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Intelligent acupuncture: data-driven revolution of traditional Chinese medicine

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Abstract

Acupuncture, a form of traditional Chinese medicine with a history of 2,000 years in China, has gained wider acceptance worldwide as a complementary therapy. Studies have examined its effectiveness in various health conditions and it is commonly used alongside conventional medical treatments. With the development of artificial intelligence (AI) technology, new possibilities for improving the efficacy and precision of acupuncture have emerged. This study explored the combination of traditional acupuncture and AI technology from three perspectives: acupuncture diagnosis, prescription, and treatment evaluation. The study aimed to provide cutting-edge direction and theoretical assistance for the development of an acupuncture robot.

Keywords: Acupuncture, Artificial intelligence, Knowledge graph

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Introduction

As a traditional Chinese medicine (TCM) therapy, acupuncture is simple to perform – by penetrating the skin with a fine metal needle – and has gone through prosperity and declines in its long history[1]. TCM is an intangible cultural heritage. Its complex theories connect nature to the human body, making it a vast database. TCM has established numerous links between diverse elements including the physiological state of the human body, medicine, and its indications. Owing to this complexity, the human brain cannot remember and utilize all connections with perfect precision. The emergence of artificial intelligence (AI) has the potential to significantly impact and advance the development of TCM, as seen in the groundbreaking research and applications of network pharmacology that utilize AI techniques. Presently, in the realm of network pharmacology analysis, techniques such as machine-learning and its subsidiary, deep learning, are utilized, thereby facilitating a more comprehensive comprehension of the intricate correlation between drug molecules and multiple targets or proteins[2]. The emergence of data-driven technologies that provide a foundation for AI systems has led to significant changes in the field of medicine, which is particularly evident in the field of acupuncture. The integration of AI and acupuncture represents an innovative approach to ancient medicine. AI technologies have been employed to position-specific acupoints and provide prescriptions. Personalized healthcare, early disease detection, and disease progression detection can be implemented using AI systems[3]. Integrative approaches combining AI and precision medicine have demonstrated promise for the personalized treatment of existing diseases[4], illness prediction[5], and evaluation of treatment response[6]. The emerging field of AI-assisted acupuncture seeks to enhance therapeutic outcomes by increasing the precision and effectiveness of acupuncture treatment. In this study, we conducted a systematic search for hundreds of reference studies from 2018 to 2023 using keywords such as acupuncture, AI, acupoint selection, acupoint diagnosis, and acupuncture efficacy. The literature was sourced from various databases, including PubMed, Web of Science, ScienceDirect, SciFinder, IEEE Xplore, and CNKI. By extensively researching and reviewing cutting-edge literature and technologies, this article discusses the current research and potential applications of AI in acupuncture practice, as shown in Figure 1.

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Bridging east and west: advancements in acupuncture diagnosis *via* AI

Acupoint diagnosis: a TCM method

Acupoint diagnosis, also known as meridian diagnosis, is a diagnostic method in acupuncture that utilizes the

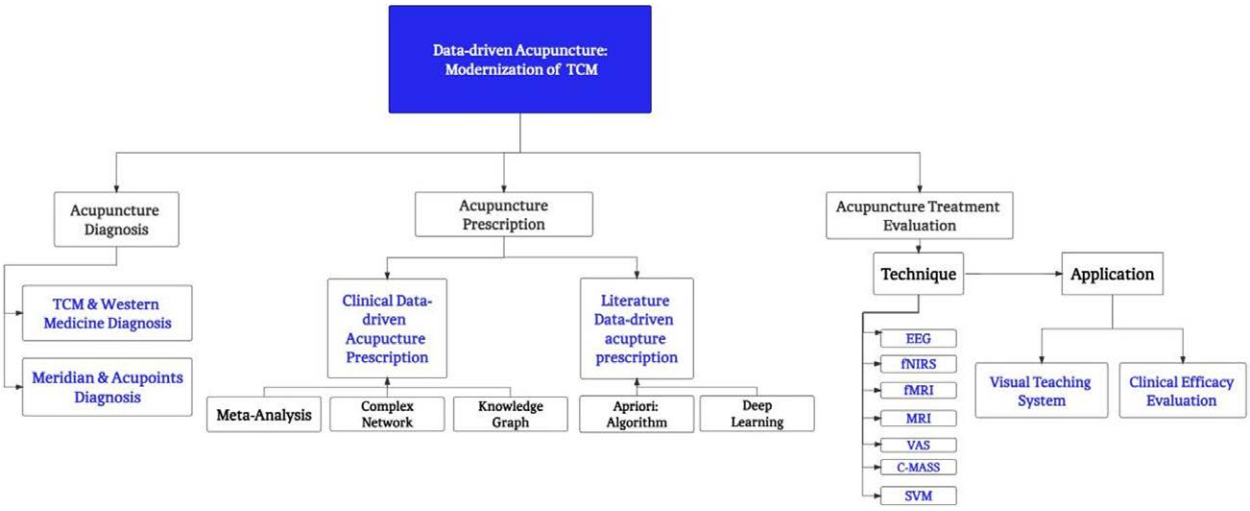

Figure 1. Data-driven acupuncture: modernization of TCM. C-MASS: Massachusetts General Hospital Acupuncture Sensation Scale; fMRI: Functional magnetic resonance imaging; fNIRS: Functional near-infrared spectroscopy; MRI: Magnetic resonance imaging; SVM: Support vector machine; TCM: Traditional Chinese medicine; VAS, visual analog scale.

acupoint sensitization theory. This theory includes the electrical characteristics of acupoints, thermal effects of meridians, electromagnetic waves of meridians, and the microcirculatory characteristics of meridians. According to the TCM acupoint sensitization theory, an acupoint represents a dynamic functional region that manifests the internal state of the body. When the body experiences illness or injury, related acupoints are activated[7] and exhibit different forms of sensitization, such as receptive field expansion, pain sensitivity, and heat sensitivity. These symptoms diminish as the patient recuperates from the illness[8]. Acupoint electrosensitivity is the most commonly used diagnostic method because of its sensitivity, objectivity, and convenience. Voll, Nakatoni, and Niboyet pioneered the work on the electrical characteristics of acupoints, particularly their bio-resistance traits[9]. Typically, the detection criteria for acupoint electrosensitivity include resistance, capacitance, electric potential, electric current, electric charge, and conductance. Detectable electrosensitive points may incorporate meridian points, auricular points, and extraordinary points[10]. The specificity of an acupoint is related to its electrical properties, particularly its bio-resistance[11]. Kovich showed that acupoints associated with the stomach[12] and lung[13] meridians reflected the function of the corresponding organs by measuring the impedance of the acupoints.

