Review

Research Prospectives of Biomaterials in Robotic Surgery

Amon Mojca[1], Petrič Miha[2,*]

1. University Medical Centre Ljubljana, Surgery Department, Ljubljana, Slovenia
2. University Medical Centre Ljubljana, Divison of Abdominal Surgery, Ljubljana, Slovenia

* **Correspondence**: Mojca Amon; **mojca.amon@kclj.si**

Citation: Amon M, Petrič M. Research Prospectives of Biomaterials in Robotic Surgery. Proceedings of Socratic Lectures. **2026**, 14, 2-6. https://doi.org/10.55295/PSL.14.2026.II1

Abstract:
Biomaterials are essential to the advancement of robotic surgery, enhancing surgical precision, facilitating tissue healing, and reducing complications. These materials support the integration of robotic systems with human tissues, improving the efficacy and safety of surgical interventions. Ongoing developments in biomaterials, especially the integration of smart, nanostructured, and biodegradable materials, are poised to greatly improve surgical outcomes and extend the applications of robotic surgery. However, overcoming challenges such as ensuring biocompatibility, managing material degradation, and addressing regulatory concerns is essential for their widespread clinical implementation.

Future research in biomaterials for robotic surgery holds significant promise to enhance surgical precision, improve patient safety, and optimize clinical outcomes. As technological progress continues, the integration of smart, customizable, and biocompatible materials into robotic systems will not only enhance surgeons' capabilities but also minimize complications and accelerate patient recovery with reduced long-term health. In this work we present the recent advancements in the field of robotic surgery.

Keywords Robot assisted surgery; Implants; Biocompatibility; Endocrine disrupting chemicals; Surgical precision; Patient safety.

1. Robotic surgical interventions

Robotic surgery allows surgeons to perform complex procedures with greater precision, flexibility, and control, than traditional methods. Robotic-assisted surgery devices include several components, including a console that allows surgeons to view a 3D reconstructed model of the surgical field and control the movement of surgical instruments (Picard et al., 2019). Such a bedside system includes mechanical arms that hold and manipulate surgical tools as needed by the surgeon, along with additional carts that store and support the necessary hardware and software components. During robotic-assisted surgery, the surgeon sits close to the patient. A small camera and surgical instruments are inserted through small incisions, allowing the surgeon to visualize the surgical field on a video monitor and manually manipulate the robotic arms that mimic the surgeon's actions. These multi-arm robotic systems feature advanced visual feedback and controlled movements. Robotic surgery could offer several advantages over conventional open surgery, including reduced pain, blood loss, risk of infection, less scarring, shorter hospital stays and shorter recovery times (Marescaux & Diana, 2015; Wen et al., 2014).

Robotic surgery is increasingly being adopted due to its enhanced visual capabilities, improved dexterity, and better ergonomic support for surgeons (Khajeh et al., 2023; Hopkins et al., 2020; Markar et al., 2011; Safiejko et al., 2022; Kamarajah et al., 2020). These robotic platforms facilitate implant placement with sub-millimeter accuracy, thereby minimizing the risk of nerve damage and implant malposition. The precision of robotic navigation is also contingent on the visibility of biomaterials in intraoperative scans, including fluoroscopy and 3D CT imaging. In recent studies, researchers reviewed over 247 publications on robotic technical skill metrics, spanning manual rating scales, simulators, and AI-driven performance tools. Although many AI models demonstrated accuracy rates of ≥90% in controlled laboratory settings, validation in real surgical environments showed accuracy levels ranging from 67% to 100% (Boal et al., 2024). AI systems frequently utilize sensor-integrated simulators and smart surgical instruments to capture force application, motion trajectories, and procedural errors, enabling objective assessment of surgical performance and skill acquisition. Moreover, robotic guidance significantly improves pedicle screw placement accuracy, with clinically acceptable Grade A/B placement rates frequently approaching 98–99%, while also reducing intraoperative revision rates, radiation exposure, and perioperative blood loss compared with conventional manual or fluoroscopy-guided techniques (Wei et al., 2022).

Biomaterials play an essential role in the design and integration of these implants and guidance interfaces, supporting both surgical precision and patient safety. A scoping review of 129 studies published up to mid-2022 revealed that most AI interventions remained at low levels of autonomy, predominantly offering the assistance rather than task autonomy; these interventions were largely focused on non-clinical models, such as in silico simulations or animal studies (Vasey et al., 2023). Biomaterial sensors, such as those providing force and tactile feedback, are essential components of these systems, facilitating real-time data capture and enhancing their overall functionality (Miyazaki et al., 2019).

