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ARTIFICIAL INTELLIGENCE-POWERED SPINE SURGERY: A SYSTEMATIC REVIEW OF CURRENT TRENDS AND FUTURE PROSPECTS

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ABSTRACT

Artificial intelligence (AI) in spine surgery is a revolutionary technology that can significantly assist clinicians in more accurate and efficient patient diagnosis, treatment planning, and outcome prediction. This review examines the recent applications of AI technologies in spine surgery, which are becoming increasingly common in our daily practice and are expected to play an important role in the future. For this purpose, the PubMed electronic database was searched between September 2023 and September 2024 using keywords related to spinal pathologies, anatomical structures, diagnostic methods, and AI applications. A total of 217 articles met the inclusion criteria for the study. The country of study, anatomical region, data size, spinal pathologies, and purpose of the study were evaluated from the data. In conclusion, the application of AI in spine surgery is revolutionizing the field by increasing diagnostic accuracy, surgical precision, and postoperative care. As the technology continues to evolve, the integration of AI into spine surgery can further improve patient outcomes and surgical efficiency, making AI an essential component of modern surgical practice.

Keywords: Artificial intelligence, deep learning, machine learning, spine, surgery

INTRODUCTION

Artificial intelligence (AI) originated in the 1950s with Alan Turing's query, "Can machines think?". Since then, AI has found widespread application in the medical field and has been the focus of extensive research. AI is employed in various medical domains, including assessing patient risk factors, enhancing the accuracy and efficiency of medical imaging diagnosis, creating new chemical compounds for treatment, and optimizing hospital operations[1]. The utilisation of AI enables physicians to reduce the time required for diagnosis, thereby facilitating more accurate conclusions. By analysing the data entered, it can identify relationships that are not perceptible to the physician through visual means. It is also important to note that the objective of this technology is not to replace the physician. Conversely, it serves to reinforce the physician's capabilities and enhance the efficiency of their work[2]. In spine surgery, AI is considered a revolutionary technology that can significantly assist clinicians in making more precise and efficient patient diagnoses, treatment planning, and outcome prediction[3-7].

AI is a branch of computer science that aims to equip computer systems with advanced intelligence using algorithms to simulate reasoning and decision-making[8]. Machine learning (ML) and deep learning (DL) are subfields of AI. ML uses statistical techniques to make predictions and can quickly identify crucial imaging features necessary for diagnosis that may elude the average clinician[9].

On the other hand, DL is a subset of ML that employs artificial neural networks with multiple layers to analyze diverse data types[10]. The increasing global prevalence of spine-related conditions and the escalating healthcare costs call for a transformative approach[11]. Integrating AI technologies into spine surgery represents a significant advancement in this field and can positively impact diagnostic accuracy, treatment efficiency, and postoperative outcomes. Applications of AI technologies in spine surgery, which are becoming increasingly prevalent in our daily practice and are expected to continue playing a pivotal role. The rapid advancement of AI technology presents a challenge for clinicians attempting to keep pace with developments in this field. This review aims to provide a summary of spine AI studies conducted over the past year.

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MATERIALS AND METHODS

Search Strategies

In a systematic review following the Preferred Reporting Items for Systematic reviews and Meta-Analyses guidelines (Figure 1)[12], we searched the PubMed electronic database between September 2023 and September 2024 using keywords related to spine pathologies, anatomical structures, diagnostic methods, and AI applications (Table 1). A search of the formula presented in the table, conducted by entering "Advanced" in the PubMed database, yielded 577 studies. Six articles in the publication phase or withdrawn were excluded, along with 40 articles not in English or with inaccessible full texts. Finally, 217 articles met the inclusion criteria for the study.

Exclusion Criteria

• Animal experiments, cadaver studies, microscopic and biochemical studies
• Studies on technical issues, such as improving radiological imaging and removing artifacts
• Studies to distinguish the brands and materials of the materials used as implants
• Studies related to rheumatology and physical therapy and rehabilitation applications
• Studies on non-vertebral anatomical structures and pathologies in the cervical, thoracic, and lumbar regions
• Studies that include other bone tissues (skull, pelvis, ribs, etc.) along with the spine in radiologic imaging
• Systematic review and meta-analysis studies

Data Collection and Analysis

The following main headings were identified, and data were obtained from the 217 articles included in the study.

