Robotics and Computer-Integrated Manufacturing 27 (2011) 261–266

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Surgical robotics: Reviewing the past, analysing the present, imagining the future

Paula Gomes *

Cambridge Consultants, Science Park, Milton Road, Cambridge CB4 0DW, UK

ARTICLE INFO

Keywords:
Surgical robotics
Robotic surgery
Computer-assisted surgery
Robot-assisted surgery
Minimally invasive surgery

ABSTRACT

This paper presents an overview of the surgical robotics field, highlighting significant milestones and grouping the various propositions into cohorts. The review does not aim to be exhaustive but rather to highlight how surgical robotics is acting as an enabling technology for minimally invasive surgery. As such, there is a focus on robotic surgical solutions which are commercially available; research efforts which have not gained regulatory approval or entered clinical use are mostly omitted. The practice of robotic surgery is currently largely dominated by the da Vinci system of Intuitive Surgical (Sunnyvale, CA, USA) but other commercial players have now entered the market with surgical robotic products or are appearing in the horizon with medium and long term propositions. Surgical robotics is currently a vibrant research topic and new research directions may lead to the development of very different robotic surgical devices in the future—small, special purpose, lower cost, possibly disposable robots rather than the current large, versatile and capital expensive systems. As the trend towards minimally invasive surgery (MIS) increases, surgery becomes more technically demanding for surgeons and more challenging for medical device technologists and it is clear that surgical robotics has now an established foothold in medicine as an enabling technology of MIS.

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1. Introduction

This paper does not aim to be an exhaustive review but rather to highlight how surgical robotics is acting as an enabling technology for minimally invasive surgery. As such, there is a focus on robotic surgical solutions which are commercially available; research efforts which have not gained regulatory approval or entered clinical use are mostly omitted. For additional background information, see [1–4]. Surgical robotics is now 25 years of age and is gaining traction. According to Intuitive Surgical, 205,000 da Vinci-assisted procedures were performed in 2009, up 51% from 2008.

As was the case with industrial robotics, surgical robotics was started under the premise that higher speed and accuracy could be achieved in surgery, particularly when high accuracy (such as that required in neurosurgery) or repetitive tasks (such as resecting a prostate gland with a wire loop resectoscope) were required. This is corroborated by first reports of robot-assisted

* Tel.: +44 1223 420024.
E-mail address: paula.gomes@cambridgeconsultants.com

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doi:10.1016/j.rcim.2010.06.009

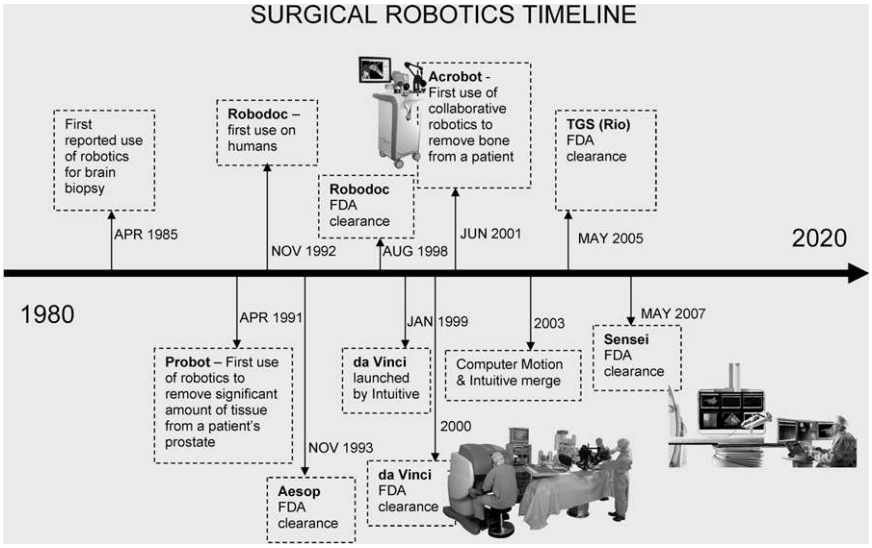

Fig. 1. Surgical robotics timeline.

surgeries. Kwoh et al. [5] claim improved accuracy and faster procedures as the rationale for their adoption of robotics in brain biopsy. Davies et al. [6] indicate a dramatic potential reduction of TransUrethral Resection of the Prostate (TURP) times from 1 h to 5 min.

