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Advancements in Medical Devices for Surgical Precision: Exploring the Role of Robotics, AI, and Minimally Invasive Technologies

Aya Rfaat Majeed, Aseel Falah Hassan Ali, Mohammed Qasim Hassan, Mohammed Jawhar Ghareeb, Mohammed Fuad Kakarash
Medical Instrumentations Technique Engineering, Alkitab University

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Abstract: This weighs heavily upon my shoulders every single day; therefore, my success is intertwined with their success. Moving forward, the page will showcase a variety of differing thoughts and perspectives regarding this latest piece of work and its implications. Generally, academicians are encouraged to establish a robust foundation composed of solid references, be clear about their ultimate end goals, and present a unique perspective along with innovative solutions for the evolving future of health care. By doing so, they can effectively contribute to the advancement of the field.

Keywords: Surgical Precision, Medical Devices, Robotics, Artificial Intelligence, Minimally Invasive Surgery, Real-Time Decision-Making, Imaging Technologies, Cognitive Robotics, Surgical Innovations.

1. Introduction to Surgical Precision and Medical Device Advancements

Surgical precision and the ability to perform highly intricate procedures are paramount for positive patient outcome. These medical procedures rely not only on the surgical expertise of the entire team but also on the capabilities of the equipment used. With recent advancements in robotics, medical practice is finding innovative ways to take this next step toward better patient outcomes. Another emerging technology, alongside the use of AI technologies, robotics, or a combination of them, as the future of surgical precision. Alongside traditional methods, robotic or AI-assisted medical procedures might soon become a staple of operating rooms worldwide. With these new and highly precise medical devices, doctors can perform a slew of innovative keyhole surgeries that were not previously possible with human hands. On the other hand, AI algorithms for real-time treatment planning can help avoid damaging surrounding tissue during procedures and improve the success of the surgery. Laparoscopic surgery, while being a method of surgically avoiding large incisions in bodily organs, has proven to be greatly beneficial for the patients who undergo the procedure. This method usually results in shorter postoperative recovery times, a decrease of postoperative pain, and a greatly reduced risk of accidents during surgeries. It is highly preferred for being minimally invasive and for preserving the physical integrity of the operated patient. The traditional method of laparoscopic monitoring, via a 2D camera, is not the most efficient way for surgeons to diagnose the procedure. Legibility of tissues is not exemplary, thus impairing the visual ease of diagnosis of the procedure. This significantly decreases the extensivity of procedures possible to conduct. [1][2][3]

2. Historical Development of Surgical Robotics

Surgery has always played an important part in medicine and is the crucial treatment option for many conditions. Advanced technologies for sensing, actuation, and intelligent control have enabled various devices to operate efficiently within the human body. This technology has been integrated into the surgical procedures over the years, resulting in the development of surgical robotic systems. This paper reviews the historical development of such systems from the open to robotic-assisted approach, and highlights the capability of advanced surgical systems which have been implemented in surgical robots. Robot-assisted surgery was introduced in the mid-1990s and offered the benefits of a smaller incision, which in turn reduces the risk of infection and blood loss. Other benefits include shorter recovery time as a result of less trauma to soft tissues, accurate and precise task execution providing a safer procedure for patients. Current interests in the development of minimally invasive techniques for early detection and prevention of diseases have led to the advancement of special surgery robots. Currently, these systems are large and expensive and the procedures are carried out in the operating theatre. Design and development of a small, safe, and affordable surgical robotic system will bring the potential benefits of such robotic surgery systems to the wider community. Despite the advantages of this modern, more advanced technology, the implementation of autonomous surgical intervention systems is still under development. Currently available surgical robots perform as a master-slave system, which requires intensive human intervention during surgery. Furthermore, these systems are pre-procedural, therefore do not have the capability to make cognitive decisions or execute unforeseen tasks during surgery. Robotic systems that are equipped with these advanced capabilities can potentially increase the accuracy and safety of surgery. Expert systems or Artificial Intelligence (AI) schemes can be embedded in surgical robotic systems to assist the surgeon in carrying out difficult tasks [4]. The aim of this work is to present an overview of the development of surgery from the open to the robotic-assisted approach. This includes recent trends in surgery and the potential impact on defining the next generation of surgical robotic systems. It also discusses the state-of-the-art tools or systems involved in the development of surgical robots.

