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Article

Application research on mechanical assessment and training based on intelligent physical training system in the rehabilitation of athletes' ankle injuries

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Abstract: As the only hinge connection between human body and the ground, ankle joint plays an important role in sports. Based on the theory of rehabilitation medicine, this paper puts forward an intelligent physical training system integrating mechanical evaluation and training functions, and applies it to the rehabilitation of athletes' ankle injuries. The system adopts virtual reality (VR) technology, realizes active ankle rehabilitation training through high-precision sensors and advanced computer simulation technology, and provides accurate evaluation, monitoring and personalized training scheme for ankle rehabilitation. The system creates an immersive training environment for athletes by simulating real sports scenes and processes. The experimental results show that the system is excellent in training convergence speed and performance, and the error is small. Compared with the traditional algorithm, the accuracy is improved by 19.27%. The main contribution of this paper is that the intelligent physical training system integrating mechanical evaluation and training is applied to the rehabilitation of athletes' ankle injuries, and good rehabilitation results have been achieved.

Keywords: mechanical assessment; physical training; athletes; ankle; injury rehabilitation

1. Introduction

In today's competitive sports arena, ankle injury has become a common challenge for athletes, which seriously interferes with their training plan and competitive performance [1]. According to statistics, the incidence of ankle injuries among athletes is high, and the specific injury rate varies with sports events and levels, but it is generally high, and the common types include sprain and ligament tear [2]. These injuries not only cause swelling and pain, but also may cause long-term problems such as ligament relaxation, chronic instability and recurrent sprain [3]. Although traditional rehabilitation methods can promote recovery to a certain extent, their limitations such as high repeatability, lack of interaction and difficulty in real-time monitoring and adjustment often make athletes face a long rehabilitation period, and the rehabilitation effect is not satisfactory [4].

As the only hinge connection between human body and the ground, ankle joint plays a vital role in lower limb movements such as standing, walking, running and jumping [5]. For athletes, the health of ankle joint is the key to maintain the peak state [6]. Therefore, the high incidence of ankle injuries among athletes highlights the urgent need for innovative and efficient rehabilitation methods. Rehabilitation medicine, as a discipline dedicated to restoring and improving human functions, aims to alleviate the dysfunction caused by injuries [7]. However, the traditional rehabilitation strategy is not enough to meet the needs of ankle rehabilitation in many aspects, especially in the aspects of interaction, personalization and real-time feedback [8,9].

With the continuous progress of VR technology, its application in the field of medical rehabilitation has attracted much attention because of its immersion, interaction and high customization [10]. Chen et al. [11] think that it is necessary to analyze the development status of ankle joint robot and study its appropriate driving mode, so that it can not only carry out three-degree-of-freedom mixed-axis movement, but also be safer in the training process. Zhao et al. [12] developed an ankle rehabilitation system for patients, realized the movement control of ankle joint, and built a virtual environment simulation platform, which enabled patients to feel the force on ankle joint through the force feedback function of tactile perception interface. Rose and Messer [13] pointed out that the introduction of VR technology into ankle rehabilitation training can realize three combinations, improve rehabilitation efficiency and improve rehabilitation effect. Yue [14] emphasized that active functional rehabilitation training can not only effectively prevent muscle atrophy, restore muscle tension and coordinate the dominance of muscle balance, but also stimulate the development of bones and nerves in the motor system, enhance the activity of motor centers in the cerebral cortex, improve the excitability of cells, and make full preparations for patients' comprehensive rehabilitation. Although these development prospects are encouraging, the current VR solutions for ankle rehabilitation may still be limited by factors such as lack of realism, incomplete functional evaluation or limited customization options.

This study has the following innovations:

(1) An intelligent physical training system based on VR technology is proposed. The system is specially designed for athlete's ankle rehabilitation, and integrates mechanical evaluation and training functions.

(2) By simulating real sports scenes, it aims to stimulate athletes' interest in training, improve the rehabilitation effect, and monitor and evaluate their rehabilitation progress in real time. At the same time, the system also combines personalized rehabilitation plan, fully considering individual differences and specific rehabilitation needs.

(3) By providing a new method, this study solves the limitations of traditional methods and current VR-based solutions, paying special attention to improving the rehabilitation process of athletes with ankle injuries, and making contributions to this field.

