A Comprehensive Review of Artificial Intelligence and Hybrid Intelligent Systems in Veterinary Orthopedic Surgery: Current Applications, Challenges, and Future Perspectives

Tara Marzban[1*], Maryam Kermanshahian[1]
[1]Department of Veterinary Medicine, School of Veterinary Medicine, Islamic Azad University, Babol Branch, Babol, Iran.

*Corresponding author: Tara Marzban, Department of Veterinary Medicine, School of Veterinary Medicine, Islamic Azad University, Babol Branch, Babol, Iran. tara.marzban@iau.ir

ABSTRACT

Rapid advances in artificial intelligence (AI) and hybrid systems in recent years have opened new frontiers in precision medicine. In veterinary orthopedic surgery, which faces challenges such as anatomical variability across species, the complexity of joint reconstruction, and the need for high precision in implant placement, the application of these technologies can be transformative. This comprehensive review article aimed to investigate the applications of artificial intelligence (AI) and hybrid systems in veterinary orthopedic surgery between January 2020 and December 2025. A systematic search was conducted in reputable databases, including PubMed, Scopus, Web of Science, and Google Scholar, using keywords related to artificial intelligence, machine learning, neural networks, expert systems, orthopedic surgery, and veterinary medicine. From a total of 428 initial articles, after removing duplicates and screening the title and abstract, 21 full articles that met the inclusion criteria (original studies, systematic reviews, and case reports with a minimum follow-up of 6 months) were included in the final analysis. The findings showed that AI was mainly used in three main areas: 1) automatic detection and classification of fractures and dislocations from radiographs and CT scans with an accuracy of over 89%, 2) preoperative planning and simulation of implant placement in hip and knee surgeries, and 3) prediction of postoperative complications such as nonunion, infection, and implant failure based on demographic and clinical data. Hybrid systems that combined machine learning with rule-based veterinary expert systems showed the greatest success in reducing surgeon error and optimizing the bone-cutting path. However, significant challenges remain, including the lack of large, standardized veterinary datasets, explainable AI algorithms for clinical decision-making, and randomized controlled trials. It is concluded that AI and hybrid systems have great potential to transform veterinary orthopedic surgery, but widespread adoption in clinical practice requires further clinical validation and the development of user-friendly software.

Keywords: *Artificial intelligence, hybrid intelligent systems, veterinary orthopedic surgery, fracture detection, surgical outcome prediction*

1. INTRODUCTION

Veterinary orthopedic surgery has always been one of the most challenging clinical fields due to its anatomical complexities, racial and species diversity, and the need for extreme precision in reconstructing bones and joints [1]. Traditional surgical methods rely largely on the surgeon's skill, visual experience, and clinical judgment, which can be associated with human error, fatigue, and limited understanding of the three-dimensional relationships among internal structures. In recent years, the digital revolution and the emergence of Artificial Intelligence (AI) have created unprecedented opportunities to overcome these limitations. Machine Learning and Deep Learning algorithms can learn subtle diagnostic patterns from thousands of radiographs, CT scans, and MRI images that are hidden even from the most expert veterinary radiologist [2]. This ability has paved the way for the development of decision-support systems that can work alongside surgeons to significantly improve diagnostic accuracy and surgical planning [3].

Despite the remarkable successes of data-driven AI, pure machine learning methods also have weaknesses. AI algorithms usually require a very large amount of labeled data, which is rarely available in veterinary medicine due to high costs and data heterogeneity [4]. In addition, AI models often act as "black boxes" and do not explain the reason for their decisions, which is crucial in emergency medicine and surgery. To overcome these shortcomings, the concept of Hybrid Intelligent Systems has been proposed. These systems combine data-driven methods, such as neural networks, with knowledge-driven methods, such as rule-based expert systems and fuzzy logic. For example, in canine hip replacement surgery, AI can predict the optimal implant size and angle from images, while a veterinary knowledge base applies breed-specific biomechanical constraints. This hybrid approach not only increases accuracy but also improves the system's interpretability and reliability [5].

Several studies have reported high accuracy in detecting femoral and tibial fractures [6]. Second, preoperative planning and simulation, in which artificial intelligence algorithms determine the optimal bone cutting path, position, and size of screws and plates on 3D models obtained from CT scans [7]. This reduces operative time and prevents complications such as implant collision with vital structures. Third, prediction of postoperative complications, including nonunion, deep infection, and implant failure, based on a combination of preclinical data (age, weight, race), imaging data, and intraoperative variables [8].

