Artificial Intelligence in Orthopedics: Clinical Applications, Challenges, and Opportunities

Ivo Dumić-Čule[1], Denis Tršek[1,2], Marko Pećina[*3]

[1] University North, 42000 Varaždin, Croatia
[2] Special Orthopaedic Hospital "Akromion", 10000 Zagreb, Croatia
[3] University of Zagreb, School of Medicine, 10000 Zagreb, Croatia

Abstract

This review provides a comprehensive overview of the rapidly expanding role of artificial intelligence (AI) in orthopedic practice, highlighting its applications across prevention, imaging, surgery, and rehabilitation. AI encompasses technologies such as machine learning and deep learning, which enable the analysis of complex datasets and support predictive, personalized medical approaches.

In prevention and early disease detection, AI-driven models utilizing wearable sensors and biomechanical data demonstrate strong potential in identifying injury risk and early pathological changes before clinical symptoms emerge. In musculoskeletal imaging, AI significantly enhances diagnostic accuracy in fracture detection, osteoarthritis assessment, and tumor identification, often matching or exceeding human performance while improving workflow efficiency.

Robot-assisted surgery represents a major advancement, enabling highly precise implant positioning, improved surgical planning, and reduced variability in procedures such as total hip and knee arthroplasty. Despite improved technical accuracy, current evidence shows only modest improvements in short-term clinical outcomes. Additionally, virtual reality technologies are increasingly used for surgical training, planning, and rehabilitation, contributing to improved procedural understanding and patient recovery.

AI also plays a crucial role in postoperative monitoring and rehabilitation through remote data collection, predictive analytics, and personalized therapy adjustments, ultimately reducing complications and readmissions.

Although physician acceptance of AI is growing, challenges remain, including limited knowledge, concerns about reliability, data security, and high implementation costs. Overall, AI is transforming orthopedics by augmenting clinical expertise, enhancing precision, and enabling data-driven, patient-specific care, with continued development and validation necessary for broader clinical integration.

Keywords: artificial intelligence, orthopedics, musculoskeletal imaging, robot-assisted surgery

Sažetak

Umjetna inteligencija u ortopediji: klinička primjena, izazovi i prilagodbe

Ovaj pregledni članak daje sveobuhvatan prikaz ubrzanog razvoja i sve značajnije uloge umjetne inteligencije (Artificial Intelligence - AI) u ortopediji, obuhvaćajući njezinu primjenu u prevenciji, dijagnostici, kirurškom liječenju i rehabilitaciji. AI obuhvaća tehnologije poput strojnog i dubokog učenja koje

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Correspondence:
Marko Pećina
pecinahazu@gmail.com

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omogućuju analizu složenih skupova podataka te podržavaju prediktivne modele čime doprinose personaliziranom medicinskom pristupu.
U području prevencije i ranog otkrivanja bolesti, modeli temeljeni na AI, koji koriste nosive senzore i biomehaničke podatke, pokazuju velik potencijal u prepoznavanju rizika od ozljeda i ranih patoloških promjena prije pojave kliničkih simptoma. U muskuloskeletnom oslikavanju, AI značajno povećava dijagnostičku točnost u otkrivanju prijeloma, procjeni osteoartritisa i identifikaciji tumora, često postižući rezultate usporedive ili bolje od ljudskih stručnjaka, uz istovremeno poboljšanje učinkovitosti radnih procesa.
Robotom potpomognuta kirurgija predstavlja značajan napredak, omogućujući iznimno precizno pozicioniranje implantata, unaprijeđeno kirurško planiranje i smanjenu varijabilnost zahvata poput totalne artroplastike kuka i koljena. Unatoč poboljšanoj tehničkoj preciznosti, trenutačni dokazi ukazuju na tek umjerena poboljšanja kratkoročnih kliničkih ishoda. Također, tehnologije virtualne stvarnosti sve se više koriste u edukaciji, planiranju zahvata i rehabilitaciji, pridonoseći boljem razumijevanju postupaka i oporavku pacijenata.
AI ima važnu ulogu i u postoperativnom praćenju i rehabilitaciji kroz daljinsko prikupljanje podataka, prediktivnu analitiku i individualiziranu prilagodbu terapije, čime se smanjuje učestalost komplikacija i ponovnih hospitalizacija.
Iako prihvaćenost AI među liječnicima raste, i dalje postoje izazovi, uključujući ograničeno znanje, zabrinutost oko pouzdanosti i sigurnosti podataka te visoke troškove implementacije. Zaključno, AI transformira ortopediju nadopunjujući kliničku stručnost, povećavajući preciznost i omogućujući podatkovno vođenu, individualiziranu skrb za pacijente, uz potrebu za daljnjim razvojem i kliničkom validacijom.