AI holds promise for enhancing acupoint diagnosis in several ways. First, AI algorithms can scrutinize large-scale datasets encompassing patient information, including symptoms, medical histories, and treatment outcomes, thereby enabling the identification of patterns and associations. This analytical process can help identify pertinent acupoints under specific conditions. Moreover, AI can support the classification and clustering of acupoints based on their therapeutic effects, thereby aiding acupuncturists in making informed decisions when selecting the most suitable points for treatment. Furthermore, AI can offer real-time feedback during acupuncture sessions by monitoring physiological signals such as heart rate and skin conductivity and subsequently adjusting treatment parameters accordingly. To synthesize empirical knowledge and theories, AI effectively deploys diverse techniques, including machine-learning and natural language processing. Machine-learning algorithms can scrutinize extensive volumes of acupuncture-related literature, including classical texts and research papers, to extract valuable information and discern the relationships between acupoints, meridians, and health conditions. The application of natural language processing techniques facilitates the extraction and organization of information from textual sources, thereby enabling the integration of diverse knowledge sources. AI has acquired and advanced acupoint theories through extensive data processing to identify meaningful patterns. By analyzing clinical data and treatment outcomes, AI algorithms can reveal the associations between specific acupoints and their effectiveness in addressing particular conditions. Moreover, AI can generate hypotheses and predictions based on these findings, paving the way for further exploration and validation in clinical trials and empirical studies. This iterative learning process empowers AI to continuously refine and enhance its comprehension of acupoint theory. However, challenges arise when attempting to replicate the subjective and experience-based aspects of a traditional AI diagnosis. These aspects often rely on the practitioner's intuition, tactile examination, and the nuanced interpretation of patient feedback, making it difficult to quantify and replicate them using AI algorithms. While AI can effectively analyze objective data, such as symptoms and medical records, it may not be able to capture the subtle nuances and individualized characteristics inherent in traditional diagnosis. To address this issue, efforts are underway to develop AI models capable of integrating qualitative and subjective data. For instance, researchers are exploring machine-learning algorithms that can interpret and analyze patient narratives or practitioner notes, enabling the incorporation of qualitative diagnostic aspects. Moreover, advancements in sensor technology and wearable devices have enabled the collection of more nuanced physiological data during acupuncture sessions, enriching AI analysis with additional insights. It is essential to acknowledge that AI is not intended to supplement the

expertise and experience of acupuncturists but rather to augment their knowledge and decision-making processes by providing additional tools and insights for more effective and personalized treatments.

Several AI applications have assisted in the detection and status assessment of acupoints. Xu used a cloud-TCM-PC acupoint detector to test the electric impedance on 12 Yuan points of 194 people and found variations in electric impedance on relevant acupoints and relationships between acupoints and body health state[14]. Li used an Agilent digital multimeter to detect changes in the electric impedance of acupoints during needle retention by ordinary acupuncture needles and insulated needles, as well as the resistances of acupoints and non-acupoints[15]. Chen et al.[16] used a CL-1024A acupoint detector to investigate the differences between patients with Bell's facial paralysis and normal individuals, as well as the relationship between the dynamic changes in the electric impedance characteristics of acupoints and the pathological state of patients with Bell facial paralysis during different periods and TCM syndromes. Yang and Zhou employed an NQ-1B conductivity meter to assess the electrical impedance on pertinent acupoints of 30 individuals with sound health across various time intervals throughout the day. The study revealed a discernible fluctuation in the electrical impedance of the subjects[17]. Hua et al.[18] used a JXT2008 acupoint detector to test the difference in the electric impedance of acupoints between healthy individuals and patients with breast cancer. The integration of acupuncture and AI is still in its preliminary stages as the intelligence of many technologies has not yet been completed. Researchers and practitioners are exploring the potential applications of AI in acupuncture diagnosis. Recently, researchers have actively explored the utility of AI in synthesizing empirical knowledge accumulated in TCM from ancient times to the present day. This study aimed to develop a powerful and efficient meridian diagnosis system that could significantly improve current acupuncture treatments.

Synergizing diagnostic approaches: integrating TCM and Western medicine in acupuncture diagnosis

Acupuncturists can provide more effective and comprehensive healthcare by considering both TCM and Western medicine diagnostic results during acupuncture therapy. Below are some examples of how AI helps researchers identify the characteristics of the tongue, pulse, and state of patients. Dong et al. employed a TCM facial digital detection device to gather and examine the color characteristics of patients faces across diagnoses of coronary heart disease, chronic kidney failure, and chronic hepatitis B. The results uncovered notable disparities in facial color indices between the three disease states[19]. Zhang et al.[20] utilized a DS01-B tongue imaging device to collect tongue color data from 273 patients with non-traumatic osteonecrosis of the femoral head. Frequency and cluster analyses were then conducted on the acquired information to examine patterns in the data distribution. The research determined that tongue color indices displayed distinct features corresponding to different Association Research Circulation Osseous staging classifications[20]. Allwood et al. provided a survey of the progress made in applying AI techniques for the identification and analysis of abnormally heightened bowel sounds[21]. Lin et al.[22] employed an electronic nose device to accurately determine the odor profiles of individuals with type 2 diabetes compared to healthy subjects. This research was grounded in the fundamental operating principles of e-nose technology. Jin developed a portable three-position pulse measurement system suitable for both home healthcare needs and experimental research purposes. Remote pulse diagnosis systems for TCM have increasingly become available in recent years[23].

Customized therapy as dictated by syndrome differentiation in TCM incorporates the personalized healthcare principle, comparable to precision medicine - the approach espoused in Western medical traditions. Automatic quantitative diagnosis has emerged as a compelling area of interest[24], with AI combined with TCM diagnosis to understand the distribution features of syndromes in diseases[25], examine the correlation between clinical symptoms and syndrome elements[26], and simulate pathogenesis diagnosis[27]. For example, Zhang et al.[28] introduced an expert system designed to provide assistance in the diagnosis of a wide range of 187 common TCM diseases and their associated syndromes. The system demonstrated high accuracies in predicting the top three and top five disease types were 80.5%, 91.6%, and 94.2%, respectively, demonstrating a high level of diagnostic precision. Acupuncture, along with TCM and Western medicine diagnostic methods, is a more effective treatment for patients. Physiological signals, such as respiratory, electrocardiographic, and pulse wave signals, inform individuals of the most opportune time to receive acupuncture. A system was devised to record these signals and control the acupuncture device for targeted therapy. These physiological signals are used in the diagnosis of human body imbalances or diseases, drawing upon findings from modern medical science and TCM's eight-principle differentiation, defense-qi nutrient differentiation, organ visceral differentiation, six-meridian differentiation, qi blood body fluid differentiation, and triple-warmer differentiation diagnostic approaches[29]. Wang et al.[30] set up an auxiliary acupuncture system that analyzes the patient's symptoms of illness and determines a series of combinations of acupoints with a therapeutic effect, allowing the acupuncturist to treat patients with different acupoint prescriptions. Medical imaging techniques provide valuable supplemental support for TCM practitioners in the diagnosis of transient ischemic attacks. Medical imaging in TCM focuses primarily on identifying categories, assessing the effectiveness of TCM treatments, and integrating TCM with Western medicine[31]. These developments demonstrate that TCM is progressive in nature, satisfies modern diagnostic and therapeutic demands, and has yielded favorable outcomes in clinical studies and applications[32–33].

To develop an acupuncture application that integrates diagnostic information from TCM and Western medicine, the potential complementarity between TCM and Western medical principles must be identified by carefully analyzing the underlying theories and principles of both approaches. Collaboration with experts in both fields is essential to ensure that the application is grounded in rigorous evidence-based practices that meet the needs

of patients and healthcare professionals. Moreover, for both TCM and Western medicine, appropriate diagnostic criteria and tools are selected based on accuracy, reliability, validity, and practicality. Customized algorithms should be developed to allow users to input data from both sets of diagnostic tests to generate an accurate and comprehensive diagnosis. Subsequently, validation and testing, including usability testing, clinical trials, and case studies, are necessary. Ongoing maintenance and upgrades are required to ensure that this application remains effective as new diagnostic technologies and treatments emerge. In conclusion, TCM and Western medicine diagnoses are based on syndrome and disease differentiation, respectively. By combining diagnostic information from both approaches, patients can receive appropriate and efficient treatment for both syndromes and diseases[34].

