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Design on Exoskeleton System of lower extremity in Medical Rehabilitation

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Abstract: The driving DOF for people's lower extremity was analyzed concerning the difficulty of the rehabilitation training for patients with ischemic stroke and spinal cord injury, a kind of exoskeleton rehabilitation system of lower extremity for walking training in the treadmill was designed, the rehabilitation physiotherapists' training experience and the robots' repeatability were integrated. Five-bar model of man-machine coupling system and corresponding kinetic equation were established, the driving torques for the hip joint and knee joint were deduced, thus providing the reference data for the selection of drive motor for the corresponding joint. In order to get the normal people's walking gait in the treadmill, the optical motion capture system was used to collect the normal people's feature point data when walking in the treadmill, the angles for the hip joint and knee joint were deduced combined with the mathematical model of man-machine coupling system as the reference for patients' standard gait for the rehabilitation training in the treadmill. The system's feasibility and reliability were verified via the clinical experiment of patients' rehabilitation training, the experimental results and patients' actual conditions were consistent. The exoskeleton system provided a sort of scientific rehabilitation training platform for the patients with ischemic stroke.

Keywords Rehabilitation of lower extremity; Exoskeleton; Robot; Man-machine coupling system

INTRODUCTION

Along with the intensified aging of population, there are more and more patients with ischemic stroke, which endangers the health greatly. Moreover, the spinal cord injuries caused by the traffic accident, athletic injury an some other injury factors are increasing. The treatment of early rehabilitation training is attached with the mainstream that the plasticity of central nervous system is used to make the patient's affected side appear corresponding reaction, improve the muscle tension and establish the new combination relation of nervous system [Chi, *et. al.*, 2007] via the exercise training. However, it is not only inefficient but also the effect of rehabilitation effect depends on physiotherapist's experience only relying on the physiotherapist to conduct the manual rehabilitation training for the patients. The physiotherapist's heavy manual training work can be replaced effectively by the rehabilitation training system using the exoskeleton of lower extremity combined with the treadmill [Yang, *et. al.*, 2009]. Lokomat[Colombo, 2004] is a kind of typical equipment recovering the exoskeleton of lower extremity, the motor drives the movement of hip joint and knee joint of lower extremity to make the patients conduct the walking training in the treadmill. LOPES designed by Veneman et. al. [Veneman, *et. al.*,2006, 2007] used the gearing of wire rope to drive the joints on the exoskeleton of lower extremity, thus greatly reducing the weight of exoskeleton and further reducing the influence of exoskeleton on the patients in the rehabilitation training process. ALEX designed by Banala [Banala, *et. al.*, 2009],[Winfree, *et. al.*, 2011],[Stegall, *et. al.*, 2012] increased the visual feedback to improve the trainers' training enthusiasm. Although the domestic research on the rehabilitation training of exoskeleton started late relatively, certain results have been formed. Professor Zhang Lixun from Harbin Engineering University and others conducted the positive and reversal motion analysis on the gait control mechanism, pelvic control mechanism, 7-section 12-DOF human model via the robots with rehabilitation training of lower extremity, and the corresponding mechanism model was established, thus laying the foundation for the kinetic analysis and control system research [Zhang, et. al., 2009]. Professor Qian Jinwu from Shanghai University and others used the man-machine interaction information to establish the decoupling relationship for the coupling system composed by the trainer and leg for walking aid, thus providing the theoretical basis to research the control method of the training mode of "patients' initiative" [Feng, et. al., 2009].

The exoskeleton to rehabilitate the lower extremity in the design is mainly for the early rehabilitation training demand on the patients with ischemic stroke, and the patients' walking training is aided by the overhang weight reduction and treadmill. With the drive of DC servo motor, the motor output torque is passed to the joint via the synchronous belt and ball screw. The mathematical model for man-machine coupling was established in the paper for the exoskeleton system, normal people's walking gait data in the treadmill was obtained combined with the optical motion capture system, the joint driving torque was deduced via the kinetic equation of man-machine mathematics model to provide the reference basis for the selection of motor, and the system was verified finally via the clinical experiment.

KINETIC MODELING FOR MAN-MACHINE COUPLING SYSTEM

The DOF for people's lower extremity movement includes the flexion and extension of thigh, external rotation and internal rotation, abduction and adduction, flexion and extension of crus and foot, extroversion and introversion of foot as shown in Figure 1 [Niu, *et. al.*, 2006].

