
A Novel Rehabilitation Evaluation Method on Virtual Reality Based on RRR-I

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1. Introduction

With the aggravation of the population aging in the world, more and more nations and communities attach importance to the research on the rehabilitation of the aging and the disabled. Nevertheless, the conventional rehabilitation apparatus dramatically have a number of problems, regardless of their good rehabilitation effects. For instance, the conventional training techniques require enormous physical therapists such as doctors, nurses and so forth to assist the patients in completing a series of activities, so that it would waste a lot of unnecessary expense and manpower. As a result, there is an increasing emphasis placed on the rehabilitation robot which may be a solution to the problems in conventional rehabilitation technique.

Some research job is about the lower-limb, and the researchers have designed many practical devices. Y. H. Tsoi and S. Q. Xie (2008) have invented a robot which could recover the patients' ankles. However, the training environment might be boring for most patients, for it lacks of a virtual game interface which may be full of entertainments. Meanwhile, there are also a lot of researchers who pay attention to the upper-limb rehabilitation robot. Koichi Kirihara, Norihiko Saga and Naoki Saito (2010) have designed a robot which has five degrees of freedom by virtue of its link mechanism. A pneumatic cylinder, arranged and integrated with the device, was used to operate it. Nonetheless, the safety could not be assured in this device, for the control of the pneumatic device often brings about fierce impulse which may do harm to the patients. Janez Podobnik, Matjaž Mihelj and Marko Munih (2009) also have made a HenRiE (Haptic environment for reaching and grasping exercises) device with two hemiparetic subjects. The HenRiE device is intended for use in a robot-aided neurorehabilitation for training of reaching and grasping in haptic environments. But the researchers fail to add an impedance environment to the patients who are being trained so that the patients' arm muscles could not be fully stimulated.

Ken'ichi Koyanagi, Junji Furusho, Ushio Ryut (2003) and Akio Inoue, T Kikuchi, K Fukushima, J Furusho and T Ozawa (2009) have developed a practical haptic device 'PLEMO-P1' in which adopts ER brakes as its force generators. Although, by using the ER brakes, it is safer and more convenient than other similar rehabilitation robots, the ER brakes still have some disadvantages such as the leakage of the inner liquid.

This chapter mainly gives a description of a new upper-limb rehabilitation robot using the magnetic particle brake (MPB), which is named RRR-I (Remote Rehabilitation Robot-I). The robot is shown in Fig.1. After the passive training technique in the rehabilitation field is applied to the design of the robot, the MPB is made full use of to generate an impedance environment for the patients. Furthermore, in order to make the training process more interesting and more attractive, a kind of virtual reality technique is put into training process. For example, a human-machine interaction interface is devised, so that the patients could play some particular computer games to enhance their arms' movement ability and then the researchers could assess their rehabilitation level. Finally, by using some correlative mathematical statistics methods, we create a kind of evaluation technique and basically obtain a good result.

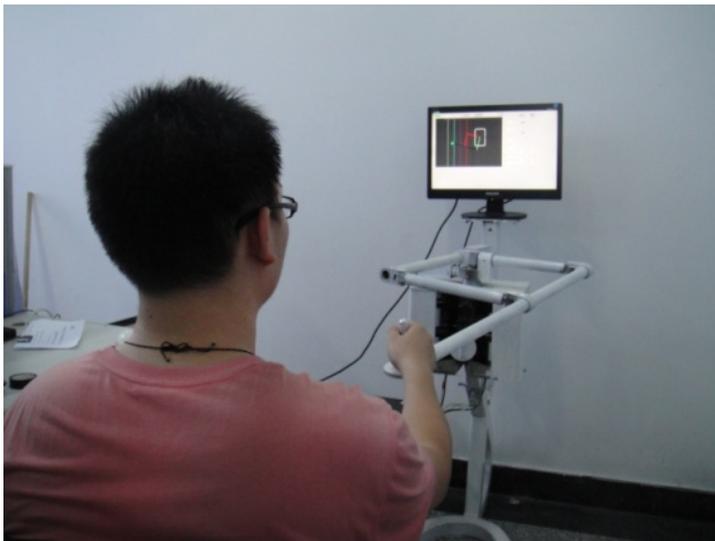


Figure 1. Experiment System of the RRR-I

2. The PNF technology in upper limb rehabilitation

PNF (proprioceptive neuromuscular facilitation) is a therapy which promotes the response ability of nerve and muscle through simulating proprioceptors. PNF was founded by Herman Kabat who was American physician and neurophysiologist in 1940s. It was originally used in cerebral palsy and multiple sclerosis patients, medical practice has proof that it also can apply to the stroke upper limb rehabilitation (2008).

