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Surgery: From Human to Robots

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Published Date: January 30, 2016

INTRODUCTION

The introduction of robots in surgery is the latest example how the modern technological advances has changed the delivery of surgical techniques over the last few decades. Until the end of last century the integration of robotic technology with standard surgical techniques was mainly market driven to attract consumers to the healthcare establishments. Many healthcare providers used robots as a face value to claim themselves as centre of excellence despite limited experience in robotic surgery. The evidence behind the clinical applications to improve patient outcome was also limited. However twenty-first century has seen exponential growth in robotic surgical procedures and safety and diversity of robotic systems in surgery is under extensive research.

This chapter will provide an overview of development of surgical robots and their use in various surgical specialties. The reader will be able to comprehend the evolution of robots, their current role in surgery and have an insight into the future of robotic surgery.

BACKGROUND AND HISTORY OF SURGERY

The word surgery has been derived from Greek word cheirourgia that means *hand work*. From the early days of human history, surgery has been seen as a branch of medicine that uses manipulation of tissue to prevent or cure an illness. Bleeding, pain and infection had been major obstacles and it was only recently that science has found solutions to overcome these, hence improving patient outcomes. Advancement in an aesthetic techniques and knowledge of aseptic measures with advent of antibiotics has results in exponential growth of surgery in twentieth century [1].

Last quarter of twentieth century saw significant technological developments in various branches of surgery. Standardization of surgical principles and sophisticated instruments improved outcomes in complex surgical procedures. As the quest to excellence continued the surgeons envisage devising innovation in surgery to minimize the suffering of patients. This led to development of minimal access surgery as the modern surgical approach in the last quarter of twentieth century.

DEVELOPMENT AND EVOLUTION OF ROBOTIC SURGERY

Robot is a machine that is programmed by computer and can carry out complex tasks automatically under direct or indirect control of human [2]. Robot is a Czech word which means forced labour or servitude. In layman language, robot is a machine that resembles human and helps in executing difficult tasks under the direct control of human. Advent of robots is one of the many examples where science fiction has now emerged as a reality.

In 1921 Karel Capek (1890-1938) used term robot in his play (Rossom's Universal Robots) as a protest against dehumanizing effect of increasing use of technology in western civilization [3]. Cinema industry went one step further to give concept of star wars (human friendly robots) and terminators (enemy robots).

From the day German motors used first commercial robot Unimate (Figure 1) in 1958 the use of robots has exponentially increased in various field [3]. The initial use of robots was in dangerous or unwanted tasks like deep-sea exploration, interplanetary exploration and launching of guided missiles in military. In 2000 the production of ASIMO (Figure 2) as first humanized robot was the ultimate unification of fiction and reality. ASIMO is able to walk like human and climb stairs [4].

Figure 1: Unimate Robot 1961.

(http://www.robothalloffame.org/inductees/03inductees/unimate.html)

Figure 2: Asimo robot by Honda.

(http://asimo.honda.com)

As mentioned earlier the initial use of robots was in industrial and then in military. There use was later incorporated into almost every field including space, underwater research and domestic use. Medical robots appeared almost at the same time and their usefulness was experimented in development of prosthetic limbs, wheelchairs, walking assistant machines and as diagnostic tools like capsule endoscopy.

An interesting fact in the evolution of surgical robots is the development of minimal access surgery. This can be seen as a major paradigm shift in the surgery after the first laparoscopic appendicectomy in 1981 and cholecystectomy in 1987 [5-6]. Surgeons did not only rapidly adopt minimal access surgery but even the patients perceived this as less invasive and preferred it to conventional surgery. Mainstay of minimal access surgery has been the laparoscopic (abdominal) surgery, which is in widespread use now. Though technical aspects of minimal access surgery modify the access and way of dissection but the time tested surgical principles remain unchanged and the principles of dissection in laparoscopic surgery remained almost the same as in open surgery. However while the surgical principles were the same, the technical aspects differ. In open surgery the surgeon has the liberty of visualizing and feeling the tissues to plan their dissection. This haptic feedback is much reduced in minimal access surgery. Surgeon has to rely on machines and to imagine the 3D anatomy in a 2D image.

