e-mail: hubschman@jsei.ucla.edu

Received: 18 December 2018
Accepted: 8 May 2019
Published: 3 July 2019

Keywords: haptic; feedback; robotic; surgery; retina

Citation: Francone A, Huang JM, Ma J, Tsao T-C, Rosen J, Hubschman J-P. The effect of haptic feedback on efficiency and safety during preretinal membrane peeling simulation. Trans Vis Sci Tech. 2019;8(4):2, https://doi.org/10.1167/tvst.8.4.2

Purpose: We determine whether haptic feedback improves surgical performance and outcome during simulated a preretinal membrane peeling procedure.

Methods: A haptic-enabled virtual reality preretinal membrane peeling simulator was developed using a surgical cockpit with two multifinger haptic devices. Six subjects (three trained retina surgeons and three nonsurgeons) performed the preretinal membrane peeling surgical procedure using two modes of operation: visual and haptic feedback, and visual feedback only.

Results: Task completion time, tool tip path trajectory, tool–retina collision force, and retinal damage were all reduced with haptic feedback used and compared to modes where haptic feedback was disabled.

Conclusions: Haptic feedback improves efficiency and safety during preretinal membrane peeling simulation.

Translational Relevance: These findings highlight the potential benefit of haptic feedback for improving performance and safety of vitreoretinal surgery.

Introduction

Modern vitreoretinal surgery involves manual handling of surgical instruments under visualization of a surgical microscope. Since retinal tissues are delicate structures, there is very limited tactile feedback during normal retina surgery, and sensory feedback provided to the surgeon is primarily visual.[1] Given these circumstances, there has been interest in the application of robotics to vitreoretinal surgery to enhance human limited abilities.[2–4] With many of the existing robotic platforms, however, the tactile feedback is completely eliminated.[5,6] Lack of tactile feedback may prolong operative times, increase risk of surgical errors, and steepen the learning curve for trainees.[7,8] To address these limitations, there has been interest in the development of surgical robotic systems that can provide haptic feedback to the surgeon.[9–14]

Haptic feedback refers to the sense of touch and can be divided into two different classes: tactile feedback transmitted through the fingers and kinesthetic feedback conveyed through muscles, joints, and tendons. Since touch is the earliest sense developed during human embryology, haptic technology should not be underestimated for surgical specialties that rely on sensory input.[11] Implementation of haptic technology into retina surgery is anticipated to improve efficiency and safety while reducing the training required to perform surgical procedures.[8,15–17]

A commonly performed retinal surgery that could benefit from haptic feedback is a preretinal membrane peel. Preretinal membrane peeling is technically challenging because the surgeon relies only on visual cues to peel an approximately 50 μm membrane from the surface of the retina. A virtual reality preretinal membrane peeling simulator was developed including a haptic device (surgical cockpit) that can provide the surgeon with force feedback as a tool tip interacts with targeted tissues. The surgical cockpit was developed for use in a future robotic system inside which a surgeon can sit and remotely control robotic instruments. In our reported pilot study, subjects conducted preretinal membrane peeling using the virtual reality simulator with and without haptic feedback. We hypothesized that haptic feedback will allow users of the simulation to perform the virtual task more efficiently and safely.

Methods

Participants

Six subjects were enrolled in the study, including three ophthalmologists with vitreoretinal surgical training (surgeons) and three engineers with no surgical experience (nonsurgeons). All subjects were at least 18 years old, possessed normal sensory and motor function of their arms and hands, and had normal or corrected-to-normal visual acuity. The subjects gave informed consent for the study, which was approved by the University of California Los Angeles institutional review board and adhered to the tenets of the Declaration of Helsinki.

