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Development of AnkleReHabit - A Low-Cost Robot-Aided Ankle Rehabilitation Platform

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ABSTRACT

The ankle joint plays a critical part for human body weight support and daily movements. Any ankle joint injury can strongly affect the patient's daily life, so ankle joint rehabilitation is essential to ensure the functional recovery of the ankle after ankle dysfunction. The AnkleReHabit system, a full system including both hardware and software for ankle rehabilitation training, was developed in this paper. To test the operation of the proposed system, one healthy subject has been enrolled. The AnkleReHabit system works well during the test with both Mobile App and serious game. The feedback from the enrolled subject shows that the system can be used with comfortable, the training process can be more exciting with the serious game developed on the computer. The AnkeReHabit platform was proven for feasibility in ankle rehabilitation training. Further work should include testing the effectiveness and the reliability of the AnkleReHabit system with the patients.

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1. Introduction

Ankle joint plays the important part involved in daily human movements such as walking, standing, running and jumping. The ankle joint helps maintain the balance, supports the body weight, and is a fundamental importance for propulsion. The ankle joint injuries are common injuries due to sports activities or accidents. A survey conducted in 38 countries with 70 different sports on a total of 201,600 patients concluded that the ankle joint is the most vulnerable area [1]. For ankle joint injuries treatment, joint replacement surgery (TAR - Total Ankle Replacement) can be performed [2] or physical therapy for non-severe cases [3].

It has been proved that if patients with ankle injury can get early rehabilitation training, they can accelerate the recovery process [4]. However, due to the lack of the number of trained therapists and high intensity of the training exercise, the need for rehabilitation training is still very high. To overcome this issue, in the recent decades, ankle rehabilitation robots have been developed and their application in physical therapy has been proven to have many advantages [5]. The robot used for ankle rehabilitation helps to save time and resources of the hospital and reduce pressure and stress on rehabilitation therapists [5]. Instead of focusing on only one patient, with the help of support systems one therapist can manage and deliver the training for other patients at the same time. Robotic system for ankle rehabilitation is a hotspot research field in recent years.

There are many types of robotic systems that have been developed, and tested for upper and lower extremities [6], [7]. For ankle rehabilitation robots, there are two main types: wearable and pedal system [8]–[11]. Liu et al. proposed a new robotic ankle rehabilitation platform to help patients in doing the exercise. This system consists of two 3-DOF robots, which can allow the patient to use their normal ankle side to teach the affected ankle size [12]. Based on the lower mobility parallel mechanism, the research group from China University of Petroleum developed a parallel ankle rehabilitation robot. The feasibility of this robot was verified by simulation analysis and virtual prototype simulation [13]. Liu et al. proposed a new soft ankle rehabilitation robot that is driven by four pneumatic muscles [14].

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However, a pneumatic muscle actuator can only pull and cannot push, that is the drawback of the pneumatic actuator in comparison with the electrical motor in rehabilitation application. The compliant ankle rehabilitation robot with the workspace and torque capacity can be adjusted was proposed by Zhang et al. [15]. A wearable parallel mechanism for ankle rehabilitation was proposed by the research group from Beijing University of Technology [16]. The proposed system has been tested with simulation, and the result showed that the system is suitable for ankle rehabilitation.

Many research groups focus on ankle rehabilitation robotic systems and have achieved reasonable results. The ankle rehabilitation system still has some limitations, such as complex structural design, lack of training software which makes the training exercise more exciting for patients. In addition, the important factor for applying the robotic system is the expense for building the system. Due to the fact that many existing ankle rehabilitation robots have complex design, or redundant degrees of freedom, these systems can be afforded by a small group of patients. Therefore, there is a need for an affordable and effective ankle rehabilitation system for all the patients in the low-income country. This is also the main aim of this research.

