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Design and Analysis of Flexible Exoskeleton for the Elderly Based on Deep Learning: From Rehabilitation Needs to Technological Innovation

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ABSTRACT

With the acceleration of the aging of the global population, the needs of the elderly for rehabilitation of movement disorders have become increasingly prominent. This paper aims to explore the potential of flexible exoskeleton design based on deep learning in meeting the rehabilitation needs of the elderly. By analyzing the limitations and challenges of existing technologies, this paper proposes a comprehensive solution and looks forward to its future development prospects. The article first introduces the background of population aging and the current situation and challenges of the rehabilitation of the elderly with motor disorders, and then expounds the social significance. In the working process of the device, the peripheral configuration and project implementation steps are introduced in detail. The discussion of key technologies focuses on the application of human intention recognition, dynamic adjustment algorithm. In addition, the paper also analyzes the existing problems of flexible exoskeleton equipment, and looks forward to the future development. Finally, the research results are summarized and the future development direction is prospected.

KEYWORDS

Deep learning; Flexible exoskeleton; Rehabilitation of movement disorders in the elderly; Human intention recognition

1. INTRODUCTION

With China entering an aging society, the problem of population aging is becoming increasingly severe. According to data from the National Bureau of Statistics, as of the end of 2022, the number of elderly people aged 60 and above in China has reached 28.04 million, accounting for 19.8% of the total population. The predicted data indicates that by 2050, this proportion is expected to surge to 34.9%[1]. In this context, movement disorders have become a common health issue among the elderly population, significantly affecting their quality of life and social participation. This trend indicates that the demand for elderly health security and elderly care services will continue to grow. However, there is a huge gap in medical rehabilitation services for the elderly in China, especially in the urgent need for rehabilitation assistive machines that can assist disabled elderly and disabled patients in rehabilitation training[2]. At present, the mainstream rehabilitation technologies for patients with movement disorders mainly include biofeedback technology and fine control technology for limb movements. However, both technologies face certain challenges in practical applications. Biofeedback technology often requires a long training cycle, high time and economic costs, and its effectiveness is easily affected by external factors, and its stability needs to be improved. However, fine control technology for limb movements lacks universality and requires personalized adjustments and design of rehabilitation plans based on the specific situation of patients. This not only puts higher demands on technical proficiency, but also increases the demand for professional personnel and financial investment[3].Therefore, the current society urgently needs a rehabilitation assistive technology that can reduce costs, improve efficiency, and meet the personalized needs of patients to cope with the increasingly severe challenges of aging[4].