According to common movement mode of human daily activities, PNF technology was founded based on the human body development learning and neurophysiology principle. One of the most commonly used PNF technology is diagonal mode (diagonal D), which is a kind of gross motor that can be seen in most function activities. It is the movement that formed by the interaction of three muscle in flexion and extension, internal and external exhibition, internal and external spin. Also diagonal mode is the last and highest form of normal development. All the diagonal movement is the merger of rotating component, which can promote the interaction of both left and right body sides because of the path across the body centre line. Common action: right hand touching left ear, resisted motion. The resisted motion was shown in Fig. 2.

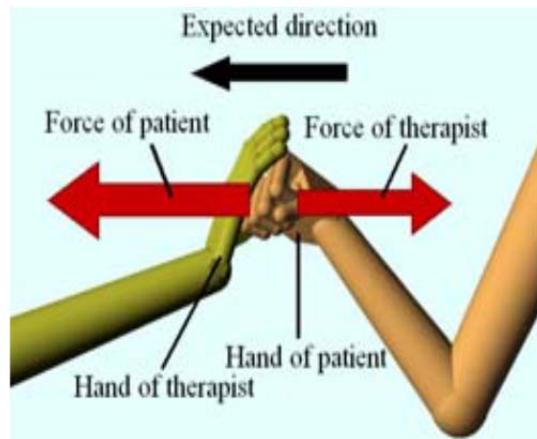


Figure 2. Resisted motion

The common promote method of PNF.

1. Command:

A short and concise command can stimulate patients to active force;

2. Visual cues:

Make patients take exercises by watching in order to help to exercising and coordinating;

3. The body location of therapists:

The therapists should be close to patients and move stable together with patients while providing resistance through their own weight;

4. Input of ontology sense:

According to the situation of patients, the resistance on the patients' sicken limbs should be suitable. The resistance will be ok while it allowing patients to do slow, stable and coordinated movement with no abnormal movement occurring.

3. Design of RRR-I

Fig. 3 shows the structure of the RRR-I. The robot mainly consists of robot arms, a handle, two balance blocks, a screen, a connection box, a computer box, a controller box and other parts. By referring to the Parallelogram Linkage Mechanism (PLM), we design the robotic arms which have balance blocks to keep the arm's balance. The absolute encoders are fixed in the connection box as well as the MPBs. But they have distinct functions. The encoders are used to attain the arms' rotation angles while the MPBs are applied to the resistance moment support. In order to control the pitching angle of the robot, which may change according to different patients, we make an attempt to design a rotation handle at the surface of the connection box. Meanwhile, the force of gripping is obtained through a force sensor on the handle. And the DSP in the controller box would receive the sensors' data information and then send the control information to the MPBs after a data analysis. In the end, a game interface would be displayed to the patients in the screen.

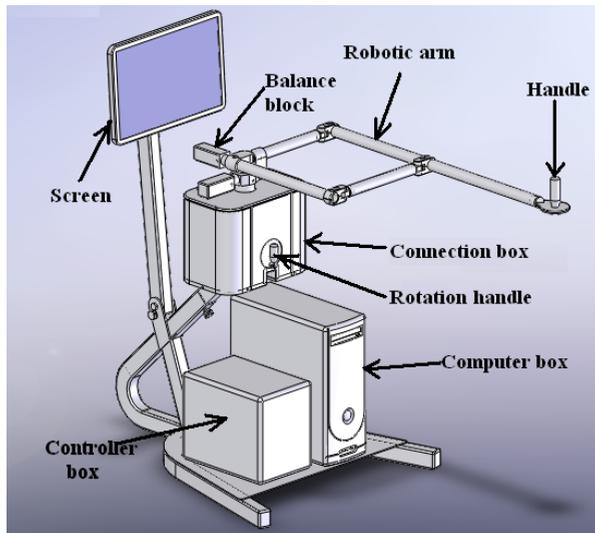


Figure 3. Overall Structure of the RRR-I

3.1. Upper limb rehabilitation robot system

The upper limb rehabilitation robot system and diagram of the whole robot system were respectively shown in Fig. 4 and Fig. 5. The hardware consisted of three parts: control unit, detect unit and execution unit.

