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Study on Multidimensional Evaluation the System for Lower Limb Rehabilitation

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***Abstract* - Rehabilitation is mainly divided into rehabilitation treatment and rehabilitation evaluation. Good functional recovery depends on correct rehabilitation treatment, and correct rehabilitation treatment must be based on correct rehabilitation evaluation, so rehabilitation evaluation is the basis of rehabilitation treatment. The establishment of a scientific rehabilitation evaluation system has an important guiding significance for doctors to understand the physical condition of patients and determine the training mode of each patient. The traditional rehabilitation evaluation system has expensive facilities, too single evaluation content, lack of comprehensive and scientific. This paper proposes a multidimensional rehabilitation evaluation system, which solves the problems of expensive acquisition equipment, cumbersome operation of evaluation system and single evaluation content by building hardware acquisition system and supporting software system. The evaluation method consists of motion of joint, gait trajectory and gait phase, and the weight of each method is quantified through The analytic hierarchy process to improve the scientific nature of the system. Related algorithms communicate with software through dynamic link library, which improves the portability of algorithms and facilitates the maintenance of software.Finally, the feasibility of the evaluation method is verified by analyzing the acquisition equipment and algorithm through experiments.**

Index Terms - Intelligent insoles, Application software, The analytic hierarchy process, Proportional fuzzy logic phase splitting strategy.

I. INTRODUCTION

The effect of rehabilitation training is often reflected through the rehabilitation evaluation system, which is a process of accurately judging obstacles and forming diagnostic conclusions by collecting and analyzing various data of patients. Different from clinical diagnosis, rehabilitation assessment is the process of determining the name of disease or trauma and making qualitative judgment, which focuses on function and is the process of making qualitative and quantitative judgment about dysfunction. Personalized rehabilitation training and evaluation methods can accelerate the recovery of limb function, effectively prevent the occurrence of complications, and play a important role in the recovery of patients' limb motor function[1].

German Lokohelp Medical Device Company designed a training system for lower limb rehabilitation robot, which is composed of caterpillar treadmill, weight loss system, gait trainer and emergency stop button, etc., which can measure and evaluate the rehabilitation effect and reflect the rehabilitation physiotherapy effect of patients after using for a period of time[2].LOKOMAT, a walking rehabilitation training robot, has been developed by the Swiss Federal University of Technology and Balgrist University in Switzerland. Training parameters such as torque and joint Angle output by LOKOMAT drive system can be measured by corresponding sensors and recorded in real time, thus serving as criteria for rehabilitation evaluation[3]. At present, the evaluation method is too single, the equipment is expensive.The traditional rehabilitation evaluation method is still used, which lacks comprehensiveness and scientificity.

To solve the above problems, this paper proposes a multidimensional evaluation system for lower limb rehabilitation, which has the characteristics of low price, diversified evaluation methods, high reliability algorithm, comprehensive supporting software. The evaluation methods include range of motion evaluation, gait trajectory evaluation and gait phase evaluation. The hardware part of the system consists of the main controller, Angle sensor and pressure sensor, and the data transmission and processing are carried out through the design of supporting software. The software part is built by Labview, and related algorithms are realized by calling dynamic link library. In the algorithm part, the maximum and minimum joint degree is used to evaluate the range of motion, the cosine similarity principle is used to evaluate the gait trajectory, and the proportional fuzzy logic phase splitting strategy is used to evaluate the gait phase.

The following is the structure of this article. The second part introduces the rehabilitation evaluation system platform, including the division of standard gait items, the construction of hardware platform and software platform. The third part introduces the methods of rehabilitation evaluation. It includes the analytic hierarchy process, maximum and minimum articulation, cosine similarity principle and phase splitting strategy of proportional fuzzy logic. The fourth part is experiment and result. The last part is the conclusion.