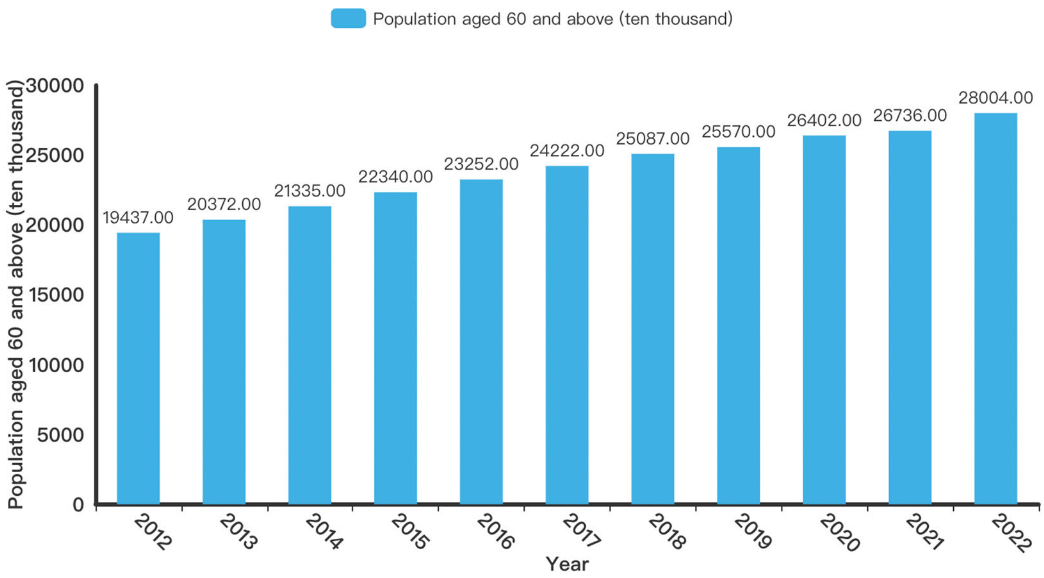

Fig. 1 Number of elderly people aged 60 and above in China from 2012 to 2022

In recent years, flexible exoskeleton, as an emerging technology, is gradually showing its great potential. This technology provides efficient strength and support for the elderly walking because of its close fitting, comfortable and lightweight characteristics. By combining artificial intelligence, control algorithm and sensing technology, flexible exoskeleton not only provides more sophisticated assistance for the elderly, but also helps to carry out and improve the training program. Compared with the traditional assistive device, the flexible exoskeleton is more convenient to use, which can improve the posture of the elderly during walking, improve the gait stability, and significantly reduce the occurrence of fall accidents. This not only avoids the risk of injury and pain, but also enhances the elderly's sense of well-being and social skills. In addition, the flexible exoskeleton is also easy to use, which enables the elderly to face daily activities more confidently, such as buying vegetables, walking, etc., without worrying about walking or falling. It is worth mentioning that the flexible exoskeleton design scheme based on deep learning, combined with key technologies such as human intention recognition, dynamic adjustment algorithm and PID control algorithm, can meet the rehabilitation needs of the elderly with movement disorders. This design scheme not only improves the use experience of the elderly, but also further ensures its safety. With the optimization of design to reduce costs, affordable flexible exoskeletons will be widely popularized, promoting the development of medical equipment manufacturing and domestic technology research, providing new possibilities for the rehabilitation of movement disorders in the elderly. This paper aims to explore the design scheme of flexible exoskeleton based on deep learning, and use the key technologies such as human intention recognition, dynamic adjustment algorithm and PID control algorithm to meet the rehabilitation needs of the elderly with movement disorders.

2. DESIGN AND IMPLEMENTATION OF FLEXIBLE EXOSKELETON BASED ON DEEP LEARNING

2.1. Configuration and integration of flexible exoskeleton peripherals

The peripheral configuration and integration of this exoskeleton device shows its advanced and humanized design in assisted walking and rehabilitation training, as shown in Fig. 2.

Fig. 2 Conceptual diagram of overall system architecture

The equipment is mainly composed of three parts: waist control bag, leg binding and shoe cover. The coordination mechanism between various parts ensures the stability and efficiency of the equipment. The lumbar control package sends corresponding commands according to the user's action intention and gait data, and the drive motor and reducer provide the necessary power, which is transmitted to the leg binding part through the Bowden line. The leg binding part ensures the fixation of the device and the stable transmission of power, and feeds back the user's action status and tension changes to the lumbar control pack[3]. The shoe cover is in direct contact with the user's feet, providing comfortable support and stable traction.

Table 1 List of exoskeleton hardware components and models

Component name	Model	Quantity	Function
Drive motor	Faulhaber 4372S036	2	Provides power
Reducer	Harmonic Drive CSH-20-100	2	Torque amplification and precise control
Force sensor	Freescale MXB2800	2	Uer interaction and force feedback
Inertial sensor	Invensense MPU-9250	3	Attitude and motion perception
Main controller	R-Car V3M	1	Data processing and control

As the "brain and heart" of the whole equipment, the lumbar control pack integrates key control components and power sources such as power module, main controller, motor, reducer, etc., and is responsible for controlling and providing power, as shown in Fig. 3. The power module provides continuous and stable power for the equipment and monitors the battery capacity. The main controller receives the data from the IMU sensor, processes and analyzes the user's action intention and gait, and then sends the corresponding command to the drive motor. The drive motor and reducer provide the necessary torque according to the command, and transmit the power to the leg binding part through the Bowden line[5].

