



## AUTONOMOUS SURGERY USING ARTIFICIAL INTELLIGENCE

## General Surgery

Aarush Shah

## ABSTRACT

This paper provides a critical evaluation of the use of Artificial Intelligence in laparoscopic surgery. It aims to evaluate and identify the feasibility of implementing machine learning in existing surgical robots to perform autonomous surgery. More specifically, it looks at whether a machine learning algorithm, given a set of simple instructions, can perform a laparoscopic cholecystectomy autonomously. It evaluates the ability of such an algorithm to identify various parts of the body during the surgery and whether it can follow short instructions step-by-step in an organised manner to conduct the surgery. The paper also considers the feasibility of implementing such an algorithm in an existing surgical robot such as the da Vinci Xi.

The paper begins by evaluating the advantages and disadvantages of a robotic cholecystectomy. It looks at the various machines used for this purpose and assesses their abilities and limitations. It then aims to identify which of these machines is most suitable for performing autonomous surgery using machine learning. It then looks at the current use of autonomous surgery in the medical field and its implementation to date. It evaluates which algorithms are suitable for this purpose and to what extent they can function. Finally, it gives the limitations of this method and the unexplored factors of this research.

## KEYWORDS

Cholecystectomy, Laparoscopy, Robotic Surgery, da Vinci XI, Artificial Intelligence, Machine Learning, Autonomous Surgery

## INTRODUCTION

Every year millions of operations are carried out across the world. The global volume of surgery was estimated using a modelling strategy and based on available data it was estimated in 2004 that the global volume of surgery was between 187.2 million and 281.2 million cases per year (Weiser, Regenbogen, Thompson, Haynes & Lipsitz, 2008). This number can easily go up to 300 million. In the absence of a national registry, it is difficult to estimate the number of surgeries conducted every year in India.

There are an estimated 1,112,727 specialist surgeons worldwide. However, this specialised work force is distributed disproportionately with low and middle income countries, representing 48 % of global population, comprising about 20 % of this workforce. An insufficiently trained surgical workforce is a major barrier to safe surgical care worldwide (Holmer, Lantz, Kunjumen, Samuel & Marguerite, 2015).

Gallstone diseases are suspected to be prevalent in 10–15 % of adult population. Cholecystectomy or gall bladder removal represents one of the commonest general surgery operations performed worldwide (Stinton & Shaffer, 2012).

Over the years the technique of removing gall bladder has changed from being open surgery to minimally invasive surgery. Laparoscopic approach to gall bladder removal is now considered a gold standard worldwide (Soper, Stockmann, Dunnegan & Ashley, 1992). With advances in technology the same surgery can now be performed by using a Robot which replicates the movements and decisions made by operator (Huang, Chua, Maddern & Samra, 2017).

Injury to the common bile duct (CBD), the channel carrying bile from liver to the intestine, can be a devastating complication of aCholecystectomy. The incidence of CBD injury during the performance of Laparoscopic Cholecystectomy ranges from 0.2 % to 1.1% (Halbert, Pagkratis & Yang, 2016). An analysis of robotic surgery to perform the same operation found it to be as safe as laparoscopic approach (Strosberg, Nguyen & Muscarella, 2017).

Training of a surgeon in safe performance of Laparoscopic or Robotic Cholecystectomy can reduce the incidence of human error related complications (Lien-Heng-Hui et al., 2007). If a similar surgery could be performed by the robot using artificial intelligence and deep learning technology, it could possibly further mitigate the chances of error. Another benefit is that it reduces operator variability in outcomes and reduces differences because of unequal access to trained surgeons globally.

Available robotic surgery platforms show a low level of autonomy and work largely on the “master–slave” pattern where movement of all instruments in robotic arms and decision making is controlled by the surgeon who operates from the same operating room with an assistant

team standing by the side of patient.