3. Key Components and Technologies in Surgical Robotics

The development of robot-assisted surgery is driven by the need for surgical systems to provide advanced dexterity and to carry out surgery in a minimally invasive manner. This trend has seen the growth of systems which have been adopted in many specialized centers. Behind the increasing scene of these systems within the hospitals is a lucrative market convinced by the medical device to be cost-effective compared to traditional laparoscopic devices. The annual increase rate of 6.9% in the number of robotic systems installed worldwide is the main driving force for an ensemble of industrial companies to shift from tele-manipulator building to fully robotized solutions. Though the need for mechanization of surgical operations has been recognized for more than a century, the technology enabling automation of all the surgical sub-operations while keeping the surgeon in control has just emerged in the last two decades. Surgery is a part of the medical branch concerned with operative treatment of injuries, deformities, and other bodily disorders. It is a manual operation in which only the hands are used. It is known as the most ancient form of medical treatment. Meanwhile, ever-enhancing healthcare requirements have been pushing the development of surgical procedures that are less and less invasive. A reduction in trauma leads to superior outcomes and shorter recovery times for patients compared to open surgery. This trend towards minimal invasiveness is particularly pronounced in the most popular surgical procedures. A majority of the abdominal cases is treated with colectomies. Standard laparoscopic-assisted colectomy was introduced at the end of the ‘80s and since then has been understood as a promising technique to reduce postoperative morbidity, faster return to bowel function in comparison to open surgical procedures. However, laparoscopy alone has shown efficacy only for a few minor procedures and is hardly applicable to the more widespread complex surgery. Robotic systems have been invented to overcome the limitations of standard laparoscopic equipment. Robot-assisted colectomy using such systems has been recently put into practice. During the last years, a considerable number of scientific papers has focused on clinical aspects of such new robotic systems. Although these devices have been designed to improve the surgeon’s performance, objectively quantifying such measures in a statistically valid population is highly complex and still debated. Since surgical robots are electromechanical devices, their associated technicalities are bound to play a pivotal role in similar surgical techniques. Among others, energy impact on patient tissue, a result of the interaction between robot and organs, exhibited a substantial relevance. Other technical aspects, less studied so far, encompass the robotic device’s impact on how the surgery is being performed. Specifically, such aspects have been investigated for the recently introduced colectomy procedure and are tailored to quantify the potential benefits of the robot on the procedure itself, as well as to provide guidelines for further technological improvement of the device. [5][6][7]

3.1. Sensors and Imaging Technologies

Advancements that could simulate the tactile characteristics of human hands and control algorithms that allow safe handover motions will be discussed. The development of haptic feedback devices is being significantly promoted by advances in teleoperation and virtual reality. Robotics could provide safe and effective handover surgical instruments. These features are particularly attractive at the earlier stage of practical training for less-experienced operators on bloody tissues. Rapid handover may thus increase availability in the operating theaters, privacy, and comfort of the patients without reducing care quality. Same surgeons could specialize on different operations due to the reduction of the operator's physical skills and rise of intellectual tasks. This could increase safety, efficiency, weighing of the workforce, and lead to lower tiredness and stress for the operator.

The possibility of performing a safe handover between a surgeon and the robot during minimally invasive surgery is investigated. This could simplify cooperative tasks in which the safety of the operator should remain the main concern. To improve performance and surgical skills, provide safe handover dynamics, and give an operator an accurate image of the interaction force between the robot and the environment, haptic feedback is essential. In most surgical robotic procedures, the instrument is used as a blunt probe to give continuous pressure on the soft tissues and enhance the perception of forces through deflection of the instruments. In traditional minimally invasive surgery, the tools are controlled directly by the surgeon who feels the force applied through them by the environment. The implementation, during handover dynamics, could be challenging for the operator since an unexpected or excessive force can easily occur, leading to serious complications.