Laparoscopic surgery initially had major ergonomic limitations due to the types of instruments used and limited 2D visualization. Fulcrum effect and loss of freedom of movements are most important of these limitations. These instruments are not user friendly in rigid cavities with limited space like pelvis and thorax. Loss of haptic feedback (force and tactile), hand-eye coordination and manual dexterity are now well-known limitations for laparoscopic surgeons and most surgeon overcome these with experience. However physiologic tremors in some surgeons readily transmit through the rigid instrument and makes precise dissection challenging. Overcoming these inherent limitations of laparoscopic surgery was a major motivation to develop surgical robots [7-8].

Puma 560 was the first surgical robot used to perform neurosurgical biopsies with great precision in 1985. Davies and colleagues used puma 560 to perform TURP. The system later led to the development of PROBOT (a purpose build robot for TURP). During the same period ROBODOC was developed for hip arthroplasty and was the first robot to get approval from FDA for surgical use [3].

While the robotic surgery was being populated a group of researchers from National Air and Space Administration **(NASA)** who was working on virtual reality focused their interest on development of tele-presence surgery. The concept was to make surgeon able to perform surgery without being physically present at operative site. This idea of telesurgery is now shaping up the future development of surgical robots. NASA research group later worked in Stanford Research Institute **(SRI)** to develop a dexterous telemanipulator for hand surgery. This success story continued when US army used the idea of telepresence surgery for war-wounded soldiers to make surgery possible in battlefield and decrease the wartime mortality. The system was never practically implemented in battlefield but led to very useful piece of research in robotic surgery [9].

The knowledge and experience gained form aviation and military research ultimately led to development of Automated Endoscopic System for Optimal Positioning **(AESOP)** (Figure 3). This was a robot arm to control endoscopic camera manipulation with voice control. After marketing of AESOP, Integrated Surgical Systems (now Intuitive Surgical) licensed the green telepresence surgical system from SRI and reintroduced it later, with extensive redesign, as Da-Vinci surgical system. Their competitor Computer motion introduced Zeus surgical system within a year and it was this system which was used in land mark project Operation Lindberg in 2001 when Jacques Marescaux successfully performed transatlantic robotic cholecystectomy in a patient in Strasbourg from New York [10].

Figure 3: AESOP cart.

(http://allaboutroboticsurgery.com/surgicalrobots.html)

TYPES OF ROBOTIC SYSTEMS

Three different robotic systems are available depending upon surgeon's interaction with the robot during the procedure:

1. Supervisory-controlled system

2. Tele surgical system

3. Shared control system

1. In supervisory control system surgeon inputs the procedure before hand into the computer and robot performs most of the procedure independently with minimal further input from surgeon. This system needs very accurate description of every procedure which makes it very expensive and is time consuming. It is not in routine use as yet.

2. In telesurgical systems surgeon directly controls the robotic arms while sitting on site or offsite and is the mainstay of available robotic systems.

3. In shared control systems surgeon performs the operation with the help of robotic arms to improve the precision of instrument manipulation.

ROBOTIC SURGICAL SYSTEMS

As previously mentioned Prodoc, ROBODOC, AESOP system, Da Vinci and Zeus systems have been FDA approved to be used in surgery. Market competition in surgical robots has led to the development of new robots and improvement in the existing systems. Da Vinci and Zeus have similar characteristics as both systems use master slave technology and surgeon controls the robotic arms from a console with the help of video assisted computer enhanced navigation software.

Table 1: Some of the robots mentioned in text.

Robot	Company	Procedures	Approval	Availability
ZEUS (2001)	Computer Motion Inc	General surgical procedures	FDA	Discontinued 2003
da-Vinci	Intuitive Surgical Inc.	General surgical procedures	FDA	Worldwide
ROBODOC	Curexo Technology Corp.	Orthopedic surgery	FDA (2008) CE Mark (1996)	No use in Europe anymore
RIO	MAKO surgical Corp.	Orthopedics surgery (TKA/THA)	FDA (2010) CE Mark (2010)	Worldwide
AESOP (1994)	Computer Motion Inc.	Assistance in general surgery	FDA	Discontinued 2003
Probot	Imperial college London, UK	Prostate resection	------	Discontinued, acquired by acrobot
ALF-X	Sofar S.p.A Milano, Itay	General surgical procedures	CE Mark (2011)	Worldwide
SurgiBot	TransEnterix Surgical Inc.	General surgical procedures	------	Worldwide
i-Snake	Imperial college London, UK	Heart surgery	------	------
SOFIE	University of Eidenhoven, Netherlands	General surgical procedures with haptic feedback	-------	-------

Da Vinci system is most popular and was developed from telepresence machine of NASA. It has three components: a vision cart hold dual light source and dual 3D cameras, operating surgeon sits in master console and instrument and camera arms are mounted on a movable cart (Figure 4-6).