Data-driven acupuncture prescription: from evidence to practice

Technologies applied in acupuncture prescription

Several technologies are involved in the development of precision acupuncture prescriptions that leverage AI techniques, leading to enhanced treatment efficacy and improved decision-making capabilities for acupuncturists[35]. This is illustrated in Figure 2. Data mining technology, a crucial component of the AI process, is based on machine-learning, statistics, visualization, and other methods. It applies clustering analysis[36], correlation analysis[37], Bayesian networks[38], complex networks, artificial neural networks, and random forest analysis algorithms to reveal previously obscure structures and relationships underlying acupuncture treatment, yielding nuanced and incisive insights into this therapeutic modality[39]. Data preparation is the first step to realizing data mining. To facilitate data mining, researchers have initiated the digitization of standard acupuncture texts, medical literature detailing diagnosis and treatment experiences, and physiological mechanisms. These efforts aimed to establish a comprehensive database for streamlined data preparation and analysis[40]. Data analysis is the second step of data mining. By leveraging data mining technologies, acupuncture prescriptions that leverage AI techniques can be trained using established databases to achieve an acupoint selection mindset that approximates human thought processes, offering targeted and superior healthcare recommendations.

Modular data mining techniques can be used to investigate the regularity of acupoint treatment for commonly encountered diseases[41]. A meta-analysis is a statistical method used to synthesize research results for specific conditions and subjects. This technique has been used to identify the main acupoint combination for Alzheimer disease management. As a statistical method, meta-analysis can provide valuable insights into data-driven acupuncture prescriptions by synthesizing the results of multiple studies, identifying consistent patterns in the effectiveness of different acupoints, and identifying potential factors that may influence treatment outcomes. The Apriori algorithm, a data mining technique utilized for the extraction of frequent patterns from datasets, has broad applications in multiple areas, including business and medicine[42]. Identifying frequent itemsets and association rules enables AI systems to uncover meaningful patterns and correlations in transactional data. An example of this is the application of the Apriori algorithm to distinguish key acupoint combinations and association rules for treating chronic obstructive pulmonary disease through acupuncture[43]. The Apriori algorithm can assist in acupoint selection

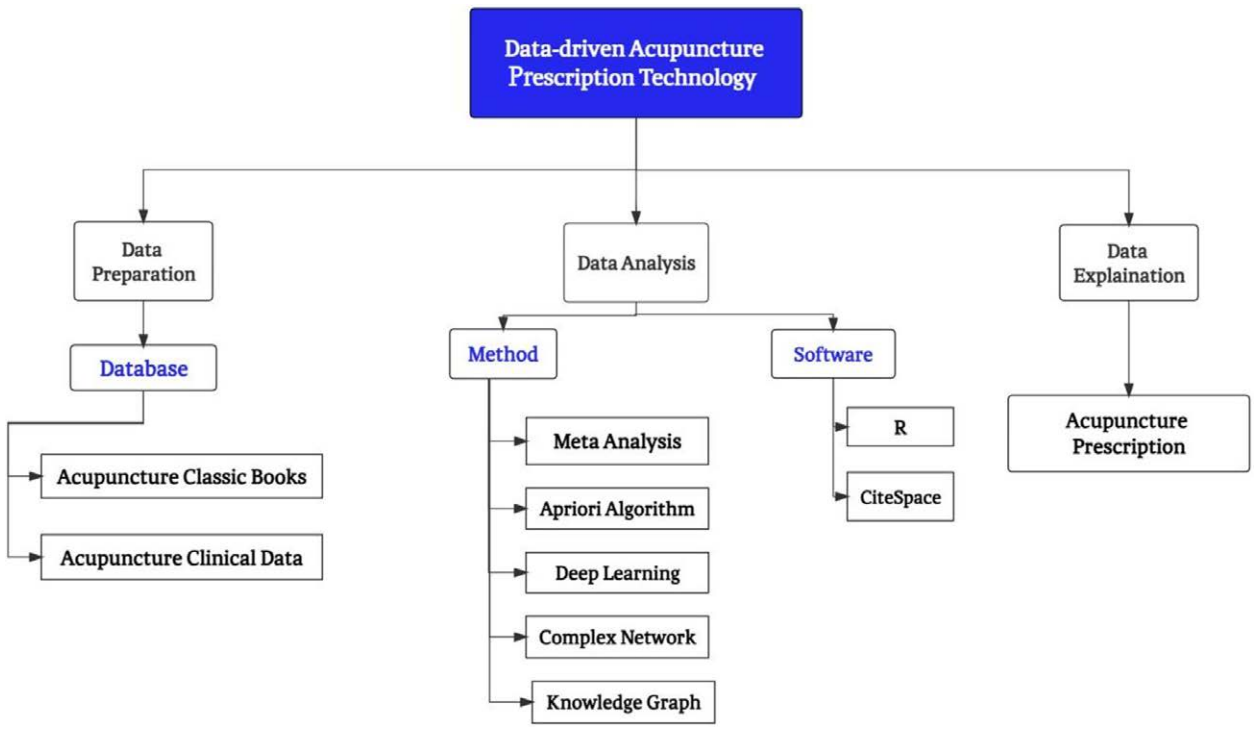

Figure 2. Data-driven acupuncture prescription technologies.

by analyzing large datasets and identifying frequent patterns in syndromes and treatment strategies. This can assist practitioners in identifying potential correlations between syndromes and acupoints, leading to more accurate diagnoses and effective treatment outcomes. Deep learning is another powerful tool within the broader field of AI that can discover the combination rules and pharmacodynamic characteristics of TCM[44]. It helps doctors stratify patient risks[45], examine histopathological images[46], and improve their understanding of diseases[47]. It also aids in acupuncture prescriptions by analyzing vast amounts of medical information and finding patterns in the data to systematically diagnose and treat various health conditions systematically[48]. Complex network analysis technology refers to learning from the interactions of complex network nodes and is a useful tool for modeling AI systems and analyzing their performance. The application of this approach has been extended to the investigation of optimal acupoints and their combinations for the treatment of chemotherapy-induced peripheral neuropathy[49]. This technology can be used to study the mechanism of acupoint selection and build a syndrome–acupoint network by analyzing correlations, core acupoint nodes, and compatibility relationships. Link prediction is a fundamental aspect of studying complex networks because it allows us to uncover implicit rules governing the connections between nodes in a graph. The underlying concepts and methodologies of this research stem from both Markov chains and machine-learning techniques. This approach has found extensive applications in various domains, including disease, drug, and social networks. By reframing the assessment of nodal connections within a network as probabilities of link formation between nodes, link prediction provides a novel viewpoint on analyzing compatibility between acupoints. Qiu's study involved constructing a weighted complex network representing real acupuncture prescriptions for cervical spondylosis that accounted for acupoint attributes. Multiple feature types were extracted based on the network's weighted connections. To gain deeper understanding and identify acupoint compatibility patterns, these features were input into a supervised learning model for training and prediction. The impacts of different features and models on predictive performance were also compared[50]. Moreover, knowledge graph technology can be used to explore and analyze data mining results. Data mining involves extracting insights and information from vast data collections, whereas knowledge graph technology visually illustrates the domains of knowledge and their interconnections. Knowledge graph technology can help visualize patterns and relationships discovered through data mining, making it easier to understand and make decisions based on the insights gained. Jiao et al.[51] employed knowledge graph technology to evaluate the existing research landscape surrounding acupuncture as a therapeutic intervention for chronic pain. This comprehensive analysis aimed to identify the current state of knowledge and outline potential avenues for future advancements in this field. Patients can receive more accurate and effective treatments based on comprehensive and up-to-date medical knowledge using knowledge graph technology to inform and improve acupuncture prescriptions. Additionally, many software packages serve as useful tools for data mining, such as CiteSpace and the R language. CiteSpace is a visualization tool commonly used in data mining that can perform a bibliometric analysis to explore the intellectual landscape and identify research trends and fronts in acupoint selection and acupuncture treatment[52]. By visually analyzing acupuncture research using CiteSpace, researchers can gain insights into the trends and progress in this field, which may inspire future research and clinical implementation. R language is an effective data mining tool that offers open-source, free, comprehensive, and user-friendly features. It integrates statistical analysis and graphic display and can analyze the law of acupoint selection, as well as the clinical effects of acupuncture on patient recovery[53]. R provides powerful statistical tools, visualization capabilities, and machine-learning algorithms that can help identify patterns and provide insights from acupoint selection data. This approach has the potential to enhance the accuracy and effectiveness of acupuncture by enabling acupuncturists to make data-driven decisions.