3.2. Actuators and Motion Control Systems

Pneumatic motors have been commonly used throughout the development of devices for MR applications due to their MR compatible features. Possible alternatives to traditional motors for robotic actuation, such pneumatic or ultrasonic motors, are a possible alternative [8]. Ultrasonic motors are electric motors powered through the ultrasonic vibration of a stator, powering a rotor.

The rotor itself is a flexible component that can “walk” along the stator wave, transitioning the oscillation into rotation. Unlike piezoelectric motors, ultrasonic motors use resonance and the stator floats freely using friction to control the rotor, which allows much higher frequency vibrations and faster motion. These motors are commonly used in the manufacturing of camera autofocus drivers due to their speed and ability to operate extremely quietly. The ultrasonic motor produced no change in SNR until it was turned on, where it caused the most significant drop with the ratio falling to around -45 dB. While all modes other than the piezoelectric position driver and turbo mode initially caused an SNR increase, once the motor was up to full speed and the stator and motion control system were vibrating, both the piezoelectric mode driver and the turbo mode driver had similar effects in terms of SNR drop. This is due to the fact the turbo motion mode driver drives the same frequency used by the MRI in the feedback loop to control the motor and sequence of the SNR images. Pneumatic controllers and drivers are by far the most effective at minimizing noise in the images. Piezoelectric motors are a type of electric motor that operate through the use of an electrically induced electric field. This electric field is created with an MRI compatible amplifier and transmitted through pick-up electrodes mounted on the motor. The driving force is produced by the linear motion of ceramics or metallic plates in response to transverse acoustic vibrations focused by a resonator horn. These motors can be constructed out of a variety of designs and drivers, but in the case of MR safety the C-DRVs and C-DRS designs are used. Ceramic drivers allow the motor to overcome the material constraints of the MRI environment but the use of electric field control forces the motor to remain off during scans.

3.3. Software and AI Integration

Artificial intelligence is currently reshaping the landscape of healthcare, having a manifold impact on disease management. Machine learning (ML) techniques are becoming increasingly ubiquitous tools for aiding the interpretation of MRI and CT scans. The automated tools are mitigating the burden of a clinician, allowing for a quicker and more accurate diagnosis. In turn, ML models are becoming powerful allies for physicians, enhancing their ability to reason and make diagnostic decisions. By feeding the AI with an array of comprehensive patient information, lab results, and historical cases, the tools are suggesting diagnostic outcomes, predicting therapies, estimating future disease risks, and even indicating the most effective therapeutic interventions. The tool-assisted diagnostic decision-making is gradually being adopted into clinical practice, especially in diagnostic specialties, such as radiology and histopathology. Surmounting the qualms about the accuracy and practicability of these tools, the AI-aided diagnosis is an everyday reality that physicians have to reckon with at the outset of their practice [9].

Evidence of the transformative potential of AI in diagnostics is incontrovertible and compelling. For example, a clinical study proved that a specially designed deep learning convolutional neural network could discern skin cancers with an accuracy at the level of expert dermatologists. To date, more than 500 different research teams have harnessed ML tools to intensively investigate the value of medical imaging sources for diagnostic purposes. Moreover, the numbers are swelling, with approximately 100 new contributions added each year [10]. Machine learning and artificial intelligence technologies are increasingly being used to support a wide array of tasks, ranging from quick image interpretation to the most complicated oncological treatment planning. On the other hand, the time barrier to the broad societal acceptance of new technologies is diminishing. Trivial day-to-day routines that were heretofore the sole domain of natural persons are being taken over by robots, algorismic machines, and automatic systems. Physical activities, measurements, calculations, and diagnostics, as well as a large proportion of cognitive, non-routine tasks, are consistently being carried out by machine algorithms known as AI.

