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RESEARCH NOTE

The Design and Realization of a Gait Rehabilitation Training Robot with Body Supporting Mechanism

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ABSTRACT

With the increasing number of people who have problems with their walking, a new type of gait rehabilitation training robot has been put forward and designed. In order to meet the requirements of the gait rehabilitation training, the whole mechanical structure and control system have been designed, and the model machine for gait rehabilitation training robot has been made. Using the human gait analysis system of the INSENCO, a large number of experiments on human bodies have been carried out, and human gait parameters have been measured and recorded. As has been shown in the experiments, the designed robot has achieved the goal of free movement and weight-reducing; the weight-reducing device is flexible in height and pull, which has accomplished the aim of rehabilitation training.

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1. INTRODUCTION

According to the report of Chinese Academy of Social Sciences (CASS), the national elderly population in China will reach 240 million and the aging level will grow to 17.17% in 2020 [1]. Many elders or patients with stroke have trouble in walking and need to perform the gait rehabilitation training. Under these conditions, it is necessary to develop a new type of rehabilitation robot for their gait rehabilitation training, which will save more human resources like therapists and prolong the training session for patients [2]. In addition, a body weight support mechanism is necessary for the rehabilitation robots and the gait rehabilitation effects with part body weight support is accepted by many doctors and researchers. It cannot only improve the gait performance of patients in a series of parameters such as temporal-spatial parameters and segmental angles [3], but also help the patients to support their body weight during stance phase [4] and meet the early rehabilitation needs of patients. Now, various gait training devices have been developed [2, 5-12] such as LOKMAT from Switzerland [2], LOPES from Netherlands [11], BWSLT from Singapore [5], and so on. Different from these gait training devices, a new type of gait rehabilitation training robot with body supporting mechanism has been developed and performed the initiatory gait rehabilitation training experiments. Its body weight support mechanism is realized by using a screw to pull the ropes connected to the waist of the patient. This robot can assist people with walking difficulty to walk indoors or outdoors and perform the gait rehabilitation training. In addition, a wearable gait detection equipment was used during the gait rehabilitation training experiments.

2. THE NEW GAIT REHBILITATION TRAINING ROBOT

The new gait rehabilitation training robot is a wheeled mobile robot, as shown in Figure 1. Its mechanical structure is divided into body weight support, height adjustment and traveling mechanisms. Its control system consists of two subsystems: DC-motor control system and stepper-motor control system.

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2. 1. The Design of Mechanical Structure

Taking the requirements of the patient's rehabilitation into account, the gait rehabilitation training device should be able to move back and forth, and turn around freely. As a result, a four-wheel traveling mechanism is designed and the robot is driven by two DC-motors installed on the rear wheels. The front wheels are a pair of universal wheels (which are oriented wheels) used for auxiliary support. The function of the robotics designed as a U-shape to support the weight of the robot and the patient.

The height adjustment mechanism, composed of a hand-wheel, two bevel gears, screw, synchronous pulley and synchronous belt, is used to adjust the height of the robot’s upper platform to adapt to the different height of the patients, as shown in Figure 2. When the patient turns the hand-wheel clockwise, the upper platform will be lift up, and when the patient turns the hand-wheel anticlockwise, the upper platform will come down. Because of the self-lock character of the trapezoidal screw, the upper platform of the robot can maintain the wanted height within the motion range of the trapezoidal screw.

The body weight support mechanism is mainly composed of two pairs of screws and sliding table powered by the stepper-motor, two ropes and a waist band. Two pairs of screws and sliding table are located symmetrically in the upper platform, as shown in Figure 3(a). The movement of the sliding table will tense or relax the rope and the waist band to adjust the weight change of the patients. The advantage of the ball screw driving is its high precision and continuity. Through the body weight support mechanism, the patient can adjust his/her weight loss in the rehabilitation training continuously. By operating the button switches on the upper platform, we can control the motors to rotate in the forward or reverse direction. The rope, on both sides of the patient’s waist gives the body a nearly vertical upward force through the waist band connected at the end of the ropes and the pressure of the feet will be reduced. The 3D structure and the prototype of developed new-type gait rehabilitation training is shown in Figure 3.

