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Development of a Virtual Reality System Based Cycling Training for Health Promotion of Individuals Post-Stroke

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***Abstract*—The objective of this paper is to develop and test the feasibility of a virtual reality system-based cycling that enables individuals post-stroke with lower extremity impairments to train balance, gait, and cardiorespiratory fitness that enhance possible transfer of training from virtual environment to real world walking. The bicycle is equipped with mechatronic components with sensors for acquiring walking kinematics and physiological parameters to monitor training safety while running serious games in a virtual cycling environment with 3D visual, audible and haptic feedback. The mechatronic components of pedal allow user to determine balance on both feet and range of motion of both ankles to detect tilt in the dorsal and plantar flexion. Novel cadence components embedded with close loop control method accommodates differences in lower extremity impairments. The control box is used to collect data from sensors on both pedals, pedal revolutions, and heart-rate, which are processed and transmitted to the computer. Moreover, a software system allows user to manipulate virtual environment and change the perception of how fast user's movement in virtual environment. From the results of the preliminary test of the prototype on two healthy control participants during 4-week cycling training, it is found that use of the prototype is safe, feasible, and efficacious for post-stroke training and improving aerobic capacity and walking endurance.**

Keywords*—*lower extremity training, walking kinematics measurement, virtual reality-based cycling, balance, gait, cardiorespiratory fitness

I. INTRODUCTION

Individuals post-stroke tend to have sedentary lifestyle and have deficit in ability to walk. Training to reverse fitness deficits specially improving walking abilities has been proposed in various ways. [1][2] had demonstrated the use of ergometer cycling training to investigate its effect on balance and gait abilities associated with walking of individuals post-stroke. This research result showed that ergometer cycling training made improvement on balance and gait after stroke. However, adding virtual reality (VR) element to the physical training of post-stroke showed more significant improvement in balance and gait than ergometer cycling training its self [3]. The use of virtual environment (VE) for individuals post-stroke rehabilitation has been widely developed to train motor disorders on lower or upper extremities to support daily living activities. The flexibility of VE that are not limited by the physical environment in real word is the main key to acceptance and use in rehabilitation. Based on [4][5], although lower extremity rehabilitation using VE showed better results than the active control condition, the transfer of mobility rehabilitation from VE to the real world was not significant due to lack of power in walking ability. The lack of power found in mobility rehabilitation related to gait and balance abilities is not enough to be overcome only by motor control training, but also requires cardiorespiratory (CR) training. Both motor control and CR fitness training are an important factor in improving health promotion and the possibility of transferring walking abilities from VE to real world.

According to the walking limitations who suffered of individuals post-stroke, the use of cycling training combined with serious games has been developed. [6] had designed a cycling wheel chair (CWC) coupled with a VR application in order to train balance skills of individuals post-stroke or individuals with brain disorders. There were four actions to manage balance when driving CWC including pedaling balance, pedaling speed control, handle steering, and obstacle avoidance. Form the experiment results obtained that the ability of pedaling and steering control were improved in active control subjects, but the evidence of individuals post-stroke was not tested. Moreover, to evaluate balance skills of individuals post-stroke, [7] developed a virtual reality-cycling training system (VRCTS), which could obtain input from pedaling force and pedaling speed control of the user. The data obtained from the cycling sensor was used to generate feedback to the user who controlled the running of virtual car by maintaining the balance of the pedals on both feet. [8][9] had designed a virtual reality-based stationary bike for post-stroke training that was equipped with pedal balance, steering control and heart-rate (HR) components. However, no modular systems above that can accommodate the sensorimotor abilities of individuals post-stroke, where the mechatronic components were not able to analyze all of the user's kinematic abilities so that the transfer of user abilities from real world walking to virtual environment training was weak. Training results could not show walking endurance. Thus, the existing systems from previous research were not determine whether it was safe, feasible, and efficacious to use them in post-stroke training.

To overcome some weakness in physical post-stroke training, we have proposed a VR system-based cycling training to promote motor control and increase CR endurance. This system has been built using a low-cost stationary recumbent bicycle equipped with several modular mechatronic components and coupled with a non-immersive VR application that stimulate cycling training to engage individuals post-stroke in long term physical training, by also promoting adherence through motivation. The objective of this paper is to explain a VR system-based cycling training to achieve all physical training goals for individuals post-stroke.

II. VR SYSTEM BASED CYCLING TRAINING OVERVIEW

A. System Overview

A VR system-based cycling training for post-stroke training is shown in Fig. 1, while its block diagram is explained in Fig. 2.

