Proceedings of 2021 IEEE
International Conference on Mechatronics and Automation
August 8 - 11, Takamatsu, Japan

Design of the Lower Limb Rehabilitation Training System Based on Virtual Reality

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Abstract - Cerebral apoplexy is easy to cause nerve damage, which brings a lot of inconvenience to patients' life. A large number of studies have shown that rehabilitation training through the use of rehabilitation robots can have a very positive impact on the injury of stroke patients. In this paper, a virtual reality rehabilitation training system based on the lower limb rehabilitation robot of our team was proposed, which organically combined visual feedback, vibration feedback and sound feedback with the lower limb rehabilitation robot. First of all, a standard human body model was established. According to the ergonomics principle, the common movements of lower limb rehabilitation were made into standard animations. We have built the mannequin here and import the mannequin into the virtual reality software. Through the communication between the MCU and the virtual reality software, the patients can realize the visualization in the process of rehabilitation training.

Index Terms - Rehabilitation robot, Virtual reality, Visual feedback, Vibration feedback, Voice feedback

I. INTRODUCTION

Every year hundreds of thousands of people suffer from stroke, unfortunately is very easy to cause permanent disability, stroke in patients with stroke disease outbreak will interrupt blood flow to the brain, blood will release toxic substances, which can lead to physical damage, muscle weakness, loss of feeling, the symptom such as cognitive impairment, serious can lead to hemiplegia patients, leading to lower limb dysfunction, unable to walk normally, quality of life will be severely affected[1]. Although it is difficult for most patients to recover 100% after muscle damage, a large number of studies have shown that through active rehabilitation training, most stroke patients can recover most of their physical functions and live on their own. At present, rehabilitation robots are developing rapidly, and many kinds of rehabilitation robots have been born, such as single-degree-of-freedom robots, wearable robots and weight-loss walking rehabilitation robots[2].The single-degree-of-freedom robot looks simple in structure the operation is simple, high performance, the application is currently on the market the most robots. Fig.1 is the most representative limbs rehabilitation robot linkage, wearable rehabilitation robot. The robot helps patients with disability in their lower extremities undergo rehabilitation training. And it can help patients recover certain walking ability to a certain extent. It is mainly used in mid and late and rehabilitation, gait rectified, wearable robot can help patients with gait correction can help lighten the load[3].

Fig. 1 Limb linkage rehabilitation robot

With table sit horizontal rehabilitation robot was developed by Japan Yaskawa electric corporation LR2. It has 6 kinds of training model, smooth, fine display installed physical therapy techniques, the interaction of human and machine created a new mode of rehabilitation training. LR2 runtime start up various monitoring function, through the contact sensors, equipment load displacement monitoring, patients of tenderness of control and emergency stop switch to monitor patients and the state of the system[4]-[6].

The rehabilitation robot also has a lot of problems, however, heavy, inflexible, etc. The most important thing is that the price is very expensive, often, dozens or even hundreds of millions of ordinary patients difficult to afford, and cannot directly observe their recovery status. In the long convalescence gradually lost interest, lead to recovery by the wayside, and virtual reality is now booming technology, compared with traditional robot virtual reality has the price is relatively cheap, brings the immersive experience, as well as the advantages of improving the user experience[7]. It is a development trend of rehabilitation medicine to apply virtual reality to rehabilitation robots, because there is already evidence that the rehabilitation effect will be more obvious when patients have active willingness to recover, and virtual reality technology improves patients' active willingness to

978-1-6654-4098-1/21/$31.00 ©2021 IEEE

recover, which has a very positive effect on patients' rehabilitation.

In recent years, our team has carried out a lot of research on it. Based on the research of, this study will develop a set of lower limb rehabilitation training system based on virtual reality. Lower limb rehabilitation movement data is picked by three-axis inertial attitude sensor, through the laboratory of lower limb model to interact with virtual reality software, through the action of repeated training can be very good for rehabilitation training, real-time visual feedback but let patients observed their own motion, provide real-time motion data to prevent action is not standard cause secondary damage, at the same time can make the training more interesting.

