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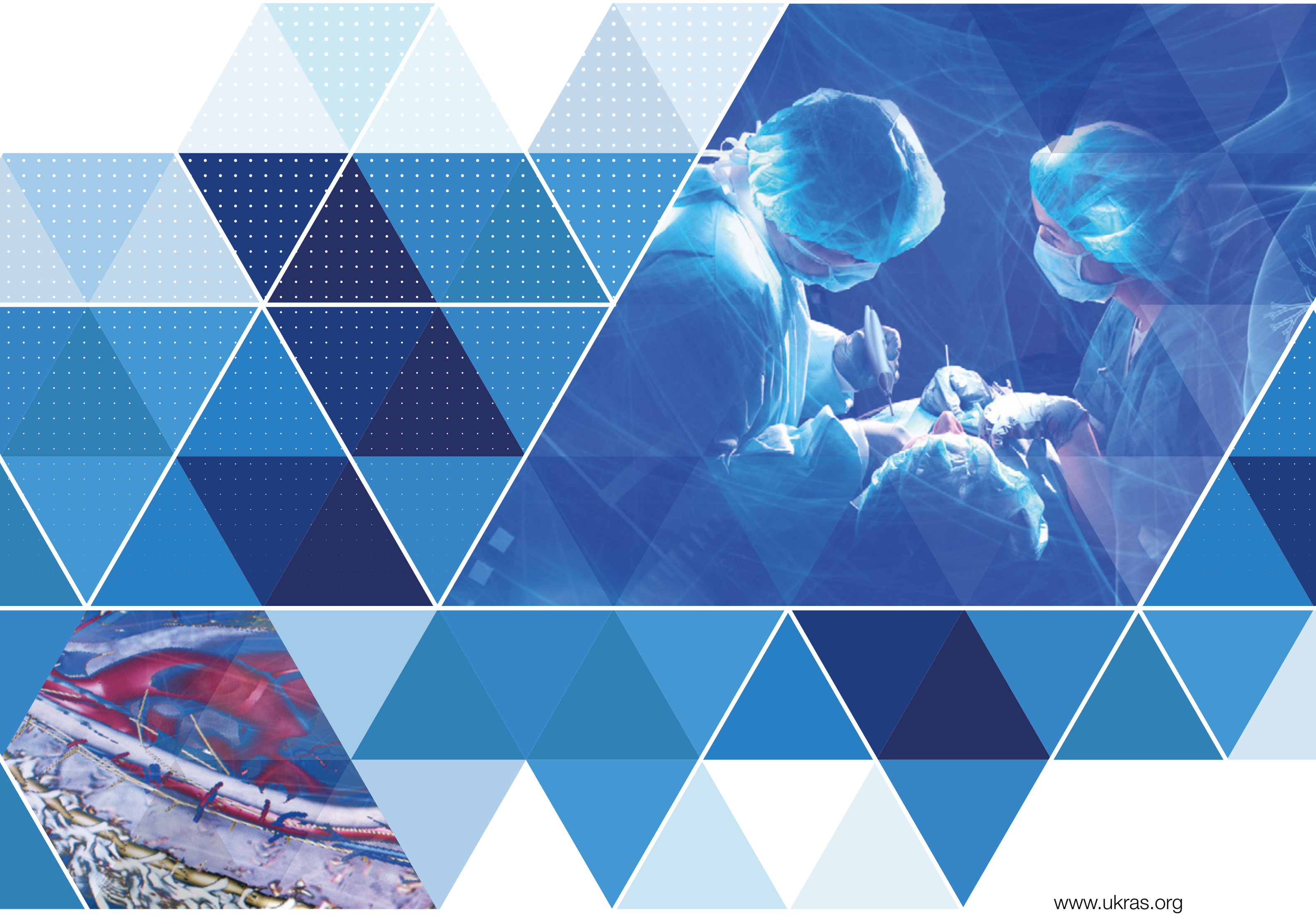
Surgical Robotics:
The Next 25 Years
Successes, Challenges, and the Road Ahead



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FOREWORD

SURGICAL ROBOTICS

Welcome to the UK-RAS White Paper Series on Robotics and Autonomous Systems (RAS). This is one of the core activities of UK-RAS Network, funded by the Engineering and Physical Sciences Research Council (EPSRC). By bringing together academic centres of excellence, industry, government, funding bodies and charities, the Network provides academic leadership, expands collaboration with industry while integrating and coordinating activities at the EPSRC funded RAS capital facilities, Centres for Doctoral Training and partner universities.

Medical robots, whether used for minimally invasive surgery, targeted therapy, emergency response, prosthetics or home assistance, represent one of the fastest growing sectors in the medical devices industry. One of the key areas of medical robotics is the development of surgical robots for minimally invasive surgery and microsurgery. In this paper, we look back through the last 25 years at how surgical robotics has evolved from a niche research field to a major area of innovation and development. With improved safety, efficacy and reduced costs, robotic platforms will soon approach a tipping point, moving beyond early adopters to become part of the mainstream surgical practice. These platforms will also drive the future of precision surgery, with a greater focus on early intervention and quality of life after treatment. We also project forward, on how this relatively young yet rapidly expanding field may reshape the future of medicine, as well as the associated technical, commercial, regulatory, and economic challenges that need to be overcome.

The UK-RAS white papers are intended to serve as a basis for discussing the future technological roadmaps, engaging the wider community and stakeholders, as well as policy makers in assessing the potential social, economic and ethical/legal impact of RAS. It is our plan to provide annual updates for these white papers so your feedback is essential - whether it be pointing out inadvertent omission of specific areas of development that need to be covered, or major future trends that deserve further debate and in-depth analysis.

Please direct all your feedback to white-paper@ukras.org. We look forward to hearing from you!

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on behalf of the UK-RAS Network, established to provide academic leadership, expand collaboration with industry while integrating and coordinating activities at EPSRC funded RAS capital facilities, Centres for Doctoral Training and partner universities.