Fig. 1. VR system-based cycling components for post-stroke training; A: pedal module; B: cadence module; C: calibration tool and sensors monitoring; D: heart-rate monitor module; E: data acquisition box; F: central processing unit; G: virtual environment

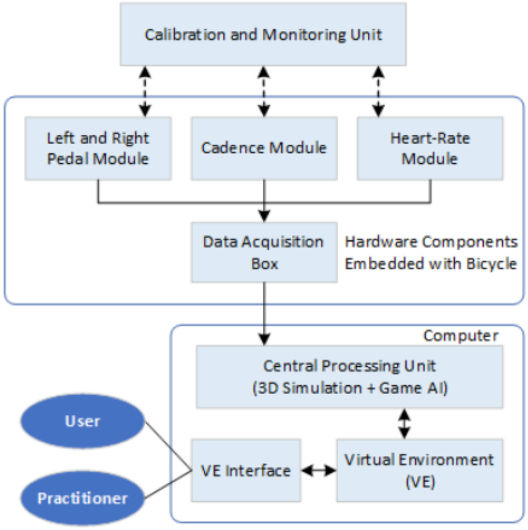


Fig. 2. A block diagram of VR system-based cycling for post-stroke training

Based on Fig. 1 and Fig. 2, the proposed system has the following parts: first, a recumbent stationary bicycle equipped with a balance module on both pedals having two load cell sensor and an accelerometer sensor in plantar flexion and dorsi flexion positions which are placed on each pedal pad; a cadence sensor is located in the pedal crank to measure revolutions per minute (RPM); an arm-mounted HR module; control and data acquisition module mounted on the bicycle frame. The second part is a computer equipped intelligent cycling game that processes data received via an UTP cable from data acquisition box and runs a non-immersive VR cycling simulator that can manipulate VE, manage virtual objects behavior, monitor physiological parameters, and give visual feedback. The monitor displays VE of cycling training and configuration interface that can be accessed by practitioner and user.

B. Pedal Module Specifications

As shown in Fig. 1 (A), this recumbent stationary bicycle is equipped with two pedals, namely the right pedal mounted on the right crankshaft and the left pedal (not shown) mounted on the left crankshaft. The design of the pedal mat can adapt to various foot sizes providing maximum area of foot pressure. Each pedal has a pedal strap that can be adjusted for different foot sizes and prevents the feet from slipping out when pedaling the bike.

Fig. 3. Pedal design without strap and cover box

The design of pedal is shown in Fig. 3. The mechatronic components of each pedal include: 1) a foot pressure balance gauge module with two load cell sensors. The pedal balance is calibrated using IK 5.04.01 with the reference calibration method according to CSIRO [10][11] to measure the effect of off-center loading, hysteresis, repeatability of reading, effect of gravity, and estimation of uncertainty. The calibration results are used as a reference for correcting the pedal balance value; 2) the ankle joint range of motion module uses an accelerometer sensor to determine the orientation of the ankle tilt in dorsi and plantar flexion positions. It is needed to make gait analysis; and 3) an Arduino Nano microcontroller module equipped with wireless RF nRF24L01 to transmit data to the data acquisition box.

The use of a vibration element provides haptic feedback when an imbalance warning appears in the virtual cycling environment when pedaling. Both haptic feedback and visual feedback can improve motor learning in walking [12][13].

C. Cadence Module Specifications

As shown in Fig. 1 (B), the cadence of the bicycle crank arm rotation is measured using an optocoupler sensor which will count the number of holes in one rotation cycle and its results are sent via cable to the microcontroller unit in the data acquisition box (Fig. 1 (E) to count revolutions per minute (RPM). New cadence modules embedded with the close loop control method using Fuzzy system as a controller and Pulse Width Modulation (PWM) as a plant are implemented on a recumbent stationary cycle to produce a desired cadence, regardless of the uncertainty of abilities of the participants. The concept is to control magnetic resistance flywheel movement by using an electric motor. The closed loop control method has three modes as shown in Fig. 4, namely 1) assist mode; 2) normal mode; 3) braking mode. Switching between cadence modes depends on the feedback of the current cadence compared to the cadence limit desired by the user or set by a physical therapist. The desired cadence range of 50-55 RPM is selected for the preliminary test based on American College of Sports Medicine (ACSM) guidelines [14].