The following is a brief introduction to the content of this paper. Section IIis an overview of the system, which mainly introduces the system process, sensor data acquisition and data processing, attitude calculation and Kalman filtering of the character model, as well as the application of Arduino development board and sensor. Section III is about the production of character model, animation production and the interactive control of Arduino and Unity character model. Section IV of the experiment and conclusion, mainly introduces the lower limb rehabilitation robot and virtual reality combined experiments and experimental results. Section Vis the summary and prospect of the whole article.

II. System Overview

This design establishes the model and animation of the system in Maya software. Use Unity3D software to build training scenes[8]. In this article, the virtual character is introduced to synchronize data with the lower limb robot. The upper computer plays the presupposed rehabilitation actions, and the patient learns the actions in the animation, drives the model uniformly, and observes the actions of the patient. Safety thresholds for the patient's trunk and back during rehabilitation exercise were set to prevent the patient from secondary injury caused by non-standard movements[9]. The overall block diagram of the system is shown in Fig. 2.

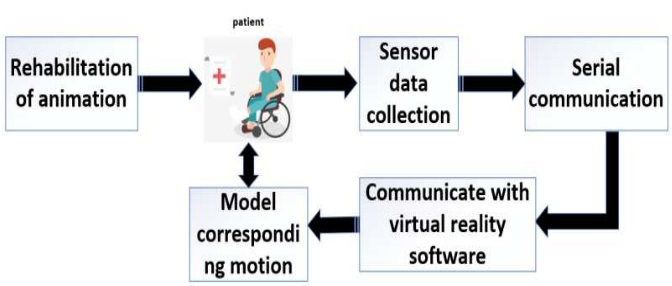

Fig. 2 System block diagram

A. Sensor data acquisition and processing

In this paper, the sensor MPU6050 is used for data acquisition, which consists of four parts: accelerometer, gyroscope, DMP and temperature sensor[10].

Formally known as six axis Motion gyroscope sensor can measure 3 d acceleration, the three dimensional angular velocity and the three dimensional point of view, is referred to as "six axis", because it is a 6 axis Motion processing components, contains 3 shaft axis of gyroscope, accelerometer and 3 can be output triaxial acceleration and three-axis angular velocity, respectively, and then according to the above the original data in DMP (Digital Motion Processor, Digital sports Processor) calculated using algorithm fusion of three axis Angle data[11].

(1) Attitude solution method

In the three-dimensional space, the world coordinate system can better help us obtain the specific position of the target. The coordinate system of the sensor MPU6050 is shown in the figure below. Therefore, in order to better obtain the data of the sensor, we need to settle all directions of the sensor[11].

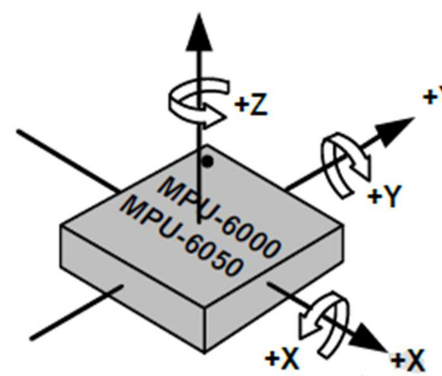

Fig. 3 The coordinate system of MPU6050

The MPU6050 provides attitude measurement and resolution, in which there are several important concepts, Euler Angle and quaternion being the two most important concepts[12].

Euler Angle is used to represent the rotation of an object around the coordinate axis in three-dimensional moving space, that is to say, the posture of an object at any moment in the process of motion can be represented by Euler Angle. This method is the most common way of representing the position of an object.

Quaternion is a super complex number, Q = (Q0, Q1, Q2, Q3), the first is the real number, the last three is the real number of the imaginary part, can be understood as a four-dimensional space, that is, the original three-dimensional space with a rotation Angle added. It is more convenient to express Euler angles in terms of quaternions[13]. The following part will explain how the Euler Angle is converted into a quaternion

Firstly, Euler Angle is used to describe a plane rotation, that is, coordinate transformation The initial position of the coordinate system is the familiar plane rectangular coordinate system, which can be rotated by a degree counterclockwise to obtain a new coordinate system. The schematic diagram is shown in Fig. 4. A new coordinate system can be obtained after the coordinate system rotates by an Angle of α[12]. The relationship between vectors after rotation is shown in Equation (1).