4. Applications of Surgical Robotics in Various Medical Specialties

With continual advancements in imaging, navigation, and robotics, surgeons now have access to tools which can improve their preoperative planning, intraoperative visualization, and postoperative outcomes. A significant amount of the early work in spine surgery has been centered around the applications of RA (robotic-assistance). This has helped in the realization that RA procedures go far beyond the placement of pedicle screws. However, there are numerous obstacles that can stand in the way of widely integrating these new technologies in the operating room [11]. These include, but are not limited to, cost, learning curves, and the general hesitance towards adopting new methodologies. Therefore, more work will have to be done on larger patient populations in order to continue optimizing the safety and accuracy of single and multi-level RA procedures in the thoracic and lumbar spine.

Robotic surgery, alternatively known as robot-assisted surgery (RAS), is a revolutionary technology enabling more minimally invasive and precise approaches. The dawn of minimally-invasive surgery has radically revolutionized the surgical field. In contrast to the ipsilateral approach the contralateral approach minimally invasive is associated with decreased postoperative pain, less blood loss, shorter hospital stay and better patient satisfaction, with no significant differences in terms of survival and long-term outcomes. However, prescribing HI VATS to lung cancer patients remains a challenge especially in low- and middle-income countries [12]. The novel implementation of the use of RAS has the potential to overcome the limitations of more traditional laparoscopic and thoracoscopic surgeries. Moreover, adding that RA has given rise to the possibility of augmenting conventional procedures, while also prompting the development of new surgical techniques. Parcelling the irritation of the phrenic nerve could be useful, though technically challenging, to prevent cough and pain that may hinder the procedure.

4.1. General Surgery

The technology landscape for MedTech continues to change rapidly, spearheaded by several revolutionary breakthroughs that have forever altered surgical procedures in all spheres and subspecialties. Significant advancements have been realized within the healthcare sector, delivering radical outcomes for people's health and quality of life; for instance, novel prescription drugs and treatment therapies, cutting edge medical imaging systems, and medical interventions like catheters and stents have been developed. However, the most momentous advancements are observed in the ecosystems of medical devices and surgical instruments. Numerous breakthroughs have been achieved in the recent past in the field of medical devices, surgical robotics, equipment, and prosthetics. Regardless of individual view on the productiveness of med-tech industry, it cannot be denied that new groundbreaking technologies have made massive changes to many tens of thousands people’s lives and saved the lives of millions globally. Of all the medical procedures, surgical procedures are by far the most complicated and the most fastidious. The newer technologies have opened new horizons for visualization, manipulation, and mitigation of disease and flesh when in the past it might have been completely incurable or unmanageable. Robotics, AI, and arthroscopic devices represent the fundamental edge to improve the advantageous facets of surgical procedures, being on their way to carry out precise hurdle surgeries previously unbearable.

4.2. Neurosurgery

Since the end of the last century, the number of current research activities and publications in robots and mechanisms technologies for neurosurgery has grown steadily. This has produced significant progress in this field, although there is still a need for safe, reliable, and efficient systems. Solid, soft and hybrid robot devices, the most common associated systems for medical applications, are here summarily reviewed. The advances made so far and the many technical challenges are assessed. The large number of works on the underlying technologies is definitely too wide to be exhaustively treated within a single paper, although efforts have been made to report what are judged as the most innovative and effective research results. To conclude, some observations are made about the future development trends of robots and mechanism design for medical applications together with an assessment on the research activities currently underway.

4.3. Cardiothoracic Surgery

Cardiothoracic surgery was one of the first fields to employ the robot, and it may arguably be its most complex geographical application field [13] ; [14]. Robotic systems offer the surgical team an improved dexterity, precision, vision and reduced hand tremor when compared to equivalent conventional procedures. One of the major advantages of robotic cardiac surgery is a minimally invasive surgery, which offers a great potential for the patients who can benefit from high-quality treatment as the time spent in the intensive care and recovery can be reduced to a minimum. Yet, perhaps the biggest advantage of the minimally invasive surgical procedures is that patients recover from surgery sooner, which can only mean, given the high demands on healthcare systems, that robotic-assisted surgery offers significant potential for reducing the healthcare costs associated with a particular treatment. Surgeons can get this advantage because minimal invasiveness is achieved by advances in technology, in particular, by the improved surgical tools and imaging equipment, as well as the sophisticated software for pre-operative planning that all facilitate the precision of surgery. Furthermore, as the robot gives the surgeon a magnified, highly detailed vision of the operating field, it can therefore have a profound impact on the future of telemedical applications in the future.

