Robotic Systems in Ophthalmology

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Abstract

The use of robotic systems has developed extensively in various surgical subspecialties. This article attempts to provide an overview of the applications of these systems in the field of ophthalmology. The robotic surgical platforms available for ophthalmic use are discussed with their inherent advantages and disadvantages, including the da Vinci and the IRISS (Intraocular Robotic Interventional Surgical System). The potential for complete automation of ophthalmic surgical procedures in the recent future makes the field of robotics an exciting development.

Keywords: robotics, da Vinci, IRISS, femtosecond laser

Introduction

The word ‘robot’ was introduced by Czech writer Karel Capek in his play R.U.R. (Rossum’s Universal Robots), which was published in 1920. It comes from the Slavic word robota, which means labour. Over the years, robotics has found applications in numerous fields including medicine. Robotic systems have been utilized in the surgical environment for the past 20 years. During this period, the use of robotic systems has proliferated in various subspecialties including urology, gastroenterology, gynecology, cardiovascular and thoracic surgery, orthopedics, and neurosurgery. Of late, the use of robotic systems in the field of ophthalmology has received significant attention. This article attempts to provide an overview of the applications of these systems in ophthalmology.

Robotics in Medicine - A brief history

Probot was one of the first surgical robots to be developed, in the late 1980s. It was developed by the Mechatronics in Medicine Laboratory at Imperial College London, United Kingdom. This system was designed to assist with transurethral resection of the prostate, and the first patient was treated in April 1991. This was the first time a robot was used to remove tissue from a patient. Later, many robotic surgical systems were developed. These included the Zeus (Computer Motion) and the da Vinci (Intuitive Surgical Inc.) systems. By 2001, more than 40 Zeus and more than 50 da Vinci systems were being used in clinical practice worldwide. Few years down the line, Computer Motion was acquired by Intuitive Surgical and the manufacture of the Zeus system was discontinued. The da Vinci thus became the most widely used robotic surgical system. This system was evaluated initially for ophthalmic robotic surgery because of its widespread acceptance as the premier robotic system in the market. However, several shortcomings of this system with respect to ocular surgery have led to efforts by several teams towards customizing robotic platforms solely dedicated for intraocular surgery.

Uses of robotic systems: Do they work in the field of ophthalmology?

The advantages of robotic surgery include improved ergonomics, a three-dimensional view with greater magnification, motion scaling (scaling down of a surgeon’s movements to improve accuracy), tremor filtration (reduced tremor), extensive instrument articulation and superior instrument maneuverability, and technical precision. The overwhelming advantage of minimally invasive robotic surgery is its ability to provide access to critical surgical sites without collateral tissue damage secondary to direct visualization or instrumentation. This has made robotic surgery an attractive option in procedures like laparoscopic abdominal surgery, cardiac valve replacement surgery etc. In each case, maximal implementation has been achieved when open access to the surgical site would require pronounced collateral tissue trauma. Ophthalmic surgery is unique, as the surgeon has direct visualization of the surgical site and ocular structures via the cornea. Direct, non-invasive visualization via the transparent cornea and microscopic techniques has promoted the development of elegant, minimally invasive surgical instrumentation for intraocular surgery. Thus, one of the foremost advantages of robotic surgery - direct visual access and microsurgical manipulation in a confined surgical site - may not be as relevant to ophthalmic surgery. The number of procedures using robotic surgical systems has grown exponentially over the past 15 years. However, during the same period the number of ophthalmology related studies on the topic has remained surprisingly low since the first publication in 1995. This is probably because ocular surgery already is a minimally invasive microsurgery yielding excellent results. This however, does not prevent robotic surgery from providing other distinct advantages for ophthalmic surgery like technical precision, reproducibility of results and ability to simultaneously manipulate three surgical instruments and cameras. Robotics, as shown by Tribas et al, can provide the level of precision necessary to perform ophthalmic surgery with a short learning curve. In addition, the utilization of robotic surgery may facilitate telemedicine and provide access to ophthalmic sub-
specialty surgery in geographically isolated areas. This may be of great importance in underdeveloped and developing nations with shortage of healthcare facilities where these devices may facilitate surgery that would otherwise be unavailable.14

