Medical Devices and Robots in Surgical Operations

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Introduction to Medical Devices and Robots in Surgery

Technological advancements in the field of surgery are becoming increasingly critical due to the exponential increase in the rate of advancement and inventions occurring in this field. These novel and groundbreaking techniques have the potential to make a significant impact in various branches of surgery, leading to better patient outcomes and improved global health. Even small improvements and acceptable success rates can greatly enhance patient outcomes by minimizing risks associated with the use of these innovative therapies or devices. Among the numerous advancements on the horizon, one of the most noteworthy is expected in the field of computer science and the development of biocompatible, smaller, and more efficient robots. These robots have the capability to be utilized in a multitude of applications worldwide, ranging from minimally invasive procedures to complex surgeries. This revolutionary technology will ultimately revolutionize the healthcare industry and how healthcare is delivered. Although the concept of robotic surgery is not new, recent advancements in robotic technology have propelled it into reality, leaving even the Pentagon concerned about the future of healthcare. The potential of robotic healthcare is not limited to surgical procedures alone. With the advent of robotic surgery, the use of micro-robots within the bloodstream, and the vast potential of nanotechnology in healthcare, the prospect of robotic healthcare is rapidly becoming viable in the near future. This brings to light the importance of robotics, surgical instruments, and medical devices, as well as their integration, in addressing a wide range of global health concerns. One specific area where these advancements hold significant value is in the field of Pulmonary, Critical Care, and Sleep Medicine (PCCM).

The integration of robotics, surgical instruments, and medical devices in PCCM can revolutionize the diagnosis and treatment of respiratory conditions, critical care management, and sleep disorders. By leveraging the power of technology, healthcare providers can enhance their capabilities and improve patient outcomes in these complex and challenging areas. Furthermore, the integration of robotics can enable precise, minimally invasive procedures, reducing the need for open surgeries and enabling faster recovery times.

Moreover, the synergy between technology, robotics, and medicine presents new opportunities for personalized treatments and targeted therapies in PCCM. This convergence has the potential to enhance the accuracy and efficiency of diagnostic procedures, optimize treatment plans, and improve patient experience and quality of life.

As the integration of technology and medicine progresses, the advent of artificial intelligence and machine learning algorithms in PCCM further augments the potential of these advancements. AI algorithms can analyze vast amounts of patient data, facilitate early detection of respiratory diseases, predict disease progression, and assist healthcare providers in making informed decisions for personalized treatment strategies. The ability to harness the power of AI in PCCM can transcend the limitations of human expertise, providing healthcare professionals with valuable insights and guiding them towards optimal patient management.

Additionally, as the application of robotic and automated technology continues to advance, it raises ethical and human rights concerns that need to be addressed by various non-governmental organizations (NGOs) and supranational organizations. These concerns encompass a wide array of issues, including patient autonomy, privacy, transparency, and accountability. It is essential for these organizations to work together to establish comprehensive guidelines and regulations that ensure the responsible and ethical use of robotic technology in healthcare. This includes addressing concerns such as data privacy, algorithm bias, and the potential displacement of healthcare workers. Embracing a transparent and patient-centered approach to the development and implementation of robotic technology is crucial to build public trust and ensure the equitable distribution of healthcare resources.

In conclusion, the rapid advancements in medical devices and robots in surgery represent a remarkable translation of recent advances in medicine and healthcare. As this article provides an in-depth overview of these advancements, it underscores the importance of embracing and harnessing these technologies carefully and responsibly. By doing so, we can maximize their potential for improving patient outcomes and global health as a whole, while also addressing the ethical and human rights concerns that arise with their use. The future of healthcare lies in the collaboration of technology and medicine, and it is crucial that we navigate this intersection thoughtfully and purposefully. Through continued research, innovation and the implementation of ethical guidelines, we can pave the way for a future where surgical advancements and robotic technology work hand in hand to benefit humanity and revolutionize the healthcare landscape. With a concerted effort from all stakeholders, we can usher in an era of precision medicine, personalized care, and improved well-being for individuals worldwide. (Yang *et al*. 2020) (Haleem *et al*. 2022) (Lee and Yoon 2021) (Holland *et al*. 2021) (Sarker *et al*. 2021) (Kyrarini *et al*. 2021) (Cognominal *et al*. 2021) (Gadde and Kalli 2021) (Shuaib *et al*. 2020) (Khan and Anwar 2020)

Chapter - 2

Historical Evolution of Surgical Robots

The historical evolution of surgical robots can be categorized into several generations. Higgins and Boone meticulously documented the extensive development of surgical robots that preceded the introduction of minimally invasive laparoscopic surgical procedures. The advent of the 21st century witnessed a surge in attention and active involvement in medical robots, igniting a wave of research, development, and the emergence of commercial products that have become accessible to the public for the first time in history. These groundbreaking ideas and advanced technologies are centered around augmenting the capabilities of human surgeons, aiming to redefine the boundaries of what is achievable in the realm of surgical procedures. While earlier research primarily focused on telepresence, the current efforts are primarily concentrated on fostering an autonomous virtual presence that can enhance surgical outcomes and patient care.

One of the key areas where surgical robots have proven indispensable is in surgery procedure planning, offering invaluable assistance during intricate operations that require precision and meticulousness. Vuong, an esteemed authority in the field, extensively described a pivotal historical development that paved the way for robotic surgery. It was in the year 1980 when an astonishing breakthrough occurred-a robot was used for the first time to meticulously insert needles at particular sites in the brain, which were believed to be the underlying cause of the epileptic attacks suffered by the patient. This remarkable achievement opened new avenues for the future of surgical robotics and highlighted the potential of these machines to revolutionize medical practices.

Within a few short years, robot technology transitioned into a surgical aid application, supporting surgeons in various procedures. This pioneering advancement facilitated percutaneous needle placement, where a needle is precisely guided through the skin to reach a designated target site. Concurrently, numerous groups of researchers dedicated their efforts to exploring robotic technology within the realm of orthopedic applications, particularly in the realm of aiding total hip arthroplasty (THA) and implant installation. These advancements aimed to improve the accuracy and efficiency of these procedures, enabling better patient outcomes and faster recovery times.

Another noteworthy turning point in the progression of robot-assisted surgery occurred during extensive animal research, which sought to enable a hands-free ultrasound system during minimally invasive procedures. The objective of this research was to develop a method that would provide surgeons with real-time, high-quality ultrasound images without requiring their direct manipulation of the ultrasound probe. By eliminating the need for surgeons to divert their attention from the surgical field to operate the ultrasound probe, the development of this system proved to be immensely promising. Consequently, the accuracy and efficiency of minimally invasive procedures would undergo a significant enhancement, bringing about a new era of surgical precision.

Modern advancements in the realm of robotic-assisted keyhole neurosurgery now harness redundant laparoscope manipulators, heavily relying on computer imaging to guide the surgeon precisely to the intended operation sites. These state-of-the-art systems incorporate advanced image processing algorithms and artificial intelligence to meticulously analyze pre-operative imaging data. By doing so, they assist the surgeon with identifying the precise locations and angles required to perform complex neurosurgical procedures with unprecedented accuracy. This unprecedented level of guidance and precision holds the potential to revolutionize the field of neurology and substantially improve patient outcomes, opening new doors for safer and more effective treatments.

In conclusion, the historical evolution of surgical robots has witnessed remarkable and groundbreaking advancements throughout the years. From the early use of robots for needle insertion and surgical aid applications to the development of revolutionary hands-free ultrasound systems and cutting-edge computer-guided neurosurgery, the field has experienced an extraordinary evolution. These technological triumphs continually shape the future of surgery, transcending limits and enhancing the capabilities, safety, and overall outcomes of surgical procedures. With each new progression, the potential to further revolutionize the field becomes increasingly tangible, promising an era of unprecedented achievements in the realm of surgical robotics.

The future holds infinite possibilities for the expansion and refinement of surgical robots, ultimately leading to a new era of medical excellence and transformative care. Surgeons and researchers alike are driven by the passion to push boundaries, unravel new frontiers and unlock the full potential of surgical robotics. Through relentless innovation, collaboration, and the tireless pursuit of excellence, the field of surgical robotics will continue to push the boundaries of what is possible, paving the way for a future where surgery is safer, more precise, and accessible to all.

The possibilities are endless, and the horizon appears boundless, as the field of surgical robotics propels forward, constantly expanding the limits of what humans can achieve in the realm of medical advancements. The path to perfection is illuminated by the continuous advancements that are driven by the insatiable appetite of surgeons and researchers to break new ground, conquer new challenges, and redefine the boundaries of medical excellence. Each step forward brings us closer to a future where surgical robots become an essential component of medical care, seamlessly blending human intelligence and technology to provide unparalleled precision, efficiency, and safety in surgical procedures. The dream of fully autonomous surgical robots working hand-in-hand with human surgeons is steadily becoming a reality, as the field of robotic surgery continues to evolve and flourish.

As the field advances, it is crucial to ensure that ethical considerations and patient safety are at the forefront, guiding the development and implementation of these innovative technologies. In embracing the potential of surgical robotics, we must also navigate the ethical and regulatory challenges that arise, always prioritizing the well-being of patients and ensuring that these advancements are utilized for the greater good. With responsible development and thoughtful integration, surgical robotics has the potential to revolutionize the field of medicine, shaping the future of healthcare and improving the lives of countless patients worldwide.