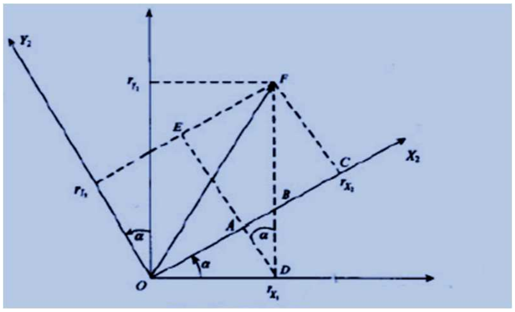

Fig. 4 Rotate the coordinate system

$$\begin{cases} r_{x2} = OA + AB + BC \\ r_{y2} = DE - AD \end{cases} \tag{1}$$

Convert that to matrix form:

$$\begin{bmatrix} r_{x2} \\ r_{y1} \\ r_{z1} \end{bmatrix} = \begin{bmatrix} cos\,\alpha & sin\,\alpha & 0 \\ -sin\,\alpha & cos\,\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{x1} \\ r_{y1} \\ r_{z1} \end{bmatrix} \tag{2}$$

After sorting out, we get:

$$r^1 = \begin{bmatrix} r_{x1} \\ r_{y2} \\ r_{z1} \end{bmatrix} \tag{3}$$

$$r^2 = \begin{bmatrix} r_{x2} \\ r_{y2} \\ r_{z2} \end{bmatrix} \tag{4}$$

$$C_1^2 = \begin{bmatrix} \cos\alpha & sin\,\alpha & 0 \\ -sin\,\alpha & cos\,\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5}$$

Where C is a rotation matrix. If the Euler Angle in three-dimensional space rotates three times (suppose that ψ, θ, γ are rotated about the three axes of ZYX respectively), the following matrices can be obtained:

$$C_n^b = C_2^b C_1^2 C_n^1 = \begin{bmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos\gamma\cos\varphi + \sin\gamma\sin\theta\sin\varphi & -\cos\gamma\sin\varphi + \sin\gamma\cos\varphi\sin\theta & -\sin\gamma\cos\theta \\ \sin\varphi\cos\theta & \cos\varphi\cos\theta & \sin\theta \\ \sin\gamma\cos\varphi - \cos\gamma\sin\theta\sin\varphi & -\sin\gamma\cos\varphi - \cos\gamma\cos\varphi\sin\varphi & \cos\gamma\cos\theta \end{bmatrix}$$

To see attitude of Euler angles is intuitionistic and easy to understand, but the amount of calculation is very big, so we introduce the quaternion, the quaternion is a four dimensional space, for the convenience of said, we use q = (x, y, z), (w) = (v, w), in which v is a vector, w is real, the formulas to represent a quaternion, through a computer can converts Euler Angle quaternion, this sensor can control the characters in the animation model, and the error is small[14].

(2) Kalman filtering

Since we collect the attitude data of the sensor in real time, to make the data more accurate, we need to denoise the data[15]. Kalman filtering does not require the assumption that both signal and noise are stationary processes. For the system perturbations and observational errors at each moment, by processing the observational signals containing noise, an estimate of the true signal with the smallest error can be obtained in the sense of average, provided that some appropriate assumptions are made about their statistical properties[16][17].

The process of Kalman filtering is roughly as follows:

Step 1 the state variables are extrapolated forward

$$\hat{x}_{\bar{k}} = A\hat{x}_{k-1} + Bu_{k-1} \tag{6}$$

Step 2 calculate the error covariance

$$P_{\bar{k}} = AP_{K-1}A^T + Q \tag{7}$$

Step 3 calculate the Kalman gain

$$K_k = \frac{P_{\bar{k}}H^T}{HP_kH^T + R} \tag{8}$$

Step 4 the estimate is updated by the observed variable ZK

$$\hat{x}_K = x_{\bar{k}} + K_k(zk - H\hat{x}_{\bar{k}}) \tag{9}$$

Step 5 update the measurement error

$$P_k = (I - K_kH)P_{\bar{K}} \tag{10}$$

Some of the letters mean: X_{k-1} and X_K represent the posterior state values at time k-1 and k, respectively.

P represents the covariance, H is the transformation matrix of the state variable to the measurement, and ZK is the input of the measurement to the filtering.

In this paper, Kalman filtering was used to fit the collected data for denoising. The results are shown in Fig. 5, which shows that the data fitting degree after filtering is good.

