Design of an immersive neuro-muscle-motor rehabilitation robot system

Xingfu Zhang¹, Yi Lu² and Wei Meng¹*

¹School of Information Engineering, Wuhan University of Technology, Wuhan, Hubei, 430070, China
²School of Information Engineering, Wuhan University of Technology, Wuhan, Hubei, 430070, China
*Corresponding author’s e-mail: weimeng@whut.edu.cn

Abstract. Traditional rehabilitation methods neither have accurate training records and training feedback nor can they complete high-intensity and repetitive training. Moreover, the training mode is relatively dull and monotonous, which cannot mobilize the positive initiative of patients in rehabilitation training. Therefore, this article proposes a new kind of rehabilitation scheme by integrating functional electrical stimulation, virtual reality, and rehabilitation robot technology: Through the induction effect of electrical stimulation, the muscle activity can be improved as far as possible, and the rehabilitation training can be completed by using the patient's muscle contraction. Besides, the game, diagnosis, treatment, and psychological guidance can be integrated to improve the interest of training, to improve the enthusiasm of patients to participate in training, the three can coordinate to control and improve the rehabilitation efficiency.

1. Introduction
The combination of functional electrical stimulation (FES) and robotics for motor recovery have been a focus of attention for the past decade. The FES technology is integrated into the rehabilitation robot, and the assistance of FES and the rehabilitation robot is used as two driving methods to assist the patient to move. The sensors installed on the robot can sense muscle-related information and adaptively adjust the intensity of electrical stimulation. Electrical stimulation induces muscle contraction, which can improve the patient’s muscle activity and enable the patient to use their muscle contraction as much as possible to complete the exercise. Nicholas A.et al[1]. combined FES and power orthotics, and adopted a dynamic distribution control method based on NMPC to distribute the required torque between the FES and the motor, which can reduce the effect of muscle fatigue caused by FES, while ensuring the required Expect trajectory. Chen et al[2]. proposed an exoskeleton robot for lower limb rehabilitation, aiming to study the feasibility of combining functional electrical stimulation with robots for rehabilitation training. Through impedance control, the initiative of the robot is established and the patient's voluntary effort in completing the training task is stimulated.

The development of virtual reality technology has opened a new development direction for the field of rehabilitation treatment. At present, its application in the medical field has become one of the research hotspots[3]. The application of virtual reality combined with ankle robots has undoubtedly become a boon for ankle patients. Michael Girone and others [4]have developed the "Rutgers Ankle" ankle rehabilitation mechanism, which can assist patients in self-rehabilitation training and generate virtual scenes through PCs, allowing patients to play games while performing rehabilitation training, which can
increase the interest of the patient's entire rehabilitation process. It brings about effective rehabilitation effects, but the rehabilitation robot is difficult to achieve precise control. Ruili Wang and others[5] developed a set of immersive virtual scenes that can perform ankle rehabilitation training. To avoid patients with insufficient active exercise ability, an ankle joint rehabilitation robot is introduced for auxiliary training. The designed training model includes active training and passive training, which can allow patients to perform flexibility and strength training in a virtual scene.

2. The overall design of the immersive neuro-muscle-sports rehabilitation robot system
This immersive neuromuscular rehabilitation robot first provides a virtual environment that is in line with the wishes of the patient, which enables the patient to get rid of the single and repressed training atmosphere of traditional rehabilitation training and gives real-time sensory feedback, so that the patient can maintain the initiative and enthusiasm of rehabilitation training. During the patient's active training, the Angle sensors located in the three axes of the auxiliary motion robot and the force sensors located in the pneumatic muscle will collect the actual motion track, which will be uploaded to the upper computer through the data acquisition card and compared with the expected value. If the patient fails to meet the due training requirements through active training through virtual reality, the rehabilitation system will coordinate and distribute the torques generated by FES and the robot to ensure the completion of the overall movement and the activity of the muscles, so that the patient can complete the rehabilitation training with its assistance. The overall structure diagram is shown in Figure 1.

3. Design of virtual training scene and training mode
The system proposed in this paper adopts Unity3D to develop the virtual training scene task for ankle rehabilitation, which is mainly composed of park roaming scenes suitable for ankle 2-DOF training, indoor storage scene, and aircraft combat scene of ankle joint training with 3-DOF. From daily life scenes to challenging aerial scenes, from fully passive robot-driven training to patient-controlled robot autonomous training, the whole process is not only interesting but also can make the rehabilitation training process step by step.