Ključne riječi: umjetna inteligencija, ortopedija, muskuloskeletna dijagnostika, robotski potpomognuta kirurgija

Introduction

Artificial intelligence (AI) refers to the use of computer systems and complex algorithms designed to simulate intelligent human behavior, including learning, reasoning, pattern recognition, and decision-making, in order to perform tasks more efficiently and accurately.
AI is an umbrella term encompassing technologies such as machine learning (ML), deep learning (DL), natural language processing (NLP), and computer vision (CV) (Figure 1). Over the past decade, these technologies became increasingly integrated into medicine, where they are applied in diagnostics, medical image analysis, clinical record processing, disease monitoring, and clinical decision support (1).
In orthopedics, AI has become an integral component of numerous tools that enhance risk detection, prevention, and diagnosis, while also improving the safety of surgical procedures, treatment planning, and patient rehabilitation. This review article aims to provide a comprehensive overview of the current and emerging applications of AI across all major aspects of orthopedic practice.

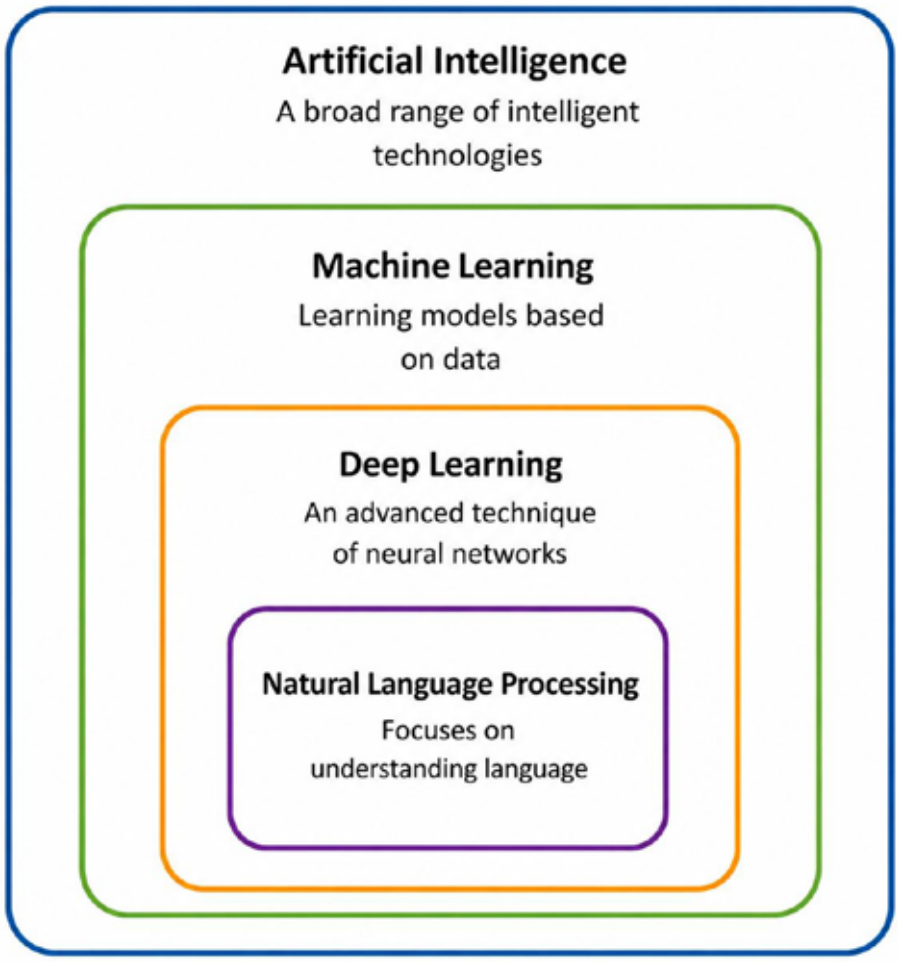

Figure 1: Schematic representation of the hierarchy within artificial intelligence

