VR-DLR: A Serious Game of Somatosensory Driving Applied to Limb Rehabilitation Training

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Abstract. Hemiplegia is one of the common symptoms of stroke, especially the motor dysfunction of upper limb has a great impact on the patients' daily life, and it is also one of the difficult problems in rehabilitation treatment. However, traditional rehabilitation training lacks pleasure and easy to make patients shrink. We use virtual reality technology to design VR-DLR (VR driving for limb rehabilitation), a serious game of somatosensory driving that combines hardware, software and integrates sight, hearing and tactile sensations. We design parameterized steering wheel training actions according to the level of the patients' limb disorders and the rehabilitation physician's treatment plan. The patients' training task is to control the virtual car to collide more coins and to avoid fewer obstacles. We collect and record the patients' interactive operation data, and design evaluated model to evaluate the patients' score and rehabilitation effect. VR-DLR supports two modes of fixed speed and free driving and has adapting difficulty in each mode according the limb disorders of patients. Moreover, in order to meet the needs of different patients, VR-DLR has two display modes of VR headset and 3D annular projection screen. A user study shows that VR-DLR can significantly increase the interest, initiative, confidence of patients in rehabilitation training compared with traditional training methods.

Keywords: Rehabilitation training · Virtual reality · Driving simulator · Serious game.

1 Introduction

In recent years, persons who suffer from stroke become younger and younger. The rehabilitation of limb function after stroke has always been one of the difficult clinical problems. 85% of stroke patients have disorders of upper limb at the early stage of onset[19], and about 30%-36% of stroke patients still have dysfunction of upper limb 6 months after the onset[9]. This seriously affects the patients' motor function and daily life. Although the traditional treatment methods based on artificial and physical equipment have a certain effect, the patients' movement

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cannot be quantified into data and collected, which is not conducive to the analysis of the rehabilitation physician. The patients' initiative is affected by the tedious training process. Therefore, it is of great significance to find active and effective rehabilitation treatment methods to improve the limb function of stroke patients.

Virtual reality technology refers to the use of integrated technology to form a realistic 3D virtual environment. Patients use the VR equipment to interact with objects in the virtual world in a natural manner, thereby generating immersive experience[16]. Many studies have shown that serious games based on virtual reality technology have a positive promotion significance for rehabilitation training[3, 18]. However, most of these serious games use fixed scenes, that is, pre-built scenes and fixed tasks, which may make the patients' interest decrease with the increase of training days. Many virtual serious games do not consider the balance between the degree of different limb disorders and the difficulty gradient, which may reduce the effectiveness of training. In addition, in order to improve the patients' rehabilitation confidence and the fun of the game, the virtual serious game needs more interactive feedback and encouragement mechanism.

In order to overcome these shortcomings, we apply VR driving technology with rich somatosensory interaction experience to the rehabilitation training of patients, so that the patients can play gamified rehabilitation training driven by the training tasks with fun.

The contribution of this article is to design and develop a serious game of somatosensory interactive VR driving called VR-DLR for patients with moderate and mild limb disorders(levels 2-4 in Muscle Strength Classification[13]). We parameterize the training actions customized by rehabilitation physicians for different patients to automatically generate random scenes and training tasks. VR-DLR has two driving modes (free driving mode, fixed speed mode) according to the degree of disorders of the patients. The adaptive difficulty of the game is dynamically controlled through resistance of steering wheel, speed of the car, number of obstacles, limited time, etc. According to the patients' preferences, VR-DLR provides two presentation methods (VR head-mounted display(HMD) and annular projection screen). In addition, according to the tasks' completion time, operation data, score and historical data are recorded in the back-end, VR-DLR gives a score after each training and encourages users by details of improving operations compared with the historical data.

2 Related Work

2.1 Rehabilitation Training Based on Traditional Methods

In the traditional rehabilitation training method, the rehabilitation physician mainly performs stretching and other training on the patients' limbs in a freehand manner. Generally, this rehabilitation training method is operated by the rehabilitation physician and the patient one-on-one. Because training mainly depends on the operation of rehabilitation physicians, or uses some physical training equipment, the training intensity and efficiency of traditional training methods are not stable, and the training effect is difficult to be guaranteed. The lack of data collection and feedback on the training process of the patients makes physicians difficult to[11]. In the traditional rehabilitation training methods, there are also the problems of limited training venues, lack of professional rehabilitation physicians, expensive treatment and monotonous training procedures. Many patients do not get obvious rehabilitation effects. Losing confidence and interest in rehabilitation brings a big psychological burden to patients[14].