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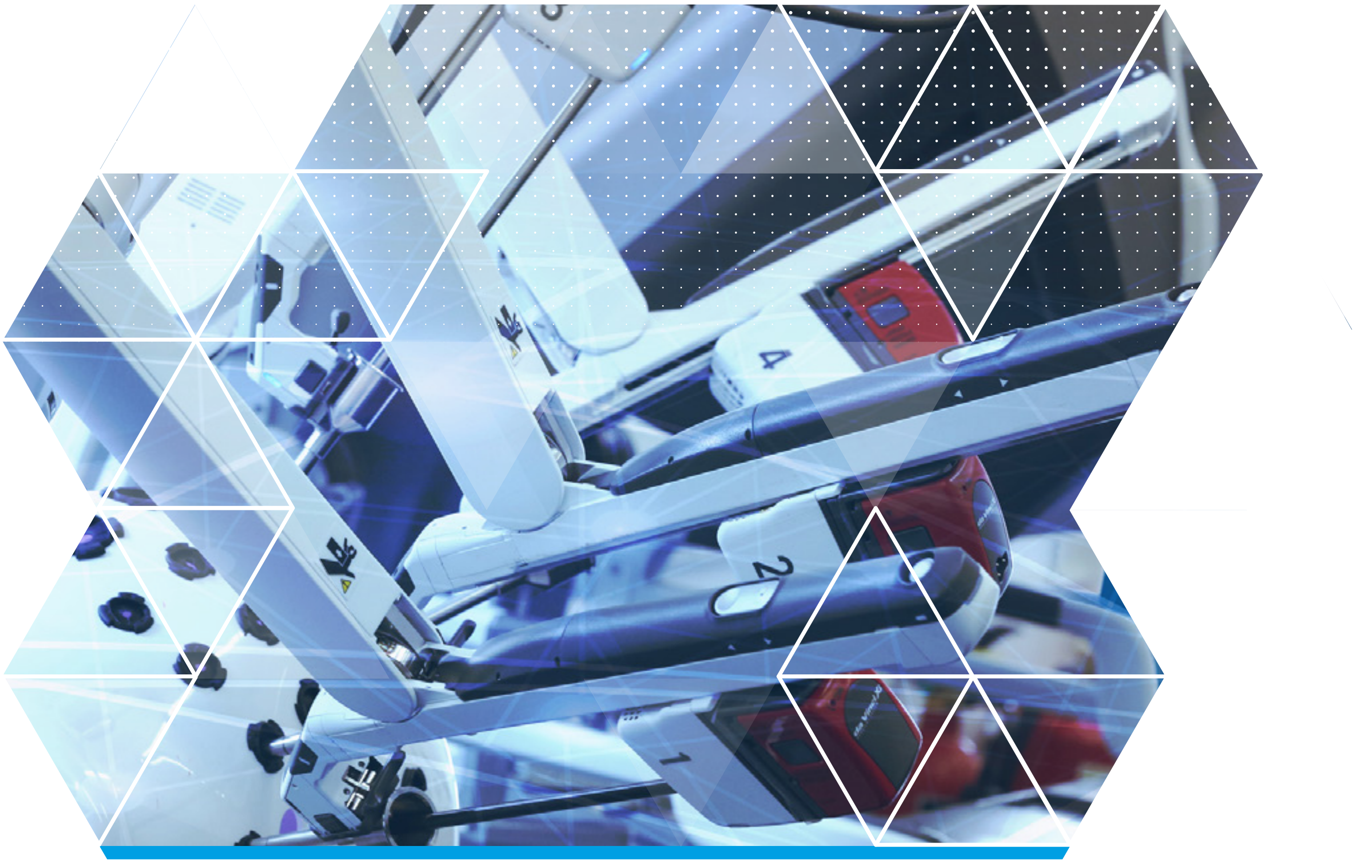


Surgical robotics has evolved from a niche research field 25 years ago to a burgeoning area of innovation and development, spearheading evolution in precision medicine, personalised healthcare, and quality-of-life improvements. The commercial success of the first generation clinical robotic systems has inspired an ever-increasing number of platforms from both commercial and research organisations, resulting in smaller, safer, and smarter devices that aspire to roam the human body and blur the lines of disease prediction and prevention. For such endeavours to be clinically successful, challenges relating to not only research, but also regulation, intellectual property protection, and potential litigation need to be addressed.

FROM RESEARCH TO PATIENTS:

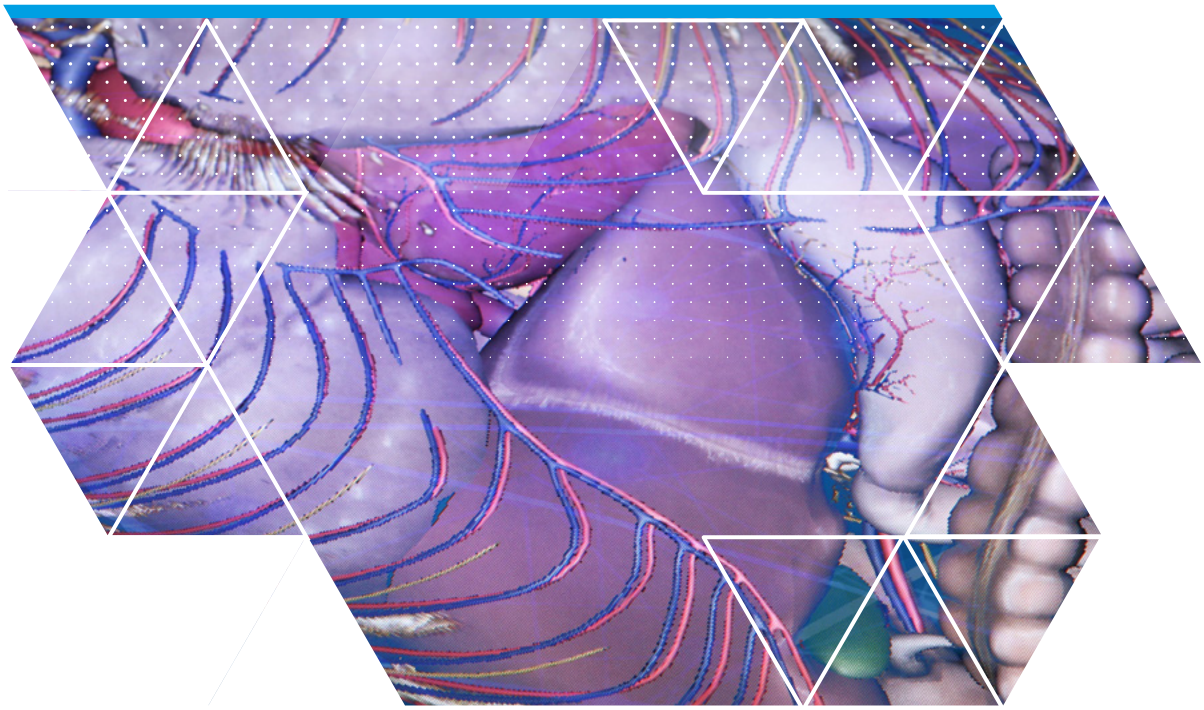
PIONEERS AND EARLY ADOPTERS

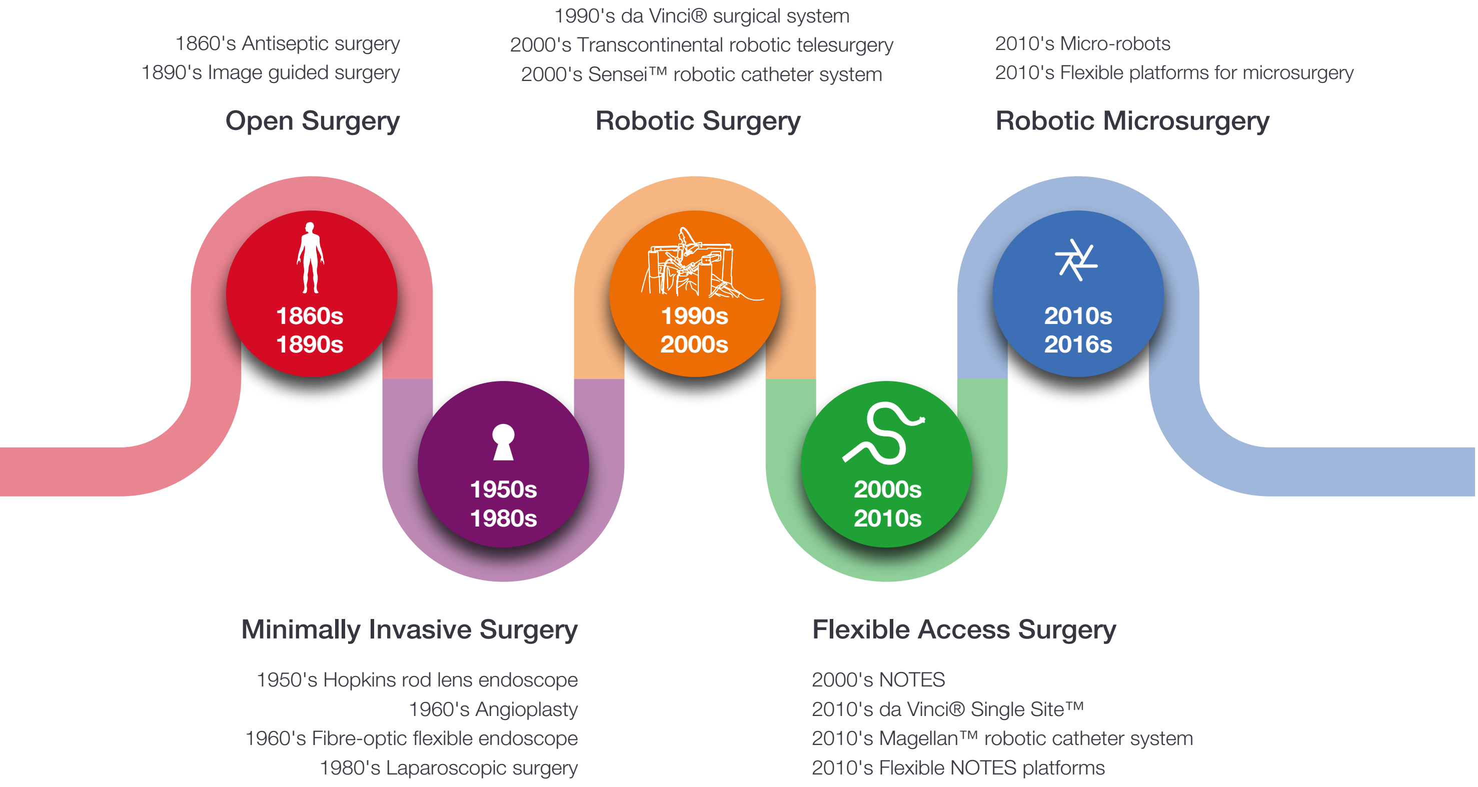
It was just over 25 years ago that researchers first attempted to improve surgical outcome by using robotic technology, which had been slowly gaining acceptance as a powerful tool for precise automation. Indeed, the first surgical robot was a lightly customised industrial manipulator that was re-purposed to direct a needle into the brain [Kwoh et al., 1988].

Early ventures
The first well-known surgical robots, ROBODOC® [Kazanzides et al., 1992] and Acrobot [Davies et al., 1997] for orthopaedic surgery, and Probot [Harris et al., 1997] for prostate surgery, initiated from similar design considerations prior to evolving into customised surgical platforms. ROBODOC® was developed in the United States by Taylor et al., while Probot and Acrobot were developed in the United Kingdom by Davies et al. Our vignettes illustrate the parallel but different stories of Acrobot and ROBODOC®, despite both systems being contemporary and developed in countries of similar economic and social backgrounds. These efforts led to a multitude of academic centres and research institutions undertaking research in the field of surgical robotics.

The story of ROBODOC®

Initial research on ROBODOC® began through collaboration of University of California, Davis, and IBM Thomas J. Watson Centre. First clinical trials took place in 1992. Commercialisation of ROBODOC® begun in Europe already in 1994, but the robot was withdrawn from the market. In 2007, Korean Curexo acquired ROBODOC® and completed clinical trials in the United States. ROBODOC® obtained FDA clearance in 2008, and is currently used as a branded system worldwide.





1860's Antiseptic surgery
1890's Image guided surgery

Open Surgery

1990's da Vinci® surgical system
2000's Transcontinental robotic telesurgery
2000's Sensei™ robotic catheter system

Robotic Surgery

2010's Micro-robots
2010's Flexible platforms for microsurgery

Robotic Microsurgery

Minimally Invasive Surgery

1950's Hopkins rod lens endoscope
1960's Angioplasty
1960's Fibre-optic flexible endoscope
1980's Laparoscopic surgery

Flexible Access Surgery

2000's NOTES
2010's da Vinci® Single Site™
2010's Magellan™ robotic catheter system
2010's Flexible NOTES platforms

FIGURE 1.

Fig. 1: Timeline of surgical technology development (adapted from [Vitiello et al., 2013]).

The story of Acrobot

The development of Acrobot (Active Constraint Robot) by Dr Brian Davies at Imperial College London started in 1992. In 2000, Dr Davies founded Acrobot Ltd as a spin-off company with the help of Imperial Innovations. The first clinical trials took place in 2001, with the first randomised trial in 2006. The company was then acquired by Stanmore Implants Worldwide (SIW) in 2010. In 2011, SIW obtained a 510K license to use the Acrobot robot in the USA. Shortly after, Mako Surgical bought all the Acrobot patents and technology. Finally, in 2013 Stryker Medical acquired Mako.

Minimally invasive surgery

In parallel to the pioneering integration of robotics in orthopaedics and neurosurgery, Hopkins' rod lens transformed the early developments of laparoscopic surgery. However, these procedures are ergonomically difficult to perform due to the use of long, rigid instruments, coupled with the fulcrum effect and misalignment of visual-motor axes (see Fig 1). Augmentation of surgical skills was thus sought in robotics, building on the early research on tele-manipulation, millimetre-scale tendon-driven wrists, and hardware-based remote centres of motion (RCM) resulted in two innovative platforms: the Zeus by Computer Motion [Ghodoussi et al., 2002], and the da Vinci® from Intuitive Surgical [Guthart and Salisbury, 2000].

The first version of the da Vinci® and Zeus tele-operated systems featured a surgeon master console and a patient slave manipulator with three arms, two for tissue manipulation and one for endoscopic camera positioning. Each arm could provide 6 degrees-of-freedom plus the instrument actuation, while respecting the RCM constraint at the tool entry point on the patient skin. A key difference between the two robots was the use of voice control commands to actuate the camera arm of the Zeus, also known as the AESOP (Automated Endoscopic System for Optimal Positioning) robotic system.

The Zeus system was used to perform the first transatlantic telesurgery between Manhattan, New York, USA and Strasbourg, France [Marescaux et al., 2001], but is no longer in production since the merging of Computer Motion with Intuitive Surgical in 2003. On the other hand, the da Vinci® system quickly expanded in the United States and eventually became a global market leader (see Fig. 2).

