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Upper Limb Rehabilitation Device with Force Control Feedback

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Abstract: Stroke is one of the most common causes of long-term disability in humans and will be undergoing a rehabilitation process where it is a long and difficult process for motor recovery. Currently, existing methods of therapy are less attractive and exhausting, which can lead patients to discontinue their therapy. The aim of this project is to introduce game-based therapy that interfaces with an upper limb rehabilitation device. A video game is developed using the Unity Engine. The mechanical structure is based on a human arm anatomy skeleton that provides physical assistance and supports the stroke patient's movement during their therapy since stroke patient has difficulty moving their hand. The upper limb rehabilitation exoskeleton was designed with one degree of freedom (DOF) with the range of motion (ROM) from angle 0º to 90º. The force control method can follow or imitate the resistive training motion of flexion or extension patient's movement. Finally, the upper limb rehabilitation devices are tested with three healthy subjects. The result shows that the device is reliable for stroke patients to use for their rehabilitation therapy. The device has the potential to increase the motivation of stroke patients to continue the rehabilitation process. However, further studies need to be conducted.

Keywords: Upper Limb Exoskeleton, Game-Based Therapy, Force Control

1. Introduction

According to World Health Organization (WHO) stroke is at second place leading causes of death and disability [1]. Stroke is one of the most common causes of long-term disability in humans and making it impossible to carry out everyday activities [2][3]. These patients will be undergoing a rehabilitation process and it is a long and difficult process for post-stroke spasticity and motor recovery. Problem with current rehabilitation is patient just doing the manual exercise such as stretching. Other than that, existing methods of the therapy such as using dumbbells are less attractive and exhausting which is can lead patients to discontinue their therapy and it will give impact to their recovery process [4].

For stroke patients, repetitive functional motion is an effective therapeutic treatment that has a good impact on their recovery. A game-based concept therapy is one of the best therapy methods for

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patient to exercise their muscle during rehabilitation process without feel boring. A game-based therapy also can reduce a patient's reliance on the physiotherapist while also can attract patient's attention and boost their motivation to continue their exercise or training process [5][6].

The main objective for this project are to design a simple upper limb exoskeleton rehabilitation device interface with a single degree of free game-like based system for stroke rehabilitation. The hardware design is exoskeleton structure and preassembled cuffs using one degree of freedom for elbow joint. Arduino Uno will be used as a microcontroller to control the device and Unity engine will be used to create a video game. The exoskeleton's structure will be designed using SolidWorks and 3D printer to construct the elbow exoskeleton. The upper limb rehabilitation device is attached with a 5 kg load cell and servo motor. Upper limb rehabilitation device for hand rehabilitation is using a servo motor and load cell act as force sensor together. The movement of the single joint of elbow is flexion and extension. The control system of this device is using the Proportional-Integral-Derivative (PID) controller.

2. Materials and Methods

2.1 System Architecture

The mechanical structure of this project is based on a human arm anatomy skeleton that provides physical assistance and supports the stroke patient motion. 3D design for upper limb exoskeleton in this project is single degree of freedom exoskeleton. This elbow exoskeleton contains seven parts in total contains three cuffs with different size depends on the hand level start from the upper arm cuff until lower arm cuff, the upper arm segment which is to connect the two upper arm cuff and motor adapter where motor adapter connected to second upper arm cuffs and also connect to the servo motor. Then, the interface motor and the others side are connect to the load cell and lower arm cuff where it connected to the load cell.

The Arduino Uno is used as main microcontroller of the system. Both of the load cell and servo motor are attached to the mechanical structure of upper limb rehabilitation device. The servo motor is used to control the device joint when there is applied force. The load cell attached to the device to provide the input force for the measurement. The force control feedback is used to control the motor more precisely in order to get the desired force for the stroke patient. A video game is developed using the Unity Engine. The laptop or computer is used to connect the serial port with Arduino where the data from the Arduino, they will send to the Unity to move the flappy bird in Unity. The laptop is also used so that the stroke patient can play the video game. Block diagram for the system architecture shown in Figure 1.