However, there are obstacles that still need to be overcome to achieve the ambitious goals of safer cardiac robotic surgery. These are the need for development and clinical implementation of image-guided and A.I. technologies, the widespread introduction of novel medical devices based on smart technologies and wireless communication, and the long operational life cycles of these medical devices. Regarding the latter requirement, wireless nodes made from biocompatible materials need to operate for at least 10 years once inserted into the human heart. This is due to the fact that it is technically difficult to physically retrieve broken or worn out miniature devices that are localized within the functioning human heart, with sensors as small as grains of sand. [15][16][17]

5. Challenges and Limitations of Current Surgical Robotics

While robotic systems for surgery have been around for quite some time and, in fact, today find many successful applications worldwide in a variety of different clinical areas, they are not considered the standard of care in a surgical environment. As robotic surgery continues to develop, there will be many investigations and considerations of potential malfunctions involving surgical robots [18]. As always in development of a new technology, it has taken time to understand the failure modes that might occur as well as some of the failure analyses that might be used to explain these. Design issues and requirements unique to surgical robotics are discussed as they pertain to the development of a custom that performs tissue repositioning and suturing tasks. In-vivo robots that are potential subjects of future accident investigation from the Sidekick Surgical Robot series are also discussed. The surgical robot is complex, composed of many subsystems, and as such, can fail in many different ways. Unlike traditional mechanical robots which often fail in the same way, the wide range of failures that a surgical robot may experience combine to create difficulty in safety analysis and increasing the likelihood of error in a broad sense. The standards applied to a surgical robot are very exacting, and when real-world events fall short of these expectations, the normal result is often litigation, citing negligence on the part of the designer, manufacturer, or operator. Past accidents involving automated high-risk systems are reviewed, both in surgery and in other domains. It is hoped that an understanding of the ways these systems have failed in practice will aid designers in creating future systems that will alter the current fears of the coming robotics revolution in surgery.

6. Emerging Trends in Minimally Invasive Technologies

Instruments and devices are constantly being improved to enable the physician to carry out less traumatic operations. Cameras with very small diameters enable the interiors of self-contained hollow organs such as intestines to be inspected through very small incisions. Instruments with the decorator sheath and the operating rod that can be inserted through a >12-mm diameter trocar are also manufactured in the same configuration for a 5- or 2-mm trocar. Coagulation like a bistoury cauterize sections in a watertight way and very thick blood vessels are carried out using a bipolar coagulating forceps with a very small tip (e.g. 2 mm). Instrumentation for immobilizing organs by sucking a part of them is also prepared. The technological drive and sophisticated technologies underlying the development and advancement of medical robotic devices stem from the adoption of the minimally invasive surgery (MIS) paradigm in healthcare. MIS has been widely proved to offer reduced pain and complications, shorter hospital stay, reduced recovery time, and better cosmetic results compared to traditional open surgery. However, such results come at a price. MIS gynecological and heart procedures, for example, are very challenging and require extremely skilled physicians. The very restricted space in the body cavity makes tools and cameras cumbersome to handle, while surgeons must also rely on imaging systems during manipulation that are often monoscopic. Japan in particular is at the forefront in the development of miniaturized tools and single-port access (SPA) devices, and a paper is presented whose goal is to provide a small grasp tool that has a 5-mm diameter for minimally invasive surgery with a minimum assembly thickness when the arm and tool are assembled [19]. This configuration is well adapted to enable SPA since a multi-degree-of-freedom (DoF) robot is able in principle to manipulate the tool similarly to multiport laparoscopy.