Fig. 3 Design of waist control package

The leg binding part is a bridge connecting the waist control bag and the shoe cover, as shown in Fig. 4. It is responsible for fixing the equipment and ensuring smooth power transmission. The IMU sensor on the binding structure monitors the user's joint trajectory and posture changes in real time, and these data are transmitted to the main controller in the lumbar control package through IIC protocol. At the same time, the Bowden line fixing device ensures the stability and tension of the Bowden line, so as to ensure the accurate transmission of power[5][3].

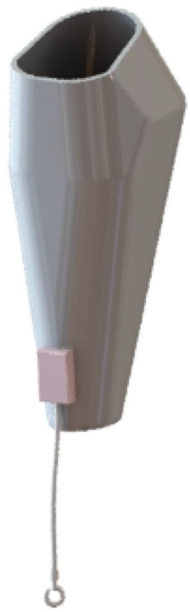

Fig. 4 Design of leggings

The shoe cover is in direct contact with the user's feet, which is the direct interface between the device and the user, as shown in Fig. 5. The shoe cover is made of flexible material, which fits the user's foot and provides comfortable support. The sole is closely contacted with the ground through the transmission mode of Bowden wire, providing users with stable grip and balance. At the same time, the force sensor on the shoe cover monitors the tension change in real time to provide feedback for the control processor, ensuring that the device will not exert too much pressure on the user while providing assistance[6].

Fig. 5 Design of Shoe cover

In general, the ankle assisted walking device for the elderly fully uses the excellent characteristics of machine learning technology for reference, and uses the lumbar power source and Bowden line transmission design to achieve a high degree of stability and flexibility. At the same time, the three parts are also designed with flexibility, making the device more in line with the basic principles of ergonomics when used. It has certain intelligent and personalized features, can accurately perceive and respond to the sports needs of the elderly, and provide more convenient and comfortable auxiliary services.

2.2. Implementation process of exoskeleton equipment

2.2.1. Acquisition of signal data:

The exoskeleton device comprehensively captures and records various biological parameters of the human chassis and lower limbs through a variety of IMU (inertial measurement unit) sensor technologies integrated inside. These parameters include but are not limited to posture, stress distribution, joint torque, etc., and are designed to obtain detailed motion data. These data are then transmitted to the main controller of the device for further processing.

2.2.2. Identify human intent:

In the main controller, the advanced machine learning algorithm is used to analyze the collected signal data in depth. The algorithm can accurately extract the signal features directly related to the action, and then quickly identify the human movement intention. For example, the system can distinguish different gait categories such as "start walking", "stop walking", or "turn left", "turn right".

2.2.3. Dynamic adjustment:

Once the human movement intention is recognized, the system will calculate the ideal gait posture and gait mode according to the preset algorithm and model. At the same time, the system will dynamically adjust according to the user's real-time physical conditions (such as fatigue, physical status, etc.), so as to ensure that the exoskeleton can assist walking in the way that best meets the user's needs, and provide personalized walking support.

2.2.4. PID control algorithm:

In order to accurately control the movement of the exoskeleton machine, the system uses PID (proportional integral differential) control algorithm. The algorithm can adjust and correct the walking force in real time, and ensure the stability of body posture in the process of movement. Through PID control, the system can reduce the deviation in the process of movement, and make the adjustment of exoskeleton closer to the natural state, so as to improve the accuracy and comfort of movement.

3. KEY TECHNOLOGIES AND CHALLENGES OF FLEXIBLE EXOSKELETON

3.1. Exoskeleton technology

3.1.1. Research meaning:

Exoskeleton technology is a revolutionary robot technology. It simulates and enhances the skeleton structure of the human body by wearing special mechanical devices outside the human body to provide users with motion support and strength enhancement. This technology aims to help people with physical impairment or disability recover their walking ability, improve their quality of life, and bring them more autonomy and independence.

Exoskeleton technology, as a cutting-edge mechanical auxiliary system, its key lies in the cooperation with human skeleton and muscle system. Through the structural framework worn outside the human body, the exoskeleton can share the burden of the human body, enhance muscle strength, improve gait stability, and help users carry out various daily activities. This technology integrates precise control system and advanced sensor technology, which can sense the user's movement intention, body posture and force demand in real time, so as to make corresponding response and adjustment, and ensure the cooperation and security between human and machine.