System

A computer-based multimodel feedback simulator was developed for preretinal membrane peel in which a user can practice grasping and peeling a virtual preretinal membrane. The simulation screen consists of a virtual retina, preretinal membrane that can be peeled, and movable robotic forceps. The simulation software was developed with an open-source haptic simulation platform (CHAI3D) controlled by a custom surgical haptic device (surgical cockpit). The retina and preretinal membrane models were created as triangular meshes with interconnected vertices, and the physics of each vertex was modeled as a spring-damper system connecting to neighboring vertices. A simple flat membrane model with dimensions of 2×2 mm and a uniform membrane peeling force were used. The tool-tissue interaction forces, the membrane peeling forces, and the vertex force propagations were custom implemented with virtual spring-damper models. The retinal bleeding and whitening events were determined by the tool–retina penetration force and duration, and the graphic rendering was produced using OpenGL (Beaverton, OR) on a 2D monitor. The software ran at 60 Hz for graphic rendering and 1000 Hz for haptic rendering. The software is able to provide multimodel feedback to operators, such as audio, visual, and force feedback. For this study, only the tool–membrane collision force feedback and tip–retina distance visual feedback were provided to operators, while the tool–membrane peeling force and audio feedback were not used (Fig. 1).

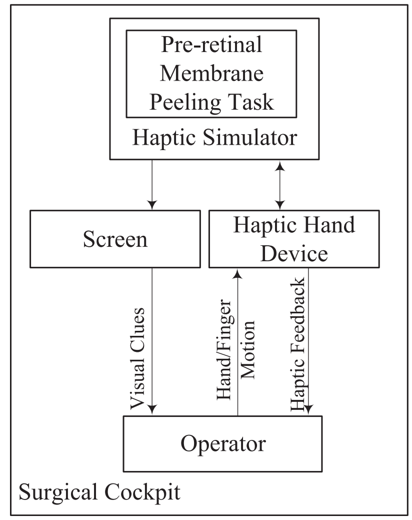


Figure 1. Block diagram of surgical simulator. The operator controls the simulator via a haptic device while receiving visual and haptic feedback.

To let operators control the simulator, a surgical cockpit was designed equipped with two multifinger haptic hand devices configured for transmitting surgical movements of an operator to the remote surgical instruments (Fig. 2). Each multifinger haptic hand device has motion sensing and haptic feedback capabilities with six degrees of freedom for hand and three degrees of freedom for fingers. In our simulation, only the right hand device was used. Movement of the master controller on the hand device directly translated into movement within the software of the membrane peeling forceps tip, and the movement of the finger devices controlled the opening and closing of the simulated forceps. The pivot effect of the instrument shaft at the trocar site was cancelled; therefore, the surgeon peeled the preretinal membrane as if peeling with his or her fingertips. An armrest was provided to stabilize the forearm while the wrist and hand were free to move the hand device. The simulator allowed learners to practice a range of vitreoretinal surgery skills relevant to preretinal membrane peeling, such as instrument navigation, tissue grasping, and simple dissection.

Figure 2. Surgical cockpit with simulation software and hand/finger device.

For the current simulation, haptic feedback was provided based on the distance from the instrument tip to the retina (z-axis). When the forceps were at the plane of the retina, the resistance of the haptic device along the z-axis was increased and downward motion toward the retina was limited. When haptic feedback was turned off, the only feedback provided to the surgeon was through visual cues of the two-dimensional computer screen, the shadow of the instrument over the retina, a displayed gauge indicating the proximity of the tip to the retina, and whitening or bleeding of the retina during instrument–retina collisions (Fig. 3). The simulator used an algorithm to document and measure collisions between the deformable retina and the nondeformable forceps. A penetration distance of 0.025 mm into the retina was set to produce retinal whitening, and a distance of 0.06 mm produced retinal bleeding. The tool–retina collision force was calculated by multiplying tool–retina penetration distance times retina stiffness. For simplicity for calculations, the retina stiffness was set at 1.0 N/mm.