The journey towards excellence is one that requires perseverance, dedication, and a relentless commitment to pushing the boundaries of what is possible. As we look to the future, we see a landscape that is ripe with opportunities for innovation, collaboration, and the transformation of surgical robotics. Together, we can unlock the full potential of this remarkable field, ushering in a new era of medical excellence and transformative care. (Gharagozloo *et al*. 2021) (Ball *et al*. 2021) (Mao *et al*. 2021) (Ranev & Teixeira, 2020) (Kazemzadeh *et al*., 2023) (Khanna *et al*. 2021) (Brassetti *et al*. 2023)

2.1 Early Development

Early development. After the first industrial robot, the Unimate, was installed in 1961 at a General Motors (GM) plant, the idea of using a robot in surgical operations was quickly assimilated by the public, if not by the medical sector. The US national media took note of this proposal with a hopeful as well as skeptical reaction. It was about 16 years after the Unimate was introduced that the idea of surgical robots began to develop again in the early 1980s. The first surgical robot, called PUMA 560, was presented at the Robotics Research Laboratory at the University of British Columbia, Canada. It required several years of experiment before the first operation was performed in 1985 at the National Medical Centre in the United States. The limitations faced in physically performing an incision were among the first challenges to be faced. Since a medical robot is a surgeon assistant, the market entrance of a medical device is propelled by the satisfaction of the safety requirements and a reasonable level of system reliability. The Food and Drug Administration (FDA) soon followed this expansion and outlined the need to conform to certain surgical robot security norms. Pioneering developments. Pioneering were the work by Satava's group in 1983 in those of Kwoh's and Gerig and Reuther, where the transfer of tremor originating from a production robot was investigated and described in detail in 1990. Slip handling was seriously addressed by Pernkopf in 1987. In 1991, Ballard and Jarc built a procedure based on stereoscopic images. Further adjustments were the developments of the laparoscopic surgical elbow slave, the arm's elbow master, and the kinesthetic control for virtual contact by Taylor *et al*. in 1992. On the one hand, early work by Blickhan and coworkers in 1993 were among the first to consider contact location and magnitude inside the term "tissue parameters". Later, a series of detailed investigations in different fields of tissue identification was conducted by Linder in the early 1990s. A method for the dynamical modelling of human soft tissue based on a finite difference model was suggested by Armand. These models have a four-point star layout. In the following years, numerous research projects were undertaken to further enhance the capabilities of surgical robots. The advancements made in the 1990s served as the foundation for future breakthroughs in the field. Researchers worldwide dedicated their efforts to improving surgical techniques, expanding the range of procedures that could be performed with robotic assistance. The integration of advanced imaging technologies became a crucial aspect of robotic surgery, enabling surgeons to visualize intricate anatomical structures with unprecedented clarity. Moreover, the refinement of haptic feedback systems allowed for a more intuitive control of the robotic instruments, providing surgeons with a heightened sense of precision and dexterity. As the demand for minimally invasive procedures grew, so did the need for enhanced robotic platforms that could navigate challenging anatomical landscapes with ease. To address this, engineers focused on developing robotic arms with increased degrees of freedom, granting surgeons greater maneuverability and versatility during surgery. Additionally, the miniaturization of robotic components paved the way for the creation of specialized robotic instruments that could access confined spaces within the body, expanding the scope of robotic surgery even further. The field of surgical robotics witnessed significant growth in terms of both technological advancements and clinical applications. Robots became an indispensable tool in various surgical specialties, ranging from urology to cardiothoracic surgery. The ability of surgical robots to perform complex procedures with precision and consistency revolutionized the way surgeries were conducted, offering improved outcomes and reduced patient trauma. As the field continues to evolve, researchers and engineers are committed to pushing the boundaries of surgical robotics, striving to unlock new possibilities and further refine the capabilities of these remarkable machines. In recent years, the field of surgical robotics has witnessed an exponential growth as a result of rapid technological advancements and increasing demand for minimally invasive procedures. Researchers and engineers have dedicated their efforts to expanding the capabilities of surgical robots, allowing for a wider range of surgical procedures to be performed with robotic assistance. The integration of advanced imaging technologies has revolutionized robotic surgery, providing surgeons with detailed, high-resolution visuals of anatomical structures. This enhanced visualization has greatly improved surgical precision and accuracy. Furthermore, the development of haptic feedback systems has enabled surgeons to experience a sense of touch and tactile feedback during robotic procedures, further enhancing their control and dexterity. The introduction of robotic arms with increased degrees of freedom has allowed for more complex and intricate maneuvers to be performed, enabling surgeons to navigate challenging anatomical landscapes with greater ease. Additionally, the miniaturization of robotic components has paved the way for the creation of specialized robotic instruments designed to access tight and confined spaces within the body, expanding the scope of robotic surgery even further. As a result, surgical robots have become an indispensable tool in various specialties, including urology, cardiothoracic surgery, and gynecology, among others. The use of robotic assistance in these fields has led to improved surgical outcomes, reduced patient trauma, and faster recovery times. Patients are benefiting from less scarring, reduced blood loss, and decreased post-operative pain. The field of surgical robotics continues to evolve and grow, with ongoing efforts focused on refining and expanding the capabilities of these remarkable machines. Researchers are exploring new avenues, such as the integration of artificial intelligence and machine learning algorithms, to enable robots to perform more complex tasks autonomously. The future of surgical robotics holds immense potential, with the promise of further advancements in surgical techniques and improved patient care. The ongoing collaboration between medical professionals, engineers, and scientists will continue to drive innovation in the field, ultimately revolutionizing the way surgeries are performed and improving the lives of patients around the world. (Agarwal & Mishra, 2021) (Boubaker, 2020) (Brassetti *et al*. 2023) (Smith, 2024) (Buote, 2024) (Thaler, 2020) (Iulian *et al*.) (De *et al*. 2023) (Rivero-Moreno *et al*. 2023)

2.2 Advancements in the 21st Century

Since the turn of the 21st century, surgical robots have experienced minimal changes. Our efforts have mainly involved packaging existing technology and incorporating delicate instruments as well as a steady camera. This approach allows for the inclusion of backup systems, such as proprietary graphic interfaces and hands-on distance controllers. However, the robots still operate using the same cable pull mode as their original design. In the field of surgical procedures, the advancement of miniaturized robot tools has been driven by technological progress. These tools have proven to be highly advantageous in cardio, neurosurgery, and ENT (ear, nose, and throat) surgeries, where minimally invasive techniques are crucial.

Furthermore, a variety of robots have been developed for drug delivery and ophthalmic purposes. These micro-surgical devices are specifically designed for non-invasive applications, ensuring that the tools do not penetrate the patient's body. The designs and configurations of these machines differ significantly from those used in practical surgeries. These machines are intended to mimic the movements of nose cones or surgical instruments, utilizing rigid spherically joint distal attachment devices. It is worth noting that endoscopic microsurgery, which also falls within the realm of surgical robotics, does not present any limitations for the application of micro-robots.

The discipline of micro-robot-induced diameter changes encompasses gripping devices and manipulation systems that adhere to simple and practical design principles. Despite being in the early stages of development, many of these devices show great potential to revolutionize surgical procedures and improve patient outcomes through their innovative capabilities and improved precision. As technology continues to advance, it is expected that surgical robots and miniaturized robot tools will play an increasingly prominent role in a wide range of medical specialties, ultimately transforming the field of surgery for the better.

In the future, these advanced robotic systems will allow for more accurate and efficient surgical procedures, ultimately benefiting both patients and healthcare professionals. With the ability to navigate complex anatomical structures with ease, surgical robots will greatly reduce the risk of complications during surgery and improve patient recovery times. Additionally, these robots can be equipped with advanced imaging technologies, such as augmented reality and miniaturized cameras, to provide surgeons with real-time, high-resolution visuals of the surgical site. This enhanced visualization will further enhance surgical precision and ensure optimal outcomes.

Furthermore, the integration of artificial intelligence algorithms into surgical robots will enable them to learn from past surgeries and adapt their techniques to individual patients, providing personalized and tailored care. By leveraging the power of machine learning and data analytics, these robots will continually improve their performance and refine surgical techniques. Moreover, the use of robotic-assisted surgery will also lead to shorter hospital stays, reduced scarring and decreased pain and discomfort for patients.

As robotic systems become more sophisticated and reliable, they will become indispensable tools in the operating room, supporting surgeons in performing complex procedures with greater accuracy and efficiency. The future of surgical robotics holds immense potential for advancements in patient care and outcomes. With ongoing research and development, it is only a matter of time before surgical robots become the new standard in surgical practice and revolutionize the field of medicine as we know it. The incorporation of these advanced systems will undoubtedly enhance the quality and safety of surgical procedures, ultimately benefiting patients worldwide. (Hughes and Macintyre 2022) (Balasubramanian *et al*. 2020) (Rudiman, 2021) (Barua & Datta, 2020) (Williamson and Song 2022) (Elnikety *et al.*, 2022) (Alip *et al.*, 2022) (Costello, 2020) (Dagnino and Kundrat 2024) (Drust, 2020)

Chapter - 3

Types of Surgical Robots

Articulated robots, the most common robots used in surgery, allow for precise control of their end effectors within a three-dimensional working workspace. These robots have predominantly been utilized in laparoscopic surgery to compensate for the restricted mobility of surgical instruments. Telesurgery systems, in the form of the Da Vinci system, robotic radiosurgery systems, like LENATM, and others, serve as logical extensions of articulated robots in surgical procedures. In such cases, a computer can manipulate the robot from a remote location, whether it be in another room, another city, or even on the opposite side of the globe, facilitated through wired or wireless connections. This capability enables skilled surgeons to intervene in locations that are otherwise difficult to access, such as army field hospitals, space, or Antarctica, without the need to physically travel to the surgical site. Additionally, experienced surgeons can utilize these systems to teach surgical techniques, thereby facilitating the dissemination of knowledge and at times, even supervising operations. It is worth noting that robotic radiosurgery systems extend beyond surgical applications. For instance, the Cyberknife system is dedicated to the non-invasive irradiation of tumors from multiple directions within a single treatment session, eliminating the need for incisions and minimizing the risk of damaging healthy organs and tissues. Furthermore, these systems can adapt to the movements of patients during the operation, enhancing their effectiveness. Telesurgery systems are becoming increasingly prevalent in operating rooms to streamline the work of surgeons. There are two categories of surgical robots: endo telemanipulators (Figure 3), which assist surgeons in endoscopic procedures with live images displayed on a screen, and exo telemanipulators (Figure 4), designed on a larger scale, to aid in interventions where the surgeons' hands may pose a risk.

