Humanoid Surgeon: The Future of Surgery

Date: Fri Mar 28, 2025

Christian Grant, Deep AI Mind

Table of Contents

I. Introduction: The Advent of Humanoid Surgeons in the Future of Surgery

The landscape of surgical interventions has undergone a remarkable transformation over the centuries, evolving from rudimentary manual procedures to sophisticated, technology-driven operations. This progression has been marked by a relentless pursuit of enhanced precision, reduced invasiveness, and improved patient outcomes. In recent decades, the emergence of robotic surgery has represented a significant leap forward, providing surgeons with advanced tools to perform complex procedures with greater dexterity and visualization. Building upon this foundation, the concept of the humanoid surgeon has emerged as a potentially transformative next step in the field of medical robotics. This vision entails the development of robots that not only resemble the human form but also possess the capabilities to assist in or even conduct surgical procedures with a high degree of skill and autonomy.

The increasing demand for advanced surgical solutions is driven by factors such as an aging global population, a rising prevalence of chronic diseases, and a persistent need to improve the efficiency and accessibility of healthcare services [1]. While current surgical techniques, including robot-assisted surgery, have achieved significant advancements, they still present limitations in certain scenarios. These limitations include the physical demands on surgeons during long procedures, the challenges of accessing confined anatomical spaces, and the variability in surgical skill and outcomes. The exploration of humanoid surgeons as a future modality aims to address these challenges and unlock new possibilities in surgical care, potentially leading to more consistent, precise, and less invasive treatments for patients worldwide. This report endeavors to provide a comprehensive analysis of the potential, challenges, and broader implications associated with the realization of humanoid surgeons in the future of surgery.

II. Defining the Humanoid Surgeon in Medical Robotics:

The term "humanoid surgeon" necessitates a clear understanding of its constituent parts: "humanoid robot" and "surgeon," particularly within the context of medical robotics. A humanoid robot, in its general definition, is a robot designed to resemble the human body in shape. This resemblance typically includes a torso, a head, two arms, and two legs, although some humanoid robots may only replicate a portion of the human anatomy [3]. The design of these robots is often driven by functional purposes, such as the ability to interact with tools and environments specifically designed for human use [3]. Additionally, humanoid robots serve as valuable research tools in various scientific areas, including biomechanics, where studying human body structure and behavior aids in their construction, and conversely, the attempt to simulate human form leads to a better understanding of human physiology [3]. It is important to note the distinction between a humanoid robot and an android; while both resemble humans, androids are specifically built to aesthetically mimic human appearance [3].

Defining a "surgeon" in the realm of medical robotics is more nuanced. In the current paradigm of robotic surgery, the surgeon remains the central figure, operating from a remote console to control the movements of robotic arms equipped with surgical instruments [4]. These systems act as sophisticated extensions of the surgeon's hands and eyes, enhancing their capabilities in terms of precision, dexterity, and visualization [4]. However, the concept of a humanoid surgeon extends beyond this traditional role. One emerging vision is that of a miniaturized humanoid robot serving as an avatar for the surgeon, replicating their full upper body motion and allowing for minimally invasive procedures through a single small incision [9]. This approach aims to essentially "miniaturize" the surgeon, enabling them to operate within the patient's body with enhanced dexterity and minimal trauma [9]. Furthermore, advancements in artificial intelligence and machine learning are paving the way for robots capable of performing surgical tasks autonomously, based on skills learned from observing experienced surgeons [11]. In this context, the humanoid robot itself could be considered the "surgeon," executing procedures with varying degrees of independence.

The distinction between humanoid surgeons and existing robotic surgery systems lies in several key aspects. Current systems like the da Vinci Surgical System and the Versius Surgical System typically involve multi-armed robotic platforms controlled by a surgeon seated at a console [4]. These robots do not inherently possess a full humanoid form and primarily focus on providing enhanced manipulation and visualization capabilities to the surgeon [8]. In contrast, the concept of a humanoid surgeon often implies a robot with a more anthropomorphic design, potentially capable of replicating a broader range of human movements, as seen in the idea of a full upper body avatar [9]. Moreover, the increasing emphasis on autonomy in the development of humanoid surgical robots suggests a future where these systems may perform surgical tasks with less direct, real-time control from a human operator [11]. While existing robotic systems are undoubtedly transforming surgery, humanoid surgeons represent a potential evolution towards a more embodied and potentially autonomous form of surgical assistance.

III. Potential Benefits of Humanoid Surgeons:

The advent of humanoid surgeons in the operating room holds the promise of numerous benefits, potentially revolutionizing surgical procedures and patient care.
One of the most significant potential advantages is the **enhanced precision and dexterity** that humanoid robots could offer during surgical procedures. Current robotic systems have already demonstrated their ability to increase the accuracy and control of surgical movements [4]. Humanoid robots, particularly those designed with advanced features like decoupled actuators, could further refine this precision, allowing for even more intricate and delicate maneuvers [9]. The potential for superhuman accuracy and stability could be transformative in

fields like microsurgery, where even the slightest tremor can have significant consequences [21]. These robots could be designed to mimic the movements of a human wrist but with a greater range of motion, enabling surgeons to access and operate in tight anatomical spaces with unprecedented ease [5]. Furthermore, the inherent stability of robotic systems can effectively filter out any natural hand tremors, leading to more precise and consistent surgical outcomes [8]. This level of enhanced precision and dexterity could translate to improved outcomes, reduced complications, and faster recovery times for patients undergoing complex surgical interventions.

Humanoid surgeons also hold the potential to significantly advance the field of **minimally invasive surgery**, leading to reduced patient trauma. Existing robotic surgery platforms have already enabled surgeons to perform a wide range of complex procedures through tiny incisions [4]. The development of miniaturized humanoid robots could take this concept even further, allowing for surgical interventions through a single, very small incision [9]. The benefits of such minimally invasive approaches are well-documented and include fewer complications, such as surgical site infections, less postoperative pain and blood loss, shorter hospital stays, and quicker overall recovery for patients, as well as smaller, less noticeable scars [4]. By minimizing the physical trauma associated with surgery, humanoid surgeons could contribute to improved patient comfort, faster rehabilitation, and a quicker return to normal activities. Another compelling benefit of humanoid surgeons lies in their potential to enable **remote surgical capabilities**, thereby expanding access to specialized medical care. While current robotic surgery allows for remote console operation within the confines of the operating room, the development of humanoid avatars could facilitate telesurgery across significant geographical distances [25]. A surgeon could potentially control a humanoid robot located in a remote hospital or clinic, replicating their movements and performing complex procedures without being physically present [9]. This capability could be particularly impactful in addressing the shortage of specialized surgeons in rural or underserved areas, allowing patients to receive expert care that might otherwise be unavailable [16]. The ability to conduct remote surgery through humanoid platforms could revolutionize healthcare delivery, bridging geographical barriers and ensuring that patients have access to the best possible surgical expertise, regardless of their location.