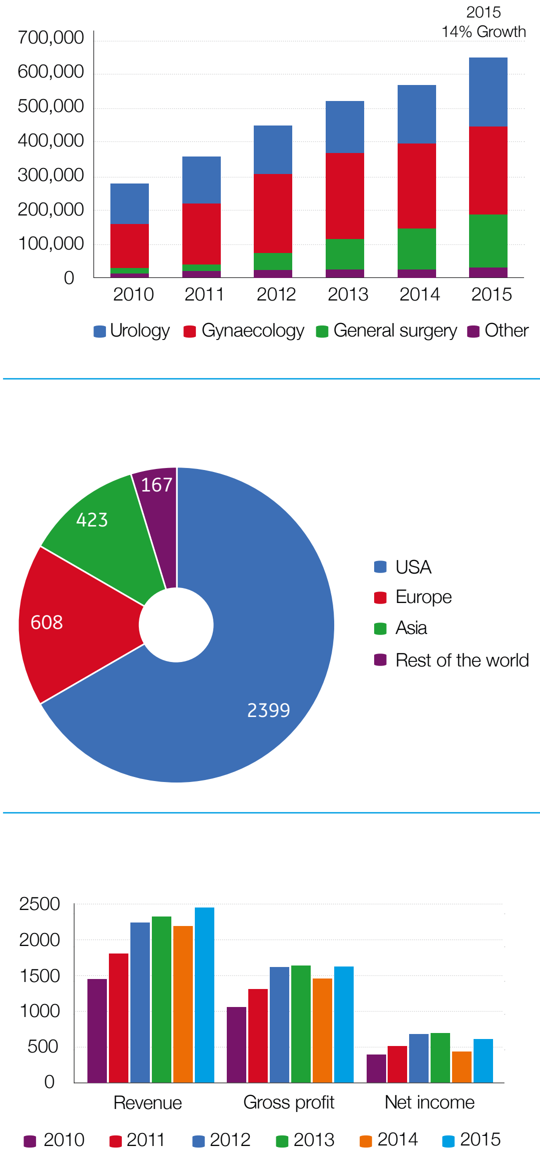


FIGURE 2:

Surgical procedures conducted by the da Vinci® worldwide (TOP), number of systems sold as of 31st of December 2015 (MIDDLE) and company financial data in million dollars (BOTTOM) (data from the Intuitive Surgical 2015 Annual Report, available at www.intuitivesurgical.com).

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THE STORY OF ZEUS

In 1989, Yulun Wang founded his medical robotics company Computer Motion with funding from the U.S. government and private sources. The robotic system he developed for NASA as a graduate student at the University of California Santa Barbara became the seed for the AESOP, which was FDA approved for use in 1994. In October 2001, the FDA also cleared the ZEUS surgical system, just a few months after the da Vinci®. In 2002, competition between Intuitive Surgical and Computer Motion began to mount fiercely, as the market became ready to embrace surgical robotic technology. After some complicated IP disputes, on March 7, 2003 the two companies announced that "they are merging into one company that combines their strengths in operative surgical robotics, telesurgery, and operating room integration, to better serve hospitals, doctors and patients."After the merger, the Zeus was discontinued.

Recent innovations

Following the success of da Vinci®, research and development by academia and start-ups intensified. Flexible snake-like and microrobotic platforms are emerging and are expected to further improve surgical outcomes and blur the boundaries between prevention and intervention [Vitiello et al., 2013; Bergeles and Yang, 2014].

The next 25 years

Surgical robotics is acknowledged worldwide as a technological field primed for investment, where major breakthroughs are expected. The future will be defined by developments in two disparate yet interconnected settings: the research front and commercial organisations. Research and development within academic institutions is expected to intensify and innovative solutions for patient benefit will continue to appear. On the other hand, economic sustainability and societal demand require a revisit of institutional pillars that govern clinical translation. After all, despite the staggering amount of work, very few systems have seen clinical translation, and the penetration of robotic surgery and systems has been inhomogeneous.

Leveraging insights from the past developments and current situation, this paper attempts to lay out the challenges that need to be addressed to further support clinical translation of surgical robot technology, currently a worldwide phenomenon (see Fig.3).

FIGURE 3:

Example surgical robotics companies worldwide: Americas (left), Europe and Middle East (middle), Asia (right) (data from www.therobotreport.com, www.allaboutroboticsurgery.com and www.surgrob.blogspot.com).

REGULATORY CHALLENGES:

CONSISTENT REGULATIONS AND PATIENT EMPOWERING

Unified directives in a common market
Robotic surgery affects more and more patients and disrupts the healthcare system. Contrary to industrial robotics that could be seen as an insular research-and-development area confined to product making, the proximity of surgical robotics to the human invoked serious regulatory intervention from the field's onset.

The Food and Drug Administration (FDA, USA), undertook regulatory measures for medical devices already in 1976, establishing the fundamental concepts of safe operation of devices that interact directly with the human body. In 1984, the United States Congress decided the support of healthcare robotics [Engelhardt et al., 1986].

The top-down guidelines by the Congress and FDA untapped the huge economically profitable market of the United States, with all interested parties being aware that health regulations and economic opportunities span the entirety of the national market. This granted stability to United States' based companies and the possibility to expand to a large wealthy market without unexpected hurdles.

In comparison, early endeavours in the United Kingdom, and Europe in general, were not able to capitalise on such a streamlining. The European Union (EU) has only recently regulated the medical device sector among its member states, and only in the past two decades has the notion of a single market become a reality. Early pioneering work on surgical robotics could not attract the significant investment required also due to a lack of potential market.