Despite the high potential of these technologies, the path to their widespread adoption in veterinary clinics faces significant obstacles. The most important challenge is the lack of large, standardized, and gold-labeled datasets. Each veterinary species has a unique anatomy, and even within a breed, there is considerable variation in bone size and configuration. Building a database that includes all this variation requires multicenter collaboration and large investments. Another challenge is the poor generalizability of models; a model trained on data from one training center may perform poorly in another clinic with a different radiographer or imaging technique [3, 9]. Also, ethical and legal issues, such as liability for surgical errors arising from algorithmic recommendations and concerns about the privacy of animal data, have not yet been clearly resolved [10]. Finally, resistance to change and inadequate training among older veterinarians are also real, non-technical barriers.

Given the rapid advances in this field and numerous knowledge gaps, the need for a comprehensive, up-to-date review article that provides a complete picture of the current state of artificial intelligence and hybrid systems in veterinary orthopedic surgery is increasingly felt.

2. SEARCH STRATEGY

A systematic search for articles was conducted between January 1, 2020, and December 31, 2025, in internationally recognized electronic databases, including PubMed/MEDLINE, Scopus, Web of Science Core Collection, Google Scholar, as well as specialized veterinary databases such as CAB Abstracts and Veterinary Information Database (VID). The search strategy was designed using a combination of keywords and MeSH (Medical Subject Headings) terms related to four main areas: (1) artificial intelligence and its subfields ("Artificial Intelligence" OR "Machine Learning" OR "Deep Learning" OR "Neural Networks" OR "Computer Vision" OR "Expert Systems" OR "Fuzzy Logic" OR "Hybrid Intelligent Systems"), (2) orthopedic surgery ("Orthopedic Surgery" OR "Fracture Fixation" OR "Joint Replacement" OR "Osteotomy" OR "Bone Plating" OR "Cruciate Ligament Surgery"), (3) veterinary medicine ("Veterinary" OR "Veterinary Medicine" OR "Small Animal" OR "Canine" OR "Feline" OR "Equine" OR "Large Animal"), and (4) application areas ("Image Analysis" OR "Preoperative Planning" OR "Surgical Navigation" OR "Outcome Prediction" OR "Complication Risk"). To increase the sensitivity of the search, Boolean operators (AND, OR) were used, along with wildcards (*) and quoted phrases to find exact terms. Reference lists of relevant review articles and key studies were also manually reviewed (snowballing) to find other potentially eligible articles. Inclusion criteria included original articles, case reports, and systematic reviews published in English that directly addressed the use of artificial intelligence or hybrid systems in veterinary orthopedic surgery. Irrelevant articles, letters to the editor, conference abstracts without full text, and studies that only addressed nonsurgical diagnostic aspects or conservative management were excluded. A total of 428 initial articles were identified, and after removing duplicates (n = 87), screening the title and abstract (rejecting 302 articles), and evaluating the full text of the remaining articles (n = 39), 21 articles finally met the final inclusion criteria and were included in the analysis.

3. APPLICATIONS OF AI AND HYBRID INTELLIGENT SYSTEMS IN ORTHOPEDIC SURGERY

The first and most widespread application of AI in veterinary orthopedic surgery is the automated detection and classification of bone and joint lesions using deep learning algorithms, especially convolutional neural networks (CNNs) [11]. Several studies have shown that CNN algorithms can detect fractures of the femur, tibia, and humerus in dogs and cats on plain radiographs with an accuracy between 89 and 96%, in some cases exceeding that of experienced veterinary radiologists [6, 11, 12]. Beyond simply detecting a fracture, intelligent systems can also classify the type of fracture (simple, comminuted, spiral), the displacement of fragments, and joint involvement [13]. In addition to radiography, the application of these algorithms to 3D CT and MRI images has also been successfully reported for the diagnosis of anterior cruciate ligament (CrCL) rupture, Legg-Calvé-Perthes disease, and hip dysplasia [14-16]. The hybrid systems here operate in such a way that the output of the neural network (e.g., "92% probability of comminuted fracture") is fed into a rule-based expert system that, based on the patient's age, race, and weight, recommends whether immediate surgery is necessary or a conservative approach can be used. This two-step approach minimizes diagnostic error and helps the surgeon make the fastest possible decision in an emergency situation (Figure 1).