Finally, humanoid surgeons offer the potential for **increased efficiency and reduced surgeon fatigue**. The ergonomic design of current robotic surgical consoles already helps to minimize the physical strain on surgeons during lengthy procedures [7]. Humanoid avatars, with their potential for more natural and intuitive control interfaces, could further enhance surgeon comfort and reduce physical demands. Moreover, the increasing development of autonomous capabilities in surgical robots could offload repetitive and less critical tasks from the human surgeon, allowing them to focus on more complex decision-making and critical aspects of the operation [12]. By automating certain steps or providing enhanced assistance, humanoid surgeons could contribute to more efficient surgical workflows, potentially reducing the duration of procedures and alleviating the physical and mental fatigue experienced by human surgeons, ultimately benefiting both the surgical team and the patient.

IV. Challenges and Limitations in Developing and Implementing Humanoid Surgeons:

Despite the promising potential of humanoid surgeons, their development and implementation face a multitude of significant challenges and limitations that must be addressed.
One of the most formidable hurdles lies in the **technological advancements** required in areas such as artificial intelligence, robotics, and sensor development. Replicating the intricate movements and nuanced awareness of a human surgeon is an exceptionally complex engineering challenge [43]. The creation of humanoid robots necessitates robust skeletal structures and highly sophisticated actuators capable of exerting a wide range of force while maintaining sub-millimeter accuracy [43]. Developing artificial intelligence algorithms for complex tasks like motion planning, real-time interaction with unpredictable biological tissues, and autonomous decision-making in critical situations remains a significant undertaking [43]. Challenges persist in areas such as surgical tool and environmental perception, precise 3D tissue tracking and reconstruction, and seamless human-robot interaction [44]. A major bottleneck in advancing AI for surgery is the difficulty in collecting substantial amounts of high-quality, accurately labeled training data required for machine learning models [44]. Furthermore, the development of advanced sensor technologies that can provide humanoid robots with comprehensive situational awareness, including not only vision but also proprioception and tactile feedback akin to a surgeon's sense of touch, is crucial [45]. Current robotic systems also face limitations such as the lack of specialized microsurgical instruments designed for delicate procedures [46]. Overcoming these technological hurdles will require significant breakthroughs and sustained research efforts across multiple disciplines.

The **high development and implementation costs** associated with humanoid surgeons represent another major limitation. Current robotic surgery systems are already expensive to acquire, maintain, and operate, often involving substantial initial investments and ongoing operational expenditures [33]. Advanced humanoid robots, with their complex hardware, sophisticated software, and advanced sensor suites, are projected to be even more costly to develop and manufacture [1]. The costs associated with training clinical professionals to operate and maintain these advanced systems will also be significant [48]. Moreover, initial studies have indicated that robotic surgery can be more expensive than traditional laparoscopic procedures [47]. The high financial barriers to entry could limit the initial accessibility of humanoid surgeon technology, potentially creating disparities in healthcare access.

Navigating the complex **regulatory landscapes and approval processes** for medical devices poses another significant challenge. The development of humanoid surgeons will necessitate rigorous preclinical testing and extensive clinical trials to demonstrate their safety and efficacy [63]. Regulatory agencies like the FDA have complex pathways for approving new medical technologies, and the rapid pace of innovation in robotics often outpaces the development of corresponding regulatory frameworks, leading to uncertainty [63]. Currently, there is a lack of standardized training and credentialing for robotic surgery, which will need to be addressed for humanoid surgeons [65]. Furthermore, the increasing autonomy of these systems will likely require the development of new regulatory guidelines and reforms to ensure responsible deployment [45]. Successfully navigating these regulatory hurdles will be a critical factor in the widespread adoption of humanoid surgeons.

Finally, ensuring the **reliability, safety, and preventing malfunctions** of humanoid surgeons is paramount. Robotic systems, like any complex machinery, are susceptible to mechanical malfunctions [5]. The risk of software glitches and programming errors in highly autonomous systems also presents a significant concern [67]. Robust engineering practices, including the incorporation of redundancy, fault tolerance, and comprehensive alerting systems, will be essential to minimize the potential for harm to patients [66]. For fully autonomous humanoid surgeons, the development of sophisticated safety mechanisms that can detect and respond to unexpected situations will be critical [45]. Rigorous testing and validation will be necessary to ensure the reliability and safety of these advanced surgical robots before they can be widely implemented in clinical practice.

V. Current Research and Development Efforts:

The field of humanoid surgical robotics is currently witnessing significant research and development efforts aimed at overcoming the challenges and realizing the potential benefits of these advanced systems.

Several key **projects and prototypes** are at the forefront of this innovation. Vicarious Surgical is actively developing a miniature humanoid robot designed to facilitate minimally invasive laparoscopic procedures through a single 15mm incision. This robot aims to replicate the full upper body motion of a surgeon, providing enhanced dexterity and reducing injury to the patient [9]. Tesla's humanoid robot, Optimus, while still in its early stages of development, has shown the potential for performing intricate tasks that could eventually extend to surgery, particularly if its hand and finger dexterity can be further refined [69]. Sony has unveiled a prototype of a microsurgery assistance robot, featuring a compact design, miniature automatic instrument exchange, and high-precision control, demonstrating the feasibility of robotic assistance in highly delicate procedures [70]. SkySurgery LLC has developed a prototype for a surgical simulation system designed to train surgeons in robot-assisted laparoscopic surgery, incorporating virtual surgical instruments and physics simulation to enhance the learning experience [71]. Furthermore, a landmark, multi-institution project funded by ARPA-H is underway with the goal of creating a surgical robot capable of performing an entire surgery without human intervention, utilizing a breakthrough in concentric tube robot technology [72]. These diverse projects highlight the active exploration of various humanoid and humanoid-inspired robotic systems for surgical applications.