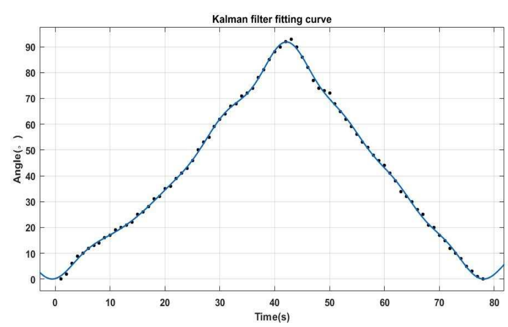

Fig. 5 Kalman filter fitting curve

B Vibration feedback and sound feedback

Studies have shown that visual feedback is considered to be the most complex feedback. Indirectly, visual feedback dominates other sensory feedback, but sometimes visual feedback can be confused[18]. To solve this problem, tactile feedback and visual feedback are introduced.

Auditory feedback can timely help patients to point out the non-standard degree of movement in rehabilitation training, convey important information to patients, and put forward the matters needing attention in the next cycle of training.

Vibratory haptic feedback has the characteristics of safety and low delay, and will not cause any harm to patients.

Therefore, vibration feedback is often applied to favor patients' rehabilitation. The vibration feedback adopted in this paper is a vibration motor module, which is cheap, has strong vibration sense, obvious feedback, small volume and low delay time, which is in line with the design of this paper.

III. Model Building

For human lower limbs can't normal operation caused by stroke, rehabilitation exercise is an important way to restore the body function, for patients with early rehabilitation, does not need the movement of large and complex, but should pay attention to the frequency and normative rehabilitation exercise, avoid the secondary damage during rehabilitation, below is the early rehabilitation of lower limb commonly used a few simple actions[19].

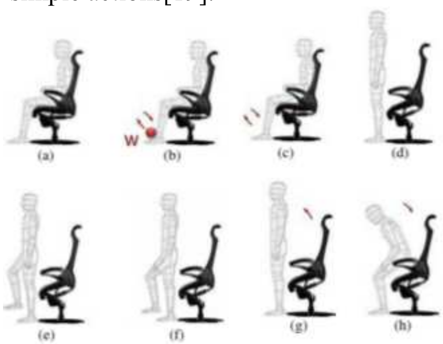

Fig. 6 Moving down to common rehabilitation movements

A. *Animation model making*

In this paper, Maya software is used for animation production. The content of the production is several commonly used lower limb rehabilitation movements in the figure above. The above several rehabilitation movements are based on sitting posture, and for the purpose of stimulating muscles, they are respectively sitting, flexing legs and stretching legs, sitting up, standing on one foot and reset[20].

A team of researchers in Thailand recruited dozens of volunteers and had them bend their heads every two minutes. They found that bending their heads at an Angle of 0 to 15 degrees had the lowest overall muscle tension and was most effective in preventing neck pain. The offset Angle of human head is shown in Fig. 7.

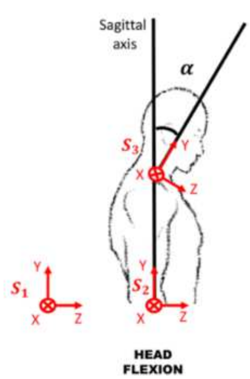

Fig. 7 Neck safety threshold


Fig.8 Animated character model

Similarly, the offset Angle of the trunk during the rehabilitation exercise is similar to Fig. 6.

When making animation, the character model is first established in Maya, and then the character skeleton is bound and the character skin is rubbed. The animation model is completed through the complete modeling process, and the model is shown in Fig.8.

B. *Unity3D character model.*

In the same way, create another character model in Maya and import it into Unity3D.

Unity3D is a very excellent game engine software, which is also the key to realize human-computer interaction.

After the model is imported into Unity, the Unity control script is established in it. In order for the sensor to control the characters in Unity, the communication between Unity and Arduino should be written first, so that the data captured by the sensor can be transmitted to Unity. In the scene of Unity, the code controls the bones of the characters and further controls the characters through the bones.

IV. Experimental Results

A Lower limb rehabilitation robot.

