1 Robotic Technologies (Past, Present and Future)

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1.1 Introduction

Surgical robotic technologies and their ancillary systems have been proposed to improve patient outcomes via shorter recoveries and limited scarring while allowing surgeons increased dexterity and visualization [1]. The prototype for discussion of modern robotic systems capable of application in the surgical theater is the *da Vinci*, a well-established platform whose development dates to the turn of the century. Additionally, implementation of and demand for robotic surgical platforms has fueled growth in the sector leading to an increase in the number of products in development as well available for purchase. General surgery trends indicate movement toward minimally invasive procedures when available, many of which are well suited to robotic-assisted surgical platforms [2].

With each new implementation of a robotic-assisted surgical platform, the foothold technology has secured in the operating theater strengthens. Therefore, to understand the general picture and survey the minimally invasive robotic-assisted surgery landscape, a historical review of the origins of these entities is indicated. Here the critical developments, evolutionary phases, adverse events, cost of development and purchase, as well as barriers to care and training will be

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discussed. The historical record on safety and feasibility of robotic assisted surgery platforms throughout their evolution may elucidate the current state of affairs.

1.2 Ancient Past

The journey of understanding the origin of robotic-assisted surgery begins in the centuries leading to the Age of Pericles and the founder of the Hippocratic School of Medicine, Hippocrates of Kos. Greek physicians in the years Before the Common Era (BCE) limited their practice to surgery of bone and muscle while ignoring internal organs as inconsequential causes of disease [3]. The sequence of examination, diagnosis, prognosis and treatment was developed and refined, while magical and religious hypotheses of pathology were ostracized [3]. Historically the evolutionary origin of robotics is rooted in the mythology and scholarship of ancient Greece, China, and Egypt [4].

During the age of Hippocrates, the likeness of a robotic entity was not unknown and could be found in Greek mythology via poetry. For instance, the Greek dactylic hexametric poem the Iliad portrayed Hephaestus as the forefather of modern technological platform designers via his Automata [5]. The Greek god of blacksmiths and craftsmen, Hephaestus was said to have a workshop on Olympus where he engineered items for the gods while delegating executive design oversight to a team of Cyclopes forgers [5]. Hephaestus' automata, self-operating machines capable of autonomous actions of their own free will, are an example of man's predilection for creativity and imagination and a starting point for the discussion of robotic evolution. Each Automaton was said to be mobile, functional, and programmable [6]. These early entities of mechanical operation foreshadow the existence of modern controllable computer programmable devices by millennia and in this text act as the genesis of robotic ideation.

The passage of time from Before Common Era (BCE) to Common Era (CE), is marked by several other written examples of creative manifestations prefiguring robotic technology. For instance, Yan Shi's Chinese automatons who in the Lie Zi text (1000 BCE) were capable of walking, posturing, and performing humanlike mannerisms. These designs of leather and wood were designed by Yan Shi to be compartmentally dependent on hierarchical systems [7]. When a component controlling a specific movement was removed, that movement was lost while unaffected functionality remained [7]. Shi's automaton design incorporating subdivision of process by systematic control is a remarkable example of fiction's harbingering ability and generally parallels modern platforms.

A further example of invention with foundational influence on modern robotic technology is the work of Hero of Alexandria. An Egyptian engineer, Hero wrote several works on his efforts in mathematics and mechanical experimentation. His user-configurable automated systems were described in text as incorporating pneumatic, catoptric, and mechanical components to manipulate objects and light [8]. One such effort, Heron's aeolipile, was a radial steam turbine which created rotational force via propulsive jet expulsion [8]. While the aeolipile had only loose similarities to modern day robotic-assisted surgical technology platforms, it serves as an ancient surrogate for intellectual thought on the input/output computing communication utilized in modern day computer processing. Just as the data input into a processing system is that which is received, the heat added to the aeolipile acted as a signal in the interaction between user and system. Similarly, the steam producing torque was the output corollary.

The connection between ancient tinkerer and today's billion-dollar industry is not direct, rather a chain that has been established over time through the individual links created by each contributor to robotic technology evolution. One such connection was formed by Ismail al-Jazari, the 1206 CE Muslim author of *The Book of Knowledge of Ingenious Mechanical Devices*. The Anatolian artisan contributed automata capable of the first-known feedback control function. The device incorporated mechanical design elements which allowed an operator to fine tune fluid dynamics through a manual interface which regulated operational outputs [9]. Al-jazari's illustrated descriptions clearly delineate progress in input and feedback control system innovation; reservoir volume regulation via valve modulation dependent flow rate in temporal water clock design [9].

Note that technology progressed in a stepwise fashion and successive progressions were made based on principles set forth in preceding scientific efforts. Each generational achievement progressed the ceiling of technology synergistically and various contributions combined to facilitate future achievements. For instance, the mechanical engineering advancements made by the Greeks utilizing air, vacuum, and balance principles profoundly influenced the work of al-Jazari [10].

1.3 Modern Period

In the eighteenth century, Swiss watchmaker Pierre Jaquet-Droz developed automata capable of programmable actions arguably equivalent to computing as it is currently understood [11]. His mechanical devices incorporated elements derivative of his own work on intricate watch complications, or those functions of a timepiece in addition to displaying the hours, minutes, and seconds [11]. One invention, The Writer, was comprised of 6000 individual parts and could systematically interpret a program disk and translate the input into hand written text up to 40 characters [11]. Crank loaded spring power enabled the android's system of interchangeable cams and gears to actuate the read-only program, in addition to various mannerisms, sans outside intervention [11].

Countless others contributed: Philon of Byzantium, Giovanni de la Fontana, Juanelo Turriano, Athanasius Kircher, Heri Maillardet, Leonardo da Vinici, Wolfgang von Kempelen, Salomon de Caus. Attributing the origin of an entire faction of science to a single person, geographical location, or even millennium would be erroneous. The list presented here should not be considered exhaustive and merely represents a fraction of the applicable contributions to the sector.

1.4 Robot

Heretofore the term automaton was described in myth, literature, and historical engineering design as a machine with the capability of actuating movements or functions, complex or otherwise. However, in 1920 Czech author Karel Čapek penned a play entitled *R.U.R. Rossumovia Univerzální Roboti* (Rossum's Universal Robots). In this work, Čapek modified the Slavnoic word for forced-labor servitude (rabota), and the term Robot was coined [12]. The fictional play describes the use of robotic biotechnological workers who were mass produced to complete tasks unappealing to residents of its dystopian central European setting [13]. The etymology of the word robot developed further when, in 1979, The Robot Institute of America bestowed a formal definition: "a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks" [12].

1.5 Contemporary Period

Born in the United States, though raised and educated in England, William Grey Walter was a neuroscientist known for his contribution to the increased clinical use of electroencephalograms (EEG) [14]. In addition to the use of EEG to treat epilepsy, Walter pioneered the use of EEG to detect localized brain tumors through delta and theta patterns of activity. His work in the 1940s to understand the cerebral rhythm lead to the construction of an apparatus which incorporated electrodes and a camera to visualize and scrutinize the phase and frequency of the EEG. The device contained cathode ray tubes (CRT), like those used in that era's televisions, each connected to an electrode attached to the patient [15]. The collection of 22 individual CRTs was then photographed, resulting in a brain mapping technique that predates neuro-imaging as it is now known [15]. Additionally, Walter's research in neurophysiology eventually led to his involvement in a project with lasting contributions in the field of robotics. During the late years of the 1940s Walter created a series of mechanical inventions designed to mimic human behavior [16]. A pair of successive iterations were named the Electromechanical Robot (Elmer) and the Electro Light Sensitive with Internal and External Stability (Elsie) respectively [14]. The robots were comprised of vacuum tubes, motors, and a photoelectric cell, and were collectively named Machina Speculatrix. This manifestation of robotic ingenuity was separated from preceding automata through its ability to autonomously interact with an environment. The sensory system of M. Speculatrix could identify the presence of physical objects, the intensity of light, and would modulate its motility as a function of those environmental characteristics [16]. While exploring its environment M. Speculatrix could travel towards moderate light, avoid bright light and objects, thus effectively decide on the most favorable conditions in which to exist [16]. A mobile photosensitive tactile robot that displayed complex environmental condition recognition, M. Speculatrix incorporated biological principles in its design which would persist in future robotic development efforts [17].