3.2. Control unit

The micro control chip was one 32-bit fixed-point DSP TMS320F2812 made by TI, in charge of the control calculation of force feedback system, handle position and communication with PC; PC was responsible for the human-computer interaction.

3.3. Detection unit

Detection unit consisted of position detection and force detection.

The handle was a force sensor which can sense force in four directions and measure the force to limb. Because of the low moving speed of sicken limb, AD7705 with low working frequency was choose as A/D conversion chip. AD7705 can receive the weak signal directly came from sensors. Thus, error caused by the analog signal amplifier circuit can be avoided and the circuit was greatly simplified;

As the position detect unit, 14-bit accuracy absolute encoder ensured the movement tracking precision of patients' upper limb.



Figure 4. Upper limb rehabilitation robot based on magnetic powder brakes

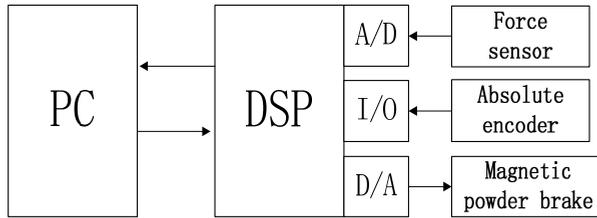


Figure 5. Diagram of upper limb rehabilitation robot system structure

3.4. Execution unit

As actuators, two magnetic powder brakes were responsible for the generation of resistance of 2 DOF. Two magnetic powder brakes were respectively linked to the inner and outer shaft through belt, so as to realize independent torque control of the inner and outer shaft of 2 DOF, as shown in Fig. 6.

Based on the principle of electromagnetic, magnetic powder brakes convey torque through magnetic powder, where relationship between torque and exciting current is linearity. So the torque can be easily controlled by changing exciting current. Normally, the relationship between exciting current and the conveyed torque is proportion linearity (2009) in the range of 5% to 100% of rated torque.

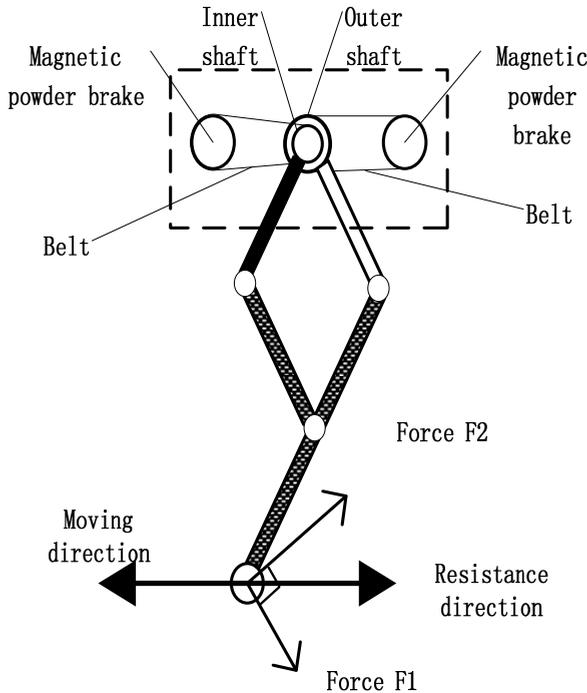


Figure 6. Braking force diagram of 2 DOF

When exciting current remain unchanged, the conveyed torque wouldn't be influenced by the differential speed between master driver and follower (sliding speed), i.e. there is no difference between static torque and dynamic torque (2004), so the constant torque can be stably conveyed. Then magnetic powder brakes only generate resistance torque result from its fixed follower. Magnetic powder brakes parameters were shown in table 1. Because of the feature above used in the handle force control, the required force to sicken limb can be achieved simply and effectively.

Rated voltage (V)	24
Rated torque (N. m)	12
Sliding power (W)	100
Max current (A)	0.6
Max rotate speed (rpm)	650
Diameter (mm)	150
Height (mm)	56

Table 1. Magnetic powder brakes parameters

3.5. Software

In this chapter, the man-machine interface of whole upper limb rehabilitation robot was realized by Visual C++. The interface consisted of virtual mechanical arm display and basic information display.