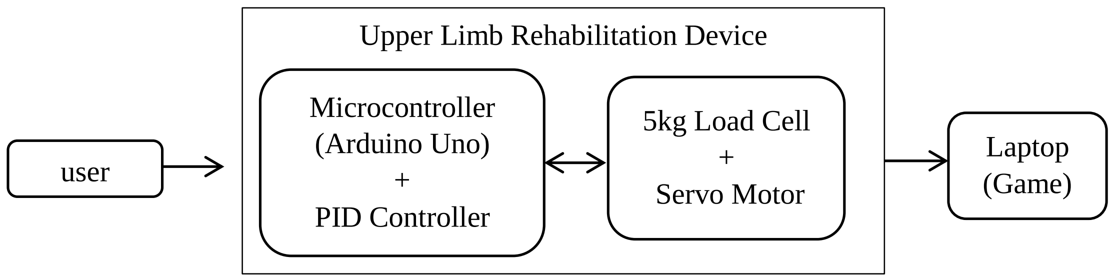
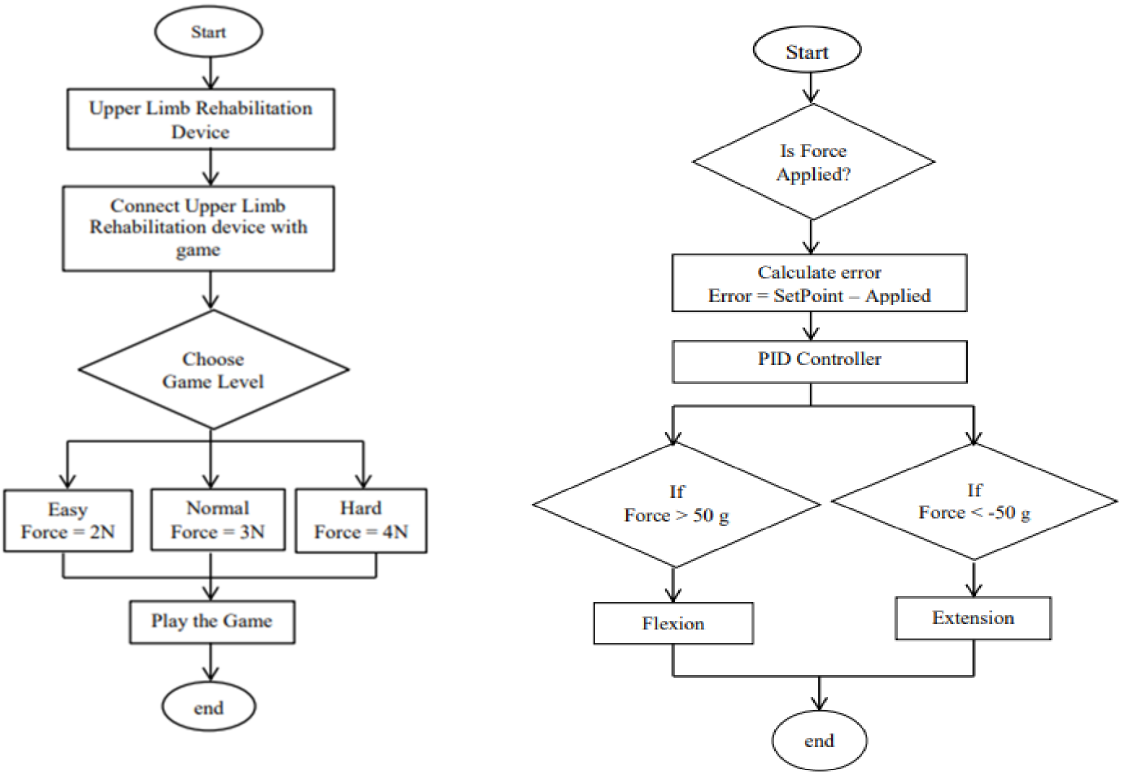


Figure 1: Block diagram for the system architecture

2.2 Flowchart

Figure 2(a) shows the flowchart for game level. The stroke patients are required to choose the game level based on their force level. Figure 2(b) is the force control flowchart using the PID controller. The process begins when force is applied to the load cell. The error obtained from the desired force and the actual force acts as the input to the controller. If the output from the PID controller is more than 50 grams, the upper limb exoskeleton will move forward (flexion) and it move backward if the input of applied force is less than -50 grams (extension).