Joseph F. Engelberger and George C. Devol founded the first proper robotics company Unimation [Danbury, Connecticut] after their initial collaboration in 1956 [18]. As the Korean War waned, Engelberger's position as an engineer of aircraft parts for military contracts became vulnerable. Eventually, after corporate reorganization by his employer, he was able to secure funding and transition his team to a division focused on developing an industrial robot [19]. It was Devol who developed and patented the applicable technology, but Engelberger acted as spokesperson and championed the cause by serving up his visionary promotional showmanship in a calculated manner conducive to securing the interest of investors [18]. During its initial development, the anthropomorphic robot named *Unimate* was built using a polar coordinate design: a two-dimensional system where points on the plane are relative by distance and angle to a central reference point and direction respectively [19]. The platform was capable of 5 degrees of freedom (DOF) via a pair of axes and gears powered by 1000 psi hydraulics [19]. Novel design innovations allowed the incorporation of digital controls, magnetic drum memory, optical positioning feedback, and intrinsic power supplies [19]. The result was a complex programmable system containing technological elements with scope and scale surpassing any previously known robotics platform. The Unimate was utilized by industrial applications such as diecasting, spot welding, and eventually automobile manufacturing and assembly [19]. Engelberger's advocacy for the incorporation of "smart" machines like the Unimate promised safer work site conditions and increased productivity, ultimately leading to licensing agreements with companies including Nokia, Kawasaki, General Motors, BMW, and Mercedes [18, 20].

Once the development and industrial implementation of new technology had been established, the door opened for broader applications of use. Accordingly, the capabilities of the Unimate platform were quickly adapted for use in the medical field. While working at Unimation, Victor Sheinmann adapted a Unimate platform in 1978 into a Programmable Universal Machine for Assembly (PUMA) (Westinghouse Electric, Pittsburgh, PA) [21]. The evolution of PUMA's application from agent of industrial assembly efficiency to one of greater surgical precision sparked a movement and signified a turning point in the origin of robotic-assisted surgery.

1.6 Healthcare Robotics

One of the first implementations of a robot-assisted surgery platform in healthcare was in 1985 by Kwoh et al. [22]. Kowh and his team adapted a PUMA for use in stereotactic brain tumor biopsy, with radioactive implantation and deep brain stimulation theorized as secondary indications for use (Fig. 1.1) [22]. Previously, frame mounted CT-guided stereotactic apparatuses were used to navigate instruments through brain tissue. However, these stereotactic devices were difficult to couple with their CT imaging counterparts; manually adjusting instrument position via graduated positioning scales on the frame according to CT imaging findings was inefficient and limiting. Therefore, improvements in automation and

Fig. 1.1 PUMA 200

instrument manipulation capability were desired. Kwoh et al. retrofit the commercially available industrial robot UNIMATION PUMA 200 with a Siemens DRH CT scanner [22]. This combination resulted in a platform that could be programed, controlled by a computer, and allowed instrument manipulation accurate to 0.05 mm. Interfacing a computerized tomographic scanner with contemporary robotic technology resulted in faster procedure times than previously available with stereotactic frames adjusted by hand [22]. Iterations of the PUMA ushered in a new era in medicine, one where the realization of robotic-assisted surgery was no longer fiction but reality.

Another pioneering application of technology was the development of the robotic-assisted surgery platform the Arthrobot [Vancouver BC] for bone mountable hip arthroplasty [23]. Biomedical researchers Dr. James McEwen, Geof Auchinlek, and Dr. Brian Day oversaw the development of the system which assisted an orthopedic surgeon by manipulating the position of the joint by adjusting the limb held in the robotic arm's gripper [23, 24]. Voice recognition capabilities allowed the surgeon to interact with the system using 20 spoken words for command input and speakers emitting closed-loop communication for command confirmation [23]. Like many integrations of technology in medicine, the goal of the Arthrobot was safer procedures and quality improvement in outcomes over existing techniques [24].

Extending previous efforts of orthopedic surgeons to incorporate robotic technology by adapting the foundational principals of the PUMA 560, the Thomas J. Watson Research Center developed ROBODOC (Curexo Technology Corporation). The milling robot was used in 1986 for total hip replacement procedures to core the femoral shaft thereby facilitating femoral-prosthesis integration with 96% precision [25]. This "press fit" preparation of the femoral canal allowed fitting a prosthesis without the use of bone cement [26]. The robotic platform's accuracy was accomplished through the combination of a high-speed drill and CT imaging [21]. Hip arthroplasty prosthesis sizing via image-directed robotic-assisted femoral preparation was shown to improve on the conventional hand broach femoral coring technique, which was 75% accurate [25]. After a successful clinical trial of 300 patients, ROBODOC earned FDA approval becoming the first robotic-assisted surgery platform to do so (Fig. 1.2) [27]. Preoperative planning and programming of autonomous robotic platforms operating under the supervision of medically trained personnel was thus available for the first time to provide a level of execution beyond that which is capable by the human hand [12].

Temporally paralleling the previously described orthopedic platform was the development of a robotic-assisted surgical platform for use in urology. The PROBOT (Integrated Surgical Supplies Ltd.) was an adaptation of the PUMA 560 system for use in transurethral resection of the prostate (TURP). Its design incorporated a novel circular metal safety frame which maintained the robotic arm and resection instrumentation position within the relatively small prostatic operating window [25, 28]. The platform incorporated on-line imaging and used a 3D model of the prostate to enhance the interface between surgeon and system. The PROBOT was proven successful in clinical trials for robotic-assisted resection of prostatic tissue, although it failed to gain traction necessary for widespread clinical adoption [29].

Foundational advancements in robotic-assisted surgical platforms were necessary for the development of future efforts. The successful demonstration of each

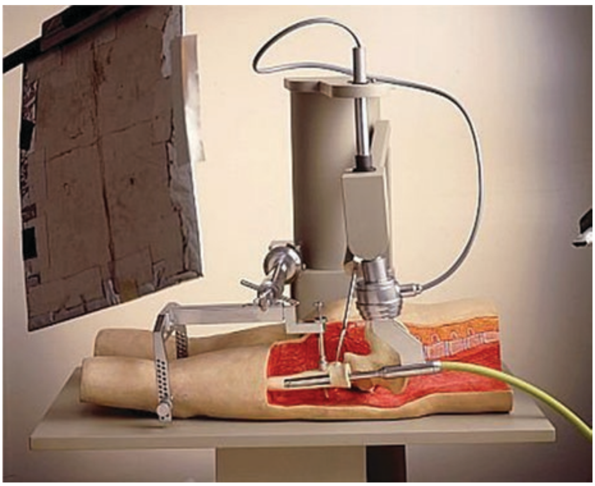

Fig. 1.2 ROBODOC developed by Integrated Surgical Supplies, Inc

subsequent system provided a tangible bastion for continued development and progress. Previously in this historical review of robotic-assisted surgical platforms, developers strove to integrate programmable computer controlled robotic technology into open surgery to positively impact procedures. Modern Robotic Hernia Surgery, however, is founded on the use of laparoscopy. The crux of the transition from the former to latter was the development of a technology for remotely manipulating robotic platform extensions while separated by a distance. This spatial detachment of operator control and mechanical actuation was termed telepresence by the technologist Scott Fisher, PhD [27].

