Application and Prospect of Artificial Intelligence in Orthopedic Surgical Robots

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ABSTRACT With the spurt of progress in artificial intelligence (AI), its application to orthopedic surgical robots has gradually become a current research hotspot. Though after decades of development, traditional orthopedic surgical robots have become the core equipment for perfecting various clinical orthopedic surgeries, there is still a lot of room for improvement in terms of precision, safety, minimal invasiveness and intelligence. Therefore, machine learning (ML) and deep learning (DL), which are now playing a significant role in many fields such as education, industry, and transportation, show their promising potential in driving continuous innovation of orthopedic surgical robots. This review outlines the current development of orthopedic robots, describes the application of AI in joint surgical robots, spine surgical robots and trauma surgical robots in detail, and analyzes the prospect of orthopedic robots according to the advancement trend of AI.

INDEX TERMS Orthopedic surgical robot, Artificial Intelligence, joint surgical robot, spine surgical robot, trauma surgical robot.

# I. INTRODUCTION

In 1956, the term "Artificial Intelligence (AI)" was first coined, marking the birth of AI as an independent research discipline. Currently, AI is usually considered as a branch of computer science and technology or a cross-discipline involving academic fields like computer science, mathematics, cognitive science and neurophysiology to develop theories, techniques and applications for simulating and expanding human intelligence. AI technologies represented by deep neural networks such as image classification, speech recognition, knowledge quizzing, and unmanned driving have achieved significant technological breakthroughs, ushering in a new wave of explosive growth. With the development of machine learning (ML) and deep learning (DL), AI technology has been widely used in education, industry, commerce, healthcare and other fields, which has brought great economic and social benefits to mankind, greatly promoted the development of society, and effectively improved people's quality of life[1].

Orthopedic surgery is a typical kind of hard tissue operation, with complex surgical procedures, high surgical risks and high requirements for physicians' clinical experience[2]. With the progress of computer information technology, the development of machinery manufacturing industry and the emergence of minimally invasive surgical concepts, robotic technology has been gradually introduced into the medical field. And after decades of development, orthopedic surgical robots have become the core equipment for advancing precise and personalized orthopedic treatments, which can well solve some of the problems existing in traditional orthopedic surgeries, such as high trauma, long operation time and slow postoperative recovery. Orthopedic surgical robots are now mainly categorized into joint surgical robots, spine surgical robots, and trauma surgical robots based on the type of surgery it is involved in[3].

ML and DL are now widely used in the medical field[1]. This includes the automatic detection of strokes, retinopathies, and cancerous histology, with the same level of accuracy as the relevant field experts[4]-[9]. Although traditional orthopedic surgical robots have perfected some clinical surgeries, there is still a lot of room for improvement in terms of precision, safety, minimal invasiveness, and intelligence. Therefore, the integration of AI into orthopedic surgical robots has the potential to drive continuous innovation in the field, leading to improved patient care, enhanced surgical techniques, and ultimately, better outcomes for orthopedic patients. This article reviews the current applications of AI in the field of orthopedic surgical robots and looks at its prospects for development.

# II. AI IN JOINT SURGICAL ROBOTS

Currently, joint surgery robots are mainly used in arthroplasty and its revision. And in arthroplasty, total hip arthroplasty (THA), total knee arthroplasty (TKA) and uni-compartmental knee arthroplasty (UKA) are the main robotic-assisted surgeries, aiming at realizing precise treatment, increasing the survival rate of implant and improving the clinical efficacy[10]. In 1992, ROBODOC, the world's first orthopedic surgical robot, completed the robot-assisted THA for the first time[11]. Since then, a number of THA surgical robots have been available for operators to choose from, such as CASPAR, ACROBOT and MAKO robotic systems. At the same time, joint surgical robots have been gradually introduced to TKA and UKA, in addition to the ROBODOC and MAKO robotic systems, there are also iBlock, Navio FPS and Rosa Knee robotic systems[12]. Although existing joint surgery robots have been successful in improving surgical precision in arthroplasty, with the widespread use of AI, it has now been found that the use of AI in joint surgery robots can lead to more efficient and accurate preoperative planning for arthroplasty and its revision.

