Research Progress of Intelligent Intervention Modeling for Ankle Injury Rehabilitation and Prevention

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Abstract: There are some problems in the traditional rehabilitation methods of ankle injury such as lack of individuation. In this paper, intelligent intervention model is proposed, integrates multi-modal data, and constructs a full-cycle closed-loop management system of "acquisition - analysis - decision - feedback".The data acquisition layer uses wearable sensors and imag-ing technology to obtain ankle kinematic parameters and soft tissue status; the intelligent analysis layer realizes accurate assessment with the help of deep learning algorithms; the dynamic decision-making layer formulates personalized treatment plans according to patients' characteristics; and the feedback implementation layer realizes accurate rehabilitation training with the help of flexible robots, biofeedback systems, and intelligent protective gears. The model shows significant advantages in ankle injury rehabilitation and prevention but still faces challenges such as data fusion.In the future, intelligent intervention models are ex-pected to provide better medical services for patients.

1 INTRODUCTION

The ankle joint, as a key weight-bearing joint of the human lower limb, has a complex structure and various functions, which not only needs to maintain the stability of standing and walking and adapt to the needs of high-intensity sports such as jumping and steering. However, it is this functional specialization that makes it a high incidence of sports injuries. The ankle joint consists of the tibia, the distal fibula, and the talus, and is surrounded by ligaments, tendons, and the joint capsule. Among them, the lateral collateral ligaments (anterior talofibular ligament, posterior talofibular ligament, and calcaneofibular ligament) are weaker than the medial ligaments because of their anatomical position, and they are more prone to tearing or rupture due to excessive inversion or eversion during sports. According to statistics, ankle injuries account for 15%-30% of all sports injuries, of which about 80% are lateral ligament injuries, especially in basketball, soccer, and other sports that require sharp stops and jumps are the most common (RobsoN,H. E.,1988). According to some studies, about 710,000 people suffer from ankle sprains of different degrees every day. According to the statistics of the Dutch Health Security Administration, of the 120,000 ankle injuries registered annually, 36% (43,000) require surgical treatment at a later stage, with an average annual treatment cost of nearly 40 million dollars. Minor ankle sprains can be recovered with simple treatment, while 70% of patients with acute sprains develop ankle instability and recurrent sprains, and 20% to 40% of acute ankle sprains develop chronic ankle instability (CAI) due to inappropriate treatment or insufficient attention (Coronado, R. A.,2011). Traditional rehabilitation methods are mainly based on static assessment and doctor's experience to formulate treatment plans, which have the problems of insufficient personalization and untimely monitoring of patient's dynamic changes, resulting in unsatisfactory rehabilitation effect and a high recurrence rate of injury. The intelligent intervention model integrates multimodal data, covering biomechanics, imaging, exercise physiology, and other fields, which can realize accurate assessment and personalized intervention for ankle injuries and promote the change of ankle injury management mode to the direction of precision and dynamization (Zhang, Y.,2013).

This paper takes the "intelligent intervention model" as the core research framework, and through the deep integration of deep learning algorithms, wearable biomechanical sensing technology and digital biomimicry model constructs a full-cycle

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closed-loop management system covering "data acquisition-intelligent analysis-dynamic decision-making-real-time feedback". This system is designed to solve the problem of traditional ankle joint management. This system aims to solve the three core problems of traditional ankle injury management: lack of personalized rehabilitation programs (e.g., only 32% of patients receive biomechanically adapted training programs), lagging in prevention (less than 60% of high-risk movements identified accurately), and sloppy prognosis assessment (static imaging misdiagnosis rate as high as 18%).

2 CORE TECHNICAL FRAMEWORK OF INTELLIGENT INTERVENTION MODEL

The intelligent intervention model is a kind of model that uses artificial intelligence technology to realize automatic intervention and optimization of specific objects or systems through the analysis and processing of data. Among them, for the medical field, it can firstly assist doctors in formulating personalized treatment plans by analyzing massive medical data and achieving precise interventions in chronic disease management, disease risk prediction and other aspects.

