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3-DOF Parallel robotics System for Foot Drop therapy using Arduino

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Abstract
This paper discusses a robotic system used for physical therapy for foot drop case, caused by brain stroke. This device provides most exercises practiced by patient for treatment at any time or any place without going to the rehabilitation center located in hospitals.
The robotics system designed according to the mechanism of parallel robot and controlled by computer or microcontroller (Arduino). This robot allows the patient to do the exercise without any need for any knowledge about computer or programing.
The developed robot system show a good potential to be developed and distributed for large number of physical therapy clinics with low cost and good reliability.
Keywords: *3DOF Robot, Parallel Robot, Foot Drop Physical Therapy, Arduino.*

1. Introduction

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Foot drop is the inability to lift the front part of the foot [1].
This causes the toes to drag along the ground while walking. To avoid dragging the toes, people with foot drop may lift their knee higher than normal. For treatment, several exercises are designed for the treatment of ankle sprains and they should be used under the guidance of a physician or health care professional. The strategy of the physical therapy is shown in table (1)[2].

Table (1)

Step No.	**Exercises**
Step 1	Exercises 1 and 2
Step 2	Exercises 3 and 4
Step 3	Add Exercise 1,2 to 3,4

The exercises are the mainstay of treatment for patients suffering from stroke, which caused foot drop. The benefit of exercises includes reducing spasticity, and increasing muscle power. These exercises are shown in Fig.(1)

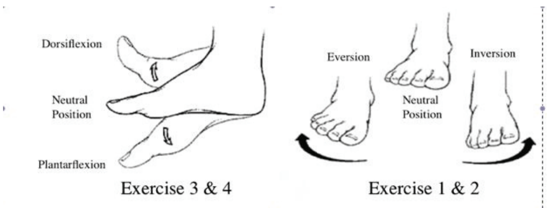

Fig (1) Foot Drop Exercises

The range of each exercise is shown in table (2).

Table (2) Range of the Ankle Angle Rotation

Angle	Ankle motion	Range of motion (°)
$+\alpha$	Inversion	14.5 to 22
$-\alpha$	Eversion	10 to 17
$+\beta$	Dorsiflexion	20.3 to 29.8
$-\beta$	plantarflexion	37.6 to 45.75

There are many papers for physical therapy for example, The Rutgers Ankle rehabilitation device based on Stewart platform structure driven by six double-acting pneumatic actuators as shown in Figure (2) had been developed by **Jungwon Yoon *et al.* (2002) [3]**. Each cylinder input is controlled by one set of on/off solenoid valves. For overall system control, an interrupt handler loop is designed based on hardware interrupts. For precise flow rate control of the solenoid valves, a PWM scheme is proposed for a set of two on/off valves. The proposed PWM logic compensates the dead band of the valve response time.

Fig (2) Ankle rehabilitation device using Rutgers technique

Daniel P. Ferris *et al. (2005)* [4] used myoelectric controller to construct a powered ankle–foot orthosis for human walking as shown Figure (3) .The orthosis included a carbon fiber and polypropylene shell, a metal hinge joint, and two artificial pneumatic muscles. The improvements of the design are being easier to don and doff and simpler to use. The novel controller allows naive wearers to quickly adapt to the orthosis without artificial muscle co-contraction. The orthosis may be helpful in studying human walking biomechanics and assisting patients during gait rehabilitation after neurological injury

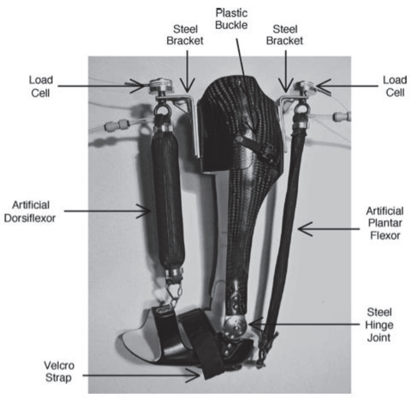

Fig (3) Pneumatically powered ankle–foot orthosis

2. Mechanical Design

A schematic of a parallel manipulator SPS is shown in Figure (4). The manipulator consists of upper platform three extensible links, fixed link with ball joint with the upper platform, and a base platform. The first upper platform is connected to the links by ball joints, which are equally spaced at 120^0 and at a radius $\boldsymbol{r}$ from the center of the upper platform. The other ends of the links are connected to the base platform through equally spaced ball joints at a radius R from the center of the base platform [5]. By varying the link lengths, the upper platform can be manipulated with respect to the base platform.

