Development of a Lower Limb Rehabilitation Wheelchair System Based on Tele-Doctor–Patient Interaction

Shuang Chen, Fang-fa Fu, Qiao-ling Meng and Hong-liu Yu

Abstract Portable rehabilitation training devices are coming into normal families and becoming an important part of home rehabilitation. At the same time, the rehabilitation system combining virtual reality technology and tele-doctor–patient interaction and portable rehabilitation devices is a new research trend. In this paper, an intelligent rehabilitation training system which is one of the first product that make it possible for patients to do lower limb training at home is proposed. It includes an electric wheelchair with lower limb training function, a multivariate control module, a virtual reality training module and a tele-doctor–patient interaction module. This system can solve the shortcomings of large volumes of existing products. The lower limb training games module which is based on virtual reality technology make the rehabilitation procedure more interesting. The tele-doctor–patient interaction module enables patients to do lower limb training at home, meanwhile doctors can give assignments to patients based on the score of the last game to save more medical resources and time effectively.

Keywords Lower limb rehabilitation wheelchair · Virtual reality · Tele-doctor–patient interaction

1 Introduction

As is known to all that China has gradually entered the aging society. According to statistics, the number of stroke patients over the age of 40 in China has climbed to 10 million. The number of new stroke patients is coming out up to nearly 200 million people each year (Zhang 2011). Limb dysfunction seriously affects life quality of patients. In the rehabilitation of stroke patients, limb function recovery is

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the most difficult one. Modern rehabilitation theory and practice show that effective rehabilitation after stroke can speed up the recovery process, mitigate functional disability, reduce the high cost of potential long-term care needed and save social resources (Visintin et al. 1889).

A lot of lower limb rehabilitation equipment have been developed in recent years. Lokohelp is a lower limb training and assessment system based on BWSTT (Body Weight Support Treadmill Training). It improves patient outcomes by increasing therapy volume and intensity, providing task-specific training and increasing patient engagement (Freivogel et al. 2008). Flexbot is an intelligent lower limb training robot. It can do ambulation training in different body positions. Virtual reality scene is used to simulate walking state. HAL-5, designed by a Japan technology company called Cyberdyne, is an exoskeleton robot and can be driven by neural signals of brain. It can help users stand, walk, and climb upstairs (Kawamoto et al. 2003).

As we can conclude, existing lower limb rehabilitation devices can be divided into three kinds: BWSTT system, intelligent lower limb training robot, and assistive exoskeleton. BWSTT system mainly aimed for patients whose muscle strength are weak and do rehabilitation in hospitals. Also, the training procedure is quite boring (Hornby et al. 2005). In order to imitate human gait, intelligent lower limb training robot usually have large volume, and very expensive, not suitable for family use (Lv 2011). Lower limb exoskeleton is more portable than the other two kinds of devices and is designed for patients with stronger muscle strength. Because of its wearable feature, uncertain danger may occur during outdoor usage (Adam and Kazerooni 2005). Although the history of lower limb rehabilitation equipment is very short but it has become quite a trend. But there are only a few independent research and development of such products in China.

According to the requirement of the lower limb rehabilitation, a lower limb rehabilitation wheelchair with virtual reality games based on tele-doctor–patient interaction is designed. Mobile phone software is used for controlling of the wheelchair and virtual reality interactive system is added to the rehabilitation wheelchair to realize a variety of lower limb training. Also, a tele-doctor–patient interaction is designed for doctors to assign tasks for patients to do lower limb training at home. The structure of the system is as shown in Fig. 1.

2 Mechanical Design of Lower Limb Training Module

2.1 Preparing Manuscript

The lower limb training module is designed based on a multi-posture electric wheelchair so that it can be used as a common wheelchair while not doing rehabilitation training.