The deeper level is its core technology framework: the intelligent intervention model follows the closed-loop operation logic of "acquisition-analysis-decision-making-feedback", and its technical architecture consists of multiple interoperable modules:

2.1 Data Acquisition Layer

Wearable sensors, such as accelerometers, gyroscopes, and pressure sensors, are utilized to acquire the 3D kinematic parameters of the ankle joint in real-time during movement, including information such as angle, velocity, and acceleration. Meanwhile, the combination of imaging techniques such as weight-bearing CT and MRI can accurately capture the state of the soft tissues of the ankle joint, such as the damage to ligaments, tendons, and cartilage. In this regard, this subsection focuses on flexible wearable sensors. The acquisition, sensing, and analysis methods of their motion signals include electrophysiological signal-based monitoring (EMG signals, ECG signals, EEG signals), photoelectric sensing-based sign monitoring (heart rate, heart rate variability, oxygen saturation), and electrochemical biosensing-based monitoring (lactate, glucose).

Among the electrophysiological signals monitored: EMG: Electrophysiological signals generated by the nerve cells of the muscular system are monitored through electrodes attached to the body surface, which can be used for movement analysis and early warning of muscle fatigue. Jianyong Ouyang of the National University of Singapore has achieved a good fit to the skin under wet skin conditions by introducing an organic dry electrode film based on sorbitol-modified poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) composite with an electrical conductivity of 545 S-cm-1. Electrocardiographic signals: electrophysiological signals from the heart's regular changes that are relatively easy to monitor. To solve the problems of allergy and poor contact with traditional electrodes, Chen et al. prepared biocompatible composite electrodes by interfacial polymerization of silk protein and polypyrrole. EEG signals: Electrophysiological signals are generated by the electrical activity of neurons in the brain, which are mainly collected by multi-site point electrodes on the surface of the scalp. Vörös et al. from ETH Zurich, Switzerland, proposed a conductive-based soft micropillar polymer electrode to realize high-quality acquisition of EEG signals.

Photoelectric sensing monitoring: The core of photoelectric sensing is a photoelectric sensor, which is mainly used to monitor the changes in blood volume by photoelectric volumetric tracing (PPG) to realize the monitoring of human vital signs. Based on organic phototransistors and inorganic LED doping, Zhao Niobium of the Chinese University of Hong Kong has developed ultra-thin flexible sensors, which are applied to heart rate, pulse, blood pressure, and other physiological signals detection.

Electrochemical biosensing monitoring: Electrochemical sensors consist of a receptor and an electrochemical conversion element, and are used to detect metabolites, electrolytes, ions, and other components in human body fluids. Jia et al. at the University of California were the first to propose the use of a tattoo electrode electrochemical sensor based on flexible printing for the detection of sweat lactate with a sensitivity of 220 nA-mM-1 (Su, B. T.,2022).

2.2 Intelligent Analysis Layer

Deep learning algorithm, Deep learning is a branch of machine learning, since Geoffrey Hinton proposed the idea of deep learning in 2006, it has made breakthroughs in the field of speech recognition, image recognition, etc. CNNs are an important model in deep learning, which is inspired by the hierarchical processing mechanism of the biological visual cortex, and it has a powerful feature learning and feature expression capability.

The basic structure of CNNs includes a convolutional layer, a pooling layer, and a fully connected layer. The convolutional layer extracts image features through convolutional operations, the pooling layer reduces the feature dimensionality and enhances the translational invariance of features through aggregation statistical operations, and the fully connected layer is used for classification or regression tasks (Lu, H. T.,2016).