In this research, an ankle rehabilitation system – AnkleReHabit – was developed. In general, the AnkleReHabit system consists of two parts: the hardware system and the software system. The aim of this research is to develop one effective and affordable ankle rehabilitation system for every patient. The hardware is a pedal model, which can support the ankle joint movement in one degree of freedom. The software system includes one Mobile App and two serious games, which is specially designed for the hardware system. The combination of both hardware and software make the proposed system more suitable for ankle rehabilitation training. The feasibility of the AnkleReHabit system was tested by experimental training with one healthy subject.

2. Materials and Methods

2.1. Hardware design of the system

AnkleReHabit system includes the hardware subsystem and the software subsystem (Figure 1). The patient's foot will place on the hardware pedal, the pedal's rotation angle will be read by the microprocessor, this microprocessor will be the communication device between the hardware and the software, after the rotation angle of the hardware is available. Hardware sub-system is built in another paper of Vi Do Tran – 2021 [17]. Hardware is a device used for the patient to put his/her feet on to practice and play games. Hardware is designed and constructed of metal, using the central processor as Arduino and communicating with the computer via the UART standard. Hardware images and components of hardware are shown in Figure 2.

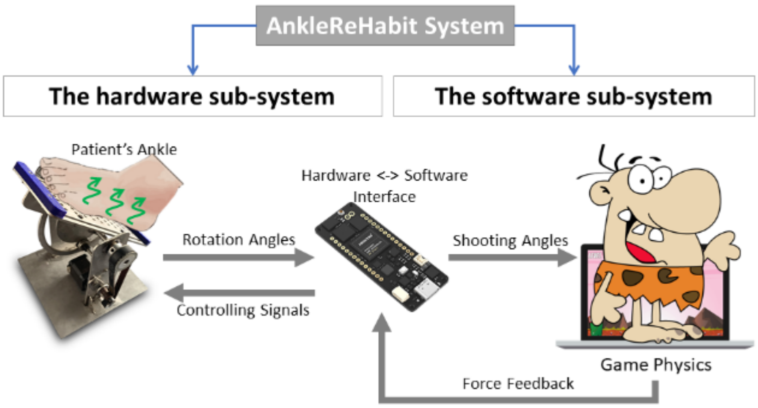

Figure 1. *Overall structure of the AnkleReHabit system*

Hardware is designed to be on a pedal with 1 degree of freedom (DOF). The pedal is plate metal fixed to the main shaft and a distance from the shaft center and the surface closest to the main shaft (plane (P)) called d. The shaft is connected to an encoder to read the value of the axis angle from which to deduce the angle of the plane that the patient's foot places on the pedal, this rotation angle is used to control the game and send a feedback signal that makes the system a closed loop.

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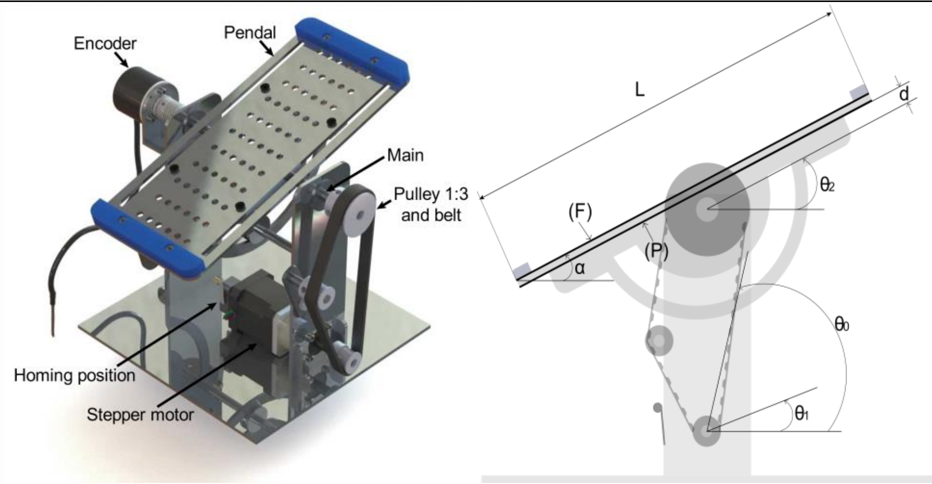

Figure 2. *AnkleReHabit hardware subsystem*

The shaft is connected to the pedal-driven by a stepper motor with a pulley and belt drive with a ratio of 1:3. This stepper motor is used to drive the pedal back to the position where the return value for the microcontroller rotation is 0 degrees, this position is defined as the homing position. When starting to start, connecting the device, the stepper motor will be driven to the homing position. Before the game starts the stepper motor will also drive to the device positions to control the game. In addition, stepper motors are also used to create force feedback effects in the case of collisions in the game.