Robotic ophthalmic surgery may potentially provide outstanding sub-specialty surgical training for new and experienced surgeons without requiring extensive travel.17 It is often difficult to communicate the art of ophthalmic surgery without direct ‘hands on’ training. Although surgical training as a sole purpose for implementation would be cost-prohibitive, this technology offers the potential to substantially improve surgical training and, as a result, patient care.14 Since 2009, basic skills training courses have been organized by international groups like the Robotic Assisted Microsurgical and Endoscopic Society (RAMES). These basic courses are performed on training models in five levels of increasing complexity. This may help surgeons develop and improve robotic surgery skills.18 The hurdles to broad implementation of robotic surgery include high direct robotic costs (usually costing more than US $ 1 million19) as well as ancillary staff training, but these considerations are common during the introduction of novel sub-specialty instrumentation.14

Robotic telemanipulators have often been criticized for not having tactile feedback. In reality, it has been clearly demonstrated that force or tactile feedback is not absolutely necessary in microsurgery: first, because the range of motion in the microsurgical field is minimal, and second, because the perception of a 9/0 and 10/0 nylon yarn voltage is at the limit of human physiology.20 In addition, the issues of tactile feedback, which may be a problem in other fields, are not a major drawback in ocular surgery, where visual feedback is used to gauge suture tightness or tissue manipulation.16

Also, the placement of sutures is much slower than with standard ophthalmic microsurgical instruments leading to longer surgical times. The visualization of the surgical field has also been criticized to be poorer than that afforded by an ophthalmic operating microscope.16 However, technical innovations and surgical facility will undoubtedly improve with experience. For example, a new robotic platform, the Amadeus telemanipulator (Titan), that will be available soon, will be equipped with tactile feedback.18

Robotic Systems in Ophthalmology

While most surgical specialties have incorporated robotic platforms into routine use, ophthalmic surgery poses a number of unique challenges that have thus far limited this technology’s applicability. A microsurgical robotic system for intraocular use must satisfy certain requirements with respect to the following: (1) ease of maneuverability within a confined workspace; (2) ability to execute motion of seven degrees of freedom or DoF [The degrees of freedom of a mechanical system are the number of independent parameters that define its configuration. For example, a robotic arm (similar to the human arm) has seven degrees of freedom: shoulder pitch, yaw, and roll; elbow pitch; wrist pitch, yaw, and roll]; (3) remote centre of motion (RCM), or pivot joint, located at the tissue entry sites; (4) stereoscopic visualization system; (5) efficient assembly/disassembly of sterile instrumentation from the unsterile platform; and (6) compatibility with the surgical environment (i.e. assimilates to patient movement).20

The da Vinci surgical robot (the only surgical telemanipulator currently available on the market) has been used in the field of ophthalmology for various anterior and posterior segment procedures in porcine and cadaver eyes like corneal laceration repair21, pars plana vitrectomy, intraocular foreign body removal, and anterior capsulorhexis22, penetrating keratoplasty22 and recently, pterygium surgery23. The da Vinci system consists of three components: a mobile instrument cart with four articulated arms, an imaging cart, and a console for the surgeon to control the robotic arms. Out of the four articulated robotic arms, three carry surgical instruments and the fourth manipulates the digital stereoscopic camera to visualize the surgical field. Each of these arms has multiple joints providing three-dimensional movement of the surgical instruments and optics. The surgical tools have articulation that provides intracorporeal range of movement to 360°, called “EndoWrist” technology. The tools available vary: dissecting forceps, scissors, scalpels, spreaders, etc. The stereoscopic camera of the fourth arm has a lens comprising a video imaging column and two light sources and dual stereoscopic cameras for three-dimensional vision with progressive magnification up to 12-15 times. The surgeons’ console is equipped with an optical viewing system, two telemanipulation handles, and five pedals. The optical viewing system, called the stereo viewer, offers a three-dimensional view of the operating field and displays text messages and icons that reflect the status of the system in real time. The two telemanipulation handles allow remote manipulation of the four articulated robotic arms. In its latest version, the da Vinci SI, the robot is equipped with 2 surgeon consoles to allow for simultaneous use with two operators: the primary robotic surgeon and a surgical assistant. In this mode, the 3 robotic arms can be utilized at the same time by the two operators.18

