Head-mounted Surgical Robots for Big-bubble Formation During Deep Anterior Lamellar Keratectomy on a Moving Patient

Zachary J. Olson[1,2], Cole M. Yearsley[2], Nicholas R. Posselli[1,2,3], Brittany Coats[2], Brian E. Zaugg[4], and Jake J. Abbott[1,2]

[1]*Robotics Center, University of Utah*
[2]*Department of Mechanical Engineering, University of Utah*
[3]*Department of Biomechanical Engineering, University of Twente*
[4]*Dept. of Ophthalmology and Visual Sciences, Moran Eye Center, University of Utah*
{*zach.olson, jake.abbott*}*@utah.edu*

INTRODUCTION

Deep anterior lamellar keratectomy (DALK) is a common technique for cornea transplantation that works well in treating anterior corneal pathology. DALK is performed using a dissector to penetrate into the space between the anterior lamella of the cornea and Descemet's membrane (DM). Air is then injected to form a "big bubble" (BB), causing separation between these membranes, enabling the pathological tissue to be safely excised while preserving the living tissue of the host. To consistently form a BB, the dissector should attempt to achieve a corneal depth of at least 74.9% [1], which corresponds to a target window of 137 μm for a typical human corneal thickness of 545 μm. The surgeon must deal with patient head motion due to breathing and other voluntary and involuntary actions, which can be on the order of several millimeters [2], [3]. DALK failure occurs up to 39% of the time [4], typically occurring when DM is perforated by the dissector. This leads to a change from DALK to penetrating keratoplasty, which negatively affects the long term recovery of the patient [5].

A number of groups are pursuing robotic assistance to improve the success rate in DALK [6]–[8]. Although results are encouraging, all experimental evaluation of these systems to date has been on stationary benchtop eyes, which does not account for the complicating factor of patient head motion (although one may argue that the system of [8], which directly attaches to the eye, is inherently accounting for head motion). In our group, we are pursuing an overarching conjecture that noninvasive head-mounting [3] of a high-precision teleoperated robot [9], combined with intraoperative optical coherence tomography (OCT), is sufficient to enable the most challenging eye-surgery procedures, even when contending with patient head motion. We recently showed that this paradigm is promising for subretinal injections [10].

This work was supported by the National Eye Institute of the National Institutes of Health under Award Number R21EY027528.

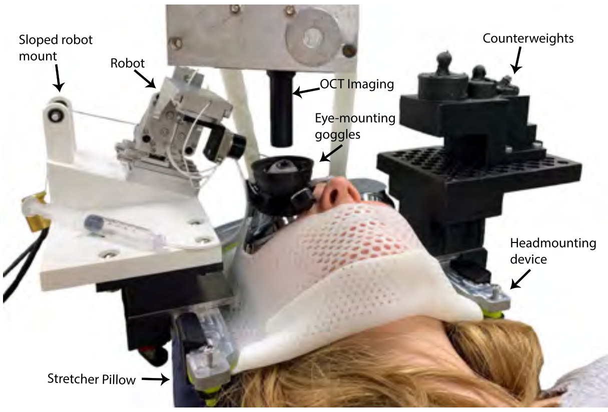

Fig. 1 Experimental setup.

In this study (Fig. 1), we find compelling evidence that head-mounting a high-precision robot results in the positioning precision necessary to safely form a BB. We used the surgical robot from [9], which has a precision of $\sim$1 μm. We use the goggles from [11] to mount an enucleated eye directly in front of the eye of a healthy human volunteer. The goggles permit the enucleated eye to rotate in its socket due to applied forces, with a rotational stiffness matching that of an anesthetized patient's eye. This results in a hybrid ex-vivo/in-situ study in which we are able to capture motion and soft-tissue effects of a living human head while performing surgical procedures on a postmortem animal eye.

MATERIALS AND METHODS

Although we are working toward a general-purpose eye-surgery robot, needle insertion for BB formation in DALK (the critical step of the procedure) is fundamentally a one-degree-of-freedom task that does not require a robot with the complexity of ours (e.g., see [8]). To clarify this aspect of the study, we mounted our robot using a sloped block such that only one of the robot's actuators is used. The angle of the sloped block, which is also the angle of

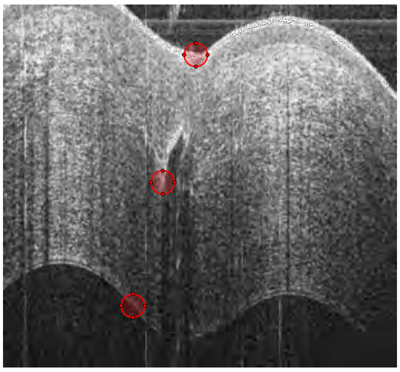

Fig. 2 Example OCT image. Red circles indicate points manually selected for conversion from pixel location to depth in μm, using the full-thickness measurement.

approach of the needle into the cornea, is 21° relative to horizontal [12]. Because the gravity-balance mechanism of our robot was not designed for this configuration, we used a weight and pulley to compensate for gravity; this is necessary due to the nature of the robot's actuators. Needle insertion was performed on fresh porcine eyes mounted to the goggles worn by a volunteer (under the approval of the University of Utah IRB) who was lying supine on an eye-surgery stretcher. OCT imaging (Bioptigen Envisu R2200) with a 12-mm telecentric lens was used to visualize and measure needle placement within the cornea and relative to DM (Fig. 2).

We began the experiment by pressurizing the eye with saline to 20 mmHg, as is normal for a human eye. We then advanced the needle until it penetrated the cornea to a depth approximating 407 μm (i.e., 74.9% of a human cornea), with the needle oriented with the bevel outlet upward to maximize penetration. We then held the robot stationary and took volumetric OCT scans at evenly spaced intervals over 90 s (a value determined in pilot testing to maintain the target intraocular pressure) to capture any changes in the depth of the needle due to head motion, soft-tissue effects, etc. This was repeated for two eyes. Needle depths were then calculated offline.