The symbol of parameter and its value of hardware subsystem has shown in Table 1 below. The mathematical model of the system is calculated with the input as the motor gear's angle and the output as the rotation angle of the surface on which the patient's foot is placed (plane (F)). The plane (F) is parallel to the plane (P) so the angle α equal the angle θ_2. The angle θ_2 is 3 times the angle θ_1 so:

$$\theta_2 = 3\theta_1 \quad (1)$$

Table 1. *System parameters*

Symbol	Description	Value
L	The pedal's length	250mm
d	Distance from the shaft center and the surface closest to the shaft	10mm
t	Pedal thickness (distance from the plane (P) to plane (F))	3mm
r	The ratio of belt drive	1:3
θ_0	Homing angle	76°
θ_1	Motor gear angle	-
θ_2	Main shaft angle	-
α	Plane (F) angle	-
P	The surface close to the main shaft	-
F	The surface for patient to place foot	-

2.2. Mobile-app development

A mobile application was developed with MIT App Inventor with the main functions: create and program functionality for UI (user interface such as buttons, labels, text, checkbox, toggle, list view, list picker, and image), establish Bluetooth connection on MIT App, read and transfer data via Bluetooth.

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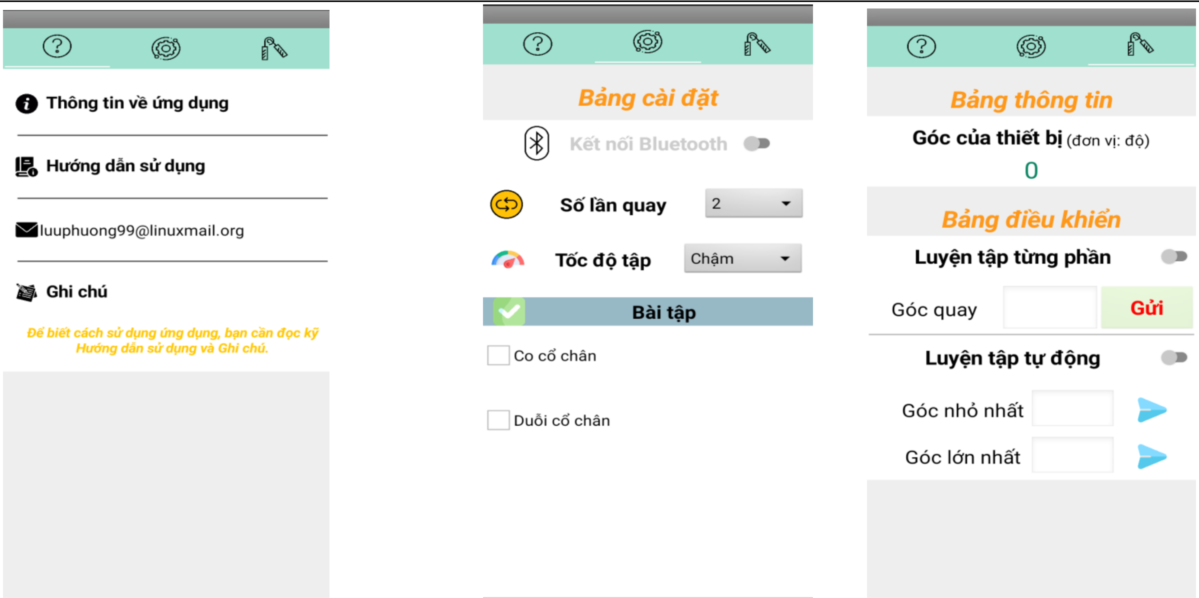

(a) *(b)* *(c)*

Figure 3. *Mobile App of the system with a) Home screen, b) Setup screen and c) Control screen.*

With this App, users can set the number of training exercises, the speed and the level of exercise (Figure 4a-b). If the user does not set these parameters, the system returns with the default setup as: the number of repetitions is 1 time, the exercise speed is slow and the exercise is blank.