II. REHABILITATION EVALUATION SYSTEM PLATFORM

A. Acquisition system construction

This paper uses sensor technology to obtain the motion parameters of human lower limbs and complete rehabilitation evaluation.The range of motion and gait trajectory were evaluated by collecting attitude sensor data. The posture sensor is installed on the thigh and calf, so that it is not only convenient to wear, but also more stable to measure the Angle. As shown in Fig.1, θ_{hip} is the measurement Angle of hip joint, θ_{knee} is the measurement Angle of knee joint. The Y axis is along the direction of the lower leg, the Z axis is vertical forward, and the X axis is perpendicular to the sagittal plane of the human body. The X axis measures the rotation Angle of the front and back joints when the human body walks.Due to the coupling of the knee and hip joints, the true knee Angle is the measured knee Angle minus the hip Angle.Gait phase separation is evaluated by measuring plantar pressure data. Because of the high price of the plantar pressure board, we make our own plantar pressure collection insole. The pressure sensor selects the thin film pressure sensor. According to human kinematics, the force area of human feet during walking is divided into heel, fourth to fifth metatarsal, first metatarsal and thumb. The plantar pressure data can be obtained by installing thin-film pressure sensors in these four parts.

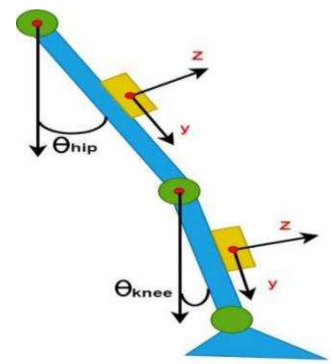

Fig. 1 Installation position

The main controller adopts *STM32F103ZET6*, which has five serial ports, two *DMA* controllers and three 12-bit *ADCs,* all of which meet the construction of acquisition platform. Attitude sensor using *MPU0650*, module internal voltage stability circuit, can be compatible with 3.3V-5V embedded system, easy to connect. In addition, its internal integrated attitude solver, with dynamic Kalman filter algorithm, can accurately output the module's current attitude in the dynamic environment, attitude measurement accuracy of 0.05 degrees, high stability. When the *MPU0650* is fixed to the thigh or calf, installation errors may occur and the initial Angle is not 0. Therefore, the primary controller sends the *0xFF 0xAA 0x52* command to the *MPU6050* to initialize the Angle. The thin film pressure sensor uses *MD30-60*,Its accuracy is 200g, it is a resistive sensor, the output resistance decreases with the increase of pressure on the sensor surface, through a specific pressure-resistance relationship, can measure the size of the pressure, it has low power consumption, excellent stability, fast response speed, high sensitivity. Single-leg hardware system connection is shown in Fig.2. The thin film pressure sensor is sent to the supporting software through the four-channel voltage conversion module, *ADC* and main controller. The attitude sensor sends the data to the master controller through the serial port, and then to the supporting software. In order to improve the acquisition speed and reduce the pressure of *MCU*, the program sends data to supporting software through *DMA*.

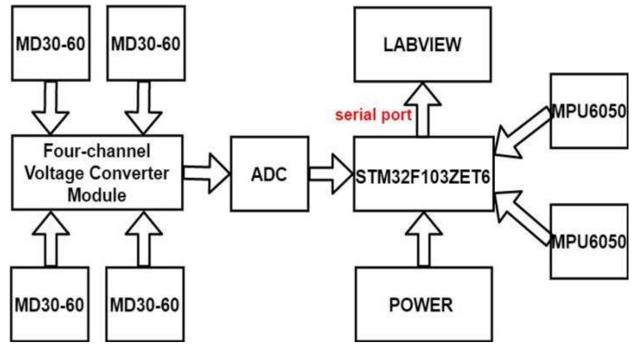

Fig. 2 Hardware schematic

B. Software system construction

According to the functional requirements of the rehabilitation evaluation system, the software system functions are divided into login function, serial communication function, algorithm analysis function, data display function, database storage function and rehabilitation evaluation function. This paper illustrates the functional module of rehabilitation evaluation. As shown in Fig.3.