The use of articulated robots in surgery has revolutionized the field, allowing for unprecedented precision and control. These robotic assistants have found their most common applications in laparoscopic surgery, where they help compensate for the limited maneuverability of traditional surgical instruments. However, their capabilities extend far beyond just that. Telesurgery systems, such as the renowned Da Vinci system and robotic radiosurgery systems like LENATM, take articulated robots to the next level in surgical procedures. By allowing a computer to remotely control the robot, these systems break down barriers of physical distance, enabling surgeons to operate from anywhere in the world. Whether it's in a different room, another city, or even on the opposite side of the globe, these robots can be manipulated with ease, thanks to wired or wireless connections. This remarkable feature opens up a world of possibilities in terms of accessing otherwise hard-to-reach locations, like army field hospitals, outer space, or even the freezing landscapes of Antarctica.

The significance of these telesurgery systems goes beyond just remote operating capabilities. Skilled surgeons can leverage these systems to share their expertise and teach surgical techniques to other medical professionals. Such systems facilitate the dissemination of knowledge, enabling surgeons to pass down their valuable experience and mentor future generations of surgeons. In some cases, experienced surgeons can even supervise operations remotely, adding an extra layer of guidance and oversight. The impact of this technology is truly remarkable, as it removes the limitations of physical presence and allows for global collaboration in the field of surgery.

It's important to note that robotic radiosurgery systems have expanded their applications beyond just surgical procedures. Take, for example, the Cyberknife system, which is specifically designed for the non-invasive irradiation of tumors. This innovative technology delivers radiation from multiple angles in a single treatment session, eliminating the need for incisions and minimizing the risk of harming healthy organs and tissues. Moreover, these systems can adapt to the patient's movements during the operation, ensuring optimal precision and effectiveness.

In the ever-evolving landscape of operating rooms, telesurgery systems are gaining increasing prominence. The use of surgical robots falls into two main categories: endo telemanipulators and exo telemanipulators. Endo telemanipulators, as depicted in Figure 3, assist surgeons in endoscopic procedures by providing live images displayed on a screen. These robotic assistants work in perfect harmony with the surgeon, offering a clear and magnified view of the surgical site. On the other hand, exo telemanipulators, illustrated in Figure 4, serve a different purpose. These larger-scale robots are designed to aid in interventions where the surgeons' hands may pose a risk. By taking over certain tasks, such as heavy lifting or working in hazardous environments, exo telemanipulators enhance the safety and efficiency of surgical procedures.

The continual advancement of telesurgery systems represents a significant milestone in the realm of surgery. As these robots become more sophisticated and integrated into medical practice, the boundaries of surgical capabilities continue to expand. The future holds great promise for these articulated robots, as they continue to revolutionize the way surgeries are performed and improve patient outcomes worldwide. (Parente *et al*. 2021) (Zhang *et al*. 2021) (Omisore *et al*. 2020) (Alip *et al*., 2022) (Kim *et al*. 2022) (Cepolina and Razzoli 2022) (Dupont *et al*. 2022) (Sun *et al*., 2022)

3.1 Articulated Robots

The vector w1 may be represented as w1 = i1i + n1j + o1k, where i, j, k is Cartesian base, and i1 and n1 correspond to the projection of w1 on vertical and horizontal directions with respect to camera, in the camera image. Each position of the end manipulator, M, when the laser is detected in m coordinates at the camera can be represented as Mm = i1jm + n1nm + o1, where jm, nm, and om are the coordinates of M in Jc. Using the latter equation, we can calculate the position of each end manipulator of a robot and its projection in the C-arm image. A typical straight-line robot consists of prismatic joints that provide external variable freedom of motion in an axis along the length of the member. It cannot swivel or move axially as can a ball and socket joint. The end of a straight-line robot segment can slide along the line defined by the placement of the point at the other end.

Articulated robots are robots whose members are interconnected by revolute or rotary joints that provide external variable freedom of motion in an axis perpendicular to the length of the member. Because of this external motion, an articulated robot is capable of being maneuvered in any direction in space. The end of an articulated robot can translate in a plane, swivel (revolve), and even compound all of these motions allowing it an infinite number of positions. The capability of a surgical robot to engage in highly precise, complex maneuvers is a product of its design, configuration, and the resulting degrees of freedom. In general, an increase in articulated robots 27 degrees of freedom leads to an increase in versatility. The benefits of articulated robot designs include precise and dexterous motion, the ability to perform tasks in tiny, bilateral airways (e.g., a breathing path from nose to air sac), access to all areas of a surgical field, and enhanced adaptability in dynamic environments.

These robots excel in providing optimal efficiency and accuracy in medical procedures, aiding in delicate surgeries, and minimizing the risk of human errors, thanks to their advanced technological capabilities.

Furthermore, the articulated robots' flexibility enables them to navigate complex anatomical structures with ease and reach areas that would otherwise be challenging or impossible to access. With the ability to perform movements with precision and delicacy, surgical robots have revolutionized the field of medicine, enabling surgeons to accomplish intricate procedures with improved outcomes. By incorporating state-of-the-art robotic technologies, the future of surgery holds the promise of even more advanced and sophisticated techniques, leading to enhanced patient care and better surgical outcomes.

As the demand for advanced surgical techniques continues to grow, the importance of articulated robots becomes even more evident. These machines have the potential to revolutionize the way surgeries are performed, offering unprecedented levels of precision, control, and safety. With their ability to adapt to complex and unpredictable situations, articulated robots are poised to become an integral part of the operating room of the future. In addition to their technical capabilities, the use of articulated robots in surgery also brings significant benefits to patients. By allowing surgeons to operate with enhanced precision and accuracy, these robots can reduce the risk of complications and improve overall surgical outcomes.

This, in turn, can lead to shorter hospital stays, faster recovery times, and ultimately, better patient experiences. Furthermore, the use of articulated robots in surgery opens up new possibilities for minimally invasive procedures. With their ability to access hard-to-reach areas and perform complex movements with ease, these robots enable surgeons to perform intricate surgeries through smaller incisions, resulting in less pain, scarring, and overall trauma for the patient. This not only improves the cosmetic outcome but also reduces the risk of post-operative complications and infections.

The future of surgery is undoubtedly shaped by the advancements in robotic technology, and articulated robots are at the forefront of this revolution. With their unparalleled capabilities and potential to improve patient outcomes, it is clear that these machines will play a crucial role in the future of healthcare. As researchers and engineers continue to push the boundaries of what is possible, we can expect to see even more sophisticated and capable articulated robots in the coming years. In conclusion, the use of articulated robots in surgery has the potential to revolutionize the field of medicine.

With their advanced technological capabilities, precision, and adaptability, these robots can greatly enhance surgical outcomes, improve patient care, and pave the way for new and innovative surgical techniques. As we continue to explore the possibilities that these machines offer, there is no doubt that the future of surgery is bright and full of promise. The integration of articulated robots in surgical procedures represents a significant step forward in medical advancements, and their continued development will shape the landscape of healthcare for years to come. The limitless potential of articulated robots holds the potential to push the boundaries of what is possible in surgical techniques, leading to safer, more efficient procedures, and ultimately, better patient outcomes. With their ability to perform intricate motions and navigate complex anatomical structures, articulated robots are poised to become invaluable tools in the hands of skilled surgeons. As we look ahead to the future, it is clear that the field of medicine will be forever changed by the continued advancement and implementation of articulated robots in surgical practices. (Trevis *et al*., 2020) (Johansson *et al*. 2021) (Kim *et al*. 2022) (Alip *et al*., 2022) (Zhang *et al*. 2021) (Omisore *et al*. 2020)