1. Virtual mechanical arm

This section displayed the real-time virtual mechanical arm, which gave patients more intuitive feelings. At the same time, path strategies, resistance strategies and command stimulating strategies were set in this section according to different mode, which would be mainly introduced in next chapter.

2. Basic information

This section recorded and displayed some information, e.g. running time, rehabilitation level, rehabilitation status and rehabilitation period, which would be the basis for doctor's diagnosis and rehabilitation plan.

4. Transformation of coordinate

Because the coordinate in the virtual reality has to be associated with the coordinate in the reality and the data obtained from the absolute encoders is just about the arms' angles, it is crucial for us to make a coordinate transformation in order to make an easier analysis on the arms' movement.

At first, it is necessary to set a coordinate system for the robot arms in the reality. Referring to the paper of Chieh-Li Chen, Tung-Chin Wu and Chao-Chung Peng (2011), we set the 2D rectangular coordinate system showed in Fig. 7.

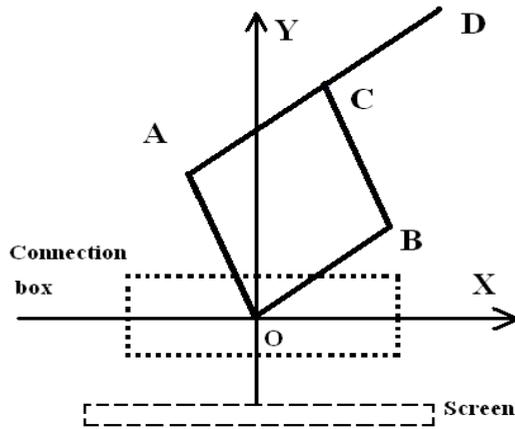


Figure 7. The Rectangle Coordinate System in which the Robot Arms Move

Since the arms' lengths in the virtual reality are not required to equal to the ones in the reality, it is assumed that the arms' lengths are all equal. It means

$$OA = OB = AC = BC = CD = 1 \tag{1}$$

Furthermore, in order to attain the coordinate figure of the handle (point D), we have to transfer the angle data got from the encoders to the position data in the XOY coordinate. However, because the range of the data from the encoder is from 0 degree to 360 degree and the positions of the 0 degree lines from two encoders are more likely to be different, it is a little complicated for us to deduce all situations. Thus, we initially consider only one situation showed in Fig. 8.

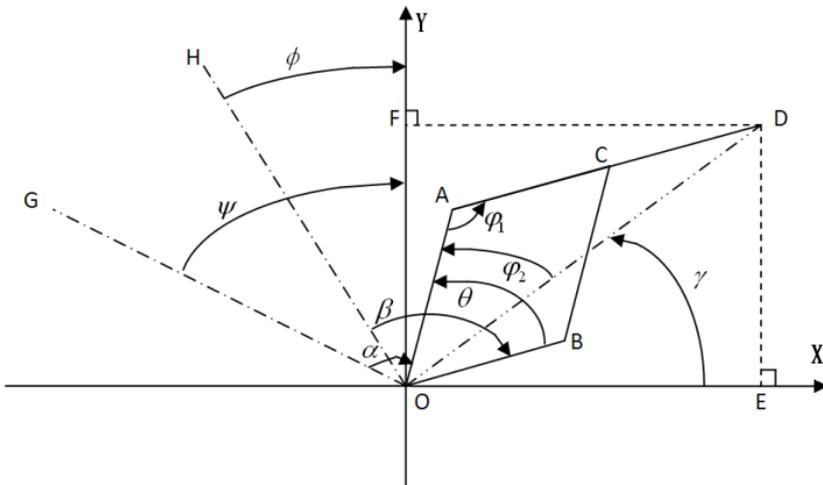


Figure 8. Coordinate transformation graph. OG and OH are the 0 degree lines from two encoders, OA, OB, BC and ACD are the robot arms.

According to Fig. 8, obviously, the position of D is:

$$\begin{cases} x = OE = OD \cdot \cos\gamma = 1 \cdot \cos\gamma \\ y = OF = OD \cdot \sin\gamma = 1 \cdot \sin\gamma \end{cases}, 0 < \gamma < \frac{\pi}{2} \quad (2)$$

Because the angle from the encoder is only measured clockwise, in Fig. 8, $0 \leq \phi \leq \psi \leq \frac{\pi}{2}$, $0 \leq \alpha \leq \beta \leq \pi$.