Significant advancements are also being made in enabling **autonomous surgical capabilities** through the integration of artificial intelligence and machine learning. Researchers at Johns Hopkins University and Stanford University have achieved remarkable success in training robots to perform fundamental surgical tasks by having them watch videos of experienced surgeons [4]. This approach, known as imitation learning, allows robots to learn complex maneuvers without the need for explicit programming of every step, bringing the field closer to true autonomy in robotic surgery [11]. These robots have demonstrated the ability to autonomously execute tasks such as manipulating a needle, lifting body tissue, and suturing wounds with a skill level comparable to that of human doctors [12]. Researchers at UC Berkeley and Intuitive Surgical have introduced the concept of "augmented dexterity," where AI-driven robots overlay digital surgical plans onto real-time images, allowing human surgeons to supervise and adjust, potentially enhancing surgical skills and outcomes [13]. The Smart Tissue Autonomous Robot (STAR), developed by researchers funded by the National Institute of Biomedical Imaging and Bioengineering (NIBIB), has demonstrated the ability to perform bowel surgery with minimal assistance from a surgeon, even outperforming expert surgeons in preclinical models [42]. These advancements in autonomous surgical capabilities underscore the transformative potential of AI and machine learning in this field.

Another critical area of research focuses on the **development of dexterous manipulation and haptic feedback** for humanoid surgical robots. The miniature humanoid robot being developed by Vicarious Surgical aims to provide exceptional dexterity through its design, which includes decoupled actuators allowing for precise and independent control of the robot's wrist, elbow, and shoulder movements [9]. Current robotic systems like the Versius Surgical System are designed to biomimic the human arm, offering surgeons a wide range of motion and dexterity with fully-wristed instruments [17]. Researchers are exploring methods to engineer proprioception into robotic hands, enabling them to perform highly intricate tasks with a sense of touch [69]. The integration of force feedback technology, as seen in the da Vinci 5 system, is crucial for providing surgeons with a sense of tissue tension, enhancing their ability to manipulate tissues safely and effectively [18]. Furthermore, projects like Faros are investigating the use of non-visual sensing technologies to improve the autonomy and decision-making capabilities of surgical robots, aiming to create systems that can "hear and feel" in a manner analogous to a human surgeon [73]. These developments in dexterous manipulation and haptic feedback are essential for enabling humanoid surgeons to perform complex surgical procedures with the necessary skill and control.

VI. Ethical Implications of Humanoid Robots in Surgery:

The integration of humanoid robots into surgical practice brings forth a range of complex ethical implications that demand careful consideration.
The increasing autonomy of humanoid surgeons raises fundamental questions about **patient safety and accountability** in the event of errors or malfunctions. Determining who bears responsibility when an autonomous robot makes a mistake during a surgical procedure is a critical ethical and legal challenge [74]. Ensuring the safety and effectiveness of these autonomous systems is paramount, requiring rigorous validation and testing [74]. The ethical principle of "First, do no harm" (primum non nocere) must be central to the development and deployment of these technologies [78]. While current robotic systems have a low reported rate of malfunction, the potential for mechanical failures and unintended injuries in more complex and autonomous humanoid surgeons necessitates robust safety protocols and clear lines of accountability [5].

Defining the level of **autonomy** in humanoid surgeons and understanding the evolving **role of human surgeons** is another crucial ethical consideration. While much of the current robotic surgery is described as "robot-assisted," emphasizing the surgeon's control, the trend towards greater autonomy raises questions about the appropriate balance between machine capabilities and human oversight [5]. Expert opinions often emphasize that robots should serve as tools to augment, rather than replace, the skills and judgment of human surgeons [9]. Concerns exist about potential over-reliance on technology, which could undermine surgeons' critical thinking and decision-making abilities [76]. The future role of human surgeons may shift towards supervising autonomous procedures, intervening in complex or unforeseen situations, and providing the crucial element of human judgment and adaptability [13].

Addressing concerns regarding the **patient-robot relationship and human dignity** is also ethically vital. The human connection and empathy inherent in the traditional patient-doctor relationship are considered essential aspects of healthcare [79]. Ethical obligations exist to uphold a person's dignity and ensure that the use of robot surgeons is humane and compassionate [74]. The potential for the "uncanny valley" effect, where robots that closely resemble humans but are not quite perfect can evoke feelings of unease or revulsion, is a consideration in the design of humanoid surgeons [3]. Patient trust and acceptance of robotic procedures, particularly those involving highly human-like robots, will be critical for their successful adoption [82].

Finally, ensuring **equitable access** to humanoid surgical technologies presents a significant ethical challenge. The high costs associated with the development and implementation of these advanced systems could limit their availability, potentially exacerbating existing healthcare disparities [33]. Ethical principles of justice demand a fair and impartial distribution of healthcare resources, and efforts will be needed to ensure that the benefits of humanoid surgical technologies are accessible to all patients, regardless of their socioeconomic status or geographical location [74].

VII. Expert Opinions and Perspectives:

Gauging the perspectives of experts from various fields is crucial to understanding the future trajectory of humanoid surgeons.

Surgeons generally express a nuanced view, recognizing the potential of robotic assistance while emphasizing the enduring importance of human expertise. They acknowledge that current robotic technologies offer benefits such as enhanced precision and improved ergonomics for the surgeon [7]. However, there is a prevailing sentiment that technology should complement, not replace, the skills and critical judgment of human surgeons [9]. Some surgeons have voiced concerns about the learning curve associated with robotic surgery and the potential impact of over-reliance on technology on the development of traditional surgical skills [50]. There is a strong emphasis on the need for surgeons to be actively involved in the development process of robotic medical equipment to ensure that these technologies truly meet the needs of surgical practice [50]. While the prospect of robots taking on certain tasks is appealing, skepticism remains about the complete replacement of human surgeons, particularly due to the necessity of adaptability and the crucial role of empathy in patient care [78].

Roboticists tend to be more optimistic about the potential of humanoid surgeons, driven by the rapid advancements in artificial intelligence and robotics. They are focused on developing robots with increasingly human-like dexterity, precision, and sensory capabilities [9]. The success of imitation learning in training robots to perform surgical tasks has generated considerable excitement, as it offers a pathway towards more autonomous surgical systems [11]. Many roboticists believe that autonomous surgical robots have the potential to address the growing shortage of surgeons and improve the accuracy and consistency of surgical procedures [12]. However, they also acknowledge that significant technological challenges remain in areas such as AI, robotics control, and sensor development before fully capable and reliable humanoid surgeons can become a widespread reality [21].

Medical ethicists provide a critical lens, focusing on the moral and societal implications of humanoid surgeons. They emphasize the urgent need for robust ethical frameworks to guide the development and application of artificial intelligence in surgery, ensuring that these technologies are used responsibly [76]. Key concerns include establishing clear lines of accountability in autonomous procedures, safeguarding patient autonomy in the decision-making process, and mitigating the potential for bias in AI algorithms that could lead to inequitable outcomes [49]. The importance of obtaining informed consent from patients regarding the use of robotic surgery, particularly as systems become more advanced, is consistently highlighted [49]. Ethicists also consider the broader societal impact, including the potential effects on human dignity and the nature of the patient-robot relationship [74]. Ensuring equitable access to these potentially transformative but likely expensive technologies is a central ethical imperative, as is the need to prevent the exacerbation of existing healthcare disparities [33].