2.2 Rehabilitation Training Based on Robot

The PERCRO laboratory in Italy has designed a set of virtual rehabilitation training robots for the right limb of stroke patients[6]. The external equipment of the system is a five-dof upper limb skeleton robotic arm. And they develop a virtual system of rehabilitation training for the robotic arm[5]. The University of California and the Chicago Rehabilitation Research Center jointly researched and developed a robotic training system with multi-joint called Spring[12], which is specifically aimed at patients with regaining active mobility in the early stages of rehabilitation. Although the use of robots can reduce the artificial burden and achieve better rehabilitation training results compared with traditional rehabilitation training, the robotic method cannot effectively increase the enthusiasm and interest of patients.

2.3 Rehabilitation Training Based on Virtual Serious Games

In recent years, with the development of CG technology and VR technology, rehabilitation training methods based on virtual serious games have become popular. Laffont et al.[10] study video games for treatment of stroke and they found that using video games in the first month after a stroke is more effective than traditional methods. Ines et al.[2] study the impact of serious games on elderly people participating in rehabilitation programs. Their research results show that game-based rehabilitation is very helpful to improve the balance of the elderly. Jo˜ao et al.[1] study the impact of serious games on rehabilitation physicians' actual work. The results show that rehabilitation physicians play an important role in making serious games work properly.

Gamito et al.[7] develop a serious VR-based game application for cognitive training. The results show that the patients' attention and memory functions can be significantly improved. OGUN et al.[15] found that the immersive VR programs in rehabilitation has a positive effect on the upper limb function and daily activities of stroke patients. Santos et al.[17] design medical rehabilitation experiments to explore the effect of VR rehabilitation program in SCAs patients. Keshner et al.[8] provide the decision-making for the VR technology systems suitable for clinical intervention therapy. Feng Hao et al.[4] design a VR system to help patients with Parkinson disease recover gait and balance and achieved good results.

However, most of these serious games have only a single interactive scene, lack of scientific and fun training tasks, and lack of different game modes and difficulty for different levels of limb disorder.

3 Design and Implementation

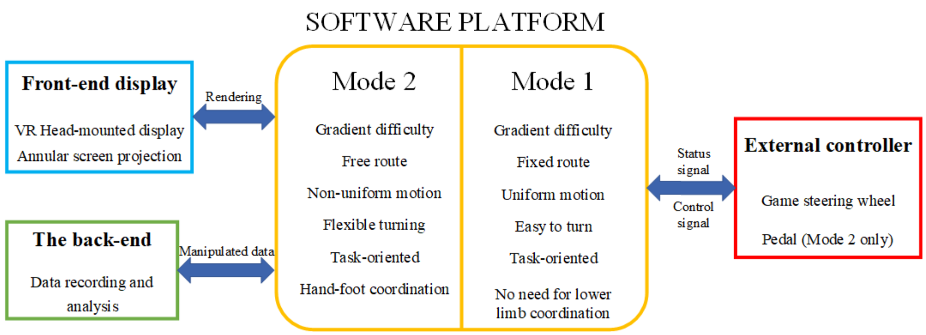


Fig. 1. Structure of VR-DLR.

3.1 Structure Design

The structure design of VR-DLR is shown in Fig. 1. In terms of hardware, it consists of a pedal(mode 2 only) and a steering wheel that can adjust the resistance according to instructions. VR-DLR divided into fixed speed mode (mode 1) and free driving mode (mode 2). The front-end display is free to choose whether to wear a VR HMD or 3D glasses to view the annular projection screen according to the patients' preferences. In the process of rehabilitation training, we will record some key operation data of patients into the database and establish an evaluation model.

3.2 Function Design

Before the patients undergo rehabilitation training, the rehabilitation physician determines the rehabilitation stage for the patient based on professional knowledge. Based on the training actions and training intensity designed by the rehabilitation physician for the patient, we design training tasks with different difficulty gradients, so that rehabilitation training can be carried out more scientifically. The virtual environment of VR-DLR is configured according to the treatment plan. The treatment plan can be described by the parametrically training action. The functions of VR-DLR can be divided into module of training tasks, module of training information collection and evaluation module of effect. Fig. 2 shows the relationship between the modules.