2. Related work

In recent years, technological advancements have fueled continuous innovation in ankle injury rehabilitation treatments, aimed at enhancing rehabilitation outcomes, patient experience, and training efficiency. Sudo et al. [15] introduced a novel rehabilitation robot mechanism, designing an ankle rehabilitation robot that accurately executes training based on ankle joint motion modeling, effectively promoting recovery. However, the study did not delve into the patient's engagement or experience during rehabilitation. Taslimipour et al. [16] highlighted the application of

VR technology in ankle rehabilitation, creating an immersive virtual training environment that integrates psychotherapy and physical therapy. This method provides diverse feedback and enhances training motivation but may lack real-time personalization. Plechatá et al. [17] emphasized the prevalence of ankle injuries in sports and the importance of preventive measures, suggesting improvements in training environments and physical fitness to reduce injury risk. Their focus on prevention offers valuable insights but does not directly address rehabilitation techniques. Covaciu et al. [18] noted the advantages of VR-based rehabilitation devices in sports rehabilitation, simulating real-world training environments and providing diverse training scenes. While these approaches offer immersive experiences, they may not fully personalize training programs based on individual athlete needs. Kim [19] discussed robot-assisted ankle rehabilitation, emphasizing the reduction of physiotherapist workload and improved efficiency through robotic assistance. However, their study did not explore the integration of VR for enhanced patient engagement. Li et al. [20] implemented ankle active rehabilitation based on virtual scenes, encouraging patient participation. Yin et al. [21] emphasized the instability of the ankle joint and the importance of injury prevention and treatment, offering a holistic perspective but not specifically addressing rehabilitation methods. Taito [22] also studied the application of robot system in ankle rehabilitation, and emphasized the potential of robot assistance to reduce the burden of physical therapists and improve the effectiveness of rehabilitation work.

Based on these studies and the concept of mechanical evaluation and training, this paper proposes an intelligent physical training system combining VR technology. Traditional rehabilitation methods have some limitations, such as long rehabilitation period, unstable rehabilitation effect and low patient participation, so it is particularly necessary and urgent to develop this new system [23]. The system solves the problems of personalization, real-time monitoring and patient participation, and simulates real sports scenes and tasks with the help of high-precision mechanical sensors to accurately analyze and evaluate athletes' ankles. This design can stimulate athletes' interest in rehabilitation, improve the rehabilitation effect, and realize real-time monitoring and real-time feedback of mechanical data.

3. Methodology

3.1. Identification method of ankle joint injury and assessment of ankle joint function

Ankle joint is one of the most important sports joints in human body, which bears the weight of the whole body and is also one of the joints with complex structure [24]. There are many reasons for ankle sprain, and the pathogenesis has not formed a unified statement, leading to inconsistent treatment [25]. Choosing neural network as the core component of our intelligent sports training system is based on its proven ability to learn complex patterns and predict based on historical data. Neural network processes the input from high-precision sensors, which capture the ankle movement and biomechanical parameters of athletes during rehabilitation training. Through iterative training, the network learns to identify the best sports mode and provide real-time feedback to guide athletes' performance. In order to realize realistic simulation of motion scenes and processes, we use a series of high-precision sensors, including accelerometers, gyroscopes and force measuring plates. These sensors are strategically placed on athletes' ankles and surrounding areas to capture subtle movements and biomechanical stress. Then the collected data are processed by advanced computer simulation technology, which reproduces the dynamics of ankle movement in virtual environment. VR technology plays a key role in our system by providing an immersive training environment for athletes. We integrated VR head display and controller, which enabled athletes to interact with simulated sports scenes naturally. The real-time feedback of neural network is transformed into visual and auditory cues in virtual reality environment, which enables athletes to adjust their actions and experience the consequences of their actions in real time. This immersive approach not only improves participation, but also speeds up the learning process by providing immediate and intuitive feedback.

In the intelligent physical training system based on VR, joint injury identification is a key technical link. The system realizes real-time monitoring and damage identification of athletes' joint state by comprehensively using sensor technology, computer vision and machine learning algorithm. **Figure 1** shows the ankle joint injury identification method and the ankle joint function assessment process.

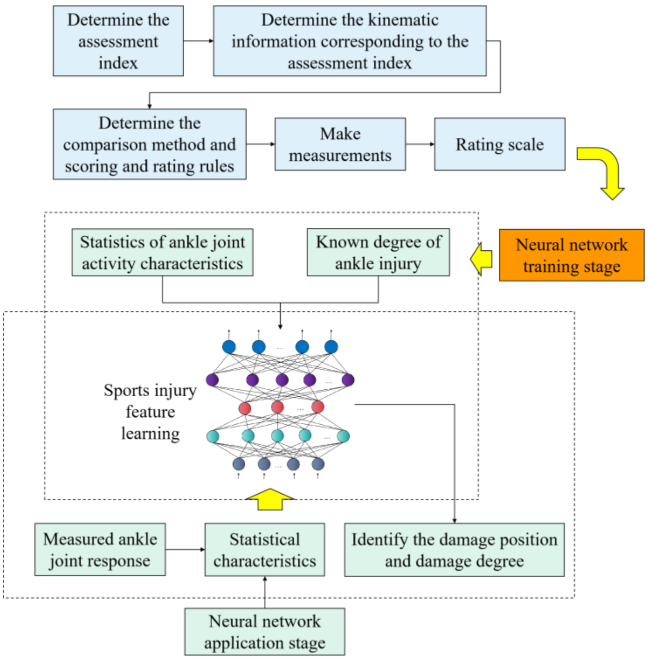

Figure 1. Ankle joint injury identification method and ankle joint function assessment flow.