AI-Driven Diagnostics in Prevention and Early Disease Detection

Primary prevention in orthopedics involves the identification of individuals at risk before the occurrence of injury or the onset of disease. The application of AI included the assessment of biomechanical and functional risk factors using sensors and wearable devices that enabled continuous monitoring of body movement and biomechanical function. Recent advances in wearable sensor technologies, such as inertial measurement units and surface electromyography, allowed continuous and non-invasive acquisition of biomechanical data, enabling the early detection of abnormal joint kinematics and muscle activation patterns. AI-driven models can process these complex datasets to detect subtle deviations such as joint-angle asymmetry or muscle-force imbalance, which have been shown to predict the risk of musculoskeletal injuries, including ligament injuries and muscle strains (2). Furthermore, AI techniques demonstrated an increasing ability to identify injury-prone movement patterns and biomechanical risk factors across different sports and populations, enabling proactive and personalized injury prevention through continuous movement analysis and real-time feedback (3).

ML models trained on large biomechanical datasets have demonstrated substantial potential in predicting anterior cruciate ligament injury risk by identifying complex movement patterns that are not detectable through conventional clinical assessment (4, 5). These models integrate multiple biomechanical inputs, including kinetic, and demographic variables, and have achieved moderate-to-high predictive performance, with pooled area un-

der the curve (AUC) values around 0.79 and reported accuracies up to 96% in recent studies. Importantly, AI approaches enable the identification of subtle interactions between variables, such as joint loading patterns and neuromuscular control strategies, thereby improving the precision and scalability of injury risk stratification. Moreover, recent experimental and computational studies further demonstrate that machine learning models can identify key biomechanical predictors of anterior cruciate ligament injury, including early-phase ground reaction forces and joint loading characteristics, with classification accuracies exceeding 90% in controlled datasets (6). These findings highlight the capacity of AI to detect early biomechanical signatures of injury risk, even before clinically observable symptoms occur.

In addition, AI systems have demonstrated high effectiveness in the early recognition of degenerative spinal disorders on MRI, such as intervertebral disc herniation, spinal stenosis, and degenerative structural changes. Recent scoping reviews of convolutional neural network applications in spine MRI confirmed that AI models achieve high diagnostic performance in identifying disc herniation and spondylolisthesis, with consistent use of segmentation and classification architectures such as U-Net and ResNet for automated detection of structural abnormalities (7). In pediatric orthopedics, machine learning algorithms were utilized for the early detection and quantification of spinal deformities (8). Furthermore, AI is applied in the identification of inflammatory and infectious conditions, such as septic arthritis and osteomyelitis, through the analysis of radiological patterns, which may accelerate the diagnostic process and reduce the risk of permanent damage.

Artificial Intelligence in Musculoskeletal Imaging

AI is increasingly being recognized as a valuable tool in musculoskeletal radiology, with particularly notable impact in fracture detection, diagnosis of osteoarthritis, bone tumors and orthopedic implant-related pathology (9).

AI enabled the automated detection of acute and stress fractures that may be overlooked by the human eye during the early stages of patient assessment. An estimated error rate of about 4% occurs in imaging interpretations, even when performed by a trained radiologist, while misinterpretation is significantly higher among non-radiology clinicians, which are usually present during the night shifts (10, 11). Recent systematic reviews and meta-analyses demonstrated that DL systems, especially convolutional neural networks, achieved high diagnostic performance in fracture detection across multiple anatomical regions, often reaching AUC values above 0.90 and showed robustness in real-world clinical datasets (12, 13). These models were capable of learning complex spatial hierarchies within imaging data, enabling automated identification of fracture patterns that may be subtle or difficult to detect during initial human interpretation, particularly in emergency radiology settings.

Several algorithms specific for a single anatomic area were recently developed and shown to have comparable performance to skilled musculoskeletal radiologists. Two separate groups created deep learning-based hip fracture and classification detection model and DenseNet based architecture model that was able to detect hip fracture from frontal pelvic radiographs (14). Furthermore, Chen and collaborators developed ResNeXt architecture with power to detect vertebral fractures on abdominal radiographs (15). Lindsey et al created a deep neural network which enabled detection and localization of fractures on radiographs suitable for emergency medicine physicians (16). However, there was a great need to combine AI capabilities in different anatomical regions within one interconnected software module that could detect a fracture in any anatomic region. Jones and collaborators utilized huge radiographic database processed with 10 convolutional neural networks for fracture detection and reached mean area under the curve above 0.98 in the half of analyzed sites (17).

