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

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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

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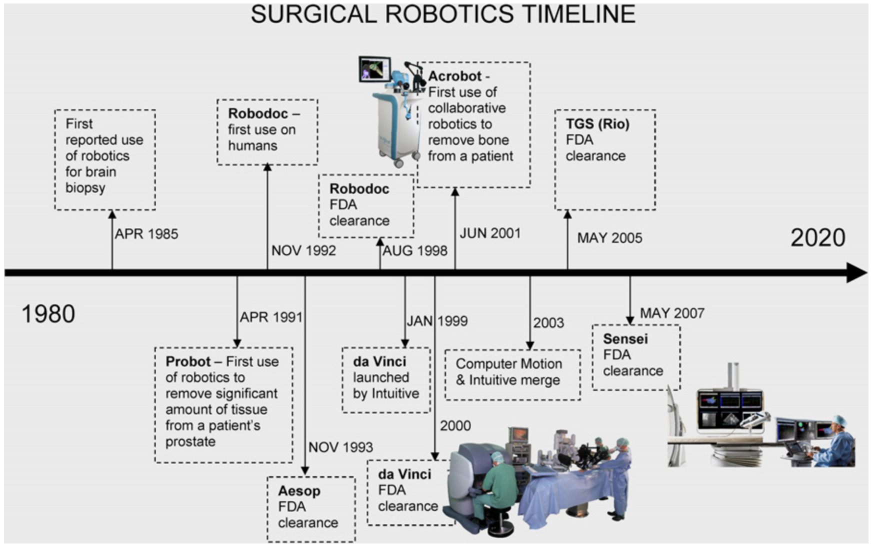

Fig. 1. Surgical robotics timeline.

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.