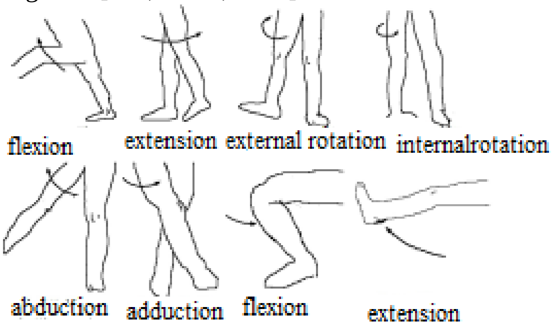

Figure 1 Movement of each part of people's lower extremity

The biomechanical simulation and experimental research showed that people's power consumed at the movement within the vertical plane was the largest when compared with that in the frontal plane and horizontal plane [Racine, *et. al.*, 2003]. Therefore, the flexion and extension of thigh and crus were selected as the DOF driven by the motor at the modeling of man-machine coupling system. The hip joint was mainly used to swing the legs, realize the stepping, the forward or backward of upper limb in order to balance in the walking process; the keen joint was mainly used to adjust the centrobaric height and the grounding height of swinging leg so as to adapt to the state at the ground. For the patient conducted the rehabilitation training with the treadmill under the weight loss of overhang, the flexion and extension of foot were not served as the DOF driven by the motor, and the patients were conducted the passive movement [He, 2008] of ankle joint under the synergy effect of exoskeleton and treadmill in the rehabilitation training process. The mathematics model for man-machine coupling system was established according to the above analysis as shown in Figure 2, the thigh and crus in the model included those of exoskeleton and people, therefore, the moulding was established on the system composing the basis of exoskeleton and human being. The patients' initial effect on the exoskeleton was ignored for the patients did not have the initiative basically at the early time. A kind of exoskeleton in the weight loss of overhang was designed in the paper, a vertical overhang traction force at 1/2 of the gravity of human being shall be considered in the mathematics model.

The following kinetic equation was obtained via the analysis of man-machine coupling system:

$$m(\theta)\ddot{\theta}+C(\theta)\dot{\theta}^2+G(\theta)=M_\mathrm{m}+M_\mathrm{a}-M_\mathrm{f}-M_\mathrm{T}-M_\mathrm{h} \qquad (1)$$

$$\mathrm{m}(\theta)=\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}, C(\theta)=\begin{bmatrix} C_1 & C_2 \\ C_3 & C_4 \end{bmatrix} \mathrm{m}_{11}=m_1 d_1{}^2+J_1+m_2 l_1{}^2-\sin^2\theta_1 l_1(m_2 l_1-m_1 l_1+2m_1 d_1)\operatorname{sgn} f$$

$$\mathrm{m}_{12}=m_2 l_1 d_2\cos\theta_1\cos\theta_2+\sin\theta_1\sin\theta_2[m_1(l_1-d_1)l_2\operatorname{sgn} f+m_2 l_1 d_2\operatorname{sgn} s]$$

$$\mathrm{m}_{21}=m_2 l_1 d_2\cos\theta_1\cos\theta_2+\sin\theta_1\sin\theta_2[m_1(l_1-d_1)l_2\mathrm{sgnf}+m_2 l_1 d_2\operatorname{sgn} s]\ \mathrm{m}_{22}=m_2 d_2{}^2+J_2+\sin^2\theta_2 l_2(m_1 l_2+m_2 l_2-2m_2 d_2)\operatorname{sgn} f$$

$$C_1=(-0.5m_1 d_1{}^2+0.5m_1(l_1-d_1)^2-0.5m_2 l_1{}^2)\sin 2\theta_1\operatorname{sgn} f$$

$$C_2=-m_2 l_1 d_2\cos\theta_1\sin\theta_2+m_1(l_1-d_1)l_2\sin\theta_1\cos\theta_2\operatorname{sgn} f+m_2 l_1 d_2\sin\theta_1\cos\theta_2\operatorname{sgn} s$$

$$C_3=-m_2 l_1 d_2\cos\theta_1\sin\theta_2+m_1(l_1-d_1)l_2\sin\theta_1\cos\theta_2\operatorname{sgn} f+m_2 l_1 d_2\sin\theta_1\cos\theta_2\operatorname{sgn} s$$

$$C_4=(-0.5m_2 d_2{}^2+0.5m_2(l_2-d_2)^2+0.5m_1 l_2{}^2)\sin 2\theta_2\operatorname{sgn} f\ \ G(\theta)=\begin{bmatrix} g\sin\theta_1(-m_1 d_1+m_1 l_1\operatorname{sgn} f-m_2 l_1\operatorname{sgn} s) \\ g\sin\theta_2[-m_2 d_2+(m_1 l_2+m_2 l_2)\operatorname{sgn} f] \end{bmatrix}$$