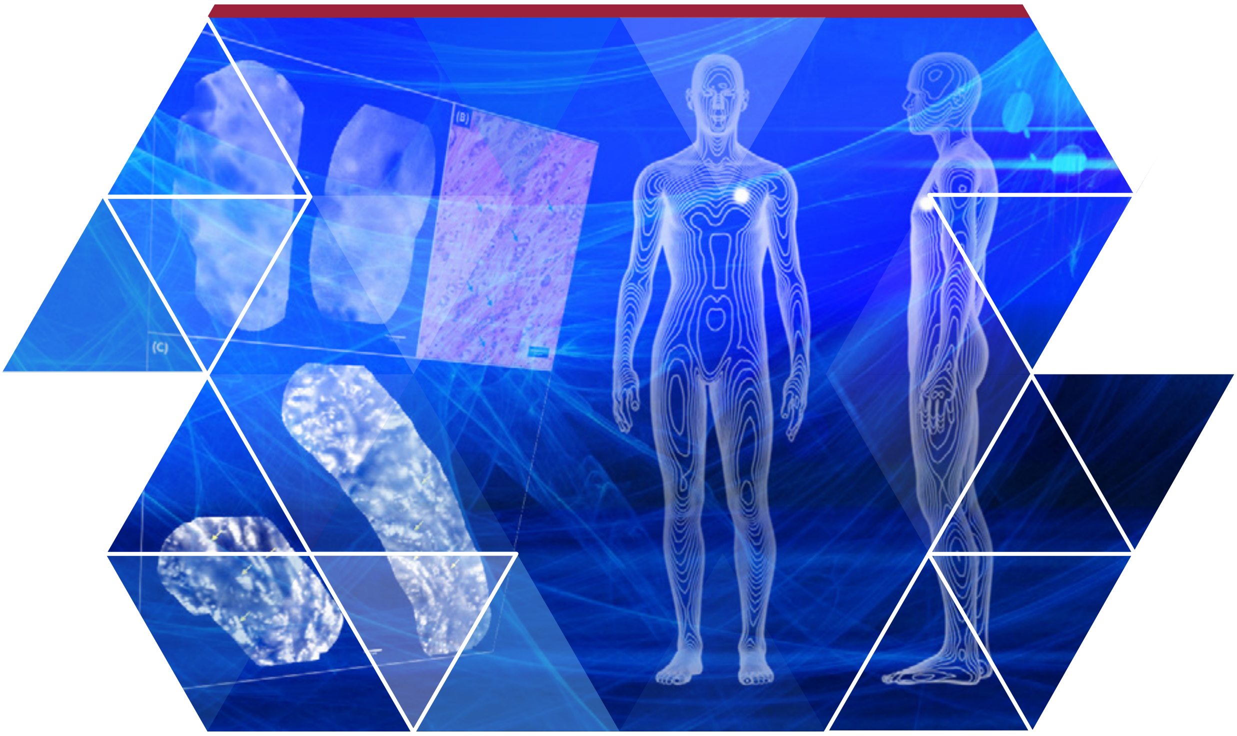
With the United Kingdom’s position within the EU under negotiation, the loss of a common regulatory framework and wealthy market may disrupt capital-intensive large-scale research and innovation.

Power-to-the-patients

Innovation in surgical robotics is in several aspects close to undertakings of the pharmaceutical industry. Hence, even though the previous subsection raised the issue of consistent regulatory standards among the expanding market, it is important to also understand that for research and development to be fruitful, a certain amount of deregulation is required.

Patients should be informed of robotic system developments and be empowered to lobby and share the risks and benefits of robotic surgical systems that are currently under development. The burden of clinical approval is huge, both time-wise and financially, and the ease of access to surgical robots that may be beneficial should be encouraged. This is particularly true for future robotic systems that will entail smart untethered microrobots that directly target cancer cells – making them closer to drugs than robots.

There are lessons to be learned here from the HIV deregulation that successfully sped up innovation in the United States in the early 1990s. Caution should be advised, however, not to succumb to libertarian anti-regulatory sentiments that may put public health at risk [Perrone, 2014]. Europe and the United States could draw lessons from Japan, which has successfully implemented regulations on a similar scope.



ECONOMIC CHALLENGES:

ROBOTIC SURGERY AND HEALTH ECONOMICS

The effect of the healthcare system

It is widely accepted that the healthcare systems of the United Kingdom/Europe and the United States have several differences, broadly summarised in the public orientation of the former, versus the private approach of the latter. This differentiation exposes robotic systems to different stakeholders, which affected the early adoption of robotic systems.

For example, wealthy private hospitals in the United States were able to acquire the da Vinci® robot primarily to showcase their technological proficiency. This drove early adoption and increased demand for the robot by hospitals first, and patients second. The cost of using the robot, further, could be offloaded directly to the patients or insurance companies through increased hospitalisation and surgical fees.

In contrast, such an approach was more complex to implement within the National Health Service (NHS) structure in United Kingdom. In public-funded NHS, the cost could not be offloaded to the patients but would have to be funded from the national budget. Hence, early adoption in such government-regulated health-related domain is much more challenging.

The effect on healthcare economics

Several studies have demonstrated that skilled laparoscopic surgeons are able to deliver outcomes on par with what is achievable via robotic surgery. Rather than making proficient surgeons better, one could argue that robotic surgery would improve the overall consistency, safety, and quality. It would also make long procedures less strenuous. Any improvements, however, come at the expense of the significant capital cost of the robot, and the recurring cost of the tools and maintenance, stressing the already fiscally unsustainable healthcare systems.

The cost-effectiveness of robotic surgery, with the da Vinci® as the case study, has been discussed in several recent investigations. Studies also indicate how the cost of such a system and its usage can be further reduced [Freschi et al., 2014]. It is understandable for research intensive development such as the surgical robots, the need to return, progressively, the significant initial investment made in early years. We argue that it is premature to evaluate the cost-effectiveness of novel robotic systems so early in their adoption phase. Most studies assessing the financial burden of robotic surgery have only access to data from interventions conducted with earlier generation robotic systems while for a fairer comparison we should probably wait until more systems have been adopted and experience has been gained.

Moreover, it should be understandable that early adoption is more costly – this example has been recurring with technological breakthroughs throughout history, from telephones to cars to personal computers. Costs are driven down as competitors enter the market and the technology matures.

High-entry level cost

Another challenge that innovation in surgical robotics faces is the extremely high cost of entry in the field. This applies particularly to academic institutions that need to be backed through grant funding, but could also be seen as negatively impacting start-up companies that need to attract a significant amount of seed investment. Successful research and development of surgical robots, not even accounting for regulatory overheads, amounts to several millions. Such levels of funding are unattainable for entry-level researchers, particularly under the current economic climate. We need national centres of excellence to embed talented researchers to establish a critical mass and more importantly a vibrant eco-system linking academia and industry, for addressing some of the major challenges in surgical robotics.

This issue is analogous to the high cost (time-wise) of software development for robotics, which has been largely disrupted by the Robotics Operating System (ROS). ROS (www.ros.org) allows reuse of code and modularity to a degree previously unprecedented, and is removing the cost-to-entry for several research projects.

A similar approach is required for hardware, and this need has started to be addressed through the da Vinci® Research Kit and the RAVEN™ platform. In essence, however, these are complete hardware systems, whereas what the academic community would really benefit from is reusable and modular compact hardware components and open source hardware platforms. Existing endeavours such as OpenBionics (www.openbionics.org) and Yale OpenHand (www.eng.yale.edu/grablab/openhand) for rehabilitation and bionics should be encouraged and looked upon for inspiration.

INTELLECTUAL PROPERTY

PATENTING VS OPEN INVENTION

One important aspect to consider when discussing intellectual property (IP) rights is the wealth of industrial patents that are unrealised or unrealisable. The patentscape is slowly morphing into a collection of proposed systems and mechanisms that are not intended for realisation. This dilutes the meaning of “invention protection”, and poses risks to future businesses by essentially creating a “patent minefield” that may hinder capitalisation of innovation.

The academic vs. industrial approach

The importance of IP protection is exemplified by the different routes that Robodoc and Acrobot have taken. As our featured stories demonstrate, Robodoc has found its market through Curexo Technologies, whereas Acrobot has seen a series of takeovers. While there are multiple factors behind this, in his recent opinion paper [Davies, 2015], Dr. Davies raises limited intellectual property protection as one of the main reasons.