In the mid-1980s the National Air and Space Administration (NASA) Ames Research Center began working on telepresence to provide remote access surgery [30]. To provide an interface environment between a robotic entity controlled by a spatially separated operator, telepresence required the application of a virtual reality [12]. Multidiscipline research cooperation between teams led by Scott Fisher at NASA-Ames and Philip Green at the Stanford Research Institute (SRI) division focused on robotic telemanipulation and resulted in several hardware developments [30]. The team's contributions included the first head-mounted display (HMD), which was developed to display data from NASA's Voyager [25]. Additionally, the efforts of multiple collaborators resulted in the DataGlove, an interactive interface between user and 3D virtual reality environments [25]. Progress in software was necessary to drive the application of these devices and VPL, Inc. led by Jaron Lanier, developed an object-orientated program to that end. Lanier was an early proponent of the vernacular dubbed virtual reality and his visual programming language allowed the creation of computer programs using graphical elements rather than text [31]. The combination of experts with diverse backgrounds in biomechanics, robotics, and virtual reality led to collaboration which proved to be instrumental in the origin of modern robotic-assisted surgery. The late 1980s marked a time which realized crossover between robotics designed for industrial use, telepresence, and robotic telemanipulation technologies applied to medicine signifying the emergence of robotic-assisted surgery [32]. The prototype platform developed by Green for robotic telemanipulation in microsurgery at SRI showcased characteristics found in many modern systems including a control console, telemanipulation of interchangeable instruments, haptic feedback, and HD-3D visualization [32].

The Green Telepresence Surgery System possessed inherent capabilities that naturally lend themselves toward laparoscopic surgery. For instance, early laparoscopic procedures were criticized as inferior to open procedures due to their diminished 3-D visualization, decreased dexterity, and loss of haptic feedback compared to conventional means. These qualities attracted the interest of Richard Satava MD, a surgical endoscopist who was instrumental in the 1992 establishment of the advanced biomedical technologies division at the Defense Advanced Research Projects Agency (DARPA) [25]. The influx of funding provided by the Pentagon supported a nidus for further development of robotic-assisted surgery platforms [25]. The military's mission was to develop The Green Telepresence Surgery System into a platform capable of providing forward battlefield surgical care to soldiers with potentially mortal wounds through robotic telemedicine [25]. The concept was to mount the robotic arms in a Bradley Fighting Vehicle to establish Medical Forward Advanced Surgical Treatment (MEDFAST) with a surgeon operating via telepresence from the safety of a Mobile Advanced Surgical Hospital (MASH) [25]. In 1994, vascular surgeon Jon Bowersox performed an ex vivo porcine intestinal anastomosis from a MASH-to-MEDFAST unit during a combat exercise [21, 32]. The procedure utilized wireless microwave data transfer and marked the first telesurgery demonstration.

DARPA funding was influential in the development of additional systems with a catapulting effect on sector advancement. For instance, the Automated Endoscopic System for Optimal Positioning (AESOP) from Yulun Wang's Computer Motion, Inc. established in 1993, was the first platform specifically designed for abdominal laparoscopic surgery approved by the Food and Drug Administration (Fig. 1.3). The system incorporated voice recognition software to allow control of an endoscopic camera fixed to a robotic arm [30]. The robotic endoscopic camera was capable of 23 voice-controlled commands via 7 degrees of freedom and increased image stability for improved visualization of the surgical field [30]. Following its introduction, systems derivative of AESOP have been used in hundreds of thousands of minimally invasive surgical procedures in a variety of fields [32]. Advantages of AESOP

Fig. 1.3 Computer Motion's AESOP (Automatic Endoscopic System for Optimal Positioning)

over conventional hand held camera operation were described in a Johns Hopkins study showing no increase in operating time while using standard laparoscopic port placement in 17 different procedures such as nephrectomy, retroperitoneal lymph node resection, and Burch Bladder suspension [33]. In addition to providing a more stable view, AESOP eliminated the need for a camera controlling assistant, effectively allowing a laparoscopic surgeon to operate solo [21]. This seemingly small contribution brought robotic-assisted surgery platforms one step closer to autonomy by whittling the human component down to one. However, with increased dependence on technology came associated voice control drawbacks such as command to action latency, dialect recognition, integration and adaptation of technique, and potentially distracting talking [21].

Extensive modifications to the AESOP system resulted in Computer Motion's introduction of the ZEUS operating system, the first formal master-slave platform (Fig. 1.4). With this type of system, end effector instrumentation is exclusively actuated by a surgery control center workstation without autonomous programming input from the platform itself [27]. The master portion consists of a video monitor console and 2 surgeon operated handles, left and right, to control the respective robotic arm slaves. With three independent arms and all the functionality of AESOP's voice activated camera system, ZEUS could manipulate 2 instruments with 4 degrees of freedom [12]. Instruments with articulating end-effectors as well as conventional endoscopic instruments with straight shafts were available for use. Special glasses allowed the surgeon 3D visualization provided by a Storz imaging system (Karl Storz Endoscopy, Santa Barbara, CA, USA) [21]. By physically separating the surgeon and patient, ZEUS could reduce operator tremor through its electromechanical interface. Additionally, the computer system could scale operator joystick input up to a factor of 10 thereby allowing precise instrument control

Fig. 1.4 ZEUS robotic system

beyond that which is capable by hand [25]. For instance, scaling handle input from 1 cm to 1 mm allowed end effector actuation with greater accuracy. Future systems would incorporate this technology to achieve precision not otherwise possible.

In 1998, the ZEUS operating system was successfully used by Falcone et al. for laparoscopic uterine tubal reanastomosis microsuturing at the Cleveland Clinic [34]. Additionally, in 1999 Reichenspurner et al. performed the first coronary bypass anastomosis using a robotic-assisted surgical system in porcine and canine models [35]. Numerous other studies contributed to data indicating the safety, feasibility, and increased dexterity provided by the platform in gynecologic and adnexal procedures [30]. ZEUS gained FDA approval in 2001 [12]. In 2001, the French surgeon Jacques Marescaux, successfully demonstrated the capability of a robotic-assisted surgical platform to perform a tele-surgical procedure on a scale previously only theorized. Leading a team of surgeons at the Institute for Research into Cancer of the Digestive System (IRCAD) in New York, Marescaux used the ZEUS surgical robot to perform a minimally invasive cholecystectomy on a patient in Strasbourg, France without any intra-operative complications [36]. The event was named the Lindbergh Operation in homage to Charles Lindberg, the pilot who first flew an airplane across the 3600-mile transatlantic route from New York to Paris, France. The Lindbergh Operation overcame numerous technical challenges including telecommunication delay resulting from bandwidth and digital conversion limitations [36]. Utilizing Computer Motion's SOCRATES telepresence software, the distance spanning patient-side and surgeon-side components of the ZEUS platform was connected via fiber optics allowing data transfer at a rate of 10 megabits per second [12, 36]. This groundbreaking event demonstrated the realization of telesurgery and would fuel future moonshots in the development of robotic-assisted surgery platforms.

Meanwhile, following the Bowersox MEDFAST-to-MASH procedure, Frederick H. Moll MD acquired the license to the SRI Green Telepresence Surgery system and along with Robert Younge and John Freund created Integrated Surgical Systems (now Intuitive Surgical) [21]. While the future directions of long-distance telesurgery were intriguing to Moll, the surgeon entrepreneur began to focus the company's resources on improving conventional civilian minimally invasive surgery, specifically laparoscopy. Using the intellectual property from the SRI acquisition, Intuitive Surgical developed a robotic-assisted surgery prototype in 1997 [32]. Named after Leonardo da Vinci, the fifteenth century inventor known for his study of human anatomy, a lineage of prototypes were refined including Lenny, Leonardo, and MONA [37]. In 1997, MONA was used to telesurgically perform the first robotic-assisted laparoscopic cholecystectomy on a 72-year-old woman in Dendermonde, Belgium [38]. The final prototype of the system was named the da Vinci Surgical System with commercial marketing beginning in 1999. This final iteration marked the first truly integrated robotic surgical system approved by the FDA in 2000 for general laparoscopic surgery [39]. While platforms predating da Vinci utilized endoscopy equipment operated by assistants to the surgeon, the da Vinci allowed a surgeon to work solo, like the AESOP technology utilized in the ZEUS platform. Additionally, da Vinci's arms were considerably smaller in dimeter than the PUMA 560, measuring only 1-cm, and allowed incision walls without leverage which lowered infection risk by minimizing contact of exposed tissue and the robotic arms [39]. As time passed, the da Vinci Surgical system would eventually become the dominate system in the field of robotic-assisted surgery. However, in the beginning the system faced fierce competition from competitors such as Computer Motion's Zeus. Distinguishing capabilities of early da Vinci models included seven degrees of freedom owing to end effector joint articulation, haptic feedback, and 3D vision [32]. Technically, the key was a smaller size, three-dimensional binocular stereoscopic endoscopic imaging system transmitted to a surgeon console [21]. The earliest version of the system had three arms, one for the endoscope, and two for instruments. The 12 mm endoscope contained a pair of 5 mm cameras; left and right aspect perception allowed a 3D visual reproduction of the surgical field [32]. Robotic arms were controlled by the surgeon via left and right hand joysticks mounted to the console as well as foot pedals for additional operational command [32]. End effectors were capable of a variety of actions including insufflation, illumination, and cautery.