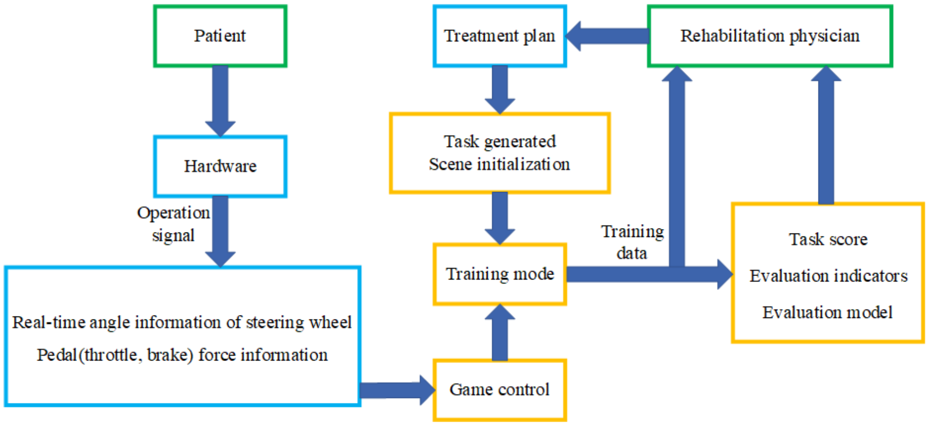
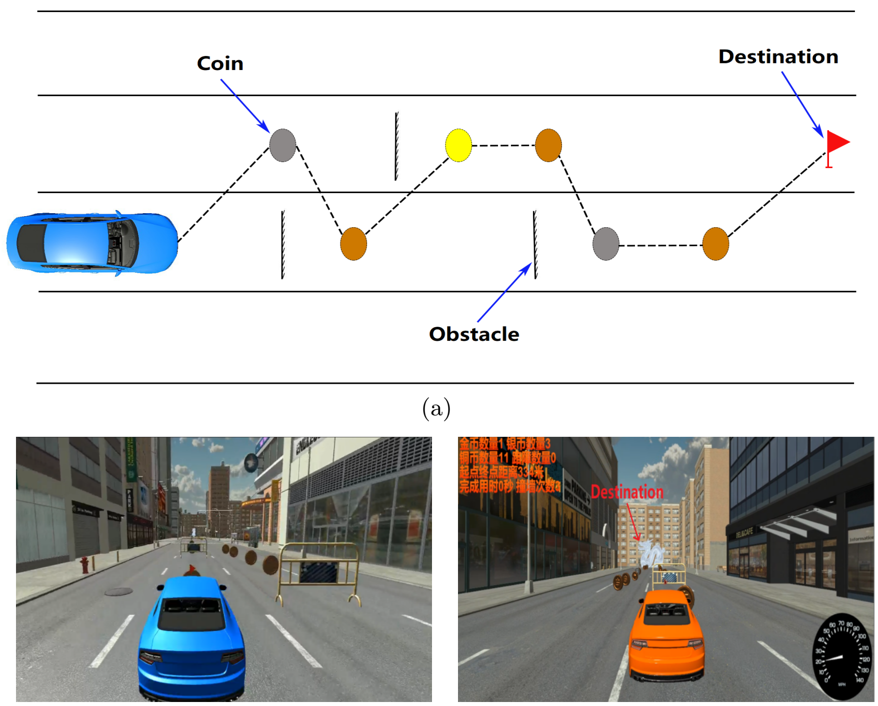


Fig. 2. Function of VR-DLR.



(a) (b) (c)

Fig. 3. Module of training tasks. (a) A schematic top view of a set of continuous training actions (b) Complete training actions guided by collide the coins and avoid the roadblocks. (c) Arrive at the destination of the designated task within the limited time.