Neural network is used to construct the core algorithm of intelligent physical training system. By training neural network, the system can learn and simulate the decision-making process of human rehabilitation experts, thus providing athletes with individualized rehabilitation training programs. The input of neural network includes athletes' basic information, injury types, rehabilitation history and other data, while the output is customized training plans and suggestions for each athlete. In this paper, Convolutional Neural Network (CNN) is used to process image data. The specific design of CNN architecture is as follows: First, the input image passes through a convolution layer, which uses 64 3 × 3 convolution kernels with step size of 1 and edge padding of' same' to preserve the image size. This is followed by a batch normalization layer to speed up training and reduce over-fitting. Then there is a ReLU activation function, which introduces nonlinearity into the network. After that, the image data passes through a 2 × 2 maximum pooling layer with a step size of 2, which is used to reduce the dimension of the feature map. Next, the data passes through four similar convolution blocks in turn, each block contains a convolution layer, a batch normalization layer and a ReLU activation function. The number of convolution kernels of these four convolution blocks is 128, 256, 512 and 512, respectively. The convolution kernel size is 3 × 3, the step size is 1, and the edge padding is' same'. Each convolution block is followed by a 2 × 2 maximum pooling layer with a step size of 2. Finally, after these convolution layers and pooling layers, the image data is flattened and input into two fully connected layers. The first fully connected layer has 1024 neurons, and the number of neurons in the second fully connected layer depends on the specific classification task. For example, for 10 classification problems, the output layer will have 10 neurons. ReLU activation function is also used between fully connected layers.

In the training process of neural network model, the following specific steps and parameter settings are adopted: First, the data set is divided into training set and test set according to the ratio of 7:3. Then, the mean square error (MSE) is selected as the loss function to measure the accuracy of the model prediction. Then, the appropriate training rounds, learning rate and batch size are set to ensure the stable convergence of the model in the training process. The specific parameter values are optimized and adjusted according to the experimental situation.

By integrating high-precision sensors and advanced VR technology, this system realizes the accurate monitoring and immersive experience of athletes' ankle rehabilitation training. The system uses motion capture sensors to track the angle change, displacement and speed of athletes' ankles in real time. These data are accurately mapped to VR environment after being processed by special algorithms, so that athletes can intuitively feel their training status in virtual space. In order to monitor physiological parameters more comprehensively, the system also integrates pressure sensor and electromyography sensor, which are used to monitor plantar pressure and muscle activity respectively. The real-time interaction between these sensors and VR system provides athletes with individualized rehabilitation training plan.

VR technology has the characteristics of immersion, interactivity and imagination. In order to enhance the therapeutic effect and patients' immersion, some scholars began to study VR technology to assist robots in rehabilitation training. Applying VR technology to ankle rehabilitation can realize the combination of game and therapy, psychological guidance and physiological therapy. Based on this, this paper will build an intelligent physical training system based on VR. With the help of VR-based intelligent physical training system and advanced computer simulation technology, active rehabilitation training for ankle joint can not only avoid the boring and boring of traditional rehabilitation training, but also integrate rehabilitation training into entertainment, thus enhancing patients' training interest and improving rehabilitation effect.

3.2. Construction of mechanical assessment and intelligent physical training system based on VR

VR technology is a burgeoning technology. This technology is characterized in that the computer generates an artificial virtual environment. This virtual environment is a kind of computer hardware and software environment constructed by interactive devices such as stereoscopic display devices and sensor gloves, which is compiled into the computer to generate a realistic "virtual environment" through a three-dimensional digital model composed of computer graphics. Its essence is to give people real experience and convenient human-computer interaction. Human-computer interaction of VR technology is also being explored and applied in the medical field by many experts and scholars, and its application in rehabilitation medicine has great potential. VR includes two parts: the main participants and the virtual world, and the core of VR is to emphasize the interaction between them, that is, users can operate with the objects in the virtual environment through professional sensing devices, and perceive and manipulate them in real time; Get the feedback from the virtual environment to the sensor devices, and get people's experience in the virtual world. In the traditional exercise therapy, patients are in a passive position, and the movements in the training process are repetitive and monotonous, so patients are prone to boredom. To some extent, this delays the treatment, which is not conducive to the continuation and deepening of treatment. In VR system, people can send various commands to the computer through body movements, and get feedback from the computer on various sensory information such as vision, hearing and touch, which makes users feel immersed in the virtual environment. This is the immersion or participation of VR technology. Applying VR technology to intelligent physical training system can avoid the boring and boring of traditional rehabilitation training, and make rehabilitation training into entertainment, thus enhancing patients' training interest and improving rehabilitation effect.