VIII. Timeline for Widespread Adoption of Humanoid Surgeons:

Predicting the timeline for the widespread adoption of humanoid surgeons in healthcare requires an analysis of current trends, expert forecasts, and the various factors that will influence the pace of this technological integration.
Industry experts and research reports project significant growth in the broader surgical robotics market in the coming years [25]. Forecasts for the overall humanoid robot market, which includes potential applications in healthcare, suggest substantial expansion by the 2030s [1]. Some experts even envision the possibility of over one billion humanoids in various applications by the 2040s [91]. Examining the adoption timeline of surgical robots in specific medical fields, such as urology, provides historical context, showing a relatively rapid diffusion of technologies like robotic prostatectomy following FDA approval [92]. While these trends indicate a growing presence of robotics in surgery and healthcare, the widespread adoption of fully capable *humanoid* surgeons for a broad range of complex procedures is likely to take more time, potentially materializing in the 2030s or beyond.

Several critical factors will influence the pace at which humanoid surgeons become integrated into mainstream healthcare. The rate of **technological progress** in areas like artificial intelligence, robotics, and sensor technology will be a primary determinant [2]. Breakthroughs in these fields will be necessary to overcome the current limitations in dexterity, autonomy, reliability, and safety. The **regulatory approval processes** for medical devices, which are rigorous and designed to ensure patient safety, will also play a significant role in the timeline [63]. Extensive testing and validation will be required before humanoid surgeons can receive widespread regulatory clearance. Demonstrating the **cost-effectiveness** and long-term value of humanoid surgery compared to existing surgical methods will be crucial for its adoption by healthcare institutions [25]. Healthcare providers will need to see a clear return on investment, whether through improved patient outcomes, reduced complications, shorter hospital stays, or increased efficiency. Finally, **public trust and acceptance** of humanoid robots performing surgery will be essential for their widespread integration into healthcare [3]. Addressing ethical concerns, ensuring transparency, and demonstrating the benefits of this technology to patients will be critical for fostering public confidence.

IX. Comparing Humanoid Surgeons with Existing Robotic Surgery Systems:

To fully appreciate the potential impact of humanoid surgeons, it is essential to compare them with existing robotic surgery systems, highlighting their respective advantages and disadvantages.

Current robotic surgery systems, such as the da Vinci Surgical System and the Versius Surgical System, offer several significant **advantages**. They provide surgeons with **enhanced precision and dexterity**, often exceeding the limitations of the human hand, along with high-definition, three-dimensional visualization of the surgical field [4]. These systems facilitate **minimally invasive approaches**, leading to reduced blood loss, shorter hospital stays, faster recovery times, and smaller scars for patients [4].

However, current systems also have **disadvantages**. They often involve **high initial purchase and ongoing maintenance costs**, which can be a barrier to adoption for many healthcare facilities [33]. The setup time for robotic procedures can be longer compared to traditional open or laparoscopic surgery [81]. A significant limitation of many current systems is the **lack of tactile feedback** for the surgeon, although advancements like force feedback in the da Vinci 5 are beginning to address this [18]. There is also a potential risk of **mechanical malfunction**, although this is reported to be rare [5]. Surgeons require **specialized training** to operate these complex systems effectively [5]. In the early stages of adoption, surgical times with robotic systems may be longer than with traditional methods as surgeons gain experience [22]. Humanoid surgeons have the potential to offer several **differentiations and added value** compared to these existing systems. The humanoid form factor could lead to a more **intuitive control interface**, particularly for avatar-based systems where the robot directly mimics the surgeon's movements [9]. The increasing focus on **autonomy** in humanoid surgical robot development could enable these systems to perform specific tasks or even entire procedures with less direct human intervention, potentially increasing efficiency and reducing surgeon workload [11]. Advancements in **dexterous manipulation**, particularly through sophisticated actuator systems, could allow humanoid robots to perform even more intricate and delicate surgical maneuvers [9]. The potential for **miniaturization** in humanoid robot design could enable surgical interventions in highly confined anatomical spaces that are difficult to access with current robotic platforms [9].

The future of surgical robotics may also involve **synergies and integration** between different types of robotic systems. Humanoid robots could potentially assist with pre-operative preparations, such as patient positioning and equipment setup, and post-operative care, including patient monitoring and rehabilitation exercises [3]. The integration of artificial intelligence and machine learning is likely to be a common thread across various robotic platforms, enhancing their capabilities in areas such as image analysis, surgical planning, and autonomous task execution [2]. It is also conceivable that humanoid robots could be designed to utilize existing robotic surgery instruments and infrastructure, facilitating their integration into current operating room environments.

Table 1: Comparative Analysis of Existing Robotic Surgery Systems (Examples)

System Name	Manufacturer	Key Features	Advantages	Disadvantages	Common Surgical Applications
da Vinci Surgical System	Intuitive Surgical	Multiple arms, 3D HD visualization, EndoWrist instruments, surgeon console	Enhanced precision, dexterity, minimally invasive, reduced blood loss, shorter hospital stays, faster recovery	High cost, lack of tactile feedback (older models), longer setup time, requires specialized training	Urology (prostatectomy), gynecology (hysterectomy), general surgery, cardiothoracic surgery, head and neck surgery, colorectal surgery
Versius Surgical System	CMR Surgical	Modular, portable, biomimics human arm, 3D HD vision, fully-wristed instruments	Versatile, adaptable, compact, portable, designed for easy adoption, ergonomic surgeon console, cost-effective potential	Relatively new to the US market, long-term outcomes still being evaluated	Soft tissue minimal access surgery, cholecystectomy (initial US indication), potential for wider applications
Mako System	Stryker Corporation	Robotic arm for joint replacement, haptic feedback (some models), pre-operative planning	Improved accuracy in implant placement, reduced soft tissue damage, potential for better long-term outcomes in joint replacement	Higher cost, longer surgical time initially, requires specific training	Orthopedics (hip and knee replacement)

Table 2: Potential Advantages of Humanoid Surgeons vs. Existing Systems

Feature/Capability	**Humanoid Surgeons (Potential)**	**Existing Robotic Systems**	**Explanation of Advantage (Humanoid)**
Control Interface	More intuitive, potentially full body replication for avatar systems	Console-based control with hand and foot pedals	Humanoid form could allow for more natural and direct manipulation, potentially reducing the learning curve and enhancing the surgeon's sense of presence.
Autonomy	Higher potential for task and procedure automation through advanced AI	Primarily surgeon-controlled with limited autonomous features currently	Could lead to increased efficiency, reduced surgeon fatigue, and potentially more consistent outcomes for standardized surgical steps.
Dexterity	Enhanced through advanced actuators, potentially exceeding human range of motion in miniaturized forms	High dexterity, but may be limited by the design and size of robotic arms and instruments	Miniaturized humanoid robots could access and manipulate tissues in very confined spaces with exceptional dexterity.
Minimally Invasive Access	Potential for single, ultra-small incisions with miniaturized avatars	Typically require multiple port incisions	Could significantly reduce patient trauma, scarring, and recovery time compared to current minimally invasive techniques.
Remote Surgery	Designed for remote operation with full sensory replication for the surgeon	Capable of telesurgery but may lack the immersive and intuitive control of a dedicated humanoid avatar system	Humanoids provide a more direct and embodied experience for the remote surgeon, potentially improving the precision and safety of tele surgical procedures.