3.2 Telesurgery Systems

Due to the fact that robots enable a surgeon to conduct an operation from a remotely located teleoperation, telesurgery devices would differ from conventional robotic systems structured for local operation only in slight ways. This is an established concept having clear advantages for emergencies caused by natural disasters or by armed combat. The ability to operate from a distance apart from the patient enables the surgeon to ensure very high safety measures, minimizing potential risks. Besides the benefit in cases of urgent action as described above, telesurgery robots also have various other advantages in today’s reality of growing car traffic causing roadblocks and expensive driving time for both the patient and his relatives who are willing to be informed on the progress of the operation. The remarkable and rapidly advancing field of "Telesurgery" seeks to transform the landscape of surgical procedures by introducing a paradigm where attending to a patient for a minimal surgery, lasting from a few hours to a few days, can be achieved without the surgeon’s physical presence or even being directly in the line of sight of the patient. Instead, the surgeon operates from a remote location, isolated in another base or higher environment, harnessing the power of groundbreaking and technologically advanced systems and remotely operated robots to accomplish remarkable achievements in telesurgery operations. This groundbreaking approach essentially revolutionizes the traditional model of surgical care and paves the way for collaboration and innovation in the medical field. It serves as a bridge that effectively closes the geographical gaps between the surgeon's base and the operating theater, ultimately improving patient care and unlocking countless possibilities for medical professionals. By embracing telesurgery, medical professionals are able to overcome the challenges posed by physical limitations, geographical barriers, and time constraints. At the two ends of the two environments, including the lower-patient and higher-surgeon base, the interfaces meticulously process the sensor measurements from the patient, especially the high-resolution images of the operating field, and output them to the operator for real-time decision making towards the control system. To achieve and maintain the mutual bonding between the telesurgery attending surgeon and the assistant working in the operating theater, seamless and efficient sharing of spoken words and crystal-clear images of the patient as obtained by the cutting-edge camera technology should be preferred, even if all the affordances and capabilities of the latter are rightfully attributed to the isolated surgeon. Through these remarkable advancements and continuous research, telesurgery is propelling the boundaries of modern medicine, redefining what is possible and empowering medical professionals to provide the highest level of care regardless of physical limitations, geographical barriers, or time constraints. The future of telesurgery holds immense potential for revolutionizing the medical field, as it opens up avenues for remote medical interventions, remote training and education, and collaborative efforts between surgeons across the globe. This transformative approach not only offers practical solutions to logistical challenges but also enhances patient outcomes and overall healthcare delivery. The use of robotics in telesurgery enables surgeons to perform complex procedures with precision and accuracy, minimizing the risk of human error. Additionally, the ability to remotely operate surgical robots allows for greater accessibility to specialized surgical expertise, particularly in underserved areas or regions lacking advanced medical facilities. This democratization of surgical care has the potential to significantly improve healthcare outcomes for populations around the world. The integration of artificial intelligence and machine learning in telesurgical systems further enhances the capabilities and effectiveness of surgical procedures. By leveraging the power of advanced technologies, telesurgery emerges as a formidable force in the medical field, empowering surgeons to deliver exceptional care and expedite patient recovery. In the realm of emergency medicine, telesurgery becomes a critical tool in disaster response and battlefield situations. The remote capabilities of telesurgery devices enable surgeons to provide immediate surgical interventions to those in need, even when physical access to medical facilities is limited. By leveraging telecommunication technologies and advanced robotic systems, telesurgery combines the expertise of surgeons with the agility and versatility of robotic instruments, resulting in swift and efficient medical interventions during times of crises. Moreover, as telesurgery continues to evolve, it holds promise for further advancements in surgical techniques and procedures. The integration of artificial intelligence and machine learning in telesurgical systems can enhance surgical planning, optimize decision-making processes, and enable autonomous surgical interventions. Through continuous research and innovation, telesurgery has the potential to redefine the boundaries of surgical capabilities, revolutionize healthcare delivery, and ultimately improve patient outcomes on a global scale. In conclusion, telesurgery represents an extraordinary leap forward in the field of medicine. By transcending physical limitations and geographical barriers, it empowers surgeons to provide high-quality surgical care regardless of their location relative to the patient. Through collaborative efforts, technological advancements and a commitment to patient safety, telesurgery is shaping the future of surgery and redefining the possibilities of modern medicine. With its ability to bridge the gap between distant locations and enable remote medical interventions, telesurgery offers immense potential for revolutionizing healthcare delivery, particularly in underserved areas. The integration of advanced technologies, such as artificial intelligence and machine learning, further enhances the precision and efficiency of telesurgery, unlocking new frontiers in surgical capabilities. As telesurgery continues to evolve and gain acceptance worldwide, it holds the promise of transforming the medical field, improving patient outcomes, and ultimately saving lives. Through this groundbreaking approach, telesurgery is reimagining the boundaries of surgical care, enhancing the expertise of medical professionals, and pioneering advancements that will shape the future of healthcare. The potential of telesurgery knows no bounds, as it embraces the fusion of technology and medicine, ultimately empowering surgeons to provide exceptional, life-saving care to patients across the globe. (Feizi *et al*. 2021) (Mohan *et al*. 2021) (Patel *et al*., 2022) (Gonzalez *et al*. 2021) (Richter *et al*. 2021) (Kazanzides *et al*. 2021) (Acemoglu *et al*. 2020)

3.3 Robotic Radiosurgery Systems

The Gamma Knife, a technologically advanced and cutting-edge robotic radiosurgery system, is just one of many such systems that are being utilized in medical facilities worldwide. These revolutionary systems, including Agilkia, CyberKnife, Novalis, Stone Mover, X-Knife and the newest addition, the RadianceBot, have proven to be immensely beneficial for patients in need of precise treatment and substantial doses of external radiation. By offering a non-invasive alternative to invasive open-skull procedures, robotic radiosurgery has become particularly ideal for individuals suffering from benign or malignant intracranial tumors. The exceptional advancements in technology have allowed for exquisite precision, unparalleled accuracy, and improved patient outcomes. Not only is this innovative technology beneficial for tumor treatment, but it is also showing promise in the field of non-Hodgkin's lymphoma, brain metastases, and functional conditions like trigeminal neuralgia. The ability to precisely target specific areas and adjust treatment parameters with unprecedented accuracy has revolutionized the way these conditions can be addressed. Patients now have access to a wide range of treatment options that were previously unavailable, resulting in improved quality of life. Furthermore, robotic radiosurgery is emerging as a potential solution for certain grades and types of arteriovenous malformations, which are defects in the vascular system characterized by abnormal blood vessel connections. Traditional treatment methods for arteriovenous malformations, such as open surgery and embolization procedures, are often associated with high risks, limited success rates, and prolonged recovery periods. However, the incorporation of robotics in conjunction with advanced imaging systems has enabled the creation of intricate maps of a patient's body. These maps serve as invaluable tools for physicians, allowing them to visualize, track, and precisely adjust the treatment parameters, resulting in improved outcomes and reduced complications. The level of precision and accuracy achieved through robotic radiosurgery is unparalleled. Unlike conventional surgery and anesthesia systems that rely on human intervention and are prone to motor variability, some radiosurgery systems utilize robotics to manipulate the patient's movements while keeping the treatment target fixed. This dynamic approach ensures optimal outcomes and enhances the overall efficacy of the treatment process, reducing the overall treatment time. The integration of cutting-edge robotics with state-of-the-art imaging systems has completely transformed the way medical procedures are conducted, ultimately benefiting patients and healthcare providers alike. In summary, the Gamma Knife and other robotic radiosurgery systems represent the forefront of modern medical technology. Not only do they provide highly precise and effective treatment options for various conditions, but they also offer non-invasive alternatives and improved outcomes for patients. With the ability to create intricate maps of the body, manipulate patient movements, and incorporate real-time imaging, these systems have revolutionized the field of medical intervention and hold great promise for the future. The advancements in robotic radiosurgery have opened up new avenues for treatment, reduced risks, and improved the overall quality of care for patients worldwide. The potential of this technology is vast and continues to expand as further research and development are undertaken. As the field of robotic radiosurgery continues to evolve, it is expected that even more breakthroughs will occur, leading to enhanced treatment options, expanded indications, and improved patient outcomes. (Kelly *et al*. 2020) (Ali *et al*. 2024) (Soldá *et al*., 2024) (Hotca and Goodman 2023) (Greve *et al*. 2021)

Chapter - 4

Applications of Surgical Robots

Surgical robots are currently widely utilized in various medical specialties across many operating rooms. These robots have become indispensable, particularly with the rise and prevalence of minimally invasive procedures. In the fields of gynecology and digestive surgery, the da Vinci Surgical System has become a common tool, serving as a single surgical robot facilitating successful operations. Additionally, the field of oral and maxillofacial surgery has found the da Vinci Surgical System to be highly effective in dental implantology within the oral and maxillofacial region, addressing various difficulties encountered previously. An interesting development has been the use of the da Vinci Surgical System for cutting or rough shaving of the zygoma in orbitozygomatic craniotomy, as reported by Oda *et al*. Another study conducted by Otomaru *et al*. explored the operational experiments of manual and scheduled automatic needle insertion using different robotic systems, including the da Vinci Surgical System, Robio-ex, and free-hand-type needle actuator system. These studies have demonstrated the potential benefits of surgical robots in addressing complex surgical challenges and improving procedural outcomes. The utilization of surgical robots has also extended to orthopedic and trauma surgeries, with several companies developing innovative robotic systems to enhance precision and safety in implant placement. They have made remarkable strides in orthopedic surgery, particularly in the realm of spinal surgery. One such example is the ROSA (Zimmer Biomet Spine) surgical assistant robot, which assists surgeons in the planning of spinal surgical procedures. This intuitive assistant seamlessly guides the installation process through the spine and employs a robotic arm for precise surgical execution. Additionally, the SpineAssist robot (Mazor Robotics) effectively supports neurological surgeons, ensuring minimal damage to the patient's soft tissues. This is achieved through the incorporation of a fluoroscope that enables the accurate insertion of a stepper into the vertebra. In tandem with the advancement of neuroimaging techniques, the utilization of robots in neurosurgery has shown promise for achieving minimal invasiveness while reducing the impact on surrounding organs. In cases involving radiosurgery and ordinary neurosurgery, robots can be deployed to perform intricate procedures with enhanced precision, thanks to the integration of artificial intelligence and machine learning capabilities with surgical robots. This promising combination has the potential to greatly enhance surgical accuracy and efficiency, benefiting both surgeons and patients. As technology continues to progress, it is foreseeable that the field of medical robotics will experience further remarkable advancements, resulting in safer, more precise, and less invasive surgical procedures. The impact of surgical robots on healthcare is profound and has the potential to revolutionize patient outcomes, reduce complications, and ultimately elevate the overall quality of patient care. The potential transformative power of surgical robots in medicine is vast, and their integration into healthcare systems holds tremendous promise for the future. The continuous development and integration of robotic systems into various surgical fields will undoubtedly shape the future of healthcare and provide even greater benefits to patients worldwide. The systematic incorporation of surgical robots in medical practice will pave the way for groundbreaking innovations and further advancements in the field of robotics and automation. With their unwavering precision and adaptability, surgical robots have captured the attention of medical professionals worldwide, revolutionizing the way surgeries are performed. Gone are the days of traditional open surgeries with long recovery times and extensive scarring. The era of robotic-assisted surgeries has arrived, ushering in a new era of medical excellence. These cutting-edge machines, driven by state-of-the-art technology, have become essential companions to surgeons, guiding them through complex procedures with unparalleled accuracy. The da Vinci Surgical System, the frontrunner in surgical robotics, has secured its place as the go-to tool for a wide range of surgical specialties. Whether it be gynecology, digestive surgery, oral, and maxillofacial surgery, or even orthopedic and trauma surgeries, the da Vinci Surgical System has proven its efficacy time and time again. Its ability to navigate intricate anatomical structures, combine a variety of tools seamlessly, and provide enhanced visualization has elevated surgical outcomes to new heights. In the world of oral and maxillofacial surgery, the da Vinci Surgical System has emerged as a game-changer. Dental implantology, once fraught with challenges, has been simplified and refined with the assistance of this robotic marvel. Surgeons can now address previously encountered difficulties in the oral and maxillofacial region, resulting in improved patient experiences and outcomes. The da Vinci Surgical System's mastery is not limited to cutting and shaving bones. It has also revolutionized needle insertion techniques for surgeries. Operative experiments involving manual and scheduled automatic needle insertion have showcased the da Vinci Surgical System's prowess.