$$M_\mathrm{T}=\operatorname{sgn} f\begin{bmatrix} F_\mathrm{f} l_1\cos\theta_1 \\ F_\mathrm{f} l_2\cos\theta_2 \end{bmatrix}$$

$$M_\mathrm{h}=\operatorname{sgn} f\begin{bmatrix} F_\mathrm{h} l_1\sin\theta_1 \\ F_\mathrm{h} l_2\sin\theta_2 \end{bmatrix}$$

In formula (1), M_m was the torque of exoskeleton driven by the motor, M_a was the torque needed for people to walk, M_f was the torque caused by the people's joint movement friction, M_h and M_T were the torques caused by the traction of weight loss of overhang and ground friction respectively. M_f ,the torque caused by the friction at the joint movement was very small, and it can be negligible when compared with M_a ,the torque needed for people to walk. F_h was the overhang traction which can be set via adjusting the overhang system, F_N was the supporting force provided by the treadmill, F_f was the friction between the planta pedis and treadmill. The people's walking speed shall be consistent with the operating speed of the treadmill at the ideal case with the friction force of zero. Moreover, m_1 and m_2 were the qualities of thigh and crus of man-machine system respectively, l_1, l_2 were the length respectively, d_1 , d_2 were the barycentric position respectively, J_1 , J_2 were rotational inertia respectively, θ_1 , θ_2 were the angle at the vertical direction respectively, f represented the flexion of hip and knee joints, therefore, 1 was taken at the flexion, and 0 was for extension; s represented the extension of hip and knee joints, therefore, 0 was taken at the flexion and 1 was for extension.

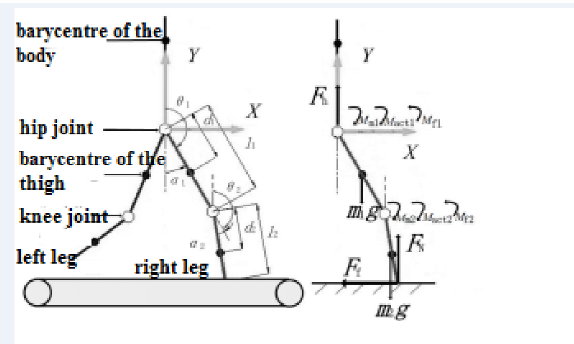

Figure 2 Mathematics model for man-machine coupling

OBTAIN THE WALKING GAIT IN THE TREADMILL

The proximity on the gait between the patients' walking assisted by the exoskeleton and the normal walking decides the scientificity of patients' rehabilitation training, remaining the consistence with the normal walking gait can help the patients to correct the abnormal gait, and establish the normal walking gait again. The existing database shall be referred generally for the standard gait data on the walking controlled by the exoskeleton, and these gait databases are obtained from the normal people's walking experience on the ground. However, there are some differences on the gait between the walking in the treadmill and on the ground. The gait inconsistency issue was pointed out by the rehabilitation training doctor in the patients' trial process, especially too large back swing of knee joint. Therefore, a dedicated gait data complying the walking in the treadmill shall be planned to ensure the coordination and nature of patients' gait in the rehabilitation training process.

The original experimental result which is the normal people's gait data when walking in the treadmill can be obtained via converting the coordinates of the angle data from the optical photograph system combined with the angle relationship among the waist, thigh and crus in the mathematics model of man-machine coupling. The smooth fitting experimental results can be obtained via the smooth fitting treatment of original experimental results, and the comparison with the gait data offered by the database in Hong Kong Polytechnic University can be shown in Figure 3. Via the comparison, we can know that the flexion angles of thigh and crus were much smaller than the reference value when walking in the treadmill, while the extension angles of thigh and crus were the same basically with the reference value. It can be seen that there was a significant difference between the walking gait on the ground and in the treadmill. Moreover, it shall be noted that the experimental result in Figure 4 was obtained for the a normal person's experiment, there are certain differences for different people. Therefore, we need to conduct the experiment for more enough normal people in order to get the universal standard gait trajectory. The standard gait was obtained via integrating the experimental result and adjusting the reference value in the later patients' experiment.