RESULTS

Figure 3 shows the results of the experiment. We find that, even with head-mounting, there is still relative motion of the needle within the cornea (as expected). In one scan, the needle had advanced 25.6 μm deeper than the initial depth. The maximum change in depth observed was a retraction of the needle by 50 μm.

DISCUSSION

Given a window of 137 μm in which we can successfully form a BB, these results suggest that head-mounting provides sufficient positioning precision. For example, based on our limited data, a good strategy might be to penetrate to an initial depth of 457 μm (i.e., 83.9% of a human cornea) to ensure a BB is formed with minimal risk of perforating DM. Of course, we would want to gather more data, preferably in human cadaver eyes, to revise these projections.

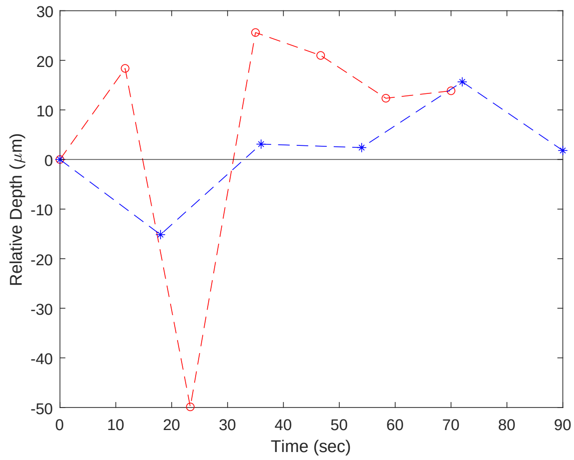

Fig. 3 Experimental results showing depth within the cornea over time, measured with respect to the initial depth, with the robot held stationary, in which each data point is calculated from an OCT scan. The red circles correspond to a trial with an initial depth of 457μm, and the blue stars correspond to a trial with an initial depth of 440μm.

REFERENCES

[1] N. D. Pasricha, C. Shieh, O. M. Carrasco-Zevallos, B. Keller, D. Cunefare, J. S. Mehta, S. Farsiu, J. A. Izatt, C. A. Toth, and A. N. Kuo, "Needle depth and big-bubble success in deep anterior lamellar keratoplasty: An ex vivo microscope-integrated OCT study," *Cornea*, vol. 35, no. 11, pp. 1471–1477, 2016.

[2] K. Brogan, B. Dawar, D. Lockington, and K. Ramaesh, "Intraoperative head drift and eye movement: two under addressed challenges during cataract surgery," *Eye*, vol. 32, no. 6, pp. 1111–1116, 2018.

[3] N. R. Posselli, P. S. Wellborn, P. S. Bernstein, R. J. Webster III, and J. J. Abbott, "Head-mounting surgical robots for passive compensation of patient motion," *J. Med. Robot. Res.*, p. 2350006, 2023.

[4] M. B. Goweida, S. Mahmoud, M. Sobhy, and C. Liu, "Deep anterior lamellar keratoplasty with large Descemet's membrane perforation: Should we stop conversion to penetrating keratoplasty?" *Curr. Ophthalmol.*, vol. 33, pp. 171–176, 2021.

[5] R. I. Barraquer, L. Pareja-Aricò, A. Gómez-Benlloch, and R. Michael, "Risk factors for graft failure after penetrating keratoplasty," *Medicine*, vol. 98, no. 17, p. e15274, 2013.

[6] W. Edwards, G. Tang, Y. Tian, M. Draelos, J. Izatt, and A. Kuo, "Data-driven modelling and control for robot needle insertion in deep anterior lamellar keratoplasty," *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 1526–1533, 2022.

[7] Y. Zhao, A.-M. Jablonka, N. A. Maierhofer, H. Roodaki, A. Eslami, M. Maier, M. A. Nasseri, and D. Zapp, "Comparison of robot-assisted and manual cannula insertion in simulated big-bubble deep anterior lamellar keratoplasty," *IEEE/ASME Trans. Mechatron.*, vol. 21, no. 6, pp. 2613–2623, 2016.

[8] J. D. Opfermann, Y. Wnag, J. Kaluna, K. Suzuki, W. Gensheimer, A. Krieger, and J. U. Kang, "Design and evaluation of an eye mountable AutoDALK robot for deep anterior lamellar keratoplasty," *Micromachines*, vol. 15, no. 6, 2024.

[9] M. Nambi, P. S. Bernstein, and J. J. Abbott, "A compact telemanipulated retinal-surgery system that uses commercially available instruments with a quick-change adapter," *J. Med. Robot. Res.*, vol. 1, no. 2, p. 1630001, 2016.

[10] N. R. Posselli, E. S. Hwang, Z. J. Olson, A. Nagiel, P. S. Bernstein, and J. J. Abbott, "Head-mounted surgical robots are an enabling technology for subretinal injections," *Sci. Robot.*, vol. 10, p. eadp7700, 2025.

[11] N. R. Posselli, P. S. Bernstein, and J. J. Abbott, "Eye-mounting goggles to bridge the gap between benchtop experiments and in vivo robotic eye surgery," *Sci. Rep.*, vol. 13, p. 15503, 2023.

[12] A.-M. Jablonka, N. A. Maierhofer, H. Roodaki, A. Eslami, D. Zapp, A. Nasseri, and C. P. Lohmann, "The effect of needle entry angle on bubble formation in DALK using the big-bubble technique," *Invest. Ophthalmol. Vis. Sci.*, vol. 61, no. 7, p. 1862, 2020.