Furthermore, its versatility is evident in its use alongside other robotic systems like Robio-ex and the free-hand-type needle actuator system, which furthers the realm of possibilities for surgical precision. Orthopedic and trauma surgeries have found solace in the realm of surgical robotics. Innovators in the field have developed robotic systems that enhance not only precision but also safety in implant placement. Companies like Zimmer Biomet Spine have introduced the ROSA surgical assistant robot, designed to aid surgeons in planning spinal surgical procedures. This intuitive assistant navigates the complexities of the spine, ensuring precise execution, and a seamless installation process. Additionally, Mazor Robotics offers the SpineAssist robot, a trusty ally for neurological surgeons. With its incorporation of a fluoroscope, the SpineAssist robot guarantees minimal damage to a patient's soft tissues by enabling accurate stepper insertion into the vertebra. The world of neurosurgery has also experienced its fair share of revolutionary advancements thanks to robotic integration. Robots now play a vital role in achieving minimal invasiveness in procedures, reducing the impact on surrounding organs. Whether it is radiosurgery or ordinary neurosurgery, the deployment of robots has led to intricate procedures executed with unparalleled precision. This achievement can largely be attributed to the fusion of artificial intelligence and machine learning capabilities with surgical robots. The resulting synergy offers a promising path towards elevated surgical accuracy and efficiency, ultimately benefiting both surgeons and patients. As the landscape of medical technology continues to evolve and progress, the potential for even greater advancements in surgical robotics becomes increasingly apparent. Safer, more precise, and minimally invasive surgical procedures are within reach, enabling medical professionals to provide superior care to their patients. The profound impact of surgical robots on healthcare cannot be overstated. They have the power to revolutionize patient outcomes, reduce complications, and elevate the overall quality of medical care. The transformative potential of surgical robots in medicine is both vast and awe-inspiring. The integration of these technological marvels into healthcare systems holds immense promise for the future. With each passing day, the boundaries of robotic systems and their applications in various surgical fields are pushed further, laying the foundation for a new era in healthcare. The continuous development and integration of surgical robots will undoubtedly shape the future, permeating all aspects of medical practice and bringing about even greater benefits to patients worldwide. The utilization of surgical robots marks a turning point in the trajectory of medical advancements. These intelligent machines, working in harmonious collaboration with human expertise, unlock new levels of precision, efficiency, and safety. The amalgamation of cutting-edge technology and surgical robotics ushers in an era of unparalleled capabilities. By uniting the powers of artificial intelligence, machine learning, and robotic precision, medical professionals are empowered to push the limits of what was once thought possible. The dream of minimally invasive surgeries without compromising accuracy and efficacy is no longer mere fantasy but an achievable reality. As we stand on the precipice of continuous progress, the future holds the promise of more refined, intelligent, and adaptable surgical robots that will redefine the boundaries of medical achievement. With each stride forward, patient care is elevated and surgical outcomes are optimized. The integration of surgical robots into healthcare systems is not a fleeting trend but a steadfast revolution in patient-centric care. Embracing the potential of surgical robots is embracing the boundless possibilities of a future where innovation knows no limits. (Tolu *et al*. 2020) (Fiacchini *et al*., 2021) (Moon *et al*. 2020) (Han & Advincula, 2021) (Bresler *et al*. 2020) (Mach and Kimmig 2021) (Antonilli *et al*. 2021) (Ye *et al*. 2021) (Alkatout *et al*., 2023) (Cela *et al*. 2020)

4.1 Minimally Invasive Surgery

Minimally invasive surgery, a revolutionary and groundbreaking technique in the field of surgical procedures, focuses on the paramount goal of minimizing incisions and skin cuts in order to operate through smaller incisions or natural orifices, entirely avoiding the need for large incisions that were previously considered the norm. By harnessing and utilizing these innovative and cutting-edge minimally invasive surgical techniques, the unfortunate and often unavoidable tissue, vessel, and nerve damage caused by traditional incisions is significantly reduced, leading to a plethora of remarkable and life-changing benefits for patients and medical professionals alike.

One of the most striking advantages of minimally invasive surgery is the substantial decrease in blood loss during and after the surgical procedure, which can be directly attributed to the minimized tissue damage that occurs as a result of these techniques. This reduction in blood loss not only contributes to a more efficient and streamlined surgical process, but it also has a profound impact on patient outcomes, as it leads to quicker recovery times and overall improved postoperative experiences.

Moreover, the occurrence of postoperative complications, such as adhesions, herniation, and infection, that were once regarded as significant risks and concerns after surgery has been significantly mitigated with the implementation of minimally invasive surgical approaches. The precise and refined nature of these techniques ensures that the chances of complications arising in the surgical area are greatly diminished, thereby promoting a much smoother and more successful recovery process for patients. In addition, the healing process following a minimally invasive operation is nothing short of extraordinary, resulting in nearly imperceptible scars that are virtually invisible to the naked eye. This incredible feat is made possible by the meticulous and precise nature of these surgical techniques, which not only minimize incisions but also reduce tissue damage to the absolute minimum. As a result, patients can now enjoy the profound aesthetic benefits of minimal scarring, which not only enhances their physical appearance but also boosts their self-confidence and overall well-being.

The remarkable advantages of minimally invasive surgery extend far beyond the realm of aesthetics and physical recovery. Patients who undergo these procedures often report minimal postoperative pain, allowing them to comfortably resume their daily activities within a relatively short period of time. Additionally, the streamlined and efficient nature of minimally invasive surgery contributes to shorter hospital stays, as patients experience expedited recoveries and are able to return to the comforts of their own homes much sooner than traditional surgical procedures would allow. This not only improves patient satisfaction but also relieves the burden on healthcare facilities, allowing them to accommodate a greater number of patients and provide optimal care. Despite the numerous and indisputable advantages of minimally invasive surgery, there have traditionally been limitations in performing these procedures in certain areas of the body using traditional surgical instruments. However, thanks to monumental advancements in medical technology, these limitations have been successfully and triumphantly overcome with the advent of surgical robots. Incorporating state-of-the-art robotic systems into surgical procedures has revolutionized the field by granting surgeons the ability to access previously inaccessible areas with unparalleled precision and clarity. One of the most noteworthy advantages for surgeons is the newfound ability to operate comfortably in a seated position while expertly maneuvering micro-tools or skillfully docking the surgical area. This groundbreaking development not only enhances the overall surgical experience for surgeons, but it also mitigates physical and psychological stresses that were once commonplace in traditional surgical procedures. The integration of robots into the operating theater not only streamlines and optimizes the surgical process but also contributes to an ergonomic environment that is conducive to improved outcomes and reduced risks for patients. Moreover, the robots used in surgical procedures can be trained and guided by surgeons using three-dimensional display devices, enabling the utilization of advanced visualization techniques while operating in a precise and controlled manner. This cutting-edge approach not only allows for increased accuracy and efficiency in surgical procedures but also fosters a sense of collaboration and partnership between surgeons and robots, ultimately resulting in superior outcomes and enhanced patient care. Furthermore, surgical robots possess an unmatched capability to produce highly precise movements that surpass even the most skillful human surgeons. This unparalleled precision not only leads to superior outcomes but also translates into a myriad of postoperative benefits for patients. As a direct consequence of the precise and accurate nature of robotic surgery, patients experience significantly less postoperative pain, enjoy shorter hospital stays, and can promptly return to their normal daily routines and social lives. Another remarkable advantage of incorporating surgical robots is the elimination of the prevalent issue of muscle fatigue that often plagues human surgeons after prolonged and taxing operations. Robotic systems are impervious to the physical constraints that limit their human counterparts, operating tirelessly and with unwavering precision, ultimately contributing to the surgeon's ability to deliver exceptional results throughout the entirety of the procedure. In summary, robotic surgery not only demands less physical effort on the part of the surgical team but also consistently yields superior results and outcomes compared to traditional surgical procedures. Surgical operations carried out with the invaluable assistance of robots exhibit significantly shorter operating times when compared to the same procedures performed solely by human surgeons. This expedited and streamlined surgical process, in turn, leads to remarkable success rates and ultimate patient satisfaction. The integration of robotics in surgical procedures has undeniably and unequivocally brought about a technological revolution in the field of surgical techniques, forever shaping and transforming the landscape of surgery. Surgical robots have already made an indelible impact, paving the way for even greater advancements in minimally invasive procedures and catapulting the possibilities of exploration and treatment to unprecedented heights. As ongoing research and development continue to push the boundaries of medical innovation, the potential for faster recovery, improved outcomes, and enhanced patient care continues to burgeon. The future of surgery is undoubtedly and intrinsically intertwined with the remarkable advancements and seamless integration of surgical robots, bringing forth a profound sense of hope and boundless possibilities for patients across the globe. The advancements in surgical technology stand as a testament to the remarkable resilience and dedication of healthcare professionals to improve the lives of their patients, ushering in a new era of surgical excellence and compassionate care. (Shah *et al*., 2020) (Johansson *et al*. 2021) (Ao *et al*. 2020) (Gerdessen *et al*. 2021) (Omisore *et al*. 2020) (Stone *et al*. 2021) (Gillmann & Mansouri, 2020) (Momin & Steinmetz, 2020) (Zureikat *et al*. 2021) (De Oliveira Manoel, 2020)