Training function is realized by four linear motors. As shown in Fig. 1, in the process of lying, motor 11 and motor 14 work together to realize the movement of the backrest and the legs. In the process of standing, motor 12, motor 11, and motor

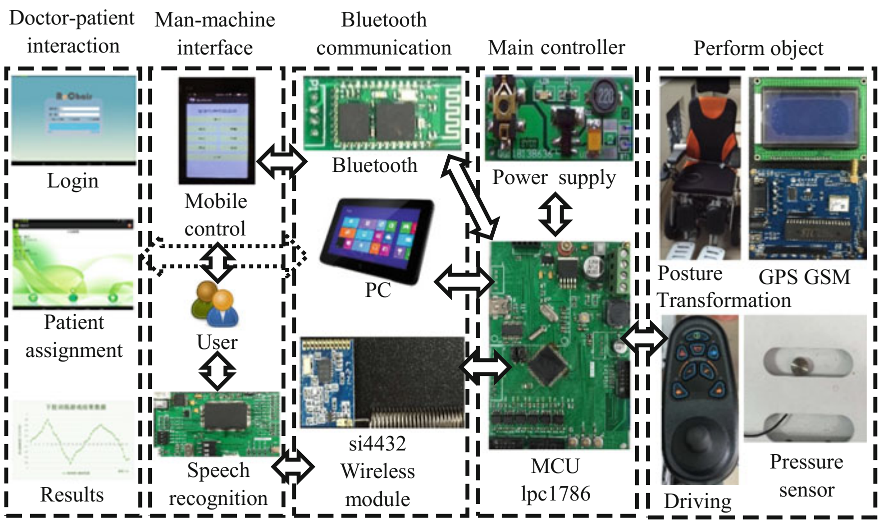
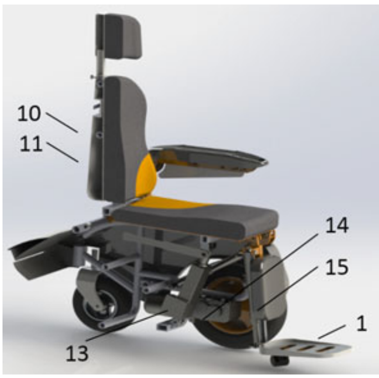


Fig. 1 Structure of a multi-posture intelligent wheelchair for rehabilitation

15 work together to realize the stand of the seat and the expend of the foothold. Motor 14 and motor 15 work together when doing lower limb rehabilitation trainings, realizing the flexion and extension of the knee joint of patient's as well as balancing trainings with virtual reality games, etc.

As shown in Figs. 2 and 3, the main control module 10 is responsible for the deployment of each module to work together. Users can select the lower limb training modes by touching tablet PC 5. Command is transmitted to the master control module 10 and converted to the corresponding command to realize posture transformations or lower limb training mode. In the process of training, pressure sensors 16 which are located in the footrests collect the state of motion in real time. The signal is transmitted via Bluetooth module to master control module, and then displayed on the tablet PC 5 to help nurses to know the training situation of the patients.

Fig. 2 Principle diagram of lower limb training structure



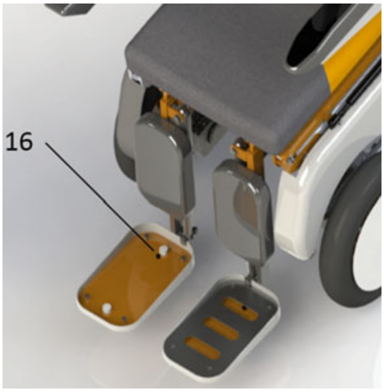


Fig. 3 Pressure sensors for lower limb training

In order to know whether the structure meets the requirements of movement, the law of motion of the structure needs to be studied. In mechanical transmission, movement analysis of the mechanical structure is the foundation of the analysis of entire mechanical system. According to the movement of the driving link, displacement, velocity, and acceleration of a specific point in the entire mechanical drive system can be obtained. To solve the disadvantages that graphic method is of low precision and time-consuming when analyzing motion mechanism, analytic methods and computer are used to help the analysis. Analytic methods can not only conduct high precision analysis, but also draw a graph of the movement, helping improving design of the mechanical design (Lin and Wang 2003).

Because of the complexity of the wheelchair structure, vector equation analytic method is used in the analysis to obtain precisely the kinematical characteristic of the components in the process of posture change. Coordinate system is established as shown in Fig. 4. *O* is the origin of coordinate the system. *OA* and OB are the *x* axis and *y* axis of the coordinate system.