3.1. Park roaming scene
The park roaming training scene is mainly composed of lawns, park paths, targets, and virtual avatars. The whole scene is concise and open, and springs in harmony, which can bring a sense of psychological comfort and help patients get rid of the oppression of traditional training. The overall scene achieved is shown in Figure 2.
During training, the interface will display the coordinate information of the virtual avatar and the time of the game in real-time. The movement of the virtual avatar in the park roaming scene mainly involves forward, backward, left turn, and right turn. After communicating with the robot, the four-movement modes corresponding to the ankle joint are shown in Table 1, which can realize the ankle dorsiflexion/plantarflexion, adduction/outreach two degrees of freedom training.

Table 1. Comparison of virtual reality sports modes in park roaming scenes

| Game operation | Ankle joint movement |
|----------------|----------------------|
| Forward        | Dorsiflexion         |
| Back           | Plantar flexion      |
| Turn left      | Adduction            |
| Turn right     | Outreach             |

3.2. Indoor storage scene
The indoor cleaning training scene is mainly composed of a room, a dining table, indoor furniture objects, items scattered on the ground, and a pair of virtual ankles. The items scattered on the ground are properly distributed on the ground as storage targets. The whole integrated scene has a strong life atmosphere and a warm atmosphere, which can give patients a sense of familiarity and relaxation. The overall scene achieved is shown in Figure 3.
In the indoor cleaning scene, the virtual ankle movement mainly involves forward, backward, left and right turns. After communicating with the robot, it corresponds to the ankle joint in four motion modes, as shown in Table 2, which can achieve two degrees of freedom movements of ankle joint dorsiflexion/plantar flexion and varus/eversion.

Table 2. Comparison of virtual reality sports modes of indoor storage scenes

| Game operation | Ankle joint movement |
|----------------|----------------------|
| Forward        | Dorsiflexion         |
| Back           | Plantar flexion      |
| Turn left      | Varus                |
| Turn right     | Eversion             |

3.3. Aircraft combat scene
The aircraft combat training scene is mainly composed of mountains, lakes, targets, dangerous objects & aircraft. The entire scene is under the blue sky. The field of vision is very wide, which is very attractive and challenging, allowing patients to break through the routine and experience the air. The feeling of flying an airplane, the overall scene realized is shown in Figure 4.

![Figure 4. Realization of aircraft combat scenarios.](image)

The aircraft combat scene is mainly used for the patient's mid-to-late rehabilitation training. At this time, the patient's ankle has recovered a certain degree of movement ability, which can drive the robot to perform active ankle joint movement in combination with scene tasks. The active exercise method is to continuously strengthen the training of muscles and ligaments around the ankle joint under the premise of emphasizing the active movement of the joints, improve the stability of the ankle joint, and promote the recovery of the ankle joint movement function. In the scene, the difficulty level of the task can be adjusted by changing the height of the target within a certain range according to the patient's situation.

In the aircraft combat scene, six operations are mainly involved in forwarding, backward, left, right, ascent, and descent. The six-movement modes corresponding to the ankle joint are shown in Table 3.
Table 3. Comparison of virtual reality movement modes of aircraft combat scenes

| Game operation | Ankle joint movement |
|----------------|----------------------|
| Forward        | Dorsiflexion         |
| Back           | Plantar flexion      |
| Turn left      | Adduction            |
| Turn right     | Outreach             |
| Rise           | Varus                |
| Decline        | Eversion             |

4. Cooperative training of functional electrical stimulation and rehabilitation robot

FES uses low-frequency weak current pulses to stimulate skeletal muscles that lose nerve control, to generate desired movements in the limbs. Meanwhile, it also works with pneumatic muscles to drive the rehabilitation robot, so that the patients can complete the target movements and achieve energy minimization and muscle fatigue minimization. Without the participation of FES and the complete passive assistance of the robot, there is no obvious interaction between the human and the machine, and the muscles are always at a low level. After the addition of functional electrical stimulation, the autonomic contraction of the muscles of the patients is stimulated, which can promote the initiative of the patients to participate in the training.

This system uses iterative learning as the outer control. Iterative learning can use the data of previous task attempts to update the control input and treat each iteration as training. It is expected that the patient will be more adaptable to the follow-up based on the previous training. Train and respond to external disturbances to a certain extent, while increasing its efforts, so that the system can accurately track the desired trajectory while also balancing the contribution of the exoskeleton and muscle stimulation, reducing muscle fatigue to a certain extent.