One may argue that this case demonstrates fundamental differences between IP protection in academia and industry. The limited funds that academia possesses for patents, together with a rigidity in licensing patents to new start-up companies, can be a reason behind the lack of patents and the raised risk that Acrobot faced. Robodoc, on the other hand, having the support of a patent-oriented company, ended up being much more protected against competition. Thus, aggressive patenting seems like a prerequisite for successful commercialisation.

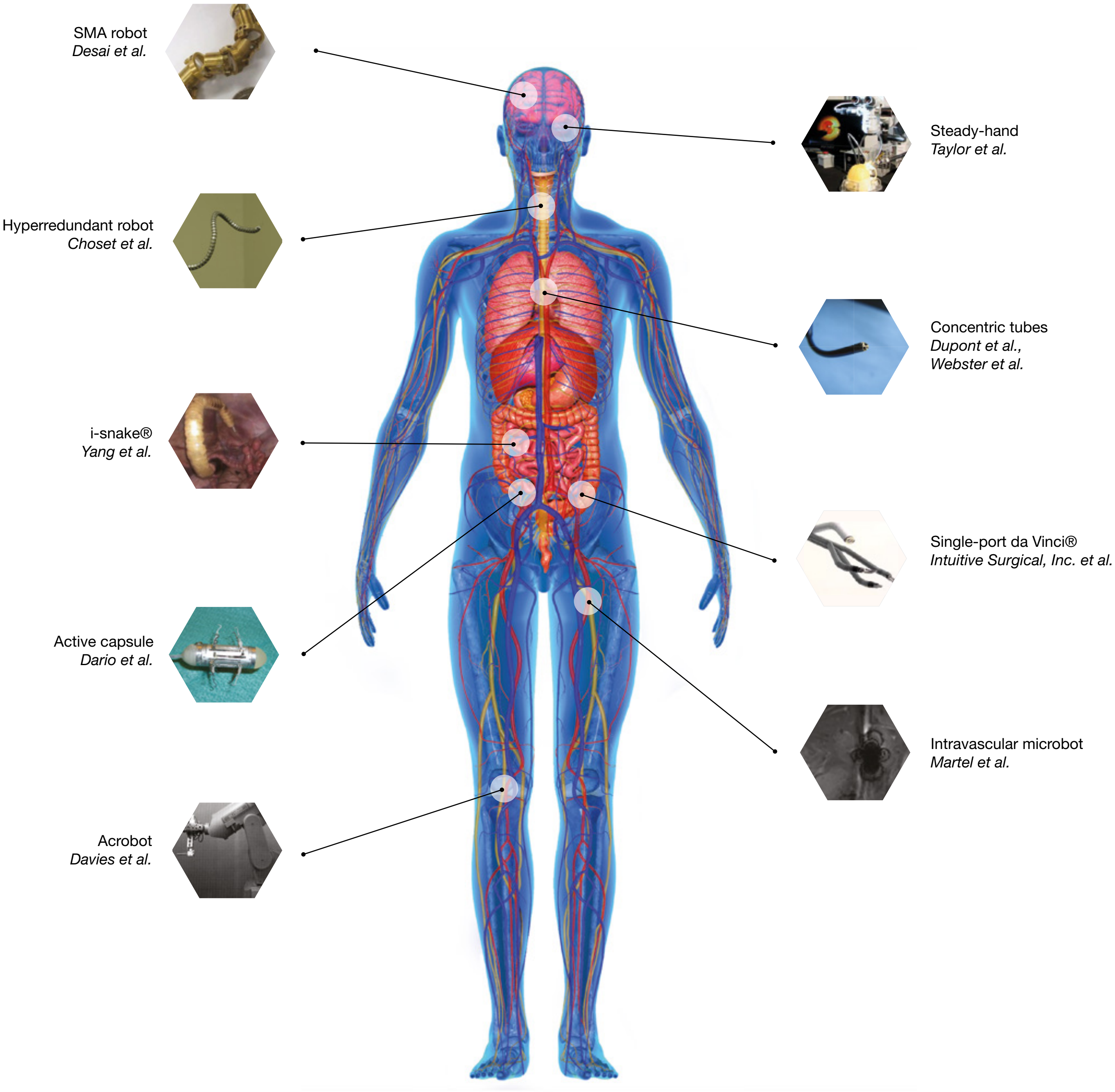


FIGURE 4:

Examples of surgical robot specialisation (adapted from [Bergeles et al., 2014]).

FUTURE SURGICAL ROBOTS:

BLURRING PREVENTION AND TREATMENT

Smaller, smarter, safer devices
Surgical robotics research is evolving towards the development of platforms for performing specific parts of the surgical workflow when robotic assistance is required, rather than following the more “traditional” approach of using a fully-fledged system to cover an entire surgical procedure (see Fig. 4). This follows the general trend of surgical robotics - in future less likely will we see the development of ever larger and more expensive platforms as we become more rational about the general access of technology for the population at large, the cost-effectiveness of these systems, and the tangible clinical benefit of robotic assistance.

Future clinical attention will likely be paid to the development of smart, miniaturised, mechatronically enhanced or robotically assisted surgical instruments. Such smart instruments will be integrated with advanced imaging and sensing techniques, combined with instrumentation passed through the device for performing early diagnosis and interventions.

Augmented vision, perception and control
Computer-assistance has been developing alongside mechatronic advances in surgical robotics to improve the surgeon’s experience by providing immersive visualisation, stereoscopic high-definition images and intraoperative feedback through different perceptual channels. The senses of vision and touch, which are severely affected by the laparoscopic approach, are now returned to the minimally invasive surgeon in an augmented fashion, resulting in safer and more accurate procedures.

Augmented reality techniques in combination with haptic feedback and active constraints (or virtual fixtures) are transforming surgical guidance into perceptually-enabled cooperative control, where the surgeon and the robot effectively share command of the tool. As computational resources become more powerful, the fusion of information from a plethora of sensors makes the robot more and more aware of the surgical environment and can potentially allow the surgeon to take full advantage of robotic-assistance by letting the robot perform autonomously high-accuracy repetitive sub-tasks under supervision.

Cellular-level intervention
Future surgical robots will interact with pathology sites at microscopic levels, either to perform surgery through miniature end-effectors, or as untethered agents that locally deliver highly concentrated drugs without system side effects. As robot development advances towards the micro and nanoscale, clinicians, engineers, and molecular biologists will have to join forces and combine their domain specific knowledge to operate at these scales, employing, for example, biomarkers to assist in robot targeting and electromagnetic energy absorption. Robot development will combine mechatronics, physics, and chemistry potentially to assist the immune system in identifying and fighting tumours.

Non-invasive approaches
Non-invasive electromagnetic radiation therapies such as focused ultrasound or proton beams may disrupt the surgical robotics market even before this market has been established. Further competitive solutions may arrive from the pharmaceutics field, with antibody-based tumour targeting methods. As a result, it is important that surgical robots seek to establish their area also outside of “traditional” tumour resection, as, for example, in reconstructive neuron surgery for paraplegia, and prosthetic limb implantation.