On the control screen (Figure 4c), user can monitor the angle value in the dashboard, and can select the training method with two options:

- Partial training: the system will support the user practice bending or stretching the ankle according to the number of repetitions, training speed and desired angle. For ankle flexion exercises, the angle limit can be selected from 0 to 30 degrees. As for the ankle extension, the user can set the angle from 0 to -50 degrees.
- Automatic training: the system will rotate automatically within the range of angles from -50 to 30 degrees at the desired exercise speed. However, users can change this limit according to their comfort.

2.3. Serious game design

The software sub-system includes a launcher interface containing games, and hardware settings interfaces. The first game developed was Arrow Game, this game was created to help patients train from basic to quick reflexes. The collision on the game will be sent to the microprocessor with a force feedback signal. The microprocessor will send the signal for hardware when a force feedback signal is available. To make the training exercise more exciting for the user, two serious games were developed with Unity software.

a) The first developed game is called Arrow Game, the game includes an overall interface then a level tree interface, and it contains the levels of the game. In this paper, this game has been developed with 3 levels.

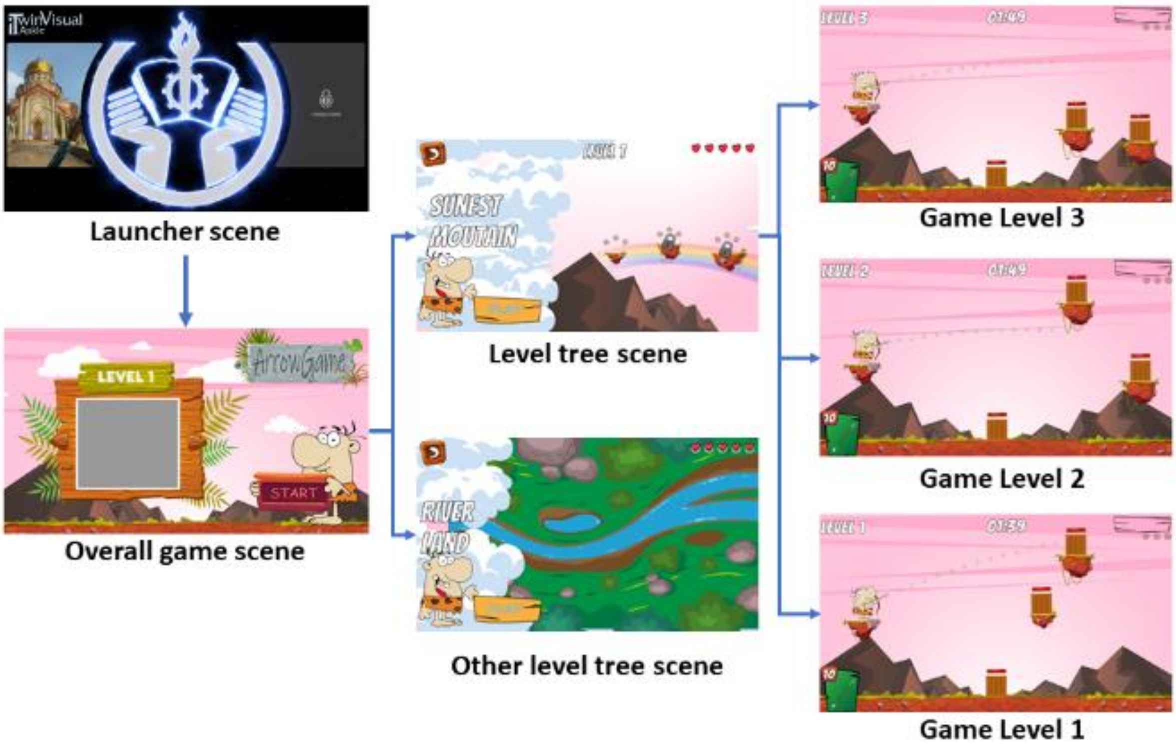

Figure 4. *Serious game designed for the AnkleReHabit system*

The hardware settings interface is designed to allow users to observe, check connections, and change the necessary parameters for the game. In the game Arrow game, the homing position is defined as the position where the arrow is parallel to the ground, the default value is 250, the user can rotate his/her ankle to the appropriate position and press the set homing button to set a new homing position. Figure 5 shows the interface of the hardware settings.

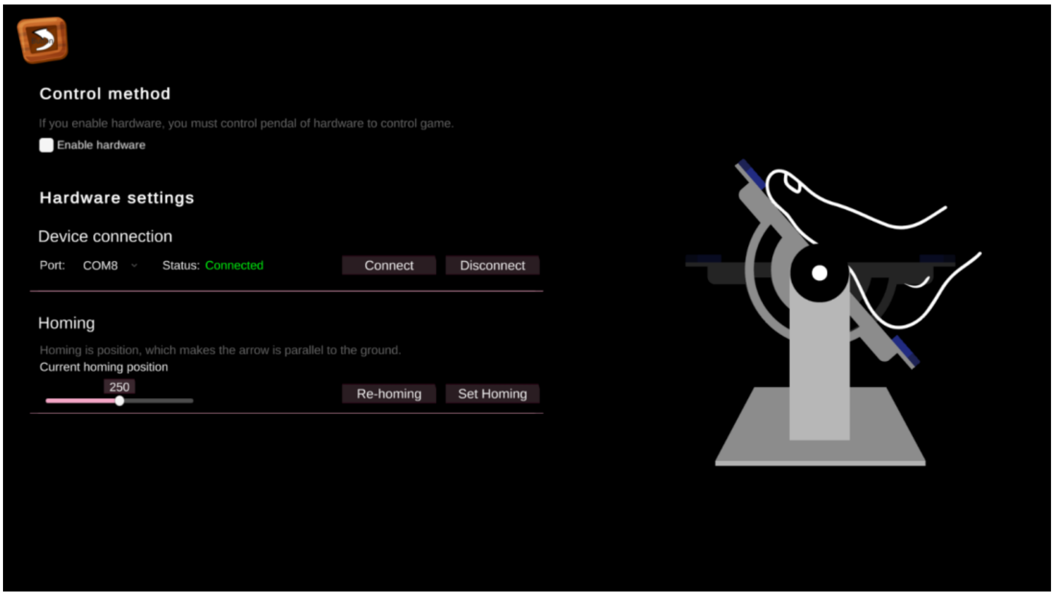

Figure 5. *Hardware settings interface*

The homing function in hardware settings, which is pressed by the user to perform when the rotation angle of the pedal is wrong compared to the hardware, after pressing the button the motor will rotate to the direction of the homing sensor and reset the value to 0 sent to the microprocessor.

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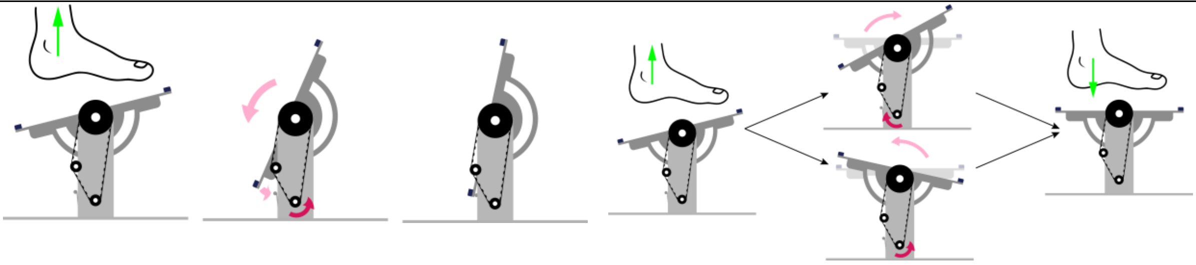