Whilst the quest for increased accuracy seems to have been fulfilled, albeit dependent on factors such as imaging and image processing, registration of imaging to the robotic system, and calibration of instrumentation, the claim of reduced times has not been as successfully met and, despite significant improvements in efficiency and workflow, set up times often make robotic procedures lengthier than their conventional counterparts [7]. This poses a conflict for surgeons and healthcare providers, as less procedures can be carried out by the surgeon, and has made the health economics case for surgical robotics a difficult one to argue. However, despite procedure times remaining important and a fundamental market driver, other reasons are driving the adoption of surgical robotics: patient demand, reduction of surgical errors, augmenting surgical capabilities and enabling MIS.

MIS refers to any procedure which is less invasive than open surgery for the same purpose. The term was coined by John E.A. Wickham, who vigorously promoted this type of surgery [8]. Wickham was the urologist surgeon who operated with the Probot system [6]. Commonly known as "keyhole" surgery, MIS typically involves the use of a laparoscopic device and manipulation of instruments using an indirect view of the surgical field provided by an endoscope. This means that, instead of the multi-centimetre scar of open surgery, there will be three or four small wounds of around ten millimetres, with laparoscopic surgery, one small incision, in the case of single incision laparoscopic surgery (SILS), or even no external incision,[1] in the case of natural orifice surgery (NOS).

In this paper, the term MIS is used in a broader sense to encompass laparoscopic surgery and also procedures less invasive than conventional. For instance, in orthopaedic joint replacement, MIS might refer to a procedure where the surgical approach requires a smaller incision or where it is more bone conserving. Patient benefits, such as less scarring, less morbidity, shorter recovery times lead surgeons to attempt to perform more and more procedures as MIS. This places higher demands on surgeons and more difficult challenges for engineers.

2. Surgical robotics evolution

The first recorded robotic surgical procedure – a CT-guided brain biopsy – took place on 11 April 1985, at the Memorial Medical Center, Long Beach, CA, USA [5]. An industrial robot, a Unimation PUMA 200, was used to place a probe for a brain biopsy using CT guidance. The rationale was to use a sturdy mechanical structure to hold a guide in position such that a probe could be inserted to reach a surgical target deep in the brain in a straight trajectory avoiding vital structures of the brain. The straight trajectory was defined by the surgeon using CT guidance such that there was no neurological damage caused by the probe. The gold standard procedure at the time was to use a manually adjustable stereotactic frame and it was intended, with the use of the robot, to achieve improved accuracy and a faster procedure. Whilst the robot used was capable of autonomous motion, it was locked in position, with power removed for safety once aligned with the trajectory, while the surgeon inserted the biopsy needles, through the guide, into the patient's brain. This approach was later adopted by other systems described further along in this paper, such as BRIGIT and Vectorbot.

There was a long gap of 6 years until the next milestone in robotic surgery (Fig. 1): the first time a robotic device was used to *autonomously* remove a significant amount of tissue from a patient, in a TURP. The device used was the Probot, a special purpose robot developed at Imperial College London, and took place in April 1991 in London, UK [6].

2.1. Autonomous approaches and industrial adaptations

Soon after Probot was used in the operating room, in 1992, another example of an industrial robot adapted for surgery, this time a 5 degree of freedom SCARA robot, manufactured by Sankyo Seiki (Tokyo, Japan), entered clinical use for total hip arthroplasty (THA): the Robodoc system (initially from ISS Integrated Surgical Systems, Sacramento, CA, USA; now Curexo Technology

[1] Radiosurgery, High Intensity Focused Ultrasound (HIFU) and Magnetic Resonance guided Focused Ultrasound Surgery (MRgFUS) are other examples of incisionless surgery.

Corporation, Fremont, CA, USA[2]). ISS was formed by IBM with a $3 m investment in November 1990 and was one of the earliest companies in the field of surgical robotics.

The Robodoc system was first used on humans in 1992 as an autonomous robot for THA. This followed trials which started in 1990 [9]. However, it was not until August 1998 that Robodoc received 510(k) clearance from the United States Food and Drug Administration (FDA) for THA procedures. And it is not until much later, in February 2009, that Curexo submitted a premarket notification 510(k) application to FDA for market clearance in the US for use of its Robodoc Surgical System for total knee arthroplasty (TKA). According to its manufacturer, the Robodoc system has assisted surgeons in more than 24,000 joint replacement procedures across the United States, Europe, Japan, Korea and India, up to this date.