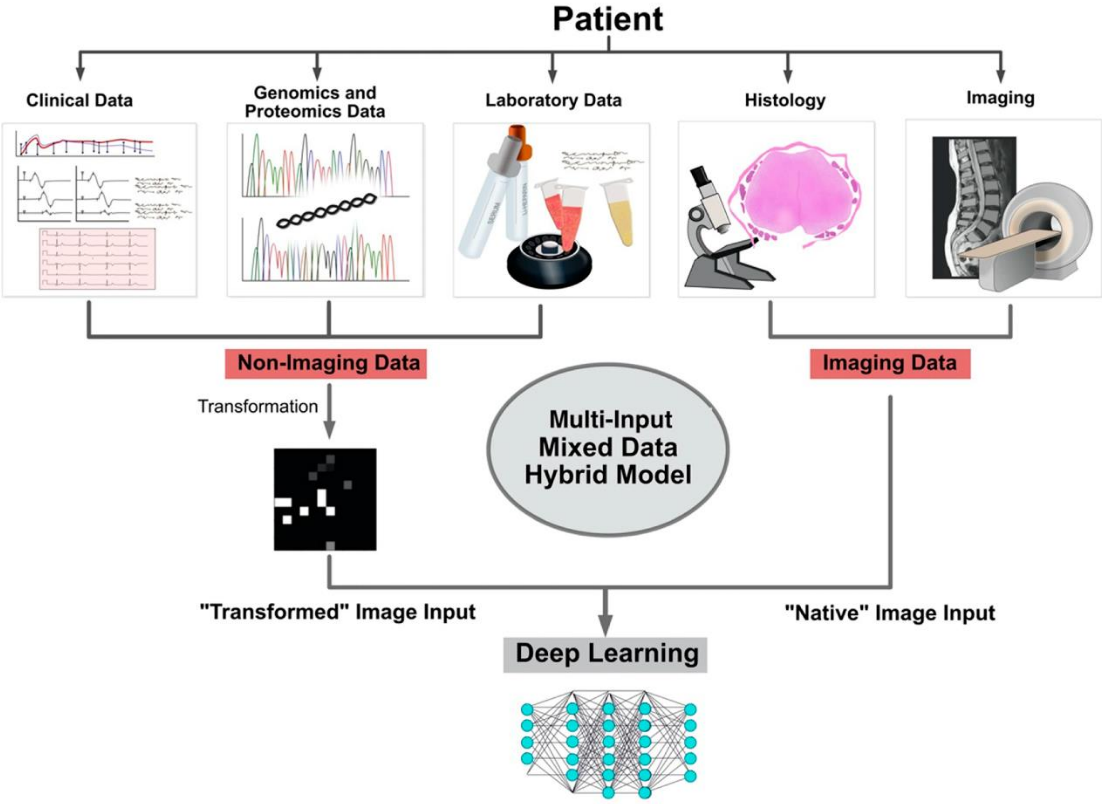

Figure 1. Illustration of multi-input mixed data model application in clinics (MDPI Copyright, 2022) [17].

The second critical application is the use of AI for accurate preoperative planning and surgical simulation. In complex orthopedic surgeries such as Corrective Osteotomy, Total Hip Replacement, or treatment of intracompartmental fractures, determining the incision angle, plate position, and screw length is critical, and an error of a few millimeters can lead to permanent gait abnormalities [18-21]. Machine learning algorithms, especially Random Forest and Support Vector Machine (SVM) models, can predict the normal anatomy of each patient and develop the optimal surgical plan by analyzing hundreds of CT scans from healthy and diseased patients [22]. Hybrid systems play an unparalleled role in this phase: a neural network extracts anatomical dimensions and angles from patient images, then an expert system containing biomechanical rules (such as "maximum tension on the plate should not exceed X Newtons") and breed constraints (such as "in the Great Dane breed, the minimum distance from the distal growth plate is 2 cm") optimizes the proposed surgical plan and refers it to an Augmented Reality environment or 3D printing for final simulation. Studies have reported that the use of AI systems has reduced actual surgical time by 20-35% and significantly reduced the number of implant replacements during surgery [23-25].