1.7 Twenty-First Century

The rush to incorporate new robotic-assisted surgical platforms led to numerous studies collecting data on feasibility, safety, and benefit over conventional techniques. Between 1999 and 2001, Gettman et al. showed data indicating that the da Vinci system could perform laparoscopic Anderson-Hynes pyeloplasty for primary ureteropelvic junction obstruction in less time than necessary for conventional laparoscopy and without open conversion or complications [40]. Additionally, in 2002, Horgan et al. successfully performed ten living donor human laparoscopic nephrectomies at the University of Illinois at Chicago [41].

Furthermore, the first open heart operation exclusively using a robotic-assisted surgery platform was completed in 1998 with the da Vinci for a minimally invasive mitral valve surgery (MIMVS) on a 52-year old woman with an atrial septal defect [42]. Each demonstration expanded the variety of procedures da Vinci was capable of. By 2000 the platform was FDA approved for adult and pediatric urologic, general laparoscopic, gynecologic laparoscopic, general non-cardiovascular thoracoscopic, and cardiothoracic surgical procedures.

Despite its many successes, in the late 1990s and early 2000s the future market domination of Intuitive Surgical's da Vinci was not guaranteed. Early on, a budding rivalry between da Vinci and ZEUS was punctuated by their unique modi operandi. Although both robotic-assisted surgical platforms were similar in their master-slave multi-limbed telepresence controlled surgeon-side console to patient-side instrument layout, each had unique strengths resulting from their varied upbringing. While the ZEUS platform's workstation provided the surgeon a comfortable chair in which to view imaging via a monitor, the inherent perception was one of being separated from the patient. In contrast, da Vinci's workstation incorporated stereoscopic image visualization located directly above the hand-held joysticks. This spatial relationship between hand-held controls and visualization modality provided the sensation that the robotic end effectors were extensions of the joystick and that the patient was directly in front of the surgeon [25]. Moreover, although ZEUS and da Vinci both utilized computer enhanced visualization, the NASA and US Army derived telepresence based da Vinci was shown to outperform ZEUS and conventional laparoscopy in a variety of tasks. For instance, in one study indicating overall usability, suturing and knot-typing times were significantly lower using the da Vinci system compared to ZEUS and conventional laparoscopy [43]. Additionally, da Vinci outperformed the competitors in task errors as well as subjective assessments such as fluidity, efficacy, precision, dexterity, tactile feedback, tremor reduction, and coordination [43]. The da Vinci platform's subjective and objective performance superiority was contributed to its greater range of motion and articulation provided by more degrees of freedom than that of the ZEUS platform. Additionally, its binocular vision, motion scaling, and joystick ergonomics were cited as attributing to its superiority [43]. Although ZEUS allowed independent right and left robotic arm control as well as AESOP voice-operated 2D endoscopic visualization, its limitations in geometric accuracy, stability, tactile feedback were unable to compensate. Ultimately, when compared to the ZEUS system, the da Vinci system's intuitive interaction characteristics were shown to produce shallower user learning curves and shorter times during laparoscopic procedures such as nephrectomy, adrenalectomy, pyeloplasty, and surgical anastomosis [44]. In this case, history was written by the victor and in 2003 Computer motion merged with Intuitive Surgical thus neutralizing the patent war. The ZEUS system was discontinued leaving the da Vinci as the sole robotic-assisted surgical platform available for commercial purchase [12]. Later versions of da Vinci including the 2006 da Vinci S, 2009 da Vinci Si, and the 2011 single-site da Vinci Si each contributed to the development of the modern platform: the da Vinci Xi and X (Figs. 1.5, 1.6, 1.7, and 1.8).

The stepwise development of successive iterations contributed to the current Xi product. For instance, the da Vinci S reduced set-up complications and improved visualization by upgrading camera technology to utilize high-definition 3-dimensional (HD-3D) technology. Additionally, the da Vinci S furthered the ease of interaction between surgeon and platform by incorporating an interactive touch screen display. A few years later, the da Vinci Si offered a dual console for use in training junior team members like a car with 2 steering wheels for driver instruction. The Si also added substantial imaging capabilities to its design. For instance, the da

Fig. 1.5 The da Vinci® Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA)

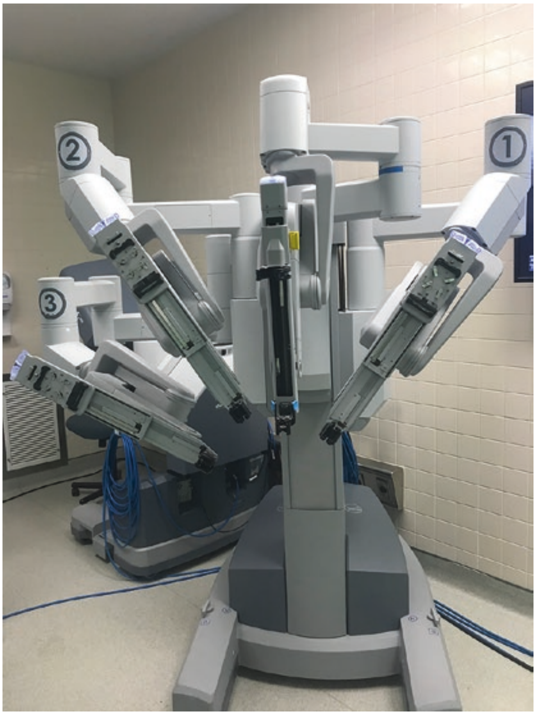

Fig. 1.6 da Vinci Si

Fig. 1.7 da Vinci Xi

Fig. 1.8 da Vinci X

Vinci Si integrated TilePro, a multi-input function that allowed additional video sources from EKG and ultrasound to be displayed alongside HD-3D video. Additionally, the Si provided near-infrared real-time imaging via the Firefly Fluorescence Imaging Endoscope [12]. The single-site da Vinci Si was released to specifically provide enhanced functionality for single incision laparoscopic surgery (SILS). Single-site specific platform design allowed instrument access via a five-lumen port entered through a 1.5 cm incision [45]. Applications of SILS via the umbilicus include cholecystectomy, hysterectomy, and salpingo-oophorectomy [45]. In 2014, the da Vinci Xi was released. The Xi was unique in that its robotic arms were orientated parallel to each other rather than the previous circular arrangement [12]. The da Vinci Xi compiled the successful characteristics of previous iterations into a single master console and mobile platform with boom-mounted robotic arm. Each of the 4 arms can provide three degrees of freedom, with an additional seven degrees of freedom provided by Intuitive Surgical's EndoWrist technology. The EndoWrist attempts to impersonate the movements of the human wrist, thereby increasing the dexterity and functionality of end effector instrumentation [46]. Visualization in the Xi is handled by HD-3D visualization via a pair of cameras while instruments are controlled through telemanipulators with adjustable finger-cuff style ergonomic loops [47]. User comfort is maximized with intraocular distance adjustment, head-rest padding, and arm rests [47]. Motion of instruments is driven by cable joints distal to the robotic arm and tremor filtration with motion scaling achieve precise movements [46].

As a result of generations of refinement, historical competitive success, and current widespread clinical application, the da Vinci Surgical System is the modern-day workhorse in the field of robotic-assisted procedures. Most current applicable discussions in the literature include data generated from procedures utilizing the da Vinci Surgical System. As a result, the platform is rightly held as the prototypical example for conversion from open surgery and conventional laparoscopy to robotic-assisted procedures.