Figure 4: Da Vinci robotic system.
(http://www.intuitivesurgical.com/products)

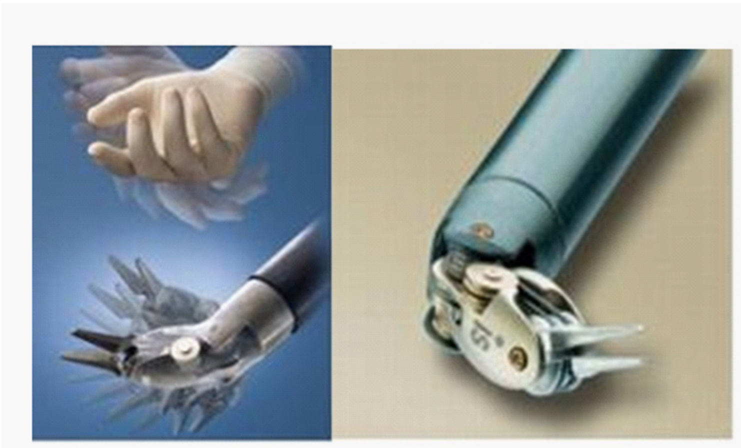

Figure 5: Endowrist instruments used in da Vinci ©2013 Intuitive Surgical, Inc.

Figure 6: The range of instruments used on the da Vinci robot©2013 Intuitive Surgical, Inc.

Master console contains various important instruments. Master control grips control the servant robotic arms, foot pedals control the electro cautery and camera focus control enables the surgeon to completely control all the manoeuvres during surgery. The Da Vinci instruments provide seven degrees of freedom (number of independent movements). Image processing happens in a computer located in the master console and surgeon can visualise three dimensional images with good depth perception in a view port. The system is designed in such a way that the image displays above the hands of surgeon which is the best ergonomic position of image in minimal access settings. This gives a real time feeling of operating at the surgical site and improves hand eye coordination.

Zeus system has a surgeon-controlled console with three robotic arms mounted on table. Right and left arms replicate the surgeon's two arms and the third arm is for camera which uses an AESOP voice controlled endoscope. The system provides ergonomically comfortable position of video monitor and instrument handles and like Da Vinci system provides seven degrees of freedom (Figure7).

Figure 7: The Zeus Surgical System.

(http://allaboutroboticsurgery.com/surgicalrobots.html)

ARTEMIS system is a master slave manipulator system developed in Eberhard Karls University Germany. In this system two robotic arms are controlled by the surgeon working in console [11]. Current research is focusing on development of reality based haptic feedback in robotic surgery.

A prototype miniature robotic system has been developed in MiTech lab of Scuola Superiore Sant'Anna Italy. The system uses an inchworm like locomotion by vacuum suction and is used initially for computer-enhanced colonoscopy. This system avoids the need of colonoscope to pass into the patient's bowel and is expected to revolutionise the endoluminal diagnosis and surgery by replacing the currently available endoscopic tools [12] (Figure 8).

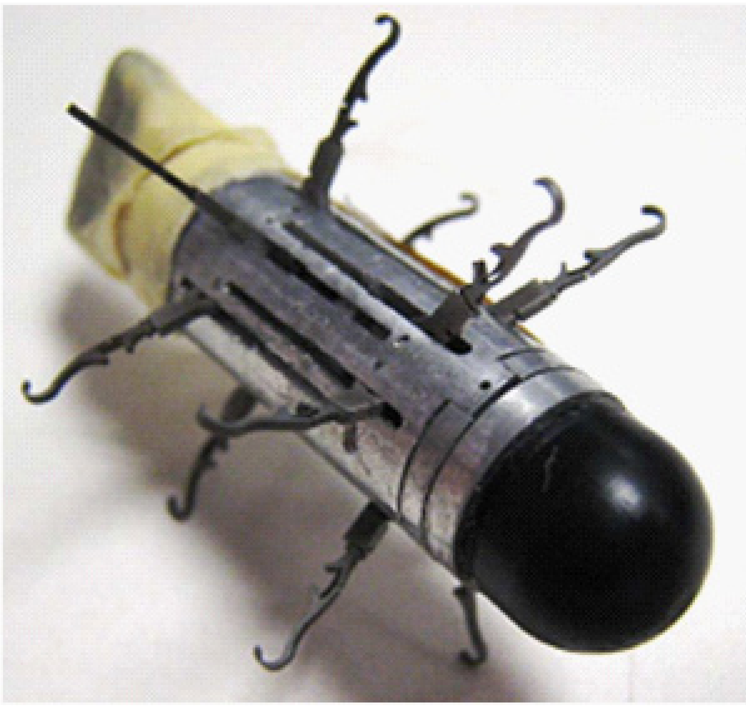

Figure 8: Prototype miniature robot for colonoscopy.