## *A. AI IN PREOPERATIVE PLANNING FOR THA, TKA AND UKA*

THA, one of the most successful procedures in medicine, is a common surgery for the treatment of end-stage hip disease[13]. Additionally, TKA and UKA are the most economical and dependably successful orthopedic procedures. They provide reliable outcomes for patients suffering from degenerative knee osteoarthritis. Though these three procedures have good efficacy, due to the increasing diversity of implant designs and models, it is difficult to choose the type of implant. Therefore, preoperative planning for THA, TKA and UKA is becoming increasingly crucial. However, most hospitals still use traditional film template measurement nowadays, which requires a high level of experience of the surgeon and is cumbersome and time-consuming, thus often leading to inaccurate preoperative planning and elevated rate of postoperative complications[14], [15]. Some studies have applied AI to preoperative evaluation for the efficient selection of prosthesis models and types, and the results show that AI has a promising future in this area.

Wu Dong *et al.* constructed a three-dimensional convolutional neural network (CNN) planning system for THA, the AIHIP system, which is the first time that AI technology is applied to THA preoperative planning. By importing DICOM data into the AIHIP system, THA 3D preoperative planning can be generated intelligently within 10 minutes. The brief construction process of the AIHIP system is as follows. Firstly, a CT image database of various hip diseases was established, including diseases such as femoral head necrosis, femoral neck fracture and hip dysplasia. Then the CNN model G-NET, which is a two-dimensional Dense-Unet, was developed and trained. The DenseBlock structure was introduced on the basis of the U-net model to combine the strengths of the UNet and the DenseNet, thus significantly improving the segmentation accuracy of G-NET compared to traditional segmentation methods. After that, the establishment of a THA implant database was carried out, including 3D models of common THA socket cups, ball heads, liners, and femoral stems. As a result of these preparations, the intelligent segmentation of the acetabulum and femur, the automatic measurement of the corresponding anatomical parameters, the determination of the rotation center of the acetabulum and, finally, the intelligent measurement of the optimal type and implantation position of the acetabular and femoral implants can be realized.Clinical validation results showed that the AIHIP system effectively predicted the actual prosthesis model needed, and the matching rate of preoperatively planned implants was significantly higher than that of traditional measurement methods[16].

For TKA and UKA surgery, the Chinese PLA General Hospital used an AI-based 3D planning system for the first time in 2020 for preoperative planning. The system used can accurately segment bones based on the patient's preoperative CT images using a pixel-level segmentation network and edge-smoothing techniques based on recurrent neural networks. Mechanical motion simulation and a neural network incorporating the attention mechanism were used to efficiently identify key anatomical points of the skeleton, resulting in near-millimeter accuracy and high robustness. Moreover, in terms of prosthesis placement, the system combined supervised learning and unsupervised learning based on reinforcement learning to calculate the optimal angle of prosthesis implantation and personalize the patient's three-dimensional preoperative planning[17].

A 2023 study by Salman *et al.* analyzed the reliability of AI in predicting sizes and types for THA. They reviewed a total of nine different AI algorithms reported between 2021 and 2022. Among these AI models, the accuracy of TKA femoral implant size prediction ranged from 88.3% to 99.7%, while the accuracy of tibial implant size prediction ranged from 90% to 99.9%, with neither deviating by more than one size, thereby exhibiting a satisfactory level of reliability in predicting TKA implant sizes[18].

## *B. AI IN PREOPERATIVE EVALUATION FOR REVISION ARTHROPLASTY*

Revision arthroplasty, a representative complex surgery in the field of orthopedics, is performed on patients who experience problems after arthroplasty. The surgical procedure of removing part or all of the artificial implant in the initial surgery and reimplanting a new artificial joint is prone to accidents, making this surgery technically and economically demanding[19]. In a survey of arthroplasty surgeons in 2012, approximately 88% of the respondents stated that identifying components of a failed implant took a significant amount of time[20]. It is therefore important to accurately identify the manufacturer and type of prosthesis during preoperative planning. However, it has been estimated that the current rate of surgeons failing to recognize prostheses preoperatively and intraoperatively is about 10% and 2%, respectively, which can lead to unpreparedness, thereby increasing operative time, perioperative morbidity, and overall healthcare costs[21]. AI techniques have therefore been proposed for preoperative evaluation of revision arthroplasty.