7. Advancements in AI for Surgical Planning and Decision-Making

Advances in surgery have made a significant impact on the management of a variety of acute and chronic diseases. Such advances are underpinned by continuing technological developments in diagnosis, imaging, and an assortment of surgical instrumentation. Complex surgical navigation and planning are made possible through a variety of pre- and intra-operative imaging techniques. Post-operative care is improved by an assortment of sophisticated wearable and implantable sensors. Of significant interest, the introduction of artificial intelligence (AI) methods has provided clinicians with effective clinical decision support at an optimal time. In its latest guise, AI is useful for a variety of risk stratification, genomics, imaging and diagnosis, personalized medicine, and also drug discovery.

In the arena of surgery, AI has made inroads through image analysis and navigation tasks. Indeed, the first attempts to incorporate this technology in surgery have a strong root in imaging and navigation, and are mostly focused on feature detection and in consequence a computer-assisted intervention for pre-operative planning as well as intra-operative guidance. With the success of the more data-driven descriptor enabled by the Deep Convolutional Neural Network (DCNN), image understanding has been the first clinical application of AI in the field of surgery. With a view to the fact that the introduction of AI methods has been hitherto mainly concentrated on the imaging modality, robotic surgery is set to be transformed through its application and in turn the future of surgery [20]. This evolution is mainly driven by an increasing demand for surgery, and also due to diminishing economic resources available for healthcare providence. As a result, the surgery of tomorrow has patient safety, and also patient outcome, as its central topic. The capability of future surgical robots to perform the sensing and understanding of a variety of complicated surroundings is of significant importance.

8. Integration of Robotics and AI in Surgical Training and Education

The field of surgery is swiftly evolving towards an era of unparalleled precision through the integration of cutting-edge technologies. Comprised of a multitude of ever-advancing instruments and techniques, surgical practice constantly progresses in a quest for new levels of safety and effectiveness. Over the past few decades, robotics and AI have risen to prominence as revolutionary additions to the surgical armamentarium. AI-powered hybrid surgical suites are capable of adjusting radiation exposure and delivering drugs to target tissues with unprecedented precision. Surgical robots are already actively operating on patients in a multitude of medical disciplines from delicate oral surgery to orthopedic procedures, capitalizing on the unrivaled degrees of freedom and precision they offer. Recent advancements from both industries are intensifying in their capabilities to dissect the most intricate neural networks and synthesize them into the most potent nanobots.

The advent of AI revolutionized robotic surgery through a cohort of machine learning algorithms that allowed the most accurate shape of the skull base trepanation to be uniquely derived. In turn, robotic systems have played a paramount role in the implementation of AI itself in the surgery proper, allowing for the most precise delivery of chemotherapeutics to a highly intricate network of blood vessels supplying the tumors. Integration of such technologies into the surgical setting is changing it dramatically, fostering a new model of surgery in which operations are largely executed by machines autonomously or in tight coordination with human surgeons. Such complex interplay of interdisciplinary technologies raises acute regulatory, ethical, educational, and even existential dilemmas, transforming the traditional surgical education and practice paradigms. [21][22][23]

9. Regulatory Considerations and Ethical Implications in Medical Device Advancements

Federal Food, Drug, and Cosmetic Act (FDCA) regulates the production and sale of medical devices in the United States. The Center for Devices and Radiological Health (CDRH) is the division within the Food and Drug Administration (FDA) responsible for ensuring that medical devices are safe and effective. As of 2021, CDRH classifies medical devices into three categories: Class I, II, and III. Class I are simple devices that pose little risk of causing harm, like tongue depressors and elastic bandages. The majority of medical devices are Class II, which are more complex than Class I devices and are required to meet additional procedural and testing standards to ensure safety and effectiveness. Class II devices include surgical instruments, powered wheelchairs, and X-ray machines. Class III encompasses devices for which insufficient information is available to ensure safety and effectiveness. Class III devices include replacement heart valves, silicone breast implants, and innovative new technologies like transcatheter heart valves [24]. Regulatory oversight is lightest for Class I devices, and increases from Class I to Class III. Classification and regulation of medical devices is the responsibility of the CDRH based on internal advisory committees. The process includes validating a device’s effectiveness and risks. However, some devices are cleared as substantially equivalent to marketed devices without adequate human testing. No device can be marketed unless it has been cleared through this process.

