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Current Concepts

The Role of Artificial Intelligence in Orthopedics

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The integration of Artificial Intelligence (AI) in orthopedics represents a transformative shift, enhancing diagnostics, surgical planning, rehabilitation, and research innovation. This manuscript outlines the evolution and application of AI across various orthopedic subspecialties, emphasizing its role in streamlining processes and improving patient outcomes. The comprehensive review highlights the historical progression, current applications, and the promising future of AI in managing conditions such as osteoarthritis, fractures, and other musculoskeletal disorders.

This study systematically categorizes AI applications into diagnostics, surgical planning, post-operative care, and research innovation. AI technologies have shown substantial accuracy in imaging analyses, including X-ray, magnetic resonance imaging, and computed tomography scans, facilitating early and precise diagnosis. In surgical planning, AI contributes to personalized implant designs and real-time surgical navigation, significantly reducing intraoperative risks and enhancing recovery. Post-operatively, AI tools such as remote monitoring and predictive analytics optimize rehabilitation processes and predict potential complications, enabling timely interventions. This work also discusses the role of AI in advancing orthopedic research, fostering interdisciplinary collaboration, and accelerating the discovery of innovative treatments. Furthermore, the implications of AI in educational settings, particularly in orthopedic resident training, are explored to underscore its potential to augment traditional medical training and patient care.

INTRODUCTION

Artificial Intelligence (AI) refers to computer systems designed to perform tasks that typically require human intelligence, such as recognizing patterns, making predictions, or supporting decision-making.[1] A key subset of AI is Machine Learning (ML), which enables computers to "learn" from data rather than being explicitly programmed with fixed rules.[2] In ML, algorithms identify patterns within large datasets and use these patterns to improve predictions or classifications over time. For clinicians, the distinction is important: AI is the broader concept of intelligent computer systems, while ML is one of the main methods by which these systems become effective. For example, AI in healthcare may include decision-support tools, while ML specifically powers applications such as predicting fracture-healing outcomes, identifying subtle imaging abnormalities, and tailoring treatment recommendations based on patient-specific data.[3,4]

Artificial intelligence has been integrated into various facets of medicine, and recent advancements continue to drive the growing role of AI in the field. While early ap-

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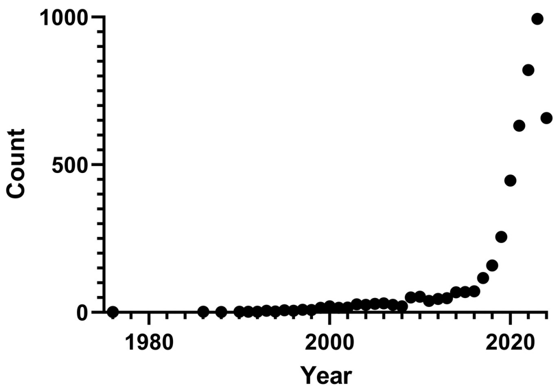

Figure 1. The number of total publications and citations containing the key terms "orthopaedic surgery" and "artificial intelligence."

Data was retrieved from PubMed on July 05, 2024, using the search terms "orthopedic surgery" AND "artificial intelligence."

plications of similar algorithms for diagnosing and managing orthopedic disorders date back to the 20th century, interest in the field has grown significantly over the past decade. It will continue to grow, as reflected in recent literature [**Figure 1**]. The number of Food and Drug Administration (FDA) approvals for AI-based medical devices has increased significantly each year since 2016, reaching 139 in 2022. AI models are being developed in nearly all orthopedic subspecialties. Specifically, these include diagnostics and management of foot and ankle fractures, Achilles tendinopathies, hallux valgus, stress fractures, sports injuries, plantar fasciitis, ankle arthroplasty, and gait abnormalities.[1-5] The nature of these AI applications within orthopedics can be categorized into four major areas: diagnostics, surgical planning, rehabilitation and post-operative care, and research and innovation [**Table 1**].