A third application that is at the frontier of knowledge is the use of AI for real-time guidance of the surgeon during surgery [26, 27]. Traditional methods of surgical navigation (computer-assisted navigation) rely on physical markers or robotic arms, both of which are expensive and impractical in the limited space of a veterinary operating room. New approaches based on computer vision and deep learning can detect the positions of bones, drills, and screws in real time from fluoroscopic or arthroscopic images without the need for markers and alert the surgeon to deviations from the surgical plan with submillimeter accuracy [28, 29]. The hybrid systems here act as a "smart companion": a 2D convolutional neural network analyzes the instantaneous fluoroscopic image to identify the instrument's position. A fuzzy logic system then determines whether the observed deviation is acceptable or requires immediate correction, taking into account factors such as the surgeon's hand tremor, arterial pulse, and patient respiratory movement. For example, in femoral fracture fixation surgery with an intramedullary pin, this system can instantly detect when the drill path deviates by 3 degrees from the optimal path and generate an alarm before damage to the sciatic nerves occurs. Despite its high potential, this area still remains mostly at the laboratory research level and requires more clinical trials.

The fourth and final major application is the use of AI and hybrid systems to predict long-term postoperative complications and treatment success [30]. After orthopedic surgery, factors such as nonunion, deep implant site infection, prosthesis loosening, and implant failure are among the most common complications that can lead to reoperation, amputation, or even death [31]. Traditional statistical models, such as logistic regression, are unable to simultaneously account for dozens of interacting variables (such as the interaction of high body weight and poor bone quality on the rate of union), but machine learning algorithms, such as XGBoost, deep neural networks, and random forests, can model these complex interactions. Hybrid systems have high added value here as well. For example, the output of a neural network that predicts a 78% probability of infection is fed into an expert system containing veterinary clinical protocols, providing not only a prediction but also a specific treatment recommendation to the surgeon [32-34]. Studies have shown that these models can predict with 82%-91% accuracy (Figure 2).

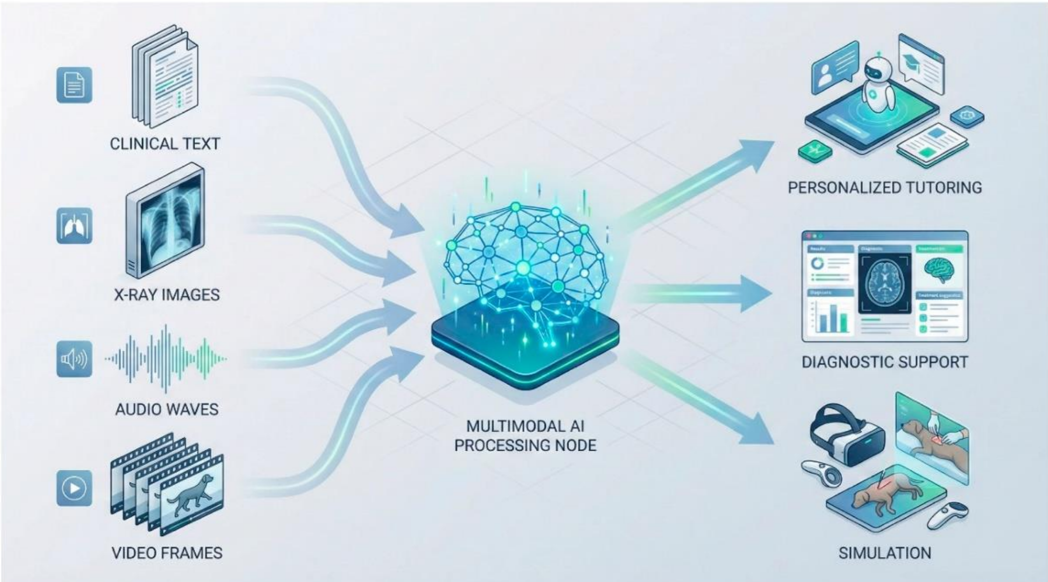

Figure 2. Representation of a multimodal AI processing architecture illustrating how clinical text, X-ray images, audio data and video frames can be integrated to generate educational outputs such as diagnostic support, personalized tutoring and simulation environments (MDPI Copyright, 2026) [35].