Through high-precision sensors and computer simulation technology, the system simulates the real sports scene and process, and provides an immersive training environment for athletes. In this environment, athletes can carry out various ankle rehabilitation training actions, such as balance training, muscle strength training, flexibility training and so on. The system customizes a individualized rehabilitation plan according to the athlete's ankle injury, physical condition and training needs. This plan will plan the time, intensity and action types of each training in detail to ensure the scientific and effective training. During the training process, the system will monitor the athletes' training situation in real time, including movement standard, strength output, balance stability and so on, and give immediate feedback through VR equipment. In this way, athletes can know their training effects in time and adjust their training strategies. Using the interactivity and gameplay of VR technology, the system can design various interesting training tasks and challenges to stimulate athletes' training interest and motivation. At the same time, the system can also set up a reward mechanism to give corresponding rewards to athletes who have completed training tasks, so as to further improve their training enthusiasm.

VR 3D modeling can show the anatomical relationship between bones and their adjacent structures from multiple angles. By adjusting the curve in the reconstruction protocol and attenuating the soft tissue information, the bone tissue can be displayed, and the fracture site, articular surface involved in the fracture, bone fragment separation and displacement can be observed intuitively. This is of great help to pry and select the needle insertion point during fracture operation, and is also helpful to judge the changes of bone structure after joint trauma. In VR modeling, let the normal vector of each triangle in the associated triangle group of vertex v_i be n_k, the center be x_k, and the area be a_k. Then the plane constructed by the normal vector and center defined below is called the mean plane of that vertex. The formula is defined as follows:

$$N = \frac{\sum n_k a_k}{\sum a_k} \tag{1}$$

$$n = \frac{N}{|N|} \tag{2}$$

$$x = \frac{\sum x_k a_k}{\sum a_k} \tag{3}$$

The washout from the point P in the three-dimensional space to the mesh model TM is defined as:

$$d(P, TM) = min\big(d(P, X)\big) \qquad X \in TM \tag{4}$$

Among them, $d(P, X)$ is the Euclidean distance from point P to point X.

The function of VR system consists of the virtual world created and the man-machine interaction between people and the virtual world. Based on this, the hardware of VR can be divided into four parts: virtual world generating device, sensing device, tracking device and interactive device based on natural way. The development of VR system requires high hardware environment, especially when there are many and complex scene models, and the hardware conditions are particularly important. Considering the cost of R&D and the application environment of the system, the intelligent physical training system studied in this paper is developed on a well-configured PC. At the same time, the database is an indispensable part of the rehabilitation system. It can record the whole process of rehabilitation training and store some key data as the basis of functional assessment, so as to analyze the effect of rehabilitation training and make the next training plan. The framework of VR-based intelligent physical training system is shown in **Figure 2**.

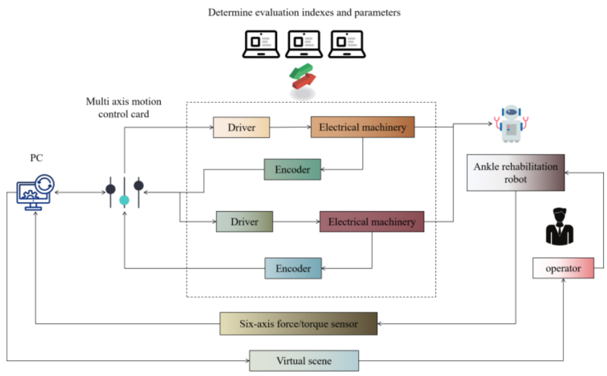

Figure 2. Intelligent physical training system based on VR.

The hardware of this intelligent physical training system includes high-precision motion capture sensor and 4K resolution VR head display, and the software is built based on Windows 10 operating system and Unity 3D development environment. In the VR environment, we comprehensively consider the initial position, kinematic constraints, dynamic model and the attributes of surrounding objects of the robot, calculate the position of the end effector of the robot through the forward kinematic equation, and calculate the movement of the robot under the action of external forces by combining the dynamic equation. At the same time, we implement collision detection algorithm to deal with the contact between robot and object, and adjust its trajectory according to physical properties. Finally, through the iterative optimization process, the final position of the robot in VR is determined to ensure that its interaction with the environment is true and conforms to the physical laws.

The whole system can be divided into three parts: virtual environment for rehabilitation training, robot body and its control system, training results and functional assessment database. The virtual environment can be generated by many methods, such as VRML, a VR modeling language suitable for the Internet, OpenGL-based virtual scene making, etc., which are popular at present. Finally, the three-dimensional scene is displayed through the display of PC. The main part of the control system is a closed-loop control system, which consists of a multi-axis motion control card, a driver and a servo motor. The multi-axis motion control card can control the motor in real time, store motion control programs, and communicate with the upper computer and other control devices. The driver gets the control signal from the multi-axis motion card and amplifies the torque or speed of the motor. The motor converts the electric signal transmitted by the driver into rotary motion. Equipped with a position sensor, the motor can compensate the position output of the multi-axis motion control card.