AI APPLICATIONS IN ORTHOPAEDICS

Pre-operatively, AI algorithms can analyze patient data, such as magnetic resonance imaging (MRI), computed tomography (CT), X-rays, and medical records, to assist surgeons in planning and diagnostics. This can help determine optimal implant sizes and placements and anticipate potential complications.[4] Concerning diagnostics, AI tools have been applied for implant identification and design, imaging for fracture and tumor recognition, and gait analysis.[4,5,7,13] Specifically, AI-powered imaging analysis allows for a streamlined approach to examining radiographic images, such as X-rays, MRIs, and CT scans, in detecting fractures, tumors, and other abnormalities with high accuracy and speed.[8,14] Studies have shown that AI has reduced the time and effort required for hip and elbow fracture diagnosis with high accuracy.[6,8,9,11,15-18] Most common applications of AI in hand surgery and rehabilitation target automated image analysis of anatomic structures, fracture detection and localization, and automated screening for other hand and wrist pathologies such as carpal tunnel syndrome, rheumatoid arthritis, or osteoporosis, as well as spine trauma, lumbar disc hernia, and spinal deformity surgery.[6,11,15-17] AI-based motion analysis systems assess gait patterns, joint movements, and biomechanics, facilitating precise diagnoses of osteoarthritis and sports injuries.[6,8-11,14-19] Recent advancements have also involved machine learning models that utilize patient data and medical records to predict the progression of orthopedic conditions, enabling proactive interventions and personalized treatment strategies.[8]

AI-powered systems can provide surgeons with real-time guidance during surgery, aiding in precise bone cutting and implant placement.[11] This can lead to better outcomes and reduced chances of errors. Concerning surgical planning and intervention, AI has been used in virtual surgical simulations, with orthopedic surgeons employing them to practice complex procedures and plan interventions with en-

Table 1. AI applications in orthopaedics are in 4 categories

Application Area	Examples of AI Applications	Advantages and Advancements
Diagnostics	Gait analysis for osteoarthritis and sports injuries[4] Automated screening for hand and wrist pathologies (*e.g.*, carpal tunnel syndrome)[6] AI-powered imaging analysis (X-ray, MRI, CT) for fracture detection and tumor recognition[7-10]	High accuracy and speed in detecting fractures and abnormalities Automated screening reduces diagnostic time and enhances early detection
Surgical Planning	Virtual surgical simulations for complex procedures[3] Patient-specific implant design and customization[4] AI-guided positioning and navigation in arthroscopic surgery[11]	Enhanced surgical precision and reduced intraoperative complications Customized implants improve fit, functionality, and long-term outcomes
Rehabilitation and Post-Operative Care	AI-powered rehabilitation devices (exoskeletons, motion-tracking sensors)[4] Remote monitoring of patient recovery progress Predictive analytics for postoperative complications[1]	Targeted therapy programs improve rehabilitation outcomes Remote monitoring enables timely interventions and reduces hospital visits
Research and Innovation	AI-driven analysis of clinical datasets and biomedical literature Collaboration platforms for interdisciplinary research AI-assisted personalized patient education and follow-up systems[12]	Accelerated research insights and innovation in orthopedic treatments Patient education tools enhance engagement and outcomes

hanced precision, thereby reducing intraoperative complications and optimizing outcomes.[3] This also applies to education, with AI training for surgical residents. AI allows for patient-specific designs, whereby AI algorithms have generated customized implants and prosthetics tailored to individual patient anatomy, optimizing fit, functionality, and long-term outcomes.[4] The assistance of AI and augmented reality enables precise positioning and navigation in arthroscopic surgery and personalized operations based on patient conditions, which lifts the objective limitations of traditional sports medicine surgery.[6,9-11,16-20] Integrating AI and augmented reality into orthopedic arthroscopy surgery is still early, yet the potential benefits are promising.