4. CHALLENGES AND LIMITATIONS

The most important and fundamental limitation in the development and validation of AI systems for veterinary orthopedic surgery is the quality and quantity of training data. Deep learning algorithms, especially convolutional neural networks, typically require thousands or even tens of thousands of labeled images to achieve acceptable performance. While in human medicine, large databases such as ImageNet and large hospital image collections are readily available, in veterinary medicine, such resources are very rare and limited. Radiographic images are acquired using different devices (digital, composite, and analog scanned), with different protocols (angles, distances, and exposures), and in different centers. An AI model trained on high-quality images from a private teaching hospital may lose 20 to 30 percent of its accuracy when confronted with dark, noisy, or motion-artifact images from a rural clinic. Another problem is the lack of a reliable ground truth. Image labeling by veterinary radiologists is inherently subject to inter-observer variability; two experienced radiologists may not agree completely on the presence of a microcrack or the degree of osteoarthritis. In such a situation, the AI algorithm is effectively learning from data that has a baseline error. Finally, there are privacy and data ownership considerations. Animal images and files belong to clinics, and sharing them to build a central database requires the consent of animal owners and complex legal mechanisms that are not yet foreseen in many countries.

The second group of limitations refers to the large gap between laboratory performance and real-world clinical efficacy. Prospective studies, and especially randomized controlled trials (RCTs) in which surgeons are randomly assigned to use or not use AI guidance, are almost non-existent. This lack of high-level evidence has seriously called into question the adoption of these technologies in the veterinary surgical community. Another practical challenge is integrating the technology into the operating room workflow. Many intelligent systems require additional hardware (such as powerful computers, peripheral displays, or connections to imaging devices) and complex software that is time-consuming to use. In an emergency orthopedic surgery case, where every minute of delay increases the risk of anesthesia and bleeding, the surgeon is reluctant to spend time setting up and calibrating an intelligent system. Also, the issue of interpretability, or the "black box" nature of many AI models, is a major psychological hurdle. When a deep neural network tells a surgeon "The probability of implant failure is 87%," but cannot explain whether the prediction is based on bone density, screw angle, or a combination of both, the surgeon will not trust it. Hybrid systems have solved this problem to some extent, but they are not yet at the point where they can provide step-by-step reasoning comparable to that of a human expert.

The third set of limitations is structural, economic, and human resources in nature. Developing and maintaining AI and hybrid systems requires a team of data scientists, software engineers, bioinformatics specialists, and veterinary surgeons. Hiring such a workforce for a medium-sized private veterinary clinic or even a veterinary school in a developing country is not economically viable. The cost of purchasing or subscribing to commercial AI software can also be very high, making these technologies the monopoly of large, wealthy clinics and deepening the equity gap in access to veterinary care. On the other hand, the lack of adequate training among practicing veterinarians and even veterinary students is a serious obstacle. Most veterinary surgeons have received little training in the principles of machine learning, interpreting model output, and recognizing when algorithms are making mistakes. This leads to two extreme reactions: on the one hand, cynicism and complete resistance to the technology ("the algorithm can never replace my experience"), and on the other, blind trust and over-reliance, which is equally dangerous. Also, the IT infrastructure in many clinics is very basic. Stable broadband Internet connections, cloud storage for large images, and computers equipped with graphics processing units (GPUs) to run deep learning models in real time are unavailable in many regions, even in developed countries.

5. CONCLUSION

This review article, which examined 21 studies between 2020 and 2025, found that AI and hybrid systems have been successfully applied in four main areas of veterinary orthopedic surgery: automated fracture detection, preoperative planning, intraoperative guidance, and prediction of postoperative complications. Despite impressive achievements such as over 90% accuracy in lesion detection and up to 35% reduction in surgical time, significant challenges remain, including a lack of standardized data, the absence of randomized clinical trials, limited interpretability, and high implementation costs. Overall, AI, as an adjunct but not a replacement for the surgeon, has the potential to significantly improve the accuracy, safety, and outcomes of veterinary orthopedic surgery, provided that the technical, ethical, and educational barriers are overcome.

Declarations and statements

Funding

No funding was received to conduct this study.

Conflict of interest

The authors declare no conflicts of interest.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethical approval

All applicable international, national, and/or institutional guidelines for writing a review paper were followed.