Evidence from large systematic reviews further confirmed that AI-based fracture detection systems improve diagnostic sensitivity and reduced missed fractures when used as decision-support tools in radiograph interpretation workflows (18, 19). In meta-analytic studies, AI-assisted interpretation has been shown to significantly enhance clinician performance, increasing sensitivity from approximately 77% to 87% while also improving specificity, highlighting its clinical utility in acute orthopedic care (19). Overall, these findings support the growing integration of AI systems into musculoskeletal imaging workflows, particularly for early and reliable detection of fractures (13, 18).

Deep learning model was able to identify rib fractures with sensitivity of 92.9% on CT images (20). Two independent groups created models capable of accurately identifying and categorizing calcaneal fractures on CT scans (21, 22). Regarding the MRI, several groups developed AI models that could perform functions like detection of anterior cruciate ligament, meniscal tears, acute cartilage injuries or rotator cuff tears (23-25). Ultrasound-based AI algorithms have been less developed and mainly focused on classification and segmentation (26).

The primary focus of AI research studies in osteoarthritis has been on classification and prediction tasks (27). Automated classification can speed up quantitative analysis that is valuable for clinical routines but takes radiologists' considerable time. AI can additionally combine clinical risk factors for osteoarthritis with imaging biomarkers. In knee osteoarthritis, AI models enabled early disease recognition by identifying subtle structural and biochemical changes on radiographic and MRI examinations, often several years before the onset of clinical symptoms (28). Deep neural network models have demonstrated high accuracy in differentiating stages of osteoarthritis, with effectiveness in detecting early disease stages. Although further clinical validation remains necessary, these findings clearly indicate that AI, when

used as a support tool for clinical decision-making, has substantial potential to improve early diagnosis, treatment planning, and the overall quality of care for patients with musculoskeletal disorders.

In orthopedic oncology, AI contributes to the early detection of benign and malignant bone tumors through automated lesion segmentation and assessment of their radiomorphological characteristics. AI has been tested in musculoskeletal tumor imaging for metastatic bone and soft-tissue lesions, mainly at the research stage (29). Soft-tissue sarcomas and primary malignant tumors represent a challenge for AI processing since they are rare and heterogeneous. Radiomics is nowadays considered as an appropriate tool to collect information about diagnosis and outcome about this pathology. Radiomics features, i.e. quantitative features extracted from medical images, might be used to support decision-making algorithms (30). Since most radiomic features are redundant, selection of informative features which can further be mined is very demanding (31). Relatively low number of patients and lack of external validation are main limitations of current studies. Clinical validation against completely independent datasets of such features is needed to achieve clinical transferability (32). Therefore, radiologists and orthopedic surgeons are asked to play a central role in moving AI and radiomics of bone and soft-tissue tumors from theory to clinical practice.

Musculoskeletal radiologists routinely assess orthopedic implants for appropriate position and detection of potential complications. So far, AI models showed 100% accuracy in classifying anatomic region and detecting the presence of implants in particular region (33-35). Recently published review presented good to excellent performance of AI in differentiating orthopedic implant models on radiographs (36). The task of identifying specific implant model is crucial for revision surgery planning. Certain AI algorithms for implant position assessment are nowadays part of commercially available software. AI models reached 70% accuracy in detecting complications after total knee or total hip arthroplasty, with improved results when combined with clinical data (37).

Artificial Intelligence and Robot-Assisted Surgery

In contemporary orthopedic surgery, it is often difficult to distinguish between artificial intelligence and robotics. Robot-assisted surgery represents one of the most prominent examples of AI application in medicine, combining the precision of machine technology with the expertise of the orthopedic surgeon. Over the past decade, robot-assisted procedures have attracted considerable interest from both clinicians and patients (38, 39). Robot-assisted surgical techniques have become an integral component of modern orthopedics and are currently used in major joint arthroplasty procedures, including the hip, knee, and shoulder (40). In knee arthroplasty, robotic systems are used for total, patellofemoral, and unicompartmental arthroplasty (41, 42). At present, robotic technology is most widely adopted in knee and hip arthroplasty, where it has reached a high level of clinical implementation and scientific validation. In contrast, its application in shoulder arthroplasty and other joint procedures remains at an earlier stage of development and is largely confined to investigational settings. The use of robotic assistance continues to increase, driven by the pursuit of greater consistency in surgical outcomes and the potential for improved long-term clinical results.