Therefore,

$$\theta = \beta + \psi - \phi - \alpha, 0 \leq \theta \leq \frac{\pi}{2} \quad (3)$$

$$\varphi_1 = \pi - \theta \quad (4)$$

$$OD = \sqrt{OA^2 + AD^2 - 2 \cdot OA \cdot AD \cdot \cos\varphi_1} = 1 \cdot \sqrt{5 - 4\cos\varphi_1} \quad (5)$$

$$\varphi_2 = \arcsin\left(\frac{AD}{OD} \cdot \sin\varphi_1\right) = \arcsin\left(\frac{\sin\varphi_1}{\sqrt{5-4\cos\varphi_1}}\right) \quad (6)$$

$$\gamma = \frac{\pi}{2} + \psi - \varphi_2 - \alpha, 0 < \gamma < \frac{\pi}{2} \quad (7)$$

After analyze other situations, we eventually conclude that (4), (5), (6) are the same while (3) and (7) are completely distinct.

In order to make calculation more convenient, we assume that:

$$\varepsilon = \beta + \psi - \phi - \alpha \quad (8)$$

$$\eta = \frac{\pi}{2} + \psi - \varphi_2 - \alpha \quad (9)$$

Thus, in connection with (3) and (7), we conclusively summarize four different situations.

Situation 1:

$$\text{if } -4\pi \leq \varepsilon \leq -3\pi, \text{ then } \theta = \varepsilon + 4\pi \quad (10)$$

Hence

$$\text{if } -2\pi \leq \eta \leq -\frac{3}{2}\pi, \text{ then } \gamma = \eta + 2\pi \quad (11)$$

Situation 2:

$$\text{if } -2\pi \leq \varepsilon \leq -\pi, \text{ then } \theta = \varepsilon + 2\pi \quad (12)$$

Hence

$$\begin{cases} \text{if } 0 \leq \eta \leq \frac{\pi}{2}, & \text{then } \gamma = \eta \\ \text{if } -2\pi \leq \eta \leq -\pi, & \text{then } \gamma = \eta + 2\pi \end{cases} \quad (13)$$

Situation 3:

$$\text{if } 0 \leq \varepsilon \leq \pi, \text{ then } \theta = \varepsilon \quad (14)$$

Hence

$$\left\{ \begin{array}{ll} \text{if } 0 \leq \eta \leq \pi, & \text{then } \gamma = \eta \\ \text{if } 2\pi \leq \eta \leq \frac{5}{2}\pi, & \text{then } \gamma = \eta - 2\pi \\ \text{if } -\frac{3}{2}\pi \leq \eta \leq -\pi, & \text{then } \gamma = \eta + 2\pi \end{array} \right. \quad (15)$$

Situation 4:

$$\text{if } 2\pi \leq \varepsilon \leq \frac{5}{2}\pi, \text{ then } \theta = \varepsilon - 2\pi \quad (16)$$

Hence

$$\left\{ \begin{array}{ll} \text{if } \frac{\pi}{2} \leq \eta \leq \pi, & \text{then } \gamma = \eta \\ \text{if } 2\pi \leq \eta \leq \frac{5}{2}\pi, & \text{then } \gamma = \eta - 2\pi \end{array} \right. \quad (17)$$

5. Strategies of upper limb rehabilitation

According to the introduction of PNF technology in the second section, some strategies of upper limb rehabilitation were presented. These strategies are just designed in ordinary frames and the detailed proposal will be described in the section 6.

5.1. Path strategies

In order to imitate diagonal movement form, such as resisted motion and right hand touching left ear, movement path of parallel lines and vertical lines was set. Before setting path, firstly, the current movement range of the patients' upper limb would be testing.

Push the handle to the foremost point;

Push the handle to the far left point;

Push the handle to the far right point.

The reachable zone of current sicken limb would be obtained through these three points above. The right upper limb movement path was shown in Fig. 9, which mainly consisted of horizontal lines. Three black points in Fig. 9 respectively represented the foremost point, the far left point and the far right point, which formed a triangle zone where patients' sicken limb can move safely. In Fig. 9, the solid line was specified path and the black dotted line in the middle was body center line.

The movement above was just in plane. Therefore, for the purpose of expanding the range of rehabilitation movement, the angle of pitch of pedestal can be changed through the regulating handle, as well as adjusting seat, so that patients had a relatively comfortable initial position, as shown in Fig. 10.