However, the syndrome differentiation and acupoint selection principles of acupuncture are vague and highly non-linear compared with the mathematical principles. Therefore, researchers must collect large-scale data for population cohort analyses and clinical verification. By transforming the difficult and obscure dialectical principles into semantic symbols that AI can understand[54], acupuncture becomes more objective and quantitative as technologies augmented by AI and acupoint selection are combined. In conclusion, the integration of AI and acupuncture holds great promise for significantly enhancing the accuracy of acupuncture prescriptions and treatment methods while contributing to the modernization of TCM[55].

Literature-based data-driven acupuncture prescription

Integrative approaches combining AI and cutting-edge technologies are used to generate optimal acupoint prescriptions for patients. This novel approach analyzed large volumes of medical data, including patient demographics, symptoms, and medical histories, to identify the most appropriate combination of acupuncture points. AI systems can offer comprehensive evaluations of patient-specific conditions by utilizing advanced data mining and machine-learning techniques, leading to more accurate and personalized acupuncture prescriptions with improved outcomes[56].

The literary archive of ancient TCM contains numerous books from various fields of acupuncture. These included valuable records of acupuncture prescriptions, monographs, numerous documents on acupuncture therapy techniques, and related research articles. The collective knowledge embedded within these ancient TCM works provides abundant insights into the fundamental principles, practices, and techniques that underlie acupuncture[57].

Advances in AI continue to emerge. Hence, an increasing tendency is to integrate knowledge into relevant technologies. For instance, algorithms that serve as tools for implementing AI have been applied to generate more

accurate and personalized acupuncture prescriptions. To achieve this, researchers have used large-scale datasets composed of both contemporary medical literature and historical TCM books, enabling the amalgamation of expert opinions from ancient and contemporary practitioners. Using the collected data, machine-learning models can be developed to discern underlying relationships between distinct patient characteristics and optimize the choice of acupoints, thereby improving therapeutic results for each individual patient situation. An important application of machine-learning to the study of ancient acupuncture involves data mining technology built around clustering and association rule algorithmic approaches. Based on these data mining techniques, researchers have mined important information such as the law of acupoint matching in acupuncture prescriptions, appropriate diseases for acupuncture, and the experience of famous and old TCM doctors in the clinical matching of acupoints. For example, information on acupuncture prescriptions in Chengdan's New Commentary on Shanghan Theory was extracted and it was found that some acupoints possessed greater compatibility for treating exogenous disorders[58]. To determine the prescription law of Dou Hanqing, researchers extracted acupuncture prescriptions from the Guide to Acupuncture Meridians[59]. Jang et al. performed a comparative analysis of acupuncture prescriptions for 14 diseases as documented in three seminal classical acupuncture textbooks: *Dongeuibogam*, *Saamdoinchimgooyogyeol*, and *Chimgoogyeongheombang*[60]. These textbooks describe unique acupuncture styles that significantly influenced clinicians during the relevant era. This study applied various machine-learning techniques, including hierarchical clustering, dimensionality reduction and visualization, network analysis, permutation tests, and random forest classifier contribution score calculation. Acupuncture prescriptions were grouped based on similarity using hierarchical clustering and an acupoint-score matrix. Acupoint and attribute score similarities were determined by calculating Euclidean distances. Multidimensional scaling visualized prescription differences using acupoint and attribute scores. Network analysis, which explores network structures using networks and graph theory, analyzed acupoint prescription network topologies. These networks were constructed based on acupoint score similarities. To quantitatively evaluate textbooks and diseases, statistical significance was calculated for mean acupoint score similarities under the null hypothesis. To determine each textbook's influence on acupoint selection, random forest classifiers were trained to classify original textbooks based on attribute scores, and feature importance was analyzed. Additionally, a Wilcoxon signed-rank test was conducted for each attribute score. The analysis revealed greater prescription diversity among textbooks than disease types.

However, additional research is needed to create an acupuncture-only prescription system that can be used in clinical practice using data from the entire area of acupuncture[61]. Taken together, the combination of traditional TCM literature and advanced AI technologies provides an invaluable resource for healthcare providers in their pursuit of efficient and effective acupuncture therapy.

Clinical data-driven acupuncture prescription

Precision acupuncture regimens incorporating AI methods have broad application in disease treatment and investigation of acupoint selection. AI can improve clinical efficacy by establishing thinking patterns in TCM. When combined with acupuncture knowledge, AI can efficiently handle large amounts of chaotic data and uncover hidden laws, patterns, and association rules that aid acupoint selection. Precision acupuncture prescriptions leveraging AI techniques are frequently used to select acupoints for a diverse range of illnesses, such as lower back pain[62], primary osteoporosis[63], and tic disorders[64], as depicted in Figure 3.

Clinical data are a fundamental element in the development of precision acupuncture prescriptions that leverage AI techniques. Acupuncture is a highly intricate and individualized medical procedure that encompasses several variables, including patient attributes, symptoms, and desired treatment outcomes. Therefore, AI requires ample clinical data to decipher patterns and correlations that can provide effective acupoints and combinations for treatment, and determine their fundamental rules[65]. For example, Lu et al.[66] investigated the correlation between acupoints and diseases in the treatment of simple obesity using a meta-analysis of 11 randomized controlled trials. Another trial was conducted to study the acupuncture prescription laws for cervical spondylosis by collecting clinical data from 60 patients[67]. Pattern identification (PI) is a crucial diagnostic approach in TCM, enabling the selection of personalized and suitable acupoints for individual patients. The development of a reliable and reproducible PI model using clinical information is of utmost importance, as it would more accurately reflect real-world clinical practice and improve treatment effectiveness. In this context, Yang et al.[68] proposed a novel deep learning-based PI model involving feature extraction using a deep autoencoder and subsequent k-means clustering. In a cross-sectional study involving patients with sleep disturbances, this model underwent evaluation. To extract features, principal component analysis (PCA) and a deep autoencoder were utilized. The resulting features were then clustered using k-means clustering. To validate the internal clusters, the Calinski-Harabasz index, silhouette coefficient, and within-cluster sum of squares were employed. External cluster validation was conducted using scores obtained from the Pittsburgh Sleep Quality Index, Berlin questionnaire, Gastrointestinal Symptom Rating Scale, and Naranjo Adverse Drug Reaction Probability Scale (NQ). A comparison was made between the clustering performance of raw data and features extracted through PCA and a deep autoencoder. The deep autoencoder, with 16 nodes for the first and third hidden layers and two nodes for the second hidden layer, demonstrated the most effective feature extraction method for clustering. The model successfully differentiated three distinct PI types, determined as the optimal number of clusters using the elbow method. External cluster validation revealed that these three PI types were characterized by variations in sleep quality, dietary habits, and concurrent gastrointestinal symptoms. The proposed PI model holds potential for the development of AI-based clinical