Surgical robots are regulated as medical devices by the FDA and European CE marking, but a clear framework for evaluating these systems, particularly their AI components, is lacking. The IDEAL framework (Idea, Development, Evaluation, Assessment, and Long-term follow-up), which aims to improve the evaluation of complex interventions, is being adapted for robotic surgery. It includes stages from first-in-human evaluation to long-term follow-up, with newer adaptations providing guidance on preclinical evaluations of surgical devices (Marcus et al., 2024). Currently, most intraoperative AI applications in robotic surgery are in the preclinical phase, characterized by low autonomy and diverse evaluation methods. As AI systems gain higher autonomy, the focus will shift from AI-specific metrics to process outcomes. Future research should emphasize standardized evaluation and structured reporting to ensure the safe integration of used technologies.

2 The role of biomaterials and robotic surgery

2.1 Physical and radiological characteristics of the biomaterials

Biomaterials are indispensable in robotic surgery, particularly as minimally invasive techniques and robotic technologies continue to evolve. Robotic surgical systems rely on biomaterials in a variety of ways, such as implants guided by robotic technology, force or pressure sensors, surgical simulators, tactile interfaces at robotic consoles, and biomaterials that serve as trackable objects. Additionally, next-generation robotic platforms are exploring algorithms capable of automatically detecting implant edges (Gómez-de-Gabriel & Harwin, 2015; Cazalini et al., 2017). Machine learning models, trained on the unique textures and densities of materials, enhance robotic targeting. To ensure optimal system performance, the biomaterials must possess consistent radiological profiles or include contrast features that aid AI in recognizing key elements. The success of robotic surgery is heavily influenced by the physical and radiological characteristics of the biomaterials used. If a material is too radiolucent, robotic guidance systems may struggle to provide real-time feedback. Conversely, if it is too reflective, imaging artifacts or misinterpretations may occur. Furthermore, if not properly calibrated, machine learning systems may fail to accurately recognize the object. Although biomaterials are essential in abdominal surgeries, their use carries inherent risks. Current research focuses on improving biocompatibility, reducing infection rates, and preventing adhesion formation to optimize patient outcomes. Clinicians must remain aware of potential complications and incorporate the latest advancements in biomaterial technology to minimize risks (Nikam et al., 2023).

2.2 Biocompatibility of materials

Biomaterials play a pivotal role in robotic surgery, as implants must exhibit compatibility with both robotic instrumentation and the biological environment of the human body. Commonly used biomaterials include titanium and its alloys, particularly Ti-6Al-4V, and polyether ether ketone (PEEK). Titanium alloys are widely utilized because of their excellent biocompatibility, high corrosion resistance, favorable mechanical properties, and capacity to support osseointegration, making them suitable for robotic spinal procedures such as pedicle screw and rod systems. PEEK, a high-performance thermoplastic polymer, is frequently employed in spinal cages and cranial implants because its elastic modulus more closely resembles that of cortical bone, thereby reducing stress shielding and implant subsidence. Additionally, the radiolucent nature of PEEK enables improved intraoperative and postoperative imaging assessment, which is particularly advantageous in robotic and image-guided surgical procedures (Toth et al., 2006). Despite stringent regulatory requirements for biomaterial safety and performance, challenges remain regarding long-term clinical effectiveness. Potential risks include inflammatory or immune responses, material degradation, wear debris generation, and inadequate osseointegration, all of which may affect implant longevity and clinical outcomes. Therefore, rigorous preclinical testing and long-term post-market surveillance remain essential to ensure patient safety and optimize surgical performance.

2.3 Potential risks associated with biomaterials

Biomaterials, including surgical meshes, sutures, implants, and surface coatings, play a critical role in tissue repair, reinforcement, and reconstruction in abdominal surgery. Despite their substantial clinical benefits, their application may be associated with several biological and mechanical risks requiring careful consideration. Following implantation, biomaterials interact dynamically with host tissues and may trigger a foreign body response characterized by protein adsorption, macrophage activation and fusion into foreign body giant cells, chronic inflammation, and fibrous capsule formation. Persistent inflammatory responses can contribute to fibrosis, chronic pain, impaired tissue integration, and, in severe cases, implant failure or rejection (Anderson et al., 2008).

Mechanical complications may also arise due to material fatigue, stiffness mismatch, fiber fracture, shrinkage, or degradation of biomaterials such as polyethylene terephthalate (PET) and expanded polytetrafluoroethylene (ePTFE) meshes. These changes can compromise structural integrity and potentially lead to tissue erosion, adhesion formation, or inflammatory reactions. Furthermore, progressive mechanical degradation or loss of implant integrity over time may increase the risk of hernia recurrence or injury to surrounding tissues and organs.