According to the relation between the vectors, we can get Eq. (1):

$$\overrightarrow{AE} + \overrightarrow{EB} = \overrightarrow{AB} \tag{1}$$

Project the vectors to the *x* axis and *y* axis and we can get Eq. (2):

$$\begin{cases} x: \left|\overrightarrow{AE}\right| \cos\theta_1 + \left|\overrightarrow{EB}\right| \cos\theta_3 = \left|\overrightarrow{AB}\right| \cos\theta_2 \\ y: \left|\overrightarrow{AE}\right| \sin\theta_1 + \left|\overrightarrow{EB}\right| \sin\theta_3 = \left|\overrightarrow{AB}\right| \sin\theta_2 \end{cases} \tag{2}$$

Eliminate θ_1 and solve Eq. (3):

$$\theta_2 = \theta_3 + \arccos\left(\frac{AB^2 + EB^2 - AE^2}{2\left|\overrightarrow{AB}\right|\left|\overrightarrow{EB}\right|}\right) \tag{3}$$

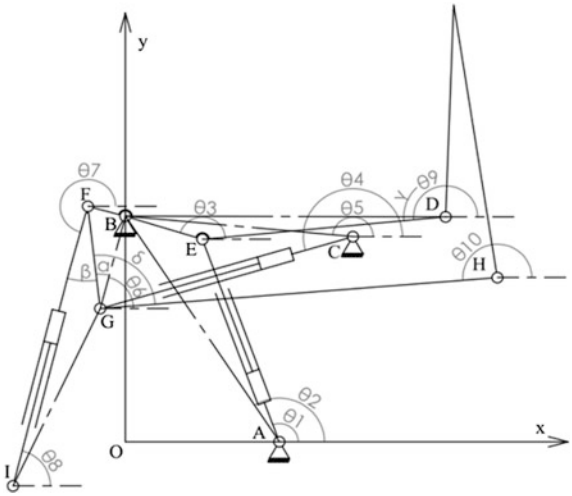


Fig. 4 Mathematical model coordinate system of the wheelchair

For A and B are fixed point on the wheelchair frame, we can get Eq. (4):

$$\theta_2 = \pi - \arctan \frac{\left|\overrightarrow{OB}\right|}{\left|\overrightarrow{OA}\right|} \tag{4}$$

$\left|\overrightarrow{AB}\right|$ mentioned above is a known variant, so θ_1 can be calculated according to the equations.

θ_4, θ_5 and θ_6 can be calculated in a similar way.

According to the geometric relationship between the vectors, expressions can be determined for each position parameter of the structure:

$$\theta_7 = \pi + \theta_6 + \alpha - \beta \tag{5}$$

$$\theta_8 = \theta_6 + \alpha - \beta \tag{6}$$

$$\theta_9 = \pi + \gamma \tag{7}$$

$$\theta_{10} = \pi + \theta_6 + \alpha - \delta \tag{8}$$

α, β, γ and can all be calculated according to the law of cosines:

$$\alpha = \arccos\left(\frac{BG^2 + GF^2 - BF^2}{2\left|\overrightarrow{BG}\right|\left|\overrightarrow{GF}\right|}\right) \tag{9}$$

When the position parameters of the structural components are known, the motion trails of the hinges of the components can be calculated. For example, the position parameter of E is as Eq. (10):

$$\begin{cases} E_x:\ -\left|\overrightarrow{EB}\right|\cos\theta_3 \\ E_y:\ \left|\overrightarrow{AE}\right|\sin\theta_1 \end{cases} \tag{10}$$

By computing the first derivative of (10) with respect to time, the velocity parameter equation of E can be obtained. By computing the first derivative of velocity parameter equation with respect to time, the acceleration parameter equation of E can be obtained. Kinematics parameters of other hinges can be calculated in the same way (Yuan and Zuomo 2001).

3 Design of Mobile Terminal Control Module Based on Bluetooth

3.1 *Bluetooth Control Design*

In order to control the wheelchair more conveniently, a special Bluetooth phone control module, which is suitable for families and rehabilitation centers, was developed. This module includes a Bluetooth communication module and a system of mobile phone software.

As shown in Fig. 5, there are several group of bottoms in the cell phone interface. Each group consisted of two bottoms, one is "open," the other is "close," correspondingly control the status of each posture. Users can touch the screen to select the posture that they want.