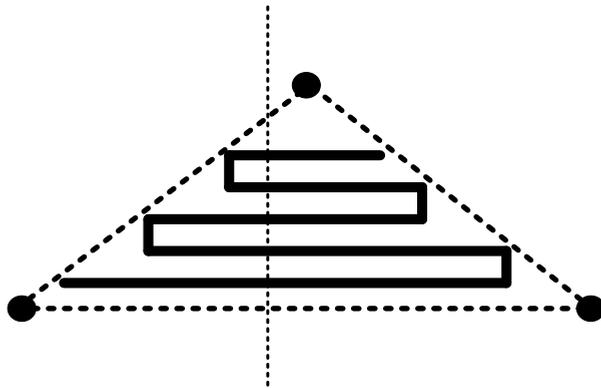


Figure 9. Schematic of right upper limb specified path



Figure 10. Rehabilitation robot under different angles of pitch

5.2. Resistance strategies

Resistance control was divided into two periods: basic period and improve period.

Basic period: the closer to the specified path, the smaller resistance was. This method can guide patients do movement along the specified path. The period should be changed into the improve period when the movement accuracy of patients' sicken limb was improved.

Improve period: the closer to the specified path, the bigger resistance was. This method can make patients do movement along the specified path more difficult, so as to further improve the flexibility and motion precision of patients' sicken limb.

A healthy people was made do the same path respectively in basic period and improve period, the result was shown in Fig. 11 and Fig. 12. The dotted line of two figures represented specified path. From these two curves of actual movement, we can see that the difficulty of tracking was bigger in improve period compared with basic period.

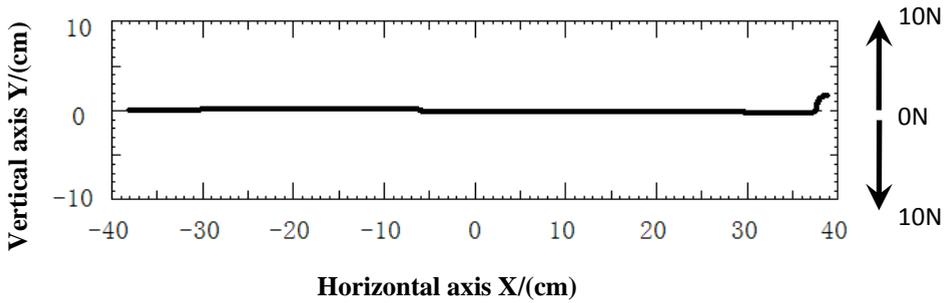


Figure 11. Movement curve in basic period

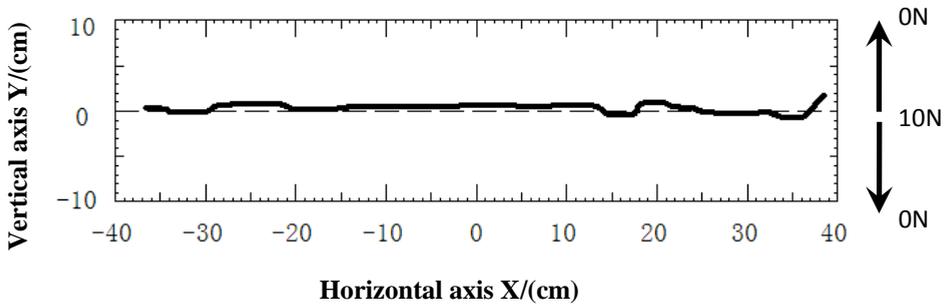


Figure 12. Movement curve in improve period

5.3. Command stimulating strategies

In the PNF promote method, command whose effect was important can stimulate patients to active force, also can give them encouragement and care.

When patients completed a movement in process, some suitable encouragements and praises can be given in speech way.

When the patients' sicken limb stopped moving in process, some encouragements should be given, e.g. "come on", "force", "you can do it".

When patients completed the whole process, some praises should be given, e.g. "very good", "such rapid process", "well done".

6. Medical training design and data analysis based on virtual reality

In this section, a medical training game, which is originated from the design in the section 5, will be presented. And, a novel data processing method will be introduced. All designs are based on a virtual game.