As in any competitive arena, challengers to the throne will come in droves. The success earned by the da Vinci Surgical System, the most commonly used robotic assisted surgical system, has given impetus to a growing sector of developers. One such platform, the Senhance was derived from a system previously known as the ALF-X Robotic Surgical System from TransEnterix, Morrisville, NC [48, 49]. Controlled remotely with three manipulator arms like that of the da Vinci, laparoscopic handles translate the surgeon's movements to actuators with multiple degrees of freedom. Although its end effector instruments do not articulate like the da Vinci's EndoWrist, the Senhance robotic system improves on the da Vinci's feedback shortcomings by integrating true haptic feedback. Whereas the da Vinci uses visually displayed cues to provide feedback to the operator concerning the force opposing the distal end of instruments while interacting with tissue, the Senhance offers actual tactile haptic force feedback. Tactile feedback provides an elevated sense of control and connectedness between physician and patient by translating sensation to the surgeon's hand [48, 49]. The tactile haptic force feedback incorporated by the Senhance works in tandem with a novel eye-tracking technology which uses the surgeon's point of visual foveation to center the camera image. This contrasts with the da Vinci system in which the surgeon controls the camera with a foot switch. The Senhance has been shown in clinical surgeries to be safe. For instance, in a 45-patient study of inflammatory bowel disease, colorectal cancer, adenoma, or diverticular disease with complications requiring surgery, the Senhance was used with three procedures converted to standard laparoscopy [50]. A champion for newcomers, the Senhance has become the first major robotic-assisted surgical platform other than the da Vinci implemented in a major hospital, being available for use at The Florida Hospital Institute for Surgical Advancement in November, 2017 [51].

The rising tide lifts all boats, and that aphorism rings true in the momentum observed in the robotic-assisted surgical platform sector. All new technologies possess inherent shortcomings that provide an angle of attack for prospective startups. For instance, console based robotic surgical systems are large, and the equipment requires a considerable amount of space and a disruptive choreography in the operating room. To reduce the impact of that footprint in the operative theater, Cambridge Medical Robotics Ltd., Cambridge, UK has developed the Versius Robotic System. The Versius Robotic System is modular, and more lightweight

Fig. 1.9 Versius Robotic System

than the aforementioned platforms (Fig. 1.9). Its design provides increased flexibility compared to the established competitors, while allowing more versatile positioning relative to the patient [52]. Functionality comparable to its contemporaries includes multiple modular wristed robotic arms with haptic force feedback and HD-3D display designed for laparoscopic renal, gynecological, upper GI, and colorectal surgeries. Estimates for FDA approval have targeted a 2018 date, with proof of success in electro-surgery, needle driving, tissue manipulation and suturing shown at The Evelyn Cambridge Surgical Training Centre in cadaveric trials [52].

General surgery has been trending toward less invasive procedures when available, with robotic-assisted laparoscopy leading the way. Laparoscopy has been shown to benefit outcomes through shorted hospitalization time and reduced scarring [53]. The rising use of robotic platforms in minimally invasive procedures has been supported by their ability to address limitations conventional laparoscopic places on a surgeon's dexterity, visualization, and sensory feedback [54, 55]. The da Vinci Surgical System has been commonly used in robotic-assisted laparoscopic surgery since 2000, with 3400 systems in use worldwide in 2015 [47, 56]. At the time of publication of this textbook, there will probably exist newer robotic platforms available to the surgical community, other than the ones previously cited. The use of robotic-assisted surgical platforms for current use in hernia repair thus indicates a retrospective view of the procedure's origin.

1.8 Hernia Repair

Surgical repair of groin hernias increases with age with one study reporting that 4.2% of patients 75–80 years old receive treatment [57]. The abnormal tissue movement through its normal wall of containment most commonly involves the inguinal and femoral type, with hiatal, incisional, and umbilical hernias among other prevalent types [58]. Throughout an adult's life, the risk of developing a groin hernia is 27% and 3% for men and women respectively [59]. When asymptomatic watchful waiting is considered prudent. However, acute incarceration and strangulation of herniated tissue indicate emergency surgery. Additionally, data shows that pain symptoms will result in surgical referral within 10 years [58]. The largest risk factors are male sex, advanced age, and family history. However, additional conditions associated with risk include chronic obstructive pulmonary disease, lower body-mass index, and smoking [58]. Counterintuitively, the risk of developing a hernia from heavy lifting was shown to be inconclusive by systematic review [60].

Because untreated hernias can become large and noticeable, the groin hernia in adults has been recorded in history as far back as ancient Greece [61]. The Greek origin of the word Hernia indicates the pathophysiology through its translation from bud or sprout [62].

Earthenware statuettes from ancient eastern Mediterranean civilizations depict female umbilical hernias dating to the fifth century BCE. Additionally, in the smooth-sided Pyramid of Teti in Saqqara Egypt a funeral complex housed a 2500 BCE solid sculpture depicting the reduction of an inguinal hernia [61]. Further evidence of ancient hernias includes the mummified inguinal hernia of the fourth pharaoh of Egypt's Twentieth dynasty [61]. The Egyptian Ebers Papyrus, which dates to 1550 BCE, includes the first medical evidence of written hernia documentation. The 20-meter-long scroll was presumably less wieldy than today's electronic medical records systems. Centuries of advances in hernia surgery included the work of Gabriel Fallopius, Fabricius Aquapendente, Lorenz Heister as well as a litany of contributors to medical science understanding, some of whom are mentioned here [61]. Heister, a German surgeon was the first to report a direct inguinal hernia. The Dutch physician Petrus Camper studied inguinal hernias in the 1750s, leading to the eponymous anterior abdominal wall fascia. Franz Kaspar Hesselbach, a German surgeon, is best known for his description of the cribriform (Hesselbach's) fascia, the interfoveolar (Hesselbach's) ligament, and the inguinal (Hesselbach's) triangle. His 1806 medical text regarding the 3 anatomical structures was highly contributory to the practice of Hernia surgery [63]. The Spanish surgeon Antonio de Gimbernaty Arbós first divided the lacunar ligament to expand the femoral ring for incarcerated femoral hernia treatment [64].

Continuing advancements in the twentieth century allowed various surgical treatments for patients experiencing the chronic pain and obstruction caused by hernias. Harvard Medical School graduate Henry O. Marcy and his 1881 text on the inguinal region and related surgical repair were foundational for the surgical curing of hernias [65]. Marcy's techniques included high ligation of the hernia sac, transplantation of the cord, and reconstructive closure of the inguinal ring [65]. However, it was Italy's Edoardo Bassini who is generally recognized as the father of modern hernia surgery. In 1884, Bassini published a method for inguinal canal repair following hernia sac displacement. It was his herniorrhaphy technique that gained lasting notoriety due to its exclusive use of sutures for the reconstruction of the inguinal canal's posterior wall [66]. Bassini's technique was shown to lower hernia recurrence from 100% to 10% compared to the conventional anterior wall repair [62]. In 1939, Chester B. McVay MD published "A fundamental Error in the Bassini Operation for Direct Inguinal Hernia", the title of which leaves little requirement for elucidation and provides an example of the stepwise progression toward modern standard operating procedures [67]. McVay, a surgeon from South Dakota, advocated the use of the pectineal ligament for its stability in holding sutures [67]. Further contributions from the French surgeon Henri Fruchaud include two texts: "Surgical anatomy of the groin region", and "Surgical treatment of groin hernias" [68]. Each of Fruchaud's books provided detailed figures regarding the anatomic surgical treatment of groin hernias via reconstruction. His research attacked the conventional dichotomy of inguinal and femoral regions in the abdominocrural area [68]. Furthermore, Fruchaud pioneered abdominal access to the thigh and first identified the peritoneal piriform fossa while advocating for a deep reconstruction of the abdominal wall in place of simply closing the inguinal canal or femoral ring [68]. Tensionless repair using Marlex mesh, a synthetic polymer material to strengthen the inguinal canal, was described by Lichtenstein in 1990 [69]. Lichtenstein incorporated the monofilament polypropylene mesh to prevent tension of suture lines while providing a physical barrier to tissue protrusion [69].