Table 3: Timeline Predictions for Robotic Surgery and Humanoid Robots (Examples)

Year/Period	Event/Milestone	Source/Reference
2025	Global surgical robotics market expected to reach USD 12.6 billion	[84]
2026	Robotic-assisted surgery market predicted to grow to over $14 billion	[88]
2030	Global humanoid robot market projected to reach approximately USD 6.72 billion	[90]
2032	Global surgical robotics market forecast to grow to USD 83 billion	[25]
2034	North American humanoid robot market expected to reach approximately USD 3.19 billion	[90]
2040s	Potential for over 1 billion humanoids on Earth	[91]
2025-2037	Healthcare Humanoid Robot Market size expected to expand by USD 15.53 billion, reflecting a CAGR of around 16.7%	[1]

X. Conclusion: Charting the Course for Humanoid Surgeons in the Future of Healthcare

The concept of the humanoid surgeon represents a compelling vision for the future of surgery, offering the potential for significant advancements in precision, minimally invasive techniques, remote access to care, and surgical efficiency. These advanced robotic systems, whether acting as remotely controlled avatars or increasingly autonomous surgical assistants, hold the promise of transforming how surgical procedures are performed and ultimately improving patient outcomes.

However, the realization of this vision is contingent upon overcoming a number of significant

challenges. Technological hurdles in artificial intelligence, robotics, and sensor development must be addressed through sustained research and innovation. The high costs associated with developing and implementing these complex systems will need to be carefully managed to ensure equitable access. Navigating the evolving regulatory landscape and ensuring the long-term reliability and safety of humanoid surgeons are also paramount considerations.
Ethical implications surrounding patient safety, accountability, the role of human surgeons, the patient-robot relationship, and equitable access must be thoughtfully addressed through ongoing dialogue and the development of appropriate ethical frameworks. Expert opinions from surgeons, roboticists, and medical ethicists provide valuable insights into the potential benefits and concerns associated with this emerging field, highlighting the need for a collaborative and responsible approach to innovation.

While the market for surgical robotics is experiencing rapid growth, the widespread adoption of fully capable humanoid surgeons for complex surgical procedures is likely a longer-term prospect, potentially unfolding in the next decade and beyond. The pace of this adoption will be influenced by continued technological breakthroughs, the evolution of regulatory guidelines, the demonstration of cost-effectiveness, and the cultivation of public trust in these advanced surgical technologies.

In conclusion, humanoid surgeons hold transformative potential for the future of surgery and healthcare. By addressing the inherent limitations of current surgical methods and unlocking new capabilities, these advanced robotic systems could pave the way for more precise, less invasive, and more accessible surgical care for patients worldwide. Continued research, careful consideration of ethical implications, and a collaborative approach involving experts from diverse fields will be essential to charting a course towards a future where humanoid surgeons play a vital role in enhancing human health and well-being.

Works cited

1. Healthcare Humanoid Robot Market Size & Share | Growth Report 2037 - Research Nester, accessed March 28, 2025, https://www.researchnester.com/reports/healthcare-humanoid-robot-market/6565
2. Orthopedics Robotic-Assisted Surgery Industry Forecast 2025-2035 - By 2035, Cost-Effective Robotic Systems Will Propel Market Expansion in Emerging Regions - GlobeNewswire, accessed March 28, 2025, https://www.globenewswire.com/news-release/2025/03/12/3041378/28124/en/Orthopedics-Robotic-Assisted-Surgery-Industry-Forecast-2025-2035-By-2035-Cost-Effective-Robotic-Systems-Will-Propel-Market-Expansion-in-Emerging-Regions.html
3. Humanoid robot - Wikipedia, accessed March 28, 2025, https://en.wikipedia.org/wiki/Humanoid_robot
4. Robotic surgery - Mayo Clinic, accessed March 28, 2025, https://www.mayoclinic.org/tests-procedures/robotic-surgery/about/pac-20394974
5. Robotic Surgery: What It Is, Examples, Benefits & Risks - Cleveland Clinic, accessed March 28, 2025, https://my.clevelandclinic.org/health/treatments/22178-robotic-surgery
6. What is Robotic Surgery? - Robotic Surgery | UCLA Health, accessed March 28, 2025, https://www.uclahealth.org/medical-services/robotic-surgery/what-robotic-surgery
7. Advantages of Robotic-Assisted Surgery, accessed March 28, 2025, https://www.washingtonhealth.com/news/2025/january/advantages-of-robotic-assisted-surgery/
8. Advancements in Robotic Surgery: A Comprehensive Overview of Current Utilizations and Upcoming Frontiers, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10784205/
9. Is a Humanoid Robot the Future of Surgery? - YouTube, accessed March 28, 2025, https://www.youtube.com/watch?v=lef6Pb-gLuQ
10. Is a Humanoid Robot the Future of Surgery? - Vicarious Surgical, accessed March 28, 2025, https://www.vicarioussurgical.com/article/is-a-humanoid-robot-the-future-of-surgery
11. Robot that watched surgery videos performs with skill of human doctor - JHU Hub, accessed March 28, 2025, https://hub.jhu.edu/2024/11/11/surgery-robots-trained-with-videos/
12. Robot That Watched Surgery Videos Performs With Skill of Human Doctor, accessed March 28, 2025, https://engineering.jhu.edu/news/robot-that-watched-surgery-videos-performs-with-skill-of-human-doctor/
13. Surgical robot learns to automate basic tasks via imitation learning, accessed March 28, 2025, https://www.rdworldonline.com/beyond-manual-control-the-