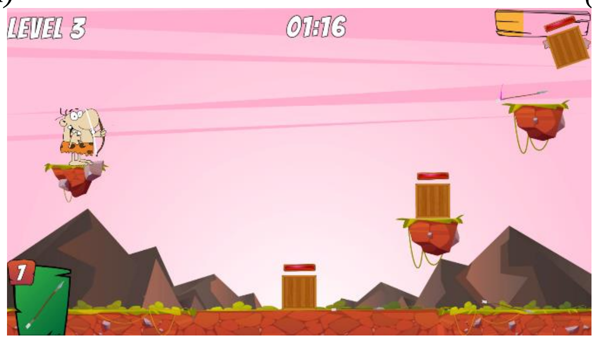
(a) *(b)*

Figure 6. *Setup for: (a) Homing function process and (b) Start process*

Before the game starts, the software sends a signal to the hardware to return to the game's homing position. The patient needs to take his/her foot off the pedal and the system will return to homing of the Arrow game, while the screen will display a countdown from 3 to 1 in 3 seconds, hold in the homing position until the word "START" appears and the game begins.

With the first level, the targets are the boxes above the island and the ground, these objects will be fixed. Characters in the game will also be fixed. The player's task is to control the pedal angle of the hardware to control the angle of the arrow, the task is to hit 3 boxes in 2 minutes and 10 arrows. The stronger the shot, the more stars the player gets. With this exercise, the patient will be trained with slow motions. The interface of the first level is shown in Figure 7a.

(a) *(b)*



(c)

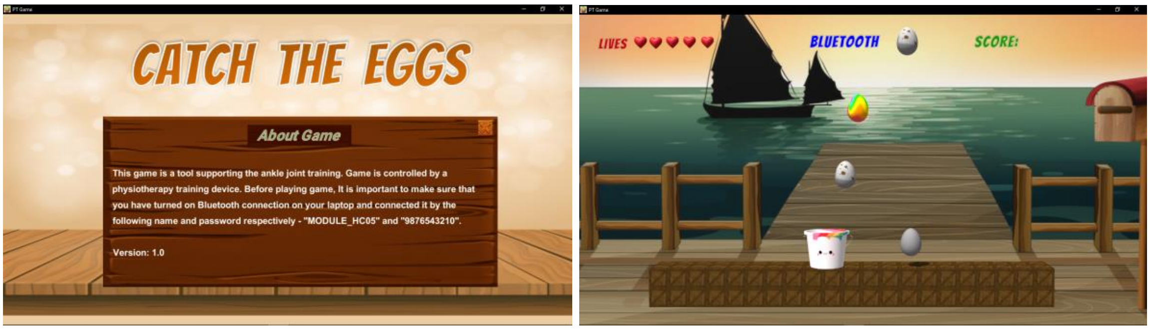
Figure 7. *(a) Arrow Game level 1; (b) Arrow Game level 2 and (c) Arrow Game level 3*

Level 2 of the game will be more difficult than the previous level. The target this time is still the boxes, but 2 boxes on the 2 islands will move up and down continuously, the character will not move. The task is still to hit 3 boxes in 2 minutes and 10 arrows. With this exercise, the patient will practice with the ankle's fast motions and reactions. The interface of the second level is shown in Figure 7b.

In level 3, the patient still has the same task as before, hitting 3 boxes of 10 arrows in 2 minutes. However, this time both the character and the 2 boxes on the island will move up and down continuously, the patient will have to focus more on the game to hit the boxes, so the patient will forget that he is training Exercise ankle rehabilitation, to help increase training efficiency. With this exercise, the patient will practice the ankle's fast-moving skills and reaction skills. The interface of the second level is shown in Figure 7c.