(a) (b)

Figure 2: (a) The flowchart for game level (b) The flowchart for force control

2.3 Mechanism structure

3D design for upper limb exoskeleton in this project is single degree of freedom exoskeleton. This elbow exoskeleton contains seven parts in total. First part is the cuff where it contains three cuffs with different size depends on the hand level start from the upper arm cuff until lower arm cuff. Each of the cuffs is secured with four screws. Second part is the upper arm segment which is to connect the two upper arm cuff and motor adapter. Third part is the motor adapter. Motor adapter will connect to the second upper arm cuffs and also connect to the servo motor. Then, fourth part is the interface motor and the others side is connected to the load cell. The last one is the lower arm cuff where it connected to the load cell and secure with four screws.

These designed are based on human arm anatomy skeleton that provide the required physical assistance for the stroke patient. This upper limb exoskeleton is designed to assist and supported the stroke patient movement during their therapy since stroke patient has a difficulty to move their hand. This device directly provides a supporting torque to the stroke patient's joint which is can help the patient to move the hand allowed for intense training of arm motions during play the flappy bird game. This device indirectly can help the stroke patient to move their hand and doing their training session. For the 3D printing process, the 3D design of upper limb rehabilitation exoskeleton SolidWorks file is converted to STL file. Cura software from Ultimaker is an open-source G-code generator that converts STL files to G-code for 3D printers**.** User play the flappy bird game using Upper Limb Rehabilitation Device shown in Figure 3.

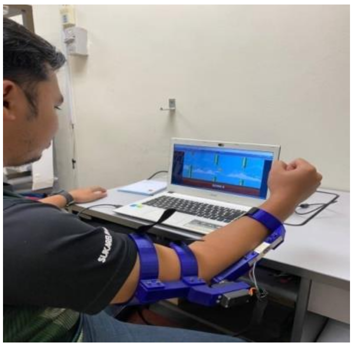


Figure 3: User play the flappy bird game using Upper Limb Rehabilitation device

The upper limb exoskeleton attached with the servo motor and load cell in order to control and move the device. Length of the upper limb rehabilitation device is 304.8 mm with the weight 250 grams which is lightweight for the stroke patient to using it. Movement of this upper limb rehabilitation exoskeleton is flexion or extension as shown in Figure 4.