A great deal of advance has been made in using robotics as the technology platform for performing multiple intra-abdominal operations including Cholecystectomy. However, despite the advances in AI and ML – the current level of automation in performance of surgery is at Level Zero or One. This means that at the current stage of development the robots are operating in a “master–slave” manner in which the entire control and command is in the hands of surgeon, including the movement of robotic arms. Presently, the robot is incapable of using artificial intelligence to make autonomous decisions and perform a surgical operation. However, with the rapid strides in improvement of AI and ML algorithms and their application to robots – it is very much possible that in the future, robots will perform an autonomous surgery using greater precision and lower error rate than humans.

## METHODS

The search included a review of the current indications and techniques of treatment for gallbladder stone through open, laparoscopic and robotic approaches. The recent advances in the use of minimally invasive techniques and robots have presented a unique opportunity to use artificial intelligence and machine learning algorithms to perform an autonomous surgery. This research also assessed the challenges and future opportunities for the further development of this technology. A Google and PubMed search for relevant articles was done using the keywords mentioned above. Online resources were tapped to learn more about artificial intelligence, machine learning and their application to medicine.

## DISCUSSION

## Cholecystectomy And Laparoscopy

The gallbladder of the human body sometimes develops stones. This process can cause various complications such as pain, infection and even jaundice. In these cases, the surgery performed to remove the gallbladder is called a Cholecystectomy. A German surgeon, Carl Langenbauch, performed the first cholecystectomy in 1882. He performed open surgery, and for the next hundred years, this procedure remained the same (Jarnagin, Belghiti & Blumgart, 2012).

The open surgery to remove the gallbladder was extremely painful. Surgeons would cut the entire abdomen to perform the surgery. The many stitches meant an ugly scar after the surgery and an increased risk of infection. It also took patients a long time to recover from the surgery. During these years, surgeon scientists like Dr George Berci developed various tools and techniques to look inside the abdomen and perform simple surgery through small cuts. This technique was called Laparoscopy (Morgenstern, 2006).

Soon Laparoscopy became standard worldwide. It was called the third revolution for surgery after Anaesthesia and Asepsis. It was a

remarkable improvement over open surgery because small cuts meant better cosmesis, less pain, and early recovery and return to work. There was also a reduced risk of surgical complications and minimal scarring (Kelley, 2008).

Laparoscopic cholecystectomy is a simple procedure in most cases. It is seemingly straightforward for a machine-learning algorithm to perform. However, like any surgery, complications are possible and can cause problems.

### Robotic Surgery

Robotics is an interdisciplinary technical field that integrates computer science, engineering and technology. Robotics deals with the recreation of certain human tasks through the use of sensors mechanisms, movement, manipulation, mobility and computers. Artificial intelligence is an integral part of robotics. The word Robot is associated with the figure of an artificial man and was introduced by the Czech writer, playwright and critic Karel Capek 100 years ago for his scientific fiction play *R.U.R.* (Rossum's Universal Robots) (Moran, 2007).

Robots which can undertake ultra-precise, repetitive and pre-programmed procedures have been prevalent in the industry for a long time. However, they have only recently been used by the medical sector and other industries to enhance the delivery of care.

Collaboration between NASA and Stanford University was the initial research and activity for using robotic systems. The aim was to enable surgeons to perform telesurgery through a remote location. Robotic surgery has been implemented successfully in several hospitals around the world and has received worldwide acceptance. There are three main types of robotic systems currently in use in the surgical arena - active, semi-active and master-slave systems (George, Brand, LaPorta, Marescaux & Satava, 2018).

Active systems can be pre-programmed and essentially the robot works independently to perform these tasks, even though they remain in control of a surgeon. The first active robotic system developed for surgery was the 'ROBODOC' (CUREXO technology corporation) which was used in conjunction with 'ORTHODOC' for precise cuts and positioning of implants in joint replacement surgery.

Semi-active robotic systems, such as 'Acrobot' & 'Rio' developed for use in computer assisted orthopaedic surgery, allow for a surgeon-driven element to complement the pre-programmed element of these robot systems.