2.3 Dynamic Decision-Making Layer

Combining clinical practice guidelines and individual patient characteristics, such as age, gender, level of exercise, and injury history, the intelligent intervention model can generate a personalized treatment plan. Children with immature skeletal development and epiphyseal injuries (e.g., Salter-Harris typing) need to prioritize growth plate protection (Xing, J. H.,2021). Smart technology simulates skeletal stress distribution through 3D biomechanical modeling to guide personalized brace design and avoid joint stiffness caused by traditional cast immobilization (Fan, J. P.,2017). Osteoporosis and decreased healing capacity are core challenges for elderly patients. Smart technology predicts the risk of delayed postoperative bone healing and guides the selection of anti-osteoporosis drugs through digital bone density assessment combined with genomic analysis (e.g., COL1A1 gene polymorphism) (Cao, F.,2010).

2.4 Feedback Execution Layer

The feedback execution layer of the intelligent intervention model is the final execution link in the closed loop of "perception-analysis-decision-making-feedback", and its core function is to transform the decision-making scheme output from the intelligent analysis layer into operable physical or digital interventions and dynamically optimize the intervention strategy through real-time data feedback. In ankle injury rehabilitation, the feedback execution layer realizes the dynamic adjustment and precise execution of personalized rehabilitation training through the integration of flexible robots, biofeedback systems intelligent protective gears, and other technologies. The core technology consists of three points: flexible robot dynamic control: flexible ankle rehabilitation robot (FARR) through the bionic ligament design and multi-degree-of-freedom motion control technology, real-time reception of the patient's joint mobility (ROM) and electromyographic signal (EMG) data, dynamic adjustment of the joint torque and movement trajectory (Zhang, W. Y., 2014; Yang, Z.,2005). The real-time interaction of biofeedback system: virtual reality (VR) augmented training system collects ankle inversion angle and ground reaction force data through wearable sensors (e.g., inertial measurement unit IMU), and combines with CNN algorithm to recognize abnormal gait patterns and generate visual/auditory cues in real-time (Fan, Z. M.,2023). Intelligent brace dynamic adaptation: intelligent brace based on plantar pressure distribution and sports scenarios, dynamically adjusting the hardness of lateral ankle joint support through an air pressure adjustment module (Yan, B.,2006).

3 PROGRESS IN THE APPLICATION OF SMART INTERVENTIONS IN REHABILITATION

3.1 Application Progress of Wearable Sensors for Ankle Injury Rehabilitation

The progress of the application of wearable sensors for ankle injury rehabilitation can be divided into three main points: the type of movement signals, the improvement of sensor performance, and scientific exercise training. The types of sports signals can be divided into sports biochemical signals, sports electrophysiological signals, sports posture signals, and bio-tissue dynamics signals, which contain specific physiological sign information, and through the real-time monitoring of these signals, it can be realized to objectively evaluate the training effect and the physical condition of the athletes.

As for the improvement of sensor performance, it is due to the cross-fertilization of various disciplinary fields that the performance and functions of sensors have been significantly improved. For example, sensors based on electrophysiological signals can collect higher quality electrophysiological signals for various types of sports analysis; sensors based on photoelectric volumetric tracing methods can realize the monitoring of multiple physiological indexes; non-invasive detection based on electrochemical sensors has made great progress.

Finally, scientific exercise training requires a complete exercise monitoring system, which requires the integration of multiple flexible wearable exercise sensors. It will be possible to build a multifunctional sports monitoring platform, which will have the functions of monitoring physiological indexes of sports training, analyzing sports technology and tactics, analyzing sports psychological conditions, and predicting sports injuries (Su, B. T.,2022).

3.2 Progress of Deep Learning Algorithms for Ankle Injury Rehabilitation

Convolutional Neural Networks (CNN), as one of the core technologies of deep learning, have shown significant advantages in the fields of medical image analysis, sports biomechanics modeling, and intelligent rehabilitation equipment in recent years. Its application in ankle injury rehabilitation mainly focuses on image diagnosis, dynamic monitoring, personalized rehabilitation program development, and intelligent equipment control.

CNN-based smart insoles and inertial sensors (IMUs) can collect ankle kinematic parameters (e.g., inversion angle, ground reaction force) in real time and realize dynamic risk assessment through feature extraction. Studies have shown that CNN models fused with multidimensional biomedical data (heart rate, EMG signals) can recognize high-risk movements such as sharp stops and jumps with 85% accuracy. For example, to address the risk of ankle inversion in basketball players, the system can analyze the plantar pressure distribution through CNN to trigger real-time warnings and guide movements.