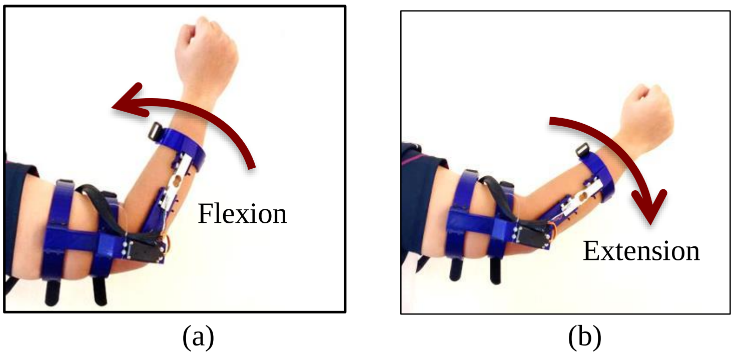


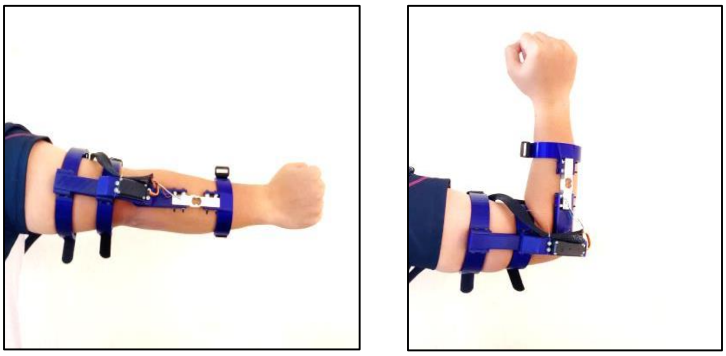
Figure 4: Elbow joint Movement (a)Flexion (b)Extension

This upper limb exoskeleton is designed with one degree of freedom (DOF) using elbow joint and the range of motion of this exoskeleton is from angle 0º to angle 90º. This device directly provides a supporting torque to the stroke patient's joint which is can help the patient to move the hand during play the flappy bird game where the game need to move the bird in y-axis at 0º until 90º. The data specification of this upper limb exoskeleton is shown in Table 1.

Table 1: Upper Limb Rehabilitation Device Data Specification

Categorized	Upper Limb Rehabilitation Device Data Specification
Range of Motion	0º - 90º
Degree-of-Freedom	1 DoF
Elbow Joint Movement	Flexion or Extension
Length	30cm / 304.8mm
Weight	250 grams

Normal elbow motion range of human is from 0º until 135º and normal range of elbow motion of rehabilitation device is from 0º until 110º [7]. For this project, after going through several testing range of motion, final range of motion (ROM) for this upper limb rehabilitation device is from angle 0º until 90º only. Minimum range of motion (ROM) for this upper limb rehabilitation device is at angle 0º and the maximum range of motion (ROM) at angle 90º. Figure 5 shows the minimum and maximum range of motion for this upper limb rehabilitation device.



(a) (b)

Figure 5: Range of Motion (a) ROM at angle 0º (b) ROM at angle 90º

2.4 PID Controller

Figure 6 shows the PID controller block diagram. PID controller was created to compute the controller's command torques. The upper limb exoskeleton can understand the intent of the user's control where when the user gives some force to this upper limb rehabilitation device, the force then is measured by the load cell and scaled by the controller, which then will send the input to the motor to control the motor torque to adjust and support the user movement.

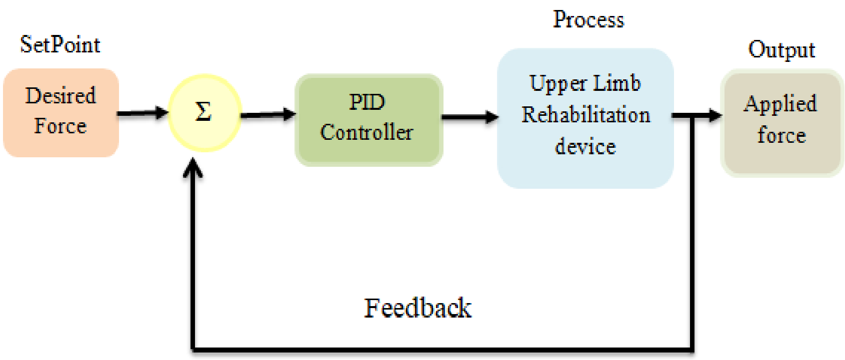


Figure 6: PID Controller Block Diagram

Without PID Controller, the error from the desired force and applied force is directly use as the input to the servo motor. $Eq.$1shows the calculation of the error.