Five properties of the da Vinci robot are essential in telemicrosurgery. The optical magnification of the operating field is obtained by the optical and digital magnification of the stereoscopic camera. The suppression of physiological tremor improves the quality of surgical movements. The scaling down of surgical movements improves accuracy by reducing the surgeon’s movements by a factor of 3 (position “fine”) or 5 (position “extra-fine”). The ergonomic design of the surgeons’ console is very useful in microsurgery because it improves the comfort of the surgical movements by simplifying the motion. The possibility of minimally invasive surgery allows the microsurgeon to work in unique operative fields with minimal incisions.18

Two design limitations, however, restrict its practical use in ophthalmic surgery. First, having a high RCM, both located above the wrist and at a long distance from the tip of the instrument, renders intraocular maneuvers less controllable and induces undue tension on the external eye surface next to the entry site. Thus, the surgeon is required to impose a second RCM at the ocular penetration site by moving the robotic arms appropriately. These motions are not as
intuitive as the wrist movements, do not mirror the exact movements of the surgeon’s arms, and, more importantly, dramatically limit the range of motion. Consequently, procedures like creation of a perfectly round, curvilinear capsulorhexis optimal for cataract surgery has proven to be quite difficult. Second, intra-operative visualization, as ophthalmologists are accustomed to, is challenging with the da Vinci surgical system as its video capture system is designed for endoscopic use and does not yield the detail of a sophisticated optical microscope. Also, the time taken for surgery is more than that taken by manual surgery.\textsuperscript{20} Various up-gradations and modifications in the system for ophthalmic use have subsequently been introduced (for example, the Si HD model).\textsuperscript{23}

These shortcomings of the da Vinci surgical system have encouraged the development of other robotic platforms solely dedicated for intraocular surgery. By mounting a microrobot, the \textbf{Hexapod Surgical System}, to the da Vinci macrorobot, an RCM located at the site of ocular penetration was achieved. This system, with an RCM dedicated to intraocular robotic surgery, provides a high level of precision and dexterity.\textsuperscript{24} Another adaptation, the \textbf{Microhand} (consisting of four fingers), was designed to mimic a human hand. It is pneumatically controlled, allowing titration of grasping force. It can thus be useful in intraocular surgery to apply calibrated forces to the ocular tissues.\textsuperscript{25} The \textbf{steady-hand manipulator}\textsuperscript{26,27} and \textbf{Micron}\textsuperscript{28} were two independently developed instruments capable of tremor filtration for microsurgical procedures. Japanese collaborators recently created a prototype robotic system designed to aid in vitreoretinal surgery. Robotic assistance increased surgeon accuracy 5- to 10-fold, and facilitated successful surgical induction of a posterior vitreous detachment (PVD), retinal vessel sheathotomy using 25-gauge microscissors, and microcannulation of retinal vessels in porcine eyes.\textsuperscript{29} A separate group of investigators have designed a novel dual-arm robot capable of high-precision maneuvers, such as vascular cannulation and stent deployment in animal models.\textsuperscript{30,31} However, no system has been capable of performing a complete ocular surgical procedure, including both anterior and posterior intraocular surgeries. Interest is growing in designing such devices, with the goal of adding speed and efficiency to the surgical experience without sacrificing precision.

This led to the development of the \textbf{IRISS} (Intraocular Robotic Interventional and Surgical System), a joint effort between the Jules Stein Eye Institute and the UCLA Department of Mechanical and Aerospace Engineering, capable of performing both anterior and posterior segment intraocular surgery. To test the feasibility of performing ‘bimanual’ intraocular surgical tasks using the IRISS, the authors defined four steps out of typical anterior (phacoemulsification) and posterior (pars plana vitrectomy or PPV) segment surgery. Selected phacoemulsification steps included construction of a continuous curvilinear capsulorhexis and cortex removal in infusion–aspiration mode. Vitrectomy steps consisted of performing a core PPV, followed by aspiration of the posterior hyaloid with the vitreous cutter to induce a PVD assisted with triamcinolone, and simulation of the microcannulation of a temporal retinal vein.\textsuperscript{30}