3.1.2. Construction of D-H model:

Denavit Hartenberg (D-H) model is a standard method in robotics and kinematics, which is used to describe the relative position and attitude between a series of interconnected rigid bodies (such as manipulator, exoskeleton, etc.). The D-H model simplifies the analysis of complex mechanical systems by defining a set of geometric parameters for each link and joint. The four key parameters are: connecting rod length(a), connecting rod torsion angle(α), Linkage offset (d) and joint angle(θ).

The link length (a) represents the distance from one joint axis to the next along the common normal direction; Connecting rod torsion angle(α)Represents the included angle between two adjacent joint axes, rotating around the common normal; The link offset (d) represents the distance from one joint axis to the next along the direction perpendicular to the common normal; Articular angle(θ)Indicates the rotation angle of the connecting rod around its joint axis.

The core of D-H model is its transformation matrix, which describes the pose transformation from one link coordinate system to the adjacent link coordinate system. The transformation matrix T consists of four basic transformations: first, rotate around the z-axisθ Angle, then translate a distance along the x axis, and then rotate around the x axis α Angle, and finally shift the distance d along the z axis. Mathematically, this can be expressed as:

$$T = Rot(z, \theta) * Trans(x, a) * Rot(x, \alpha) * Trans(z, d) \tag{1}$$

In which, Rot and Trans represent rotation and translation transformation matrices respectively.

By continuously applying these transformation matrices, the complete transformation of the entire mechanical system from the base coordinate system to the end actuator coordinate system can be calculated.

3.1.3. Significance of D-H model:

In exoskeleton technology projects, D-H model plays a crucial role. First, it provides a standardized framework for engineers to describe and analyze the geometric structure and kinematic characteristics of exoskeleton system. By clearly defining the parameters of the connecting rod and joint, the D-H model promotes the clarity and consistency of the system design.

Secondly, D-H model plays a key role in kinematic parameter identification. These parameters include link length, link twist angle, link offset and joint angle, which are critical to accurately control the exoskeleton motion. By collecting and processing sensor data (such as encoder readings and inertial measurement unit data), these parameters can be accurately identified and calibrated to ensure that the exoskeleton system moves as expected.

In addition, the D-H model also supports efficient motion planning and control algorithm development. By using the transformation matrix, engineers can calculate the joint commands required to move from one pose to another, so as to achieve accurate motion control. This is crucial for realizing the complex functions of exoskeleton system, such as assisted walking, posture adjustment, etc.

Finally, D-H model also has practical application value in the calibration and maintenance of exoskeleton system. Due to manufacturing errors, component wear and other factors, the exoskeleton system may need to be calibrated regularly to ensure its performance. D-H model provides a systematic method to adjust system parameters to compensate these errors and deviations, thus improving the stability and reliability of the system.

3.2. Sensor technology

3.2.1. Research significance:

In the elderly ankle walking aid system, the combination of sensor technology and information processing technology has far-reaching significance. These technologies not only significantly improve the accuracy and effect of the system's motion control, but also provide more personalized, efficient and convenient services for the elderly. Through real-time collection and analysis of gait data, physiological signals and environmental information of the elderly, the system can more accurately assess the movement status and needs of the elderly, so as to provide them with more accurate and effective rehabilitation training support. This will not only help improve the quality of life of the elderly, but also play a huge potential in medical treatment, rehabilitation and other fields, and make positive contributions to social welfare.

3.2.2. Research objectives:

The purpose of this research is to monitor and extract biomechanical information data through the application of IMU sensor in the ankle joint assist machine system. The specific objectives are as follows[6]:

Installation and configuration of IMU sensor: install an IMU sensor near the ankle of the elderly to ensure that the sensor can stably and reliably collect the posture angle, motion state, acceleration and other data of the human body.

Data acquisition and processing: develop special programs for real-time acquisition, storage and processing of raw data output by IMU sensors. This includes data cleaning, filtering, noise reduction and calibration to ensure the accuracy and reliability of data.