Author contribution

Conceptualization: [Maryam Kermanshahian, Tara Marzban], …; Methodology: [Maryam Kermanshahian, Tara Marzban], …; Formal analysis and investigation: [Maryam Kermanshahian], …; Writing - original draft preparation: [Maryam Kermanshahian, Tara Marzban]; Writing - review and editing: [Maryam Kermanshahian, Tara Marzban], …; Funding acquisition: [Self-funding], …; Supervision: [Maryam Kermanshahian].

Consent to participate

Not applicable

Consent for publication

Not applicable

Acknowledgments

The authors acknowledge MDPI for permission to reuse the figure(s).

Declaration of the use of generative AI

After the content was fully written, an AI-powered tool was exclusively used to review and refine the article's grammar, punctuation, and overall linguistic flow. The AI tool was used strictly as a proofreading and language-refinement assistant and was not employed at any stage to generate content, ideas, or article sections.

REFERENCES

1. Memarian P, Pishavar E, Zanotti F, Trentini M, Camponogara F, Soliani E, et al. Active materials for 3D printing in small animals: current modalities and future directions for orthopedic applications. International Journal of Molecular Sciences. 2022;23(3):1045.
2. Currie G, Rohren E. Intelligent imaging: Applications of machine learning and deep learning in radiology. Veterinary Radiology & Ultrasound. 2022;63:880–8.
3. Xiao S, Dhand NK, Wang Z, Hu K, Thomson PC, House JK, et al. Review of applications of deep learning in veterinary diagnostics and animal health. Frontiers in Veterinary Science. 2025;12:1511522.
4. Gomes C, Coheur L, Tilley P. A review of multimodal AI in veterinary diagnosis: Current trends, challenges, and future directions. IEEE Access. 2025.
5. Burti S, Banzato T, Coghlan S, Wodzinski M, Bendazzoli M, Zotti A. Artificial intelligence in veterinary diagnostic imaging: Perspectives and limitations. Research in Veterinary Science. 2024;175:105317.
6. Baydan B, Ünver HM. Detection of tibial fractures in cats and dogs with deep learning. Ankara Üniversitesi Veteriner Fakültesi Dergisi. 2021;68(3):283–90.
7. Kamrani MMR, Malekian A, Onagh M, Manian M, Shahraki M, Vasei M. Roles of Artificial Intelligence in Soft Tissue Surgery: A Review. Journal of Lab Animal Research. 2026;5(2):38–43.
8. Almalki TK, Marzok MA, Al Mohamad Z, Hereba A, El-Sherif MW, Hassan MA, et al. Artificial Intelligence in Veterinary Surgical Research: Current Applications and Prospects. Egyptian Journal of Veterinary Sciences. 2025:1–10.
9. Appleby RB, Basran PS. Artificial intelligence in diagnostic imaging. Advances in Small Animal Care. 2024;5(1):67–77.
10. Cohen EB, Gordon IK. First, do no harm. Ethical and legal issues of artificial intelligence and machine learning in veterinary radiology and radiation oncology. Veterinary Radiology & Ultrasound. 2022;63:840–50.
11. Saber AS, Selim I, Askr H, Elbahgy A, Ashraf A, Eldweek A, et al. Veterinary fracture diagnosis: a deep learning model for dogs long bone fractures. Scientific Reports. 2026;16(1):15098.
12. Baydan B, n BARIŞÇI N, Ünver HM. Determining the location of tibial fracture of dog and cat using hybridized mask R-CNN architecture. Kafkas Üniversitesi Veteriner Fakültesi Dergisi. 2021;27(3).
13. Pour ZM, Berretti S. A comprehensive review of AI methods in upper extremity/limb bone fracture detection. Artificial Intelligence Review. 2025;58(10):307.
14. Gill SS, Haq T, Zhao Y, Ristic M, Amiras D, Gupte CM. AI demonstrates comparable diagnostic performance to radiologists in MRI detection of anterior cruciate ligament tears: a systematic review and meta-analysis. European radiology. 2026;36(4):2500–17.
15. Herman H, Kumar YJ, Wee SY, Perhakaran VK. A systematic review on deep learning model in computer-aided diagnosis for anterior cruciate ligament injury. Current Medical Imaging. 2024;20(1):e15734056295157.
16. Corban J, Lorange J-P, Laverdiere C, Khoury J, Rachevsky G, Burman M, et al. Artificial intelligence in the management of anterior cruciate ligament injuries. Orthopaedic Journal of Sports Medicine. 2021;9(7):23259671211014206.
17. Saravi B, Hassel F, Ülkümen S, Zink A, Shavlokhova V, Couillard-Despres S, et al. Artificial Intelligence-Driven Prediction Modeling and Decision Making in Spine Surgery Using Hybrid Machine Learning Models. Journal of Personalized Medicine. 2022;12(4):509.
18. Eskandar K. The role of artificial intelligence in orthopedic surgery: Current applications and future perspectives—A systematic review of the literature. Revista Española de Cirugía Ortopédica y Traumatología. 2025.
19. Han F, Huang X, Wang X, Chen Yf, Lu C, Li S, et al. Artificial intelligence in orthopedic surgery: current applications, challenges, and future directions. MedComm. 2025;6(7):e70260.
20. Mozafari JK, Moshtaghioon SA, Mahdavi SM, Ghaznavi A, Behjat M, Yeganeh A. The role of artificial intelligence in preoperative planning for total hip arthroplasty: a systematic review. Frontiers in Artificial Intelligence. 2024;7:1417729.
21. Misir A, Yuce A. AI in orthopedic research: a comprehensive review. Journal of Orthopaedic Research®. 2025;43(8):1508–27.