The da Vinci XI® and ZEUS® platforms were the forerunners of the formal master-slave systems. These lack any pre-programmed or autonomous elements of other systems. They are entirely dependent on surgeon activity. Surgeons hand movements are transmitted to the robotic surgical instruments, which reproduce surgeon hand activity.

### Advantages, Disadvantages and Limitations of Robotic Surgery

The use of robotic surgery has various benefits for both patients and surgeons. The 'hands' of each arm of a robot are smaller than human hands and eliminate the need for large incisions. Smaller incisions cause less pain and have faster recovery times.

Surgeries also require a high level of accuracy and precision. Robotic surgery eliminates the possibility of strain-related mistakes or slips which a human surgeon may experience. Often surgeries can take hours to complete and be exhausting for the attending surgeon. Surgical robots allow surgeons to comfortably sit while operating, helping to keep them fresh and aware (Van Koughnett, Jayaraman & Eagleson, 2009). The robotic arms also eliminate the tremors of the surgeon's hands leading to more accurate tissue dissection and suturing (Van Koughnett et al., 2009). It also allows a surgeon 360 degree range of motion and seven degrees of freedom compared to a limited wrist movement of the surgeon in open or laparoscopic surgery.

A significant limitation of robotic surgery is lack of tactile feedback, a disadvantage inherited from laparoscopy. The surgeon does not have the benefit of palpating the tissue to enable dissection as in open surgery. There is also an issue of movement latency - the time it takes for the surgical robot to carry out the surgeon's commands. Latency becomes an especially significant obstacle in tele-surgery. It may also impede surgeon's ability to respond quickly to complications like intra

operative bleeding that occur during the operation. There is also the risk of mechanical failure during the surgery and leaking of electric current, causing burns. Robotic surgery can also cause nerve palsies or neck pain due to extreme body positioning or direct nerve compression (Morris, 2005).

The expense of the surgery is also a significant drawback to robotic surgery. The implementation and maintenance of surgical robots are expensive and can increase the cost of surgery for patients.

### The da Vinci XI®

The da Vinci platform has been developed by Intuitive Surgical (Intuitive, nd). The first Robotic Cholecystectomy was performed by Belgian surgeon Dr. Jacques Himpens in 1997, marking the first human use of the da Vinci surgical system. Robots have found an enlarging role in the performance of cholecystectomy and since then several reports of its feasibility and safety have been published (Zaman & Singh, 2018). Since then, several operations involving different organs were performed using this platform. Every year, almost 1 million minimally invasive operations using da Vinci robots are performed. These are tele-manipulators and every movement of the tool and all decisions are still made by the operator. (Tele-manipulators - is a device which through electronic, hydraulic or mechanical linkages allows a hand like mechanism to be controlled by a human operator)

When performing robotic surgery using the da Vinci Surgical System:

- The surgeon works from a computer console in the operating room, controlling instruments mounted on three robotic arms. The operating team at the bedside makes tiny incisions through which trocars are put in the abdominal cavity.
- The robot's "hands" have a high degree of dexterity and the joint has seven degrees of freedom, allowing surgeons the ability to operate in very tight spaces in the body that would otherwise only be accessible through open (long incision) surgery.
- The surgeon looks through a monitor on the console which receives image through a 3-D camera attached to a telescope on the fourth robotic arm which magnifies the surgical site, resulting in enhanced images.
- The surgeon's hand, wrist and finger movements are transmitted through the computer console to the instruments attached to the robot's arms. The mimicked movements have extended range of wrist motion without tremor, allowing the surgeon to have maximum control and more degrees of freedom than human wrist. The surgeon also controls the arm having endoscopic vision and can activate the electrosurgical devices using foot control.
- The surgical team supervises the robot at the patients' bedside.

### Artificial Intelligence

Artificial Intelligence or AI is a branch of computer science majorly concerned with simulation of machines so that they become capable of thinking like humans.

AI is the intelligence demonstrated by machines and refers to the ability of machines or computers to mimic the capabilities of the human mind.