A similar proposition to Robodoc entered clinical use in Germany a few years later: the Computer Assisted Surgical Planning And Robotics (CASPAR) system active robot (originally from OrtoMaquet[3] and then URS[4]). CASPAR was an industrial PUMA robot adapted for total hip and knee arthroplasty and for anterior cruciate ligament repair. The first robot-assisted knee replacement with this system was performed in March 2000 in the Kassel Orthopaedic Centre, Germany. Whilst Robodoc got a new breadth of life with Curexo, and is still in operation, CASPAR was discontinued in 2004.

In addition to Robodoc, there is one other existing surgical system based on an adapted KUKA industrial robot: the CyberKnife system (Accuray, Sunnyvale, CA, USA). CyberKnife is a radiosurgery robot which uses radiation to treat a tumour whilst minimizing radiation to the adjacent tissues.

Surgical robotic systems based on an industrial active robot or with an autonomous approach make up a *first cohort* of surgical robots. An autonomous approach means that the system will carry out tasks automatically at some stage, without direct intervention of the surgeon.

Other attempts to use an active robot to lock a jig or fixture in position, through which a surgical tool can be inserted by the surgeon, were made. BrainLab (Feldkirchen, Germany) sponsored a $5 m programme to develop Vectorbot, based on an articulated arm developed at DLR, Germany. Zimmer (Warsaw, IN, USA) developed Bone Resection Instrument Guidance by Intelligent Manipulator (BRIGIT). Both programmes were halted before commercialization.

BRIGIT was based on a robot developed by MedTech S.A. (Montpellier, France). MedTech's Intelligent Surgical Instrument Technology, as it was named, was acquired by Zimmer in 2006. BRIGIT was intended to be used for total knee arthroplasty (TKA) and allowed the accurate positioning of a guide according to a patient specific pre-operative plan, which would then be locked in position whilst the surgeon made the surgical bone cuts at precise angles to ensure an accurate match with the prosthetic knee implant. Whilst BRIGIT could be moved by the surgeon grabbing its tip and moving it around, it was not a backdriveable robot. The economic justification for the device was the reduction of instrumentation needed in a procedure and of procedure times. FDA 510(k) clearance was obtained in 2006. BRIGIT was exhibited by Zimmer at various international meetings throughout 2007 as part of their computer-assisted surgery portfolio. Zimmer announced that BRIGIT would be available late 2007, with a price tag of $100k, and $10k per instrument set, and estimated having 200 systems placed by end of 2008. It is not believed the system ever entered clinical use.

BrainLab's Vectorbot was an advanced 7 degrees of freedom (DoF) robotic arm and a compact design with all electronics integrated into the articulated arm [10]. The arm was developed by the German Aerospace Centre (DLR) Institute of Robotics and Mechatronics, in a partnership with BrainLab which started in 2002. Vectorbot was described as an intelligent instrument guide to enable surgeons to reliably align endoscopes, biopsy needles, deep brain stimulation electrodes, catheters, and pedicle screw drills with millimeter precision. It is not believed Vectorbot was ever used clinically.

2.2. Assistive/ collaborative approaches

A *second cohort* of robots relates to assistive or collaborative devices, i.e. robotic devices that are able to move autonomously but are not programmed to do so. Instead, they are programmed to reproduce the surgeon's motions in a master/slave configuration (such as Intuitive's da Vinci and Hansen's Sensei), or in a "hands-on" mode (such as Acrobot's Sculptor and Mako's RIO). The devices in this second cohort all intend to enable MIS.

The da Vinci surgical robot is a master/slave system consisting of a single or dual surgeon's console, a patient-side cart with three or four robotic arms, a visualization system and proprietary instruments. The da Vinci system translates the surgeon's hand, wrist and finger movements at the console instrument controls into corresponding scaled down movements of instruments positioned inside the patient in real time, filtering tremors. The surgeon operates while seated at a console viewing a 3D image of the surgical field. Supporting surgical staff by the side of the patient assist in preparing the entry ports for the instruments in the patient, installing the proper instruments and supervising the laparoscopic arms and tools being utilized.