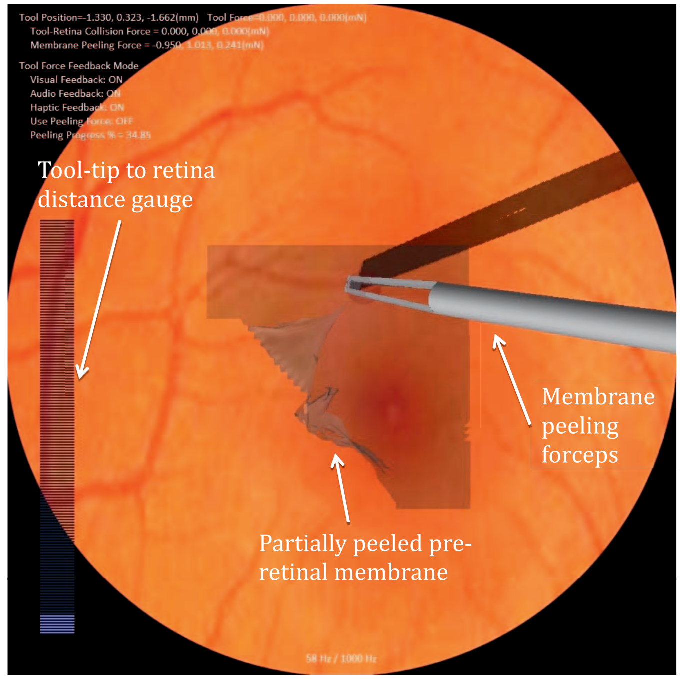


Figure 3. Preretinal membrane peeling simulation screen.

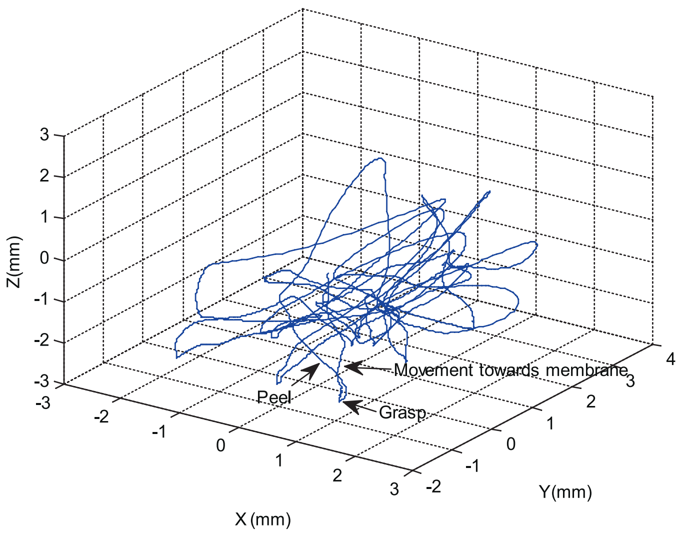
Protocol

All subjects used the same simulator to conduct the preretinal membrane peeling procedure. The subjects first received a standardized introduction to the simulator, along with two minutes of training time to become familiar with the equipment and software. Subjects then were asked to perform the timed preretinal membrane peeling task. The preretinal membrane peeling task consisted of a total of 10 trials: five with and five without haptic feedback in an alternating order. Each trial was completed when the entire virtual preretinal membrane was peeled.

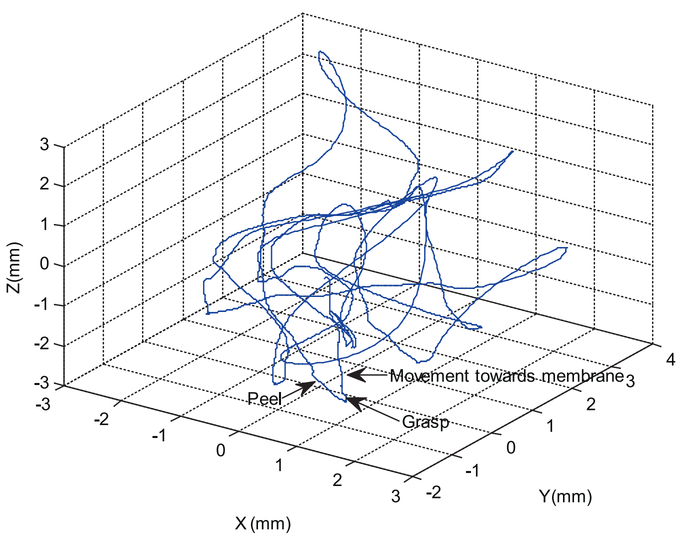
The simulation software was used to collect data from the trials, including the following: time to task completion, total length of the tool tip trajectory, number of tool–retina collisions, distance of penetration into the retina, and amount of force applied on the retina along the vertical axis.