A study in 2020 by Yi *et al.* represented the first study attempting to detect TKA implants and identify UKA and TKA implants by developing a ResNet-18 architecture which achieved AUCs of 1 for both with optimal sensitivity and specificity of 100% each[22]. Later Karnuta *et al.* for the first time successfully recognized different makes and models of knee implants from plain radiographs by applying deep learning techniques. They randomly separated implant radiographs to gain three different datasets, including a training dataset with 550 images, a validation dataset with 68 images, and a testing dataset with 74 images. And online data augmentation was used to help the model recognize features that are strongly associated with each unique implant. Then an AI-based, deep learning CNN system based on the InceptionV3 architecture was developed by training with all of the training images for a total of 1000 epochs with a variable learning rate decay algorithm. In this research, they managed to discriminate between nine unique knee arthroplasty implants from four manufacturers with near-perfect accuracy. And since this algorithm is iterative and self-updating, only a minimum of 10 radiographs of another implant design are needed for the algorithm to successfully discriminate[23]. Similarly, in hip arthroplasty, Karnuta *et al.* also succeeded in recognizing THA implants from plain radiographs based on deep learning algorithms[24].

A recent study summarized and analyzed 20 studies with three main use cases that applied AI to preoperative planning for revision arthroplasty from 2000 to this year. Sixteen of these studies analyzed implant identification, two addressed implant failure, and two analyzed implant measurement. In all of these use cases, AI algorithms had the ability to demonstrate high accuracy, positive predictive power, sensitivity, and specificity. In addition, the median AUC and accuracy for each use case exceeded 0.90 and 90%, respectively. Some studies were also able to demonstrate that these AI algorithms could outperform human experts. However, a significant limitation noted by approximately all studies was the limited radiographic dataset size, such as the lack of high-quality radiographs of different imaging locations for different types of implants, adversely affecting the performance of AI algorithms[25].

# Ⅲ. AI IN SPINE SURGICAL ROBOTS

Screw placement in posterior route pedicle is a common technique used in spine surgery at present. AI can help set the screw by capturing the images and planning the entry point and the entry direction[26]. Compared with traditional hand-to-hand screw placement technology, surgical robot-assisted screwing technique can place the screws more precisely, reduce the X-ray exposure both for the operator and for the patient and shorten the operation time[27]. Surgical robot-assisted screwing techniques are also a less time-consuming technology than 3D printing guide plate auxiliary screw placement technology, making it applicable to emergency department[28]. In a recent randomized controlled test including systematic evaluation and meta-analysis, TiRobot, SpineAssist and Renaissance robotic systems respectively achieve better, worse and similar pedicle screw placement accuracy comparing with traditional hand-to-hand screw placement technology[29]. At present, the foreign mainstream spine surgery robot systems are SpineAssist, Renaissance, Mazor X and ROSA, while internal mainstream spine surgery robot systems are TianJi II spine surgery robot jointly developed by Beijing Jishuitan Hospital and Tianzhihang Company, ORTHBOT and ZuoHang 300 spine surgery robot[30]. Markerless robotic pedicle screw placement based on structured light tracking is also being studied. Comparing with the mainstream technology, artificial intelligence can compare the images obtained by the structured light scan with those obtained by the CT scan and generate the motion command directly according to the relative position after algorithm analysis. There is no need to establish the spatial relationship between surgical tools and surgical paths through optical markers to plan the surgical path. This method is still in the in vitro mold test stage, and it is reported that the average position error of the entry point and the average angular error are smaller than normal surgical robot-assisted screwing technique[31]. ML technology and DL technology are not fully adopted in spine surgery robot in clinical practice, but the surgical planning system and intraoperative monitoring system based on machine learning and deep learning have made progress.

The high similarity among the cervical vertebrae may disturb the automatic planning from spine surgery robot. Zhang and Wang proposed a novel method for cervical vertebrae segmentation based on PointNet++ neural network structure. This method has better robustness on cervical vertebrae image segmentation and it can segment 3D image of cervical vertebrae effectively, helping to improve the ability of automatic cervical spondylosis treatment. 300 cases of CT images from different patients are used to train and test the segmentation model, making the segmentation accuracy up to 96.15%[32]. For the adult spinal deformity, Lafage *et al.* proposed a deep learning model, aiming to simulate the location planning of upper instrumented vertebra from different doctors and ensure the consistency of the upper instrumented vertebra location selection. Machine learning provides an effective method for the prediction, diagnosis and prognosis of cervical spondylotic myelopathy[33]. Hopkins *et al.* proposed two different neural network models, realizing the diagnosis of cervical spondylotic myelopathy and the prediction of cervical spondylotic myelopathy severity respectively. The experimental results can prove the feasibility of machine learning in diagnosing and predicting spinal diseases. With the rapid development of endoscopic therapy, endoscopy will be the option for all spinal diseases in traditional hand-to-hand surgery[34]. Cho *et al*. conducted a primary study on the intelligent vision of robotic endoscopy and proposed to apply robotic technology and deep learning technology to endoscopic surgery. Target detection algorithms based on RetinaNet and YOLOv2 are used to realize automatic detection of the tip of the instrument during endoscopic surgery[35].