Post-operatively, AI-powered tools can facilitate remote monitoring of patient recovery progress. Physicians can intervene, if necessary, by tracking movements, pain levels, and other relevant metrics, enabling more effective outpatient care.[19] Furthermore, other tools can be used to assess arthroplasty outcomes, length of hospital stays, and economic costs, monitoring the progress of functional rehabilitation.[3] Regarding remote patient monitoring, AI-driven wearable technology offers benefits such as tracking patient compliance with home exercise programs, monitoring range of motion, assessing postoperative outcomes, and predicting costs, including the likelihood of prolonged opioid prescription after total hip arthroplasty.[4] Concerning rehabilitation and post-operative care, AI-powered rehabilitation devices, such as exoskeletons and motion-tracking sensors, facilitate targeted therapy programs, monitor patient progress, and adjust treatment protocols in real-time.[4] AI-driven remote monitoring systems enable orthopedic surgeons to remotely track patient recovery, provide virtual consultations, and offer timely interventions, enhancing accessibility and continuity of care. Furthermore, with predictive analytics, AI algorithms analyze patient data to predict postoperative complications, allowing healthcare providers to implement preventive measures and optimize postoperative care approaches.[16]

Finally, AI is being considered in research and innovation. AI-driven platforms have been implemented to provide patients with personalized educational materials and interactive tools to better understand their condition and treatment options.[21,22] This fosters patients' active participation in their care, which is essential for successful outpatient management. One study described an AI-assisted conversational agent that selected an appropriate follow-up time for quantitative, automated, and personalized patient follow-up.[12] Overall, AI algorithms analyze large-scale clinical datasets and biomedical literature to uncover patterns, trends, and novel insights, driving and expediting innovation in orthopedic research and clinical practice, especially for conditions like osteoporosis and rheumatoid arthritis. AI fosters collaboration among orthopedic researchers, clinicians, and industry partners, facilitating knowledge exchange, interdisciplinary research, and technology translation. One particular benefit of AI is to aid clinicians in the laborious task of examining large datasets. For instance, managing spine disorders requires clinicians to interpret many multimodal data points for treatment planning and decisions. Motivated by this, we further reviewed the literature on research and innovation in spine imaging to exemplify the breadth of AI applications in orthopedics **[Table 2]**.

AI in orthopedic surgery is increasingly focused on enhancing care by improving preoperative planning, intraoperative precision, postoperative monitoring, and patient engagement. This not only improves patient outcomes but also contributes to the overall efficiency of healthcare delivery. AI tools can aid in low-resource settings with limited access to trained experts by alleviating the burdens associated with misdiagnoses and delayed diagnoses, such as increased risk of complications and potential mortality.[23] Moreover, in high-resource settings, AI can facilitate early identification and ease the workflow of clinicians and radiologists by saving time and resources. Thus, while the future of AI has been heavily debated, the question is not whether AI will have a role in orthopedics, but what that role looks like.

Given the growth of outpatient orthopedic care, AI will continue to facilitate this shift. The transition to outpatient care began nearly 20 years ago and has gained significant momentum over the past 4 to 5 years, especially in joint replacement surgeries. Minimally invasive surgical techniques and advancements in orthopedic implant technologies played pivotal roles in driving this trend.[24] Improved anesthesia for postoperative pain management has made it possible to perform major joint and spine surgeries in outpatient settings. Moreover, the increasing comfort level of surgeons in performing major procedures in outpatient settings has been bolstered by training programs that adopt this approach for younger physicians. The shift of surgeries to Ambulatory Surgery Centers (ASCs) has been accelerated by changes in healthcare practice during the pandemic. There is a critical space in the outpatient setting for the adoption and integration of AI, with AI algorithms assisting healthcare providers in prioritizing patient appointments and procedures based on factors such as medical history, severity of condition, and predicted outcomes, as well as in the care itself (diagnostic imaging analysis, pre-op planning, and post-op management).[25]