Objects in the virtual world will be endowed with specific physical properties according to their material characteristics, such as hardness, elasticity, friction and so on. These properties determine the behavior of objects in the virtual environment, such as the degree of deformation of objects when subjected to force and the reaction when colliding with other objects. Through reasonable design and implementation, this process can effectively enhance the immersion and interactivity of virtual reality system. VR system updates the spatial position of objects in the virtual scene according to the change of parameters, which brings visual feedback to patients. At the same time, the virtual environment calculates the corresponding virtual force according to the results of collision detection and the predefined material characteristics of virtual objects, such as stiffness and friction coefficient, and transmits it to the controller of the tactile sensing interface, thus generating realistic force feedback for patients. VR system aims to help patients recover the normal function of ankle joint by simulating real sports scenes and providing immersive training experience. Understanding the range of motion of ankle joint can provide important reference for the training task and design in VR system. For example, according to the limitation of ankle joint activity, we can design appropriate training movements and difficulties to ensure that patients can carry out effective rehabilitation training within a safe range. Normal ankle joint movement can realize the basic movements of ankle joint such as dorsiflexion/plantarflexion, varus/valgus, adduction/abduction. The range of motion of joints is shown in **Table 1**.

Table 1. Range of motion of ankle joint.

Movement type	Scope of activities		Movement type	Scope of activities	
	Minimum value	**Maximum value**		**Minimum value**	**Minimum value**
Back stretch	30°	42°	Ectropion	10°	17°
Plantar flexion	37°	45°	Adduction	25°	30°
Introversion	14°	22°	Extented	25°	30°

The training strategy based on trajectory adjustment integrates the subjects' motion intention into the three-degree-of-freedom rehabilitation training, so that the whole training process can adjust the motion trajectory according to the subjects' intention, thus exercising the subjects' ability to control the ankle joint. In the active training strategy, the human-computer interaction torque can be used to change the trajectory of the robot, and the combination of impedance control to correct the trajectory is also a common method.

The original medical image data need to go through a series of preprocessing steps, including denoising, enhancement, segmentation and so on, in order to improve image quality and reduce data redundancy. For example, denoising can eliminate the random noise in the image, enhancement can highlight the bone structure, and segmentation can separate the ankle from the surrounding tissues. Using professional 3D reconstruction software, the preprocessed 2D image data are converted into 3D models. In this process, it is necessary to ensure the geometric accuracy of the model and the correctness of the topological structure in order to accurately reflect the true shape of the ankle joint.

Let S={U,C,V,f} be an information system. $X \subseteq C$ is a subset of attributes, where $U/X = \{X_1, X_2, \dots, X_n\}$, the information volume of X is defined as:

$$I(X) = \sum_{i=1}^{n} \frac{|X_i|}{|U|}\left[1 - \frac{|X_i|}{|U|}\right] = 1 - \frac{1}{|U|^2}\sum_{i=1}^{n}|X_i|^2 \tag{5}$$

Among them, $|X|$ represents the cardinality of the set X, and $\frac{|X_i|}{|U|}$ represents the probability of the equivalent X_i in U. For $\forall x_i \in X$, the importance of the conditional attribute x_i is defined as:

$$sig_{X-\{x\}}(x) = I(X) - I(X - \{x\}) \tag{6}$$

From this, the weight w_i of the indicator x_i can be expressed as:

$$w_i = \frac{sig_{X-\{x_i\}}}{\sum_{i=1}^{n} sig_{X-\{x_i\}}(x_i)} = \frac{I(C) - I(C - \{c_i\})}{nI(C) - \sum_{i=1}^{n} I(C - \{c_i\})} \tag{7}$$

The expected trajectory of ankle joint motion is set as a sine function, assuming that the first triggered motion is plantar flexion/dorsiflexion, and its trajectory is defined as follows:

$$x_d(t) = A\sin 2\pi f_i(t + \phi_d) \tag{8}$$

where $x_d(t)$ is the desired trajectory in the direction of plantarflexion/dorsiflexion motion; A is the amplitude of the desired trajectory; f_i is the initial motion frequency; t represents the time variable; and ϕ_d is the initial phase of the desired trajectory. It is defined as follows:

$$\phi_d = \begin{cases} 1 & When\ F_x \geq F_{x0} \\ \dfrac{1}{2f_i} & When\ F_x < F_{x0} \end{cases} \tag{9}$$

After judging the movement intention of the subject, the system will modify its expected movement trajectory, as shown in the formula:

$$x_{md}(t) = A \sin 2\pi f_{md}(t + \phi_m) \tag{10}$$

where f_{md} is the frequency after the trajectory has been changed.

The exercise modes of ankle rehabilitation can be divided into passive exercise, active exercise and power-assisted exercise. The functions of the software include: (1) Selection of rehabilitation exercise mode. (2) Selection of speed and scene. (3) Operation modes are divided into operation and stop. In terms of technical implementation, the system adopts advanced hardware configuration and software environment. In terms of hardware, Oculus Rift S is selected as the VR headset, which provides high-resolution display and comfortable wearing experience. At the same time, a 16-channel wireless EMG sensor and a 6-degree-of-freedom motion capture system are used to ensure the accurate monitoring of athletes' ankle activities. In terms of software, a virtual training scene is built based on Unity 3D game engine, and a realistic training effect is achieved by using its powerful physical engine and cross-platform support. In the aspect of data processing, Python programming language is adopted, and the collected sensor data is processed and analyzed efficiently by combining NumPy and Pandas libraries. During the development of the whole system, Blender is also used for three-dimensional modeling, and the realistic light and shadow effect is realized through Unity Shader system.