2. 2. The Design of Control System

The main control chip of the control system chosen to meet the control requirements is ATmega16. The control system is composed of two subsystems: DC- and stepper-motor control systems as shown in Figure 4. The DC motor chooses the MTM-motor which has an output of 250W. The DC motor is controlled by therapist through HJ6 hall joystick. It is convenient and reliable. And there are four buttons on the upper platform. Using this four buttons, the patient can control the reversing motion of the stepper-motors. When the patient presses the buttons, the stepper-motors will be driven to tense or relax the ropes connected to both sides of the waist band. By this way, the purpose of part body weight support can be achieved.

3. THE GAIT DETECTION EQUIPMENT

Human gait cycle parameters testing is the key to judge whether one's lower-limb is healthy or not. We use human gait analysis system of the INSENCO, which is called smart shoes, to measure and record the human gait parameters. The system consists of two smart shoes, a universal wireless router, human gait data acquisition software, personal computer, and so on. Each shoe is mainly composed of two six-axial force sensors, a wireless ZigBee module, as shown in Figure 5.

When using the system to detect gait data in this experiment, we should do as follows. First, the power button in the ZigBee module should be pressed. The smart shoes will connect with the computer after this. Second, the human gait parameters acquisition software should be opened and initialize it. When the suitable data sampling frequency 50HZ is chosen and sampling time 20s in one trial, then data collection can be started.

4. THE REHABILITATION EXPERIMENTS

The validity of the model and the system performance characteristics can be analyzed by computing the system performance characteristics, in terms of the steady state probabilities explicitly. Some of the system performance indices are as follows:

Based on the measured three-axial GRFs and torques from the new sensor system, we can analyze the ratios of the stance and the swing phases, describe the step series using time sample matrices and calculate the CoP and its boundary area.

The coordinate system and the description of step series:

The GRF measurements are expressed in the coordinate system O-XYZ that is located on the interface between the shoe sole and the ground, as shown in Figure 6. The origin O coincides with the point on the axis of the three-axial force and torque sensor located at the heel position, which is lying on the interface plane with the floor when the heel is on the ground. The Y-axis is chosen to represent the anterior-posterior direction on the interface plane contacting with the floor from the axis of the heel sensor to the axis of the forefoot sensor. The Z-axis is vertical upward and the X-axis is chosen such that the resulting coordinate system would be right-handed. In the coordinate system, the coordinate of the point A is denoted as (P_x^A, P_y^A), which is the intersection of the axis of the forefoot sensor and the floor plane. Point B is denoted as the CoP and its coordinate is defined as (P_x^B, P_y^B) in the frame. The three-axial force and torque is defined as F composed of three components (F_x, F_y, F_z) and M composed of three components (M_x, M_y, M_z)' respectively.

Based on the measured GRFs, the coordinates of CoP can be calculated in the coordinate system referring to the soft rubber plane contacting with the ground by the following equations:

$$P_x^B = -\frac{M_y^H + M_y^F - P_y^A \cdot F_z^F}{F_z^H + F_z^F} \tag{4-1}$$

$$P_y^B = \frac{M_x^H + M_x^F + P_x^A \cdot F_z^F}{F_z^H + F_z^F} \tag{4-2}$$

Seven volunteers were recruited to participate in this study. They included five males and two females between 23 and 50 years old (mean age 33.62±9.86 years), weight from 44.5 to 76.3 kg (mean weight 62.39±9.69 kg), and height from 158 to 176cm (mean height 169.13±5.64 cm). All the subjects had no history of lower limbs or neurological injuries. Subjects were briefed regarding the procedure and methodology of the experiment before obtaining their written consent using a protocol approved by the Institutional Review Board at Zhejiang University. However, the subjects were not informed in details about the purpose of this study so as to avoid any bias or influence on the parameters recorded.

