CURRENT CONCEPTS REVIEW

Artificial Intelligence and the State of the Art of Orthopedic Surgery

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Abstract

Artificial Intelligence (AI) is rapidly transforming healthcare, particularly in orthopedics, by enhancing diagnostic accuracy, surgical planning, and personalized treatment. This review explores current applications of AI in orthopedics, focusing on its contributions to diagnostics and surgical procedures. Key methodologies such as artificial neural networks (ANNs), convolutional neural networks (CNNs), support vector machines (SVMs), and ensemble learning have significantly improved diagnostic precision and patient care. For instance, CNN-based models excel in tasks like fracture detection and osteoarthritis grading, achieving high sensitivity and specificity. In surgical contexts, AI enhances procedures through robotic assistance and optimized preoperative planning, aiding in prosthetic sizing and minimizing complications. Additionally, predictive analytics during postoperative care enable tailored rehabilitation programs that improve recovery times. Despite these advancements, challenges such as data standardization and algorithm transparency hinder widespread adoption. Addressing these issues is crucial for maximizing AI's potential in orthopedic practice. This review emphasizes the synergistic relationship between AI and clinical expertise, highlighting opportunities to enhance diagnostics and streamline surgical procedures, ultimately driving patient-centric care.

Level of evidence: V

Keywords: Artificial intelligence, Diagnostic imaging, Machine learning, Orthopedics, Personalized treatment, Predictive modeling, Robotic surgery

Introduction

Artificial Intelligence (AI) refers to the capacity of machines to replicate human cognitive functions such as learning and problem-solving. The concept was first proposed in the 1950s by Alan Turing with the question "Can machines think?"[1] Since then, AI has made significant strides across various domains—particularly in healthcare—where it has been employed since the 1960s to assist in diagnostics and data processing, ultimately enhancing diagnostic accuracy and treatment outcomes.[2] Over the decades, AI has evolved through a range of algorithms—including regression analysis, ensemble learning techniques, clustering methods, and deep learning architectures—integrating into clinical practice to support healthcare professionals in decision-making and patient management[3] rather than replacing them.

The role of AI in orthopedics has evolved significantly since the introduction of robotic systems for hip replacement surgery in 1992, marking a pivotal moment for image-guided surgery.[4] Today, AI is integral to medical image analysis, surgical planning, and predictive modeling of surgical outcomes, contributing to enhanced clinical efficiency and improved patient care. Innovations in robotic assistance and real-time navigation technologies are transforming orthopedic procedures, while advancements in automated three-dimensional imaging are setting new standards for diagnostic precision.[5-7] as these technologies continue to advance, they hold the potential to further revolutionize orthopedic practice and patient outcomes.

Despite the promising applications of AI in orthopedics, its integration into practice remains limited. This short review examines the current state of AI in the field, focusing on its impact on imaging, surgical precision, and predictive

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analytics. It aims to encourage orthopedic professionals to adopt AI-driven tools, highlighting that these technologies, when combined with clinical expertise, can significantly enhance the quality and efficiency of patient care. Additionally, the paper discusses challenges and future directions for AI in orthopedics, offering insights into how these innovations may reshape orthopedic practice and improve patient outcomes in the coming years.

Main body

AI models: Definition and Application

Artificial Neural Networks (ANNs)

ANNs, particularly deep neural networks, have been increasingly utilized in orthopedics for diagnostic purposes, including image classification and the prediction of bone fractures, degenerative diseases, and surgical outcomes. Their capacity to model complex relationships renders them particularly effective in predicting patient-specific outcomes based on medical imaging and patient data[4]. By leveraging large datasets, ANNs can enhance diagnostic accuracy and contribute to personalized treatment strategies within orthopedic practice.

Convolutional Neural Networks (CNNs)

CNNs have gained significant traction in orthopedic medical image analysis, particularly in the evaluation of radiological and MRI scans.[8,9] Their capacity to identify intricate patterns within images renders CNNs particularly effective for the detection of fractures, joint abnormalities, and various musculoskeletal disorders.[10] This capability facilitates timely and accurate diagnoses, ultimately enhancing patient management and treatment outcomes.