next-generation-of-surgical-robots-is-emerging/
14. New AI Research Foreshadows Autonomous Robotic Surgery ..., accessed March 28, 2025, https://developer.nvidia.com/blog/new-ai-research-foreshadows-autonomous-robotic-surgery/
15. Robot that watched surgery videos performs with skill of human ..., accessed March 28, 2025, https://www.sciencedaily.com/releases/2024/11/241111123037.htm
16. In a first, surgical robots learned tasks by watching videos - Robots have been trained to perform surgical tasks with the skill of human doctors, even learning to correct their own mistakes during surgeries. : r/Futurology - Reddit, accessed March 28, 2025, https://www.reddit.com/r/Futurology/comments/1hpssrb/in_a_first_surgical_robots_learned_tasks_by/
17. CMR Surgical - Transforming Surgery. For Good., accessed March 28, 2025, https://us.cmrsurgical.com/
18. Meet the New Da Vinci 5 Robotic Surgical System - Intuitive, accessed March 28, 2025, https://www.intuitive.com/en-us/products-and-services/da-vinci/5
19. Benefits of Robotic Surgery | UC Health, accessed March 28, 2025, https://www.uchealth.com/services/robotic-surgery/patient-information/benefits/
20. Robotic surgery precision, recovery - Mayo Clinic Health System, accessed March 28, 2025, https://www.mayoclinichealthsystem.org/hometown-health/speaking-of-health/robotic-surgery-precision-and-recovery
21. Breakthroughs in Robotics: Precision Surgery, Creative AI, and Next-Gen Humanoids, accessed March 28, 2025, https://lucidbots.com/robot-rundown/robots-from-sanactions-to-surgeries-0
22. Robotic Surgery: Risks vs. Rewards | PSNet, accessed March 28, 2025, https://psnet.ahrq.gov/web-mm/robotic-surgery-risks-vs-rewards
23. What Is Robotic Surgery | NYU Langone Health, accessed March 28, 2025, https://nyulangone.org/care-services/robotic-surgery-center/what-is-robotic-surgery
24. www.uchealth.com, accessed March 28, 2025, https://www.uchealth.com/services/robotic-surgery/patient-information/benefits/#:~:text=Faster%20recovery%20time%20and%20return,Minimal%20scarring
25. Role of Robotic-Assisted Surgery in Public Health: Its Advantages and Challenges - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11265954/
26. isrg.intuitive.com, accessed March 28, 2025, https://isrg.intuitive.com/news-releases/news-release-details/meta-analysis-published-annals-surgery-shows-benefits-da-vinci#:~:text=Da%20Vinci%20robotic%20cases%20saw,and%2075%20percent%20versus%20open.
27. 4 Benefits of the DaVinci Robotic Surgical System, accessed March 28, 2025, https://www.lsc-ms.com/blog/4-benefits-of-the-davinci-robotic-surgical-system
28. da Vinci® Surgical System for robotic surgery - Cancer Treatment Centers of

America, accessed March 28, 2025, https://www.cancercenter.com/treatment-options/surgery/surgical-oncology/robotic-surgery
29. da Vinci Surgery: Treatment & Recovery - Cleveland Clinic, accessed March 28, 2025, https://my.clevelandclinic.org/health/treatments/16908-da-vinci-surgery
30. About the daVinci Surgical System - UC Health, accessed March 28, 2025, https://www.uchealth.com/services/robotic-surgery/patient-information/davinci-surgical-system/
31. Robots could help close surgeons' skill gaps and improve patient outcomes | CDSS at UC Berkeley, accessed March 28, 2025, https://cdss.berkeley.edu/news/robots-could-help-close-surgeons-skill-gaps-and-improve-patient-outcomes
32. The Future of Robotic Surgery: 3 Trends to Look For - The EngineeringVU, accessed March 28, 2025, https://blog.engineering.vanderbilt.edu/the-future-of-robotic-surgery-3-trends-to-look-for
33. Human Health and Equity in an Age of Robotics and Intelligent Machines - NAM, accessed March 28, 2025, https://nam.edu/perspectives/human-health-and-equity-in-an-age-of-robotics-and-intelligent-machines/
34. 2024 surgical robotics outlook - The Robot Report, accessed March 28, 2025, https://www.therobotreport.com/2024-surgical-robotics-outlook/
35. Robotic Surgery: Applications, Limitations, and Impact on Surgical Education - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC1681689/
36. How Proprio's platform promises to tackle the surgeon shortage, accessed March 28, 2025, https://www.rdworldonline.com/proprio-ceo-charts-the-future-of-surgical-robotics-as-a-shortage-of-surgeons-looms/
37. Clinical applications of artificial intelligence in robotic surgery - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10907451/
38. pmc.ncbi.nlm.nih.gov, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10862530/#:~:text=Autonomous%20control%20of%20surgical%20robotic,some%20have%20reached%20clinical%20application.
39. Autonomous Robotic Surgery: Has the Future Arrived? - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10862530/
40. Autonomous Robotic Surgery: Has the Future Arrived? | Cureus, accessed March 28, 2025, https://www.cureus.com/articles/214232-autonomous-robotic-surgery-has-the-future-arrived
41. The Future of Artificial Intelligence in Surgery - PMC - PubMed Central, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11293880/
42. Robot performs soft tissue surgery with minimal human help, accessed March 28, 2025, https://www.nibib.nih.gov/news-events/newsroom/robot-performs-soft-tissue-surgery-minimal-human-help
43. 5 biggest challenges of building a humanoid robot [Updated], accessed March 28, 2025, https://roboticsbiz.com/5-biggest-challenges-of-building-a-humanoid-robot/
44. Artificial Intelligence in Surgery: Opportunities, Applications, Challenges -