The system has either three or four robotic arms (two or three instrument arms and one endoscope arm) that execute the surgeon's commands. The arms are inserted through 1–2 cm operating ports in the patient. The surgeon can control the position of the endoscope, and change, move, zoom and rotate the field of vision from the console. The instruments have seven degrees of motion that mimic the dexterity of the human hand and wrist, offering an even greater range of motion. Each instrument has a specific surgical task such as clamping, suturing and tissue manipulation and can be interchanged using a quick-release mechanism. The vision system uses high-resolution 3D endoscope and image processing equipment to provide 3D images of the surgical field. The da Vinci system claims it can provide the surgeon with the intuitive control, range of motion, fine tissue manipulation capability and 3D visualization characteristic of open surgery, while simultaneously allowing the surgeon to work through tiny incisions characteristic of MIS. For some time, it was claimed that loss of touch feedback was an impediment and efforts to develop haptic feedback were attempted.[5] This perceived need seems to have somewhat faded and replaced by improved and more intuitive visualization.

[2] ISS ceased operations in mid-2005 because of lawsuits and lack of funding, and it sold its Robodoc assets to Novatrix Biomedical in 2007. Using those assets, Novatrix set up a new company called Curexo Technology Corporation to continue development of Robodoc, which finally received FDA approval in 2008, and is still sold in Europe, Asia, and other regions.

[3] OrtoMaquet ceased to operate in April 2001.

[4] URS Universal Robot Systems (Rastatt, Germany) suspended technical support of the CASPAR system in July 2003, which led hospitals to discontinue robot-assisted surgical procedures with this system.

[5] Titan Medical Inc. (Toronto, Ontario, Canada), formed in November 2007, announced it is working on a master/slave system, named Amadeus, with flexible instruments, *haptic feedback* and telesurgery operation.

The Sensei robotic catheter system (Hansen Medical Inc., Mountain View, CA, USA) is a master/slave system for interventional cardiology. Hansen was founded in September 2002[6] to develop products and technology using robotics for the accurate positioning, manipulation and stable control of catheters and catheter-based technologies; it raised $75 m in its IPO in November 2006. The Sensei robotic system received FDA clearance in May 2007. Sensei is based on a master/slave control system that enables and visualizes positioning of a steerable catheter tip at a desired point inside the heart. The physician remains seated at a console and away from the x-ray radiation source[7]. Like the da Vinci, Sensei translates the physician's hand movements at the motion controller to the robotically controlled steerable catheter in the patient's anatomy.

Acrobot Sculptor is also a synergistic device but now with a "hands-on" control, first used clinically in June 2001 in a series of seven TKA procedures [11]. The device is a small, low-powered, special purpose robot built for use in a crowded sterile operating theatre environment. The robot is equipped with a milling tool, enabling bone removal (e.g. sculpting) according to a pre-operative plan. The use of a spherical burr allows intricate bone preparation which ultimately can lead to the development of new orthopaedic devices which enable MIS. i.e., more bone conserving joint replacement and joint resurfacing.

Acrobot Sculptor is a spherical manipulator with three orthogonal axes of motion: yaw, pitch, and extension. It has a relatively small reach (around 30 cm) making it inherently safer than an industrial robot. This kinematic structure was adopted so that the mechanical impedance of the axes is low and similar for all axes, allowing the robot to be moved by the surgeon with low force. The surgeon moves the robot by pushing a handle near the tip of the backdriveable robot, in a "hands-on" mode.

Acrobot is an acronym for Active Constraint robot, a type of control where the stiffness of the robot varies according to the position of the tool tip. The robot is free to move when its tip is inside a predefined safe region and gradually increases its stiffness as its tip approaches the boundary of the safe region. At the boundary, the robot becomes very stiff, thus preventing the tool from leaving the safe region. The boundaries are derived from a CT-based pre-operative plan and from the shape of the prosthetic implants. This allows the surgeon to "sculpt" bone "free-hand".

Acrobot Sculptor's accuracy was demonstrated in a regulated clinical trial, in 2004, in a series of 13 patients, this time for the more bone conserving unicompartmental knee arthroplasty [7]. Whilst the 2001 version required the patient to be rigidly clamped and a gross positioning device to place Acrobot Sculptor in position, a recent version has been streamlined and these limitations have been overcome by using mechanical tracking and a remote centre mechanism which provides additional DoF allowing more flexible orientation of the tool tip.