In addition, in all 3 levels, there is a function returning the force feedback signal when the arrow collides with boxes, this signal will create a more realistic feeling for the player during practice. Each time the arrow hits the boxes, a linear force is generated with the relative velocity, and this relative velocity is read by Unity3D's engine. Relative velocity's value is greater than or equal to a preset strong enough value will be sent to the microprocessor, the microprocessor will give the stepper motor response to create the feel of hitting the target.

b) The second developed game is called Catch the Eggs, the user will control the bucket to catch the falling eggs by moving the pedal of the system. This game aims to increase the flexibility and accuracy of the ankle.



(a) *(b)*

Figure 8. *Catch the eggs game with a) Home screen and b) Difficult mode screen.*

This game allows users to select from 3 levels: easy, medium, difficult. These levels are the same with the dropping speed of the egg. But the time between the 2 eggs to fall, or the egg falling rate, is different. The easy level will take longer and the hard level will take less time.

2.4. Ankle training exercise setup

To check the performance of the system, one healthy subject has been enrolled for the testing. The model is placed on the flat ground. The subject has been asked to sit on a chair and keep the distance from the model from 15 to 20 cm, or at the distance so that the subject feels comfortable.

The subject places one foot on the pedal, performing ankle flexion and extension. When the ankle moves, the device changes angle.

a) Test the system with mobile App

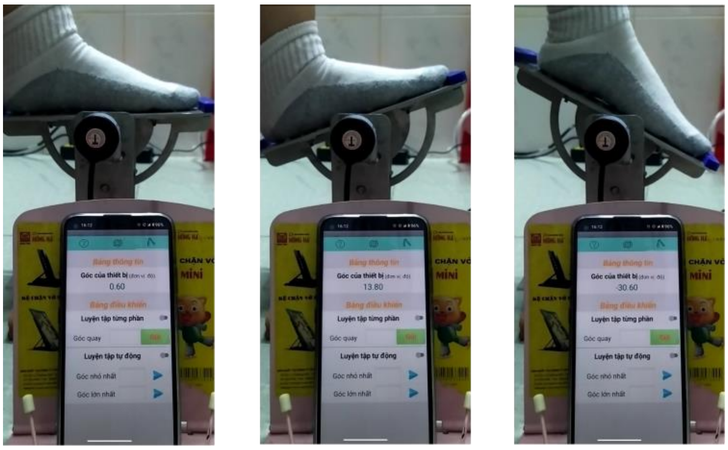


Figure 9. *Ankle movement with the model.*

Users select parameters: number of exercises, speed of exercise and exercises. On the control page, users can only choose one of two exercises: partial training or automatic training. In particular, partial

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training allows the user to practice bending or stretching the ankle with a limited number of exercises set by the user. The user enters the angle (the angle is limited from 0 to 30 degrees for ankle contraction and from 0 to -50 degrees for ankle extension) → press submit → press the practice button (Figure 4.39). When the number of spins has been completed, the device stops.

Automatic training is a combination of continuous stretching and stretching activities and an unlimited number of repetitions (please refer to the instructions included with the application). User enters the smallest angle (0 to 30 degrees) and the largest angle (0 to -50 degrees) → press send → press the practice button.

b) Test the system with the serious game

When the game starts, the user will perform ankle flexion or extension to move the bucket to catch the egg. With ankle flexion, the bucket moves to the left, and with ankle extension, the bucket moves to the right. When it stops moving, the bucket is at rest. After each egg is successfully caught, the score increases depending on the type of egg: one point for gray eggs, two points for polka dot eggs, and three points for yellow rainbow eggs. If the egg is broken, the score will not be reduced but one turn will be lost.

(a) *(b)* *(c)*

Figure 10. *The game with the ankle a) stop moving; b) move to the right; and c) move to the left.*

During the testing with the system, the user can immediately stop the system by pressing the reset button on the control box, if they feel any uncomfortable.