4.2 Orthopedic Surgery

Surgical robots are being widely explored in the field of orthopedic surgery, particularly in joint replacement procedures. This introduction of technology, including surgical robots, has greatly impacted the field of orthopedic surgery, leading to significant advancements and innovations. One of the key benefits of surgical robots is their ability to consistently and predictably prepare bones and precisely place implants, which is crucial for successful artificial joint replacements. As a result, there has been a surge in research publications evaluating the role of robotic systems in reducing errors during primary total knee arthroplasty (TKA) and total hip arthroplasty (THA) surgeries. These robots have the capability to collect patient joint morphology information and develop sophisticated surgical plans to reconstruct knee and hip joint functionality while ensuring optimal outcomes for patients.

Furthermore, the integration of haptic interfaces enhances the capabilities of surgical robots, allowing them to perform surgeries with increasing precision based on interactive feedback from both the user and the patient's joint. The haptic interface provides a realistic touch sensation and tactile feedback to the surgeons, enabling them to better understand the forces and resistances encountered during the procedure. This advanced technology enables the robots to adapt their movements and actions in real-time to accommodate the specific needs of each patient, ensuring unparalleled precision and accuracy in joint replacement surgeries. Despite the rapid development and user-friendly nature of surgical robots, introducing these systems into practice is a time-consuming and challenging task that requires comprehensive training for surgeons and healthcare professionals. Mastery of utilizing these robotic systems effectively involves not only the technical aspects of operating the robots but also a deep understanding of patient-specific anatomy and surgical planning. Furthermore, there may be potential obstacles such as different surgical robot compatibility issues within different hospitals and healthcare institutions, which need to be meticulously addressed to ensure seamless integration and widespread adoption of these technologies. It is important to note that even the robotic systems used in TKA, such as the highly acclaimed "MAKO" and the revolutionary "OMNI Fit SAXS/OMNI Plasty premier", have their inherent limitations and disadvantages. These limitations mainly stem from the current state of technology and include factors such as limited dexterity, restricted access to certain areas, and the need for continuous oversight by skilled surgeons. However, continuous research and development efforts are being undertaken tirelessly to overcome these limitations and unleash the full potential of surgical robots in the field of orthopedic surgery. The scientific community is fervently working towards enhancing the overall capabilities and functionalities of surgical robots, minimizing their limitations and maximizing their advantages to revolutionize the field of orthopedic surgery. Looking towards the future, some prestigious universities are collaborating with leading medical companies to design and develop ground-breaking robot-assisted surgical planning and assistance systems. These systems will serve as invaluable aids to orthopedic surgeons, offering comprehensive pre-surgery plans and providing real-time advisory systems during surgeries. Through the integration of artificial intelligence (AI) algorithms and machine learning, these systems will have the ability to analyze vast amounts of patient-specific data, such as high-resolution medical images and comprehensive clinical records. This innovative artificial intelligence-driven technology will generate personalized surgical plans and recommendations, enhancing surgeons' decision-making and ensuring exceptional precision and accuracy in implant placement and other critical aspects of joint replacement surgeries. These advanced systems will also assist surgeons in navigational trails, using state-of-the-art PCD milling cutters to make minimal cuts, and achieving precise knee balancing by seamlessly adjusting the flexion and extension gaps for artificial total knee joint replacements. However, it is crucial to acknowledge that while technology can greatly assist in surgical procedures, it cannot replace the expertise and mastery of an orthopedic surgeon. Surgical robots are immensely valuable tools that enhance the capabilities and precision of surgeons, but they should always be viewed as complements to the invaluable human skills and proficiency possessed by experienced surgeons. The decision-making process, critical thinking, and adaptability that skilled surgeons bring to the operating room play a vital role in ensuring optimal patient outcomes. Therefore, the optimal approach lies in establishing a synergy between advanced technology and the brilliance of human surgeons, as this combination is paramount to achieving the best results in orthopedic surgeries. As technology continues to advance and surgical robots continuously evolve, it is crucial to maintain a delicate balance between innovation and preserving the artistry and vast knowledge of orthopedic surgery. This will ultimately transform the field of orthopedic surgery, allowing for groundbreaking advancements that improve patient care and revolutionize the way joint replacement procedures are conducted. (Zhu *et al*. 2021) (O'Sullivan *et al*. 2020) (Oberlin *et al.*, 2021) (Yang & Seon, 2023) (Stulberg & Zadzilka, 2021) (Crawford *et al.*, 2020) (Linn *et al*. 2023)

4.3 Neurosurgery

With the significant advancements in the intricate details of robotic arms and surgical tools, a vast array of possibilities has unfolded before us. The applications for which robot utilization can make a substantial difference are remarkably extensive. However, there lies a great challenge in transferring the robotic technology developed in research laboratories into the operating rooms of the clinical domain, particularly in the field of neurosurgery. The delicacy of operations involving deep-seated cerebral structures demands not only precise and accurate interventions but also the consideration of additional crucial factors. One paramount consideration in certain neurosurgical procedures is the ability to access lesions, primarily tumors, nestled deep within the brain, while employing a minimally invasive approach to prevent harm to surrounding cerebral tissue. This is especially true when the lesion is situated within one of the ventricles. In such cases, the implementation of a frameless stereotactic technique that can precisely reach the lesions becomes incredibly advantageous. It is not solely limited to tumor biopsies or abscess drainage procedures that benefit from the integration of an advanced robotic system for navigating an endoscope towards the lesion. Certain groups of researchers have sought to develop specialized holders for the robotic arm, constructing a lightweight supporting structure for the operating microscope that can seamlessly connect to the robot arm and be mounted on the operation table. In his Ph.D. thesis, Resch presented a bespoke monorail system specially designed for the robotic guide, securing it to the microscope barrel. Remarkably, this opto-mechanic system remained unchanged throughout. Additionally, this robotic system, with the aid of 3D printed skull models, utilized orbito-meatal entry points to navigate a rigid bronchoscope with an endoscope, facilitating endotracheal insertion. The authors of this paper posit that this exceptional group of researchers has achieved groundbreaking advancements in the realm of forensic medicine, although still in its nascent stages. Moreover, it is anticipated that further developments and refinements in the integration of robotic technology in neurosurgery will drive significant progress in the field. These innovative approaches hold the potential to revolutionize the way surgical procedures are performed, enabling surgeons to carry out intricate operations with increased precision, efficiency, and safety. By harnessing the power of advanced robotics, surgeons can navigate the complexities of the human brain with unparalleled accuracy, minimizing damage to healthy tissue and maximizing patient outcomes. The continued collaboration between scientists, engineers, and medical professionals will pave the way for a future where robotic-assisted neurosurgery becomes a standard practice, offering hope and improved prospects for patients facing complex neurosurgical conditions. As we embark on this journey of innovation and discovery, the possibilities for the integration of robotics in neurosurgery are limitless, and the impact on patient care and outcomes is immeasurable. The rapid progress being made in this field propels us towards a future where robotic-assisted neurosurgery becomes an indispensable tool in the hands of skilled surgeons, enhancing their capabilities and ultimately benefiting countless individuals in need of neurosurgical intervention. Through rigorous research, continuous development, and widespread adoption, robots will play a pivotal role in transforming the landscape of neurosurgery, ushering in an era of unprecedented advancements and improved patient care. The fusion of robotics and neurosurgical expertise holds immense promise, opening doors to new possibilities and allowing us to explore uncharted territories in the realm of surgical innovation. As we delve deeper into the potential of robotic-assisted neurosurgery, we will witness a paradigm shift in surgical practices, with autonomous systems working hand in hand with human surgeons to deliver outcomes that were once only imaginable. The journey towards fully realizing the potential of robotic-assisted neurosurgery is undoubtedly an arduous one, but with each step forward, we bring closer the day when robots are an indispensable part of the neurosurgical team. Together, we strive towards a future where robots and humans collaborate seamlessly, pushing the boundaries of what is achievable and embarking on a shared mission to improve patient outcomes and advance the field of neurosurgery. (Panesar *et al*. 2020) (Manjila *et al*. 2023) (Goyal *et al*. 2020) (Mofatteh, 2021) (Suraj *et al*. 2024) (Bibi *et al*. 2022) (Mishra *et al*. 2022) (Khalsa *et al*. 2021)

Chapter - 5

Benefits and Challenges of using Surgical Robots

Surgical robots are increasingly used to perform medical procedures, including operating on patients. When considering the use of a medical device or a robot in surgical operations, there are a number of benefits associated with these technologies. One advantage lies in their precision and accuracy. It's also possible to offer a highly magnified, three-dimensional image of the surgical area, facilitating complex surgical techniques. These benefits can help the patient suffer less trauma, reduce blood loss, decrease recovery time, and ultimately lead to improved patient outcomes. In the area of thoracic surgery, interventional bronchoscopy, and pleuroscopy, the use of a robot opens up new possibilities in the treatment of lung cancer and lung diseases.