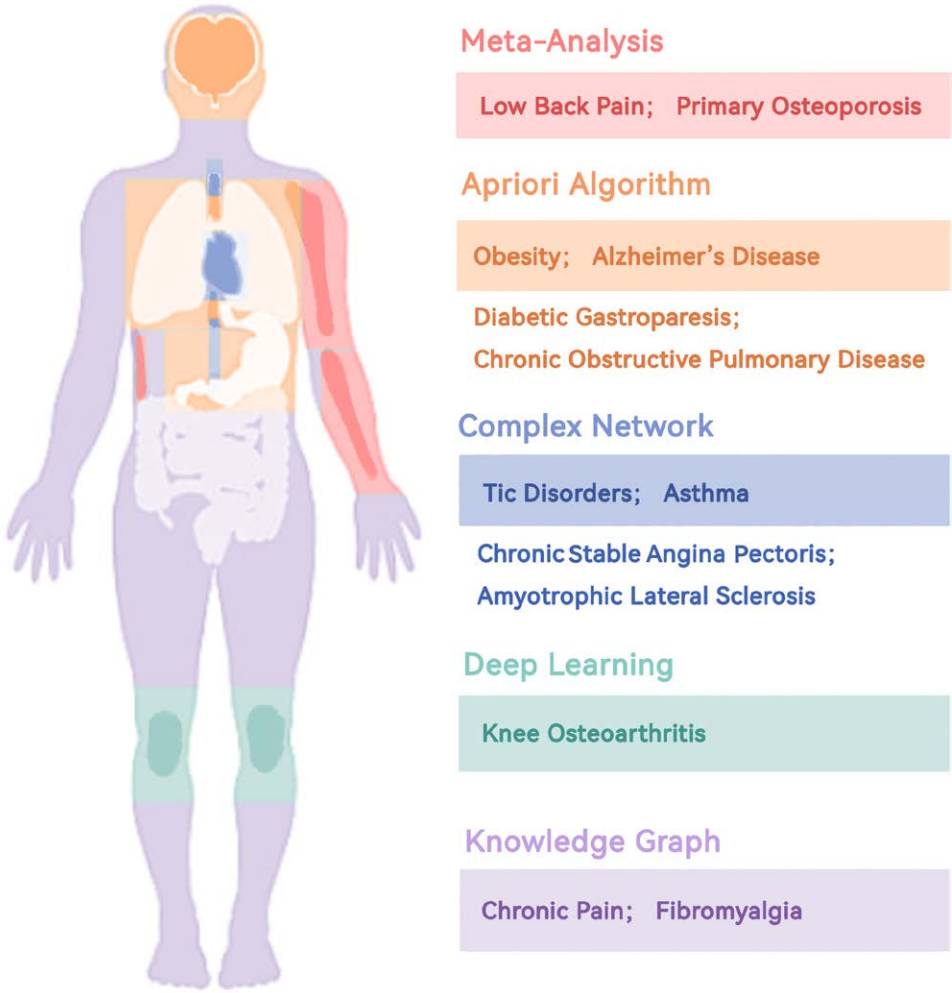

Figure 3. Data-driven acupuncture prescription for common diseases.

decision support systems, which can be integrated with electronic medical records and clinical trial protocols to evaluate treatment effectiveness.

Researchers have established mathematical models to analyze the acupoint-disease relationship, which provides a scientific way to statistically evaluate acupuncture and embodies the cross-integration of medicine, statistics, computers, and other disciplines. The use of precision acupuncture prescriptions leveraging AI techniques, backed by extensive clinical data, assists acupuncturists in comprehending the intricate patterns of syndromes and creating consistent diagnostic criteria for TCM. This approach facilitates the preservation, enhancement, and advancement of TCM diagnostic theories[69]. With the help of AI, accurate acupuncture prescriptions can significantly enhance the efficacy of treatment and improve the clinical outcomes of patients[70].

Precision acupuncture prescriptions leveraging AI techniques are still in their nascent stages as they involve the selection of specific treatment approaches, prescriptions, and medications based on dialectical analysis of individual patients' symptoms, which is a highly complex task. Moreover, this approach lacks systematicity and falls short of modern Western medicine[71]. The lack of standardization of AI acupuncture prescriptions refers to the absence of universally accepted guidelines or protocols for determining appropriate acupoints for specific conditions. TCM emphasizes individualized treatment based on the patient's unique syndrome presentation, encompassing signs, symptoms, and diagnostic factors. However, AI algorithms often rely on standardized datasets and generic disease-acupoint relationships, which may not fully capture the complexities of individual syndromes. Consequently, personalized treatment plans are lacking, which potentially leads to suboptimal outcomes. The differentiation of syndromes is a crucial stage in the application of acupuncture therapy, and precise differentiation is fundamental for the selection of acupoints. However, the definition of the acupuncture syndrome must be more precise. A syndrome, as conceptualized by TCM, involves a group of interconnected indications embodying the body's reaction to an illness together with the corresponding movements and transitions undergone[72]. The complex nature of the association between diseases and syndromes, characterized by a many-to-many relationship rather than a one-to-one relationship, presents a formidable obstacle for machines to perform syndrome differentiation[28]. Many current AI acupuncture systems primarily focus on disease-acupoint relationships rather than full syndrome differentiation. Syndrome differentiation is a vital aspect of TCM diagnosis in which the overall disharmony pattern within the body is identified and treated. This involves considering various factors such as the patient's constitution, emotional state, and

specific symptoms. However, AI algorithms often simplify patterns based on disease and overlook important nuances in syndrome differentiation. By solely emphasizing disease-acupoint relations, AI acupuncture systems may neglect the comprehensive and holistic approach of TCM. Most articles have focused on the relationship between disease and symptom acupoints rather than on detailed syndrome descriptions. In addition, objectivity, quantification, and standardization need to be improved for precise acupuncture prescriptions using AI techniques. A widely accepted framework for compiling acupuncture prescription data is yet to be established, leading to inconsistencies in the data collected by scholars and the construction of databases. These variances result in limited transferability and cross-database utilization. Patient acupoint selection is subject to the negative impacts of both artificial and subjective elements, leading to imprecise and incomplete treatment. Acupuncture specialists should use AI technology to digitize their acupoint-selection expertise and create a standardized database to solve existing problems. Addressing these issues requires the development of more sophisticated AI models that can integrate a wider range of factors for comprehensive syndrome differentiation. This could involve incorporating patient-specific information, including medical history, lifestyle, and emotional well-being, into AI analysis. Collaborative efforts between AI experts and experienced TCM practitioners are vital to ensure the development of AI algorithms based on a thorough understanding of TCM theory and practice. Furthermore, the establishment of standardized protocols for AI acupuncture is crucial. This entails the development of guidelines that consider individualized treatment based on syndrome differentiation, instead of relying solely on disease-based patterns. Such protocols should incorporate not only disease-specific acupoints but also additional acupoints that may be relevant based on the patient's overall syndrome presentation. By promoting standardization and individualization, AI acupuncture systems can better align with TCM principles and enhance treatment outcomes. This will assist in improving treatment by serving as a helpful adjunct tool that offers guidance and fresh perspectives for acupuncturists and scholars in the future[73]. Notably, AI should be regarded as a complementary tool to assist acupuncturists, rather than a replacement for their expertise. Integrating AI technology with the knowledge and experience of skilled practitioners can contribute to more effective and personalized acupuncture treatment.

