Review

Future of Healthcare Trends in Orthopaedics and Biomaterials

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Citation: Amon M, Kocjančič B. Future of Healthcare Trends in Orthopaedics and Biomaterials. Proceedings of Socratic Lectures. **2025**, 13, 26-30. https://doi.org/10.55295/PSL.13.2025.3

Abstract:
Personalized medical technologies are increasingly enhancing precision, efficiency, and patient outcomes. Innovations such as virtual surgical planning, robotic assistance, and real-time 3D navigation have revolutionized procedures like total knee arthroplasty and hip replacement, providing unparalleled accuracy and significantly reducing recovery times. The integration of artificial intelligence (AI), advanced imaging, and patient-specific 3D-printed implants further refines surgical precision, minimizes intraoperative complications, and facilitates personalized care. In the realm of sports orthopedics, wearable sensors and motion analysis technologies are transforming diagnostics, injury prevention, and rehabilitation, enabling real-time decision-making and improving patient safety. Additionally, health tracking devices are accelerating recovery and supporting preventive care, ultimately revolutionizing sports performance management. Concurrently, breakthroughs in biologics, biomaterials, and bioprinting are advancing the treatment of cartilage defects, ligament injuries, osteoporosis, and meniscal damage. These innovations are poised to establish new benchmarks in regenerative medicine. The primary aim of this review is to explore cutting-edge medical technologies employed in surgical practices and highlight significant innovations. Furthermore, we seek to underscore the importance of the biocompatibility of modern biomaterials and outline prospective directions for future research in this field.

Keywords: Artificial intelligence in healthcare; Orthopaedic innovation; Personalized medicine; Robotic surgery; Technological innovation; Biomaterials

1. Future Orthopaedics

1.1. Advances in medical engineering, biomechanics, and biomaterials

In orthopedics, research focuses on understanding the human musculoskeletal system, which is defined as an interconnected network of bones, muscles, tendons, cartilage, and nerves that support body mechanics, maintain posture and stability, and provide necessary movement. Clinical orthopedics treats musculoskeletal injuries across a variety of specialties, including sports medicine, rehabilitation, spine care, deformity correction, pediatrics, and hand care. In the past decade, advances have been made that meet the demands of modern surgery, allowing for procedures with fewer complications and greater precision (Tueni & Amirouche, 2025). Advances in medical engineering, biomechanics, and biomaterials are transforming the medical profession, which is essential for the development of personalized medicine and rehabilitation. From nanoscale biosensors to multidisciplinary molecular research, the collaboration of variety clinicians, technicians, and clients is important to achieve optimal healthcare outcomes and manage costs.

1.2. Artificial intelligence (AI) in medicine

Most fields are using AI-based solutions to automate and speed up time-consuming procedures. Specifically, in orthopedics, AI systems use massive amounts of data to explore numerous scenarios, predict surgical outcomes, and select the most appropriate treatment, providing patients with the highest level of personalized care (Federer and Jones, 2021). AI is also advancing in the creation of customized medical devices such as personalized implants created after scanning, specific to the patient, especially in surgeries such as spinal fusion (Shin et al., 2022) and bone-tumor reconstuction orthopedics (Yon et al., 2025). In addition, 3D-printed, patient-specific surgical guides are in use, offering numerous advantages in orthopedics.

1.3 Robotic surgery in orthopaedic surgery

Research consistently indicates that robotic-assisted total knee arthroplasty (rTKA) achieves better mechanical and anatomical alignment than conventional total knee arthroplasty (cTKA) (Alrajeb et al., 2024). A large-scale study results suggests that rTKA is associated with lower rates of aseptic loosening, prosthetic joint infections, revisions, and overall complications at the five-year follow-up (Wainwright et al., 2025).

Moreover, rTKA offers enhanced precision in component alignment, potentially leading to improved long-term implant survival. However, the clinical benefits in terms of functional outcomes are not consistently superior to conventional techniques. The increased surgical time and associated costs are important considerations. Further high-quality, large-scale randomized controlled trials are needed to better understand the long-term benefits and cost-effectiveness of robotic-assisted TKA (Deckey et al., 2021).

1.4 Bioprinting in orthopaedics

Three-dimensional bioprinting (3-D printing) or regenerative medicine allows for local treatment of the area where the anomaly is located in the context of minimally invasive surgery, thus avoiding complications and severe immune rejection.

The challenges in bioprinting remain in the ability to print cells that can survive, proliferate, and build a functioning matrix on a tissue-specific scaffold that provides full support for the cells using growth factors that promote cell development (Lam et al., 2019). Such products include knowledge in the fields of artificial intelligence, robotics and diagnostics, with a focus on the commercialization of technology for life science research and bioprinting (Fonseca et al., 2020), and molecular studies in the replication of human tissues such as cartilage and bone, combining synthetic biology and 3D bioprinting.