The first laparoscopic hernia repair was reported by Ralph Ger and described the closure of patent vaginal processes in beagle dogs using staples applied laparoscopically [70]. That study identified advantages of using laparoscopic technique to manage indirect inguinal hernias including: smaller incisions, elimination of dissection, decreased risk to adjacent anatomy, and reduction of recurrence [70]. The Ger technique included a peritoneal incision that allowed a polypropylene mesh to eliminate the pathologic space followed by re-approximation of the peritoneum. Methods of mesh based repair inspired advancements in techniques to secure the synthetic material such as tacking and transfascial suture fixation. Further refinements of the procedure saw the implementation of polypropylene plugs and patches. For instance, in 1991 Corbitt compared laparoscopic and conventional herniorrhaphy using a Mersilene plug and patch graft for tension free closure [71].

Eventually, advancements in technology that ead to robotic-assisted procedures such as prostatectomy resulted in the crossover of platform use to hernia repair. The first robotic-assisted inguinal hernia repairs were published by urologists who performed intraperitoneal inguinal herniorrhaphy concomitantly to robotic-assisted laparoscopic radical prostatectomies [72, 73]. Later, the feasibility of independent robotic-assisted inguinal hernia repair was shown by Cadière et al. in 2001[74]. In that study, the world premiere of an independent inguinal hernioplasty utilizing the da Vinci surgical platform was demonstrated. A cohort of 146 patients underwent a variety of procedures with no morbidity related to the system reported. In that feasibility study, the successful use of a robotic-assisted surgical platform in the anatomical confinement inherent to hernia repair displayed the benefits of computer enhanced tasks [74]. Furthermore, the da Vinci was noted to excel in intra-abdominal tasks in a small space owing to its mobility and ergonomic instrument end effectors. Several characteristics of the robotic-assisted surgical platform used were reported to improve surgical task quality, including: intra-abdominal articulation of instruments, 3-dimensional visualization, and scaling and stabilization of instrument motion [74].

Current techniques for laparoscopic hernia repair include the transabdominal pre-peritoneal (TAPP) repair, and the totally extra-peritoneal (TEP) repair. In one study, decreased recovery room time and lower average pain was found with robotic-assisted when compared to conventional laparoscopic TAPP [75]. In that study by Waite et al., the robotic-assisted approach was determined to be feasible, although robotic-assisted suturing of the peritoneal flap attributed to longer overall operative time vs. conventional laparoscopy. Additionally, that study found that the direct cost and contribution margin, the product's price less associated variable costs, was roughly equal between the two techniques [75]. In a prospective cohort study by Iraniha et al., outcomes and longitudinal life quality of patients who underwent robotic assisted TAPP inguinal hernia repair were found to be positive. In that study, 82 patients underwent robotic-assisted TAPP, with low recurrence, low pain, and high post procedural quality of life [76].

One metric with which to compare conventional and robotic-assisted incisional hernia repair techniques is hospital length of stay (LOS). In one study of intraperitoneal mesh placement, 454 patients received conventional laparoscopic treatment, with 177 patients receiving robotic-assisted treatment. It was found that the conventional group required a longer LOS of one day vs. the robotic-assisted median LOS of zero days [77]. The shorter LOS came without increases in readmission and postoperative complication. Additionally, a decreased risk was reported of wound morbidities such as surgical site infection and surgical site occurrence including cellulitis, non-healing incision, fascial disruption, ischemia, and necrosis [77]. For instance, robotic-assisted intraperitoneal mesh replacement was shown to have a 9% decreased risk of surgical site occurrence when compared to conventional laparoscopic procedures [77]. However, in that study the operative times of robotic-assisted repairs were 16% more likely to last longer than 2 h compared to conventional laparoscopy [77].

Additional studies have assessed patient outcomes while comparing conventional laparoscopic techniques their robotic-assisted brethren. For instance, in a study of 21,565 patients in New York, outcome measurements were recorded between those two techniques for ventral hernia repair. Among the measures were complications, hospital length of stay (LOS), readmission within 30 days, as well as emergency department visit within 30 days [78]. It was reported, after analysis accounting for variables to estimate treatment effect, that patients who underwent robotic-assisted ventral hernia repair has shorter LOS and lower complication rates [78].

1.9 Robotic-Assisted Surgery Logistics

The use of robotic-assisted surgical platforms in procedures such as inguinal hernia repair has been steadily increasing. A report from Data of the American College of Surgeons National Surgical Quality Improvement Program showed that 13.8% of 510 patients undergoing unilateral inguinal hernia repair from 2012 to 2016 had robotic-assisted procedures vs. 48.1% and 38.1% having laparoscopic and open approaches respectively [79].

Another multi-institutional case series reporting on robotic-assisted laparoscopic ventral and incisional hernia repair described teaching and community hospital outcomes [80]. The study of 368 patients demonstrated the safety of intra-corporeal hernia defect closure by robotic-assisted platform, with intraoperative bowel injury occurring in 0.5% of cases [80]. In that study, conversion to open procedure occurred in 3 patients for reasons of defect size unamenable to closure, adhesion density, and intraoperative bowel injury [80].

While an increase in the number of surgeons implementing robotic-assisted platforms in their practice has been shown, there are barriers to that growth. For instance, the learning curve experienced by surgeons while training on a new system may inhibit the rate at which new patients are exposed to robotic-assisted hernia surgery. One representation of the challenge to surgeons in becoming proficient at robotic-assisted hernia repair included the experience threshold of 50 cases [81]. Additionally, parameters such as operating room size, previous experience with other robotic platforms, existing routines and procedural layout contribute to the integration timeline [82].

Research organizations have forecasted that surgical robot annual revenues more than $20 billion will be realized by 2021 [83]. This growing presence increases the options of surgeons and indicates the increasing representation of robotics in the field of hernia surgery. The cost per procedure is a known barrier to the use of robotic-assisted platforms in the operating suite. One study reported that the use of the da Vinci surgical system increased the cost up to $1500.00 [84]. Further studies are indicated to determine the long-term economics of their use.

1.10 Future Directions

Meaningful predictions require a realistic assessment of current capabilities to accurately map progress. Given the explosive changes and advancements observed in robotic development, speculation on future clinical use is difficult. Machine learning, artificial intelligence, and robotics will likely become increasingly utilized in most aspects of medicine. International Data Corp (IDC), a research firm producing manufacturing forecasts for commercial robotics, predicts developments in a variety of technologies applicable to robotic-assisted surgical platforms used in hernia repair [85]. For instance, improved capability and performance may be facilitated by innovation in computer vision, navigation, and semiconductor technologies. Additionally, the cost of use will likely decrease as more vendors enter the marketplace. Increased competition leading to products in multiple price points seem likely in the face of an information and communications technology landscape estimated to breach $80 billion by 2020. The scope of that sector should provide adequate resources to support the continued research and development of robotic platforms [86]. It was reported that robotic technologies in 2006, which had considerably more capabilities than those of the 1970s, could be purchased for 80% less than those available 30 years prior [87]. Industrial robots with historical prices of hundreds of thousands of dollars can be purchased today for around $20,000. The impact of less expensive options will likely increase with healthcare companies systematically reviewing return on investment before purchasing a robotic system.

The transition of applications and resources from on premise to cloud based software hosting may also improve the capabilities of future systems [85]. For instance, cloud based software will allow robotic platforms to become part of a network of information shared by multiple systems working collectively to improve efficiency and productivity. The deployment of highly automated platforms working collaboratively in the same workspace may provide opportunities for tomorrow's surgeon to take on additional thought processes and challenges [86].