Module of training task. Rehabilitation physicians design a set of training actions suitable for patients. We parameterize the training actions to automatically and randomly generate virtual coins (gold coins/silver coins/copper coins) and roadblocks oriented to the training actions. By controlling the virtual car, the patient can complete the task of reaching the destination and collide with as many coins as possible along the way to complete training amount. As shown in Fig. 3(a), a schematic diagram of continuous training movements(left− >right− > left− >right− >left) after parameterization of some actions in the training task is shown. Guided by gold coins and roadblocks, the patient needs to complete a series of movements to turn the steering wheel to avoid roadblocks and collide coins. Have the more coins, less collision with roadblocks and reach the destination within the limited time will get the higher score. Fig. 3(b) and (c) show the screenshots of the module of our training tasks.

In this module, patients can experience immersive driving operations. In order to further improve the patients' interactive experience, the steering wheel will dynamically provide various feedback, such as vibration when collision with roadblocks, and the resistance of steering wheel will increase when the vehicle speed is faster. In addition, for patients with different levels of limb disorders, the difficulty of the automatic initialization of scene and tasks is different. The difficulty is reflected in the resistance of the steering wheel, the speed of the car at a fixed speed (mode 1), the maximum speed (mode 2), the number of roadblocks, the complexity of parameterized training actions, the distance between the destination and the car's initial positon, etc.

Module of information collection. During the rehabilitation training, VR-DLR collects the operation signals of the patients through the rotation angle information obtained by the sensor of steering wheel and the displacement information obtained by the throttle and brake sensors on the pedal. Then it converts the collected information processing and maps it to the steering wheel, throttle and brakes of the virtual car. The patients' key operation data (as shown in the left column of Table 1) is also used to evaluation model of VR-DLR and assist rehabilitation physicians in evaluating patients' rehabilitation.

Evaluation module of rehabilitation training effect. In rehabilitation assessment, joint mobility, agility of movement and amount of joint movement can be used to assess the joint rehabilitation of patients. During the training process, the greater the rotation angle of the motion, the greater the range of related joint motion; the faster the motion speed, the more agile the patients' movements; the more the number of training actions, the greater the amount of patients' movement. Therefore, the action requirements in the training program can be described by the rotation angle, speed and number of actions, which are the influencing factors of the training actions. We combine the rehabilitation medical theory, clinical practice and evaluation standards of functional movement of shoulder and elbow to construct a reasonable index of rehabilitation evaluation. In addition, we use the analytic hierarchy process to calculate the weight of each index in the evaluation of the rehabilitation effect and determine evaluation model after the rehabilitation physicians' agree. By evaluating model' calculations and specific operational steps in the game, we can quantify the score assessment in Table 1. Among them, ω_t represents the weight value between 0 and 1 that the quantization of the completed time of turning the steering wheel. The greater the amplitude of the steering wheel and the shorter the time, the higher the weight value. In addition, if patients can complete consecutive training actions (such as turn the steering wheel to the right to avoid obstacles and then turn the steering wheel to the left to collide with coins on the left road...), they will get additional score. By calculating the score of the evaluation model and comparing it with historical data, the patients' rehabilitation effect is obtained. The evaluation details will be presented to patients in the form of electronic report. Compared with the difficult progress of short term in traditional rehabilitation, evaluation feedback of VR-DLR will allow patients to feel the progress of details(Table 1) to improve the courage and confidence of rehabilitation.

Table 1. Quantified evaluation.

Key operating data	Score
Turn the steering wheel sharply (more than 120 degrees at a time)	50*ω_{t1}
Turn the steering wheel moderately (60 to 120 degrees)	30*ω_{t2}
Turn the steering wheel slightly (less than 60 degrees)	20*ω_{t3}
Hit the roadblocks	-20
Get gold/silver/copper coins	15/10/5
Arrival at the destination within the limited time	200
Complete consecutive training actions 2/3/4 times...	20/30/40...