• Country of study
• Anatomical region: Categorized into three main categories: Cervical, thoracic, and lumbosacral (Given the absence of a single study on the sacral region in the 217 articles under review, the lumbosacral region was evaluated as a single anatomical area). However, studies involve two different anatomical regions or the whole spine
• Size of the data used in the study: Number of patients or radiologic images/sections (n<100, 101-1000, n>1000)

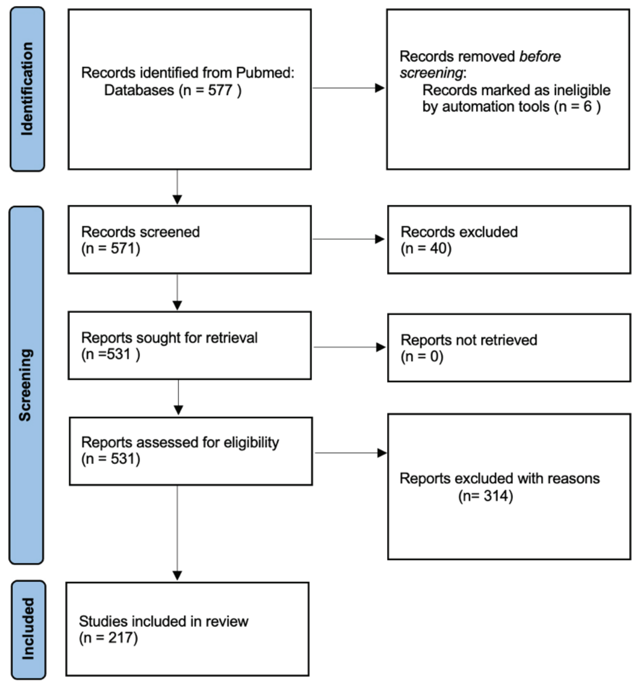

Figure 1. Flow chart of PRISMA diagram
PRISMA: Preferred Reporting Items for Systematic reviews and Meta-Analyses

Table 1. Search formula used in searching PubMed database (modified from Constant et al.)(8)

(("Spine" [MeSH] OR "back" [MeSH] OR "Zygapophyseal Joint" [MeSH] OR "Spinal Diseases" [MeSH] OR "Sciatica" [MeSH] or "Spinal Injuries" [MeSH] OR "Laminectomy" [MeSH] OR "Cementoplasty" [MeSH] OR "Diskectomy" [MeSH] OR "Intervertebral Disc Chemolysis" [MeSH] OR "Laminoplasty" [MeSH] OR "Osteotomy" [MeSH] OR "Spinal Fusion" [MeSH] OR "Spinal Puncture" [MeSH] OR "Foraminotomy" [MeSH] OR "Neuroendoscopy" [MeSH] OR "Total Disc Replacement" [MeSH] OR "Pedicle Screws" [MeSH] OR Spine [tiab] OR Spina* [tiab] OR "degenerative disc" [tiab] OR "vertebr*" [tiab] OR "scoliosis" [tiab] OR "disc degeneration" [tiab] OR "Disc Degradation" [tiab] OR "disc disease" [tiab] OR "intervertebral disc" [tiab])) AND ((("Machine Learning" [MeSH] OR "Neural Networks, Computer" [MeSH] OR "naive bayes" [tiab] OR "bayesian learning" [tiab] OR "neural network*" [tiab] OR "random forest" [tiab] OR "deep learning" [tiab] OR "machine prediction" [tiab] OR "machine intelligence" [tiab] OR "generative adversarial networks" [tiab] OR "Hierarchical Learning" [tiab] OR "computer vision" [tiab] OR "computational intelligence" [tiab] OR "computational learning" [tiab] OR "computer reasoning" [tiab] OR "machine learning" [tiab] OR "reinforcement learning" [tiab] OR "convolutional network*" [tiab] OR "artificial intelligence" [tiab] OR "Self Organizing MAP" [tiab] OR "Self-Organizing MAP" [tiab] OR "AutoEncoder" [tiab] OR "CNN" [tiab] OR "GAN" [tiab] OR "GANN" [tiab])) OR (("convolute" [All Fields] OR "convoluted" [All Fields] OR "convolutes" [All Fields] OR "convoluting" [All Fields] OR "convolution" [All Fields] OR "convolutional" [All Fields] OR "convolutions" [All Fields] OR "convolutive" [All Fields]) AND ("neural networks, computer" [MeSH Terms] OR ("neural" [All Fields] AND "networks" [All Fields] AND "computer" [All Fields]) OR "computer neural networks" [All Fields] OR ("neural" [All Fields] AND "network" [All Fields]) OR "neural network" [All Fields]))) AND (("Diagnostic Imaging" [MeSH] OR "Image Processing, Computer-Assisted" [MeSH] OR "Imaging" OR "Radiograph*" OR "x?ray" OR "Tomograph*" OR "Magnetic Resonance" OR "MR?image*" OR "MRI" OR "MRA" [tiab] OR "CT?Scan*" OR "Ultrasonograph*" OR "Ultrasound*" OR "PET?Scan" OR "c-arm" OR "fluoroscop*" OR "arthrogram*" OR "arthrograph*" OR "venogram*" OR "venograph*" OR "cone?beam CT" OR "image-guided adaptive radiation therapy" OR "IGART" [tiab])) AND (("2023/09/01" [Date-Publication]: "2024/09/24" [Date-Publication])) NOT ((systematic review [pt] OR review [pt]))