Support Vector Machines (SVMs)

SVMs are employed in orthopedics primarily for classification tasks, including the differentiation between benign and malignant tumors, the prediction of bone fracture risk, and the analysis of gait patterns in patients with musculoskeletal conditions. SVMs are particularly advantageous in scenarios characterized by high-dimensional data, such as comprehensive patient health records or biomechanical datasets. Their robustness in creating predictive models aids clinicians in making informed decisions regarding patient care.[11,12]

Random Forests

Random Forests are increasingly utilized in orthopedic research for a variety of applications, including prognosis prediction, disease classification, and feature selection from complex datasets. Their inherent ability to manage missing data and mitigate overfitting makes them a valuable tool in clinical settings. In practice, Random Forests can be employed to forecast surgical outcomes, estimate patient recovery times, and identify risk factors associated with musculoskeletal conditions, thereby contributing to improved clinical decision-making.[13-15]

Deep Learning (DL)

DL holds considerable promise for advancing personalized medicine within orthopedics. Its applications extend to optimizing treatment plans and rehabilitation protocols tailored to individual patient needs. Recent explorations into DL have focused on simulating optimal strategies for prosthesis design, robotic surgery, and rehabilitation methodologies through continuous feedback mechanisms. This iterative learning process enhances decision-making over time, adapting to patient progress and improving overall treatment efficacy.[16-18]

Gradient Boosting Machines (GBM)

GBMs, including models such as XGBoost, have become increasingly prevalent in orthopedic data analysis for predicting patient outcomes, assessing disease progression, and optimizing treatment strategies. Their proficiency in handling large datasets allows them to be effectively integrated into ensemble learning techniques, thereby enhancing the accuracy of predictive models related to surgical success, recovery times, and potential complications. Recent studies have demonstrated that GBMs can significantly improve clinical decision-making processes by providing reliable forecasts based on multifaceted patient data.[19-21]

Transfer Learning

Transfer Learning has emerged as a valuable approach in orthopedic image analysis, wherein pre-trained models developed on extensive datasets—such as general medical images—are fine-tuned for specific orthopedic applications, including fracture detection and joint anomaly identification. This methodology mitigates the necessity for large, domain-specific datasets and accelerates the model training process, making it particularly advantageous for real-world clinical scenarios characterized by limited data availability. The application of transfer learning not only enhances model performance but also facilitates the rapid deployment of advanced analytical tools in clinical settings.[22,23]

Ensemble Learning

Ensemble learning methods, such as bagging and boosting, are employed to amalgamate multiple machine learning models, thereby enhancing predictive performance and reducing bias. In the field of orthopedics, these ensemble techniques are instrumental in developing robust predictive models for disease progression, surgical outcomes, and personalized treatment plans. By integrating various models, ensemble learning contributes to increased accuracy and reliability in complex decision-making processes within clinical practice, ultimately improving patient management strategies.[3,24]

Bayesian Networks

Bayesian Networks are utilized in orthopedics for the probabilistic modeling of patient data, facilitating risk prediction, decision analysis, and the exploration of complex interdependencies among various factors, including age, medical history, and treatment types. These networks offer a transparent and interpretable framework for modeling uncertainty in patient outcomes and treatment efficacy, making them particularly valuable in the context of personalized medicine and surgical decision-making. Collectively, these machine learning methodologies enhance diagnostic accuracy, treatment prediction, surgical planning, and patient outcomes in orthopedics by leveraging complex data and delivering personalized, data-driven solutions.[25,26]

AI implementations in orthopedic conditions

Fractures

Fractures represent one of the most prevalent reasons for orthopedic consultations, and the application of AI, particularly Convolutional Neural Networks (CNNs), in fracture diagnosis has experienced substantial growth. Research indicates that CNNs consistently outperform both traditional AI models and human radiologists in terms of sensitivity, specificity, and overall diagnostic accuracy. Notable studies highlight the superior performance of CNNs in detecting various types of fractures, including distal radial fractures, proximal humerus fractures, and hip fractures. For instance, a study conducted by Gan et al. in 2019 demonstrated that a CNN achieved a diagnostic accuracy superior to that of radiologists for distal radial fractures, with an area under the curve (AUC) of 0.96.[27] Similarly, Chung et al. reported that a deep learning model for proximal humerus fractures attained an AUC of 1.00.[28] Furthermore, research by Cheng et al. on hip fractures utilizing CNNs indicated an AUC of 0.98, reflecting excellent diagnostic performance.[29] Collectively, these findings underscore the potential of AI models to significantly enhance diagnostic accuracy and, in certain contexts, surpass the capabilities of human experts.