3.3 Game Modes and Display Methods

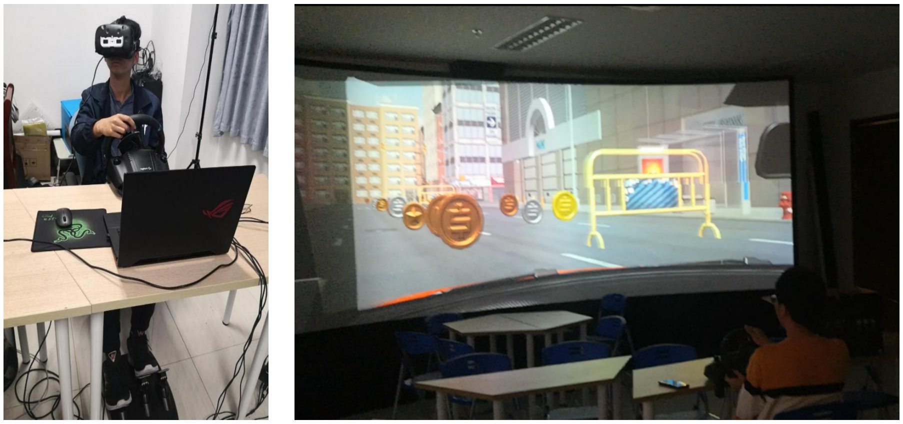
Mode 1: Fixed speed. VR-DLR is divided into two modes. Mode 1 is a fixed speed mode. In this mode, the throttle and brake will not be used. The forward movement of the virtual car relies on automatic power traction and fixed speed. Patients can concentrate on controlling the steering wheel. This mode is mainly used for patients with rate 2-3 (moderate) upper limb disorders in the Muscle Strength Rating Table[13]. We set virtual routes on every city road. By default, the car moves forward at a low speed (20km/h) at a fixed speed, and the patients can change to the left or right lane change by turning the steering wheel on a straight road. At the intersection, the patients turn left or right by turning the steering wheel. If the patients do not turn the steering wheel at the intersection or the angle of steering wheel is too small, it goes straight by default. At an L-shaped junction, whether the patient is turning the steering wheel, the car will automatically turn in the direction of the junction to avoid driving out of lane. There is an anti-deviation system, even if the angle of the steering wheel is wrong, VR-DLR will use the method of automatic interpolation to correct the direction of the car to ensure that it will not deviate route.

Mode 2: Free driving. Mode 2 is a free driving mode. We simulate a real driving mode and patients can flexibly drive a virtual car in coordination with hands and feet. In this mode, training of upper limbs is the main training task of VR-DLR, with ankle joint exercise as auxiliary training. This mode is mainly used for patients with limb disorders of rate 4 (mild) in the Muscle Strength Rating Table[13]. In this mode, in order make patients to obtain a more realistic driving experience and dynamically adjust the difficulty of driving, we simulate some physical properties of virtual car according real car, including the acceleration of the throttle-controlled and the speed of the tire, the friction between the tires and the ground, etc. For these physical properties, detailed parameter settings are shown in Table 2. In this mode, the user accelerates and decelerates by controlling the throttle. When the car has speed, stepping on the brake will slow down. When the car is stationary, holding the brake will have a reverse effect. In addition, this mode has no automatic anti-deviation protection settings. If the user hits an obstacle outside the street area (such as trees, telephone poles, bus stops, buildings, etc.), VR-DLR will deduct points and the user needs to step back on the brakes to reversing.

Table 2. Physics-based simulation.

Physical properties	Parameter settings
Vehicle weight	1.5t
Torque	800N
Down force	100N
Maximum speed	50km/h
Maximum steering angle	30°
Damping rate of wheel	0.25
Minimum forward friction	0.4
Maximum forward friction	1
Minimum lateral friction	0.2
Maximum lateral friction	1

Display methods. In most circumstances, the display method is to wear VR HMD for an immersive driving experience, as shown in Fig. 4(a). However, we consider that some patients may be dizzy when wearing VR HMD, which affects the rehabilitation effect. Therefore, we also use a method of combining 3D glasses and an annular projection screen to conduct the rehabilitation training, as shown in Fig. 4(b).



(a) (b)

Fig. 4. VR-DLR display mode. (a) VR. (b) Annular projection screen.

3.4 Development Tools

We use Logitech G29 Driving Force steering wheel and pedal. In terms of software, we use C sharp and hlsl/cg to develop driving logic on the Untiy 3D engine and put key operating data into the MySQL database.