There are ethical considerations that arise at various points across the medical device lifecycle, and it is suggested that ethical analyses of such complex scenarios involve the input of multiple perspectives using a structured approach. It has also been suggested that device developers make a checklist for possible ethical issues. This regulatory science project aims to develop tools that provide medical device developers and in-house review officers with guidance on regulatory, ethical, and patient safety considerations. These tools will provide algorithms and calculators to aid with the development of a multiperspective ethical analysis. The patient safety aspect includes the monitoring of safety data from device use. To date, the implementation of a tailored postmarket safety surveillance program for these devices has not been required by CDRH. Recommendations relating to postmarket safety and effectiveness were made following the review of the first 50 market device clearances, though none of the cleared devices were deemed to pose a public health risk related to the performance metrics referenced in the recommendation. Device implant life is to be the focus of renewed scrutiny from the medical devices directive (MDD) regulatory committee.

10. Future Directions and Potential Impact of Medical Device Innovations

Medical device technologies are rapidly evolving, driven by advancements in robotics, artificial intelligence, human-machine interface, and additive manufacturing technologies. Such advancements aim to improve the overall surgical procedure, uncertainty management, and targeting accuracy while reducing the invasiveness of the surgery. With the advancement in robotics and image-guided technologies, there is significant potential in increasing the precision of the technology used in medical devices and, more particularly, in surgical procedures. Microbotics offer the potential advantage of radically increasing the precision of the delivery of the technology as well as of the technology itself using targeted slow release techniques and therapies. Regulatory and metrological needs are also of first importance in this field to protect the clinical interests of the patients and the public health. In particular, it is essential to define standards and strategies to guarantee that medical devices comply with the pre-defined performances. This can be achieved only through efficient translation of detailed knowledge of the technology used in medical devices and of the clinical needs into practicable and internationally accepted standards. Input from different categories of specialists is essential to generate constructive discussions and proposals. Uncertainties cannot be avoided in the design, manufacture, and use of medical devices. The possibility to estimate them allows evidence-based decisions. Efforts are still required to standardize approaches to deal with uncertainty quantification and uncertainty management, and to make them accessible to SMEs and the medical device community. [25][26][27]

11. Conclusion

Surgical robotics, AI, and minimally invasive technologies play enabling roles in providing enhanced surgical precision in modern healthcare. Even in the face of the significant challenges faced by AI/ML technologies related to the need of a transparent and accountable decision-making process and questions of job displacement by the healthcare workforce, the articles displayed in the present thematic issue provide a comprehensive overview of the current clinical applications and also articulate the cutting-edge development of AI/ML-powered and laparoscopic surgical robotic technologies. Internationally well-known pioneers and researchers in the field have also contributed their perspectives on the future of AI/ML-powered surgical laparoscope and robotic technologies and have highlighted the challenges faced by surgical stakeholders and opportunities for future research. It is anticipated that this thematic issue will motivate broad participation and accelerate the translation of research outcomes into clinical settings. Of course, if the full capability of the current state-of-the-art robotic, machine learning, and algorithmic technologies should be developed, then it may well be that nearly all surgery would be better performed robotically. However, it is clear that developments in the policy, educational, regulatory, commercial and scientific arenas, are in their earliest stages, and are likely to be of a profoundly diverse scope than simple modifications and upgrades to currently existing forms of surgery. In summary, hopefully this paper and the thematic series of which it is a part can provide a solid groundwork towards the development of a unified and ethical response on the much broader, and by necessity, more speculative issues raised by the advances in medical technology that have been taking place in recent years.

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