Although previous studies have introduced mechanical orthotics to assist FES in achieving movement, human-robot interactions have rarely been considered. Most hybrid rehabilitation systems are designed to reduce mechanical power consumption or minimize robotic assist torques, with little consideration given to electrical stimulation due to large parameters, or fatigue that may result from continuous, intensive electrical stimulation. In this system, a hybrid rehabilitation system is established, which integrates functional electrical stimulation and rehabilitation robot to assist subjects’ ankle joints. The ankle joint controller of the hybrid rehabilitation system mainly adopts the layered control, the outer layer is the dynamic control system, and the inner layer is the torque control system based on FES and rehabilitation robot. Outer control is according to the human body model, ankle by iterative learning algorithm ankle movement need to come to the target torque, the inner controller for the complex control system, using the energy minimization and the minimization principle of muscle fatigue, expectations of functional electrical stimulation and robots need torque optimization allocation, make the whole control system can realize the continuous movement.

5. Ankle rehabilitation robot based on position control and force control

The overall physical picture of the ankle rehabilitation robot is shown in Figure 5 below. The whole structure is relatively simple and convenient, with three rotational degrees of freedom.
Figure 5. The physical picture of the ankle robot.

The robot is driven by 5 FESTO pneumatic muscles, and connects the pneumatic muscles with the moving platform through flexible cables, and completes the driving of the moving platform through the contraction movement of the pneumatic muscles. As for the direction change of the driving force, it is realized by the built-in pulley to meet the different rehabilitation training needs of the ankle.

In patients with the system for virtual reality interaction in the process of ankle robot ontology on the three axial Angle sensor can collect patients with ankle Angle change information, can be transmitted by data acquisition card first place machine, and then USES the real-time incoming TCP communication to the virtual scene, through the Angle change to real-time control the position of the avatar and supplemented by appropriate FES virtual task to help patients. When the desired Angle is still not reached in this process, the robot can be controlled to drive the patient's ankle to make accurate trajectory movement by giving a given trajectory.

Ankle rehabilitation robot is mainly composed of three modules, namely, the main exercise module, power transmission module, and support module. The main motion module refers to the entire moving platform connected module, including three different axial rotating joint structures of the moving platform. Three angle sensors are installed in the three rotating joint directions to monitor the rotation angle changes of each rotating shaft. The force/torque sensor is installed on the moving platform under the foot pedal, in the middle position of the two, and can be used to collect human-computer interaction force/torque information in different axial directions.

6. Summary and outlook
Given the problems existing in the traditional ankle rehabilitation training, an immersive neuromuscular motor rehabilitation robot training system is built, which improves the safety and interest of the training process, enhances the enthusiasm of the patient training, to improves the rehabilitation efficiency. The research content of this paper still needs to be further explored, and the next exploration work mainly includes the following two aspects:

(a) At present, the designed rehabilitation robot training system is only suitable for ankle joints, while the common lower limb injuries include hip injury and knee joint injury. Therefore, the future work should consider extending the rehabilitation training system to more sports rehabilitation;

(b) More personalized and humanized multi-mode rehabilitation training games can be designed and developed for ankle patients at different ages and with different disease characteristics, fully considering the interest unless and immersion of rehabilitation treatment for patients. The system can be combined with the development of telemedicine, increase the online evaluation module of doctors, and design a set of robot system with remote control, to realize the online evaluation and adjustment of doctors in
different places, carry out scientific and reasonable guiding treatment, and develop more comprehensive and accurate personalized rehabilitation strategies for patients.

References

[1] Kirsch N A, Bao X, Alibeji N A, et al. Model-Based Dynamic Control Allocation in a Hybrid Neuroprosthesis [J]. IEEE Trans Neural Syst Rehabil Eng, 2018, 26(1): 224-232.

[2] Chen Y, Hu J, Peng L, et al. The FES-assisted control for a lower limb rehabilitation robot: simulation and experiment [J]. Robotics & Biomimetics, 2014, 1(1).

[3] Davide Corbetta, ederico Imeri,Roberto Gatti. Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance and mobility after stroke: a systematic review [J]. Journal of Physiotherapy, 2015, 61(3).

[4] Girone M, Burdea G, Bouzit M, et al. A Stewart Platform-Based System for Ankle Telerehabilitation [J]. Autonomous Robots, 2001, 10(2):203-212.

[5] Boian R F, Deutsch J E, Lee C S, et al. Haptic effects for virtual reality-based post-stroke rehabilitation[C]// Symposium on Haptic Interfaces for Virtual Environment & Teleoperator Systems. IEEE, 2003.