In orthopedic procedures involving joint arthroplasty, particularly of the knee and hip, these systems facilitate implant positioning optimization and have demonstrated substantial potential for improving surgical outcomes. As in other areas of medicine, the purpose of implementing advanced computational technologies is not to replace clinical judgment but rather to complement it with objective, measurable, and reproducible parameters. Robotic technology does not replace the surgeon; instead, it enhances surgical capabilities by enabling more accurate translation of the preoperative plan into the patient's actual anatomy.

Robot-assisted total joint arthroplasty represents a continuation of the evolution of computer-assisted navigation surgery. Compared with conventional and navigation-assisted techniques, robot-assisted arthroplasty provides a more advanced approach to preoperative planning and intraoperative execution using three-dimensional models and real-time data acquired during surgery (Figure 2).



Figure 2. Robotic system in the operating room during total knee arthroplasty.

Robot-assisted hip and knee arthroplasty can be performed using CT-based systems, which rely on a preoperative three-dimensional model for precise implant positioning, or imageless systems, which generate the model intraoperatively through anatomical landmark registration and osseous surface mapping (Figure 2) (43).

For this review, the PubMed database was searched to identify relevant studies published within the five-year period preceding June 1, 2026. The search strategy included the terms "robotic," "knee," "hip," and "arthroplasty." Eligibility criteria included published clinical studies comparing robotic-assisted and conventional knee and hip arthroplasty and reporting outcomes related to implant positioning and alignment, clinical outcomes, complication rates, learning curves, operative time, cost-effectiveness, patient-reported outcomes (PROMs), and long-term implant survivorship.

In conventional total knee arthroplasty performed without robotic assistance, bone resections and implant alignment are determined using standard intramedullary and extramedullary mechanical guides, together with anatomical assessment and surgeon experience. This approach is inherently associated with variability arising from differences in patient anatomy, deformities, osteophyte formation, and soft-tissue characteristics. In contrast, robotic-assisted total knee arthroplasty has been shown to achieve the planned alignment more consistently and with fewer deviations than conventional mechanical instrumentation (38, 44). Contemporary personalized alignment strategies in total knee arthroplasty, including kinematic and functional alignment with minimal soft-tissue release, aim to preserve native knee biomechanics and thereby improve postoperative patient satisfaction (45). Robotic technology facilitates the implementation of such individualized approaches by allowing surgeons to digitally adjust varus-valgus alignment, component rotation, and implant inclination, while simultaneously assessing their effects on prosthetic stability and balance before femoral and tibial bone resections are performed. As a result, implant alignment can be tailored to each patient while maintaining predefined safety boundaries designed to prevent unfavorable biomechanical loading. The use of robotic systems also seeks to reduce procedural variability through standardization of key surgical steps, precise assessment of flexion and extension gaps, and improved control of deviations from the planned surgical target.

Meta-analyses of randomized controlled trials have demonstrated that robotic-assisted total knee arthroplasty provides more accurate radiographic alignment and fewer deviations from planned implant positioning than conventional techniques. However, differences in functional outcomes, including WOMAC and Knee Society Score (KSS) measures, have generally been modest and, in some studies, have not reached clinically meaningful significance (38, 46, 47).

According to published data, the risk of infection following total knee arthroplasty approximately doubles when operative time exceeds 120 minutes (48). Although robotic-assisted arthroplasty is generally associated with longer operative duration, no difference in the incidence of periprosthetic joint infection (PJI) within 90 days after surgery has been demonstrated compared with conventional techniques (40, 49). According to recent meta-analyses, robotic-assisted total knee arthroplasty is associated with several procedure-specific risks, including pin-related complications such as fractures and infections, as well as iatrogenic injury to soft tissues and bone and increased intraoperative blood loss. Commonly reported limitations of robotic-assisted TKA include prolonged operative time, higher procedural costs, the need to overcome a learning curve, and occasional inability to complete the procedure using robotic technology. Despite these considerations, overall complication rates have generally been reported to be comparable between robotic-assisted and conventional TKA (46, 50).