In their groundbreaking textbook *Artificial Intelligence: A Modern Approach*, authors Norvig and Russell (2009) go on to explore four different approaches that have historically defined the field of AI.

1. Thinking humanly
2. Thinking rationally
3. Acting humanly
4. Acting rationally

Artificial Intelligence algorithms are designed to make decisions, often using real-time data. The following are a few examples of Artificial Intelligence in the real world.

1. Chatbots like Siri, Alexa and Swelley use AI to communicate with humans.
2. Self-driving cars such as Tesla use computer vision (a branch of AI).
3. Spam filters and plagiarism checkers use NLP (Natural Language Processing).

In medical science AI has been applied in pre-operative diagnosis via detection of abnormalities on computed tomography and radiographic images. Furthermore, the capability of AI to detect stomach cancer &

polyps during endoscopic inspection is equal to that of skilled doctors. Thus, the use of AI can effectively improve the outcome of a therapy (Amisha, Malik, Pathania & Rathaur, 2019). Google's DeepMind® technology successfully trained a neural network to detect more than 50 types of eye disease, by analysing 3D retinal scans.

IBM Watson® and Google DeepMind® are the leaders and examples of use of AI in mining medical records and data, with the ultimate objective of creating a “cognitive assistant” equipped with a range of clinical knowledge, analytical and reasoning capabilities, alongside.

The use of AI in robotic surgery is practically nonexistent. Manufacturers and surgeons have the opportunity to create a landmark change by incorporating AI and advancing the master-slave format to active or semi-active format. In 2017, surgeons at the Maastricht University Medical Centre used AI assisted robotics to suture extremely narrow blood vessels.

### Machine Learning

Arthur Samuel is credited for coining the term, “machine learning” with his research around the game of checkers (Gabel, 2019). Machine learning is a branch of Artificial Intelligence focused on building AI algorithms using data and improving their accuracy. These algorithms are programmed to find patterns and features in large amounts of data to predict an outcome. The better the algorithm, the more accurate are its predictions and decisions. Algorithms can be improved by providing more data or changing the model used (Thomas, 2020).

Machine learning, deep learning, and neural networks are all sub-fields of artificial intelligence. Deep learning is actually a sub-field of machine learning and neural networks are a sub-field of deep learning. Deep learning automates much of the feature extraction piece of the process, eliminating some of the manual human intervention required and enabling the use of larger data sets.

There are already several machine learning algorithms that have been implemented in the medical world. These include computer vision models which can evaluate X-Rays and MRIs to find diseases (Machine Learning, 2020).

### DISCUSSION

#### Use of Artificial Intelligence/ Machine Learning in Autonomous Robotic Surgery

Richard Satava, a Surgeon from University of Washington who led the first surgical robot funded by the DARPA (US Defence Advanced Research Projects Agency) summarised his many years of experience & visions for future of Surgery as “The future of technology and medicine is not in the blood and bowels at all, but in bits and bytes” (George et al., 2018)

Use of artificial intelligence and machine learning in the conduct of automated surgery requires

1. Breakdown of Surgery into standard procedural steps.
2. Intra operative landmark and anatomy identification system.
3. Replication of surgeon movements, learnt through deep learning by feeding hundreds & thousands of surgical videos of similar surgery, following accurate identification of anatomical structures
4. Movements of robotic arms according to the tissue identification to dissect, cut, coagulate, clip or tie and do hemostasis where required.

Although there is no existing automated robotic surgical system which is capable of doing all the above actions independently but some significant developments have occurred contributing in part to the final goal.

For medical robots to play their role fully they must operate in an environment of information network that allows them to become independent. Automation in the field of vehicles currently being developed by Google, Tesla, Apple & Uber can bring technology to the field of medical robotics. The level of autonomy of the medical robots has been put on a five point scale (modelled on the SAE (Society of Automotive Engineers) International standards organisation (Nawrat, 2020)).