Motion state estimation: using mathematical models and algorithms, the data collected by the IMU sensor are analyzed and calculated in depth to calculate the motion state parameters of the human body, such as displacement, velocity and acceleration, and further calculate the angle and motion trajectory of each joint of the human body.

Biomechanical information extraction: based on the processed biomechanical information data, combined with the estimation results of the motion state, calculate the key indicators such as the axis and the center of mass, so as to extract valuable biomechanical information.

Control strategy design and implementation: according to the extracted biomechanical information data, design targeted control strategies, and use advanced control algorithms to adjust and change the working mode of the exoskeleton robot. This is designed to better adapt to the movement mode of the elderly, provide more accurate and personalized assistance, so as to help them more easily carry out rehabilitation training or daily activities.

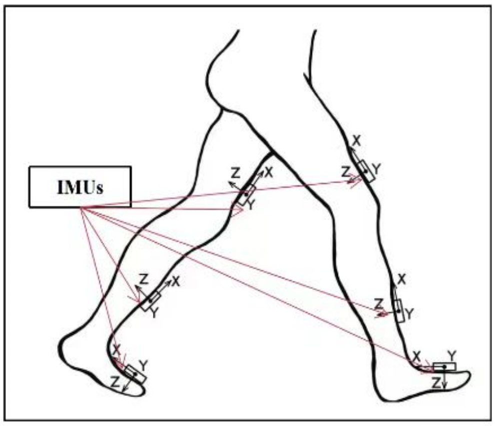

Fig. 6 Data acquisition based on IMU

3.3. Gait analysis and prediction technology

3.3.1. Research objectives

Because motion prediction is essentially a time series prediction problem, and the human body shows the overall periodicity when walking normally. This means that in the same environment and gait, the angle and acceleration information captured by the sensor are generally similar. However, the gait among individuals will be fine tuned at each step, which makes the gait unique. For this kind of time series prediction problem, the academia generally believes that deep neural network is an effective tool to capture information. Therefore, a major research focus of this project is the application of time series algorithm to accurately predict human action[7].

3.3.2. Gait analysis technology

Gait analysis plays an important role in the rehabilitation training of the elderly. By evaluating the gait characteristics, stability, muscle strength and balance ability of the elderly and other key indicators, researchers can better understand the walking patterns of the elderly, so as to create personalized rehabilitation training programs for them. In addition, gait analysis can effectively detect the stability and regularity of the gait of the elderly, timely find and deal with potential problems, and reduce the risk of falls in the elderly.

Moreover, gait analysis also provides a valuable data base for gait prediction. By carefully analyzing the gait characteristics and historical data of the elderly, an accurate prediction model can be built to predict the future gait state of the elderly. These prediction results can further optimize the rehabilitation training plan, adjust the personalized assistance parameters of the exoskeleton system, and improve its adaptability and effect.

Sensors play a key role in the implementation of gait prediction. By collecting data and combining with support vector machine (SVM) algorithm, we can effectively group the data and accurately predict each group of data. Although SVM and convolutional neural networks (CNNs) have their own advantages in time series prediction, their combination can provide us with a more comprehensive perspective. SVM is good at processing input data and identifying its state, while CNN makes accurate prediction on this basis.

For the data obtained from sensors (such as pressure sensors and IMU sensors), we first clean them, and then use the sampling point (time) as the horizontal axis to draw the sampling point (time) - angle image for data integration and conversion. Each key sample point is represented as a vector. Because the SVM algorithm can separate the data of different stages or modes by calculating the hyperplane in the two-dimensional coordinate system, we can treat the separated data as different stages in motion, so as to predict and analyze gait more accurately.

Suppose we have linearly separable training data points[8][9]:

$$(x_1, y_1), \dots\dots, (x_n, y_n) \text{or point set } D = (x_i, y_i) \quad (2)$$

D is the sample training set.

y_i is the label used to identify the mode to which the data point belongs.

x_i is the eigenvector, which is a p-dimensional real vector.

Under these conditions, we can define a hyperplane to separate data:

$$w^T \cdot x + b = 0 \quad (3)$$

Where w is the normal vector of the hyperplane, x is a point on the hyperplane, and b is the offset term (or intercept).