A second "hands-on" device for orthopaedic joint replacement is RIO (Robotic arm Interactive Orthopaedic system) from Mako Surgical (Fort Lauderdale, FL, USA). The original version of RIO, called TGS for tactile guidance system, obtained FDA clearance in May 2005 and was based on a specialised version of the backdriveable WAM arm (Barrett Technology Inc., Cambridge, MA, USA), licensed by Mako. Mako reported that, at the end of 2009, there were 36 RIO systems in operation and 2384 procedures had been performed since the first procedure in June 2006. Mako is commercializing both the robotic device and the implants, in a procedure they have called MAKOplasty.

Orthopaedic implant design has been limited to simple geometric shapes as conventional instrumentation only allows for cuts of simple geometry. With milling burrs such as those used by Acrobot Sculptor and RIO, complex geometry cuts can be produced, paving the way for patient specific, bone conserving, resurfacing implants.

2.3. Small, special purpose surgical robots

The characteristics of a *third cohort* of surgical robots are still to be defined but it is anticipated these intelligent new tools will be smaller, special purpose, lower cost, possibly disposable robots, providing alternatives to the current large, versatile and expensive systems. It is too early to predict which will be winning propositions and a few are reviewed here, to illustrate what the future may bring.

One existing type of small, special purpose robots includes guide positioning devices. The principle is similar to that adopted by Kwoh et al. [5] but in this third cohort, the devices are attached to the patient, eliminating the need for patient immobilisation or motion tracking, which greatly simplifies the robot's registration to the target anatomy.

In 2003, Shoham et al. [12] introduced the concept of a miniature parallel robot for spine and trauma surgery, which is directly mounted on the patient's bony structure near the surgical site to provide support for a drill or needle targeting. To demonstrate this concept, Shoham et al. developed the MiniAture Robot for Surgical procedures (MARS), a cylindrical $5 \times 5 \times 7$ cm^3, 200 g, six degrees of freedom parallel manipulator. The MARS concept is commercialized under the name SpineAssist by Mazor Surgical Technologies, Caesarea, Israel, formed in 2001. SpineAssist was cleared by the FDA in July 2004 and supports a variety of spinal procedures such as pedicle screw insertion, vertebroplasty and kyphoplasty.

Plaskos et al. [13] presented a bone-mounted guide positioning robot, named Praxiteles, to align a cutting guide in image-free TKA, so that the surgeon can perform the planar cuts manually using the guide. The robot architecture is comprised of two motorized DoF whose axes of rotation are arranged in parallel and are precisely aligned to the implant cutting planes with a two DoF adjustment mechanism. It is claimed one version of the device enables MIS TKA. Praxiteles is being developed by Praxim Medivision S.A. (La Tronche, France) and gained FDA approval in June 2008. A modified device renamed iBlock obtained FDA 510(k) approval in January 2010.

A totally different paradigm, yet a small, intended to be disposable, surgical robot is HeartLander, developed at Carnegie Mellon University [14]. HeartLander is a miniature mobile robot that delivers minimally invasive therapy to the surface of the beating heart. The device provides stable and localized sensing, mapping, and treatment over the entire surface of the heart, reducing the damage necessary to access the heart. HeartLander is inserted into the body through a skin incision directly below the sternum. The surgeon then makes another incision in the pericardium and uses forceps to place the robot directly on the heart surface. After the robot attaches itself to the heart using vacuum, the surgeon guides it using a joystick and graphical interface that shows the exact location of the robot on the heart. The real time location is measured using a miniature magnetic tracking sensor located on the front body of the crawling robot. HeartLander has two chambers, each 5 mm tall, 8 mm wide, and

[6] Hansen was co-founded by Frederic Moll, M.D. who has served as the company's CEO since the company's inception. In 1995, Dr. Moll founded Intuitive Surgical Inc., and was the company's first CEO. He is also a director of Mako Surgical since August 2007.

[7] Corindus Inc. (Natick, MA, USA) is developing CorPath, a vascular master/slave robotic system that drives coronary guidewires and stent/balloon catheters for percutaneous coronary inverventions.

10 mm long, and it moves by alternating the application of suction to its two chambers and using a wire transmission that runs through the tether to offboard motors. The crawling robot also contains a 2 mm working port through which tools can be deployed for a variety of epicardial interventions.