Statistical Analysis

Two-way ANOVA and Student's t-test were used to calculate P values for determining statistical significance. Statistical calculations were performed using STATA software edition 11.2 (StataCorp LP, College Station, TX).



Without haptic feedback (unit: millimeter)



With haptic feedback (unit: millimeter)

Figure 4. Example of 3D tool tip trajectories during a trial without and one with haptic feedback. Tip travel distance was reduced when haptic feedback was provided.

Results

All six participants completed all trials successfully by peeling the preretinal membranes in entirety. The tool tip trajectories were recorded for each trial and were charted into a three-dimensional (3D) Figure (Fig. 4). Average total tip distance traveled for all participants was 96.6 mm without versus 102.6 mm with haptic feedback ($P = 0.66$). Surgeons had significantly lower tool tip trajectory length (82.1 mm) compared to nonsurgeons (117.2 mm; $P = 0.03$). Further analysis revealed that tip trajectory length was significantly different between groups without haptic feedback (surgeons 81.9 mm, nonsurgeons 123.4 mm, $P = 0.03$), but this difference was no longer significant when haptic feedback was provided (surgeons 82.2 mm, nonsurgeons 111.0 mm, $P = 0.13$).

The average task completion time for all participants was significantly faster with haptic feedback (57.5 seconds) versus without haptic feedback (82.2 seconds; $P = 0.02$). All individuals completed the task in a shorter time when haptic feedback was used. There was no significant difference in task completion time when comparing surgeons versus nonsurgeons ($P = 0.99$; Fig. 5).

The average tool–retina collision force was significantly lower with (0.05 N) compared to without (0.35 N; $P = 0.01$) haptic feedback. Surgeons and nonsurgeons produced a lower tool–retina collision force when haptic feedback was provided (Fig. 6). When comparing the groups, surgeons displayed a lower tool–retina collision force compared to nonsurgeons when there was no haptic feedback (surgeons 0.14 N, nonsurgeons 0.56 N, $P = 0.04$), but there was no difference when haptic feedback was provided (surgeons 0.05 N, nonsurgeons 0.05 N, $P = 0.40$).

Without haptic feedback, participants encountered an average of 3.8 (surgeons 2.2, nonsurgeons 5.3, $P = 0.18$) retinal whitening episodes and 0.33 (surgeons 0.2, nonsurgeons 0.5, $P = 0.25$) retinal bleeding episodes per trial. When haptic feedback was provided, there were no occurrences of retinal whitening or bleeding in either group (Fig. 7).

Discussion

Modern vitreoretinal surgery involves manipulation of delicate intraocular tissues with visual feedback from the microscope, but extremely limited tactile feedback. The physiologic force from an intraoperative tool–retina collision is too small to be sensed by the human hand, which can lead to accidental retinal damage.[18] In this study, haptic feedback was produced by increasing the resistance of the input device along the *z*-axis when the instrument tip reached the retinal plane. Haptic feedback led to increased efficiency as evidenced by shorter times to completion in all participants and reduced tool tip travel distance in nonsurgeons. Membrane peels also were safer with haptic feedback, with significantly decreased tool–retina penetration distance and tool–