To determine the distance d from the data point to this hyperplane, we can use the following formula:

$$d = \frac{|w^T \cdot x + b|}{\|w\|} \quad (4)$$

When certain conditions are met, this hyperplane can separate the two types of data and indicate the category with label y, in the form as follows:

$$w^T \cdot x + b \geq 1, \text{when } y = 1 \quad (5)$$

Or

$$w^T \cdot x + b \leq 1, \text{when } y = -1 \quad (6)$$

In order to maximize the sum of the distances between the two sets of data points closest to the hyperplane.

$$d = \frac{2}{\|w\|} \quad (7)$$

And we can convert it into an optimization problem[10]:

$$\begin{cases} \underset{w,\ b}{\text{minimize}}\ \frac{1}{2}\|w\|^2 \\ \text{subject to}\ \ y_i(w^T \cdot x + b) \geq 1 \end{cases} \tag{8}$$

The goal is to find the optimal W and B. The final decision function can be expressed as[8]:

$$f(x) = \text{sgn}(w^T \cdot x + b) \tag{9}$$

When solving SVM problems, we often use Lagrange multiplier method to deal with constrained optimization problems. This optimization problem is usually a convex quadratic programming problem. To this end, we introduce Lagrange function[11]:

$$L(w, b, \alpha) = \sum_{i=1}^{N} \alpha_i (1 - y_i(w^T \cdot x + b)) + \frac{1}{2}\|w\|^2 \tag{10}$$

In order to find the optimal solution, we first need to find the stationary point of Lagrange function, and then solve the Lagrange duality problem. Lagrange dual problem is obtained by solving the minimax problem of Lagrange function, where maximization is carried out on Lagrange multipliers, while minimization is carried out on original parameters. In this way, we can get the optimal solution and find the optimal $w'$and b'.

$$f(x) = \text{sgn}(\sum_{i=1}^{N} a_i' y_i (x_i x_j) + b') \tag{11}$$

When the data sample is linearly separable, the above f(x) decision function is the optimal plane. However, this hard boundary segmentation method requires that the data must be completely separable. In order to deal with the nonlinear separable case,we introduce the soft boundary SVM. Soft boundary SVM is more robust by introducing a penalty term (usually C parameter) to balance the size of the interval and the number of misclassification[8][10]. In this case, our optimization problem is from

$$\begin{cases} \underset{w,\ b}{\text{minimize}}\ \frac{1}{2}\|w\|^2 \\ \text{subject to}\ \ y_i(w^T \cdot x + b) \geq 1 \end{cases} \tag{12}$$

to

$$\begin{cases} \underset{w,\ b}{\text{minimize}}\ \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{N} \zeta_i \\ \text{subject to}\ \ y_i(w^T \cdot x + b) \geq 1 - \zeta_i,\ \ \zeta_i > 0 \end{cases} \tag{13}$$

Other steps are consistent with the previous hard boundary method.

3.3.3. Gait prediction technology

Gait prediction technology is the most crucial link in the ankle joint walking aid system for the elderly, and it is also the focus of this project's research. Gait prediction technology refers to analyzing the movement characteristics of the elderly's body during walking, in order to predict the next walking pattern, joint movement trajectory, torque requirements and other parameters.

In flexible exoskeleton machine systems, gait prediction technology can improve the system's response speed and accuracy, enabling the system to better adapt to user needs and environmental changes, and provide more intelligent support. For example, when elderly people use assistive exoskeletons, the algorithm can adjust the output of the motor in real-time based on the user's walking status and body posture, making the assistive effect of the exoskeleton more natural and comfortable, and avoiding situations such as falls or accidental injuries during walking.

Therefore, gait prediction technology is one of the very important technologies in the flexible exoskeleton machine system for elderly ankle joint assisted walking with cable transmission. It will promote the development of flexible exoskeleton robots, improve the quality of life of the elderly, and help to deeply explore the potential of exoskeleton robots in daily operations, assisted therapy, and rehabilitation treatment.