NextGen Invent, accessed March 28, 2025, https://nextgeninvent.com/blogs/ai-in-surgery-opportunities-applications-and-challenges/
45. RFI: Possible directions in autonomous robotic surgery - ARPA-H, accessed March 28, 2025, https://arpa-h.gov/news-and-events/rfi-possible-directions-autonomous-robotic-surgery
46. Current Limitations of Surgical Robotics in Reconstructive Plastic Microsurgery - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC5931136/
47. Pros and Cons of Robotic Surgery - Narayana Health, accessed March 28, 2025, https://www.narayanahealth.org/blog/pros-and-cons-of-robotic-surgery
48. Overcoming Challenges in Robotic-Assisted Surgery: Costs, Training, and Technology Integration - Kontron, accessed March 28, 2025, https://www.kontron.com/en/blog/embedded/Challenges-in-Robotic-Assisted-Surgery
49. AMA Code of Medical Ethics' Opinions Related to Robotic Surgery, accessed March 28, 2025, https://journalofethics.ama-assn.org/article/ama-code-medical-ethics-opinions-related-robotic-surgery/2023-08
50. Human-Robot Interaction in the O.R.: How Surgeons and Medical Robots Can Work Together - Brainlab, accessed March 28, 2025, https://www.brainlab.com/journal/human-robot-interaction-in-the-o-r-how-surgeons-and-medical-robots-can-work-together/
51. Comparing the Feasibility of Robotic Surgery to Human Surgeons ..., accessed March 28, 2025, https://medium.com/@PotriAbhisri/comparing-the-feasibility-of-robotic-surgery-to-human-surgeons-779dbe02fb63
52. Is robotic surgery cost-effective: Yes | Request PDF - ResearchGate, accessed March 28, 2025, https://www.researchgate.net/publication/51756658_Is_robotic_surgery_cost-effective_Yes
53. A systematic review of full economic evaluations of robotic-assisted surgery in thoracic and abdominopelvic procedures - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10678817/
54. Surgical Robotics Economics: Cost-Effectiveness & Long-Term ..., accessed March 28, 2025, https://blog.boston-engineering.com/surgical-robotics-economics-cost-effectiveness-long-term-benefits
55. Doing the Math: Can the Robot Be Cost-Effective for General Surgery? - MEDITEK, accessed March 28, 2025, https://www.meditek.ca/math-can-robot-cost-effective-general-surgery/
56. How can robot-assisted surgery provide value for money?, accessed March 28, 2025, https://sit.bmj.com/content/3/1/e000042
57. Cost-Effectiveness of Robotic Surgery in Long-Term Healthcare Planning, accessed March 28, 2025, https://www.laparoscopyhospital.com/news/preview.php?id=543&p=3&search=
58. The Economics of Robotic Surgery: Cost-Benefit Analysis, accessed March 28, 2025, https://www.laparoscopyhospital.com/worldlaparoscopyhospital/index.php?pid=

451&p=
59. Humanoid Robots for Sale - Top 3D Shop, accessed March 28, 2025, https://top3dshop.com/robots/humanoid-robots/
60. Professional Humanoid Robots - RobotShop, accessed March 28, 2025, https://www.robotshop.com/collections/professional-humanoid-robots
61. Healthcare Humanoid Robot Market Size & Share Report, 2032, accessed March 28, 2025, https://www.gminsights.com/industry-analysis/healthcare-humanoid-robot-market
62. What are the challenges in deploying products into healthcare settings versus other industries? - EIT Health, accessed March 28, 2025, https://eithealth.eu/news-article/robots-in-medicine-the-robotics-start-ups-making-a-difference-in-healthcare/answerpack/able-human-motion/what-are-the-challenges-in-deploying-products-into-healthcare-settings-versus-other-industries
63. Navigating the Regulatory Landscape of Robotic Surgery Innovations, accessed March 28, 2025, https://www.laparoscopyhospital.com/news/index.php?id=554&p=2&search=
64. Regulatory frameworks and approval processes | Medical Robotics Class Notes - Fiveable, accessed March 28, 2025, https://library.fiveable.me/medical-robotics-and-computer-assisted-surgery/unit-14/regulatory-frameworks-approval-processes/study-guide/d2vfXJP7LOHgw5pH
65. In the Hands of a Robot, From the Operating Room to the Courtroom: The Medicolegal Considerations of Robotic Surgery - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10504870/
66. Quick Safety 3: Potential risks of robotic surgery | The Joint Commission, accessed March 28, 2025, https://www.jointcommission.org/resources/news-and-multimedia/newsletters/newsletters/quick-safety/quick-safety-issue-3-potential-risks-of-robotic-surgery/potential-risks-of-robotic-surgery/
67. Robotic Surgery Errors to Watch Out for In 2024, accessed March 28, 2025, https://www.rbrlaw.com/blog/2024/april/robotic-surgery-errors-to-watch-out-for-in-2024/
68. Vicarious Surgical completes Beta 2 system design - MassDevice, accessed March 28, 2025, https://www.massdevice.com/vicarious-surgical-completes-beta2-design/
69. Humanoid robots. Robotic surgery on humans w/in a decade? Shannon Wong, MD., accessed March 28, 2025, https://www.youtube.com/watch?v=f0bGoVnTFv8
70. Sony's careful robot is learning how to perform microsurgeries - Mashable, accessed March 28, 2025, https://mashable.com/video/sony-robot-microsurgery-precision
71. Surgical Simulation Prototype for SkySurgery - PreviewLabs, accessed March 28, 2025, https://previewlabs.com/surgical-simulation-prototype-for-skysurgery/
72. Surgical Robot Project Receives Up to $12 Million in ARPA-H Funding, accessed March 28, 2025, https://mabe.utk.edu/surgical-robot-project-receives-up-to-12-million-in-arpa-h-funding/

73. The Horizon 2020 FAROS Project: Surgical Robots That Hear and Feel in Action - YouTube, accessed March 28, 2025, https://www.youtube.com/watch?v=PAZlH_XqEf0
74. In the Hands of Machines: Ethical Challenges Surrounding Robotic Surgery - WhatNext.Law, accessed March 28, 2025, https://whatnext.law/2024/08/08/in-the-hands-of-machines-ethical-challenges-surrounding-robotic-surgery/
75. A review on legal issues of medical robots - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11124718/
76. ethical considerations of integrating artificial intelligence into surgery ..., accessed March 28, 2025, https://academic.oup.com/icvts/article/40/3/ivae192/8042349
77. Ethical Considerations in Robotic Surgical Services - Wray Hospital & Clinic, accessed March 28, 2025, https://wrayhospital.org/ethical-considerations-in-robotic-surgical-services/
78. I, Robotic Surgeon | Journal of Ethics | American Medical Association, accessed March 28, 2025, https://journalofethics.ama-assn.org/article/i-robotic-surgeon/2014-10
79. Robots can never replace human surgeons - Daily Trojan, accessed March 28, 2025, https://dailytrojan.com/2021/11/18/robots-can-never-replace-human-surgeons/
80. Robotic Surgery: A Comprehensive Review of the Literature and Current Trends - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10445506/
81. What to Know About Robotic Surgery - WebMD, accessed March 28, 2025, https://www.webmd.com/a-to-z-guides/robotic-surgery-what-know
82. A review on humanoid robotics in healthcare - MATEC Web of Conferences, accessed March 28, 2025, https://www.matec-conferences.org/articles/matecconf/pdf/2018/12/matecconf_icmme2018_02004.pdf
83. Exploring the Ethical Implications of AI and Robotics for Healthcare: A Cross-Cultural Study, accessed March 28, 2025, https://www.youtube.com/watch?v=8QDMG7pfl_A
84. Surgical Robotics Statistics and Facts (2025) - Electro IQ -, accessed March 28, 2025, https://electroiq.com/stats/surgical-robotics-statistics-and-facts/
85. Surgical Robot Systems Market and Competition Analysis, - GlobeNewswire, accessed March 28, 2025, https://www.globenewswire.com/news-release/2025/01/16/3010649/28124/en/Surgical-Robot-Systems-Market-and-Competition-Analysis-2025-2030-Featuring-Intuitive-Surgical-THINK-Surgical-Smith-Nephew-Medtronic-Stryker-Corporation-More.html
86. Robotic surgery devices market to reach $10 billion in 2024, forecasts GlobalData, accessed March 28, 2025, https://www.globaldata.com/media/medical-devices/robotic-surgery-devices-market-reach-10-billion-2024-forecasts-globaldata/
87. Positioning The Industry For Growth In Robotic Surgery - Oliver Wyman, accessed March 28, 2025, https://www.oliverwyman.com/our-expertise/perspectives/health/2023/august/positioning-the-industry-for-growth-