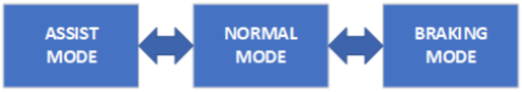


Fig. 4. Switching modes operation to maintain desired cycling cadence to accommodate varying levels in lower extremity impairments

Based on Fig. 4, If the participant can keep the cycling cadence between minimum and maximum desired cadence, the system will be in normal mode where an electric motor will generate moderate magnetic resistance on flywheel. If the participant's cadence is below the desired cadence value, the system will be in assist mode where an electric motor will generate mild magnetic resistance on flywheel so that the participant's cadence can return to the desired cadence range. On the other hand, if the participant's cadence is above the maximum desired cadence value, the system will be in braking mode where an electric motor will generate high magnetic resistance on flywheel so that the participant's cadence can return to the desired cadence range.

D. Physiological Module Specifications

As shown in Fig. 5, user of recumbent stationary bicycle is instrumented with a HR monitor using DT79 smartwatch that transmits its data via a Bluetooth 4.0 connection to a data acquisition box (Fig. 1 (E)). Monitoring HR data is needed as one of the input parameters for the Fuzzy control system to manage the bicycle speed of the virtual trainer in VE and to ensure the safety of recumbent stationary bicycle users when training using this device. Another function of DT79 smartwatch is to monitor blood pressure (BP) and oxygen saturation level (SpO_2).

Fig. 5. Wireless physiological parameters monitor: HR, BP, SpO2

E. Data Acqusition Module Specifications

The data acquisition module in Fig. 6 is shown by a white box and placed behind the display screen of the virtual environment. The data acquisition module is used to collect and process raw data from various sensors embedded in the bicycle and pass it on to a central processing unit (CPU) for visualization. This data acquisition module is equipped with an ESP32 microcontroller unit and a mini-PC (STB Linux) AMLOGIC S905X3, RAM 4GB, EMMMC 64 GB with Wireless Access Point (WAP) and Bluetooth receiver.

Fig. 6. Data acquisition module behind display screen of virtual environment

The communication between the two pedal modules and data acquisition module is connected via wireless, while the communication between the physiological module and the data acquisition module uses Bluetooth. Moreover, communication between cadence module and data acquisition module is connected directly using a cable. Only the registered MAC addresses of the modules embedded in the bicycle can connect to the data acquisition module. The results of data processing from the data acquisition module are sent to the CPU via peer-to-peer communication via UTP cable with the Modbus TCP protocol. The data acquisition module also acts as a DHCP server for the CPU client.

F. Calibration and Monitoring Modules

Fig. 7 (A) shows the calibration tool for pedal balance and crank arm velocity, while Fig. 7 (B) shows software for monitoring HR, Cadence, and both pedal balancing values. Calibration is used to check and reset the accuracy of the pedal balance and velocity of the crank arm values with pre-set default values.

Pedal Weight :
000,89 Kg

Server IP: 192.168.0.100
Port: 502

Heart Rate
78
BPM

Cadence
29.99
RPM

Load Left
9.113
Kg

Load Right
8.778
Kg

Connected to 192.168.0.100:502

Fig. 7. Additional tools; A: calibration device; B: communication indicator between CPU and data acquisition module and sensors value monitoring

G. *Virtual Reality Based Cycling Serious Game*

A VR system-based cycling training is designed to simultaneously train and improve motor control and cardiorespiratory fitness. Before starting this cycling simulation training, some initial parameters including name of user, age of user, number of laps, training level, maximum HR (Max. HR), resting HR (RHR), target HR (THR) and training intensity must be set in the simulation menu.

Fig. 8. The virtual environment of the simulator where the rider (behind) follows the cycling track of the virtual trainer (ahead) at a safe distance and monitors heart rate safely during training

This simulator software is built from 3D virtual cycling environment that simulates cycling training for individuals post-stroke as shown in Fig 8. The VE of the simulator has 2 avatars, namely a rider simulating the actions of a bicycle user and a virtual trainer who acts as a non-player character (NPC). Rider is instructed to pedal a bicycle to follow the cycling path of the virtual trainer while maintaining a safe distance, monitoring HR rhythms below THR. If current HR of rider displayed at the bottom right of the virtual environment is closer to the THR, the HR of rider image will be animated getting bigger and the heartbeat sound getting louder as a form of visual feedback. While the distance between the rider and virtual trainer is too close or too far, the rider is instructed to reduce the pedal speed or increase the pedal speed and VE displays a warning box for the rider to immediately maintain a safe distance. Moreover, if the rider is unbalanced in pedaling the bicycle, then the bicycle will tilt left or right according to the weight of one of the heavier pedals and affect the control of the bicycle on the track and VE displays a warning box to immediately balance the pedal force. The rider's ability to maintain balance on both pedals and maintain a safe distance from the virtual trainer is recorded and can be displayed in graphical form as shown in Fig. 9.