Osteoarthritis

Beyond fractures, AI has demonstrated considerable promise in the diagnosis and management of osteoarthritis (OA), a leading chronic condition worldwide. Neural network-based AI models are increasingly employed to evaluate OA severity through radiographic and magnetic resonance imaging (MRI) analyses. These models provide valuable support to clinicians in diagnosing OA and formulating treatment plans. For example, Kotti et al. developed a computational method that incorporated patient locomotion data, achieving an accuracy of 72% in estimating OA severity, thereby illustrating AI's potential to improve clinical outcomes. Additionally, Köktaş et al. confirmed that AI could enhance the detection and grading of OA, alleviating diagnostic burdens and improving the quality of patient care.[30]

Osteoporosis

AI models, particularly machine learning (ML) algorithms and artificial neural networks (ANNs), have demonstrated remarkable accuracy in detecting osteoporosis. Hussain et al. introduced the COAD system, which utilizes ML and random forests applied to DEXA scans, achieving an R^2 value of 0.99[31]—significantly surpassing traditional diagnostic methods. Other studies, such as one conducted by Xinghu et al., reported that AI models achieved higher accuracy than radiologists, with receiver operating characteristic (ROC) values reaching 0.95 for osteoporosis detection.[32] Moreover, AI models have proven particularly effective in assessing at-risk patients through computed tomography (CT) scans, offering substantial improvements over conventional diagnostic approaches.

Bone Tumors and Malignancies

AI has emerged as a powerful tool in the diagnosis of both primary and metastatic bone tumors. Recent studies have demonstrated that deep learning (DL) models can effectively differentiate between benign and malignant lesions, achieving high diagnostic accuracy. Notably, research conducted by Zhao et al. revealed that the implementation of DL models significantly enhanced the diagnostic performance of clinicians without compromising specificity.[33] Furthermore, the integration of advanced AI methodologies, such as multi-plane attention learning frameworks, has further elevated diagnostic capabilities in the field of oncology.

Risk Assessment and Prognosis in Orthopedic Conditions

AI models have shown considerable promise in evaluating risk factors associated with prevalent orthopedic conditions, including lower back pain, osteoarthritis (OA), and vertebral fractures. Given that lower back pain is a leading cause of disability, AI algorithms can play a crucial role in predicting recurrent lumbar disc herniation and diagnosing vertebral insufficiency fractures. For instance, Karabulut et al. demonstrated that AI models could accurately diagnose various vertebral pathologies. In the context of knee OA, AI has been employed to forecast disease progression, with artificial neural networks (ANNs) exhibiting strong performance metrics (AUC = 0.94 for symptomatic OA). Additionally, AI-driven models have been utilized to predict outcomes related to bone healing, opioid prescriptions, mortality following fractures, and the length of hospital stay after total knee arthroplasty, underscoring the expansive role of AI in orthopedic prognostics.[34]

AI in Orthopedic Surgery

Recent investigations underscore the expanding role of AI beyond clinical diagnosis, extending into surgical guidance and the enhancement of surgical outcomes. Notably, AI models employed in arthroplasty procedures have been shown to improve patient outcomes through more effective preoperative planning and precise prosthetic sizing.[18,35,36] Studies conducted by Yang et al. and Al-Zoubi et al. have demonstrated that AI can enhance surgical accuracy, reduce complications such as intraoperative blood loss, and optimize the duration of surgical interventions.[18,37] Furthermore, machine learning (ML) algorithms have been utilized to predict postoperative outcomes, including complications, the need for blood transfusions, and opioid consumption following surgery.[38,39] In the context of total joint arthroplasty, AI has exhibited promise in forecasting patient-reported outcomes and complications. A study by Bini et al. notably highlighted the utility of AI in predicting long-term success following joint replacement procedures.[40]

Predictive Models for Postoperative Complications

AI has also shown significant predictive capabilities in the realm of postoperative care. Various models have been developed to evaluate the risk of complications, such as dislocations following hip and shoulder arthroplasties. Hernigou et al. reported that AI could achieve a 95% accuracy rate in predicting postoperative hip dislocations.[41] additionally, research by Rouzrokh et al. and Khosravi et al.

has emphasized the efficacy of deep learning models in forecasting the risk of dislocations and other complications subsequent to hip surgeries. These findings collectively underscore AI's potential to facilitate personalized patient management strategies in orthopedic surgery.[42-45]

Conclusion

In summary, the integration of artificial intelligence (AI), particularly through the utilization of Artificial Neural Networks (ANNs) and Convolutional Neural Networks (CNNs), is making significant strides in enhancing both the diagnostic and prognostic dimensions of orthopedic care. These advanced technologies enable more accurate detection of musculoskeletal disorders, facilitate efficient analysis of imaging data, and provide personalized predictions regarding patient outcomes. AI-driven models are progressively improving the precision of early diagnoses, treatment protocols, and post-surgical assessments, thereby holding the potential to enhance clinical efficiency and optimize patient management. As the field continues to advance, ongoing refinement of AI algorithms, coupled with the incorporation of extensive and diverse datasets, is expected to further solidify AI's role in orthopedics. This evolution paves the way for more effective, evidence-based approaches in musculoskeletal care. The future of AI in this domain is promising, with the potential to transform clinical practices and significantly elevate patient outcomes.

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