In contrast with previous attempts on the da Vinci surgical system, the IRISS is the first robotic system to not only successfully create a round, curvilinear capsulorhexis essential for cataract surgery, but also the first to carry out an entire cataract extraction from start to finish. The IRISS has displayed the needed range of motion, dexterity, and accuracy for delicate intraocular surgery.\textsuperscript{20}

The IRISS design consists of two components: a master controller and a dual-arm surgical instrument slave manipulator, set on different tables in the same operating suite. Each arm of the mechanical robot apparatus is mounted on a separate stage with its own RCM, capable of seven DoF necessary for intraocular manipulation. In addition, each arm is equipped with interchangeable commercially available instruments, enabling efficient mid-surgery switching for completion of bimanual tasks. The control console where the surgeon manipulates the robotic arms remotely consists of two custom-designed joystick controls. The surgeon holds both shafts and manipulates each as if they were standard intraocular surgical instruments. Tremor reduction is achieved by processing and filtering frequency of motion. Small motion can be amplified from the joystick command to the instrument so that surgical precision is increased. The need for a superior image acquisition and visualization system, capable of delivering a 3D view to the surgeon seated away from the microscope, is satisfied with the TrueZoom 3D Surgical Camera (TrueVision Systems) mounted on the microscope. Enhanced HD 3D visualization is possible by either a head-mounted or 3D flat-panel display.\textsuperscript{30}

However, while using the IRISS, the surgical manipulator RCM has to be manually aligned to the incision made in the porcine eye. This trial and error process is time consuming and needs to be performed to compensate for any relative movement between the eye and the surgical manipulator. This would preclude the clinical use of the IRISS in its current state, as the patient is not completely anesthetized and minimally restrained by tape across the forehead, rendering even the slightest head movements potentially detrimental. Therefore, incorporation of a tracking system and motorization of the two stages to compensate for the eye movement will be the next logical steps in refining the IRISS for potential use on living subjects.\textsuperscript{20}

By extending the sense in which the term robotics is usually used, newer \textbf{femtosecond (FS) laser applications} in cataract and refractive surgery may be considered robotic systems, albeit not in a traditional way. In 2009, Nagy et al first reported the clinical application of the FS lasers for cataract surgery. In September 2009, the FDA approved the LenSx (Alcon, California, USA) laser for the creation of anterior capsulotomies prior to cataract surgery. In rapid succession, their application in the creation of corneal incisions and fragmentation of cataracts has also been approved. In 2010, the FDA cleared FS laser systems for cataract surgery. The currently available machines for cataract surgery are LenSx, LenSar (Lensesr, Inc., FL, USA), Optimedica (Abbott Medical Optics Inc., CA, USA) and Technolas FEMTEC (Technolas
Perfect Vision, MO, USA). The LenSar uses Scheimpflug imaging while the LenSx technology uses a FS laser with an optical coherence tomography (OCT) diagnostic unit, so they have the capacity for real-time analysis of the anterior segment. FS laser can be used to perform four groups of incisions: capsulotomy, lens fragmentation, astigmatic relaxing incisions, and clear corneal incisions (CCIs, including the cataract incision and paracenteses). As laser cataract and refractive surgery has dramatically evolved towards becoming a nearly automated process, requiring minimal intra-operative manipulation by the surgeon, future adaptations may contribute to the inevitable shift towards automation of other anterior segment procedures. This may plausibly be achieved by integrating robotic platforms with a FS laser device. In addition, assimilation of robotic platforms like the IRISS with intra-operative visual recognition technology, OCT, and laser technology could help facilitate creation of a ‘no-fly zone’, whereby certain vital intraocular structures (for example, the posterior capsule) can be delineated and restricted from instrumentation. For less standardized procedures, such as vitreoretinal surgery, robotic augmentation may potentially improve surgical outcomes by increasing surgeon dexterity and accuracy, decreasing complication rates by reducing tremor, and open the door for more delicate, fine-detail surgical manipulations by amplifying scale of motion.