REALIZATION OF EXOSKELETON SYSTEM

Design of joint driven structure

The design of exoskeleton structure shall guarantee the patients' wearing comfort, safety, size adjustable, structure lightness and other requirements. The 3D model diagram [Zeng, *et. al.*, 2007] for the whole exoskeleton system of lower extremity rehabilitation training was shown in Figure 4.

Each joint of exoskeleton was driven by DC servo motor, the motor output shaft converted the rotation movement into the linear motion via the synchronous belt wheel and ball screw, thus simulating the movement form of actual people's muscular tissue to drive the joint. The physical and schematic diagrams of four-bar linkage driving mechanism of hip joint were shown in Figure 5, and the relation (2) can be established. In formula (2), L1 was the length of base frame of four-bar linkage mechanism, L2 and L3 were the lengths of linked frame at the initial torque, dL was the changed length of linkage L2 in the movement process as shown in Figure 5, P was screw lead, C was optical-electricity encoder line number, R was synchronous pulley transmission ratio, A was the initial angle value, Po was the current location of motor.

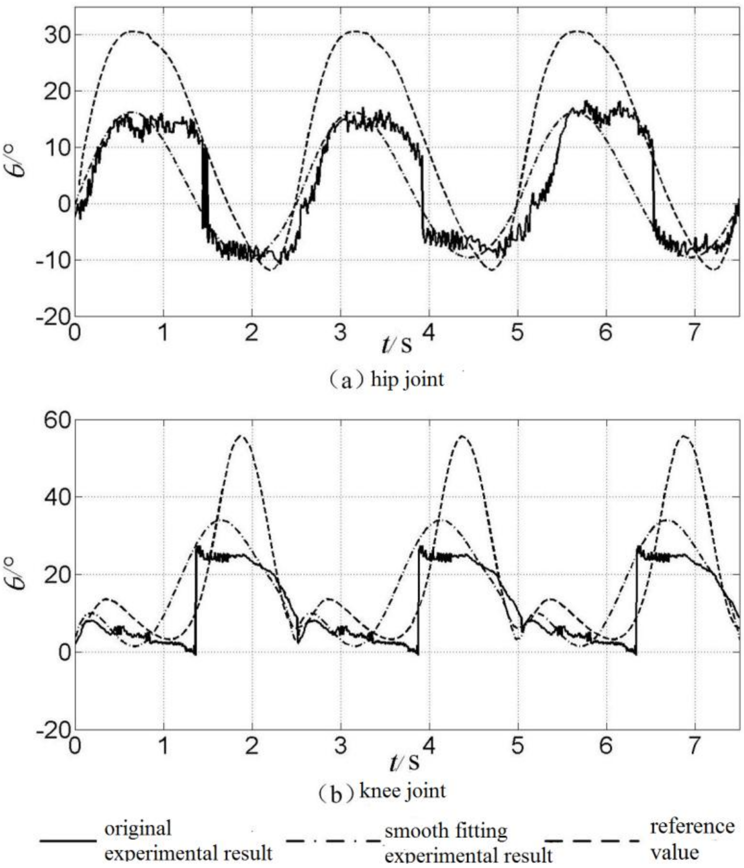

Figure 3 Optical action capture experimental result and comparison

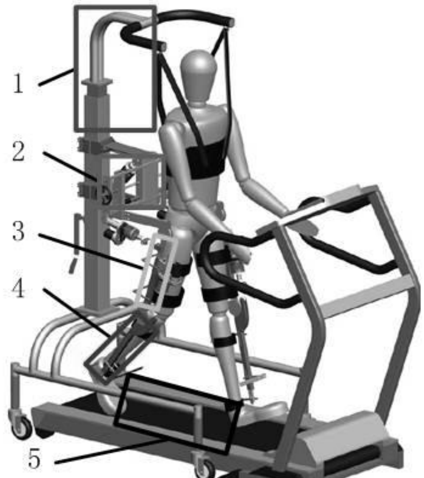

Figure 4 3D model of exoskeleton system (1- overhang weight loss frame; 2- back adjustment mechanism; 3- thigh bar, 4- crus bar; 5- treadmill).

$$\begin{cases} L_1{}^2+L_3{}^2\text{-}2L_1L_3\cos(A+\theta_1)=[L_2+dL]^2 \\ dL = PogP/(CgR) \end{cases} \quad (2)$$

The motor drive torque of T_{motor} and drive power of P_{motor} were as shown in Formula (3) and (4) respectively, wherein, θ_1 was the angle value of hip joint, η_1 and η_2 were the transmission efficiencies of lead screw and synchronous belt, T_m was the torque needed of hip joint and knee joint to walk in the treadmill. As shown in Formula (3) and (4), the corresponding motor driving torque and power can be obtained via seeking the joint's driving torque of T_m .

$$T_{motor} = \frac{T_m P/(L_2 \sin\theta_1)}{2\pi\eta_1\eta_2} \quad (3)$$

$$P_{motor} = T_{motor} Po/P \quad (4)$$

Table 1 offered the parameters of specific part in the man-machine coupling system, *L* was the length of leg bar, *d* was the barycentre location, m_h was the quality, *J* was rotating inertia.