Compared with conventional techniques, robotic-assisted total hip arthroplasty offers several potential advantages, primarily

related to implant positioning accuracy and procedural consistency. Recent meta-analyses have indicated that robotic systems enable more accurate placement of the acetabular component, resulting in a higher proportion of implants positioned within recommended safe zones and reduced error in determining the horizontal center of rotation, thereby contributing to improved radiographic outcomes (40). Furthermore, robotic-assisted procedures provide greater concordance between the preoperative plan and final implant positioning, representing a key advantage over conventional surgical techniques. In addition, recent studies have suggested that robotic-assisted total hip arthroplasty may reduce perioperative complication rates compared with conventional manual techniques, a finding that has been attributed to improved surgical precision and enhanced haptic control, which help prevent unintended bone resection. Robotic systems have also been shown to reduce postoperative limb length discrepancy and improve biomechanical reconstruction of the hip when compared with conventional approaches (51). However, a recent meta-analysis by Aamir and colleagues demonstrated that, despite improved surgical precision and more accurate implant positioning, robotic-assisted total hip arthroplasty did not result in superior short-term functional outcomes compared with conventional techniques. Furthermore, no statistically significant differences were observed in prosthetic dislocation rates or Harris Hip Score outcomes between the two approaches (52).

The learning curve for robotic-assisted total knee arthroplasty is relatively short, with a reported median of 17 cases (range 15–25), and appears to be influenced by the surgeon's prior experience. Although operative time decreases significantly with increasing experience, radiographic outcomes, complication rates, and patient-reported outcome measures (PROMs) remain comparable between the learning and proficiency phases (53). Longer operative times during the implementation of robotic-assisted TKA have primarily been observed among surgeons with limited prior experience. However, this difference decreases substantially once the learning curve has been overcome. In contrast, experienced surgeons have not demonstrated significant differences in operative duration between robotic-assisted and conventional techniques, either during the learning phase or after achieving proficiency. These findings suggest that the learning curve associated with robotic-assisted TKA is largely determined by the surgeon's previous experience with conventional total knee arthroplasty (54).

In a prospective study comparing robotic-assisted and conventional total knee arthroplasty, both groups demonstrated significant improvement in Forgotten Joint Score (FJS) following surgery. Although patients treated with the robotic-assisted technique achieved numerically higher FJS values and slightly greater satisfaction rates throughout follow-up, these differences did not reach either statistical or clinical significance, suggesting no clear advantage of the robotic approach with respect to patient-reported outcomes (55). Evidence regarding robotic-assisted total hip arthroplasty remains limited and heterogeneous (40, 56). Despite the numerous advantages reported in the current literature, the implementation of artificial intelligence and robotic-assisted systems in orthopedics continues to face several challenges, with the high costs of acquisition, implementation, and maintenance representing one of the most important limiting factors. Cotter and colleagues reported that the substantial initial costs associated with robotic-assisted arthroplasty may be partially offset by shorter hospital stays, reduced postoperative analgesic requirements, and lower utilization of inpatient and outpatient healthcare resources following discharge (57).

Analysis of data from the American Joint Replacement Registry demonstrated no difference in overall revision rates between robotic-assisted and conventional total knee arthroplasty during the first two postoperative years. Furthermore, robotic assistance was not associated with a reduction in the most common causes of early revision, including implant malposition, malalignment, stiffness, pain, and instability; notably, pain and instability were reported more frequently in the robotic-assisted cohort. These findings suggest that there is currently no evidence that robotic-assisted TKA improves early implant survivorship compared with conventional techniques, while its potential impact on mid-term and long-term outcomes remains uncertain (58).

Table 1. Evidence-Based Comparison of Robotic-Assisted and Conventional Knee and Hip Arthroplasty.