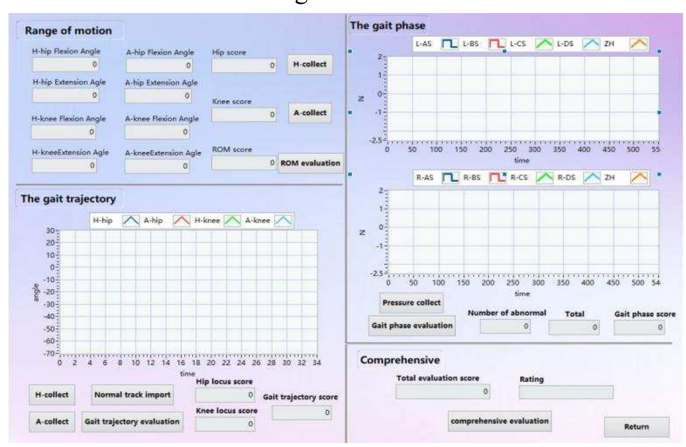

Fig. 3 Rehabilitation evaluation interface

The module is divided into four parts: range of motion, gait trajectory, gait phase and comprehensive evaluation. The range of motion shows the flexion and extension Angle of the healthy side and the affected side of the hip and knee joint. Gait trajectory shows the gait trajectory of the hip and knee joints on the healthy and affected sides. Gait phase indicates the result of plantar pressure phase separation. Comprehensive evaluation of the three. The algorithm is realized by communication between library function node and external dynamic link library, which is convenient for software maintenance. The results of rehabilitation evaluation are stored in mysql database, which is convenient for doctors to check later and judge the training effect.

III. Rehabilitation Evaluation Method

A. The analytic hierarchy process

Analytic hierarchy Process is referred to as AHP.Due to the different roles of range of motion, gait trajectory and gait phase in the comprehensive rehabilitation evaluation system, it is necessary to comprehensively evaluate the three in order to obtain scientific and accurate rehabilitation evaluation results, so the weight of the three should be determined. In this paper, AHP was used to determine the weight of each evaluation aspect. According to the analysis method of AHP, it is divided into three levels: target layer, criterion layer and scheme layer. The target layer is the degree of recovery of lower limb joint function. Criterion layer consists of three evaluation methods: range of motion, gait trajectory and gait phase. The scheme layer is the weight coefficient of each evaluation method[4].

Through the guidance of a lower limb rehabilitation physiotherapist in a hospital, the three rehabilitation evaluation methods of the criterion layer were compared in pairs. Saaty et al. proposed 1-9 scale method for quantization. Table I shows the comparison of weight of each parameter by lower limb rehabilitation physiotherapists.

TABLE I
PARAMETER WEIGHT COMPARISON VALUE

Methods \ Methods	Range of motion	The gait trajectory	Plantar pressure
Range of motion	1	1/3	1/4
The gait trajectory	3	1	1/2
Plantar pressure	4	2	1

Table I shows that the two evaluation methods of row and column are equally important; 3 indicates that row is slightly more important than column; 2 and 4 represent the median value of adjacent judgment. The fractional part is the opposite of the integer part.

Then the judgment matrix A is Equation 1:

$$A = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{4} \\ 3 & 1 & \frac{1}{2} \\ 4 & 2 & 1 \end{bmatrix} \quad (1)$$

The normalization of the column vectors is Equation 2

$$\begin{bmatrix} 0.125 & 0.1 & 0.143 \\ 0.375 & 0.3 & 0.286 \\ 0.5 & 0.6 & 0.571 \end{bmatrix} \quad (2)$$

Sum and normalize by row, ω is Equation 3:

$$\omega = \begin{bmatrix} 0.123 \\ 0.32 \\ 0.557 \end{bmatrix} \quad (3)$$

Its consistency verification,obtained Equation 4:

$$A\omega = \begin{bmatrix} 0.125 & 0.1 & 0.143 \\ 0.375 & 0.3 & 0.286 \\ 0.5 & 0.6 & 0.571 \end{bmatrix} \begin{bmatrix} 0.123 \\ 0.32 \\ 0.557 \end{bmatrix} = \begin{bmatrix} 0.369 \\ 0.968 \\ 1.689 \end{bmatrix} \quad (4)$$