Many countries worldwide have realised the anthropocentric potential of surgical robotics and the centralised support that innovation requires, and have laid down roadmaps for research and development, accompanied by commitments for significant financial support. In the following, we examine and compare two existing roadmaps.

ROADMAPS FOR THE FUTURE:

SHAPING RESEARCH AND TRANSLATION

The dichotomy between US and UK approaches to surgical robotics research is clearly represented by the respective recently published roadmap documents. While US recommendations aim at tackling the technical challenges that still limit the capabilities of commercial surgical robots, as, for example, tactile sensing, better immersion of the surgeon, detailed anatomical roadmaps, and navigation in confined spaces, the guidelines from UK are fundamentally market-driven with a focus on cost effectiveness and regulatory standards. Notably, the European Union approach strives to address both research and translational issues by promoting academic and industrial collaborations and leading innovative research to technology transfer.

We believe that the latter is the most favourable attitude for shaping the future of surgical robotics and encouraging clinical translation of promising technology. After all, as already discussed, without significant governmental seed funding, several of the innovations that sparked the surgical robotics revolution would not have been possible.

Nonetheless, the number of issues that have been identified pertaining to institutional complexities need to be addressed.

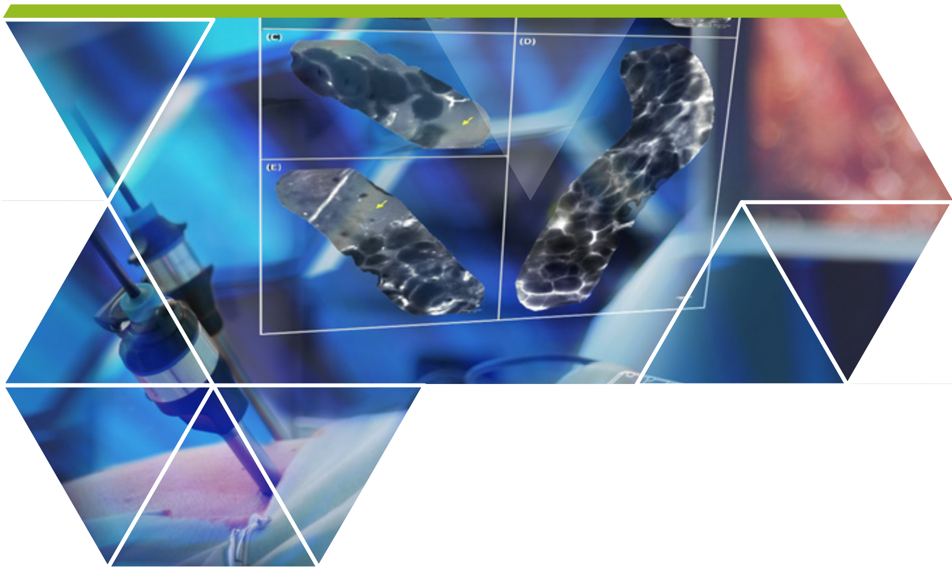
Tackling research challenges
As highlighted above, the main factors influencing the successful integration of robotics research in surgical practice are arguably high costs, a lack of institutional coordination and the absence of modular, open-source hardware platforms.

Research funds are limited and often insufficient to ensure the prototype robustness necessary for safe deployment of novel technologies into the operating theatre. Understandably, entrepreneurs are reluctant to invest large capital sums into the commercialization of early stage prototypes. Recent EU funding schemes such as the Horizon 2020 are attempting to address this issue by encouraging collaboration of academic and industrial partners at the early stage of project proposal.

Overcoming translational barriers
Regulatory standards and IP protection are core elements of the UK roadmap, which are also considered crucial for successful technology transfer by the European Union. However, the lack of a standardised framework for surgical robot benchmarking remains a major hurdle in the creation of an open worldwide market. Regulatory bodies should work together towards a common agenda for robotic surgery based on clinical evidence and patient benefits.

One crucial point of such agenda should be the identification of appropriate economic and clinical comparators. As an example, robotic-assisted procedures are usually compared to the corresponding laparoscopic approach, which in some markets still has limited adoption for certain procedures. In such cases, robotic technology has the potential to make the minimally invasive approach more accessible, thus making open surgery a better comparator.

Finally, surgical expertise plays a crucial role in obtaining a fair comparison between robotic-assisted and traditional surgery. Educational portfolios are just starting to include robotics as part of standard training for surgeons and learning curves can vary according to the version of the robotic system used. Standardization of surgical training programs thus becomes fundamental for generating a cohort of expert robotic surgeons that could validate the benefits of robotic-assistance in the surgical theatre of the future.



CONCLUSIONS

In the past 25 years surgical robotics has evolved from a specialised field to a worldwide phenomenon of technological innovation. Initial systems were complex, high in cost and with a large footprint in the operative theatre. Nowadays research focus is moving to simpler, low-cost, sensor-rich devices designed for a few specific applications. In the next 25 years, it is envisioned that robotic surgery will become more clinically relevant, but only if cost-effectiveness and tangible clinical benefits are demonstrated. On this basis, surgical robots for tumour resection may actually be disrupted by targeted therapies and early intervention. Most importantly, tackling issues such as regulatory standards and IP protection will play a crucial role in the successful clinical translation of robotic technology.

REFERENCES

Bergeles C., and G.-Z. Yang, “From passive tool holders to microsurgeons: safer, smaller, smarter surgical robots,” IEEE Trans. Biomed. Eng., vol. 61, no. 5, pp. 1565-1576, 2014.

Davies B. L., W. J. Lin and R. D. Hibberd, “Active compliance in robotic surgery – the use of force control as a dynamic constraint,” Proc Inst Mech Eng H J Eng Med, vol. 211, pp. 285–292, 1997.

Davies B. L., “Robotic surgery – a personal view of the past, present, and future,” Int. J. Adv. Robot. Syst., vol. 15, no. 54, pp. 1-6, 2015.

Engelhardt K. G., “Current status and future prospect for robotic technology in health care delivery,” Centr. Nerv. Syst. Trauma, vol. 3, no. 1, pp. 111–126, 1986.

Freschi C., V. Ferrari, F. Melf, M. Ferrari, F. Mosca, and A. Cuschieri, “Technical review of the da Vinci surgical telemanipulator,” Int. J. Med. Robot. Comp., vol. 9, no. 4, pp 396–406, 2013.

Ghodoussi, M., S. E. Butner, Y. Wang, "Robotic surgery - the transatlantic case," IEEE International Conference on Robotics and Automation, vol.2, pp.1882-1888, 2002.

Guthart G. S. and J. K. Salisbury Jr., “The IntuitiveTM telesurgery system: overview and application,” IEEE International Conference on Robotics and Automation, pp. 618–621, 2000.

Harris S. J., F. Arambula-Cosio, Q. Mei, R. D. Hibberd, B. L. Davies, J. E. A. Wickham, M. S. Nathan and B. Kundu, “The Probot – an active robot for prostate resection,” Proc Inst Mech Eng H: J Eng Med, vol. 211, pp. 317–325, 1997.