Synthetic biomaterials, particularly polypropylene-based meshes, are also susceptible to bacterial colonization and biofilm formation, which may complicate treatment because biofilms provide microorganisms with increased resistance to host immune responses and antimicrobial therapies. Biocompatibility-related issues can additionally impair tissue healing and excessive fibrotic remodeling may contribute to scar formation and functional impairment. In degradable biomaterials, the release of degradation byproducts, such as acidic compounds generated during hydrolysis of polymers including polylactic acid (PLA), may alter local tissue pH and induce irritation or inflammatory reactions. Although uncommon, hypersensitivity or allergic reactions to biomaterial components, additives, metals, or preservatives have also been reported.

3. Future research prospectives of biomaterials in robotic surgery

Ongoing innovation in biomaterials in robotic surgery is pivotal to advancing minimally invasive, personalized, and regenerative surgical approaches (Chatterjee et al., 2024). Furthermore, there is an increasing demand for the development of advanced biomaterials that are not only biocompatible but also exhibit smart, responsive characteristics, ensuring both their functionality and safety over the long term without adverse health effects.

3.1 Potential association of biomaterials and endocrine system

The potential long-term effects of biomaterials, particularly from synthetic polymers such as PVC and polyurethane, on the endocrine system are of significant concern. These materials can release plasticizers, such as phthalates and bisphenol A (BPA), which are known endocrine disruptors. Chronic exposure to these chemicals can alter hormonal balance, affect fertility, and increase the risk of cancer. However, more long-term human data are required to fully understand these risks. Recent studies have underscored that bisphenol A, phthalates, and other plasticizers can interfere with endocrine function, impacting reproductive and metabolic health. These substances may leach from implanted polymers, further complicating their safety profile. Additionally, plastic-related chemicals, including phthalates and bisphenols, have been identified as endocrine-disrupting chemicals (EDCs), neurotoxicants, and potential carcinogens. Such chemicals are linked to various health hazards, including metabolic disorders and cardiovascular diseases, as highlighted in recent reviews (Eales et al., 2022).

3.2 *Biomaterials for enhanced tissue regeneration*

The integration of mesenchymal stem cells (MSCs) with biomaterials in abdominal surgery represents a promising strategy for enhancing tissue regeneration and wound healing. MSCs exert therapeutic effects primarily through paracrine signaling by releasing bioactive factors that promote cell proliferation, angiogenesis, extracellular matrix remodeling, and immunomodulation, including macrophage polarization toward anti-inflammatory phenotypes (Wei et al., 2013). However, the clinical application of stem cell-based therapies remains limited by challenges related to cell sourcing, viability, tumorigenic potential, and regulatory issues. Increasing evidence suggests that many MSC effects are mediated by extracellular vesicles and exosomes, which offer advantages such as lower immunogenicity, improved safety, and easier handling. MSC-derived exosomes carry proteins, growth factors, and microRNAs involved in tissue repair and represent a promising cell-free approach for improving biomaterial integration and regenerative outcomes (Tan et al., 2024).