Because of,$A\omega = \lambda\omega$，Then equation 5 is:

$$\lambda = \frac{1}{3}\sum_{i=1}^{n}\frac{(A\omega)_i}{\omega_i} = \frac{1}{3}[\frac{0.369}{0.123} + \frac{0.968}{0.32} + \frac{1.689}{0.557}] = 3.018 \quad (5)$$

To verify consistency,Then equation 6 is:

$$CI = \frac{\lambda - n}{n-1} = \frac{3.018 - 3}{3-1} = 0.009 \quad (6)$$

Where n is the order of the matrix. In order to measure the size of *CI*, random consistency index *RI* is introduced.As shown in Table II.

TABLE II
CONSISTENCY INDEX RI

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The conformance ratio is generally considered CR<0.1, the degree of inconsistency is considered to be within the allowable range, with satisfactory consistency, and passes the consistency test. The normalized eigenvector can be used as the weight vector, otherwise the pairwise comparison matrix should be reconstructed and the matrix A should be adjusted.

After calculation, *CR* is Equation 7:

$$CR = \frac{CI}{RI} = \frac{0.009}{0.58} = 0.015 < 0.1 \quad (7)$$

According to the consistency test, the weight of motion is 0.123, gait trajectory is 0.32, and gait phase is 0.557.

B. Maximum and minimum articulation and cosine similarity principle

At present, the measurement of range of motion has a high reference value in the correction and rehabilitation of hemiplegia patients. Because the flexion and extension of hip joint and knee joint are limited in hemiplegia patients, the Angle change is obviously less than that of normal people. The system tentatively determined two range of motion indicators, including the flexion and extension of hip and knee joints. As shown in Fig.4, the hip joint is extended so that the upper body is upright and the thigh flexes upwards to the maximum extent possible. The Angle between the thigh and the sagittal plane is the maximum Angle of hip flexion, which is the default value in this paper. Hip extension means that the upper body should stand up straight and the thigh should extend backward to the maximum extent. In this case, the Angle between the thigh and the sagittal plane is the maximum Angle value of hip extension, which is the minimum hip Angle by default. Knee flexion means that the human body is upright and the calf is extended to the maximum extent. In this case, the Angle formed by the calf and thigh extension line is the maximum flexion activity Angle of the calf, which is the default maximum knee joint Angle in this paper. Because hemiplegia patients cannot extend their calves normally, they may suffer from softening. Therefore, when the calves are relaxed and upright, the knee joint is extended, and the minimum knee joint Angle is adopted by default in this paper. As the range of motion of joints varies greatly among individuals, it is impossible to unify the standard, so the range of motion of joints on the patient's healthy side is used as the standard value for evaluation.

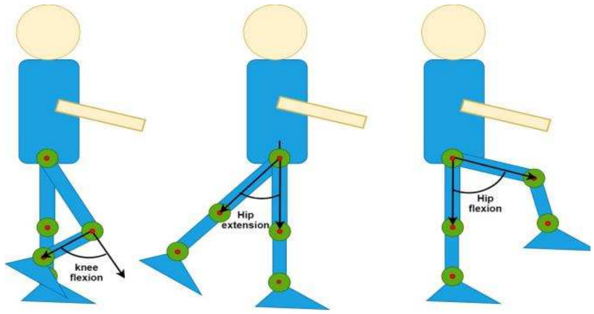

Fig. 4 Hip and knee flexion and extension

The scoring method of range of motion is shown in Table III.