$$Error = SetPoint - Applied\ Force \qquad Eq.1$$

Proportional Gain (*Kp*): The output for P controller is calculated as follow in equation $Eq.$2

$$P = Kp.e(t) \qquad Eq.2$$

Kp = Proportional gain, e(t) = error

Integral Gain (*Ki*): The output for P controller is calculated as follow in *Eq.3*

$$PI = Kp.e(t) + \int_0^{\tau} Ki.e(t)dt \qquad Eq.3$$

Ki = Integral gain and τ = Total time of operation of the controller

Derivative Gain (*Kd*): The output for PD controller is calculated using *Eq.4.*

$$PD = Kp.e(t) + Kd.\frac{de(t)}{dt} \qquad Eq.4$$

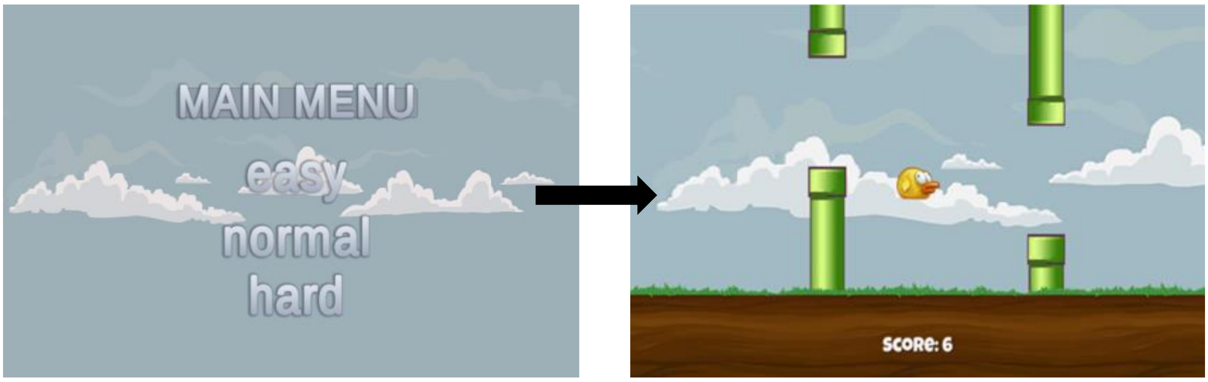
Kd = Derivative gain

Proportional Integral Derivative (PID): *Eq.5* shows the output of PID controller.

$$PID = Kp.e(t) + \int_0^{\tau} Ki.e(t)dt + Kd.\frac{de(t)}{dt} \qquad Eq.5$$

2.5 Flappy bird Game

The main menu scene and the game scene are the two main scenes developed in this game development as shown in Figure 7. There are three buttons built individually for the three game levels on the main menu screen, which is easy, normal, and hard. These three buttons are categorised by force level, with easy buttons representing level one, normal buttons representing level two, and hard buttons representing level three. Level one is for desired force or setpoint of 2N, level two is for desired force of 3N, and level three is for desired force of 4N as shown in Table 2. When a player clicked any of these buttons, scene one will load another scene where it changed to play game scene. In scene two, the level of speed will increase gradually every three-point of increment scored when player successfully pass each obstacle.



(a) (b)

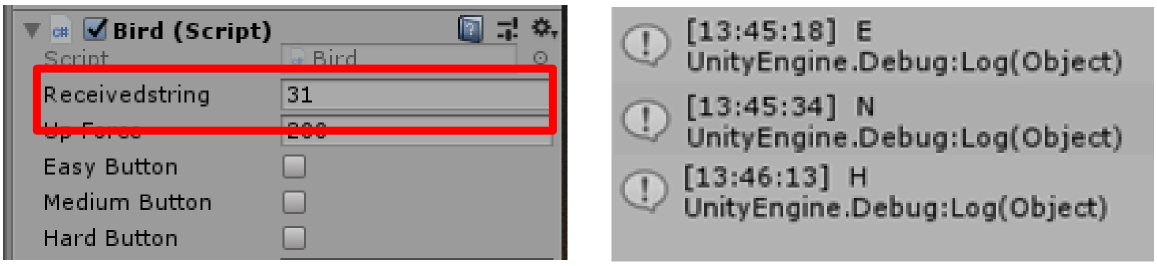
Figure 7: (a) Main Menu Scene (b) Play Game Scene