References

1. Peters BS, Armijo PR, Krause C, Choudhury SA, Oleynikov D. Review of emerging surgical robotic technology. Surg Endosc. 2018;32:1636–55. https://doi.org/10.1007/s00464-018-6079-2.
2. Armijo PR, Pagkratis S, Boilesen E, Tanner T, Oleynikov D. Growth in robotic-assisted procedures is from conversion of laparoscopic procedures and not from open surgeons' conversion: a study of trends and costs. Surg Endosc. 2018;32:2106–13. https://doi.org/10.1007/s00464-017-5908-z.
3. Suvajdzic L, Dendic A, Sakac V, Canak G, Dankuc D. Hippocrates—the father of modern medicine. Vojnosanit Pregl. 2016;73:1181–6. https://doi.org/10.2298/VSP150212131S.
4. Smith, WD. (2019) Hippocrates. Encyclopedia Britannica. Retrieved from https://www.britannica.com/biography/Hippocrates. Access date 28 Aug 2019.
5. Asthma AJ. (2019) The Theoi Project: Greek Mythology. Retrieved from https://www.theoi.com/. Access date 28 August 2019.
6. Graziosi B, Haubold J. (Eds.). (2010). Homer: Iliad. Cambridge UK: Cambridge University Press.
7. Ronan CA. The shorter science and civilisation in China. Cambridge: Cambridge University Press; 1985.
8. O'Connor J, Robertson E. (1999) Heron of Alexandria. The MacTutor History of Mathematics Archive. Retrieved from http://www-history.mcs.st-and.ac.uk/Biographies/Heron.html. Access date 28 Aug 2019.
9. Hill DR. Mechanical engineering in the medieval near east. Sci Am. 1991;264:100–5.
10. Valery JP. (2017) Fathers of Robotics: Ismail Al-Jazari. Robot Shop Community. Retrieved from https://www.robotshop.com/community/blog/show/fathers-of-robotics-ismail-al-jazari. Access date 28 Aug 2019.
11. Freed L, Ishida S. (1995) History of Computers. Hightstown, NJ USA: Ziff-Davis Publishing.
12. Marino MV, Shabat G, Gulotta G, Komorowski AL. From illusion to reality: a brief history of robotic surgery. Surg Innov. 2018;25:291–6. https://doi.org/10.1177/1553350618771417.

13. Flatow, I. (2011) Science Diction: The origin of the word ‘robot’. National Public Radio. Retrieved from https://www.npr.org/2011/04/22/135634400/science-diction-the-origin-of-the-word-robot. Access date 28 August 2019.
14. Bladin PF. W. Grey Walter, pioneer in the electroencephalogram, robotics, cybernetics, artificial intelligence. J Clin Neurosci. 2006;13:170–7.
15. Sabbatini RME (1997) The History of the Electroencephalogram. Brain & Mind Magazine. Retrieved from http://www.cerebromente.org.br/n03/tecnologia/historia.htm. Access date 28 August 2019.
16. Walter WG. A machine that learns. Sci Am. 1951;185:60–4.
17. Porter B. (2015). What the tortoise taught us: the story of philosophy. Lanham, Maryland USA. Rowman & Littlefield Publishers.
18. Feder BJ, Danbury C. He brought the robot to life. New York Times 21; 1982.
19. Munson GE. THE RISE AND FALL OF UNIMATION INC.-A story of robotics innovation & triumph that changed the world. Robot-Congers:36; 2010.
20. Anandan TM (2017) The Robotmakers-Yesterday, Today and Tomorrow. Robotic Industries Association. Retrieved from https://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/The-Robotmakers-Yesterday-Today-and-Tomorrow/content_id/6513. Access date 28 August 2019.
21. Kalan S, Chauhan S, Coelho RF, Orvieto MA, Camacho IR, Palmer KJ, Patel VR. History of robotic surgery. J Robot Surg. 2010;4:141–7.
22. Kwoh YS, Hou J, Jonckheere EA, Hayati S. A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. IEEE Trans Biomed Eng. 1988;35:153–60.
23. Lechky O. Worlds first surgical robot in BC. Med Post. 1985;21:92–3.
24. Mohammad S. Robotic surgery. J Oral Biol Craniofac Res. 2013;3:2. https://doi.org/10.1016/j.jobcr.2013.03.002.
25. Satava RM. Surgical robotics: the early chronicles: a personal historical perspective. Surg Laparosc Endosc Percutan Tech. 2002;12:6–16.
26. Spencer EH. The ROBODOC clinical trial: a robotic assistant for total hip arthroplasty. Orthop Nurs. 1996;15:9–14.
27. Lane T. (2018) A short history of robotic surgery. Ann R Coll Surg Engl. 100(6 sup):5–7. https://doi.org/10.1308/rcsann.supp1.5.
28. Davies B, Hibberd R, Ng W, Timoney A, Wickham J. The development of a surgeon robot for prostatectomies. Proc Inst Mech Eng H. 1991;205:35–8.
29. Harris S, Arambula-Cosio F, Mei Q, Hibberd R, Davies B, Wickham J, Nathan M, Kundu B. The Probot—an active robot for prostate resection. Proc Inst Mech Eng H. 1997;211:317–25.
30. Lanfranco AR, Castellanos AE, Desai JP, Meyers WC. Robotic surgery: a current perspective. Ann Surg. 2004;239:14–21. https://doi.org/10.1097/01.sla.0000103020.19595.7d.
31. Jost B, Ketterl M, Budde R, Leimbach T. Graphical programming environments for educational robots: open roberta-yet another one? 2014. p. 381–6.
32. Pugin F, Bucher P, Morel P. History of robotic surgery: from AESOP and Zeus® to Da Vinci®. J Visc Surg. 2011;148:S3.
33. Partin AW, Adams JB, Moore RG, Kavoussi LR. Complete robot-assisted laparoscopic urologic surgery: a preliminary report. J Am Coll Surg. 1995;181:552–7.
34. Falcone T, Goldberg J, Garcia-Ruiz A, Margossian H, Stevens L. Full robotic assistance for laparoscopic tubal anastomosis: a case report. J Laparoendosc Adv Surg Tech A. 1999;9:107–13.
35. Reichenspurner H, Damiano RJ, Mack M, Boehm DH, Gulbins H, Detter C, Meiser B, Ellgass R, Reichart B. Use of the voice-controlled and computer-assisted surgical system ZEUS for endoscopic coronary artery bypass grafting. J Thorac Cardiovasc Surg. 1999;118:11–6.
36. Marescaux J, Leroy J, Gagner M, Rubino F, Mutter D, Vix M, Butner SE, Smith MK. Transatlantic robot-assisted telesurgery. Nature. 2001;413:379.
37. Hoznek A. History of robotic surgery in urology. In: Anonymous Robotic UrologySpringer; 2008. p. 1–9.
38. Himpens J. Telesurgical laparoscopic cholecystectomy. Surg Endosc. 1998;12:1091.
39. Samadi D. History and the future of Robotic Surgery. 2018.