According to different rehabilitation conditions, the system selects corresponding rehabilitation programs, sets up different virtual scenes, and generates different feedback forces to adapt to the force that patients' ankles can bear, so as to obtain a gradual rehabilitation effect. In this paper, the scene model interacting with users is modeled by geometric modeling method, and the virtual scene is modeled by image-based modeling method to obtain better visual effect and user experience. This not only ensures the authenticity of the virtual scene, but also improves the immersion of the virtual scene.

4. Result analysis and discussion

The main contribution of this study is to develop and verify an intelligent physical training system based on VR technology, which is especially aimed at the rehabilitation of athletes' ankle injuries. By integrating advanced neural network algorithm, this system can provide individualized rehabilitation plan and adjust it in real time according to the recovery situation of athletes. The results show that, compared with the traditional rehabilitation methods, the system significantly improves the rehabilitation effect and enhances the training interest of athletes. The high-precision sensor we use can accurately capture the athlete's ankle movement data, which are then input into the neural network for processing. Neural network generates individualized training suggestions according to the input data and the preset rehabilitation goals, and these suggestions are presented to athletes in an immersive way through VR environment. Athletes' various training actions in VR environment, such as balance training, muscle strength training and flexibility training, have been accurately monitored and fed back in real time. The study collected data of 50 injured athletes. These athletes suffered from 10 different types of ankle injuries. The intelligent physical training system was trained using this data set, which contains data from 50 athletes with different ankle injuries. The system has achieved good performance in rehabilitation effect and patient satisfaction. In order to ensure the reliability and repeatability of the experimental results, the standardized operation was strictly carried out. Specifically, it includes: fixing the sensor according to the predetermined position and standard process, and formulating detailed data collection procedures, including collection frequency, storage format and quality control measures.

Firstly, this paper trains the algorithm, compares the training of other algorithms with the algorithm in this paper, and draws the results into a data graph. The comparison of the training results of the algorithm is shown in **Figure 3**.

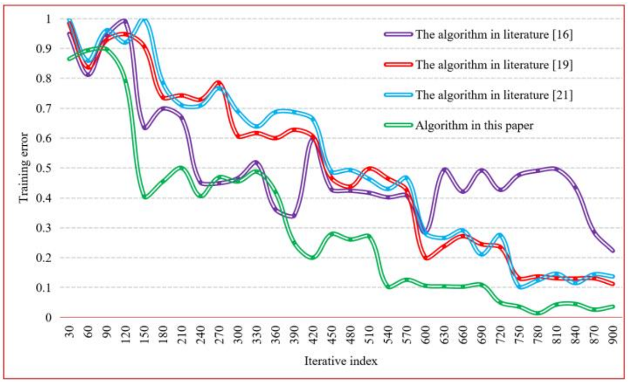

Figure 3. Comparison of training results of algorithms.

The algorithm in this paper shows a fast convergence speed at the initial stage of training. This means that the algorithm can learn and optimize more efficiently, so as to achieve better performance in a shorter time. This is of great significance to the situation that the model needs to be trained quickly in practical application. Compared with the contrast algorithm, this algorithm shows better performance in the training process. This is because the algorithm in this paper adopts more advanced optimization technology or more reasonable model structure, which enables it to process data better and learn more effective feature representation. This performance advantage makes the algorithm in this paper more accurate and robust when dealing with complex tasks. During the experiment, standardized operations, such as sensor placement and standardized data collection procedures, are emphasized to ensure the reliability and repeatability of the experimental results.

During the compound rotation rehabilitation exercise, the system must transform the given law of ankle joint rotation angle with time into the control instruction of driving rod displacement through the position inverse solution mathematical model, so as to drive the moving platform of the rehabilitation robot to realize the desired movement of a specific action. The VR scene can be set accurately, and each position has accurate coordinates. If the patient repeatedly trains under a set condition, he can know the effect of his rehabilitation from the rehabilitation data. The difficulty of rehabilitation exercise can be controlled by controlling parameters. **Figure 4** shows the compound movement of ankle joint of patients after rehabilitation training.

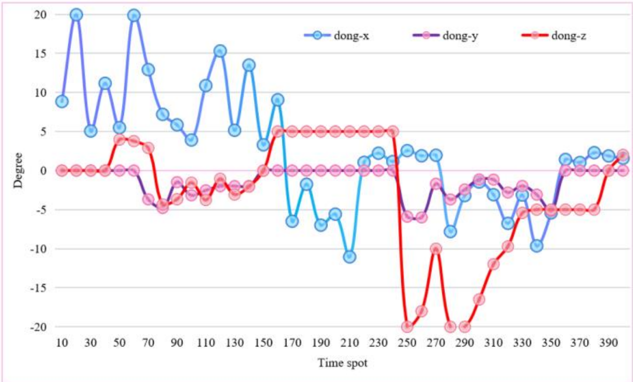

Figure 4. Compound movement of ankle joint.