Conclusion

In conclusion, the use of robotic systems in ophthalmology still seems to be in its nascent phase, with immense scope for technological development, research and support. High costs, potential steep learning curves for the novice surgeon, and patient trust all present unique challenges. However, the potential for complete automation of surgical procedures, with increased precision and better patient management, surpassing the current limitations of human-delivered surgical care more than justifies the efforts in this direction. It may not be long before robotic ophthalmic surgery becomes the norm rather than the exception.

References

1. Capek K. R.U.R. (Rossum’s Universal Robots): a play in introductory scene and three acts-translated into English by David Wyllie [e-book]. South Australia: eBooks@Adelaide; 2014 [cited 2015 Oct 10]. Available from: https://ebooks.adelaide.edu.au/c/capek/karel/rur/index.html
2. Kumar R, Hemal AK. Emerging role of robotics in urology. J Minim Access Surg 2005; 1:202–10.
3. Dasgupta P, Challacombe B, Murphy D, Khan MS. Coming full circle in robotic urology. BJU Int. 2006;98:4–5.
4. Ruurda JP, Broeders IA, Simmermacher RP, Borel Rinkes IH, Van Vroonhoven TJ. Feasibility of robot-assisted laparoscopic surgery: an evaluation of 35 robot-assisted laparoscopic cholecystectomies. Surg Laparosc Endosc Percutan Tech 2002; 12:41–5.
5. Breitenstein S, Nocito A, Puhan M, Held U, Weber M, Clavien PA. Robotically-assisted versus laparoscopic cholecystectomy: outcome and cost analyses of a case-matched control study. Ann Surg 2008; 247:987–93.
6. Kaul S, Launani R, Sarle R, Stricker H, Peabody J, Littleton R, et al. da Vinci-assisted robotic partial nephrectomy: technique and results at a mean of 15 months of follow-up. Eur Urol 2007; 51:186–91.
7. Diaz-Arrastia C, Jurnalov C, Gomez G, Townsend C Jr. Laparoscopic hysterectomy using a computer-enhanced surgical robot. Surg Endosc 2002; 16:1271–3.
8. Beste TM, Nelson KH, Daucher JA. Total laparoscopic hysterectomy utilizing a robotic surgical system. JSLS 2005; 9:13–5.
9. Katz MR, Van Praet F, de Camieri D, Murphy D, Siwek L, Seshadri-Kreaden U, et al. Integrated coronary revascularization: percutaneous coronary intervention plus robotic totally endoscopic coronary artery bypass. Circulation 2006; 114:1473–6.
10. McClure RS, Kiani B, Novick RJ, Rayman R, Swinamer S, Koder J, et al. Computer-enhanced telemanipulation in mitral valve repair: preliminary experience in Canada with the da Vinci robotic system. Can J Surg 2006; 49:193–6.
11. Kypson AP, Chitwood WR. Robotic cardiovascular surgery. Expert Rev Med Devices 2006; 3:335–43.
12. Cleary K, Nguyen C. State of the art in surgical robotics: clinical applications and technology challenges. Comput Aided Surg 2001; 6:312–28.
13. Arezzo A, Ulmer F, Weiss O, Schurr MO, Hamad M, Bues GF. Experimental trial on solo surgery for minimally invasive therapy. Surg Endosc 2000; 14:955–9.
14. Douglas R. Robotic surgery in ophthalmology: reality or fantasy? Br J Ophthalmol 2007; 91:1.
15. Hunter IW, Jones LA, Sagar MA, Lafontaine SR, Hunter PJ. Ophthalmic microsurgical robot and associated virtual environment. Comput Biol Med 1995; 25:173–82.
16. Tsirbas A, Margo C, Dutson E. Robotic ocular surgery. Br J Ophthalmol 2007; 91:18–21.
17. Rashid HH, Leung YY, Rashid MJ, Oleyourryk G, Valvo JR, Ichel L. Robotic surgical education: a systematic approach to training urology residents to perform robotic-assisted laparoscopic radical prostatectomy. Urology 2006; 68:75–9.
18. Liverneaux PA, Hendriks S, Selber JC, Parkkari S. Robotic assisted microsurgery: development of basic skills course. Arch Plast Surg 2013; 40:320–6.
19. Panchulizade I, Berner S, Mantovani G, Liverneaux P. Is haptic feedback necessary to microsurgical suturing? Comparative study of 9/0 and 10/0 knot tying operated by 24 surgeons. Hand Surg 2011;16:1–3.
20. Rahimi E, Wilson J, Tsao TC, Schwartz S, Hubschman JP. Robot-assisted intracocular surgery: development of the IRISS and feasibility studies in an animal model. Eye (Lond) 2013; 2009; 12:772–8.
21. Bourla DH, Hubschman JP, Culjat M, Tsirbas A, Gupta A, Schwartz SD. Feasibility study of intracocular robotic surgery with the da Vinci surgical system. Retina 2008; 28:154–8.
22. Bourges JL, Hubschman JP, Burt B, Culjat M, Schwartz SD. Robotic microsurgery: corneal transplantation. Br J Ophthalmol 2009; 93:1672–5.
23. Bourcier T, Nardin M, Sauer A, Gaucher D, Speeg C, Mutter D, Marescaux J, Liverneaux P. Robot-Assisted Pterygium Surgery: Feasibility Study in a Nonliving Porcine Model. Transl Vis Sci Technol 2015; 4:1–9.
24. Bourges JL, Hubschman JP, Wilson J, Prince S, Tsao TC,
Schwartz S. Assessment of a hexapod surgical system for robotic micro-macro manipulations in ocular surgery. Ophthalmic Res 2011; 46:25–30.