40. Gettman MT, Peschel R, Neururer R, Bartsch G. A comparison of laparoscopic pyeloplasty performed with the daVinci robotic system versus standard laparoscopic techniques: initial clinical results. Eur Urol. 2002;42:453–8.
41. Horgan S, Vanuno D, Benedetti E. Early experience with robotically assisted laparoscopic donor nephrectomy. Surg Laparosc Endosc Percutan Tech. 2002;12:64–70.
42. Carpentier A, Loulmet D, Aupecle B, Kieffer JP, Tournay D, Guibourt P, Fiemeyer A, Meleard D, Richomme P, Cardon C. Computer assisted open heart surgery. First case operated on with success. C R Acad Sci III. 1998;321:437–42.
43. Nguan C, Girvan A, Luke PP. Robotic surgery versus laparoscopy; a comparison between two robotic systems and laparoscopy. J Robot Surg. 2008;1:263–8.
44. Sung GT, Gill IS. Robotic laparoscopic surgery: a comparison of the da Vinci and Zeus systems. Urology. 2001;58:893–8.
45. IntuitiveSurgical (2018) da Vinci Xi Single-Site Instruments and Accessories. Retrieved from https://www.intuitive.com/en-us/-/media/Project/Intuitive-surgical/files/pdf/1025290ra-isi-brochure-single-site-digital-low-res-394110.pdf?la=en&hash=F24EC0B5DB9C62BDD688F77409A3CA50. Access date 28 August 2019.
46. Hanly EJ, Talamini MA. Robotic abdominal surgery. Am J Surg. 2004;188:19–26.
47. Simorov A, Otte RS, Kopietz CM, Oleynikov D. Review of surgical robotics user interface: what is the best way to control robotic surgery? Surg Endosc. 2012;26:2117–25.
48. Fanfani F, Monterossi G, Fagotti A, Rossitto C, Gueli Alletti S, Costantini B, Gallotta V, Selvaggi L, Restaino S, Scambia G. The new robotic TELELAP ALF-X in gynecological surgery: single-center experience. Surg Endosc. 2016;30:215–21. https://doi.org/10.1007/s00464-015-4187-9.
49. Fanfani F, Restaino S, Rossitto C, Gueli Alletti S, Costantini B, Monterossi G, Cappuccio S, Perrone E, Scambia G. Total laparoscopic (S-LPS) versus TELELAP ALF-X robotic-assisted hysterectomy: a case-control study. J Minim Invasive Gynecol. 2016;23:933–8. https://doi.org/10.1016/j.jmig.2016.05.008.
50. Spinelli A, David G, Gidaro S, Carvello M, Sacchi M, Montorsi M, Montroni I. First experience in colorectal surgery with a new robotic platform with haptic feedback. Color Dis. 2017; https://doi.org/10.1111/codi.13882.
51. Haskins O. (2015) TransEnterix completes SurgiBot pre-clinical FDA work Bariatric News. http://www.bariatricnews.net/?q=node/1856. Access date 28 August 2019.
52. Thibault M. Finally details on Medtronic's Robotics Platform. 2016.
53. Kumar A, Yadav N, Singh S, Chauhan N. Minimally invasive (endoscopic-computer assisted) surgery: technique and review. Ann Maxillofac Surg. 2016;6:159–64. https://doi.org/10.4103/2231-0746.200348.
54. Oleynikov D. Robotic surgery. Surg Clin North Am. 2008;88:1121–30.
55. Walker AS, Steele SR. The future of robotic instruments in colon and rectal surgery. Semin Colon Rectal Surg. 2016;27:144–9.
56. DACH Medical Group (2019) Retrieved from https://www.dach-medical-group.com/en/. Access date 28 August 2019.
57. Burcharth J, Pedersen M, Bisgaard T, Pedersen C, Rosenberg J. Nationwide prevalence of groin hernia repair. PLoS One. 2013;8:e54367.
58. Fitzgibbons RJ Jr, Forse RA. Groin hernias in adults. N Engl J Med. 2015;372:756–63.
59. Primatesta P, Goldacre MJ. Inguinal hernia repair: incidence of elective and emergency surgery, readmission and mortality. Int J Epidemiol. 1996;25:835–9.
60. Svendsen SW, Frost P, Vad MV, Andersen JH. Risk and prognosis of inguinal hernia in relation to occupational mechanical exposures—a systematic review of the epidemiologic evidence. Scand J Work Environ Health. 2013;39:5–26.
61. Hernia Specialists (2019) Hernia History. Retrieved from https://herniaspecialists.com/hernia-history/. Access date 28 Aug 2019.
62. Basile F, Biondi A, Donati M. Surgical approach to abdominal wall defects: history and new trends. Int J Surg. 2013;11:S20–3.
63. Tubbs RS, Gribben WB, Loukas M, Shoja MM, Tubbs KO, Oakes WJ. Franz Kaspar Hesselbach (1759–1816): anatomist and Surgeon. World J Surg. 2008;32:2527–9.
64. Puig–La Calle J, Marti-Pujol R. Antonio de Gimbernat (1734–1816): anatomist and Surgeon. Arch Surg. 1995;130:1017–20.

65. Zimmerman LM. Henry O. Marcy, pioneer of hernial surgery. Q Bull Northwest Univ Med Sch. 1949;23:501.
66. Negro P, Gossetti F, Ceci F, D'Amore L. Made in Italy for hernia: the Italian history of groin hernia repair. Ann Ital Chir. 2016;87:118–28.
67. Herzog BF. Chester B. McVay: small-town surgeon, world-famous herniologist. Surgery. 2007;141:119–20.
68. Stoppa R, Wantz G. Henri Fruchaud (1894–1960): a man of bravery, an anatomist a surgeon. Hernia. 1998;2:45–7.
69. Lichtenstein IL, Shulman AG, Amid PK. Use of mesh to prevent recurrence of hernias. Postgrad Med. 1990;87:155–60.
70. Ger R, Monroe K, Duvivier R, Mishrick A. Management of indirect inguinal hernias by laparoscopic closure of the neck of the sac. Am J Surg. 1990;159:370–3.
71. Corbitt JD Jr. Laparoscopic herniorrhaphy. Surg Laparosc Endosc. 1991;1:23–5.
72. Finley DS, Rodriguez E Jr, Ahlering TE. Combined inguinal hernia repair with prosthetic mesh during transperitoneal robot assisted laparoscopic radical prostatectomy: a 4-year experience. J Urol. 2007;178:1296–300.
73. Joshi AR, Spivak J, Rubach E, Goldberg G, DeNoto G. Concurrent robotic trans-abdominal pre-peritoneal (TAP) herniorrhaphy during robotic-assisted radical prostatectomy. Int J Med Robot. 2010;6:311–4.
74. Cadiere G, Himpens J, Germay O, Izizaw R, Degueldre M, Vandromme J, Capelluto E, Bruyns J. Feasibility of robotic laparoscopic surgery: 146 cases. World J Surg. 2001;25:1467–77.
75. Waite KE, Herman MA, Doyle PJ. Comparison of robotic versus laparoscopic transabdominal preperitoneal (TAPP) inguinal hernia repair. J Robot Surg. 2016;10:239–44.
76. Iraniha A, Peloquin J. Long-term quality of life and outcomes following robotic assisted TAPP inguinal hernia repair. J Robot Surg. 2018;12:261–9.
77. Prabhu AS, Dickens EO, Copper CM, Mann JW, Yunis JP, Phillips S, Huang L, Poulose BK, Rosen MJ. Laparoscopic vs robotic intraperitoneal mesh repair for incisional hernia: an Americas hernia society quality collaborative analysis. J Am Coll Surg. 2017;225:285–93.
78. Altieri MS, Yang J, Xu J, Talamini M, Pryor A, Telem DA. Outcomes after robotic ventral hernia repair: a study of 21,565 patients in the state of New York. Am Surg. 2018;84:902–8.
79. Charles EJ, Mehaffey JH, Tache-Leon CA, Hallowell PT, Sawyer RG, Yang Z. Inguinal hernia repair: is there a benefit to using the robot? Surg Endosc. 2018;32:2131–6.
80. Gonzalez A, Escobar E, Romero R, Walker G, Mejias J, Gallas M, Dickens E, Johnson CJ, Rabaza J, Kudsi OY. Robotic-assisted ventral hernia repair: a multicenter evaluation of clinical outcomes. Surg Endosc. 2017;31:1342–9.
81. LeBlanc KA, Kingsnorth A, Sanders DL. Management of abdominal hernias. London: Springer; 2018.
82. Randell R, Honey S, Hindmarsh J, Alvarado N, Greenhalgh J, Pearman A, Long A, Cope A, Gill A, Gardner P. A realist process evaluation of robot-assisted surgery: integration into routine practice and impacts on communication, collaboration and decision-making. Health Services and Delivery Research 5; 2017.
83. Feussner H, Ostler D, Kranzfelder M, Kohn N, Koller S, Wilhelm D, Thuemmler C, Schneider A. Surgery 4.0. In: Anonymous Health 4.0: how Virtualization and Big Data are Revolutionizing HealthcareSpringer; 2017. p. 91–107.
84. Barbash GI, Glied SA. (2010). New technology and health care costs—the case of robot-assisted surgery. New England Journal of Medicine, 363(8), 701–4.
85. Violino B. (2016) The future of robotics: 10 predictions for 2017 and beyond. ZDNet. Retrieved from https://www.zdnet.com/article/the-future-of-robotics/. Access date 28 August 2019.
86. Violino B. (2016) Meet your robot colleague: The advance of collaborative robotics. ZDNet. Retrieved from https://www.zdnet.com/article/the-advance-of-collaborative-robotics/. Access date 28 August 2019.
87. Huse B. (2006) The Perfect Swarm: Robots Past, Present and Future. Robotic Industries Association. Retrieved from https://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/The-Perfect-Swarm-Robots-Past-Present-and-Future/content_id/1040. Access date 28 August 2019.