Fig. 5 Cell phone control interface

Fig. 6 Mathematical model coordinate system of the wheelchair

Intelligent control terminal includes four parts: Lpc1768 microcontroller control part, the Bluetooth module part, Power supply part, Photoelectric coupling switch part. A HC-05 Embedded Bluetooth serial interface communication module is used in the Bluetooth module part and is controlled by AT commands. Serial port parameters are set to 9600 bit/s and the passcode is 1234. Connection mode is set to any Bluetooth address link mode so that multiple phone manipulation can be realized (Lee et al. 2004).

To enrich the usability of the tele-doctor–patient interaction module, the control interface is transplanted to the tablet PC. The tablet PC interface is as shown in Fig. 6.

3.2 Control Module Experiment

In order to know how the Bluetooth control module works during lower limb training, mobile terminal experiment is conducted. The experiment platform includes lower limb training wheelchair module and Bluetooth control module. The Bluetooth receive module and the controller are installed in the wheelchair. The experimenter sits on the wheelchair, stands two meters, five meters, and eight meters away from the wheelchair while controlling it with the cell phone. All movements of the wheelchair are tested from sitting position to standing, lying, lower limb training, going forward, going backward, turning left and right. Every movement is tested 50 times, and all the results are recorded as shown in Table 1.

We can know from Table 1 that when experimenter sits and stands two meters away from the wheelchair, the success rates of Bluetooth control are almost 100 %. When experimenter stands five meters away from the wheelchair, the success rates are above 98 %, and when experimenter stands eight meters away from the wheelchair, the success rates reduces to 94 %. The success rate is related to operating distance. Therefore, Bluetooth control function is substantially reliable

Table 1 Experiment data of Bluetooth control system

Distance		Sit	Stand	Lie	Train	Forward	Backward	Left	Right
0 m	Success/times	50	50	50	50	50	50	49	50
	Rate/%	100	100	100	100	100	100	98	100
2 m	Success/times	50	50	50	49	50	50	50	49
	rate/%	100	100	100	98	100	100	100	98
5 m	Success/times	50	49	50	50	49	50	50	49
	Rate/%	100	98	100	100	98	100	100	98
8 m	Success/times	49	49	48	49	48	49	47	48
	Rate/%	98	98	96	98	96	98	94	96

and users are suggested to be at least four meters away from the wheelchair when operating for normal use.

4 Tele-Doctor–Patient Interaction Module Design

In order to make it possible for the patients to do lower limb rehabilitation at home to relieve the strain on medical resources, the tele-doctor–patient interaction module is designed. This module provides an interaction platform for doctors and patients and is consisted of doctor client, web server, and the patient client. The following sections focus on design of the virtual reality game and software of the interaction module.

4.1 Design and Realization of Virtual Reality Games

Patient client is a tablet PC which has following functions: controlling, doing rehabilitation training with virtual reality games, and interaction with doctors. Virtual reality games used in rehabilitation training is based on Unity 3D engine (Lange et al. 2010). Status of patients' lower limb is captured by the pressure sensors to be the input of the virtual reality games realizing the human–computer interaction function (Meng 2009).

There are two JHBM-100 kg pressure sensors in the both sides of the footrests. In standing mode, patients do active lower limb exercise by changing their center of gravity to control the bird to fly up and down. The pressure sensors change the anagogic pressure signal into an electrical signal. The more the patients' center of gravity shifts, the larger the pressure of the offset side of the foot will be and the smaller the pressure of the other side of the foot will be. If the pressure becomes small, the output voltage will become small and vice versa. Output voltage is amplified by the differential amplifier circuit and after A/D convert, it will be input to the microcontroller for processing. In the game, the airplane will fly to the side whose output voltage is larger. The larger the voltage is, the more the airplane will move. The interface of the virtual reality game is as shown in Fig. 7.

Fig. 7 Interface of starting rehabilitation game

The information obtained by the pressure sensors is acted as the parameter in the game. Bombs and diamonds will be randomly generated in the game. Patients gain score by controlling the bird to capture the diamonds, and avoiding bombs. Patients can easily focus on the game and start rehabilitation training.