Table 2: Game Level Description

Game Level	Desired Force (Newton)
easy	2N
normal	3N
hard	4N

3. Results and Discussion

Figure 8 (a) shows a data send from Unity to Arduino and (b) show the data send from Arduino. Input from servo motor angle based on user movement has been successfully sent through serial port using serial communication in order to move the bird. Unity received the data from the Arduino serial port using the "data_stream.ReadLine();" command. A successful data send from Arduino to unity will display on received string as shown in the highlight red box in bird script on unity display page To send the data to Arduino, Unity used command "data_stream.Write". When user click on easy button, Unity will send the data "E" to Arduino in to change the desired force of 2N, normal button will send data "N" to change to the 3N of desired force and hard button will send data "H" to change 4N of desired force. The data 'E', 'N', and 'H' also can be seen at the play game scene at the bottom at the left corner of the scene. Table 3 shows the specification Data Send to Arduino.



(a) (b)

Figure 8: (a) Data Received from arduino (b) Data Send to Arduino

Table 3: Specification Data Send to Arduino

Game Level	Data Send To Arduino	Desired Force (Newton)
easy	" E "	2N
normal	" N "	3N
hard	" H "	4N

Figure 9 shows the output graph for the system that run without the PID controller and Figure 10 shows the output graph for the system that run with PID controller. The PID Controller was tuned using the try and error methods. From the output graph without PID controller, it shows that all the output did not reach all the setpoint. Figure 9 shows all the comparison of output graph of PID Controller for all setpoint where the setpoint 2N for easy level mode, setpoint 3N for normal level mode and setpoint 4N for hard level mode. Rise time for all the setpoint has a faster rise time. Setpoint for hard level which is 4N has a little higher overshoot compare to other setpoint but setpoint 2N has a bit higher overshoot compare to setpoint 3N. All the setpoint has a low steady state error.