- Spinal pathologies
- Degenerative: Facet joint pathologies, disc pathologies, narrow canal, spondylosis, spondylolisthesis, and myelopathy are included in this group
- Trauma: Fractures, spinal cord injuries. Separation of old and new fractures is also included in this group
- Tumor: Primary or metastatic tumors
- Infection
- Deformity: Scoliosis, sagittal-coronal balance disorders, adult spinal deformity
- Osteoporosis
- Other pathologies: Ossified posterior longitudinal ligament, tethered spinal cord syndrome, etc.
- Purpose of the study
- Diagnosis
- Clinical decision making
- Surgical planning
- Making prognostic predictions for the future during a treatment or the natural course of any disease, risk analysis

RESULTS

Country of Study

Two hundred seventeen studies were distributed across 29 countries. China alone accounted for 38% of all studies. China, the US, and Korea conducted 61% of all studies last year (Figure 2). The countries with the most studies in medicine are the US, China, and the UK[12]. China seems to have been at the forefront of AI studies on spine surgery in the last year.

Anatomical Region

Considering the anatomical regions where the studies were performed, the lumbosacral spine had the most data followed by cervical and thoracic regions. When studies involving more than one region are analysed, thoracolumbar (28.11%) and whole spine (24.88%) have similar rates (Figure 3).

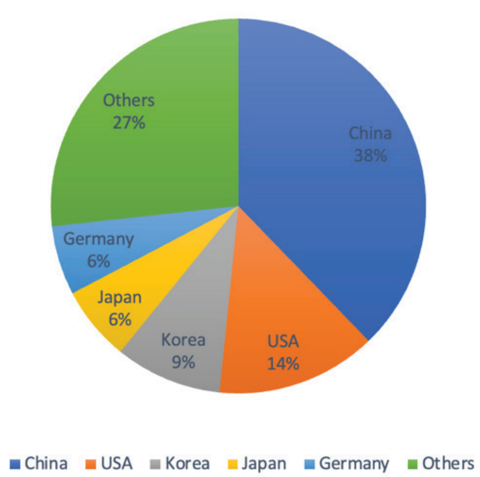

Figure 2. Distribution of countries where studies included in the review were conducted

Data Size

Among the three headings where data size, an essential parameter in AI applications, is collected, n>1000 is the most common (81.56%) (Figure 4).

Spinal Pathologies

Degenerative (30%), deformity (27%), and trauma (26%) are in the top three in close proportions. Although osteoporosis is not an area of direct interest in spine surgery, it has been analysed under a separate heading due to its high incidence and the fractures it causes. In the last year, 7.83% of the AI studies related to the spine were related to osteoporosis. In line with epidemiological data, tumours, infections and other spinal pathologies are less common in all studies (9.2%) (Figure 5).

Purpose of The Study

In terms of the intended use of the AI algorithm in the clinic, diagnosis represents the primary application, accounting for 74.65% of all cases. This is followed by prognosis prediction (16.59%) and surgical planning (5.99%). Decision-making studies represent the lowest percentage of applications at 2.76% (Figure 6).