Despite these advances, ensuring the quality, integrity, and interoperability of healthcare data remains a significant challenge for leveraging AI in orthopedic applications. AI systems can leverage data from various sources, such as Picture Archiving and Communication System (PACS), clinical records, patient monitoring systems, and arthroplasty registries.[18] In these settings, the most common ML techniques were support vector machines and neural networks, with medical imaging data being the most commonly applied input dataset.[5] More recent and novel applications in the field of arthroplasty have expanded to the use of preoperative patient data to identify risk factors for complications and adjust payment models accordingly.[16]

Although most studies use publicly available pre-trained models, one major limitation of AI production is the need for enormous amounts of high-quality medical data, which are difficult to find and share, and even more challenging to

Table 2. Summary of AI applications in spine imaging

Application	Studies	Summary
Guidance for surgeries	Shoham et al.,[26] Kraus et al.[27]	Video guidance and real-time motion control. 10–15% better accuracy than free-hand techniques in pedicle screw positioning.
	Devito et al.,[28] Hyun et al.[29]	3D fluoroscopy and CT integrated with robotic-assisted navigation. 98% clinical acceptance rate.
	Auloge et al.,[30] Racadio et al.[31]	Augmented reality guided vertebroplasty. Similar accuracy to traditional visual-guided surgery.
Diagnostic imaging	Bar et al.,[32] Tomita et al.,[33] Yıldız Potter et al.[34]	CT scans to detect osteoporotic vertebral fractures with an accuracy of up to 90%.
	Yabu et al.,[35] Han et al.[36]	MRI to detect stenosis and acute fractures with 85-88% precision.
	Galbusera et al.,[37] Zhang et al.,[38] Wu et al.,[39] Yıldız Potter et al.[40]	X-ray with spinal abnormalities, including scoliosis. Absolute errors as low as 3° to predict the vertebral slopes.
Improving image acquisition	Mardani et al.,[41] Schlemper et al.[42]	Accelerate MRI acquisition via AI-based compressive sensing. Takes only 23 milliseconds to reconstruct a 2D image.
	Wolterink et al.,[43] Giordano et al.[44]	AI-based compressive sensing to require fewer raw data points and reduce radiation exposure to patients.
Surgical outcome prediction	Scheer et al.,[45] Durand et al.[46]	85-88% accuracy in predicting severe intraoperative or perioperative problems, including blood transfusion following spine deformity surgery.

validate. In the near future, AI/ML will provide orthopedic surgeons with crucial tools in an increasingly data-driven and data-dependent world. The question becomes whether advanced ML systems can overcome the problem of missing data and how to navigate concerns over data quality. Even though some algorithms have been developed to handle minimal missing data, the absence of key parameters in the analysis can substantially affect the results. Second, validity must be ensured through accurate data documentation in the first instance and possibly through subsequent data screening and cleaning. Further, the data must initially contain all relevant information to derive complex relationships. Thus, large data sets with sufficient data depth, width, and quality are required. In orthopedics, this involves many patients and the monitoring of many parameters, yet some relevant parameters remain unknown.

AI and ML, combined with navigation or robotics, are also promising options for answering a long list of complex questions, but this all hinges on predefined parameters. AI performance (other than data quality and quantity) depends on the appropriate selection of input features. Currently, there is no gold standard for feature selection. Thus, there is still a need for a streamlined methodology that outlines the technical and medical knowledge required for the use of traditional ML algorithms. In addition, the digital infrastructure of hospitals must enable accessible data collection from various sources within the hospital and between different hospitals to allow the development of AI models that can generalize to the diversity of real-world medical data. Mitigating algorithmic bias and ensuring fairness in AI-driven decision-making processes is essential to prevent disparities and promote equitable healthcare delivery.

Overall, a valid and cited concern about the increasing role of AI in medicine has been the quality of the AI relative to the quality of the dataset.[17] Guiding AI development without high-quality datasets causes a garbage-in, garbage-out paradigm. However, datasets will only improve. The capacity to collect data, the data itself, and the management of said data will only become better and better. How we approach the use and application of that data becomes paramount. Understanding the practical challenges and effectively working around the constraints is crucial for developing and deploying AI in orthopedic care. AI models need to be trained on a larger dataset of real-world patient data to achieve higher efficiency and more accurate outcomes.