# Ⅳ. AI IN TRAUMA SURGICAL ROBOTS

In trauma orthopedic surgery, the accuracy and stability of fracture reduction are the key to the prognosis for patients. Trauma surgical robots can realize the positioning function, which is similar to joint surgical robots and spine surgical robots[2]. The stability and accuracy of fracture positioning help to maintain a good reduction of the fracture. In traditional hand-to-hand surgery on fracture reduction, the surgeon should be experienced to reset the fracture site and internal fixation through fluoroscopy. Robotic-assisted fracture reduction aims to achieve anatomical reduction with larger operation space, simpler operation, smaller secondary trauma, higher precision and higher safety[30]. In a study by HE *et al.*, 60 cases of patients with femoral neck fracture were treated with robot-assisted navigation system and traditional hand-to-hand surgery respectively. It was found that the robot-assisted group could significantly reduce the intraoperative fluoroscopy time, drilling times and operation time. The screws placed by the robot were better than the ones placed hand-to-hand in parallelism and dispersion[36]. Currently, the orthopedic surgical robots for trauma include the fracture reduction robot system developed by Hannover University in Germany, the fracture reduction robot system developed by Tokyo University in Japan and the trauma orthopedic surgical robot developed by Beijing Rosenbert Technology Company[30]. Comparing with the joint surgery robot and the spine surgical robot, the development of the trauma orthopedic surgery robot is slower. The various types of fracture surgery and the complex surgical requirements on trauma orthopedic surgical robots lead to the difficulty of clinical application. Although the existing orthopedic trauma surgery robot technology is still far away from clinical application, AI technology has been used to improve the ability of orthopedic trauma surgery. An accurate, intelligent and personalized robot for traumatic surgery is around the corner.

According to optimal classification tree, a machine learning method, Bertsimas *et al.* constructed a decision model for clinical use to predict cervical spine injuries among children. This model has a sensitivity of 93.3% and a specificity of 82.3% on the existing dataset. Compared with other ML methods or existing clinical decision rules, it has better performance and greater potential for clinical application[37]. Yabu *et al.* detected the osteoporotic vertebral fracture through the combined models of nine CNNs and finally obtained the optimal model combinations, including VGG16, VGG19, DenseNet201 and ResNet50. The area under the curve of the receiver operating characteristic was 0.949. The results show that the accuracy of the CNN-based diagnostic model is comparable to the spine surgeons, thus promising to improve clinical efficiency[38].

# Ⅴ. OUTLOOK AND CONCLUSION

Though the application of AI in medical treatment is mainly reflected in intelligent diagnosis, treatment and prognosis of diseases based on traditional ML or DL, it is less used in orthopedic surgical robots. The AIHIP system is the only orthopedic surgical robot that fully realizes clinical-use AI. Currently, joint surgical robots and spine surgical robots have achieved clinical applications while trauma surgical robots haven’t, representing a great gap between the existing orthopedic surgical robots and clinical applications, especially for trauma surgical robots. In addition, the high cost is also a great problem for applying AI to the clinic.

At present, the orthopedic surgical robot system for clinical application has four problems in general: first, there are problems with consistency since preoperative planning mainly depends on the experience of the physician. Second, intraoperative matching and navigation mainly rely on the markers in the robot operation space, while the markers are less universal or even can cause additional trauma to the patients. Third, the surgical robot system fails to make up for the error from the system and the motion error from the patients. Finally, present human-computer interaction is lack of intelligence and efficiency.

ML and DL are the major branches of AI, which have made significant breakthroughs in recent years. They have been successfully applied to computer vision, natural language processing and other fields, demonstrating the ability to achieve intelligence and solve the above problems. In the future, AI technology will become a very strong helper in accelerating the clinical application of orthopedic surgical robots and promoting the development of intelligent, safe, accurate and personalized treatments of orthopedic diseases.

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