25. Hubschman JP, Bourges JL, Choi W, Mozayan A, Tsirbas A, Kim CJ, et al. ‘The Microhand’: a new concept of micro-forceps for ocular robotic surgery. Eye (Lond) 2010; 24:364–7.

26. Mitchell B, Koo J, Iordachita I, Kazanzides P, Kapoor A, Handa J, et al. Development and application of a new steady-hand manipulator for retinal surgery. IEEE ICRA. 2007. pp. 623–9.

27. Uneri A, Balicki MA, Handa J, Gehlbach P, Taylor RH, Iordachita I. New steady-hand eye robot with micro-force sensing for vitreoretinal surgery. Proc IEEE RAS EMBS Int Conf Biomed Robot Biomechatron 2010; 2010:814–9.

28. MacLachlan RA, Becker BC, Tabarés JC, Podnar GW, Lubes LA, Riviere CN. Micron: An actively stabilized handheld tool for microsurgery. IEEE Transactions on Robotics 2012; 28:195–212.

29. Ueta T, Yamaguchi Y, Shirakawa Y, Nakano T, Ideta R, Noda Y, et al. Robot-assisted vitreoretinal surgery: development of a prototype and feasibility studies in an animal model. Ophthalmology 2009; 116:1538–43.

30. Fine HF, Simaan N, Wei W, Siman N. A novel dual-arm dexterous ophthalmic microsurgical robot: applications for retinal vascular cannulation and stent deployment. Retina Congress, 2009.

31. Fine HF, Wei W, Goldman R, Simaan N. Robot-assisted ophthalmic surgery. Can J Ophthalmol 2010; 45:581–4.

32. Liu HH, Hu Y, Cui HP. Femtosecond laser in refractive and cataract surgeries. Int J Ophthalmol 2015; 5:849-26.

33. Grewal DS, Schultz T, Basti S, Dick HB. Femtosecond Laser Assisted Cataract Surgery - Current Status And Future Directions. Surv Ophthalmal 2015 Sep 24.

34. Liu X, Balicki M, Taylor RH, Kang JU. Automatic online spectral calibration of Fourier-domain OCT for robotic surgery. Proc SPIE Int Soc Opt Eng 2011;7890.

35. Liu X, Balicki M, Taylor RH, Kang JU. Towards automatic calibration of Fourier-domain OCT for robotic vitreoretinal surgery. IEEE Transactions on Robotics 2012; 28:195–212.

36. Balicki M, Han JH, Iordachita I, Gehlbach P, Handa J, Taylor R, et al. Single fiber optical coherence tomography microsurgical instruments for computer and robot-assisted retinal surgery. Med Image Comput Comput Assist Interv 2009; 12:108–15.

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