1. *Level 1* – Not autonomous. Tele-manipulation or remote control. Surgical robots such as da Vinci are currently in this group.
2. *Level 2* – Partly automated work. They are capable of interacting with the surgeon to guide or support the execution of a particular task.
3. *Level 3* – Highly automated work. System moves independently in

the work spaces & scope of task but operator must immediately take control if the working conditions are outside the defined area.

4. *Level 4* – Fully automated work. The robot works independently but should still be supervised. In medical science example of such robots are robot radio surgical knives that move and operate in accordance with the planned trajectory and tasks specified before the surgery. Autonomous cars in which the driver takes over the control of car after warning system is also an example of this level of automation

5. *Level 5* – Robot working fully autonomously. Robot works independently; making independent decisions and performs tasks given in its specialisation. The robot has no tele-manipulation system. Example is the city car prototype developed by Google. There are currently no such medical robots.

Yang et al (2017) have given another classification on level of autonomy and discussed the regulatory ethical and legal issues relating to increasing levels of autonomy in robots. More discussion on that is beyond the scope of this paper (Yang-Cambias et al., 2017).

We are currently looking at ways to upgrade the master slave robotic surgical system like da Vinci from level 1 to Level 4. For the robot to achieve this it needs to use Artificial Intelligence. It must have the ability to use an algorithm of real time object detection based on deep learning to recognise intra operative landmarks on endoscopic camera images. It also needs the ability to process these signals based on basic knowledge that was developed during the learning process (in which thousands of images and videos have been fed to enable the performance of operative steps).

There are several significant examples of steps being taken towards a successful conduct of autonomous robotic surgery. Here, it is also important to make a distinction between Automatic and Autonomous Robot. While an automatic robot can do one task with minor variation repeatedly, it cannot make decisions with changed environment or conditions. An autonomous robot, however, can make large adaptations to a change in external conditions by planning its tasks. The planning function requires wider domain knowledge and the use of cognitive tools which do not exist in the automatic system.

In a paper published online in April 2020 issue of Surgical Endoscopy Tokuyasu et al (2021) have used artificial intelligence using deep learning to indicate anatomical landmarks during laparoscopic cholecystectomy. They used the YOLOv3 learning model which is an algorithm for object detection. More than 2000 endoscopic images based on 76 videos of LC were used. The learning model with the training datasets was applied to 23 videos of LC. Four anatomical landmarks were used and although the average precision of identification of each landmark individually was poor, the two surgeons agreed that the YOLOv3 model successfully indicated landmarks essential to avoid a CBD injury in 22 out of 23 cases. The study excluded videos which had bleeding, high fibrosis, scarred images and altered biliary anatomy (Tokuyasu, Iwashita & Matsunobu, 2021).

Robot surgeons cannot yet execute a whole procedure from start to finish. Certain high volume regular surgical operations like cholecystectomy and appendectomy may be performed in an autonomous fashion by a robot. However that may be still some way away, because surgeons are still much better than robots at weighing their past experience to make complex surgical judgments, such as what to do when a blood vessel is in a different place than expected. In situations which require contextual understanding, surgeons will outperform the robot. Similarly in situations where human mind relies on instinct, the automated response may not be sufficient. It is most likely that autonomous surgical devices will enter clinical practice gradually, just as features such as cruise control and, later, lane-keeping systems have made their way into cars ahead of full self-driving capabilities (Svoboda, 2019).

### FUTURE

Shademan *et al* (2016) designed a “Smart Tissue Autonomous Robot, ” or STAR, which consists of tools for suturing as well as fluorescent and 3D imaging, force sensing and fine positioning. With all of these components, the authors were able to use STAR for soft tissue surgery—a difficult task for a robot given tissue deformity and mobility. Surgeons tested STAR against manual surgery, laparoscopy, and robot-assisted surgery for porcine intestinal anastomosis, and found that the supervised autonomous surgery offered by the STAR

system was superior (Shademan-Decker et al., 2016).