TABLE III
RANGE OF MOTION SCORING METHOD

Parameter / Joints	Affected side rom	Unaffected side rom	Weight	The score	Total points
Hip flexion	A_1	A_{11}	0.25	$A_s = \frac{A_1}{A_{11}} \times 0.25$	R_S
Hip extension	B_1	B_{11}	0.25	$B_s = \frac{B_1}{B_{11}} \times 0.25$	
Knee flexion	C_1	C_{11}	0.25	$C_s = \frac{C_1}{C_{11}} \times 0.25$	
Knee extension	D_1	D_{11}	0.25	$D_s = \frac{D_1}{D_{11}} \times 0.25$	

The R_S is score.Then equation 8 is:

$$R_S = \frac{A_s + B_s + C_s + D_s}{4} \times 100 \quad (8)$$

Walking is one of the basic human movements, which can reflect the health status of lower limbs to a certain extent. It is of positive significance to choose gait evaluation as evaluation index. There are two methods of gait trajectory assessment for patients at different stages of rehabilitation. Patients with normal walking ability on the healthy side were assessed by collecting gait tracks on the healthy side and the affected side. For patients with abnormal walking ability on the healthy side, the normal gait trajectory was input into the evaluation system in advance to evaluate the affected gait trajectory. Gait trajectory was evaluated by calculating the coincidence degree of two curves. In this paper, cosine similarity principle is used to calculate the coincidence degree of curves.

For example, the vector composed of the healthy side gait trajectory or the standard gait trajectory is Equation 9:

$$\mathrm{a} = [\mathrm{a}_{1,} \mathrm{a}_{2,} \mathrm{a}_{3,} \mathrm{a}_{4,} \ldots . \mathrm{a}_{\mathrm{n},}] \quad (9)$$

The vector of affected side gait trajectory is Equation 10:

$$\mathrm{b} = [\mathrm{b}_1, \mathrm{b}_2, \mathrm{b}_3, \mathrm{b}_4, \ldots . \mathrm{b}_\mathrm{n}] \quad (10)$$

Then the cosine Angle of vectors a and b is Equation 11:

$$\cos\theta = \frac{a \cdot b}{|a| \cdot |b|} \quad (11)$$

The scoring method of gait trajectory is shown in Equation 12, where T_S is the score.

$$T_S = \cos\theta \times 100 \quad (12)$$

C. Phase splitting strategy of proportional fuzzy logic

Plantar pressure test is a common gait evaluation method in clinic. The fuzzy logic gait analysis strategy can be divided into six stages: initial contact stage, load response stage, intermediate standing pose stage, rear standing pose stage, expected swing stage and rear swing stage. Due to initial contact and load response, there is little difference between the mechanics of late standing and late pre-pendulum. Therefore, they are grouped together, prostatic and poststatic. This paper divides footwork into four stages: early stand, middle stand, late stand and swing[5]-[7]. According to the change of pressure data during human walking, the fuzzy logic table and fuzzy rules were reconstructed to obtain the gait phase information. Because the traditional phase segmentation strategy sets a fixed threshold value, the plantar pressure is affected by the subject's weight and walking speed, so it is not suitable for all walking conditions. Therefore, we adopt the phase separation strategy of proportional fuzzy logic. The basic flow is shown in Fig.5.

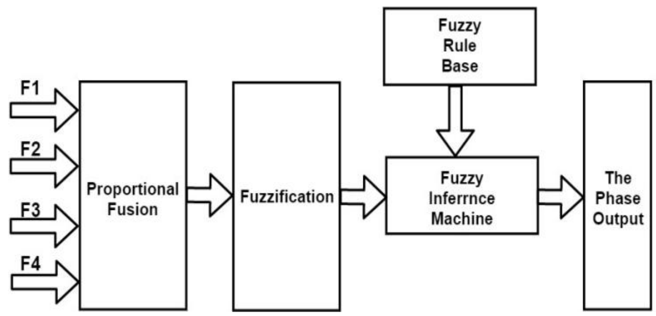

Fig. 5 Principle of phase splitting strategy in proportional fuzzy logic

Firstly, the plantar pressure signal is summed and proportioned at the same time. Where K_1, K_2, K_3 and K_4 respectively represent the ratio of sensor signals to the sum of signals, and F_1, F_2, F_3 and F_4 respectively represent the pressure received by the sensor at the same time. The expression is Equation 13,Equation 14,Equation 15,Equation 16.