6.1. Virtual rehabilitation game design

According to the strategies presented in section 5, a game based on the virtual reality is designed, as showed in Fig. 13(a). The patient would hold the handle on the robot arm and move his or her hand along the trajectory in Fig. 13(a) in the virtual game. The trajectory is designed to move across human midline. It means the hand would move from the right of the human body to the left and then repeat circle again. Meanwhile, referring to the resistance therapy, we would apply three different resistance forces in trajectory OA, AB and BC to the patient's hand. Besides, $F_{OA} < F_{AB} < F_{BC}$.

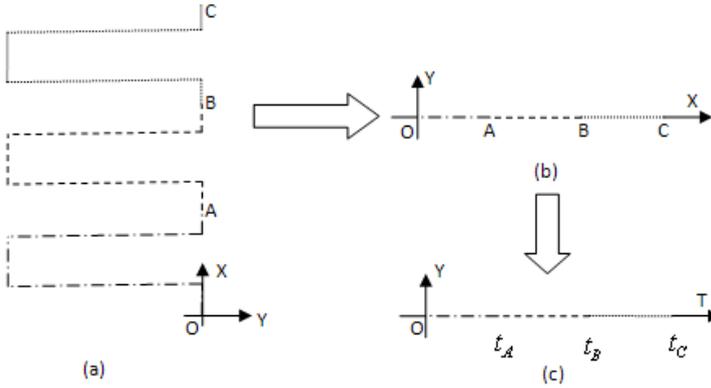


Figure 13. Virtual game's coordinate transformation graphs. The XOY coordinate system will move along the trajectory in (a), so it seems that the OABC rope is straightened to OX axis direction. (c) is obtained after the X axis in (b) is transferred to the time axis.

6.2. Data analysis method

In Fig. 13(b), the sample observation data $(x_{t_1}, y_{t_1}), (x_{t_2}, y_{t_2}), \dots, (x_{t_n}, y_{t_n})$ will be obtained according to the correlative observation time t_1, t_2, \dots, t_n . If the horizontal axis is changed to the time axis, a new coordinate system showed in Fig. 13(c) would be set up. Then the sample observation data would become $(t_1, y_1), (t_2, y_2), \dots, (t_n, y_n)$. Referring to the book written by Cook, R. Dennis (1998) and the book written by Irwin Miller, Marylees Miller (2004), it is appropriate to apply a variance function σ^2 to the rehabilitation evaluation.

Because the evaluation goal is to judge whether the trajectory of the patient's hand is the same with the expected one, we assume $\bar{y} = 0$. Then

$$\sigma^2 = E[(y - \bar{y})^2] = \frac{1}{n} \sum_{i=1}^n (y_i - \bar{y})^2 = \frac{1}{n} \sum_{i=1}^n y_i^2 \quad (18)$$

Considering that σ^2 may be zero and the time is a vital factor, we improve (18) to (19).

$$\chi = (1 + \sigma^2)t \quad (19)$$

Here the unit of the t is millisecond.

As a result of three different resistance forces, the variances and improved variances in OA, AB and BC should be calculated respectively. Then we obtain χ_{OA} , χ_{AB} and χ_{BC} .

Based on the AHP method by Lan Gan, Xuehu Wang, Rong Li (2009) and the importance of the three trajectories, we construct the judge matrix:

$$A = (a_{ij})_{3 \times 3} = \begin{bmatrix} 1 & 1/2 & 1/3 \\ 2 & 1 & 1/2 \\ 3 & 2 & 1 \end{bmatrix} \quad (20)$$

To solve the characteristic roots in (21)

$$(A - \lambda_{\max}I)\omega = 0 \quad (21)$$

We attain that $\lambda_{\max} = 3.0092$

And

$$C.I = \frac{\lambda_{\max} - n}{n - 1} = 0.0046 \quad (22)$$

$$R.I = 0.58 \quad (23)$$

$$C.R = \frac{C.I}{R.I} = 0.0088 \quad (24)$$

Because the random consistency ratio $C.R < 0.10$, judge matrix will get a satisfactory consistency. Then value of ω would be got:

$$\omega = [\omega_{OA}, \omega_{AB}, \omega_{BC}]^T = [0.1634, 0.2970, 0.5396]^T \quad (25)$$

Therefore, finally, we define a rehabilitation evaluation function γ :

$$\gamma = \omega_{OA} \cdot \chi_{OA} + \omega_{AB} \cdot \chi_{AB} + \omega_{BC} \cdot \chi_{BC} \quad (26)$$

Theoretically, according to the properties of the time and variance, the same patient would become better, if the value of γ becomes smaller.