3. Results and Discussion

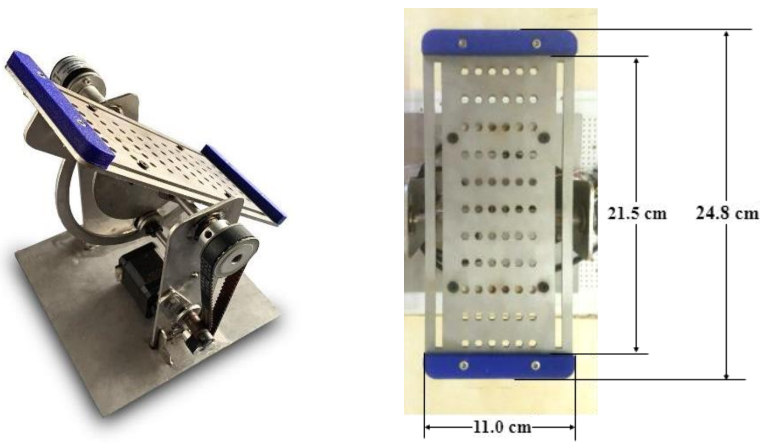

Figure 11. *The hardware subsystem when completed*

The hardware sub-system was developed in the previous study. The current version of this system was improved with the homing sensor and another practicing method.

The Software sub-system was developed with both Mobile App and two serious games with Unity platform. Both Mobile App and serious games can connect and work well with the hardware system.

The mobile App works well with no error during the experiment. The actuator rotates according to the speed and number of revolutions shown in the configuration screen. The angle value is updated to the information screen. The subject reported that there is no uncomfortable with the training system.

The serious game Catch the Eggs was used to test system operation with a healthy subject. The game works stably with no error during the system operation. There is a minor bug with the game where the eggs break before they hit the ground, but this does not affect the working of the system. The subject reported that it is more exciting playing games with the system than using the mobile App, and there is no uncomfortable with the training system.

The total expense for building the hardware system can be found in the Appendix 1. For the whole hardware system, the expense is reasonable. The system can be affordable by the patient with lower investment.

Although only one healthy subject was enrolled for the testing, the feedback from the subject shows that the system can be applied for ankle rehabilitation training. The limitation of this research is the lack of the patient for testing the system effectiveness in rehabilitation training. The further work will perform these testing to verify the effectiveness of the system for applying in the clinical treatment.

4. Conclusions

The whole system for ankle rehabilitation training has been developed in this research. The hardware of the system has been designed and built. Both Mobile App and serious games for training with computers have been developed. A healthy subject has been enrolled to test the operation of the system with both Mobile App and serious game. The results from the feedback of the enrolled subject show that the system can be used for ankle training with no error, and the serious game makes the training exercise more exciting than the Mobile App. Based on the above results, the proposed AnkleReHabit system proved the feasibility in application. The further work is testing the effectiveness of the system with the patient to evaluate the reliability of the AnkleReHabit system.

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APPENDIX

Appendix 1. *Total expense of the hardware system*

Item	Description	Number	Price (VND)	Total (VND)
Push button		3	8.000	24.000
Resistor	470 Ohm	3	500	1.500
Module Bluetooth	HC-05	1	90.000	90.000
LED	5mm	3	1.000	3.000
Wrap coil	Diameter 12mm	2,5 m	7.000	17.500
Belt	140XL size, step 5.08mm	1	45.000	45.000
Pulley	XL size, 8mm, 20 step, step size 5.08mm	1	70.000	70.000
Pulley	XL size, 8mm, 10 step, step size 5.08mm	1	30.000	30.000
Rotary Encoder	Incremental Encoder, 600 p/r	1	250.000	250.000

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Stepper motor	2 phase, with gear box	1	780.000	780.000
Microstep Driver	TB6600, 4A/42V	1	135.000	135.000
Arduino Mega		1	160.000	160.000
Power sypply	24V/5A output	1	150.000	150.000
Adapter	9V/1A output	1	30.000	30.000
CNC cutting				1.500.000
Mica cutting for the control box	Mica 3mm, white			100.000
	Total expense			**3.386.000**