$$K_1 = \frac{F_1}{F_1 + F_2 + F_3 + F_4} \quad (13)$$

$$K_2 = \frac{F_2}{F_1 + F_2 + F_3 + F_4} \quad (14)$$

$$K_3 = \frac{F_3}{F_1 + F_2 + F_3 + F_4} \quad (15)$$

$$K_4 = \frac{F_4}{F_1 + F_2 + F_3 + F_4} \quad (16)$$

Proportional coefficient is related to the status of all sensors, represents the relative relationship between sensors, reflects the transmission of plantar pressure during the walking cycle, and can better solve the influence of body weight and walking speed of subjects.

Secondly, fuzzy processing is carried out on the data after proportion fusion. To determine the appropriate membership function, since the scale fusion data range from 0 to 1, in order to eliminate the sharp boundary of traditional gait stage division, this paper selects the exponential function as the membership function, and its expression is Equation 17.

$$f(K_i) = \frac{1}{1+e^{-s(K_i-K_{0i})}} \quad (17)$$

$f(K_i)$ is the output of the function, K_i is the proportional value of the pressure collected by the sensor, K_{0i} is the proportional threshold, and S is the sensitivity coefficient. The exponential function can control the smooth transition between different states through the sensitivity coefficient, which is conducive to the smoothness and continuity of the output fuzzy logic value in the range of 0-1. In order to describe the possibility that the proportion value is close to 1 or close to 0, since the exponential function is a symmetric function, its inverse function can be directly obtained and And divide the exponential function into $f^H(K_i)$ and $f^L(K_i)$ .The expressions is Equation 18,Equation 19.

$$f^H(K_i) = \frac{1}{1+e^{-s(K_i-K_{0i})}} \quad (18)$$

$$f^L(K_i) = 1 - f^H(K_i) = 1 - \frac{1}{1+e^{-s(K_i-K_{0i})}} \quad (19)$$

According to the analysis of membership function. Set K_{0i} to 0.5. As the sensitivity coefficient S increases, the slope of the membership function increases, so when the sensitivity coefficient S approaches infinity, there are only 0 and 1 membership states. When K_i=K_{0i}, the membership degree is equal to 0.5, which is in the transition stage of gait, so it can be set as K_i> K_{0i}, the fuzzy set is in the state of "large" (H), when K_i < K_{0i} the fuzzy set is in the state of "small" (L). Therefore, PP can be adjusted to determine the proportion of fuzzy set in "large" or "small".

Finally, the formulation of fuzzy rules. Phase division was performed by pressure collected from the heel, fourth metatarsal, first metatarsal, and thumb. It can be divided into *AS* in early standing, *BS* in middle standing, *CS* in late standing and *DS* in swinging stage. Thus, a table of fuzzy logic rules can be obtained, as shown in Table IV, where H stands for "large", L for "small", and * is irrelevant.

TABLE IV
GAIT PHASE SEPARATION FUZZY RULE

Proportion / Phase	Hell (K_1)	The fourth metatarsal (K_2)	The first phalanges (K_3)	Thumb toes (K_4)
AS	H	*	L	L
BS	*	H	H	L
CS	L	*	*	H
DS	L	L	L	L

From the fuzzy logic rule table, the phase separation formula can be obtained, as shown below.

Pre-standing *AS* is Equation 20.

$$AS = f^{H}(K_1) \times f^{L}(K_3) \times f^{L}(K_4) \quad (20)$$

Middle standing *BS* is Equation 21,Equation 22.

$$BS = f^{H}(K_2) \times f^{H}(K_3) \times f^{L}(K_4) \quad (21)$$

Post-standing *CS* is Equation 23,Equation 24.

$$CS = f^{L}(K_1) \times f^{H}(K_4) \quad (22)$$

Swing period *DS* is Equation 25.