This article is based on the lower limb platform of our team. As shown in the Fig. below, the robot is composed of seven parts. After being worn, it penetrates the entire lower limb of the person. It consists of thighs, legs and other basic structures. In order to enhance the wearability, it also has a waist structure, so that it can be worn more firmly. At the same time, the four motors not only ensure enough power, but also control the weight of the whole robot. The thigh, knee, and lower leg are connected in sequence, which has sufficient flexibility. While ensuring wearing comfort, a safety threshold is set to prevent accidents. The robot is equipped with a pressure sensor to determine the user's movement intention according to the pressure of the user's legs in various directions, to change the motor speed to obtain different torques, and to provide a rehabilitation platform for the patient. Previous research has proved the reliability and practicability of the platform. The schematic diagram of the robot platform structure is shown in Fig. 9.

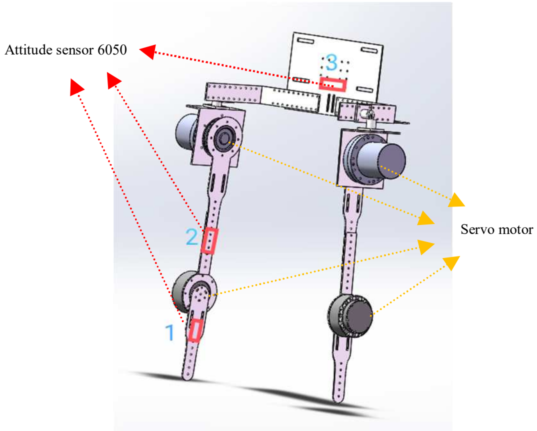

Fig.9 Robot structure

As the rehabilitation movement is a continuous process, it requires high control accuracy. If hydraulic and pneumatic transmission are adopted, the control accuracy and response speed will be greatly reduced. However, the motor transmission has a fast response speed, and the control method is simple and high precision. Patients wear the robot to complete virtual reality rehabilitation training, so the selection of sensor position is very important. In the second chapter of this paper, the selection of sensor direction under world coordinates has been introduced, and the following will analyze where the sensor needs to be placed. The sensor can be fixed on the human body, but it is more troublesome, and easier to fall off, so this design will be fixed on the sensor rehabilitation robot. Already know in unity3d, movement is one of the characters by controlling the bones in the body further control character movement, so all people bone places need to put sensors, this sensor placement is roughly coinciding with the robot's legs, waist, after testing the sensor location in red highlighted above. Since both the robot and the character model mentioned in this paper are symmetrical, the sensor position on the other side is in a symmetrical position.

B The experimental results.

This article mentioned each standard rehabilitation action time as follows, the first is seated, as ready to action, time of 168 frames, 2 it is seated leg, the leg lift 90 ° 120 frames, action process 48 frames, the next move is to stand, the time length of 240 frames, the last action to stand on one foot, the time length of 168 frames, standards of animation is beautiful mark contains 24 frames.

After all the actions have been played, the animation returns to the initial state, and each action continues to be repeated. The following four pictures represent a part of each action when the animation is played.

In this article chose the five healthy subjects, respectively, for many times without any feedback training, training with visual feedback and visual feedback and vibration feedback of training, training with visual feedback vibration feedback and auditory feedback, record bend sensor values, observe each training neck and back beyond the number of preset thresholds to prove that a variety of sensory feedback training attitude play a positive role on the patients.

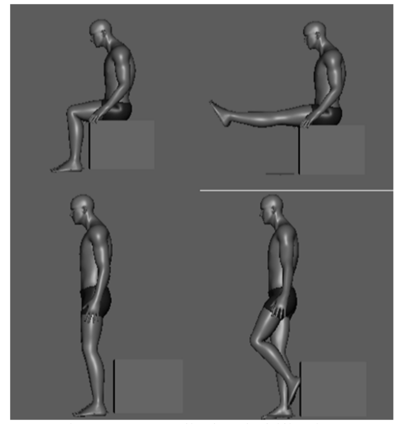

Fig. 10 Lower limb rehabilitation

The experimental results are shown in Fig. 11 and Fig. 12. Fig. 11 is the value of the torso bending sensor and Fig. 12 is the value of the back value of the torso bending sensor.