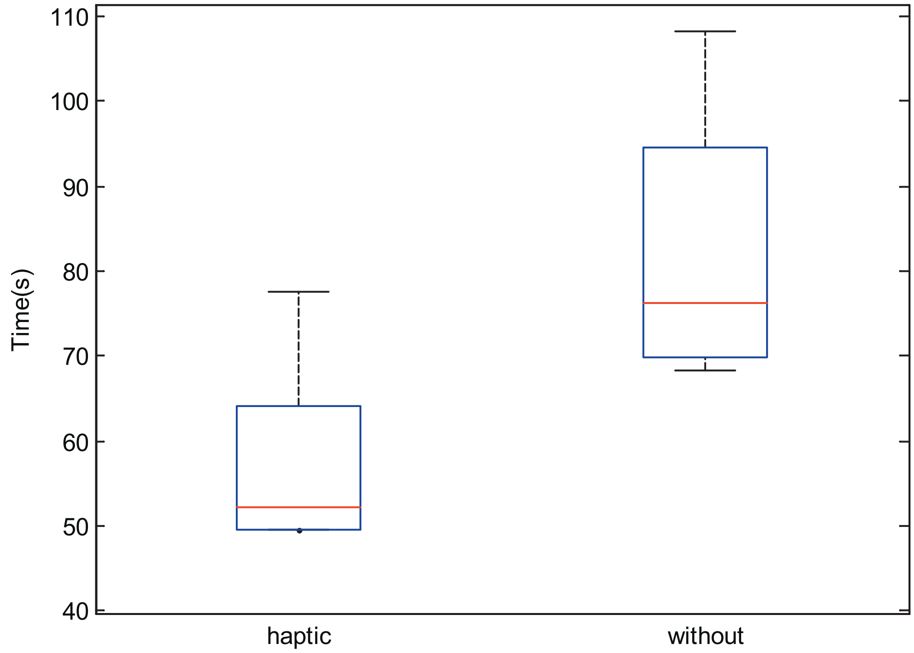


Figure 5. Task completion time was significantly shorter with compared to without haptic feedback.

retina collision force. In the haptic feedback trials, the tool–retina collision force was reduced far below retinal whitening and bleeding thresholds. As a result, there were no occurrences of retinal whitening or bleeding in any trial by any participant. These findings revealed the potential for haptic feedback to improve surgical outcomes.