Comparison Dimension	Evidence-Supported Takeaway	Citations
Clinical Outcomes	More accurate knee prosthesis alignment, with no clinically significant differences in WOMAC and KSS scores. Improved implant positioning accuracy, but no superior short-term functional outcomes, dislocation rates, or Harris Hip Scores.	Clement ND, 2026 (38) Alrajeb R, 2024 (46) Möller A, 2025 (47) Aamir M, 2026 (52) Zhang J, 2022 (56) Ruangsomboon P, 2023 (59) Ruangsomboon P, 2024 (60)
Complication Rates	Robotic knee arthroplasty carries risks of pin-related complications, tissue injury, and greater intraoperative blood loss. Longer operative time, but no difference in 90-day PJI rates after knee arthroplasty.Fewer perioperative complications with robotic-assisted hip arthroplasty.	Bensa A, Pagliazzi G, 2025 (40) Alrajeb R, 2024 (46) Nogalo C, 2023 (50) LaValva SM, 2024 (49) Mustapha MB, 2025 (51)
Implant Positioning & Alignment	More accurate knee prosthesis alignment and fewer positioning deviations than conventional techniques.More accurate hip prosthesis acetabular component placement, with higher rates within safe zones and improved radiological outcomes.	Clement ND, 2026 (38) Bensa A, Pagliazzi G 2025 (40) Sun C, 2025 (44)
Learning Curve	Learning curve depends largely on prior experience in conventional knee arthroplasty.	Abdel Khalik H, 2025 (53) Neira I, 2024 (54)
Operative Time	Longer operative times during the learning phase of robotic-assisted knee and hip prosthesis implantation, with differences decreasing after proficiency is achieved.	Neira I, 2024 (54)
Cost-Effectiveness	High costs are a major limitation of AI and robotic systems in orthopaedics. Potential cost savings through shorter hospitalization and lower postoperative resource use may offset higher initial costs.	Cotter EJ, 2022 (57)
Patient-Reported Outcomes	No significant differences in Forgotten Joint Score (FJS) or patient satisfaction between robotic-assisted and conventional knee arthroplasty. Evidence regarding robotic-assisted total hip arthroplasty remains limited and heterogeneous	Bensa A, Pagliazzi G, 2025 (40) Chen Q, 2026 (55) Zhang J, 2022 (56)
Long-Term Survivorship	No reduction in common causes of early revision, including malposition, malalignment, pain, stiffness, and instability.No improvement in early implant survival after robotic-assisted TKA; mid- and long-term benefits remain uncertain.	Kirchner GJ, 2024.(58)

Artificial intelligence has considerable potential to transform total joint arthroplasty by enabling a more precise, data-driven, and patient-specific approach to treatment. Robotic-assisted arthroplasty of major joints has demonstrated clear advantages in terms of surgical accuracy and procedural consistency when compared with conventional operative techniques. However, when clinical outcomes such as pain relief, functional recovery, and patient satisfaction are considered, the available evidence suggests only modest or inconsistent benefits. Further multicenter studies with long-term follow-up are required to determine whether improved technical accuracy ultimately translates into enhanced implant survivorship and clinically meaningful improvements in patient outcomes (40, 59, 60, 61).

Applications of Virtual Reality in Surgical Procedures

Artificial intelligence is increasingly being integrated with virtual reality (VR) technologies to enable surgeons to plan and simulate procedures before the actual intervention. VR is being progressively introduced into orthopedic and trauma surgery, and over the past two decades many VR systems have been developed, although a considerable proportion of them remain in the experimental stage.

Systematic reviews indicated that VR and augmented reality technologies enhance anatomical understanding and procedural planning, particularly in complex fracture management, thereby improving surgical precision and potentially reducing operative time and complications (62). This review emphasized that immersive three-dimensional visualization enables surgeons to better conceptualize fracture patterns and anticipate intraoperative challenges.

Extended reality platforms have been shown to improve spatial awareness and facilitate navigation, contributing to safer interventions and reduced surgical trauma (63). The authors reported that these technologies can enhance precision in instrument placement and reduce dependence on fluoroscopic imaging. This reduction in imaging utilization may decrease radiation exposure for both patients and operating room staff.

Multicentric randomized clinical trial demonstrated that immersive VR training significantly improves surgical skill acquisition among senior orthopedic residents compared with conventional methods (64). Participants trained using VR achieved higher performance scores, improved procedural accuracy, and reduced error rates, particularly in arthroscopic simulations. The study also found that VR training enhanced learner engagement and confidence, suggesting a more effective educational experience.

VR-based rehabilitation has shown promise in improving functional recovery, pain control, and patient engagement following musculoskeletal trauma (65). VR interventions often incorporate interactive and gamified elements, which enhance patient adherence to rehabilitation protocols. These approaches have been associated with improved range of motion, neuromuscular coordination, and reduced perception of pain. Furthermore, VR enables the possibility of remote rehabilitation, potentially increasing accessibility to care while reducing the burden on healthcare systems.

Current simulation approaches have been categorized into fracture fixation, drilling techniques, and prosthetic design and implantation, with each group characterized by distinct technical features and clinical applications. Virtual reality based platforms, including both high- and low-fidelity systems, are increasingly used in bone trauma education and surgical planning, with reported benefits for training, operative performance, and patient outcomes, although further technical development and stronger clinical validation are still needed (66).

Despite these promising results, rigorous clinical validation of existing VR systems remains essential, including assessment of their face, content, concurrent, and transfer validity, as well as continued development in accordance with industrial standards.