Kazanzides P., J. Zuhars, B. Mittelstadt, B. Williamson, P. Cain, F. Smith, L. Rose and B. Musits, “Architecture of a surgical robot,” IEEE International Conference on Systems, Man and Cybernetics, pp. 1624–1629, 1992.

Kwoh Y. S., J. Hou, E. A. Jonckheere, and S. Hayati, “A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery,” IEEE Trans. Biomed. Eng., vol. 35, no. 2, pp. 153–160, Feb. 1988.

Marescaux J., J. Leroy, M. Gagner, F. Rubino, D. Mutter, M. Vix, S. E. Butner and M. K. Smith, “Transatlantic robot-assisted telesurgery,” Nature, vol. 413, pp. 379–380, 2001.

Perrone M., “AIDS activist now fights for FDA,” Associated Press, August 11th 2014.

Vitiello V., S.-L. Lee, T. P. Cundy and G.-Z. Yang, “Emerging robotic platforms for minimally invasive surgery,” IEEE Rev. Biomed. Eng., vol. 6, pp. 111-126, 2013.

APPENDIX A

Table 1. Companies with commercial platforms for robotic surgery.

Company Name	Clinical Application	Reference
Accuray	Proton therapy	www.accuray.com
Aeon Scientific	Vascular surgery	www.aeon-scientific.com
Alf-X by Sofar	Laparoscopy	www.alf-x.com
Applied Dexterity	Laparoscopy	www.applieddexterity.com
Auris Surgical Robotics	Laparoscopy	www.aurisrobotics.com
AVRA Surgical Robotics	Laparoscopy	www.avrasurgicalrobotics.com
Biobot Surgical	Laparoscopy	www.biobotsurgical.com
Blue Belt	Orthopedics	www.bluebelttech.com
Cambridge Medical Robotics	Laparoscopy	www.cmedrobotics.com
Catheter Robotics	Vascular surgery	www.catheterrobotics.com
Corindus Vascular Robotics	Vascular surgery	www.corindus.com
Covidien Surgical	Laparoscopy	www.covidien.com/covidien
Curexo Technologies	Orthopedics	www.thinksurgical.com
CyberHeart	Proton therapy	www.cyberheartinc.com
EndoControl	Endoluminal surgery	www.endocontrol-medical.com
Freehand	Laparoscopy	www.freehandsurgeon.com
Hansen Medical	Vascular surgery	www.hansenmedical.com
IBA	Proton therapy	www.iba-protontherapy.com
Intuitive Surgical	Laparoscopy	www.intuitivesurgical.com
Magnetecs	Vascular surgery	www.magnetecs.com
Mako Surgical	Orthopedics	www.makosurgical.com
Mazor Robotics	Spine surgery	www.mazorrobotics.com
Medrobotics	Endoluminal surgery	www.medrobotics.com
Medtech	Neurosurgery	www.medtech.fr
Meercompany	Laparoscopy	www.meerecompany.com
OMNI	Orthopedics	www.omnils.com
Renishaw	Neurosurgery	www.renishaw.com
Restoration Robotics	Hair transplantation	www.restorationrobotics.com
Rob Surgical Systems	Laparoscopy	www.robsurgical.com
Stereotaxis	Vascular surgery	www.stereotaxis.com
Surgica Robotica	Laparoscopy	www.surgicarobotica.com
Titan Medical	Laparoscopy	www.titanmedicalinc.com
TransEnterix	Laparoscopy	www.transenterix.com
Varian Medical Systems	Proton therapy	www.varian.com

APPENDIX B

Table 2. Examples of emerging platforms for robotic surgery.

Platform Name	Clinical Application	Institution	Reference
Active catheter	Vascular surgery	University of Western Ontario, Canada	Jayender J. et al., 2008
ARAKNES	Single-access surgery	Scuola Superiore Sant'Anna, Italy	Tortora G. et al., 2014
Catheter operating system	Vascular surgery	Kagawa University, Japan	Guo S. et al., 2007
Concentric tubes	Vascular surgery Prostate surgery	Boston Children's Hospital/ Harvard Medical School, USA Vanderbilt University, USA	Dupont P. et al., 2010 Webster R. et al., 2009
Force feedback system for endovascular catheterisation	Vascular surgery	Imperial College London, UK	Payne C. J. et al., 2012
Gift-Surg	Single-access surgery	University College London, UK KU Leuven, Belgium	Devreker A. et al., 2015
HapCath-System	Vascular surgery	Darmstadt University of Technology, Germany	Meiss T. et al., 2009
HARP	Cardiac surgery	Carnegie Mellon University, USA	Ota T. et al., 2009
HVSPS	Endoluminal surgery	Munich Technological University, Germany	Can S. et al., 2012
IREP	Single-access surgery	Vanderbilt University, USA	Bajo A. et al., 2012
i-Snake®	Single-access surgery	Imperial College London, UK	Shang J. et al., 2012
iTrem	Microsurgery	Nanyang Technol. University, Singapore	Latt W. T. et al., 2009
MASTER	Endoluminal surgery	Nanyang Technological University, Singapore	Phee S. J. et al., 2010
Micro-IGES	Endoluminal surgery	Imperial College London, UK	King H. et al., 2015
Micron	Ophthalmic surgery	Carnegie Mellon University, USA	Riviere C. et al., 2003
MicroTactus	Microsurgery	McGill University, Canada	Yao H.-Y. et al., 2006
Miniature robots	Single-access surgery	University of Nebraska Medical Center, USA	Farritor S. M. et al., 2011
MRI-steerable catheter	Vascular surgery	Ecole Polytechnique Federal de Montreal, Canada	Gosellin F. P. et al., 2011
Octomag	Ophthalmic surgery	ETH Zurich, Switzerland	Ulrich F. et al., 2013
Remote catheter navigation system	Vascular surgery	University of Western Ontario, Canada	Thakur Y. et al., 2009
Robotic catheter system	Vascular surgery	Harbin Institute of Technology, China	Fu Y. et al., 2011
SETA	Vascular surgery	State University of New York at Buffalo, USA	Srimathveeravalli G. et al., 2010
Single port system	Single-access surgery	Waseda University, Japan	Sekiguchi Y. et al., 2011
SPRINT	Single-access surgery	Scuola Superiore Sant'Anna, Italy	Petroni G. et al., 2013
Steady Hand	Ophthalmic surgery	Johns Hopkins University, USA	Taylor R. et al., 1999
STRAS	Endoluminal surgery	University of Strasbourg, France	De Donno A. et al., 2013
Telesurgery system for intravascular neurosurgery	Vascular surgery	Nagoya University, Japan	Tanimoto M. et al., 2000
ViaCath	Endoluminal surgery	Purdue University, USA	Abbott D. J. et al., 2007
VISR	Vascular surgery	Beijing University of Aeronautics and Astronautics Robotics Institute, China	Wang T. et al., 2010

> “The commercial successes of the first generation clinical robotic systems have inspired an ever-increasing number of platforms from both commercial and research organisations, resulting in smaller, safer, and smarter devices that will underpin the future of precision surgery.”

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