The system constructs ontology scene and game scene, which are realized by VC++ split screen window. Ontology scene is used for passive training of sports medicine, while game scene is mainly used for active training and strength training. During the experiment, the system emphasizes standardized operations, such as sensor placement and standardized data collection procedures, to ensure the reliability and repeatability of the experimental results. At the same time, the system also sets the limit angle of the mobile platform to prevent the patient's ankle rotation angle from exceeding the maximum limit during training. From the overall effect, after rehabilitation training, the patient basically realized the rehabilitation movement of ankle joint in three rotation directions, which basically met the requirements of ankle joint rehabilitation.

In ankle joint rehabilitation training, passive training mode specifically refers to a training method where the subject does not need to actively control the movement of the ankle joint. In this mode, the active information transmission between the subject's brain and ankle joint is significantly reduced because the movement of the ankle joint is mainly guided and controlled by external devices (such as rehabilitation robots). In contrast, active training of the ankle joint emphasizes the subject's realization of their own movement intentions during the training process, which requires the subject to have a certain level of control over the ankle joint in order to actively trigger and guide the movement of the robot.

When the subject's control over the ankle joint is weak and they are unable to effectively trigger the robot to perform the expected movement, how to effectively incorporate their movement intentions into the rehabilitation training becomes an urgent challenge to be addressed. **Figure 5** illustrates the ankle joint passive training mode guided by the subject's movement intentions. This mode aims to assist the subject in expressing and realizing their movement intentions as much as possible while maintaining passive training, with the help of external devices.

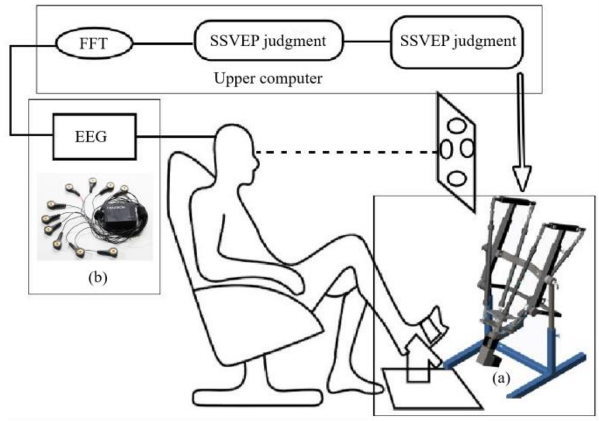

Figure 5. Ankle joint passive training mode guided by subject's movement intentions.

In this section, three commonly used algorithm error assessment indexes are used for assessment. The performance assessment indexes of several algorithms are shown in **Table 2**. Comparison of accuracy results of several algorithms is shown in **Figure 6**.

Table 2. Experimental results of index of algorithm.

Algorithm	MSE	RMSE	MAE
Traditional algorithm	0.164	0.398	0.621
The algorithm in literature [16]	0.102	0.301	0.583
The algorithm in literature [19]	0.084	0.312	0.561
The algorithm in literature [21]	0.092	0.246	0.547
Algorithm in this paper	0.068	0.251	0.511

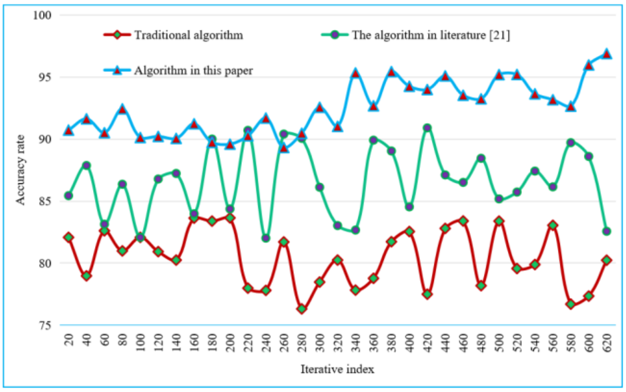

Figure 6. Accuracy results of algorithm.

The experimental results in **Table 2** and **Figure 6** show that the error of this algorithm is small and the accuracy rate is good. Among them, the accuracy rate is improved by 19.27% compared with the traditional algorithm. This proves that the performance of this algorithm is better.

Load test and stress test are both performance tests, and they can be combined. Through the load test, the performance of the system under various workloads is determined. The goal is to test the changes of various performance indicators of the system when the load gradually increases. Stress test is a test to obtain the maximum service level that the system can provide by determining the bottleneck or unacceptable performance point of a system. The interactive function of the system-patients can communicate with the virtual scene of ankle rehabilitation training through mutual understanding or language, and complete the functions of information management and processing for patients to the greatest extent. The interactive scoring results of the VR-based intelligent physical training system and the other two systems are shown in **Figure 7**. **Figure 8** shows the stability comparison results of different systems.