The future of AI in orthopedics is projected to become more predictive and personalized. AI algorithms can analyze vast patient data to predict outcomes and identify potential risks. This allows surgeons to personalize treatment plans and optimize postoperative care, particularly in outpatient settings where patients are discharged sooner. AI-driven precision medicine approaches will enable tailored interventions and treatment strategies based on individual patient characteristics, preferences, and outcomes. From patient-specific implant designs to tailored rehabilitation protocols, every aspect of orthopedic care will be meticulously crafted to align with each individual's biological, physiological, and lifestyle characteristics. By harnessing insights from AI-driven predictive analytics, orthopedic practitioners will diagnose and treat conditions more accurately and preemptively intervene to forestall disease progression, thereby optimizing patient outcomes and quality of life.

The future of AI in orthopedics also lies outside the typical clinical responsibilities of orthopedic surgeons. Studies have already demonstrated that AI algorithms improve hospitals' and clinics' administrative and management processes, electronic healthcare databases, outcomes monitoring, and safety controls.[14] Moreover, AI-driven virtual assistants can streamline administrative tasks, documentation, and workflow management, liberating clinicians to devote more time to patient care and fostering a culture of empathy, compassion, and human connection at the heart of orthopedic practice. Nevertheless, addressing regulatory requirements, privacy concerns, and liability issues associated with AI adoption in orthopedics poses ethical and legal challenges.

A key point of the future of AI is that it will not replace the orthopedic surgeon but rather augment their role.[23] The future of AI in orthopedics lies in augmented intelligence, where AI systems complement and enhance human capabilities, fostering synergistic collaboration and shared decision-making. Generally, AI lacks several features of human mind functioning, such as common-sense reasoning, empathy, compassion, emotion, creativity, judgment, and responsibility.[22] Thus, clinicians ought to oversee these processes. Continued research and development in AI technologies, including deep learning, natural language processing, and reinforcement learning, will drive continual innovation and transformation in orthopedic care. With increased understanding, establishing effective frameworks is critical for acceptance and adoption.

Additionally, the long-term effects of AI on the healthcare field are still being determined. In particular, daily clinical use vs. experimental studies have to be differentiated, as these research areas are not yet within the clinical realm and require further validation/external generalizability before they are adopted in mainstream clinical care (for example, using AI in imaging).[13] In other words, additional studies are needed to determine the effects in real-world clinical-care environments, a common theme amongst existing studies.[21] In this process, AI technologies may prove disproportionately expensive upon introduction. They may be met with skepticism from some surgeons and patients, so the practice of translating experimental studies into practice must be carefully translated.

CONCLUSION

The future of AI remains promising, contingent on meaningful formulations, rigorous and transparent methodologies, rich data, and externally validated models. The role of AI in orthopedics is poised to expand rapidly, reshaping care across all stages. From diagnostic precision to personalized interventions and rehabilitation, AI holds immense promise in improving patient outcomes, enhancing clinical workflows, and advancing orthopedic research. However, realizing the full potential of AI in orthopedics requires addressing technical, ethical, and regulatory challenges while fostering interdisciplinary collaboration and innovation. This also requires recognizing that the landscape of care is changing, with a shift toward outpatient care, and that the primary sectors where AI can meaningfully impact currently lie in diagnostics, where AI augments rather than replaces the expertise and empathy of the physician.

DECLARATION OF CONFLICT OF INTEREST

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DECLARATION OF ETHICAL APPROVAL FOR STUDY

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DECLARATION OF INFORMED CONSENT

Please declare that there is no information (names, initials, hospital identification numbers, or photographs) in the submitted manuscript that can be used to identify patients. If there is identifiable information and this information is essential for scientific reasons, written informed consent must be obtained from the patient (parent or guardian) and submitted along with the manuscript.

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