Rehabilitation and Postoperative Recovery Monitoring

The postoperative recovery phase is often highlighted as a period during which AI may have substantial clinical impact. An increasing number of studies have described the use of smartphones for the continuous and remote collection of patient data, including vital parameters and rehabilitation progress following total knee arthroplasty (67). ML algorithms enabled monitoring of physiotherapy participation and exercise performance, with the capacity to alert healthcare professionals when rehabilitation goals are not being achieved. Similarly, the literature extensively documented the monitoring of vital signs, general patient condition, and potential complications such as deep vein thrombosis (68). These AI applications have been associated with reduced readmission rates following total knee and total hip arthroplasty (69).

The potential use of ML algorithms has also been proposed for improving rehabilitation after anterior cruciate ligament reconstruction, where biomechanical data are used to assess asymmetries in gait analysis. Several studies have highlighted the ability of deep learning models to predict the risk of postoperative complications based on radiographs obtained after hip arthroplasty. Single algorithm, trained on more than 90,000 postoperative images, demonstrated the ability to predict hip prosthesis dislocation within five years after surgery, with a relatively high negative predictive value (70).

AI also played an increasingly important role in the rehabilitation of athletes, particularly in monitoring recovery and supporting return-to-sport decision-making (71).

AI may further enhance rehabilitation after limb amputation through intuitive control of prosthetic devices. Using neural networks and ML algorithms, systems can decode neurologi-

cal signals from peripheral nerves, enabling users to control a prosthetic hand in real time, with finger-movement accuracy approaching 97–98%. Such integration of AI and neural interfaces allows amputees to use prosthetic limbs as a natural extension of their own body, significantly improving functional capacity and independence in daily activities. This combined approach involving robotics and AI clearly demonstrates the growing impact of these technologies on rehabilitation processes (72).

Perception and Acceptance of Ai Among Physicians

The role of AI in medicine underwent significant transformation over the past decade (73). Recently published questionnaire-based study surveyed more then 120 orthopedic surgeons to assess their knowledge, attitudes, and perceptions of AI. The authors found that while most surgeons had limited understanding of core AI concepts, they were generally aware of its applications in areas such as joint replacement and spine surgery. Importantly, many respondents expressed concerns regarding the safety and reliability of AI systems, reflecting a degree of skepticism. Nevertheless, there was a strong interest in adopting AI technologies in clinical practice, suggesting a gap between enthusiasm for innovation and confidence in current knowledge and evidence (74). This study showed that over 60% of pediatric orthopedic surgeons reported low familiarity with AI, but most believed it could improve efficiency and productivity. Concerns about patient data security were highly prominent, and greater AI knowledge was associated with more positive attitudes toward its use (75).

Initial skepticism, including concerns that AI might replace physician everyday work, has gradually shifted toward increasing acceptance of AI-driven solutions. It is now more widely recognized that such technologies are more likely to redefine professional roles and responsibilities rather than replace physicians. Early perceptions were characterized by uncertainty, particularly regarding system autonomy, diagnostic accuracy, and the potential erosion of human expertise (76). By 2023, attitudes toward AI had become more positive, largely due to growing practical experience. A cross-national survey conducted by Orešković and colleagues reported that more than 70% of radiologists from Croatia and Slovenia believed AI could enhance the quality, reliability, and accessibility of radiological services. Those already using AI tools demonstrated higher levels of trust, although human supervision remained a key requirement, as many respondents were still reluctant to rely on AI independently. Most participants anticipated considerable changes in radiologists' work within the coming decade, consistent with findings from similar research (77).

Our group was among the first to investigate the perspectives of radiologists actively using AI-based technologies in routine clinical practice regarding the integration of AI education into medical school curricula. Their responses provided early evidence that direct clinical exposure to AI is associated with greater recognition of the need for structured education for future physicians (78). Medical students, who are generally more open to emerging digital tools, should therefore be supported through formal education in their responsible use. This need is further supported by a recent large-scale study demonstrating widespread use of ChatGPT among students, alongside a clear demand for guidance and improved digital literacy within formal education systems (79).

Collectively, AI represents a new era in orthopedics—from early recognition of pathology and precise diagnosis to personalized treatment planning, robotic assistance in surgery, and dynamic rehabilitation systems. AI does not replace the expertise of the orthopedic surgeon; rather, it augments clinical capabilities, reduces risk, and contributes to improved patient outcomes. These technologies are expected to continue evolving and to become more deeply integrated into all aspects of orthopedic and trauma care.

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