There is an ongoing research project on using the da Vinci platform for Autonomous Robotic Surgery. The framework for autonomous robotic surgery will include five main research objectives. The project addresses various research objectives in a graded manner starting with analysis of robotic surgery data to extract action and develop knowledge models for intervention. The second objective will focus on planning, which will consist of instantiating the intervention models to a patient specific anatomy. The third objective will address the design of the hybrid controllers for the discrete and continuous parts of the intervention. The fourth research objective will focus on real time reasoning to assess the intervention state and the overall surgical situation. Finally, the last research objective will address the verification, validation and benchmark of the autonomous surgical robotic capabilities. The research results to be achieved by ARS will contribute to paving the way towards enhancing autonomy and operational capabilities of service robots, with the ambitious goal of bridging the gap between robotic and human task execution capability (Autonomous Robotic Surgery, 2021).

## CONCLUSION

Presently, there are no precedents for a medical system based on artificial intelligence for intra-operative decision making. If we teach robots to read information (measurable data) from sensors and provide algorithms for the formation of correct decisions based on this information, we will achieve an automated device. We will need big data analytics to help the computer process information gained through thousands of surgical images and videos. If we then allow it to modify decisions and actions and assess their effects, we will have a self-learning system that can make decisions different from that we consider appropriate. Artificial intelligence can contribute to reducing errors, improving standards, quality of performed operation and increase patient safety. There are larger challenges related to complex decision making progress in surgery, which can be dynamic and also amalgamating instinct which comes subconsciously from experience.

Many of the tasks that will result in ultimate culmination of fully autonomous surgery have been achieved in steps. However, along with technology a change in the regulatory framework will also have to be done to allow autonomous robots to operate. There are larger ethical and legal questions of the appropriateness and liability when allowing a robot to operate. This is a very interesting field of development and much like the advancement in autonomous cars, flight navigation and space technology – the future will be here.

## REFERENCES

- Weiser TG, Regenbogen SE, Thompson KD, Haynes AB, Lipsitz SR, et al. An estimation of the global volume of surgery: a modelling strategy based on available data. *Lancet* 2008;372:139-44.
- Holmer H, Lantz A, Kunjumen T, Samuel F, Marguerite H et al, Global distribution of surgeons, anaesthesiologists, and obstetricians. *The Lancet Global Health* 2015;3:S9-S11.
- Stinton LM, Shaffer EA. Epidemiology of gallbladder disease: cholelithiasis and cancer. *Gut Liver*. 2012 Apr; 6(2):172-87.
- Soper NJ, Stockmann PT, Dunnegan DL, Ashley SW. Laparoscopic Cholecystectomy .The New 'Gold Standard'? *Arch Surg*. 1992; 127(8):917-923.
- Yeqian Huang, Terence C. Chua, Guy J. Maddern, Jaswinder S. Samra. Robotic cholecystectomy versus conventional laparoscopic cholecystectomy: A meta-analysis, *Surgery*, Volume 161, Issue 3, 2017, Pages 628-636
- Halbert, C., Pagkratis, S., Yang, J. et al. Beyond the learning curve: incidence of bile duct injuries following laparoscopic cholecystectomy normalize to open in the modern era. *Surg Endosc* 30, 2239–2243 (2016)
- Strosberg, D.S., Nguyen, M.C., Muscarella, P. et al. A retrospective comparison of robotic cholecystectomy versus laparoscopic cholecystectomy: operative outcomes and cost analysis. *Surg Endosc* 31, 1436–1441 (2017)
- Lien, Heng-Hui MD ; Huang, Chi-Cheng MD ; Liu, Jung-Sen MD ; Shi, Min-Yean MD ; Chen, Der-Fang MD ; Wang, Nai-Yuan MD ; Tai, Feng-Chuan MD ; Huang, Ching-Shui MD System Approach to Prevent Common Bile Duct Injury and Enhance Performance of Laparoscopic Cholecystectomy, *Surgical Laparoscopy, Endoscopy & Percutaneous Techniques: June 2007 - Volume 17 - Issue 3 - p 164-170*
- Jarnagin WR, Belghiti J, Blumgart LH (2012). *Blumgart's surgery of the liver, biliary tract, and pancreas* (5th Ed.). Philadelphia: Elsevier Saunders. p. 6. ISBN 978-1-4557-4606-4.
- Morgenstern L. George Berzi: past, present, and future. *Surg Endosc*. 2006 Apr; 20 Suppl 2:S410-1.
- Kelley WE Jr. The evolution of laparoscopy and the revolution in surgery in the decade of the 1990s. *JSLs*. 2008 Oct-Dec; 12(4):351-7.
- Moran ME. Rossum's universal robots: not the machines. *J Endourol*. 2007 Dec; 21(12):1399-402.
- George EI, Brand TC, LaPorta A, Marescaux J, Satava RM. Origins of Robotic Surgery: From Skepticism to Standard of Care. *JSLs*. 2018 Oct-Dec; 22(4):e2018.00039.
- Van Koughnett, J.A., Jayaraman, S., Eagleson, R. et al. Are there advantages to robotic-assisted surgery over laparoscopy from the surgeon's perspective? *J Robotic Surg*, 79–82 (2009)
- Morris B. Robotic surgery: applications, limitations, and impact on surgical education. *MedGenMed*. 2005 Sep 27; 7(3):72.
- Intuitive. nd. Retrieved from <https://www.intuitive.com/en-us>.
- Zaman JA, Singh TP. The emerging role for robotics in cholecystectomy: the dawn of a