3. Conclusions

The integration of biomaterials in abdominal robotic surgery holds substantial promise for enhancing surgical outcomes; however, several challenges remain, including issues related to biocompatibility, mechanical properties, infection risks, and regulatory hurdles. Advancements in smart biomaterials, 3D printing, and nanotechnology, coupled with the establishment of standardized evaluation protocols, are essential for addressing these challenges and maximizing the potential of robotic surgery.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Anderson JM, Rodriguez A, Chang DT. Foreign body reaction to biomaterials. Semin Immunol. 2008; 20:86-100. DOI: 10.1016/j.smim.2007.11.004.
2. Boal MWE, Anastasiou D, Tesfai F, Ghamrawi W, Mazomenos E, Curtis N, Collins JW, Sridhar A, Kelly J, Stoyanov D, Francis NK. Evaluation of objective tools and artificial intelligence in robotic surgery technical skills assessment: a systematic review. Br J Surg. 2024; 111:znad331. DOI: 10.1093/bjs/znad331.
3. Eales J, Bethel A, Galloway T, Hopkinson P, Morrissey K, Short RE, Garside R. Human health impacts of exposure to phthalate plasticizers: An overview of reviews. Environ Int. 2022; 158:106903. DOI: 10.1016/j.envint.2021.106903.
4. Cazalini EM, Miyakawa W, Teodoro GR, Sobrinho ASS, Matieli JE, Massi M, Koga-Ito CY. Antimicrobial and anti-biofilm properties of polypropylene meshes coated with metal-containing DLC thin films. J Mater Sci Mater Med. 2017; 28:97. DOI: 10.1007/s10856-017-5910-y.
5. Chatterjee S, Das S, Ganguly K, Mandal D. Advancements in robotic surgery: innovations, challenges and future prospects. J Robot Surg. 2024; 18:28. DOI: 10.1007/s11701-023-01801-w.
6. Gómez-de-Gabriel JM, Harwin W. Evaluation of Sensor Configurations for Robotic Surgical Instruments. Sensors (Basel). 2015; 15:27341-27358. DOI: 10.3390/s151027341.
7. Kamarajah SK, Bundred J, Saint MO, Jiao LR, Manas D, Abu Hilal Met al. Robotic versus conventional laparoscopic pancreaticoduodenectomy: a systematic review and meta-analysis. Eur J Surg Oncol 2020; 46:6–14. DOI: 10.1016/j.ejso.2019.08.007
8. Khajeh E, Aminizadeh E, Dooghaie Moghadam A, Nikbakhsh R, Goncalves G, Carvalho Cet al. Outcomes of robot-assisted surgery in rectal cancer compared with open and laparoscopic surgery. Cancers (Basel) 2023; 15:839. DOI: 10.3390/cancers15030839
9. Hopkins MB, Geiger TM, Bethurum AJ, et al. Comparing pathologic outcomes for robotic versus laparoscopic Surgery in rectal cancer resection: a propensity adjusted analysis of 7616 patients. Surg Endosc. 2020; 34(6):2613-2622. DOI:10.1007/s00464-019-07032-1
10. Markar SR, Karthikesalingam AP, Venkat-Ramen V, Kinross J, Ziprin P. Robotic vs. laparoscopic Roux-en-Y gastric bypass in morbidly obese patients: systematic review and pooled analysis. Int J Med Robot 2011; 7:393–400 DOI: 10.1002/rcs.414
11. Marescaux J, Diana M. Inventing the Future of Surgery. World J. Surg. 2015; 39: 615–622. DOI: 10.1007/s00268-014-2879-2.
12. Picard F, Deakin AH, Riches PE, Deep K, et al. Computer Assisted Orthopaedic Surgery: Past, Present and Future. Med. Eng. Phys. 2019; 72:55–65. DOI: 10.1016/j.medengphy.2019.08.005.
13. Miyazaki R, Kanno T, Kawashima K. Pneumatically driven surgical instrument capable of estimating translational force and grasping force. Int J Med Robot. 2019; 15:e1983. DOI: 10.1002/rcs.1983.
14. Marcus HJ, Ramirez PT, Khan DZ, et al. The IDEAL framework for surgical robotics: development, comparative evaluation and long-term monitoring. Nat Med. 2024; 30: 61–75. DOI:10.1038/s41591-023-02732-7
15. Nikam SP, Hsu YH, Marks JR, Mateas C, Brigham NC, McDonald SM, Guggenheim DS, Ruppert D, Everitt JI, Levinson H, Becker ML. Anti-adhesive bioresorbable elastomer-coated composite hernia mesh that reduce intraperitoneal adhesions. Biomaterials. 2023; 292:121940. DOI: 10.1016/j.biomaterials.2022.121940.
16. Safiejko K, Tarkowski R, Koselak M, Juchimiuk M, Tarasik A, Pruc Met al. Robotic-assisted vs. standard laparoscopic surgery for rectal cancer resection: a systematic review and meta-analysis of 19,731 patients. Cancers (Basel) 2022; 14:1036. DOI: 10.3390/cancers14010180
17. Tan F, Li X, Wang Z, Li J, Shahzad K, Zheng J. Clinical applications of stem cell-derived exosomes. Signal Transduct Target Ther. 2024; 9:17. DOI: 10.1038/s41392-023-01704-0.
18. Toth JM, Wang M, Estes BT, Scifert JL, Seim HB 3rd, Turner AS. Polyetheretherketone as a biomaterial for spinal applications. Biomaterials. 2006; 27:324-34. DOI: 10.1016/j.biomaterials.2005.07.011.
19. Vasey B, Lippert KAN, Khan DZ, Ibrahim M, Koh CH, Layard Horsfall H, Lee KS, Williams S, Marcus HJ, McCulloch P. Intraoperative Applications of Artificial Intelligence in Robotic Surgery: A Scoping Review of Current Development Stages and Levels of Autonomy. Ann Surg. 2023; 278:896-903. DOI: 10.1097/SLA.0000000000005700.
20. Wei FL, Gao QY, Heng W, Zhu KL, Yang F, Du RM, Zhou CP, Qian JX, Yan XD. Association of robot-assisted techniques with the accuracy rates of pedicle screw placement: A network pooling analysis. EClinicalMedicine. 2022; 48:101421. DOI: 10.1016/j.eclinm.2022.101421.
21. Wei X, Yang X, Han ZP, Qu FF, Shao L, Shi YF. Mesenchymal stem cells: a new trend for cell therapy. Acta Pharmacol Sin. 2013; 34:747-54. DOI: 10.1038/aps.2013.50.

Wen R, Tay WL, Nguyen BP, Chng CB, et al. Hand Gesture Guided Robot-Assisted Surgery Based on a Direct Augmented Reality Interface. Comput. Methods Programs Biomed. 2014; 116: 68–80. DOI: 10.1016/j.cmpb.2013.12.018.