$$DS = f^{L}(K_1) \times f^{L}(K_2) \times f^{L}(K_3) \times f^{L}(K_4) \quad (23)$$

According to medical standards, for a particular lower limb, the gait cycle consists of standing phase and swinging phase, of which standing phase accounts for about 60% of the whole gait cycle, and swinging phase accounts for about 40% of the whole gait cycle[8]. Gait phase is divided into abnormal gait cycle and total gait cycle. The abnormal cycle was divided into two conditions: discontinuous gait phase or continuous gait phase with wrong proportion of each phase. *AS* accounted for 10%, *BS* 20%, *CS* 30%, *DS* 40% of the normal state.6% fluctuation of each phase is normal.The scoring method is shown in Equation 26, where P_S is the score, A_n is the number of abnormal cycles, and T_n is the total number of cycles.

$$P_S = (1 - \frac{A_n}{T_n}) \times 100 \quad (24)$$

The comprehensive score of the lower limb rehabilitation evaluation system is Equation 27.

$$C_S = R_S \times 0.123 + T_S \times 0.32 + P_S \times 0.557 \quad (25)$$

IV. EXPERIMENTS AND RESULTS

To verify the rationality of the algorithm and platform.The experiment selected a 24-year-old male with height of 178cm, weight of 60kg and foot size of 42 to test the rehabilitation evaluation system. The experiment assumes that the left leg is on the healthy side and the right leg is on the negative side. The wearing effect of the device is shown in Fig.6.Where, A is the general view of the device, B is the rear view, and C is the front view[9-10].

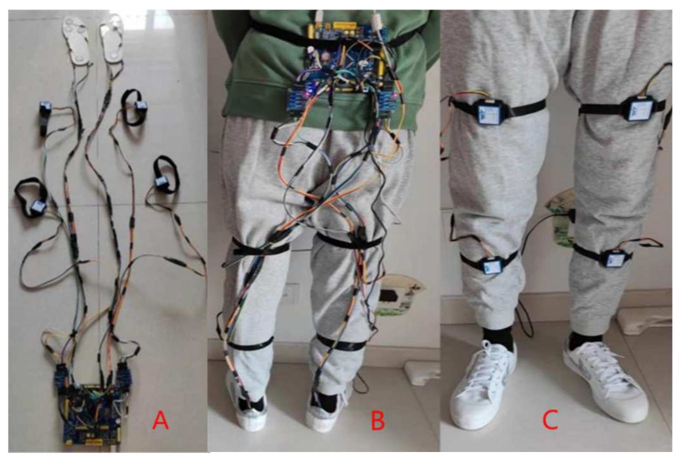

Fig. 6 Rehabilitation evaluation system wearing schematic

First, the subjects' range of motion (ROM) was measured. The healthy hip was flexed to the maximum Angle and gradually extended back to the maximum Angle. The knee joint is then flexed to the maximum Angle and gradually extended to the maximum Angle. The affected side and the healthy side steps, finally get the joint Angle number and score and the supporting software display. Secondly, the gait trajectory is evaluated.Participants first walked normally on the healthy side and then on the affected side. They were tested with their legs behind them while walking. Because the MPU6050 has a built-in Kalman filter, filtering is not required[11]. Its gait trajectory is shown in Fig. 7.

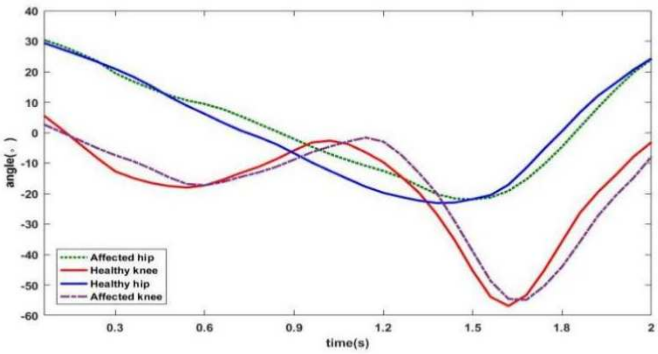

Fig. 7 Gait trajectory after denoising

Finally, the gait phase is evaluated. The test subjects walked normally and the pressure information collected was analyzed and processed. The plantar pressure data were also processed by average filtering. The plantar pressure after denoising is shown in Fig.8.