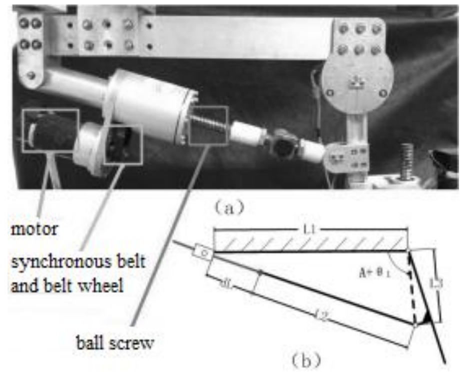

Figure 5 Four-bar linkage mechanism driven by hip joint

Wherein, the exoskeleton rotational inertia was measured directly by 3D modeling software, and that of human leg bar was measured by trilinear pendulum in Modern Sports Biomechanics[16] combined with the regression equation of human part's rotational inertia.

The driving torque of each joint and people's joint driving torque when walking in the treadmill at the weight loss of overhang can be obtained via solving the kinetic equation by using the existing hip joint and knee joint angle data at the normal walking. The joint driving torque obtained via solving the kinetic equation was the torque needed by the joint driven by the motor supposing the torque was not provided by the lower extremity in the rehabilitation training process for the rehabilitation trainer. For the people's joint friction, the friction between the planta pedis and treadmill and other influencing factors were ignored, 2 was taken for the safety coefficient, and the torque value needed by the joint driven by the motor was enlarged. The needed torque driven by motor was offered in Figure 6, and the comparison was made with the joint driving torque measured by Hong Kong Polytechnic University and the University of Strathclyde[17]. These two research agencies obtained the ground walking gait via the camera system, and solved the joint torque at walking by referring to the people's parameter combined with the inverse kinetic equation. Via the comparison, we can find that there were some differences among three torque curves of hip joint with the same overall change trend, while there were significant differences among three torque curves of knee joint, and only a part of change trends were the same. The reasons causing the difference included the ignorance of influence caused by the friction resistance and the influence at the selection of people's reference value. Meanwhile, the consideration on the quality and inertia parameter of exoskeleton when solving the inverse kinetics in the research also influenced the final results.

Table 1 Main parameter for the exoskeleton model for rehabilitated lower extremity

Man-machine leg bar	L/m	d/m	m_h/kg	J/kgm^2
Human's thigh	0.503	0.263	8.253	0.145
Human's crus	0.376	0.222	2.358	0.022
Exoskeleton thigh	0.503	0.263	1.43	0.02
Exoskeleton crus	0.376	0.222	1.82	0.04

The torque and power needed by the motor to drive the the hip and knee joint can be calculated from the torque value from man-machine coupling system model combined with the formula (3) and (4) as shown in Figure 7. The Switzerland maxon DC servo motor RE40 was selected as the joint driving motor with the rated torque of 170 mN•m and rated power of 150W in order to meet the torque and power requirements in Figure 7, and equip with the features of integration, lightweight and high precision.