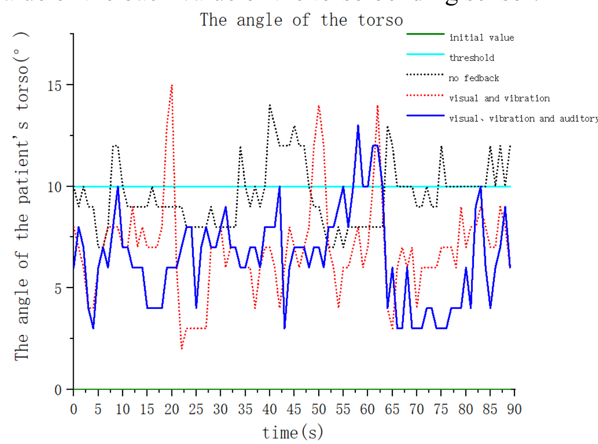

Fig. 11 Angle of torso bending sensor

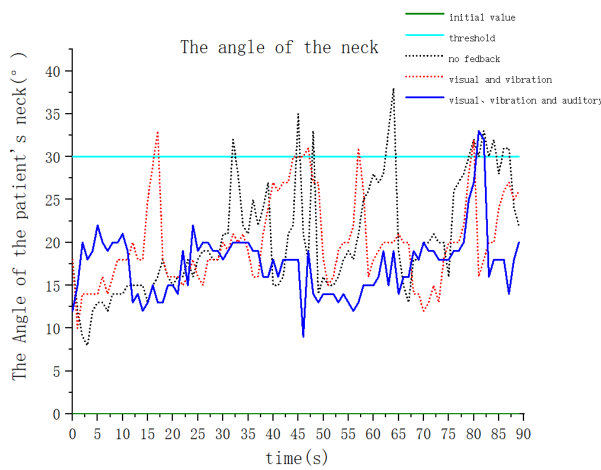

Fig. 12 Angle of neck bending sensor

In the two pictures, the green curve is the initial value of the sensor, the curve of the light blue respectively represents the preset threshold of the trunk and neck, exceeds the threshold, will be accompanied by the emergence of vibration feedback and voice feedback. The black dotted line means no feedback when subjects were recovered when the torso and neck point of view, the red dotted line refers to the visual feedback and vibration under the action of the participants of the trunk and neck Angle, the blue line refers to the visual feedback, vibration and sound feedback subjects under the Angle of the trunk and neck.

From the experimental data of matching curve we can see intuitively, without any feedback within 0-90 subjects with an average of eight times more than the presupposed safety point of view, more visual feedback and vibration feedback numerical for 5 cases, with visual feedback under the condition of vibration feedback and force feedback, change value is 1, and the subjects in the three feedback, under the joint action of immediately correct the posture of the individual, returned to the suitable Angle range. The same experimental conclusion exists in Fig. 12.

V. CONCLUSIONS AND FUTURE WORK

This paper puts forward a new idea of combining virtual reality technology with rehabilitation robot. Through the experiment, it is concluded that when the visual feedback, vibration feedback and sound feedback are combined, the patients can carry out rehabilitation exercises within the range of safe Angle to the greatest extent. For many stroke patients, rehabilitation is a very important part, so the starting point of this paper is how to greatly improve the patient's interest in rehabilitation at the lowest cost, and presents a visual rehabilitation during rehabilitation to greatly avoid the occurrence of secondary injury.

In the future work, we will continue to improve this design, add virtual reality games to improve the user's sense of participation, and then improve the rehabilitation evaluation method.

ACKNOWLEDGMENT

This research is supported by National Natural Science Foundation of China (61703305)；Key Research Program of the Natural Science Foundation of Tianjin (18JCZDJC38500) and Innovative Cooperation Project of Tianjin Scientific and Technological Support (18PTZWHZ00090).

REFERENCES

[1] G. Florian, N. Georgios, and G. Alireza, “Compensation or Restoration: Closed-Loop Feedback of Movement Quality for Assisted Reach-to-Grasp Exercises with a Multi-Joint Arm Exoskeleton,” *Frontiers in Neuroscience*, Vol. 15, pp.1201–1215,2016.

[2] S. Guo, H. Cai, and J. Guo, “A Method of Evaluating Rehabilitation Stage by sEMG Signals for the Upper Limb Rehabilitation Robot,” *International Conference on Mechatronics and Automation,* pp.1338-1343, 2019.