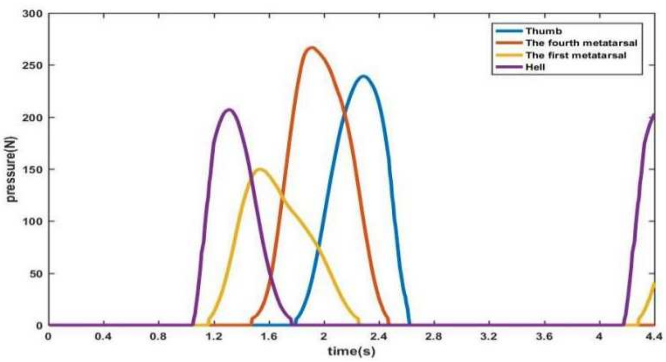

Fig. 8 Plantar pressure after denoising

Then the denoised plantar pressure was processed by proportional fuzzy logic phase separation strategy to obtain the gait phase. See Fig.9.

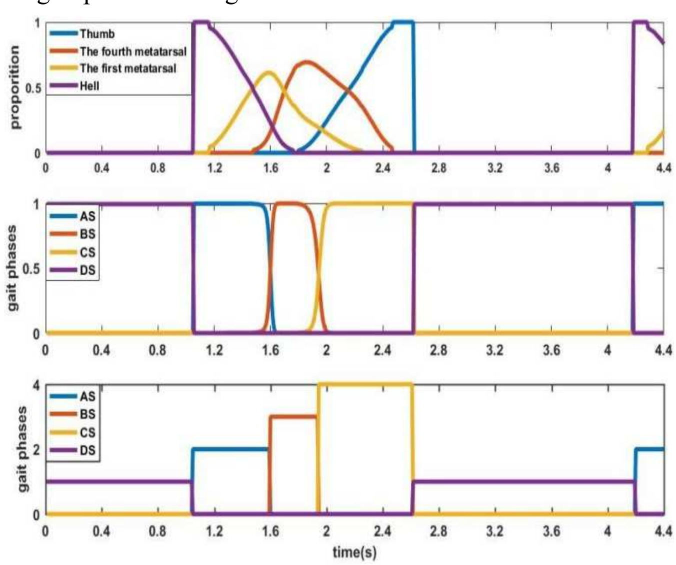

Fig. 9 Phase separation result of proportional fuzzy logic

The curve is taken from the abnormal gait curve of 20 gaits. It can be seen from the analysis that the phase is in the transition state everywhere at 0.5 after scaling. In order to ensure the subsequent judgment of its abnormal phase, the intersection point of each curve is taken AS the phase cut-off point, and AS is 2,BS is 3,CS is 4,DS is 1 The continuity and phase proportion of the periodic curve were judged. After analysis, there was no phase missing, but phase proportion error occurred. *AS* accounted for 17.5%,*BS* accounted for 10%,*CS* accounted for 22.5%,*DS* accounted for 50%, so it was judged *AS* abnormal phase.

The final evaluation results of the testers were 100 points for range of motion, 85 points for gait trajectory, 95 points for plantar pressure, and 92.415 points for overall score, which was best.

V. Conclusion

This paper proposed a multidimensional evaluation system for lower limb rehabilitation. The multi-dimensional evaluation method was constructed through motion range, gait trajectory and gait phase. The weight of each evaluation method is analyzed scientifically by using analytic hierarchy process. The problem of single evaluation method was solved. Through the construction of supporting software, a complete set of rehabilitation evaluation method was realized. Finally, through experiments, the articulation degree, gait trajectory and gait phase are analyzed to verify the correctness of the algorithm and the rationality of the platform. In the future, muscle strength evaluation and other methods can be added to improve the evaluation system.

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