The forces and torques measured by the developed wireless GRF sensor systems of subject A (age 39, weight 70 kg) are shown in Figures 7 (a)-(h) for the 20s walking without the rehabilitation training device. We can see that the three-axial GRF and torques at the position of heel and forefoot can be detected by the four three-axial force and torque sensors continuously in a series of walking gait. The consistency of these measurements during all the walking steps was good. The total ground reaction force of each foot was calculated as shown in Figures 8 (a) and 8 (b). These force plots reflect the interlaced walking of the left and right foot. These results demonstrate the validation of our wearable GRF sensor system in quantifying the normal gait.

The ratios of the stance phase and the swing phase in all the subjects' gait experiment were calculated as shown in Table 1. In order to identify potential points that can be used to qualify as the heel-strike and the toe-off moment, a threshold value -100 N of F_z was chosen here and the average ratios of the stance phase and the swing phase were obtained in continuous gait series. The subjects' average ratios of the stance phase were distributed in the region from 63.9% to 70.4% and were close to the regular gait values reported in other research in literature [13].

As a result, the experiments and demonstration in this study provide a method to perform the quantitative evaluation and the improvement in the rehabilitation training course by using our gait rehabilitation robot and the gait detect sensor system.

Figure 1. The new gait rehabilitation training robot

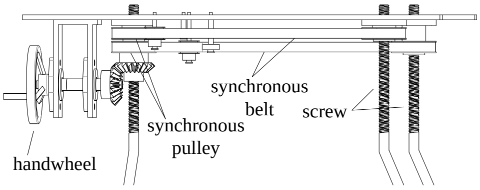
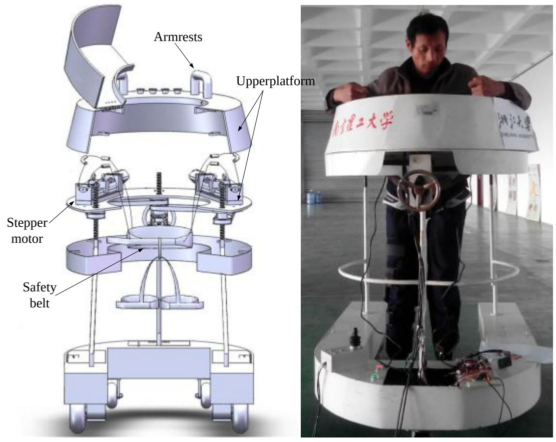


Figure 2. The height adjustment mechanism



(a) The 3D structure (b) The prototyp

Figure 3. The developed gait rehabilitation training robot

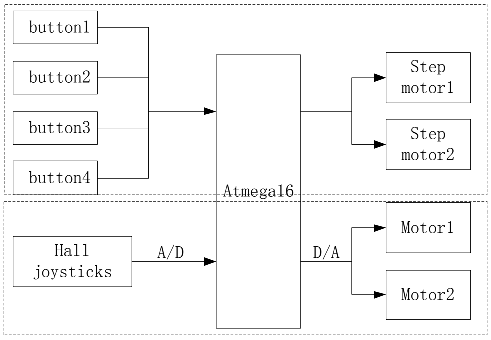


Figure 4. The control system block diagram of the gait rehabilitation training robot