4 User Study and Analysis

4.1 Subject of Research

We select the patients from a center of rehabilitation training as the subject of user study. With the help of rehabilitation physicians, we recruit 16 patients rated 2+, 3-, 3+, 4- and 4+ based on the Muscle Strength Rating Table[13] who volunteered to participate in the research. There are 10 males and 6 females. The patients' ages range from 26 to 67. Based on the age, muscle strength rating and gender, patients are divided into group A (training with VR-DLR) and group B (training in the traditional way). Both groups have been composed with the goal having no differences regarding the criteria. There are 8 patients in each group. The average age of patients in group A is 49.5, and 48.625 in group B. There is no remarkable difference in age and muscle strength rating between the two groups ($P>0.05$) after statistical analysis.

4.2 Method of Research

Design of daily training. Our research on the two groups of patients is completed by experienced rehabilitation physicians and the patients' family. The study lasts 10 days. Patients in both groups are required to conduct traditional limb rehabilitation training 30 minutes a day. The training includes scapular loosening training of the affected upper limb, active assistance and active training of the upper limb of the affected side, joint movement training of the upper limb of the affected side, object retrieval training of the upper limb of the affected side, and training of grasping and opening of the affected side. The training is mainly on the affected side, including a small amount of training on the healthy side. The training intensity of the affected side is basically the same. Then, based on their own situation and their own wishes, the additional training programs of the corresponding group will be carried out with no time limit every day. That is, in addition to the traditional limb rehabilitation training for 30 minutes per day, group B can increase the time of the same rehabilitation training programs according to individual wishes. For group A, after receiving traditional rehabilitation treatment, patients can use our VR-DLR for training with the assistance of rehabilitation physician. For individual patients who are not suitable for immersive VR devices, they can also choose to wear 3D glasses and look at the annular screen for training. In group A, 2 patients appeared dizziness due to the VR HMD mode on the first day, and used the annular screen for the next few days. We record the feedback of the rehabilitation experience of the two groups of patients and obtain the rehabilitation treatment data of the two groups of patients from the rehabilitation physicians, especially the time for the patients to perform voluntary training in addition to the fixed traditional training every day.

Design of questionnaire. After 10 days of group training, the patients are asked to complete a questionnaire with the assistance of rehabilitation physicians. The patients' cognitive feedback and attitude to rehabilitation training from 4 dimensions are obtained by the questionnaire. A corresponding score should be given in each question, from 0 to 5. The design of the subjective question is shown in Table 3.

Table 3. Questionnaire of rehabilitation training.

Question 1	Degree of psychological stress in rehabilitation training. (The more relaxed you feel, the higher the score.)
Question 2	Degree of physical stress in rehabilitation training. (The more relaxed you feel, the higher the score.)
Question 3	Sense of achievement in rehabilitation training. (The higher sense of achievement, the higher the score.)
Question 4	Degree of interest in the rehabilitation training. (The higher the level of interest, the higher the score.)

4.3 Analysis of user data

Statistics of autonomous training time. We record the length of time that the two groups of patients spent everyday (excluding the necessary traditional

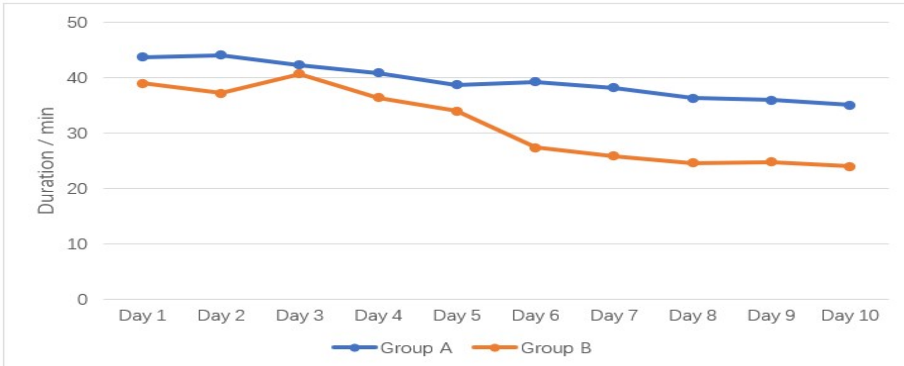


Fig. 5. The time of daily training for two groups of patients.

training), and use the t-test to determine the difference. In the 10-day experiment, we find that there is no significant difference in the autonomous training time of the two groups of patients only on day 3 ($p>0.05$). In the remaining days, group A is significantly higher than group B (average of group A>average of group B, $p<0.05$). Fig. 5 shows the average duration and standard deviation of autonomous training for each group of patients per day.