[3] S. Guo, Z. Wang, J. Guo, Q. Fu, and N. Li, “Design of the Speech Control System for an Upper Limb Rehabilitation Robot Based on Wavelet De-noising,” *International Conference on Mechatronics and Automation*, pp.2300-2305, 2018.

[4] J. Yoon, B. Novandy, and C. Yoon, “A 6-DOF gait rehabilitation robot with upper and lower limb connections that allows walking velocity updates on various terrains,” *ASME Trans Mech*, Vol. 15, pp. 201–215,2016.

[5] Y. Liu, S. Guo, H. Hideyuki, I. Hidenori, and T. Takashi, “Development of a powered variable-stiffness exoskeleton device for elbow rehabilitation,” *Biomedical Microdevices*, Vol.20, No.3, pp.1085-1089,2018.

[6] M. Weber, “Immersive Virtual Reality Mirror Therapy for Upper Limb Recovery After Stroke: A Pilot Study,” *American Journal of Physical Medicine & Rehabilitation,* Vol. 15, pp. 120–125,2019.

[7] D. Coraci, and C. Santilli, “Parkinson's disease and virtual reality rehabilitation: cognitive reserve influences the walking and balance outcome,” *Neurological Sciences*, vol.12, pp. 201–215,2021.

[8] C. Luque-Moreno, “Virtual Reality to Assess and Treat Lower Extremity Disorders in Post-stroke Patients,” *Methods of Information in Medicine*, Vol. 7, pp. 1021–1075,2016.

[9] Q. Liu, M. Li, S. Fan, and M. Abbod, “Sample entropy analysis for the estimating depth of anaesthesia through human EEG signal at different levels of unconsciousness during surgeries,” Vol. 6, No.3. 2018.

[10] M. Tang, and S. Hao, "Human Parameter Acquisition System Design Based on Three-axis Gyroscope," *Proceedings of 2019 8th International Conference on Advanced Materials and Computer Science(ICAMCS 2019)*. Vol.10, pp.405-409,2019.

[11] Y. Chen, and J. Chen," Design and Implementation of Wind Plate Control System Based on MPU6050 Module," *Proceedings of 2018 2nd International Conference on Applied Mathematics, Model and Simulation (AMMS 2018)* pp.257-262.,2018.

[12] K. Zhang, and X. Ye, "Design of Body Posture Recognition System Based on Body Area Network," *Proceedings of 2018 IEA 3rd International Conference on Frontier of Computer Science and Information Engineering (ICFCI 2018)*. Vol.1, pp 8-13, 2018.

[13] E. Sardini, and V. Pasqui, “Wireless wearable t-shirt for posture monitoring during rehabilitation exercises,” Vol.64, No2, pp.439–448,2015.

[14] H. Jian, “Design of Angle Detection System Based on MPU6050,” *Proceedings of the 7th International Conference on Education, Management, Information and Computer Science (ICEMC 2017)* Vol.2, pp.185-202,2016.

[15] J. Zeng, and Y. Gao, "Positioning and Tracking Performance Analysis of Hypersonic Vehicle Based on Cubature Kalman Filter," *Proceedings of the 2018 International Conference on Transportation & Logistics, Information & Communication, Smart City)*. Vol.10, pp.51-60,2018.

[16] S. Hu, and B. Yan, "Ship Tracking with Static Electric Field Based on Adaptive Progressive Update Extended Kalman Filter," *Proceedings of 2018 2nd International Conference on Electronic Information Technology and Computer Engineering*. Vol.18, pp 1178-1181,2018.

[17] B. Zeng, "Structural Parameters Identification Based on Extended Kalman Filter," *Proceedings of 2018 3rd International Conference on Computer Science and Information Engineering*. Vol.3, pp.260-268,2018.

[18] B. Rafaely, and S. Elliott, “An adaptive and robust feedback controller for active control of sound and vibration,” *UKACC International Conference on Control*. Vol.1, pp.96-105,1996.

[19] Y. Zhu, "Exploration on Blending in VR Technology into Aerobics Teaching in Colleges and Universities," *Proceedings of 2019 International Conference on Computer Information Analytics and Intelligent Systems (CIAIS 2019).* pp.184-187,2019.

[20] S. Guo, "The Current Situation and Solving Strategies of MAYA Three-Dimensional Animation Teaching," *Proceedings of 2017 International Conference on Economic Development and Education Management*. pp.417-419,2017.