(https://my.vanderbilt.edu/stormlab/files/2013/01/IEEE_TRO_Valdastri_Dario.pdf)

Cyber knife system developed by Stanford University and marketed by Accuracy Company Calefornia has made it possible to give targeted radiotherapy for various tumours. The system consists of a linear particle accelerator (linac) to produce radiations and a robotic arm is used to direct the energy to a specific body part. The system is successfully used to deliver radiotherapy in deep seated tumors including prostate, breast, lungs and liver to name a few (Figure 9).

Figure 9: Setup of cybernife system (Sagina future, CC-BY-2.0).

The RIO system by MAKO surgical is similar to ROBODOC except that there is option to limit the boundaries of surgical field as per CT guidance. This helps to better control the robotic arm and avoid overshooting (Figure 10).

Figure 10: Robotic arm of RIO system (stryker Inc).

PATIENT SIDE ROBOTIC SURGERY

While major robotic systems operate on the idea of telepresence where surgeon is physically away from patient, some systems integrate laparoscopic instruments into robotics. This minimizes the reliance on assistants during surgery and let the surgeon perform robotic assisted tasks while staying within the operative field. SurgiBot by Trans Enterix is one such example which is not yet approved by FDA (Figure 11).

Figure 11: Surgibot 2015 TransEnterix, Inc.©

ADVANTAGES OF ROBOT ASSISTED SURGERY

Robots are the future of surgery as they have successfully overcome most of the limitations of laparoscopic surgery while holding all the benefits of minimal access surgery. Robotic surgical systems provide improved dexterity and hand eye coordination with better visualization and ergonomically comfortable position for surgeon.

The degree of freedom available with robotic instruments greatly enhances the capability of surgeon to manipulate tissues with great precision and perform delicate tasks. The system design excludes fine tremors in surgeon's hand by specific software and allows precise movements at instrument tip. The system is also capable to gauge movements thus allows large movements at control grip to be transferred into small movements inside the patient. The robotic systems also eliminate the fulcrum effect of laparoscopic instruments, which improves the hand eye coordination. The comfortable position at the console enables surgeon to perform long duration surgery more efficiently with less exertion.

The image navigation systems used in robotic surgery allows surgeon to directly control the visual field. Three dimensional vision and better magnification effectively eliminates the depth perception issue of conventional laparoscope. The location of image screen on control console replicates the open surgery with image just above the hands.

LIMITATIONS OF ROBOTIC SURGERY

Robotic surgery is relatively new and unlike laparoscopic surgery it has not been universally adopted as a gold standard in most surgical specialities. The literature about safe use of robotic surgery is still scarce in field of general surgery although the techniques are now well established in urology and gynaecological surgery. High cost of installation and maintenance of robotic systems has been a major limiting factor in universal adaptation of robotic surgery. The speculation is that with increased number of competitors in the market and development of new robotic systems will reduce the cost constraint in future. It is however possible that parallel development of technology and up gradation of systems will continue to keep cost limitation as a hindrance in development of robotic surgical development. Currently most hospitals use robotics for urology and gynaecological surgery however multidisciplinary use can make their usage more cost effective [13-14].

Large physical footprints of currently available robotic systems hinder their installation in standard operating theatres and need extra space. It is expected that future systems will be more compact hence needing less space. Latest da Vinci Xi system has wall mounted robotic arms to free the available theatre space.

Lack of force feedback in robotic surgical systems is a potential drawback for novel surgeons and creates a steep learning curve unlike laparoscopic surgery. Eind-hoven Sofie (*Surgeon's Operating Force-feedback Interface Eindhoven*) robot from Netherlands and TELELAP ALF-X from Italy have the capability of force feedback. New upgrades in currently available robotic systems will likely to have this capability installed and this factor should not long last as a limitation [15-16].