in-robotic-surgery.html
88. 5 ways that robotics are transforming healthcare - The World ..., accessed March 28, 2025, https://www.weforum.org/stories/2024/09/robots-medical-industry-healthcare/
89. Humanoid Robotics: Progress, Challenges, and the Road to Adoption | CloudSyntrix, accessed March 28, 2025, http://www.cloudsyntrix.com/blogs/humanoid-robotics-progress-challenges-and-the-road-to-adoption/
90. Humanoid Robots Market: Shaping the Future of Healthcare ..., accessed March 28, 2025, https://www.roboticstomorrow.com/news/2025/01/24/humanoid-robots-market-shaping-the-future-of-healthcare-education-and-automation/23992/
91. The Rise of Humanoids, Explained - Global X ETFs, accessed March 28, 2025, https://www.globalxetfs.com/the-rise-of-humanoids-explained/
92. Diffusion and adoption of the surgical robot in urology - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8185660/
93. ROBOTS AS SURGEONS THE ADOPTION OF SURGICAL SAFETY STANDARDS TO ROBOTIC SURGERY Kanika Kalra, accessed March 28, 2025, https://www.ijlet.org/wp-content/uploads/2025/01/2.1.1.pdf
94. Upcoming multi-visceral robotic surgery systems: a SAGES review ..., accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11615118/
95. Robotic Surgeries Need Regulatory Attention, accessed March 28, 2025, https://www.theregreview.org/2020/01/08/kunwar-robotic-surgeries-need-regulatory-attention/
96. Computer-Assisted Surgical Systems | FDA, accessed March 28, 2025, https://www.fda.gov/medical-devices/surgery-devices/computer-assisted-surgical-systems
97. First FDA-Approved Robot-Assisted Microsurgery for Head and ..., accessed March 28, 2025, https://www.cedars-sinai.org/newsroom/first-fda-approved-robot-assisted-microsurgery-for-head-and-neck-cancer-performed-at-cedars-sinai/
98. Momentis Surgical wins FDA clearance for its surgical robot - MassDevice, accessed March 28, 2025, https://www.massdevice.com/momentis-surgical-wins-fda-clearance-for-its-surgical-robot/
99. Memic Receives FDA De Novo Marketing Authorization for First-Ever Surgical Robotic System with Humanoid-shaped Robotic Arms - Momentis, accessed March 28, 2025, https://www.momentissurgical.com/news/memic-receives-fda-de-novo-marketing-authorization-for-first-ever-surgical-robotic-system-with-humanoid-shaped-robotic-arms/
100. FDA Authorizes First Robotically-Assisted Surgical Device for Performing Transvaginal Hysterectomy, accessed March 28, 2025, https://www.fda.gov/news-events/press-announcements/fda-authorizes-first-robotically-assisted-surgical-device-performing-transvaginal-hysterectomy
101. CMR Surgical receives U.S. FDA Marketing Authorization for next-generation Versius Surgical System, accessed March 28, 2025,

https://us.cmrsurgical.com/news/cmr-receives-fda-marketing-authorization-for-versius
102. Is da Vinci robotic-assisted surgery worth it? - Intuitive Surgical, accessed March 28, 2025, https://www.intuitive.com/en-us/-/media/ISI/Intuitive/Pdf/Da-Vinci-Total-Cost-to-Treat.pdf
103. Lowering Surgical Costs: Is Robotics the Answer? - Paid Program - WSJ, accessed March 28, 2025, https://partners.wsj.com/intuitive-surgical/at-the-point-of-possibility/lowering-surgical-costs-is-robotics-the-answer/
104. Human-Robot Collaboration for Healthcare: A Narrative Review - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10739095/
105. Ethics 4.0: Ethical Dilemmas in Healthcare Mediated by Social Robots - PMC, accessed March 28, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9989998/
106. Humanoid patient robot for diagnostic training in medical and psychiatric education, accessed March 28, 2025, https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2024.1424845/full
107. Advances in Robotic Surgery: A Review of New Surgical Platforms - MDPI, accessed March 28, 2025, https://www.mdpi.com/2079-9292/13/23/4675
108. Beyond The Code: Human Factors In Robotic Surgery Risk ... - Forbes, accessed March 28, 2025, https://www.forbes.com/councils/forbestechcouncil/2024/09/30/beyond-the-code-human-factors-in-robotic-surgery-risk-management/
109. Comparative Evaluation of Major Robotic Systems in Microanastomosis Procedures: A Systematic Review of Current Capabilities and Future Potential - MDPI, accessed March 28, 2025, https://www.mdpi.com/2076-3425/14/12/1235
110. Pros and Cons of Robotic Assisted Surgery | Carrothers Orthopaedics, accessed March 28, 2025, https://carrothersorthopaedics.co.uk/pros-and-cons-of-robotic-assisted-surgery/
111. Transforming Healthcare With Humanoid Robotics - Medindia, accessed March 28, 2025, https://www.medindia.net/news/healthwatch/transforming-healthcare-with-humanoid-robotics-218443-1.htm
112. Human-Robot Interaction and Social Robot: The Emerging Field of Healthcare Robotics and Current and Future Perspectives for Spinal Care - Neurospine, accessed March 28, 2025, https://www.e-neurospine.org/m/journal/view.php?number=1606
113. Human-Robot Interaction and Social Robot: The Emerging Field of Healthcare Robotics and Current and Future Perspectives for Spinal Care - Neurospine, accessed March 28, 2025, https://www.e-neurospine.org/journal/view.php?number=1606

This report was generated with the assistance of AI tools to enhance accuracy, efficiency, and clarity. AI was also used for data analysis, drafting, and editing.