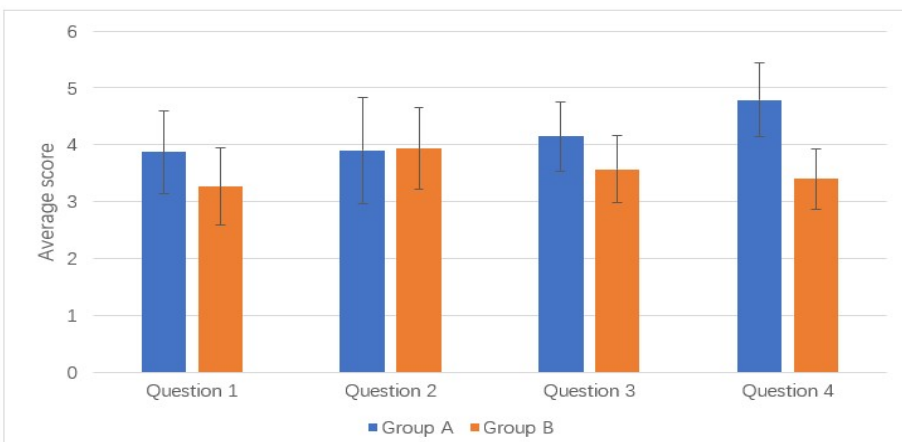


Fig. 6. Result of questionnaire.

Statistics of questionnaire. At the end of the 10-day experiment, we collect feedback from the patients' questionnaire and make statistics. Fig. 6 shows the scores given by the two groups of patients. We use t-test to analyze the significance of the two sets of data. The results show that on questions 1, 3 and 4, group A is significantly higher than group B (average of group A>average of group B, $p<0.05$). There is no significant difference between the two sets of data on question 2 ($p>0.05$).

Analysis of differences. It can be found in Fig. 5 that as the number of exercise days increases, the average autonomous training time of both group A and B show a decreasing trend. However, the trend of group A declines more slowly than group B, which shows that compared to traditional training way, VR-DLR is more attractive to patients. It can be seen from Fig. 6 that patients using VR-DLR have less psychological pressure, higher sense of achievement and more interest than traditional rehabilitation training.

We have analyze the causes of these differences based on daily patients' feedback and the evaluation of rehabilitation physicians. In the traditional rehabilitation training, artificial stretching and physical training are more likely to cause pain than the use of VR-DLR, which is more likely to cause the patients to develop a psychological resistance. In the process of using VR-DLR, the patients completely control the movements of joints and muscles (in the traditional training, many actions are subject to the control of rehabilitation physicians and mechanical equipment), and the patients' attention is focused on the game, which will distract the patients' attention in pain and be more willing to accept this treatment. In addition, compared with group A, the patients in group B generally lacked the confidence to recover and the courage to conduct the rehabilitation training(Question 1 and 3). This is because the patients are monotonously treated for a long time and could not make progress in a short time. Group A received triple encouragement from rehabilitation physicians, the process of the game and the evaluation models of the game. VR-DLR will also compare to historical data and give more detailed progress (such as the key operating data in Table 1). All of these provide patients with better encouragement and increase the patients' confidence in their own recovery.

On question 2 (physical stress) of the questionnaire, there is no significant difference ($P>0.05$) in the scores given by the two groups of patients. However, after our research, some patients say that the physical weight of the VR HMD will cause a certain amount of pressure. But because of immersion of VR, this pressure will not significantly affect the them. The use of an annular projection screen will produce less pressure than a VR HMD, but it will reduce the immersion of virtual driving.

5 Conclusion

We have developed a sense of VR driving serious game called VR-DLR for the treatment of limbs disorders, in order to overcome some shortcomings of traditional rehabilitation training and serious games. Results of the experiment show that compared with traditional training, VR-DLR has a better attraction and experience for patients, including less psychological pressure, higher sense of achievement and fun. This is also confirmed in the time of daily autonomous training.

6 Future Work

This study aims to explore the attractiveness, experience and acceptance of VR-DLR to patients. In the future, we will continue to improve VR-DLR and conduct longer user studies to study the impact of VR-DLR on rehabilitation effects.

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