The flexible ankle rehabilitation robot combines CNN algorithms to achieve precise control of multi-degree-of-freedom movements. Through bionic ligament design and impedance adjustment, its joint torque fluctuation is 40% lower than that of traditional equipment, and its workspace covers 98% of the physiological activity range. The brain-computer interface foot and ankle rehabilitation robot from Tsinghua Changgeng Hospital further integrates EMG signals and eye tracking, utilizes CNN for multimodal data fusion, and significantly improves the patient's active mobility and balance function of the ankle joint, with a gait abnormality improvement rate of 73% at 20 days post-surgery (Lu, H. T.,2016).

3.3 Personalized Rehabilitation Training

For complex ankle fractures (e.g., Weber type C), 3D-printed guides assist in the precise placement of internal fixation screws, reducing intraoperative fluoroscopy time and soft tissue stripping (Liu, S. H.,2018). In postoperative rehabilitation, the flexible ankle robot balances joint stability and bone healing needs through low-intensity progressive training (torque fluctuations reduced by 40%) (Wang, X. Z.,2016).

Severe injuries (e.g., large talar cartilage defects): arthroscopic bone graft repair is used to implant autologous cancellous bone to promote cartilage regeneration, and postoperatively, with weight-bearing CT to assess the effect of force line correction, avoiding the trauma of traditional osteotomy (Zhang, Z. H.,2012).

Intelligent protective gear recommendation system for amateur athletes based on arch type and sports scenarios (e.g., running, basketball) reduces the probability of inversion injuries by 37% Professional athletes combine dynamic load monitoring with platelet-rich plasma (PRP) injections, which promotes cartilage repair while adjusting the training intensity to shorten the time to return to the field of play by 30%(Su, D. Y.,2025; Ming, P. J.,2017).

3.4 Specific Application of the Three Core Technologies of the Feedback Execution Layer

Flexible ankle rehabilitation robot for patients with ankle dorsiflexion limitation, the robot can adaptively reduce the resistance in the direction of plantarflexion based on the kinematic model, and at the same time increase the dorsiflexion auxiliary torque, so that the joint torque fluctuation is reduced by 40% compared with the traditional equipment (Zhang, W. Y., 2014; Yang, Z.,2005). Virtual reality (VR) augmented training system: when the patient's inversion angle exceeds the safety threshold (>15°), the system triggers a red alert and suspends training until the patient adjusts to the correct posture (Fan, Z. M.,2023). Intelligent protective gear based on plantar pressure distribution and sports scenarios: when a basketball player stops sharply and jumps, the protective gear automatically enhances the hardness of lateral support (up to 80 kPa), reducing the probability of inversion injury by 37% (Yan, B.,2006).

4 TECHNICAL CHALLENGES AND FUTURE DIRECTIONS

4.1 Existing Technical Challenges and Future Research Directions for Lower Limb Exoskeleton Robots

Although great progress has been made in the field of intelligently powered lower limb exoskeleton robots, they still face many challenges: firstly, the joint actuators of intelligently powered lower limb prostheses have problems such as large weight and small output torque, which limit the motion characteristics of the joints of the prostheses. Then there is insufficient research on the correlation control of multi-joint prostheses, which affects the stability, safety, and comfort of disabled people in different walking gaits. Secondly, although the accuracy rate of motion intent recognition is high, there is still a risk of falling in practical applications, and there are limitations in the existing sensing methods. At the same time, there is insufficient research on motion intention recognition in complex dynamic environments, and the influence of environmental changes on the recognition model is significant. Finally, the stimulation device of the sensory feedback system is simple, the variety of stimulation modes is limited, and the sensing alternatives are not natural enough and need long time training.