- new era? *Hepatobiliary Surg Nutr*. 2018 Feb; 7(1):21-28.
- Artificial intelligence—a modern approach by Stuart Russell and Peter Norvig, Prentice Hall. Series in Artificial Intelligence, Englewood Cliffs, NJ. Published online by Cambridge University Press; 07 July 2009
- Amisha, Malik P, Pathania M, Rathaur VK. Overview of artificial intelligence in medicine. *J Family Med Prim Care*. 2019 Jul; 8(7):2328-2331.
- Mike Thomas, S. (2020). Retrieved from <https://builtin.com/artificial-intelligence/machine-learning-healthcare>.
- Machine Learning. 2020. Retrieved from <https://www.ibm.com/cloud/learn/machine-learning>.
- Frank Gabel, S.(2019). Retrieved from [https://hci.iwr.uni-heidelberg.de/system/files/private/downloads/636026949/report\\_frank\\_gabel.pdf](https://hci.iwr.uni-heidelberg.de/system/files/private/downloads/636026949/report_frank_gabel.pdf)
- Nawrat Z. MIS AI - artificial intelligence application in minimally invasive surgery. *Mini-invasive Surg* 2020;4:28
- Guang-Zhong Yang, James Cambias, Kevin Cleary, Eric Daimler, James Drake, Pierre E. Dupont, Nobuhiko Hata, Peter Kazanzides, Sylvain Martel, Rajni V. Patel, Veronica J. Santos, Russell H. Taylor. Medical robotics—Regulatory, ethical, and legal considerations for increasing levels of autonomy. *SCIENCE ROBOTICS* | EDITORIAL 2017
- Tokuyasu, T., Iwashita, Y., Matsunobu, Y. et al. Development of an artificial intelligence system using deep learning to indicate anatomical landmarks during laparoscopic cholecystectomy. *Surg Endosc* 35, 1651–1658 (2021)
- Elizabeth Svoboda, S. (2019). Retrieved from <https://www.nature.com/articles/d41586-019-02874-0#author-0>.
- Azad Shademan1, Ryan S. Decker1, Justin D. Opfermann1, Simon Leonard2, Axel Krieger1 and Peter C. W. Kim1. Supervised autonomous robotic soft tissue surgery. *Science Translational Medicine* 04 May 2016; Vol. 8, Issue 337.
- Autonomous Robotic Surgery. (2021). Retrieved from <https://cordis.europa.eu/project/id/742671>. <https://www.ars-project.eu/>.