As a predictive model, there are many algorithms that can be used. Convolutional neural networks (CNNs) can be used for learning here. Although convolutional neural networks are usually used for training images, they can still be trained and predict the current content based on model modifications. Because the SVM algorithm has been used to classify the data, it means that category labels have been assigned to each sample. Therefore, these labeled datasets can be used as training datasets for CNN models. Before transferring data to the CNN model, it is necessary to ensure that the format of the data is consistent with the expected input format set by the model.

So, it is necessary to build a CNN model and design a CNN model suitable for processing temporal data. When designing the model, considering the characteristics of temporal data, one-dimensional convolutional layers and pooling layers can be used to extract temporal features, because for example, time series can be seen as a one-dimensional network sampled at fixed time intervals. The architecture of the CNN model can be adjusted and optimized according to the characteristics of your data and prediction tasks. Subsequently, use the SVM processed dataset as the training set to train the CNN model. During the training process, monitor the loss function and performance indicators of the model, and update and optimize the model parameters.

CNN uses the mathematical operation of convolution, and its default formula is applicable to two-dimensional data, such as images. However, in this model, it should be adjusted to one dimension to adapt to the characteristics of time series:

The mathematical operation of one-dimensional convolution is as follows:

$$y[t] = \sum_{k=0}^{K-1} w[k] \cdot x[t + k] \tag{14}$$

Where $y[t]$ is the t-th element of the output sequence, $w[k]$ is the k-th coefficient of the convolution kernel, $x[t + k]$ is the value of the input sequence at the $t + k$ position, and k is the size of the convolution kernel.

The one-dimensional convolution operation moves the convolution kernel along the time dimension of the sequence (or the dimension of other one-dimensional features), so as to extract the local patterns and features in the sequence. The subsequent one-dimensional convolution operation usually combines other layers for feature extraction and prediction, which is not significantly different from the operation of standard CNN.

Therefore, SVM can be used to analyze gait and clean up classification data, and then the data can be transferred to the adjusted one-dimensional CNN model for training and prediction, so as to achieve accurate prediction of time series. This model architecture allows to better adapt to the characteristics of time series data, so as to improve the application of gait prediction technology in the elderly ankle assisted flexible exoskeleton machine system.

4. CONCLUSION AND DEVELOPMENT PROSPECT

4.1. Summary and evaluation on the application of flexible exoskeleton design in the field of rehabilitation for the elderly

The flexible exoskeleton design scheme based on deep learning in this paper accurately meets the rehabilitation needs of the elderly with movement disorders under the background of the current aging population. Through deep learning and advanced sensing technology, the program is expected to not only provide a more comfortable and efficient rehabilitation experience, but also show great potential in personalized customization and intelligent assistance. This innovative research not only solves the problems of the existing flexible exoskeleton equipment, but also opens up a new path for the development of technology in the field of rehabilitation.

4.2. Improvement suggestions and development strategies for existing problems and challenges

Aiming at the problems of data privacy, algorithm bias and technology out of control in the field of artificial intelligence, this paper puts forward some improvement suggestions and development strategies. Firstly, by strengthening data privacy protection, such as using differential privacy, homomorphic encryption and other technical means, the security and privacy of user data are ensured, which lays a trust foundation for the wide application of flexible exoskeleton technology. Secondly, the fairness of the algorithm is improved. By introducing multiple evaluation indexes and establishing algorithm audit mechanism, the algorithm bias is reduced and the fairness and impartiality of technical decision-making are ensured. Finally, strengthening technical supervision and establishing sound technical ethics ensure the controllability and reliability of AI technology, which provides a strong guarantee for the sustainable and healthy development of flexible exoskeleton technology.

4.3. Prospects and expectations for future research directions and practical applications

Looking forward to the future, with the continuous progress of artificial intelligence technology, the application of flexible exoskeleton in the field of elderly rehabilitation will be more extensive and in-depth. We look forward to seeing more innovative applications of cutting-edge technologies such as cross modal learning and adaptive learning in the design of flexible exoskeleton, so as to further improve the performance and user experience of the device. At the same time, it is also expected that flexible exoskeleton technology can play an important role in more fields such as medical health, environmental protection, education and training, and create a better future for mankind.

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