Breakthrough in acupuncture treatment evaluation: leveraging AI for deeper insight

A new frontier in acupuncture manipulation analysis: the role of AI technology

AI is increasingly used in acupuncture to support clinical decision-making in diagnostics and treatment. A significant challenge in acupuncture treatment lies in the marked variation in the acupuncture manipulation techniques employed by different practitioners, which impedes the effective instruction of students in appropriate acupuncture manipulation. Currently, acupuncture manipulation can be evaluated accurately, and students' manipulation skills can be enhanced with the help of AI.

AI integration holds tremendous promise for refining the accuracy and efficacy of acupuncture manipulation, with the potential to bolster patient outcomes and drive innovation within the field of acupuncture research. TCM manual acupuncture measurement systems commonly cause disturbances and inconveniences in clinical practice as they are unable to precisely detect the tactile signals generated by the physician's finger during procedures. Polyvinylidene fluoride (PVDF) has shown promise for pressure sensing in biomedical devices due to its outstanding piezoelectric properties. However, for manual acupuncture involving delicate and sequential motions, a specialized PVDF film-based tactile sensor capable of picking up the piezoelectric signals from fingers at the conclusion of each movement in an action sequence has not been created. To bridge this gap, Su et al.[74] designed a multi-PVDF film-based tactile sensor to effectively capture the piezoelectric signals produced by physicians' fingers during manual acupuncture procedures. Su et al. also developed specific action modeling and recognition methods tailored for manual acupuncture. By considering the unique types of manual acupuncture techniques, Su et al. defined the capturing techniques for "Independent windows" and "Action windows" within a complete sequence of piezoelectric signal data associated with each acupuncture technique. Moreover, rules for feature extraction were established for an "Action window." Subsequently, using the features extracted from these captured "Action windows" an ensemble learning-based action recognition system for manual acupuncture techniques was developed. Finally, the study demonstrated the effectiveness and accuracy of both the tactile sensors and the manual acupuncture technique action recognition method by collecting piezoelectric signals from 15 physicians performing various manual acupuncture techniques.

In recent years, the field of clinical medicine has experienced a diversification of research methods, particularly due to advancements in machine-vision technology. Deep learning-based methods have been utilized for target detection, while depth map data containing depth of field information have been employed to accurately determine the position of the human body. To meet the demands of high-performance embedded vision systems, field-programmable gate arrays, known as high-performance programmable logic devices, have emerged as convenient solutions. These devices can be easily reprogrammed to modify internal logic functions, enabling fast hardware calculations and parallel operations. Manual acupuncture (MA) is a widely utilized therapeutic technique in which acupuncturists' selection of stimulation parameters, such as needling amplitude and frequency, significantly affect treatment outcomes and clinical safety. However, these stimulation parameters in clinical settings lack convenient measurement solutions. Consequently, the development of a real-time monitoring system for MA operations, based on a single camera, is urgently needed. To tackle this challenge, Xu et al.[75] proposed an adaptive orientation-based domain adaptation framework that effectively addresses domain shifts and achieves improved performance. In addition, Xu et al. curated a benchmark dataset comprising 20 videos of

on-body MA operations and 30 videos of on-simulator MA operations, each accompanied by corresponding 3D coordinates. This benchmark dataset serves as a valuable resource for future developments in real-time MA monitoring. Extensive experiments conducted on this dataset demonstrate the superiority of the proposed method in accurately estimating both the movement and frequency parameters of hand acupuncture. The application prospects of this framework in clinical MA work are promising, including investigating the dose–effect relationship of MA and enhancing the safety of MA operations.

One other machine-learning approach involves the self-organizing feature map (SOM), an unsupervised artificial neural network developed by Kohonen as a form of competitive learning model. Self-organizing feature maps have been widely used in various fields, including data visualization, pattern recognition, clustering, and data mining. It is particularly useful for exploratory data analysis, dimensionality reduction, and discovering meaningful representations of complex data. SOM has multiple applications in the analysis of acupuncture manipulation and related data. They can be used for pattern recognition by training on datasets containing information about different acupuncture techniques and manipulations, enabling the network to identify the distinctive features of effective techniques. Additionally, SOM can simplify complex acupuncture data by visualizing them in a lower-dimensional grid, thereby facilitating the identification of relationships, clusters, and patterns that may not be immediately apparent. These applications offer valuable insights for practitioners and contribute to the understanding of acupuncture practice. Tang et al.[76] conducted an analysis using SOM to examine the manipulation parameters of instructors obtained from a Simi Motion 3D moving image analysis system in Germany. This study aimed to classify and characterize acupuncture manipulations based on these parameters. This technique holds the potential for quantitative analysis and the study of technical inheritance in various acupuncture manipulations.

The intelligent location of acupoints based on machine-vision has garnered significant attention in the field of acupuncture. The emerging field of intelligent diagnostic and treatment equipment for acupuncture shows great potential. Researchers are leveraging advanced image processing and machine-learning techniques to improve the accuracy and efficiency of acupoint detection and positioning. One notable algorithm used in this study is the convolutional neural network (CNN), a deep learning model renowned for its ability to recognize actions in various types of datasets[77]. In recent years, CNNs have seen a significant increase in efforts to develop deep learning architectures for the purpose of automatic feature learning. While traditional CNNs have mainly focused on tasks involving 2D images, such as image classification, advancements have been made to extend these architectures to 3D CNNs. This extension allows for the capture and learning of both spatial and temporal features from video sequences. In the field of human action recognition, optical flow features have become widely used as a way to represent dynamic information. Several CNN-based approaches have been proposed, including two-stream CNNs, three-stream CNNs, and pose-based CNNs (P-CNNs), which utilize optical flow features to enhance action recognition performance. Moreover, CNN-based frameworks that aim to automatically learn spatiotemporal features directly from raw RGB video sequences enables a more comprehensive understanding of the underlying visual data. In 2022, Masood and Qi[78] realized 3D localization of hand acupoints by applying RGB-D CNN fusion-based hand geometry and landmark points. CNNs are employed to automatically detect acupoints from images of the human body, thereby contributing to more precise acupoint localization and reducing human errors in manual identification. Another significant algorithm, the Mediapipe framework developed by Google, has also been adopted to facilitate the analysis of acupoints, offering a comprehensive set of pre-trained models and tools specifically designed for media processing tasks, including pose estimation, hand tracking, and facial recognition. By leveraging the pose estimation capabilities of Mediapipe, researchers can efficiently detect the coordinates of acupoints and streamline the acupoint-mapping process. In conclusion, ongoing studies on intelligent acupoint location using machine-vision and sophisticated algorithms such as CNN and Google's Mediapipe framework demonstrate the potential to revolutionize the field of acupuncture-related diagnosis and treatment equipment. The application of such cutting-edge technology holds great promise for enhancing the accuracy and efficiency of acupuncture therapy, ultimately benefiting patients and practitioners in the realm of TCM.