After each game, patient's movement in training will be saved as a line chart. As is shown in Fig. 8, relative position of patient's center of gravity is compared with the normal relative position which is the average value from 10 normal experimenter. A score is given calculated by Eq. (11).

$$S = \sum_{n=1}^{t} |F_0 - F_n|, \quad t = 1, 2, 3\ldots \tag{11}$$

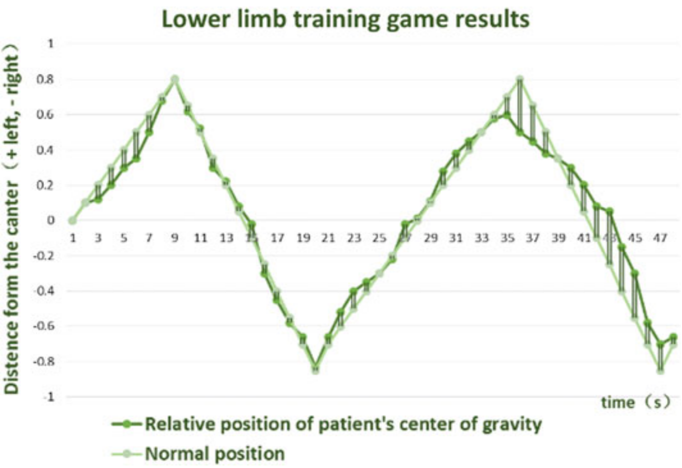


Fig. 8 Line chart of relative position of patient's center of gravity during training game

F_0 refers to the value of normal relative position at a certain time point while F_n refers to the one of patient. T refers to a time point, and S refers to the score of game.

This score quantify the result of game and reflects patient's rehabilitation progress. Also, it can be used as a recovery judgement.

4.2 Software Design

The software is a link between doctors and patients, so two interfaces are necessary for both patients and doctors, also, doctors should have permission to query patients' information. To satisfy the needs, JAVA is used to write the program. Login interface is as shown in Fig. 9, user can select a certain identity to login. After typing in user name and password, patient can login with their account. As can been seen in Fig. 10, patients can control the wheelchair, do lower limb training, see current position (Fig. 11) and check today's tasks assigned by doctor. After patients finish each training game, the score and the line chart of relative position of patient's center of gravity during training game will be sent automatically to the doctor to help detecting patient's recovery condition. Doctors' interface is as shown in Fig. 12. Doctors can manage their patients, check their training results, and assign everyday tasks with the system.

With the help of the tele-doctor–patient interaction module, patients can concentrate more on rehabilitation than worrying about going to rehabilitation center while they have mobility impairments. On the other hand, doctors can deal with more patients because the system can help save the score and the line chart of patient's movement which are the key to their recovery progress. This is also what makes the system different from existing products.

Fig. 9 Login interface

Fig. 10 Patient interface

Fig. 11 Current position

Fig. 12 Doctor interface

5 Conclusion

This study completed the structure design of a multi-posture intelligent rehabilitation wheelchair and successfully developed a module of mobile control and a module of Bluetooth communication which realize posture conversion and lower limb training control by a cell phone. In order to improve training effectiveness and stimulate patients' interests in training, Unity 3D engine and two pressure sensors were combined to realize rehabilitation game. Pressure sensors were set in the footplate of wheelchair to capture the information of patients' center of gravity as input signal to the game. A tele-doctor–patient interaction software is designed to enable doctors check patients' recovery condition and assign tasks remotely.

Experiments have been done to ensure the safety of the posture transformations and the reliability of the Bluetooth phone control module. And the results show that the wheelchair can fully fulfill the functions we expected. But mass of data is needed to show how the rehabilitation wheelchair can help the patients with lower limb dysfunctions and the efficiency of the system.

In order to improve the rehabilitation evaluation system to help the patients do lower limb rehabilitation according to their extent of dysfunction and their needs, a database of the patients' information should be established to help the design of the content and intensity of rehabilitation games. Also, we will continue doing clinical experiments on patients with lower limb dysfunction in the rehabilitation hospitals and more data will be taken to further verify the effectiveness of lower limb rehabilitation with the rehabilitation wheelchair.

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