In the future, the bionic structure design of intelligent powered prostheses and human-machine integration for complex environments will become the focus of research. Clinical trial-driven control algorithms, sensing methods, and perceptual feedback will become new research highlights in this field. Nevertheless, the research on smart-powered lower limb prostheses still needs to solve many basic scientific problems and technical difficulties to realize more natural and smooth motion control and better human-machine integration (Wang, Q. N.,2016).

4.2 Current Shortcomings of Deep Learning Algorithms and Future Optimization

Firstly, regarding data standardization and privacy protection, the integration of cross-modal data (imaging, genome, exercise physiology) requires unified protocols (e.g., DICOM, HL7), and although blockchain technology can encrypt the storage, the real-time processing efficiency still needs to be improved (Meng, C. B.,2004; Mu, S., Cui,2021; Yuan, Y.,2016).

Secondly, algorithm generalization ability is improved, existing CNN models are limited in performance in small sample data (e.g., rare injury types), and need to be combined with migration learning and generative adversarial networks (GAN) to enhance generalization (Wang, K. F.,2017). Finally regarding clinical translational validation, most studies are limited to single-center trials, and multicenter randomized controlled trials (RCTs) are needed to validate long-term efficacy (Liu, G. B.,2017). For example, the cumulative effect of carbon plate running shoes on ankle joint loading in non-professional athletes needs to be supported by more than 10 years of cohort studies.

Its future directions mainly include: the fusion of regenerative medicine and CNN: 3D-printed bionic cartilage scaffolds combined with PRP injections, optimizing the scaffold porosity and matching mechanical properties through CNN (Sun, X.,2006; Wang, L.,2014); group intelligence platform: building a collaborative network in the cloud, integrating data from doctors, patients and rehabilitators, and realizing the optimization of dynamic solutions (He, Y.,2019)s.

4.3 Deficiencies and Optimization of Personalized Rehabilitation Programs

Firstly, for data standardization: cross-modal data (imaging, genomic, exercise physiology) integration needs to be a unified protocol to avoid algorithmic bias (Meng, C. B.,2004; Mu, S., Cui,2021). Secondly, in the human-robot interaction bottleneck, the existing rehabilitation robots are not flexible enough, and so on, bionic materials (e.g., shape memory alloys) need to be developed to improve comfort. Finally, regarding ethics and privacy, genetic data and motor biometrics need to be encrypted and stored in compliance with the Code of Practice for Medical Data Security Management.

4.4 Technical Challenges and Innovative Directions for the Feedback Execution Layer

First, multimodal data fusion bottleneck: the existing system has insufficient cross-modal fusion capability for imaging (e.g., MRI), exercise physiology (EMG), and genomic data, and a heterogeneous data mapping model based on graphical neural networks needs to be developed to improve the biological suitability of intervention strategies. Secondly, the optimization of human-robot interaction flexibility: the joint impact of traditional rigid robots is prone to secondary damage, and variable stiffness actuators based on magnetorheological fluid need to be explored in the future to achieve smooth torque transition (fluctuation <5 Nm). Finally, a long-term efficacy validation system is missing: most studies rely on short-term laboratory data (<6 months), and a multicenter follow-up platform (e.g., blockchain-based healthcare data consortium) needs to be established to validate the 10-year cumulative risk impact of smart interventions on traumatic arthritis (Zhang, W. Y., 2014; Yang, Z.,2005; Fan, Z. M.,2023; Yan, B.,2006).

5 CONCLUSION

The intelligent intervention model brings new opportunities for ankle injury rehabilitation and prevention by integrating multidisciplinary technologies. It demonstrates significant advantages in accurate diagnosis, personalized rehabilitation training, and injury prevention, effectively improving the accuracy and efficiency of ankle injury management. However, technical challenges such as data fusion, human-computer interaction, and clinical validation still need to be overcome to realize the widespread clinical application of intelligent intervention models. In the future, with the continuous innovation of technology and in-depth interdisciplinary intersection, the intelligent intervention model will develop in the direction of more personalized, intelligent, and universal, providing better medical services for patients with ankle injuries.

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