Acupuncture is a sophisticated procedure requiring extensive expertise and proficiency. The integration of AI technology has the potential to enhance acupuncture manipulation by providing practitioners with instantaneous sensory information through sensors and image-recognition technology. This innovation enables practitioners to optimize needle positioning and regulate needle depth, thereby ensuring optimal efficacy while minimizing the risk of adverse side effects. Furthermore, it is imperative to conduct further quantitative research on the diverse modes of acupuncture manipulation to improve acupuncture education and achieve higher levels of effectiveness.

A new era in acupuncture therapy: measuring efficacy with evaluations aided by technological advancements in AI

Recently, AI is being integrated into acupuncture diagnosis and prescription. In addition to detecting patient ailments, evaluating the efficacy of acupuncture treatment is integral to this process, as shown in Figure 4.

This study[79] explored the mechanism at play within a patient-acupuncturist dyad during acupuncture stimulation in a natural clinical setting. Researchers utilized functional near-infrared spectroscopy hyperscanning to concurrently map the neural activity of patient-acupuncturist pairs receiving either true or sham acupuncture treatments. Their findings indicated heightened interbrain neural synchronization between patients and acupuncturists, with an emphasis on the role of the prefrontal cortex in shaping dyadic interactions during acupuncture treatment. Research in this field has predominantly focused on utilizing modern techniques to gauge

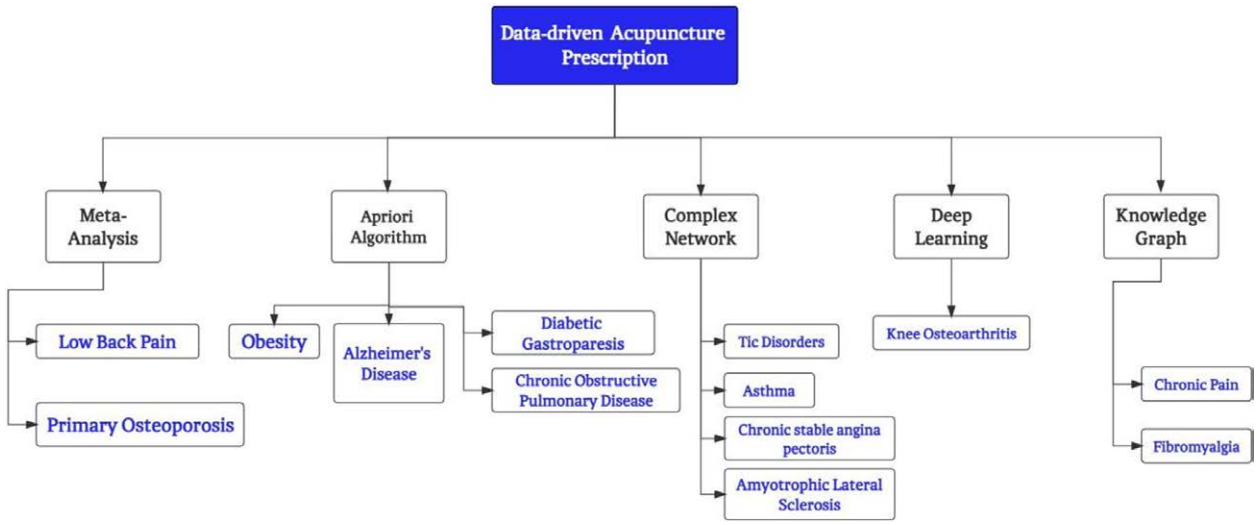

Figure 4. Technological advancements in AI to evaluate acupuncture treatment efficacy. AI: Artificial intelligence.

the effectiveness of acupuncture-based interventions for treating various common conditions. Many advanced technologies can provide valuable insights into the efficacy of acupuncture treatment, helping practitioners better understand its therapeutic effects and mechanisms of action (Figure 3). In its multifaceted nature, acupuncture therapy involves rousing diverse senses, namely visual and tactile sensations as well as feelings of embodiment.

During acupuncture treatment, imaging techniques can be employed to track the patients' physiological responses and deqi sensations such as electroencephalogram (EEG)[80], functional near-infrared spectroscopy (fNIRS)[81], and functional magnetic resonance imaging (fMRI)[82]. Recently, a combination of AI and imaging technologies has been used to evaluate the efficacy of acupuncture. This approach provides a powerful tool for analyzing and interpreting complex data generated by imaging technologies such as fMRI and fNIRS. Researchers can use an EEG device to collect visual data to assess the therapeutic efficacy of acupuncture because brain oscillation alteration is a crucial part of the neurophysiological mechanisms underlying acupuncture[83]. Recently, fNIRS has become a prevalent imaging technique in the field of neuroscience[84], owing to its high temporal resolution and ability to monitor patients in real-world clinical environments[85]. Thus far, it has attracted increasing attention in the field of acupuncture treatment[86]. fNIRS is also utilized to investigate the central mechanism of acupuncture reinforcing-reducing manipulation, which has been shown to elicit notable cerebral responses[87]. Due to its noninvasive nature, portability, affordability, wearability, and minimal contraindications, fNIRS can be used continuously and repeatedly in both natural and clinical settings. This makes it an essential tool for assessing the immediate therapeutic effects of acupuncture on patients[88]. Task-based fMRI is an essential approach for investigating the underlying mechanisms of acupuncture, as it can reveal both the immediate and long-lasting effects of acupuncture on the brain[89] and assess the hemodynamic blood oxygen level-dependent effects to assess its therapeutic effects[90]. Recently, significant research has been dedicated to exploring acupuncture treatments. For instance, fMRI offers a means of detecting changes in cerebral activity in patients with functional dyspepsia, enabling researchers to gauge the effectiveness of acupuncture as a treatment option[91]. The brain response to acupuncture stimulation can be investigated using fMRI to determine the differences in brain activity between verum and sham acupuncture[92]. fMRI is an innovative modality for evaluating brain activity elicited by acupuncture[82]. This technique contributes to the study of the functional connectivity network in the brain during acupuncture stimulation while also enabling the quantification of the effectiveness of acupuncture treatment[93]. In summary, imaging techniques have been used to objectively measure changes in blood flow, brain activity, and neural activity caused by acupuncture. These techniques also aid in visualizing the precise location of acupuncture points and the depth at which needles should be inserted, thereby lowering the risk of complications. Moreover, imaging technologies have elucidated the physiological mechanisms underlying acupuncture, including the release and accumulation of ATP[94]. Moreover, they can track treatment progress by comparing pre- and post-treatment scans, providing valuable feedback to both acupuncturists and patients. Imaging technologies have the ability to assess the effectiveness of acupuncture, especially when utilized alongside complementary therapies like physical therapy, massage, and herbal medicine. Overall, imaging technology is crucial in AI to evaluate the efficacy of acupuncture treatment. Through capitalizing on recent technological innovations, researchers now have the means to gain valuable new insights into the physiological processes influenced by acupuncture and devise enhanced, evidence-based treatment protocols informed by rigorous data analysis. The convergence of acupuncture and AI is currently in its nascent phase, with scholarly investigators and practitioners actively investigating prospective applications of AI within the realm of acupuncture. It is imperative to note that the maturation of numerous technological facets has not reached fruition, necessitating substantial groundwork that delves into the areas tangentially linked to AI.