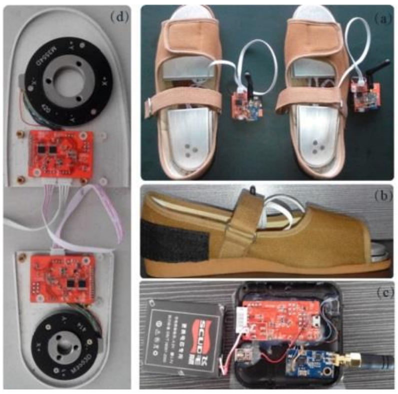


Figure 5. Hardware for the wearable system

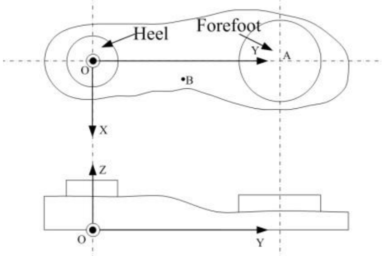


Figure 6. The coordinate system on the left shoe

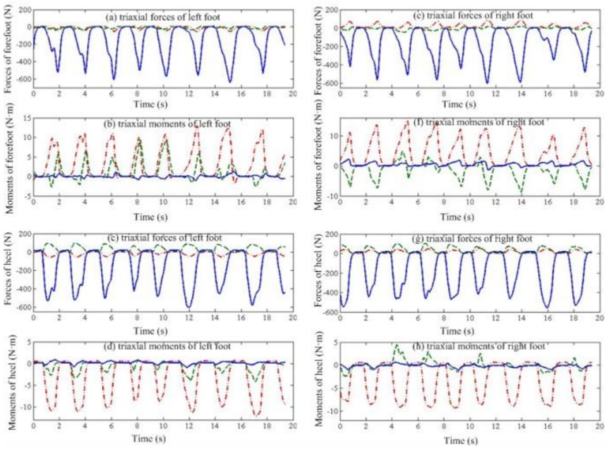


Figure 7. The measured triaxial GRFs and torques of subject A during 20s walking without the rehabilitation training device (X-axis: Dash-dotted. Y-axis: Dotted. Z-axis: Solid)

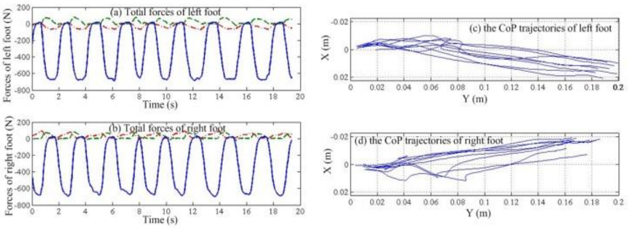


Figure 8. The total GRFs (X-axis: Dash-dotted. Y-axis: Dotted. Z-axis: Solid) and CoP trajectories of subject A in 20s successive walking

TABLE 1. The subjects' ratios of stance phase and swing phase with the rehabilitation training device

Subject	Limbs	Stance%	Swing%
A (age 39, weight 70kg)	left	65.59	34.41
	right	65.40	34.60
B (age 26, weight 76.3kg)	left	64.11	35.89
	right	66.00	34.00
C (age 30, weight 44.5kg)	left	67.21	32.79
	right	64.73	35.27
D (age 23, weight 59.8kg)	left	66.27	33.73
	right	66.77	33.23
E (age 25, weight 65.6kg)	left	65.25	34.75
	right	64.10	35.90
F (age 47, weight 51.2kg)	left	65.66	34.34
	right	63.91	36.09
G (age 50, weight 63.3kg)	left	68.50	31.50
	right	70.40	29.60

5. CONCLUSIONS

A new gait training system with the function of using a screw to support body weight for the people who have problems with their walking was proposed and developed. Combining with a gait detection device, which is a pair of smart shoes, we implemented and demonstrated through extensive human subject experiments. Seven human subjects were required to walk with and without the assistance of the rehabilitation training device under the designed experimental protocol and wearing the smart shoes. The experimental results supported our hypothesis that the developed gait rehabilitation robot can be used to help people to train their legs with difficulty in walking. As a future research direction, experiments on more diverse subjects and various walking conditions will be conducted to fully support clinical applications by using the developed rehabilitation robot.

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چکیده

با افزایش تعداد افرادی که مشکلات راه رفتن دارند، نوع جدیدی از ربات راه رفتن با توانایی آموزش توان‌بخشی مطرح و طراحی شده است. به منظور پاسخ‌گویی به نیازهای آموزش توان‌بخشی راه رفتن، کل سیستم، ساختار و کنترل‌های مکانیکی آن طراحی، و یک ربات الگوی آموزش توان‌بخشی راه رفتن ساخته شده است. با استفاده از سیستم تحلیل راه رفتن انسان، INSENCO، تعداد زیادی آزمایش بر روی بدن انسان انجام، و پارامترهای راه رفتن انسان اندازه گیری و ثبت شده است. همان طور که آزمایش‌ها نشان داده‌اند، ربات طراحی شده هدف حرکت آزاد و کاهش وزن را به دست آورده است. دستگاه کاهش وزن در مورد ارتفاع و کشش انعطاف پذیر است، که هدف از آموزش توان‌بخشی را برآورده می‌سازد.

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