22. Guido R, Ferrisi S, Lofaro D, Conforti D. An overview on the advancements of support vector machine models in healthcare applications: a review. Information. 2024;15(4):235.
23. Guni A, Varma P, Zhang J, Fehervari M, Ashrafian H. Artificial intelligence in surgery: the future is now. European Surgical Research. 2024;65(1):22–39.
24. Varghese C, Harrison EM, O'Grady G, Topol EJ. Artificial intelligence in surgery. Nature medicine. 2024;30(5):1257–68.
25. Loftus TJ, Tighe PJ, Filiberto AC, Efron PA, Brakenridge SC, Mohr AM, et al. Artificial intelligence and surgical decision-making. JAMA surgery. 2020;155(2):148–58.
26. Morris MX, Fiocco D, Caneva T, Yiapanis P, Orgill DP. Current and future applications of artificial intelligence in surgery: implications for clinical practice and research. Frontiers in surgery. 2024;11:1393898.
27. Bukhari SM, Kumar I. Real-Time AI in Surgery: A Review of Precision, Innovation, and Future Directions in Surgical Assistance. International Journal of Performability Engineering. 2025;21(5).
28. Lalehzarian SP, Gowd AK, Liu JN. Machine learning in orthopaedic surgery. World journal of orthopedics. 2021;12(9):685.
29. Fan X, Zhu Q, Tu P, Joskowicz L, Chen X. A review of advances in image-guided orthopedic surgery. Physics in Medicine & Biology. 2023;68(2):02TR1.
30. Liu L, Zhang P, Jia Y, Hou L, Peng D, Li Z, et al. Artificial intelligence in ambulatory surgery: current Applications, Challenges, and future directions. Journal of Medical Systems. 2025;49(1):146.
31. Sharma AC, Azeem A, Omari IH, Premkumar A. Artificial Intelligence for Predicting Postoperative Complications in Orthopedics: A Review of Clinical Applications, Challenges, and Future Directions. Cureus. 2025;17(12).
32. Akbarein H, Taaghi MH, Mohebbi M, Soufizadeh P. Applications and considerations of artificial intelligence in veterinary sciences: A narrative review. Veterinary Medicine and Science. 2025;11(3):e70315.
33. Akinsulie OC, Idris I, Aliyu VA, Shahzad S, Banwo OG, Ogunleye SC, et al. The potential application of artificial intelligence in veterinary clinical practice and biomedical research. Frontiers in veterinary science. 2024;11:1347550.
34. Awaysheh A, Wilcke J, Elvinger F, Rees L, Fan W, Zimmerman KL. Review of medical decision support and machine-learning methods. Veterinary pathology. 2019;56(4):512–25.
35. Pérez-García E, Ramírez AS, Quintana-Suárez MÁ, Conde-Felipe MM, Carrascosa C, Morales I, et al. Artificial Intelligence in Veterinary Education: Preparing the Workforce for Clinical Applications in Diagnostics and Animal Health. Veterinary Sciences. 2026;13(2):181.