6.3. Experiment and results analysis

Through using Visual C++ and OpenGL, we eventually design a shovelboard 3D game interface showed in Fig. 14. The patient would move the robot handle of the RRR-I along the trajectory in the game. Meanwhile, the patient would feel resistance forces which are different in different area in the game. Moreover, the timer starts to record when the ball begins at the start line and ends in the finish line.

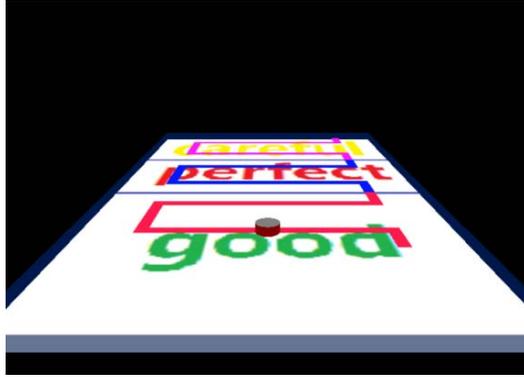
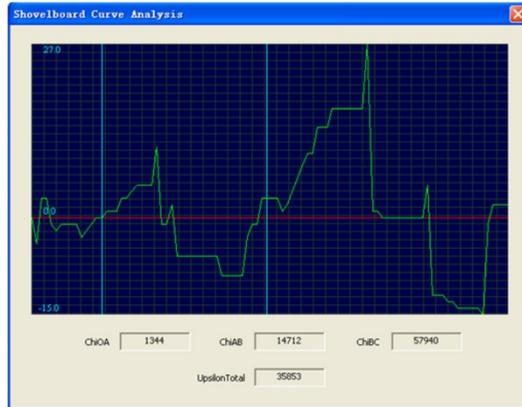
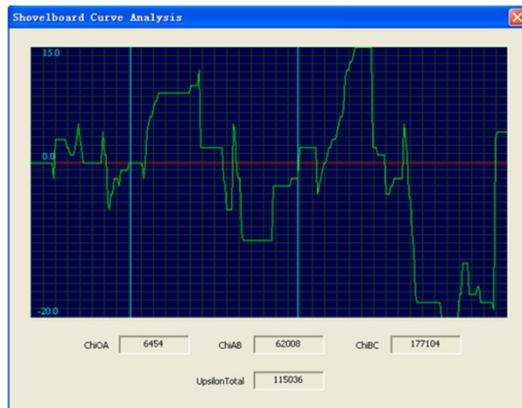


Figure 14. Shovelboard 3D game interface



(a) $\chi_{OA} = 1344$, $\chi_{AB} = 14712$, $\chi_{BC} = 57940$ and $\Upsilon = 35853$.



(b) $\chi_{OA} = 6454$, $\chi_{AB} = 62008$, $\chi_{BC} = 177104$ and $\Upsilon = 115036$.

Figure 15. Shovelboard curve analysis graph.

After a healthy individual plays this 3D game by using the RRR-I, a curve such as the one in Fig. 13(c) would be measured and then displayed. And the parameters such as χ_{OA} , χ_{AB} , χ_{BC} and Υ would be calculated and then showed. Although the proportions of the resistance forces in the three different areas always remain unchanged, the size of the forces under the circumstance showed in Fig. 15(b), it is three times larger than the one showed in Fig. 15(a).

In comparison with the two different curves and parameters' values in Fig. 15(a) and Fig. 15(b), it is obvious that, in Fig. 15(b), the values of every parameter become bigger. Meanwhile, the length of the time in every area also changes longer. It means the individual would spend more time to complete this game. Besides, the fluctuation of the curve in Fig. 15(b) is evidently fiercer. It means the movement of the individual's hand becomes harder. In a word, we could observe the changes by checking the variation of the value of every parameter.

7. Conclusion

In this chapter we realized an upper-limb rehabilitation robot named RRR-I and a new virtual 3D game used to recover patients. A new variance method and the AHP method are applied to the analysis on the rehabilitation level of the 3D game. Through an experiment on a healthy individual, a good consequence is obtained. In the future, the patients should be invited to participate in this experiment so that the effects of the RRR-I and other research could be proved more convincible. Besides, some new rehabilitation methods would be applied to the training on the patients.

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