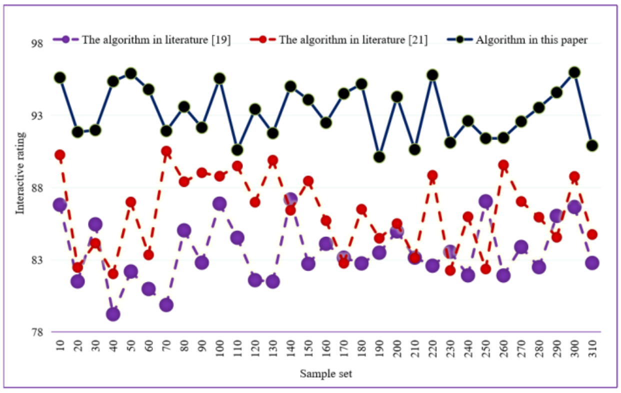

Figure 7. Interactive scoring results of different systems.

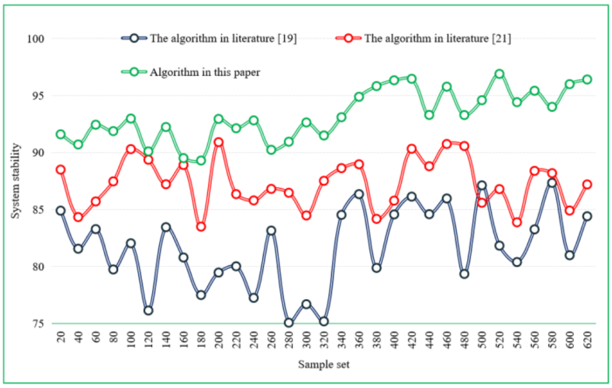

Figure 8. Comparison of system stability.

As can be seen from the scoring results in the figure, compared with other systems, this system has higher interactivity and higher stability. In addition, the experimental results in this section show that the error of this algorithm is small, the accuracy rate is better, and the accuracy rate is increased by 19.27% compared with the traditional algorithm.

This system realizes the real-time monitoring, mechanical evaluation and accurate feedback of athletes' rehabilitation training. By integrating high-precision mechanical sensors and advanced data analysis technology, the system can accurately capture and analyze the mechanical parameters, subtle movements and physiological reactions of athletes during training. This kind of mechanical feedback is helpful for athletes to adjust their training postures and strategies in time and optimize their action patterns according to mechanical principles. The intelligent physical training system, which integrates mechanical evaluation and training, is put forward in this paper, so that users can actively participate in the mechanical rehabilitation training of ankle joints. Compared with other systems, users will enjoy a more professional, accurate and immersive rehabilitation experience when using the intelligent physical training system based on VR technology and integrating mechanical evaluation. The system also has some limitations. The cost problem is a factor that cannot be ignored. The integration of high-precision sensors and advanced technology leads to the high cost of the system, which may limit its popularization and application scope. In terms of user adaptability, different athletes may have different acceptance and adaptability to the system, so it is necessary to further optimize the system design to improve user friendliness. Data security challenges can not be ignored, and a large number of sensitive data collected by the system need to be properly protected to prevent data leakage.

5. Conclusions

The development of intelligent physical training system based on VR technology and integrating mechanical evaluation and training provides an important way to solve the shortage of professional rehabilitation medical resources for athletes with ankle injuries. The system provides an efficient rehabilitation method for patients with ankle injuries, and to some extent alleviates the contradiction between the limited professional rehabilitation medical resources and the high demand of patients.

This paper analyzes the types and mechanisms of ankle joint injury, and combines the theories of rehabilitation medicine, sports anatomy and clinical medicine to construct the bionic mechanism model and rehabilitation movement model of ankle joint. As a multi-functional, safe and reliable rehabilitation tool, the proposed intelligent physical training system based on VR has significantly improved patients' enthusiasm and participation in the rehabilitation of ankle muscle function.

The experimental results of ADAMS software show that the rehabilitation path planned by the system has high accuracy, and the accuracy is improved by 19.27% compared with the traditional algorithm. This proves that the application of intelligent physical training system based on VR in the rehabilitation of athletes' ankle injuries can achieve good results and meet the needs of rehabilitation training and patients.

Although the system shows obvious advantages, it still faces challenges such as high cost, user adaptability, data security and specialization and personalization. In order to meet these challenges, future research will focus on reducing costs through technological innovation, optimizing user experience to cover a wider range of users, strengthening data protection measures, and working closely with rehabilitation medicine experts. In addition, efforts will be made to enhance the user-friendliness and interactivity of the system, so as to further enhance the application of the intelligent physical training system in the rehabilitation of ankle injuries.

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curation, LZ; writing—original draft preparation, LZ; writing—review and editing, LZ and ZY; visualization, LZ; supervision, LZ; project administration, LZ; funding acquisition, ZY. All authors have read and agreed to the published version of the manuscript.

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