Tanggal Latihan	Max HR (BPM)	RHR (BPM)	THR (BPM)	LEVEL	WAKTU LATIHAN (MENIT)
23-05-2022 15:39:27.342	180	64	100	1	30
22-05-2022 15:39:26.459	180	63	100	1	30
21-05-2022 14:39:25.649	180	65	100	1	30
20-05-2022 17:39:24.999	180	60	100	1	30

Fig. 9. Logging of the rider's balance and ability to follow the trainer's trajectory at a safe distance

The track, number of laps taken and training time are displayed in a virtual cycling environment. To improve the rider's ability to transfer visual information from the real world to VE, manipulation of VE is carried out which includes the level of difficulty of the track and constant gain in pedalling a bicycle to produce bicycle pedal control according to the rider's ability [15]. The level of difficulty of the track can be selected from wide track, wide track with obstacles, and narrow track with obstacles. Furthermore, the gain constant from the rider's pedal rotation includes low gain, normal gain, and high gain. The bicycle speed of the virtual trainer is set using Fuzzy system with two input parameters including the rider's HR and the distance between the rider and the virtual trainer.

If the rider of this simulator experiences symptoms such as dizziness, nausea, eye strain due to exposure to VE, or current HR exceeds THR, then the rider can press the stop button on the top left of the VE to stop the training to prevent further serious incidents.

III. PRELIMINARY TEST

Preliminary test of this VR system-based cycling training aims to find out in general how the safety, feasibility and efficacy of using this simulator. we hypothesized that cycling training coupled with non-immersive VR would enhance transfers to longer walking abilities.

A. *Participants*

Two healthy sedentary participants (2 males, age 45 years old and 46 years old) were included in this preliminary test. Participants were requested to perform their usual training activities without any manipulation.

B. *Testing*

Before starting the preliminary test, each participant signed informed written consent that was approved by the research ethics commission from the State Polytechnic of Jember to participate in the research until it was completed.

The safety of this prototype was defined by the absence of side effects such as fainting, dizziness, nausea, eye strain due to watching VE for long time where its indicators could be measured by HR, BP, and RPE (Rated of Perceive Exertion). Meanwhile, the feasibility of the prototype was measured by the number of participants attending the training, total training time, ability of participants to maintain balance and safe distance from the virtual trainer, the perceived experience of using VE measured using the Witmer–Singer presence questionnaire (PQ) [16][17]. Attendance and training time were recorded for each training. While PQ was assessed at the end of the preliminary test. The PQ had 32 items rated on a Likert scale in the range of 1 (lowest) to 7 (highest). In this preliminary test, PQ items 2, 3, 5, 6, 10, 18, 23, 32 were assessed. The eight items were related to the assessment of control factors, sensory factors, and involvement factors. Efficacy of the prototype was measured by the increase in maximal VO_2 and walking ability using TUG (Timed Up-and-Go) for balance assessment, and 6-MWT (6-minute walk test) for gait assessment.

C. Intervention and Data Analysis

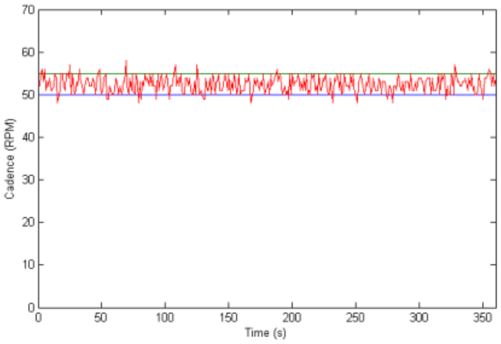
The VR system-based cycling training was conducted for 4-week. Participants attended 2 times a week and cycled for 60 minutes in each session. Training intensity was set at the start of the session between 20 and 30 beats per minute above RHR. The HR intensity of the participant might exceed the HR at the start of the session as long as the RPE value was at least 10 or below and did not experience fatigue or dizziness. Improvement of immersion of participant was conducted by manipulating VE such as path width, path difficulty level. The gain of the pedals and the speed of the virtual trainer on the cycling ability of the participant is also modified using Fuzzy system to present natural cycling pedal movements in VE. This system can adjust the user's sensorimotor abilities to pedal a cycle in desired cadence range so that it can produce an immersive presence. To ensure the safety of cycling training, physiological parameters such as HR, BP, RPE and SpO_2 of the participants was always measured. Current HR of participants could be seen on the interface of the VE. Cycling training should be discontinued if HR of participant exceeds his THR and/or BP of the participant exceeds 200/100 mm Hg during training.