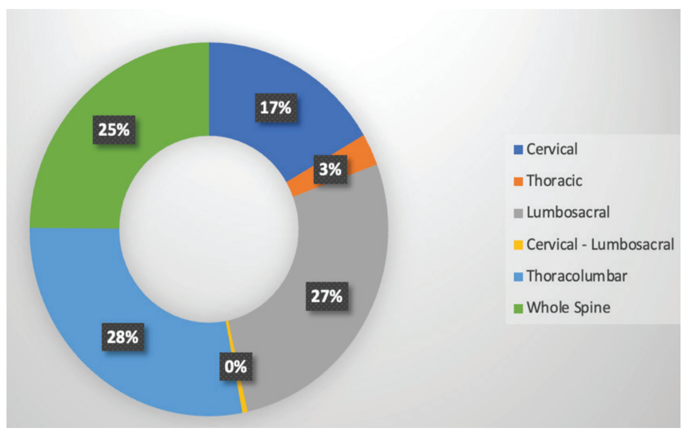

Figure 3. Distribution of anatomic regions

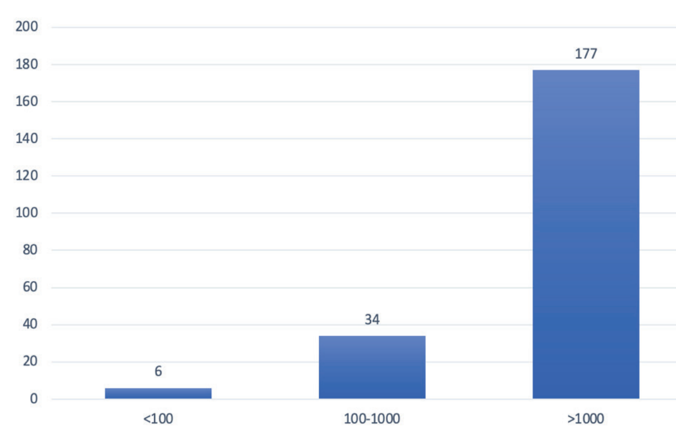

Figure 4. Distribution of data size

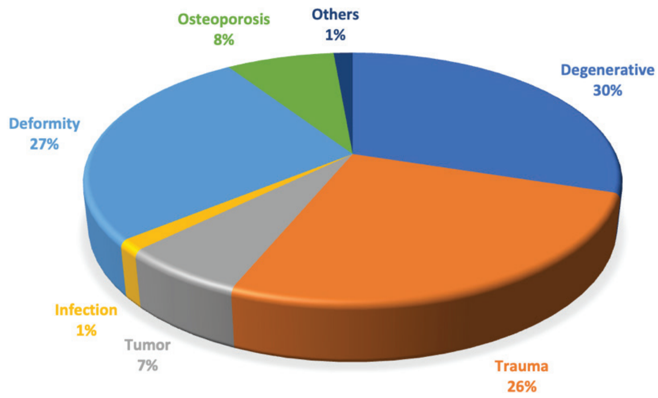

Figure 5. Distribution of spine pathologies

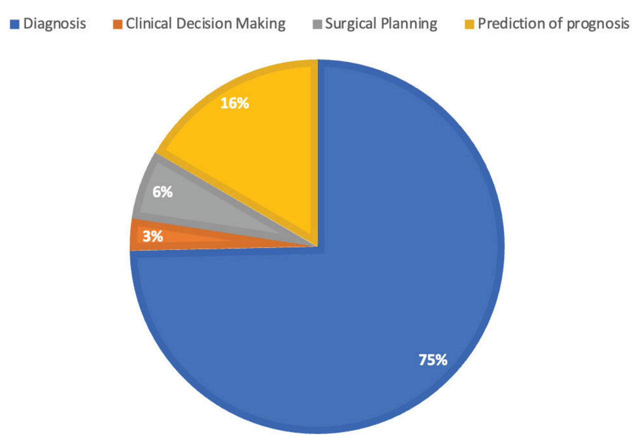

Figure 6. Distribution of the main purpose of the study

DISCUSSION

The article provides a comprehensive overview of the applications of AI in spinal surgery, focusing on the past year. The review draws on data from PubMed, a medical database, and proposes the potential for more extensive research utilizing scientific databases. The prevalence of Chinese studies in this field aligns with China's aim to become a global leader in AI by 2030[13]. The limited involvement of other countries underscores the need for increased investment in AI, particularly in densely populated countries, to enhance the quality and quantity of data and findings.

The study highlights the prominence of the lumbosacral region (27%) when considering anatomical locations, reflecting epidemiological trends. Research on deformities or tumors typically evaluates the entire vertebra as a whole. However, the thoracolumbar region is prominently featured in studies related to compression fractures and osteoporosis (28%). Given the paucity of research examining the sacral region as a discrete entity, it was assessed in conjunction with the lumbosacral region. Nevertheless, in the future, sacral region pathologies may be evaluated under a distinct heading or may be the subject of a standalone study.