In addition to bioprinting, collaboration between physicians and scientists has led to the discovery of noninvasive treatments such as stem cell therapy, which involves directing stem cells placed in patients to replace and repair diseased cells and eventually generate healthy cells (Lee & Hui, 2006; Akpancar et al., 2016; Im, 2017), and exosomes, which contain valuable molecular components of the stem cell, such as proteins and RNA (Wu et al., 2022). Different administration of exosome treatments to improve cell-to-cell communication are being elaborated.

The advantages of image segmentation and the development of patient-specific 3D models before and during surgery, image segmentation for 3D printing has become a key aspect of orthopedic surgery. Recently, with the advancement of AI technology, organ anomalies can be accurately identified and modeled from CT or MRI images, and 3D objects can be accurately rendered. Patient-specific three-dimensional constructs can be printed using rendered volumes, with the goal of using the patient's cellular components to replace damaged or diseased tissue (Yazdanpanah et al., 2022).

1.5 Virtual surgical planning

The transition from surgery to recovery is marked by the post-operative phase, where advances in rehabilitation tools, wearable technologies, and virtual reality ensure effective healing and faster recovery of mobility. Artificial intelligence technologies will give surgeons capabilities they did not have before. Automation also allows for seamless communication and storage of all data in an easily accessible and organized format, while managing operations by tracking all supplies and ensuring that all components arrive at the hospital on time. Supplies and delivery procedures are another factor that can occasionally cause delays in surgeries. The computational technique such as finite element analysis plays a key role in optimizing implant design that allow the simulation and analysis of implant behavior under various physiological loads and conditions. Using finite element analysis, designers can identify stress distributions, potential failure points, and areas for improvement in the implant structure (Tueni & Amirouche, 2025).

2. Limitations of technological innovation in orthopaedics

Among the technical limitations is the assumption that systems may not accurately capture real-world scenarios, which can lead to performance gaps. In addition, issues with system compatibility and integration with existing healthcare technologies can hinder usability. Technology adoption among users, especially older adults who may not be comfortable with virtual reality or telehealth systems, may be another limitation related to participation rates and overall satisfaction with the treatment approach.

Data security and privacy are significant limitations to modern AI-assisted treatment approaches. As more and more patient data is shared across digital platforms, the risk of data breaches increases. Ensuring the privacy and security of patient data is critical to maintaining trust.

A major limitation is financial; while the long-term benefits can be significant, the initial costs of advanced systems and training are prohibitive for some healthcare facilities. These costs include software licensing, hardware purchases, and maintenance costs. Additionally, regulatory compliance for new devices and therapies can be lengthy and complex, which can delay the adoption of innovative technologies. Additionally, a significant limitation to the use of modern treatment trends is the dependence on technology, as overreliance on virtual platforms can lead to a lack of practical training for healthcare professionals, reduced quality of care in cases where personal approaches to surgery are necessary (Tueni & Amirouche, 2025; Wah, 2025).

Furthermore, it is imperative that AI systems are trained on accurate and up-to-date procedures, particularly within the context of a rapidly evolving medical landscape where surgical techniques and best practices are continuously advancing. Given this dynamic environment, careful and deliberate input into the training process is crucial to ensure that AI systems are equipped to adapt to new research findings and clinical discoveries.

2.1 Biomaterials and biocompatibility

Nanobiomaterials science requires a deep clinical understanding of the cellular and molecular basis that governs the function of nanostructures and cells. The challenges of developing optimized structures with properties that mimic those of natural bone or cartilage and respond to loading and stress without premature failure are still being explored.

The use of nanotechnology in combination with bioprinting is emerging as a novel approach in orthopedic research due to its potential to improve current orthopedic biomaterials and facilitate the development of tissue engineering innovations and tissue regeneration solutions for muscle, tendon, bone, and biodegradable implants (Tueni & Amirouche, 2025; Kumar et al., 2025).

2.2 The healthcare trends, opportunities and risks

The growing integration of new technologies is driving a fundamental revolution in the healthcare sector. The development of AI, machine learning, and massive data analytics is slowly transforming the way patients are diagnosed, treated, and cared for. AI-powered solutions are improving the efficiency and accuracy of healthcare delivery, demonstrating exceptional capabilities in personalized medicine, early disease detection, and predictive analytics. Just as telemedicine and remote patient monitoring systems have already overcome geographic limitations to some extent and offered easy and accessible healthcare services, especially in underserved areas, AI in orthopedics is following the trends ((Tueni & Amirouche, 2025).

In medical rehabilitation, wearable technology, and sensor technologies have already enabled individuals to actively participate in tracking and managing their health. Such devices enable real-time data collection, enabling preventive and personalized rehabilitation care. As these technologies continue to develop and integrate into standard healthcare practices, the future of healthcare is likely to be more accessible, efficient, and effective than ever before, but adoption, adaptation, and entry costs will be significant (Thacharodi et al., 2024). Practical experience and findings from different surgical specialties will be essential to ensure a comprehensive understanding of the transformative role of AI. Awareness will also be important for policymakers, healthcare institutions and technology developers to address barriers and promote equitable access to AI-powered surgical solutions. Among the limitations of current technologies is the reliance on recent studies, which requires long-term evaluations of clinical outcomes. Future research should focus on integrating AI with new technologies such as augmented reality, fostering interdisciplinary collaboration as well as addressing socio-ethical dimensions to fully realize the potential of AI in advanced healthcare and biomaterials technology (Wah, 2025).