Without haptic feedback, surgeons displayed

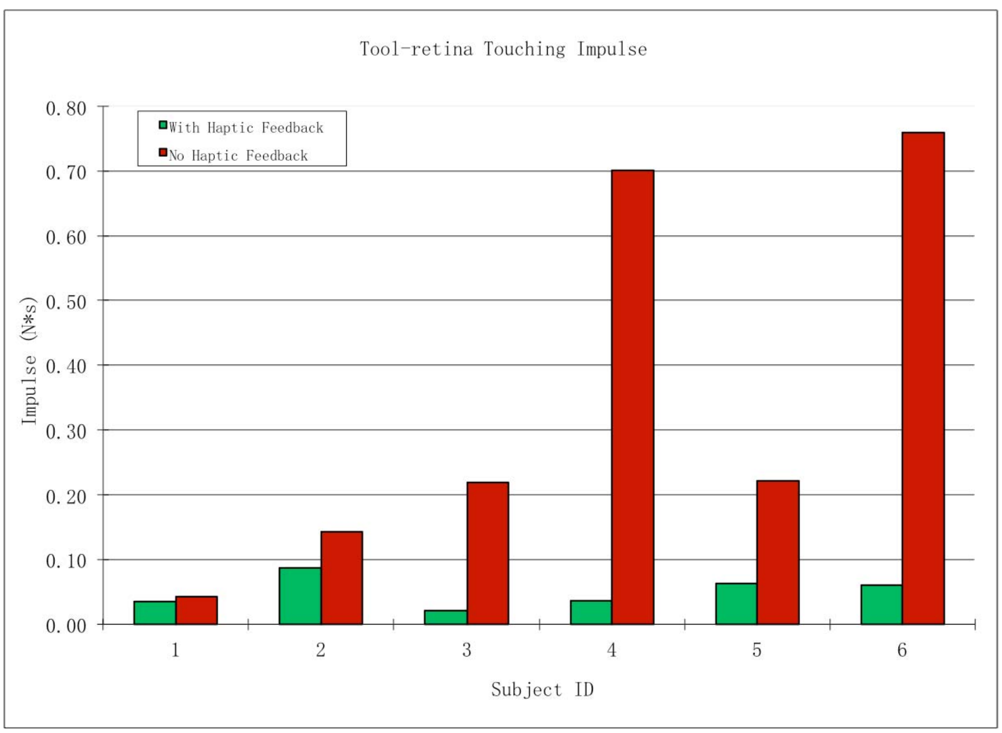
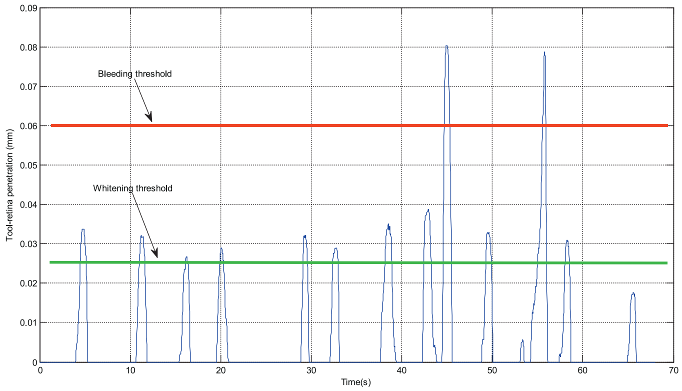
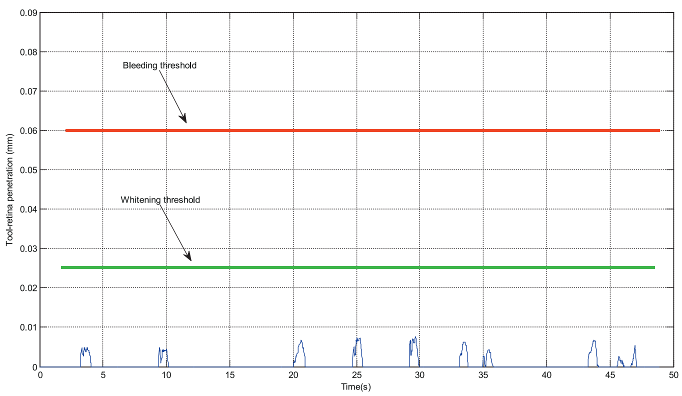


Figure 6. Tool–retina collision force was lower with than without haptic feedback. Nonsurgeons (subjects 4–6) displayed a greater reduction in tool–retina collision force when haptic feedback was used, but surgeons (subjects 1–3) displayed a reduction as well.



Tool-retina collision without haptic feedback



Tool-retina collision with haptic feedback

Figure 7. Example of tool–retina collision chart in trials without and with haptic feedback. When haptic feedback was provided, there were no instances of retinal whitening or bleeding.

shorter tool tip travel distance and reduced tool–retina collision force compared to nonsurgeons. Subjects with prior vitreoretinal surgical training are likely to be more efficient with their surgical movements and more attentive to preventing retinal damage than subjects with no surgical experience. With haptic feedback however, differences in these metrics disappeared. These results showed that haptic feedback may be beneficial to surgical trainees by easing the surgical learning curve. Haptic feedback may allow surgeons to perform surgery more efficiently and safely early in their training.