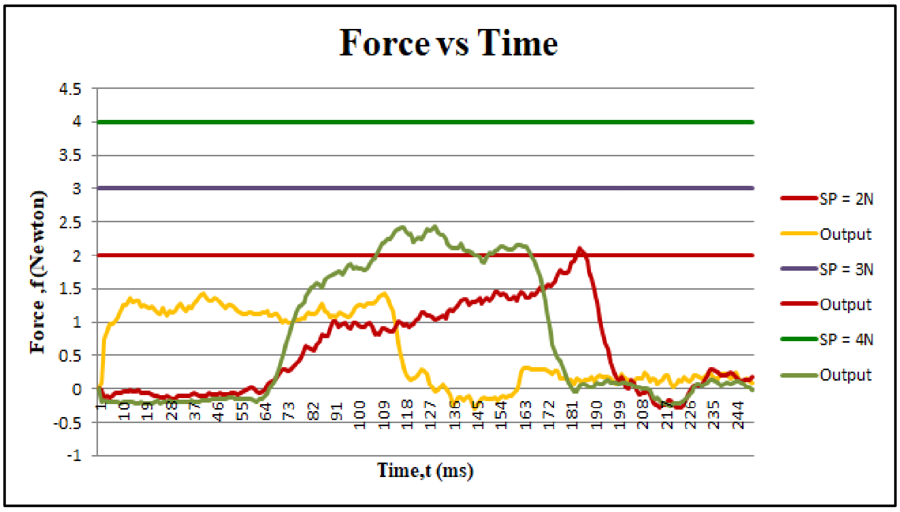


Figure 9: Output graph for the system without PID controller

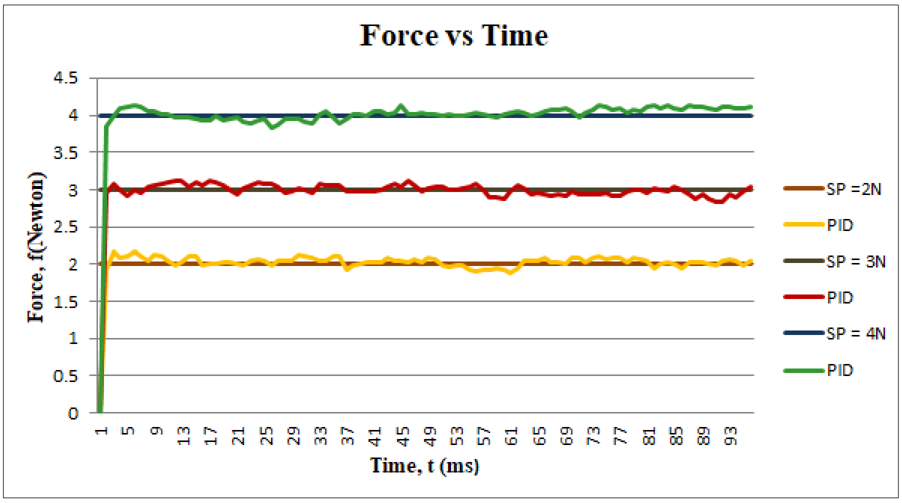


Figure 10: System Step Respond for all SetPoint

Easy level mode in flappy bird game is set with setpoint of 2N for force control feedback. From the output graph of PID Controller for easy level where the setpoint are set to 2N, the proportional gain (Kp) is set to 1.11, integral gain (Ki) is set to the 0.0000000000002 and the derivative gain (Kd) is set to the 0.01. The graph shows that there is a little overshoot but a faster rise time and the have a low steady state error. Tolerance % of this PID controller in easy level is ± 10% which mean maximum and minimum is ± 20.2 where easy level maximum is 224.14 grams or 2.2N and minimum easy level is 193.74 grams or 1.9 N.

Normal level mode in flappy bird game is set with setpoint of 3N for force control feedback. From the output graph of PID Controller for normal level where the setpoint are set to 3N, the proportional gain (Kp) is set to 1.01, integral gain (Ki) is set to the 0.0000000000000008 and the derivative gain (Kd) is set to the 0.00000000000001. According to the graph, setpoint 3N also has a faster rise time and a little overshot compare to setpoint 2N. The SP 3N has a low and more stable steady state error. Tolerance % of this PID controller in normal level is ± 6.8% which mean maximum and minimum the is ±20 where normal level maximum settling time is 325.91 grams or 3.2 Newton and minimum normal level is 285.91 grams or 2.8 N.

Hard level mode in flappy bird game is set with setpoint of 4N for force control feedback. From the output graph of PID Controller for hard level where the setpoint are set to 4N, the proportional gain (Kp) is set to 1.032, integral gain (Ki) is set to the 0.000000000000000008 and the derivative gain (Kd) is set to the 0.00000000000001. The graph show that the SP 4N got the low steady state error same with other setpoint. Setpoint 4N for hard level has a bit higher overshot compare to SP 2N and 3N. Tolerance % of this PID controller in normal level is ± 5% which mean maximum and minimum the is ±20.4 where hard level maximum is 428.28 grams or 4.2N and minimum hard level is 387.48 grams or 3.8N. Table 4 shows the PID controller parameter gains.

Table 4: PID Controller Parameter Gains

Gains	2N	3N	4N
Kp	1.11	1.01	1.032
Ki	0.0000000000002	0.00000000000000008	0.000000000000000008
Kd	0.01	0.00000000000001	0.00000000000001

4. Conclusion

As a conclusion, upper limb rehabilitation device using force control feedback has already achieved the first objective which is to design a simple and develop a simple upper limb rehabilitation device. A single degree of freedom upper limb rehabilitation device has been designed and developed using the 3D printing. The upper limb rehabilitation device can be controlled using the servo motor and 5kg load cell. Then, a video game has been successfully developed which is the Flappy Bird game. Flappy Bird game designed with three levels based on force where easy level for desired force of 2N, normal level for desired force 3N and hard level for 4N desired force. The intensity of the game also increased each time player score the increment of score three. The device has a potential to increase the motivation of stroke patient to continue the rehabilitation process. However, further study need to be conducted.

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