While "nano" and "micro" surgical robots that "swim" along the blood stream may remain fantasy for a long time, "mini" devices such as HeartLander which truly enable MIS may be a reality within the next 5 years. There are huge engineering challenges to overcome, such as new methods of propulsion, power supply and power management, sensing and communications but first prototypes are beginning to emerge.

3. Market drivers and roadblocks

Whilst the initial drivers motivating the development of surgical robotics were improved accuracy and shorter procedure times, the main current driver appears to be patient demand. Well informed patients research available treatments for their condition and seek the latest medical technology which can potentially provide them with the best surgical outcome and clinical benefits. In the private sector, healthcare providers may respond to this demand by purchasing the technology and using it to market themselves to patients and even surgeons to increase patient numbers. In the context of a nationalized healthcare system, a stronger case of cost benefit needs to be made and, whilst patient benefit drives adoption, the cost should at least be similar to previous treatments to win the support of decision makers. Reimbursement codes can hamper the introduction of new technology as the added cost of the latter has to be met from the same budget of the current treatments. It is plausible that, as the pressures on a nationalized healthcare system increase, only emergency and critical treatment costs are met whilst patients pay for preventative, early intervention and elective treatments. Surgical robotic manufacturers will have to position their offerings in accordance to their specific customer base.

It is suggested that, in the future, augmenting capabilities and allowing new procedures to be carried out rather than improving procedures which can already be done will enable growth of MIS and provide a drive for the development of new surgical robots. Innovative devices for SILS and NOS are being developed and companies in the MIS industry are acquiring or licensing in these new developments.

Some robotic surgery manufacturers seem to have found, at last, business models which lead to profitability. These involve, in addition to one-off system sales, a recurring income stream from service contracts, instruments and disposables. As an example, the cost associated with a da Vinci system is indicated as $1–2.3m with an annual service agreement of $100–180k, and instruments and accessories of $1.3–2.2k per procedure. To take advantage of a global market, companies tend to generate innovation in the US, obtain regulatory approvals in Europe to enable clinical use and early revenue generation, and then apply for FDA approvals so they can enter the US market and grow their revenues stream.

The computer-assisted surgery field is known as an intellectual property (IP) "minefield". IP disputes have led to consolidation in the past. One significant example is the merger of Computer Motion and Intuitive in 2003, after 2 years of patent disputes. Computer Motion was founded in 1989 and obtained FDA clearance of its Automated Endoscope System for Optional Positioning (AESOP) device in November 1993. AESOP possessed innovative voice-activated control to provide the surgeon with hands-free control of an endoscope. Computer Motion also developed ZEUS master/slave surgical robot, a less dextrous version of Intuitive's da Vinci, with 4 degrees of freedom instead of the 6 degrees of freedom of da Vinci.

Companies such as Intuitive and Mako maintain a portfolio of hundreds of patents and spend considerable sums of money licensing in IP rights. This is a hurdle which newcomers need to negotiate. On one hand, new entrants to the market need to steer clear of potential infringements. On the other hand, they need to protect their IP so that they can establish a solid foundation for product and business development. This requires appropriate levels of funding.

The commercial success of Intuitive is attracting new players. However, Intuitive's success and dominance of the market, and first to market position, also acts as a barrier to entry as their installed base grows and the number of procedures addressed by da Vinci increases, leaving less space for competitors.

Developing surgical robots to a state where they are deployed in the operating room and generate profits requires considerable capital. By the end of the 1990s, Intuitive raised $127m and a further $47m in its 2000 IPO, although it now generates large revenues ($1.05b in 2009, up 20% from 2008). Mako raised $55m in its IPO in February 2008 and a further $60m in private placements from healthcare investment firms in October of the same year and it is still to reach breakeven point. Time to revenues is long and all the current key players in operation raised finances through Initial Public Offerings.

Regulatory approvals are key to progress and commercial success and several companies are now obtaining FDA approvals relatively quickly and easily, using previous cleared devices as predicates of substantial equivalence. In contrast, early entrants in the surgical robotics arena had a long and protracted path to gain FDA clearance. It took ISS 6 years to gain FDA approval of Robodoc. Part of the reason was the difficulty in proving clinical benefits. Showing that the longevity of implants implanted with Robodoc increased naturally implied a long timeframe was needed to assess the veracity of this claim.