Safety of cycling training was observed by practitioner and noted in data collection sheet. The feasibility of cycling training was measured by the total attendance of participants in cycling training, the total time of cycling training achieved after 4-week, and the average PQ value of all participants. The efficacy of cycling training was assessed from the result of measuring recorded time from TUG (It began when practitioner said "Go" and started the stopwatch. Participant would then be timed as participant rose from the chair, walked 1,5 meters, turned around, returned to the chair, and sat down), the distance from 6-MWT with a track length of 30 meters and the result of measuring the maximal VO_2 at the beginning of the first week of training and at the end of the fourth week of cycling training. VO_2 was measured by a metabolic testing system, COSMED K4b, using measurement of breath-by-breath.

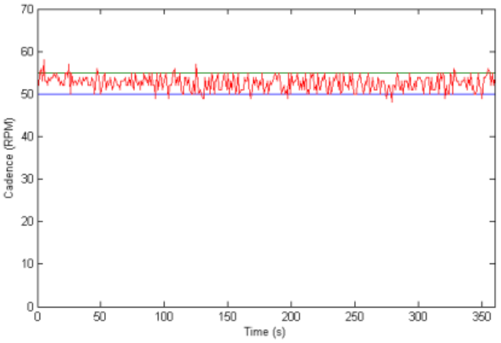
D. Results

All participants had completed the cycling training program twice a week for 4-week with the duration of each training session was 60 minutes. the total attendance of all participants reached 100% and no serious undesirable events were found. Fuzzy system-based adaptive gain settings had succeeded in preventing participants from getting dizzy when pedaling a VR system-based cycling training. Foot strap on both pedals had made it easier for participants to pedal a bicycle using both lower extremities and participants also did not experience foot slipping out from the pedals during 8 training sessions. Moreover, all participants could maintain desired cadence range by simulating switching to the three operating modes as shown in Fig. 10. It indicated that cadence controller worked to keep cadence range in spite of varying levels in lower extremity impairments after stroke. This is a preliminary study with a small number of participants to demonstrate a new cadence method. It is needed to test with involving individuals post-stroke to get more accurate results.

An assessment of the perceived experience felt by participants when using a virtual cycling environment was carried out after the last session of cycling training in the fourth week and the average PQ for both participants was 52,5 (out of a possible 56) with standard deviation (SD) of 0,71. It could be shown that there were no significant differences when pedaling in various VE condition between two participants and both participants could respond to a change in gain order. The total training time achieved by the two participants during 8 training sessions was 960 minutes.



(a) Participant 1



(b) Participant 2

Fig. 10. Cycling cadence compared to the desired cadence range during 6-minute testing

All participants who performed TUG decreased their walking time (first participant decreased from 07.16 seconds to 05.87 seconds, and second participant decreased from 06.13 seconds to 05.66 seconds). Moreover, all participants who conducted 6-MWT increased their walking endurance (first participant increased from 601 meters to 684 meters, and second participant increased from 636 meters to 663 meters). Both participants improved their maximal VO_2 (first participant increased from 38,65 mL· kg−1· min−1 to 43,63 mL· kg−1· min−1, and second participant increased from 39,19 mL· kg−1· min−1 to 40,81 mL· kg−1· min−1).

VR system-based cycling training was safe and suitable for use in healthy participants. Total exercise attendance reached 100% and no serious adverse events were reported. Although the perceived experience of using VE was only conducted once at the end of the training session in the fourth week, both participants got a good immersion after eight training sessions. Both participants could achieve 60 minutes of practice time in each training session. Neither participant's feet were released or slipped out the pedals during the bicycle training. The results of the assessment related to walking showed that both participants experienced improvements in aerobic capacity and walking endurance after 4-week of cycling training.

IV. CONCLUSIONS

In this paper, a VR system-based cycling training is presented. This prototype is equipped with mechatronic components with sensors for acquiring walking kinematics and physiological parameters to monitor training safety while running serious games in a virtual cycling environment with 3D visual, audible and haptic feedback. The novel combined cadence components and a close loop method has been designed to accommodate user with varying levels of lower extremity impairment to pedal in a comfort way. Manipulation of cycling gain, path width, and path difficulty could be used to modify HR of the user and keep their engagement. From the preliminary test during 8 training sessions for 4-week has been shown that the use of prototype involved two healthy participants make improvements in balance, gait, and walking endurance of them.

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