3. Conclusions

Artificial intelligence and robotics are revolutionizing surgical practices by improving precision, efficiency, and patient outcomes. As global healthcare systems increasingly embrace AI-powered technologies, the integration of robotics into surgery addresses key challenges along the importance of biocompatibility of new biomaterials is raising.

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

References

1. Akpancar S, Tatar O, Turgut H, Akyildiz F, et al. The Current Perspectives of Stem Cell Therapy in Orthopedic Surgery. Arch Trauma Res. 2016; 5: e37976. DOI: 10.5812/atr.37976.
2. Alrajeb R, et al. Robotic-assisted versus conventional total knee arthroplasty: a systematic review and meta-analysis of randomized controlled trials. Eur J Orthop Surg Traumatol. 2024; 34: 1333-1343. DOI: 10.1007/s00590-023-03798-2.
3. Deckey DG et al. Robotic-assisted total knee arthroplasty improves accuracy and precision compared to conventional techniques. Bone Joint J. 2021; 103-B (6 Supple A):74-80. DOI: 10.1302/0301-620X.103B6.BJJ-2020-2003.R1.
4. Fonseca AC, Melchels FPW, Ferreira MJS, Moxon SR, et al. Emulating Human Tissues and Organs: A Bioprinting Perspective Toward Personalized Medicine. Chem. Rev. 2020; 120: 11128–11174. DOI: 10.1021/acs.chemrev.0c00342.
5. Im G.I. Clinical Use of Stem Cells in Orthopaedics. Eur. Cell. Mater. 2017; 33:183–196. DOI: 10.22203/eCM.v033a14
6. Lam T, Dehne T, Krüger JP, Hondke S, et al. Photopolymerizable gelatin and hyaluronic acid for stereolithographic 3D bioprinting of tissue-engineered cartilage. J. Biomed. Mater. Res. B Appl. Biomater. 2019; 107: 2649–2657. DOI: 10.1002/jbm.b.34354.
7. Lee E.H., Hui J.H.P. The Potential of Stem Cells in Orthopaedic Surgery. J. Bone Joint Surg. Br. 2006; 88:841–851. DOI: 10.1302/0301-620X.88B7.17305.

8. Kumar R, Sporn K, Ong J, Waisberg E, et al. Integrating Artificial Intelligence in Orthopedic Care: Advancements in Bone Care and Future Directions. Bioengineering (Basel). 2025; 12:513. DOI: 10.3390/bioengineering12050513.
9. Shin J, Lee Y, Li Z, Hu J, et al. Optimized 3D Bioprinting Technology Based on Machine Learning: A Review of Recent Trends and Advances. Micromachines. 2022; 13: 363. DOI: 10.3390/mi13030363.
10. Thacharodi A, Singh P, Meenatchi R, Tawfeeq Ahmed ZH, et al. Revolutionizing healthcare and medicine: The impact of modern technologies for a healthier future-A comprehensive review. Health Care Sci. 2024; Oct 9; 3: 329-349. DOI: 10.1002/hcs2.115.
11. Tueni N, Amirouche F. Branding a New Technological Outlook for Future Orthopaedics. Bioengineering (Basel). 2025; 1:494. DOI: 10.3390/bioengineering12050494.
12. Wainwright JD, et al. Robotic-assisted total knee arthroplasty reduced mid-term incidences of multiple orthopaedic complications: A large database study. Arch Orthop Trauma Surg. 2025; 145:235. DOI: 10.1007/s00402-025-05856-2.
13. Wah JNK. Revolutionizing surgery: AI and robotics for precision, risk reduction, and innovation. J Robot Surg. 2025; 19: 47. DOI: 10.1007/s11701-024-02205-0.
14. Wu R., Li H., Sun C., Liu J., Chen D., Yu H., Huang Z., Lin S., Chen Y., Zheng Q. Exosome-based strategy for degenerative disease in orthopedics: Recent progress and perspectives. J. Orthop. Transl. 2022; 36:8–17. DOI: 10.1016/j.jot.2022.05.009.
15. Yazdanpanah Z, Johnston JD, Cooper DML, Chen X. 3D Bioprinted Scaffolds for Bone Tissue Engineering: State-Of-The-Art and Emerging Technologies. Front. Bioeng. Biotechnol. 2022; 10:824156. DOI: 10.3389/fbioe.2022.824156.
16. Yon CJ, Choi BC, Lee JM, Lee SW. Personalized 3D-Printed Prostheses for Bone Defect Reconstruction After Tumor Resection in the Foot and Ankle. Journal of Functional Biomaterials. 2025; 16:62. https://doi.org/10.3390/jfb16020062