Another major limitation is staff training to use robotic systems. In laparoscopic surgery the instruments are simpler and with minimal training almost all theatre staff is capable to assisting the laparoscopic cases. However in robotic systems, special staff training is required which is not universally available and is not readily transferable. It is expected that with time when robotic systems will become more common the pool of trained staff will eventually rise.

CURRENT CLINICAL APPLICATIONS

Initial design of da Vinci system kept robotic platform to a fixed position once docked to the patient. This was more suited for pelvic surgery and not surprisingly the system was quickly embraced by urology and gynae surgeons to an extent that in 2008 70% of all prostatectomies were performed robotically in Unites States.

The most important lesson learned from the experience of uro-gynacological surgeries were that robotic systems are much more convenient for construction of anastomosis than conventional laparoscopic producers requiring dissection. This has led the general surgeons to explore the role of robots in major abdominal surgeries.

Currently the robotic surgical procedures are being performed in all major specialities including neurosurgery, cardiac surgery, paediatric surgery, plastic surgery and general surgery [17-20]. Although we are still awaiting universal acceptance of these robotic techniques.

FUTURE OF ROBOTIC SURGERY

Robotic surgery although well established is still in developmental stage. The new systems will be improved and better equipped to overcome the any technical limitations. In view of modern cost conscious healthcare systems, the cost effective systems are expected to appear in future. More literature containing robust scientific evidence will emerge to answer the questions of negligence claims, accreditations, training requirements and opportunities, ethical and jurisdiction issues around tele-surgery and need of international licensing body for trans-Atlantic surgeons.

Operation Lindbergh was initially promoted as a new era in robotic surgical development. However later events proved that we are still not ready for telerobotic surgery. Modern warfare technology will make it possible that robotic surgery can be successfully implemented in the battlefields to the same extent as once thought. Unmanned surgical ambulances with robotics systems installed would likely to be seen in future and would make a major impact on patient management in battlefield and in disastrous situations. The use of telesurgery in a disaster means that trained surgeons will be available to operate from remote hospitals which will help to overcome a major obstacle of staff shortage in disaster management plans.

The robotic systems run latest information technology software and have the inherent ability to incorporate the other software. It is possible to see the fusion of preoperative imaging with intra operative images in real-time to guide the surgeon about dissection plane. Amadeus surgical robot from Titan medical has incorporated the technology of a German aerospace agency robot (DLR) and can incorporate ultrasound imaging into its hardware, which can be used for surgical dissection plan. The same company is developing a single incision robotic surgical system called single port orifice robotic technology **(SPORT)**. This is a collapsible system and can be inserted from a 25mm incision and can be deployed into working con Figuration within the bodycavities [20].

Development of protein and DNA based microrobots and nanorobots are in its infancy. Future can see these robots as a reality, which will have the ability to travel within body systems and manipulate at cellular level. The harmful cells can be destroyed and this can be an ultimate cure for many cancerous conditions. There might be new branches of surgery in future like nanorobotics surgery and cellular surgery which can change surgery from minimal invasive to non invasive [21].

Recent successful application of brain-machine interface where paralysed people were able to control a remotely located robot by their thoughts means that we may see surgical robots in future which can be controlled by surgeons mind allowing surgeon to operate without physically performing the surgical steps [22]. An ultimate outcome could be computer led surgery in which technical details of operation can be fed into the computer which then controls the robot performing surgery without any direct control of human.

CONCLUSION

The use of robots is a latest example of union of fiction with science and technology. Robotic surgery is no more an experimental field and with further technological developments, surgical robots are expected to shape up the future of surgery. Addition of augmented reality and 3D vision will make surgery safer and hence improving patient outcomes.

GLOSSARY

1. **Augmented reality:** Augmentation of physical or real world environment by the help of computer aided technology e.g. transmission of surgical field on a screen as magnified image.
2. **Dexterity:** Skill in performing the manual tasks.
3. **Degree of freedom:** Number of independent movements the robot can perform.
4. **Haptic feedback:** Tactile sensation of holding a physical object. Surgeons use it to evaluate various tissues and plan dissection.
5. **Telesurgery:** A form of telepresence where surgeon performs operation while physically away from surgical site (see Operation Lindberg in text).
6. **Virtual reality:** Artificial creation of sensory experience with the help of computer aided technology, which replicates the sense of physical presence in real world or imaginary environment.

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