Another block to success is the increase in procedure times which can deter surgeons and healthcare providers from adopting novel technologies. Changes to the workflow, for instance the reliance of some robotic systems on a surgical planning stage based on pre-operative imaging, can add additional treatment stages and decrease the throughput of the healthcare system and dilute the business case.

Events in the past have led healthcare providers and purchasers of surgical robotics to become wary of the volatility of surgical robotics companies. Some companies have failed (e.g. OrtoMaquet and URS) forcing clinical use of expensive equipment to stop due to cessation of technical maintenance and support (e.g. CASPAR). Small early-stage companies are perceived as particularly risky, as a large percentage fail, usually because of insufficient funds. In some sectors, for instance in orthopaedic surgery, hospitals had acquired surgical navigation systems[8] and were reluctant to replace that still new technology and investment with newer and more expensive surgical robots which would render the former obsolete.

4. Engineering meets surgical robotics

Robotics in general and surgical robotics in particular are examples of translational research. The original motivation and funding stemmed from research, government grants and defense

[8] Surgical navigation systems are an example of passive computer-assisted surgery comprising a tracking system able to measure the spatial position of surgical instruments and patients and to provide visual feedback to the surgeon who uses this information to orient the instruments.

budgets. For instance, the original prototype for Intuitive Surgical's da Vinci System was developed in the late 1980s at SRI International under contract to the US Army. Initial work was funded to develop a system for performing remote surgery in the battlefield. Intuitive Surgical was founded in 1995 to bring this technology into commercial applications and use it for a range of MIS procedures.

When a new field emerges, it is often not obvious what skill set is needed to better develop the area. Research in surgical robotics involves engineers, scientists and clinicians. Harnessing the research to transform it into medical devices which find application in the operating room requires a systems engineering approach. Engineers working in surgical robotics are likely to have deep core expertise in mechatronics, or in at least two disciplines, such as electrical engineering and computer science, or in electronics and mechanical engineering. The profile of the biomedical engineer is also suited to the surgical robotics development as they are essentially good engineers with an understanding of the human body's anatomy and physiology.

The ability to think across disciplines and to understand tradeoffs and interactions between them is crucial. The experts in electronics need to appreciate and consider the user environment. Will the electronics survive the harsh conditions of instrument sterilization? Will the surgeon favour a powered instrument with a trailing cord or one, most likely heavier but easier to handle, with disposable batteries? The sensors experts must appreciate the impact on communications of embedding sensors in an instrument which is inserted deep into the body and may require custom antenna development to enable communication outside the body.

Human factors is also a fundamental discipline. The surgical robotics development team has to design and build the system in possession of a deep understanding of how the user (the surgeon and the surgical staff) will interact with it. Involving surgeons from the onset of the development is crucial particularly if the adoption of surgical robotics is to move from the first enthusiastic early adopters into widespread use.

In addition to the engineering skills, including computer science, human factors and surgical knowledge, there is a surrounding set of skills needed to bring research into practice: knowledge of regulatory approval pathways, clinical trials and healthcare economics are key pieces to ensure success in the market place.

5. Conclusions

Existing commercial solutions for robotic surgery, such as the da Vinci master/slave robot, are multi-million dollars systems but have nevertheless been commercially successful. Yet the future of surgical robotics may be not only this type of system, but also small, low cost, even disposable, special purpose surgical robots to deliver great value to the healthcare economy. Some of these devices seek inspiration from biomimetics. Biologically inspired devices such as snake-like robots for colonoscopy and wasp-like ovipositor devices to penetrate tissue and, for instance, crawl across the surface of the brain and collect data about it, have been demonstrated in research environments.

What is required from the medical engineer to transform these research visions of the future into surgical instruments of the present? Existing surgical robots are very far from the active strand of research which aims at developing devices the patient can swallow and that can target and treat tissues at a cellular level. This is a departure from current multi-function platform robotics systems, towards low cost, even single use, specific function, micro or nano devices. Whilst patient benefits will drive the long term future of surgical technology, healthcare economics and technology advances will play a major role in short to medium term developments.

It seems feasible that major surgery may one day be performed without skin incisions, using natural orifices as entry points for the surgical intervention. This could be the holy grail of true keyhole surgery which today still involves skin incisions albeit small. Multidisciplinary teams are needed to develop the tools and methods required to ensure safe procedures, as unforeseen complications, additional to those which may arise from open surgery and are understood by the medical community, may develop. Before surgical robotics matures, there is a lot of work to be done.

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