While haptic feedback reduced task completion time in all participants compared to no haptic feedback, there was no difference in task completion time when comparing surgeons to nonsurgeons. Nonsurgeons displayed similar completion times to surgeons regardless of whether haptic feedback was provided. Although one may expect participants with prior membrane peeling experience to complete the task in a shorter time, the movements required for nonrobotic preretinal membrane peeling are different than those required for our simulation. Currently, preretinal membrane peeling involves movement of the intraocular forceps across a fulcrum provided by a trocar at the sclerotomy site. The fulcrum fixes the movement of the forceps shaft at the sclera. Movement of the forceps handle in a plane parallel to the sclera then produces movement of the forceps tip in the opposite direction. Our simulation is designed with the intention that a future robotic system would automatically adjust the angle of the instrument through the fulcrum. Hence, the movement of the surgical console directly controls the trajectory of the forceps tip. Such a system allows for implementation of motion scaling in which a large movement by the surgeon can be translated into a small movement of the instrument tip. Surgeons in our study may not have an advantage over nonsurgeons with regard to task completion time because of these differences in instrument handling and movement.

Other studies have evaluated the efficacy of auditory feedback. Kitagawa et al.[19] found that real-time auditory feedback in robotic surgery improved precision of applied force during suture tying. Cutler et al.[20] found that the presence of auditory feedback reduced forces applied during simulated preretinal membrane peeling. Auditory feedback can improve precision in surgery, but our study revealed that haptic feedback also decreased the duration of surgery. Sensing force through touch may be more instinctual than a force-to-auditory sensory output. Additionally, increasing resistance through haptic feedback provides a physical barrier that improves safety and may increase a surgeon's comfort level in manipulating surgical instruments, leading to increased speed.

In our simulation, the software-measured tool–retina distance dictated the amount of resistance applied to the surgical console. While such a system is not currently available, we envision a system in which tool–retina distance could be measured intraoperatively with a device, such as optical coherence tomography. Alternatively, several force-sensing instruments are in development, and input from such an instrument could be used to dictate the resistance output on the surgical console.[21–23]

Limitations of the study include the low number of participants, although given the marked improvement in efficiency and safety in all participants, we do not believe this to be a significant limitation. Another limitation is that visual feedback in our study was not equivalent to the 3D visualization during normal surgery. Nevertheless, we believed that the visual feedback provided in the study was sufficient to test the potential benefit of haptic feedback. The virtual retina in the simulation was flat rather than curved as in a normal eyeball. However, because peeling was only performed in the macula where the globe curvature is minimal, we do not believe that this difference would significantly affect the results. Lastly, our study was performed in a simulated environment, and future studies are needed to determine the safety of haptic feedback in a real-world setting.

Haptic feedback during preretinal membrane peeling simulation significantly improved surgical performance regardless of the level of prior surgical experience. Implementation of haptic feedback into future robotic systems offers the potential to increase patient safety, improve surgical efficiency, and enhance surgical training.

Acknowledgments

The authors thank Peter Ferguson, Wayne Gui, Xiongfei Liu, Sahba Pedram, Eric Shieh, Vidal Soberon, David Stark, and Elaine Wang for their participation in the project.

Supported by the Hess Foundation and Research to Prevent Blindness.

Disclosure: **A. Francone**, None; **J.M. Huang**, None; **J. Ma**, None; **T.-C. Tsao**, None; **J. Rosen**, None; **J.-P. Hubschman**, Alcon (C), Allergan (C)

*AF and JMH are joint first authors.