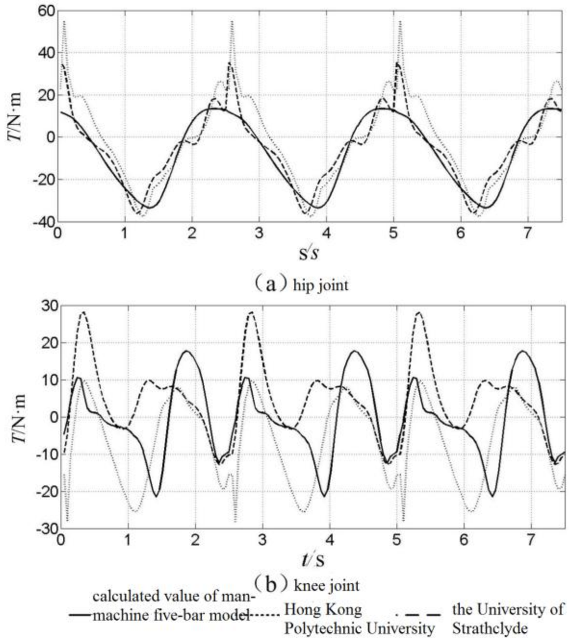

Figure 6 Torque curve of hip joint and knee joint

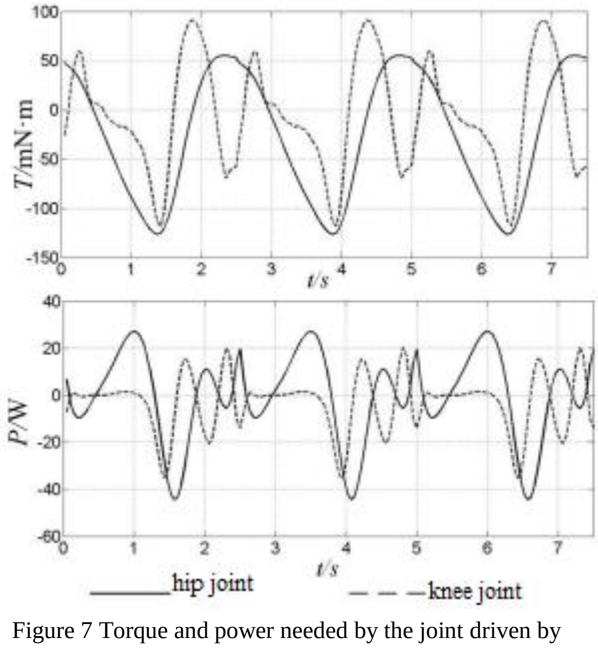

Figure 7 Torque and power needed by the joint driven by motor

PATIENT EXPERIMENT

The patient experiment at 60 person-time was conducted at the cooperation of rehabilitation training doctor in order to verify the actual performance of exoskeleton system for lower extremity rehabilitation, and one patient's experimental results were analyzed (patient's information can be seen in Table 2). The experimental time was 20 minutes, and the operating speed of exoskeleton was 2.5s for a gait cycle, the experimental process was shown in Figure 8.

Table 2 Patient's information

Gender	Height/m	Weight/ kg	Muscle force of left leg/ level	Muscle force of right leg/ level
Male	1.72	60	0	5

The patient's angle value at each joint in the training process was measured for the exoskeleton in the experimental process as shown in the full line of Figure 8. Meanwhile, the theoretical joint angle value sending to the exoskeleton from the upper computer was also offered. We can find that each joint angle curve measured in the experiment was lagged behind the theoretical value via comparing the experimental measured value and theoretical value, 0.6s was lagged at the largest on the hip joint and knee joint for the left leg, and 0.3s was for the right leg. The lag of system response was caused by the driving load of exoskeleton joint motor increased by the weight and inertia of human body and each part and the joint resistance.

Seen from Table 2, the experimental patient's muscle force of left leg was 0-level, it was unconscious basically, and the left leg movement was driven by the exoskeleton completely in the experiment process; while that of right leg was 5-level, it was normal completely, the patient cooperated with the exoskeleton movement subconsciously in the experiment process, thus reducing the operating resistance. Therefore, The difference on the lagged response of left and right leg joints offered in the experimental result in Figure 8 was consistent with the actual case of the patients with rehabilitation training.

Figure 8 Experiment process of rehabilitation exoskeleton

CONCLUSION

A kind of rehabilitation training exoskeleton at the weight loss of overhang was designed in the paper aiming at the demand of rehabilitation medical field on the rehabilitation training equipment. The gait suitable to walk in the treadmill was provided via the modification based on the normal people's walking gait data. Meanwhile, the torque and power of each joint at working for the normal people were calculated to provide the reference for the selection of the motor. The experiment of rehabilitation training exoskeleton was conducted for the patients at 60 person-time, and the reliability of the system was verified by the experimental results, and it has certain guiding significance on the patients' rehabilitation effect of lower extremity myodynamia.

There are still some problems to be researched further. At the middle of the rehabilitation training, the early passive training has not complied with the patients' demand, for they have certain walking ability at the period. The gait curve shall be amended at the real time according to the patients' rejection and adaptation on the standard gait track in the training process to reduce the patients' discomfort, and gradually improve the patients' initiative walking ability with the assistance of the exoskeleton. At the late of the rehabilitation training, the patients' active walking shall be the focus to monitor the walking quality at the real time via the sensor, and the exoskeleton shall only provide the auxiliary force when the patient can not realize certain action.

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