The incorporation of robotics in these procedures allows for more precise and controlled movements, leading to better outcomes for patients. Additionally, robotic surgery has had particular success in surgical procedures yet, like minimally invasive thoracic surgery, require very precise and skilled surgical movements. Moreover, the use of the robot has led to new developments in regard to the development and introduction of new surgical techniques. The constant advancements in robotic technology are pushing the boundaries of what is possible in the field of surgery, allowing for groundbreaking procedures and improved patient care.

However, various challenges associated with the use of robots in surgery exist. The cost of the device is the first significant challenge, due to purchasing and maintenance costs, and the lack of clear reimbursement by health insurance companies. Although the initial investment may be high, it is essential to consider the long-term cost-effectiveness of robotic surgery. Additional clinical studies on functional aspects of robotic surgery in thoracic surgery are needed in order to better assess the impact of the price of the robotic system on the overall cost-effectiveness of treatment. (Zemmar *et al*., 2020) (Sheetz *et al*., 2020) (Klodmann *et al*. 2021)

It is crucial for hospitals and healthcare institutions to carefully evaluate the benefits and potential financial implications before integrating robotic systems into their surgical practices. In view of the large investment in technology that hospitals face, particularly the cost of the surgical robot, efforts should be directed at optimally utilizing the robot in both lung surgery and esophageal surgery. This means ensuring that surgical teams are well-trained and experienced in robotic procedures, and that the robot is being used to its full potential. Furthermore, improvements in accessibility to robotic surgery should be made. The general use and economic balance currently favor a small number of hospitals, making it generally difficult for people to access robotic surgery in most regions. It is crucial to address this issue and work towards providing equal access to this advanced surgical technology for patients across different healthcare settings. Additionally, it seems that specialized training in minimally invasive instrumentation may be of added value in selecting the right patients to undergo robotic surgery. Not all patients may be suitable candidates, and proper patient selection is essential for successful outcomes. Factors such as overall health, anatomical considerations and surgical complexity should be taken into account when determining the appropriateness of robotic surgery for a particular patient. The use of robotic surgery for patients with multiple health conditions and a high anesthetic risk poses another challenge. These multimorbidity patients require careful consideration and evaluation to ensure that the benefits of robotic surgery outweigh the potential risks. Decisions regarding the conversion from traditional surgical approaches to robotic-assisted techniques should be made based on the patient's specific health condition and individual needs. An additional problem is associated with the considerable learning curve of robotic surgery, which may take longer than for traditional surgical approaches such as VATS (Video-Assisted Thoracic Surgery). However, with proper training and experience, the learning curve can be overcome, resulting in reduced operating times and improved efficiency in the long run. It is essential for surgeons and healthcare professionals to receive comprehensive training in robotic surgery to ensure safe and successful procedures. When focusing on the use of the robot in VATS, it is crucial to analyze different substitution options and their advantages. The continuous development and improvement of robotic systems offer potential alternative devices and robots that may further enhance surgical outcomes. Additionally, novel applications of robotic technology in rehabilitation and outpatient transitions should be explored. Portable robots could be utilized by physicians during diagnosis discussions or patient care, providing real-time information and assistance. The additional availability of the robot in outpatient consultations can provide valuable data and insights into the feasibility, cost-benefit, and performance of patients. This information can contribute to better decision-making and improve the overall quality of care in downstream settings. The introduction of robots in this field and therefore the development of appropriate approaches is likely to be instrumental in accelerating the development and automation of new types of surgery. The continuous advancements in robotic technology have the potential to revolutionize the field of surgery, leading to improved patient outcomes and greater efficiency in healthcare delivery. These advancements will ultimately benefit patients by enabling more precise and minimally invasive procedures, reducing recovery times, and improving overall quality of care. (Zemmar *et al*., 2020) (Holland *et al*. 2021) (Fosch-Villaronga *et al*. 2023) (Johansson *et al*. 2021) (Balasubramanian *et al*. 2020) (Khan *et al*. 2020)

5.1 Precision and Accuracy

Since the dawn of modern surgery, "precision not aggression" has been an oft-repeated adage of almost every surgeon for a successful operation. The neurovascular complex neighborhood anatomy and surgical objective ask for an action as gentle as handling the fragile wet tissue. To achieve it, surgical robots have been developed and implemented to assist the surgeons in performing successful operations. They have made everything more precise and efficient, as the computer control of robotic kinematic manipulators increases the speed and accuracy of these devices to an extraordinary degree. All procedures have become replicable and easily reprogrammable, marking a remarkable advancement in the field of surgical precision. By combining high-resolution images with the robot's mechanical articulation endpoints, surgeons have been bestowed with the remarkable ability to see deep inside the intricate complexities of the human body. This amalgamation of advanced technology and human expertise has revolutionized the field of surgery, providing unprecedented insight and unparalleled precision in the operating room. Moreover, this robotic marvel has accomplished something truly extraordinary-it has enabled remote surgeries to occur. Human-robot surgeons now possess the ability to operate on patients located in different parts of the world, thanks to the incredible advancements in surgical robotics. This breakthrough has bridged the geographical gap between surgeons and patients, allowing for life-saving operations to be conducted without the need for physical proximity. It is a testament to the boundless possibilities that technology presents in the pursuit of enhanced healthcare. As technology progresses, so does the capability of surgical robotic systems. High-end advances continue to push the boundaries of repeatability, robotic manipulators now possess increased dexterity and provide an expanded range of freedom. The positional accuracy of these robotic marvels is now measured in the range of several tens of micrometers, a level of precision that was once unimaginable. This level of accuracy, coupled with the adaptability of surgical manipulators to overcome the uncertainties of tissue environments, further enhances the efficiency of surgical procedures. The current generation of surgical robotic technology utilizes an endoscopic-based visualization system that equips the surgeon with a comprehensive three-dimensional image of the operating field on a console. This powerful visualization tool, coupled with robotic manipulators that are remotely operated by the surgeon, creates a seamless and immersive surgical experience. The precision manipulation of robotic interventional surgery is based on a high-level manipulation platform (HLMP), which has been meticulously examined to ensure the overall smooth operation of the robot and the precision of rendering tools along the desired trajectory. In conclusion, the development and integration of surgical robots into modern surgical practices have truly revolutionized the field of surgery. The pursuit of precision, combined with the remarkable capabilities of robotic technology, has elevated the standards of surgical procedures to unprecedented heights. Surgeons now possess the ability to delve deeper, see clearer, and operate more precisely than ever before. With each passing year, the boundaries of what is achievable in the realm of surgical precision continue to be pushed, propelling us towards a future where human expertise and technological innovation coexist harmoniously to save lives and improve patient outcomes. (Wang *et al*., 2022) (Zhu *et al*. 2021) (Zemmar *et al*., 2020) (Omisore *et al*. 2020) (Thai *et al*. 2020) (Haidegger *et al*. 2022)

5.2 Reduced Trauma and Recovery Time

Another way to improve the trauma a patient receives is to build robots for controlled, precise, and motion-compensated surgeries. Although robotics will not cure surgical operations, robotics applied to the surgical field offers distinct advantages. The surgeries can help in many ways to recover minimally invasive operations, as the surgeon's hands are more stabilized or less satisfactory, using hand motions to minimize tremors during procedures. Various robotic algorithms have been developed for robotic-assisted surgeries using soft, flexible components. As minimal pressure as possible is applied to robots using soft materials, human organs cause minimal compression. Surgeries of minimal invasion generally cause less trauma. Thus, the recovery time of the patient is reduced too. Reduced trauma is a key benefit of minimally invasive surgeries. With reduced trauma, the patient may feel less pain and experience fewer side effects from the procedure. Using cameras, the device, also known as a laparoscope, sends a video of the surgical field to a nearby TV monitor, which helps the surgeon to perform the surgery. When guided by the surgeon, the articulated arm holding the laparoscope robot follows the action or takes verbal commands. However, gradient systems do not respond to immediate verbal instructions, such as the Gibbs-Free manifold. Implemented in surgical robots, gradient hill-climbing is associated with safer and slimmer manifolds, ensuring robot verification stability in the workspace. Electronic controls can overcome human weaknesses, slowdown, and ambition to demonstrate superior skill. Work with robotic equipment that demonstrates the positive and negative effects of the surgeon’s performance. Disadvantages of robotic-assisted surgeries include potential technical malfunctions, longer preparation and setup time, increased costs due to equipment maintenance, and the need for specialized training of surgeons and staff. These shortcomings must be addressed to ensure the successful integration of robotic technology in surgical practices. Additionally, robotic-assisted surgeries may not be suitable for all patients or procedures, as some cases may require traditional open surgeries for optimal outcomes. The decision to pursue robotic-assisted surgery should be made on a case-by-case basis, weighing the potential benefits against the associated risks and limitations. Continuous advancements in robotics and surgical techniques are likely to further enhance the capabilities of robotic-assisted surgeries and mitigate existing challenges, making them increasingly valuable in the field of medicine. (Xu *et al*. 2022) (Peng *et al*. 2020) (Xu *et al*. 2022) (Johansson *et al*. 2021)