References

1. Barthel A, Trematerra D, Nasseri MA, et al. Haptic interface for robot-assisted ophthalmic surgery. *Conf Proc IEEE Eng Med Biol Soc*. 2015;2015:4906–4909.
2. Ida Y, Sugita N, Ueta T, Tamaki Y, Tanimoto K, Mitsuishi M. Microsurgical robotic system for vitreoretinal surgery. *Int J Comput Assist Radiol Surg*. 2012;7:27–34.
3. Nasseri MA, Eder M, Nair S, et al. The introduction of a new robot for assistance in ophthalmic surgery. *Conf Proc IEEE Eng Med Biol Soc*. 2013;2013:5682–5685.
4. Ueta T, Yamaguchi Y, Shirakawa Y, et al. Robot-assisted vitreoretinal surgery: development of a prototype and feasibility studies in an animal model. *Ophthalmology*. 2009;116:1538–1543; 1543.e1531–1532.
5. de Smet MD, Naus GJL, Faridpooya K, Mura M. Robotic-assisted surgery in ophthalmology. *Curr Opin Ophthalmol*. 2018;29:248–253.
6. Wilson JT, Gerber MJ, Prince SW, et al. Intraocular robotic interventional surgical system (IRISS): Mechanical design, evaluation, and master-slave manipulation. *Int J Med Robot*. 2018;14.
7. Kothari SN, Kaplan BJ, DeMaria EJ, Broderick TJ, Merrell RC. Training in laparoscopic suturing skills using a new computer-based virtual reality simulator (MIST-VR) provides results comparable to those with an established pelvic trainer system. *J Laparoendosc Adv Surg Tech A*. 2002;12:167–173.
8. Zhou M, Tse S, Derevianko A, Jones DB, Schwaitzberg SD, Cao CG. Effect of haptic feedback in laparoscopic surgery skill acquisition. *Surg Endosc*. 2012;26:1128–1134.
9. Amirabdollahian F, Livatino S, Vahedi B, et al. Prevalence of haptic feedback in robot-mediated surgery: a systematic review of literature. *J Robot Surg*. 2018;12:11–25.
10. Griffin JA, Zhu W, Nam CS. The role of haptic feedback in robotic-assisted retinal microsurgery systems: a systematic review. *IEEE Trans Haptics*. 2017;10:94–105.
11. van der Meijden OA, Schijven MP. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surg Endosc*. 2009;23:1180–1190.
12. Abiri A, Juo YY, Tao A, et al. Artificial palpation in robotic surgery using haptic feedback. *Surg Endosc* 2019;33:1252–1259.
13. King CH, Culjat MO, Franco ML, et al. Tactile feedback induces reduced grasping force in robot-assisted surgery. *IEEE Trans Haptics*. 2009;2:103–110.
14. Wottawa CR, Cohen JR, Fan RE, et al. The role of tactile feedback in grip force during laparoscopic training tasks. *Surg Endosc*. 2013;27:1111–1118.
15. Koehn JK, Kuchenbecker KJ. Surgeons and non-surgeons prefer haptic feedback of instrument

vibrations during robotic surgery. *Surg Endosc*. 2015;29:2970–2983.
16. Girod S, Schvartzman SC, Gaudilliere D, Salisbury K, Silva R. Haptic feedback improves surgeons' user experience and fracture reduction in facial trauma simulation. *J Rehabil Res Dev*. 2016;53:561–570.
17. Thawani JP, Ramayya AG, Abdullah KG, et al. Resident simulation training in endoscopic endonasal surgery utilizing haptic feedback technology. *J Clin Neurosci*. 2016;34:112–116.
18. Balicki M, Uneri A, Iordachita I, Handa J, Gehlbach P, Taylor R. Micro-force sensing in robot assisted membrane peeling for vitreoretinal surgery. *Med Image Comput Comput Assist Interv*. 2010;13:303–310.
19. Kitagawa M, Dokko D, Okamura AM, Yuh DD. Effect of sensory substitution on suture-manipulation forces for robotic surgical systems. *J Thorac Cardiovasc Surg*. 2005;129:151–158.
20. Cutler N, Balicki M, Finkelstein M, et al. Auditory force feedback substitution improves surgical precision during simulated ophthalmic surgery. *Invest Ophthalmol Vis Sci*. 2013;54:1316–1324.
21. Sunshine S, Balicki M, He X, et al. A force-sensing microsurgical instrument that detects forces below human tactile sensation. *Retina*. 2013;33:200–206.
22. Kuru I, Gonenc B, Balicki M, et al. Force sensing micro-forceps for robot assisted retinal surgery. *Conf Proc IEEE Eng Med Biol Soc*. 2012;2012: 1401–1404.
23. Gonenc B, Balicki MA, Handa J, et al. Evaluation of a micro-force sensing handheld robot for vitreoretinal surgery. *Rep U S*. 2012;2012:4125–4130.