In AI, the volume of data used to develop algorithms is a crucial factor influencing the success of results[14]. The model's capacity to capture complex data relationships and variations significantly improves with exposure to a broader array of samples, leading to higher prediction accuracy[15]. More data not only yields more precise results but also aids clinicians and saves time[16]. Nevertheless, it is imperative to emphasize that merely increasing data input is insufficient; the quality of data input is equally critical for application success[17]. Most studies in our review involved datasets with over 1000 entries (81.5%), and studies with even more significant data inputs are anticipated to bolster confidence in AI. The field of spinal surgery encompasses a wide array of diseases, making it more practical to categorize them rather than study each individually. This study classified diseases into degenerative, trauma, tumor, infection, deformity, and osteoporosis, with a small percentage falling under the "other" category. Degenerative diseases, trauma, and deformity disorders comprised the majority (93%) of the studies. It is anticipated that there will be an increase in the number of studies and meta-analyses for each category and subgroup. Additionally, using AI applications will be crucial for identifying less common pathologies such as infections and tumors.

Since its inception in the medical field, AI has developed algorithms focused on diagnostic accuracy, yielding similar results to those observed in this review. While 75% of recent studies have concentrated on recognition applications, there has also been a rise in research on crucial aspects such as surgical planning, prognostication, and decision-making in clinical scenarios. Surgical planning, especially in deformity surgery, is essential, and systems designed for this purpose utilize real-time imaging and intelligent operation planning to guide surgeons, ultimately improving surgical outcomes and reducing intraoperative radiation exposure[18]. Incorporating AI into surgical interventions enhances accuracy and minimizes human error by detecting and rectifying potential errors during procedures[19].

The utilisation of AI technologies has markedly improved patient safety in the field of spine surgery. A study has demonstrated that the integration of ML can mitigate the risks associated with surgical procedures by optimising patient selection and preoperative planning, thereby reducing complications and enhancing overall outcomes[20]. The use of AI for risk stratification has been demonstrated to be effective, with studies demonstrating that predictive models can achieve high accuracy rates. For example, an 87.6% prediction accuracy for perioperative complications in spinal deformity surgeries has been reported. This capability allows for more informed decision-making and tailored surgical approaches, which ultimately lead to improved patient safety[21].

The clinical applications of AI in improving imaging and predictive pattern detection are of crucial importance for effective surgical decision-making in complex cases. The ability of AI to analyse vast datasets and identify patterns that may not be immediately apparent to human practitioners represents a significant advancement in surgical practice[22]. ML models can accurately predict the outcomes of lumbar spinal fusion surgeries, thereby facilitating the optimisation of surgical strategies and postoperative care[23]. Furthermore, personalized discussions with patients in the preoperative phase can make the surgeon-patient relationship more reliable by providing quantitative data on expected benefits and risks[24-27]. Specific studies have focused on various surgical procedures and their associated complications, employing ML models to predict hospital readmissions and artificial neural networks to anticipate complications following posterior lumbar spine fusion[28,29].

AI can potentially enhance clinical decision-making and may even supplant human judgment in certain healthcare functions[30]. However, it also facilitates shared decision-making between clinicians, patients, and their families[31]. On the other hand, the least common use of AI in spinal surgery is currently decision-making, but this is expected to change with more studies in the future.

Despite the promising advancements in AI, its application and adoption in spine surgery present several challenges. Ethical considerations regarding patient data privacy, the necessity for rigorous clinical studies to validate AI applications, and the integration of AI tools into existing clinical workflows are crucial areas for ongoing research and discussion[32]. Additionally, there is a need to establish standardized protocols and guidelines for AI implementation in clinical practice to ensure improved surgical precision and patient outcomes[6].

CONCLUSION

In conclusion, the application of AI in spine surgery is revolutionising the field by increasing diagnostic accuracy, improving surgical precision and optimising postoperative care. As technology continues to evolve, the integration of AI into spine surgery promises to further improve patient outcomes and operational efficiency, making it an essential component of modern surgical practice. This will require surgeons to collaborate with AI practitioners and data scientists, and universities and research centres to adopt a multidisciplinary approach that includes departments in AI and computer science.

Footnote

Conflict of Interest: The authors have no conflicts of interest to declare.

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