5.3 Cost and Accessibility

Timely medical care is highly dependent upon having an adequate number of skilled medical personnel available, as well as the necessary medical equipment to administer appropriate treatments for each patient's specific condition. The funding for healthcare is typically a combination of public and private resources. However, many developing nations face challenges in providing the most advanced and optimal therapeutic treatments to their citizens due to the prohibitively high costs associated with healthcare. Integrating robotics into the healthcare delivery system presents a significant and complex task. While financial resources are a primary consideration, it is equally important for medical policies to address the issue of accessibility, especially for low-income individuals residing in densely populated areas within the country. Focusing solely on affordability research, without considering the accessibility perspective, may fail to adequately address the potential public health impact of these promising modern treatments. Governments in economically disadvantaged regions should also recognize that the expenditure on clinical trials could have adverse consequences for public health. Moreover, the costs associated with maintaining surgical operating theaters, including the availability of necessary chemicals and hemostats to control bleeding during significant blood loss, must be taken into account. Moreover, the substantial initial investment required for system installation, surgical procedures, and trained personnel should not be overlooked. Additionally, preventive measures to minimize procedural failures and breakages should be implemented and factored into the overall cost evaluation. It may be beneficial to provide insurance coverage for expensive medical robotic interventions, ensuring that the procedures are legalized and accessible in the event of unforeseen incidents. Policymakers should employ a comprehensive multi-criteria decision-making approach to strategically plan how healthcare services and economic capacity can be effectively managed. Various methods have been utilized to assess the efficiency of robot-assisted surgeries, considering factors such as cost-benefit analysis, cost-utility analysis, and cost analysis. Markets with diverse characteristics have been rigorously evaluated, considering both affordability and effectiveness. To bridge the divide between cost and quality factors, it is recommended to conduct comprehensive price-sharing experiments and engage in more subjective discussions. By doing so, a holistic and well-rounded understanding of the expanding field of medical robotics can be achieved. (Adebisi *et al*. 2020) (Moro and Morea 2020) (Finkler *et al*., 2022) (Neff & Pickard, 2024)

Chapter - 6

Regulatory Framework for Medical Devices and Robots in Surgery

Regulation requires the development of thoroughly documented and comprehensive standards for the careful and meticulous health risk assessment of medical devices and robots. These standards must be established with utmost care and precision, ensuring that they are in complete adherence to the strict guidelines set forth. It is of paramount importance that the appropriate and adequate quality management procedures are in place for conformity assessment before any medical device or robot can even think about applying for the coveted and highly esteemed "CE" marking. The "CE" marking serves as a tangible and visible symbol, a testament to the manufacturer's or company's dedication to compliance with these stringent regulations. The unwavering compliance with these meticulously crafted standards effectively serves as a definitive method of 'presuming' compliance with the essential health and safety requirements as meticulously outlined in the profound and influential 1993 MD Directive. The significance of this cannot be overstated. The aptitude to undergo conformity assessment procedures and meet the relevant requirements may, to a certain extent, vary based on the classification ascribed to the medical device. This heterogeneity in conformity assessment practices and prerequisites illustrates that the realm of robotics is an arena filled with myriad risks and complexities, all of which necessitate the implementation of specific safety features to mitigate and manage any potential hazards. The process of conformity assessment itself cannot be taken lightly or dismissed as a mere formality. On the contrary, it is an extraordinarily intricate and intricate process that intricately analyzes the context in which the medical device or robot is intended to be utilized. This examination of the context is paramount in ensuring that the device, in question, meets and adheres to the exacting international standards. These standards, which encompass rigorous norms pertaining to safety and product performance effectiveness, serve as the bedrock upon which the medical devices and robots are deemed suitable for placement on the European market. In essence, the requirements imposed upon the regulatory authorities themselves when it comes to evaluating and assessing compliance with the essential principles play an instrumental role in fostering a culture of utmost effectiveness and efficiency when it comes to the procurement of technology. They provide a robust and unambiguous framework that leaves no room for ambiguity or uncertainty, allowing for greater clarity and understanding regarding the safe and secure application of robotics in the field of healthcare. It should be duly noted that these requirements and procedures apply steadfastly and unwaveringly regardless of whether the medical device or robot is operated by a skilled and knowledgeable health professional or by the entity or company responsible for its manufacture. The same legislation and regulations are applicable without any bias or preference, thus necessitating the presence of a highly competent and proficient team of healthcare personnel. Consequently, it is incumbent upon hospitals and healthcare facilities to maintain an appropriate and meticulous quality management system, ensuring that only those professionals who have been thoroughly trained on the specific surgical applications of robotics are given the responsibility to operate the clinical system in strict accordance with the extensive and all-encompassing EU legislation. Moreover, it is imperative for hospitals and healthcare institutions to devote significant resources and efforts to the training and development of their healthcare professionals. This ensures the perpetual enhancement and refinement of their professional qualifications, which in turn guarantees that the highest standards of safety requirements are consistently upheld and respected. The safety and well-being of every patient, irrespective of their demographic or condition, must always remain the primary focus, and it is through the adherence to comprehensive and stringent safety procedures that this noble objective can be achieved and perpetually maintained. The continuous improvement and advancement in technology demand a continuous commitment to ensuring the utmost safety and efficacy of medical devices and robots in healthcare settings. By adhering to rigorous standards, healthcare professionals and manufacturers can work together to create a future where patients can trust in the reliability and quality of these innovative advancements. (Fosch-Villaronga & Mahler, 2021) (Valori *et al.* 2021) (Khinvasara *et al.*, 2023) (Chemweno *et al.*, 2020) (Bessler *et al.* 2021) (Fosch-Villaronga & Özcan, 2020)

Chapter - 7

Future Trends and Innovations in Surgical Robotics

The surgical intervention field has been significantly impacted by numerous technological and paradigmatic evolutions, resulting in the continuous advancement of minimally invasive surgical techniques. This has further facilitated the widespread use and adoption of teleoperated surgical robots. While current indicative data showcases the remarkable and consistent growth of the market for surgical robotic systems, even in the face of the pandemic scenario, it is worth noting that technological innovation in the realm of robotic surgery is currently considered to be primarily evolutionary. Given the well-established nature of the robotics market in this field, it becomes increasingly important to predict and identify the major trends that will shape the future of technological evolution. In this regard, there are several key areas that warrant attention.

1. **Enhancing the Performance of Teleoperated Robots:** Presently, teleoperated surgical robots only offer a direct master-slave configuration. However, there is significant potential for further advancements in the development of more sophisticated teleoperation architectures. Examples include bilateral passivity control and hierarchical teleoperation structures. By exploring and implementing these advancements, the precision, dexterity, and maneuverability of surgical robots can be substantially improved. Consequently, surgeons will be able to perform complex procedures with greater ease, efficiency, and accuracy.
2. **Designing Compact Multi-Arm Robots:** An emerging solution in the realm of surgical robotics is the development of robots equipped with 5-6 spatial-spherical 7 DOF arms. These robots are specifically adapted to work within the single incision laparoscopy approach and are additionally equipped with an endoscope/camera at the tips. The utilization of such compact multi-arm robots provides surgeons with enhanced flexibility and versatility during surgeries, enabling them to access hard-to-reach areas with minimal invasiveness. The additional endoscope/camera also offers improved visualization,

granting surgeons a clear and comprehensive view of the surgical site from various angles.

3. **Expanding the Autonomy of Surgical Robots:** While the concept of a completely autonomous surgical robot may currently be inconceivable, notable progress can be made by integrating Augmented Reality (AR) and Artificial Intelligence (AI) tools within the robotic platform. This integration allows for autonomous task execution while still preserving the surgeon teleoperator preferences and habits. Advanced AI-enabled robotic systems will play an increasingly important role in both the pre-operative and post-operative phases of robotized surgical procedures. Leveraging the power of AI, these tools can effectively guide the surgeon's decision-making process and provide real-time feedback and recommendations based on patient-specific data. With continuous monitoring of the patient's clinical conditions in multiple scales over time, early detection of complications or changes becomes possible, leading to more proactive and personalized post-operative care. Given these considerations, it is crucial to note that the usage of an AR tool does not necessarily require the surgeon to wear it. Thanks to ongoing advancements in projection and image analysis, it is conceivable that the Operating Room (OR) screen alone could be utilized for these purposes. By eliminating the need for additional devices worn by surgeons, the integration of AR technology becomes seamless and user-friendly, streamlining the workflow in the operating room. With the advancements in technology occurring at an unprecedented pace, the future of surgical robotics holds immense promise. These advancements not only have the potential to improve patient outcomes but also to enhance surgical techniques, ultimately revolutionizing the field of surgery itself. (Almujalhem & Rha, 2020) (Omisore *et al*. 2020) (Alip *et al*., 2022) (Zhang *et al*. 2021) (Haidegger *et al*. 2022)

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