In recent studies exploring the relationship between baseline clinical data and the effectiveness of acupuncture therapy, machine-learning models have become valuable resources. These models, including generalized linear models (GLMs) like logistic regression and multiple linear regression, have gained popularity due to their ability to predict the efficacy of acupuncture treatment and assist in identifying patients who are most likely to benefit from it[95]. As an example, Plunkett et al.[96] utilized logistic regression to identify predictors of positive treatment outcomes in patients with chronic pain who underwent acupuncture. The study found a correlation between higher baseline pain scores and improved efficacy. The implications of these findings are substantial, as they contribute to the development of evidence-based medical strategies and the implementation of personalized and precise treatments. However, responder screening methods based on the GLM are vulnerable to outliers and often over-simplify the complex relationships between features, leading to the disregard of implicit predictive features[97]. Support vector machines (SVMs) have gained widespread acceptance for efficacy prediction due to their exceptional performance and strong generalization capabilities, making them one of the most commonly used machine-learning algorithms in this context. As an illustration, Yin et al.[98] effectively developed a prediction model based on SVM, utilizing baseline functional neuroimaging features to forecast the effectiveness of acupuncture in patients with functional dyspepsia. In a study by Liu et al.[99], an SVM algorithm was employed to predict the outcomes of an 8-week sham acupuncture treatment in patients diagnosed with migraine without aura (MwoA). The AI model developed by Liu et al. achieved an impressive accuracy of 84.0% in forecasting treatment outcomes. MwoA, a chronic neurological disorder characterized by headaches, has been thoroughly investigated, and the SVM algorithm has emerged as the preferred choice for analysis[100]. SVM shows enhanced reliability, especially in studies with a smaller patient population, particularly those involving fewer than 200 individuals[101]. The results of this study underscore the potential of utilizing pre-treatment brain structures as predictors of acupuncture efficacy in patients with MwoA. In addition, recent research has investigated the use of a support vector machine (SVM) algorithm in conjunction with innovative biomarkers, such as high-throughput neuroimaging metrics, to forecast acupuncture efficacy, yielding promising results. In one such study, Tu et al.[102] applied the support vector regression algorithm to identify baseline functional brain connectivity patterns that could predict symptom improvement in individuals suffering from chronic low back pain. The findings demonstrated that SVM models developed using routine clinical data exhibit enhanced translational potential, offering valuable insights into personalized acupuncture treatments. Yu et al.[103] employed an SVM-based multivariate pattern analysis (MVPA) technique to predict the efficacy of acupuncture in patients diagnosed with primary dysmenorrhea. In predicting the changes in visual analog scale (VAS) scores after treatment, this model demonstrated a squared correlation of 0.27 ($P = 0.002$) and a mean absolute error (MAE) of 0.36. Additionally, it achieved a squared correlation of 0.30 ($P = 0.000,9$) and an MAE of 2.26 in predicting the rate of VAS change. As data accumulation continues, deep learning-based approaches, including CNNs, probabilistic neural networks, sparse representation-based CNN (SRCNN), and generative adversarial networks, hold significant promise for widespread future applications. These deep learning methods excel in automatically and effectively learning data features and have demonstrated the ability to generate realistic images. The continuous development and growing application of deep learning techniques hold tremendous promise to radically transform numerous domains in the years ahead. These models demonstrate the potential of acupuncturists to anticipate patient responses to acupuncture treatment, which can be adjusted and tailored accordingly. By being proactive rather than reactive, this approach may enhance the overall effect of acupuncture therapy, resulting in reduced clinical expenses. Various acupuncture manipulation determination equipment have been developed to automatically identify the acupuncturist's manipulation and enhance the measurability, objectification, and standardization of acupuncture treatment[104].

Overall, cutting-edge equipment offers an accurate and objective assessment of physiological reactions, enabling researchers to better understand the intricate physiological mechanisms underlying the curative activity of acupuncture. These technological advancements have guided clinical practice and enhanced patient outcomes.

Summaries and future perspectives

The application of data-driven technologies aided by AI techniques in acupuncture has the potential to transform the TCM industry by improving the dependability and precision of diagnoses, reducing human error and fatigue, and increasing access to successful therapeutic methods for patients. However, it should comprehensively combine modern technology while retaining and further developing its characteristics to promote objectivity, standardization, and traceability.

While integrative approaches combining AI and acupuncture offer potential advantages, several issues must be resolved, such as the lack of personalization due to the use of statistical data and machine-learning algorithms that may not accurately reflect each patient's requirements and preferences. To counter the prevailing lack of data standardization and strengthen the generalizability and interpretability of outcomes, strict research parameters must be instituted. Furthermore, AI cannot fully utilize the range of diagnostic and therapeutic skills required by trained acupuncturists, such as active listening, clinical observation, and communication. Further research and development of data-driven technologies aided by AI techniques that can account for individual variations and collaborate with human practitioners to provide personalized and effective treatment plans will be required.

Moreover, potential disputes and problems concerning AI intervention in acupuncture need to be addressed and resolved in detail in future research. First, the underlying logic of AI makes it look for statistical

correlations among massive events and predictions based on the correlations of events, which is the knowledge that AI has learned or the results of training. This means that the more cumulative the results of this kind are, the stronger the AI ability is. However, the limitations of AI lie in that it can look for correlations, but it cannot find the reason behind these strong correlations, and it cannot be fully sure of such correlations, only probabilities. Having no access to an unknown field and requiring high computing resources are other limitations of AI. Second, ethical aspects should not be ignored because AI cannot understand human emotions or identify various meanings due to cultural differences, which leads to a drawback in that it may not digitalize the patient's description with complete accuracy and compare it with information in the database, influencing the diagnosis and the operation of treatment. The lack of relevant laws and regulations also makes the relevant medical accountability system unable to improve construction, so acupuncture diagnosis and treatment involving AI are not recognized by the public and are blocked in universal implementation. Finally, relying too much on AI, but not practitioners, will cause several problems, among which the most probable one is the decline of practitioners' professionalism. Furthermore, the increasing dominance of AI in the diagnosis and treatment of acupuncture may potentially diminish the significance of manual acupuncture as an intangible cultural heritage.

The ability to appreciate AI strategies in the health sector and convert that appreciation into usable guidance for on-the-spot care is crucial for acupuncturists, as demonstrated by all of these considerations. Future studies could concentrate on areas that are developing, including bioinformatics, AI medical clouds, and visualization platforms. It is anticipated that acupuncture applications that leverage advanced AI methodologies will offer regular clinical diagnoses and treatment services in the future. While concerns exist regarding AI replacing human practitioners, researchers do not intend to do so because AI is intended to complement and enhance the skills of acupuncturists.

Conflicts of interest statement

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Author contributions

Yunfan Bao did the analysis and wrote the original draft. Haokang Ding wrote, review and edited the manuscript. Zhihan Zhang did the visualization. Kunhuan Yang, Queena Tran and Qi Sun wrote, review and editing the manuscript. Tiancheng Xu take charge of conceptualization and methodology of the manuscript.

Ethical approval of studies and informed consent

This study involved the analysis of publicly available data from on-line forums and social media platforms. As such, no human participants were directly involved in this research. Consequently, ethical approval and informed consent were not applicable for this study.

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None.

Data availability

The data that support the findings of this study are available on request from the corresponding author where appropriate.

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