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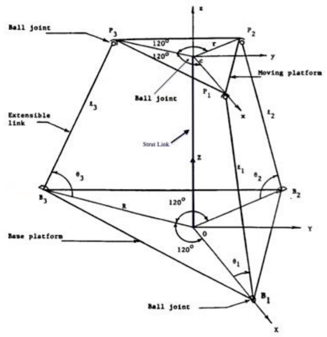

Fig.(4) Parallel actuated mechanism schematic

A base Cartesian coordinate frame XYZ is fixed at the center of the base platform with the Z-axis pointing vertically upward and the X- axis pointing towards the ball joint $\boldsymbol{B_i}$. Similarly, a coordinate frame xyz is assigned to the center of the upper platform, with the z- axis normal to the platform and the x-axis pointing towards the ball joint $\boldsymbol{P_i}$. Hence, the coordinates of the pin joints in XYZ frame are

$$B_1 = \begin{bmatrix} R \\ 0 \\ 0 \end{bmatrix} \quad B_2 = \begin{bmatrix} \frac{-1}{2}R \\ \frac{\sqrt{3}}{2}R \\ 0 \end{bmatrix} \quad B_3 = \begin{bmatrix} \frac{-1}{2}R \\ \frac{-\sqrt{3}}{2}R \\ 0 \end{bmatrix}$$

$$p_1 = \begin{bmatrix} r \\ 0 \\ 0 \end{bmatrix} \quad p_2 = \begin{bmatrix} \frac{-1}{2}r \\ \frac{\sqrt{3}}{2}r \\ 0 \end{bmatrix} \quad p_3 = \begin{bmatrix} \frac{-1}{2}r \\ \frac{-\sqrt{3}}{2}r \\ 0 \end{bmatrix}$$

The position of the center of moving platform is

$$P_0 = \begin{bmatrix} 0 \\ 0 \\ h \end{bmatrix}$$

the transform matrix is represented as following

$$T = \begin{bmatrix} C\beta & 0 & S\beta & 0 \\ S\alpha S\beta & C\alpha & -S\alpha C\beta & 0 \\ -C\alpha S\beta & S\alpha & C\alpha C\beta & h \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The Cartesian position of the ball joints with respect to the base frame ***XYZ*** can be expressed as

$$\begin{bmatrix} P_i \\ 1 \end{bmatrix} = [T] \begin{bmatrix} p_i \\ 1 \end{bmatrix}$$

The length of the actuators will change as shown in the table (3)

Table (3) the change in the length of actuators with exercises

Exercise No.	Actuator 1 Change (mm)	Actuator 2 Change (mm)	Actuator 3 Change (mm)
0	-	-	-
Exercise (1)	0	33	-33
Exercise (2)	0	-24	24
Exercise (3)	-73	36	36
Exercise (4)	46	-23	-23

The actuator velocity matrix will be

$$\begin{bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \end{bmatrix} = [J]^{-1} \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ 0 \end{bmatrix}$$

Where $\dot{d}_i$, $\dot{\alpha}$, and $\dot{\beta}$ is the actuator velocity and angular velocity about x and y axis respectively.

3. Dynamic Analysis

The equations of motion describe the actuating forces required to cause motion

$$\begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \ddot{\alpha} \\ \ddot{\beta} \\ 0 \end{bmatrix} + T_F \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} + \begin{bmatrix} \tau_{1X} \\ \tau_{2Y} \\ 0 \end{bmatrix} = 0$$

$$T_F = \begin{bmatrix} 0 & r\,\frac{\sqrt{3}}{2}[S\theta\ C\alpha + C\theta\ S\alpha\,] & r\,\frac{\sqrt{3}}{2}S\theta\ C\alpha - \frac{\sqrt{3}}{2}C\theta\ S\alpha] \\ r\ S(\beta+\theta) & 0.5r\ \ S(\theta-\ \beta) & 0.5\ r\ \ S(\theta-\ \beta) \\ 0 & 0 & 0 \end{bmatrix}$$

$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix}$ the actuator forces

$\begin{bmatrix} \tau_{1X} \\ \tau_{2Y} \\ 0 \end{bmatrix}$ is the external torque by patient foot

$$I_{xx} = I_{yy} = \frac{1}{2} I_{zz} = \frac{1}{4}\ mr^2$$

$\ddot{\alpha}$ And $\ddot{\beta}$ is the angular acceleration about X and Y-axis respectively.

4. Experimental Work and Robot Simulation

The robotics system is composed of the computer, controller interfacing circuit (Arduino) [6], driver motor, and the parallel robot with force and angle sensors. The overall system is represented by figure (5).

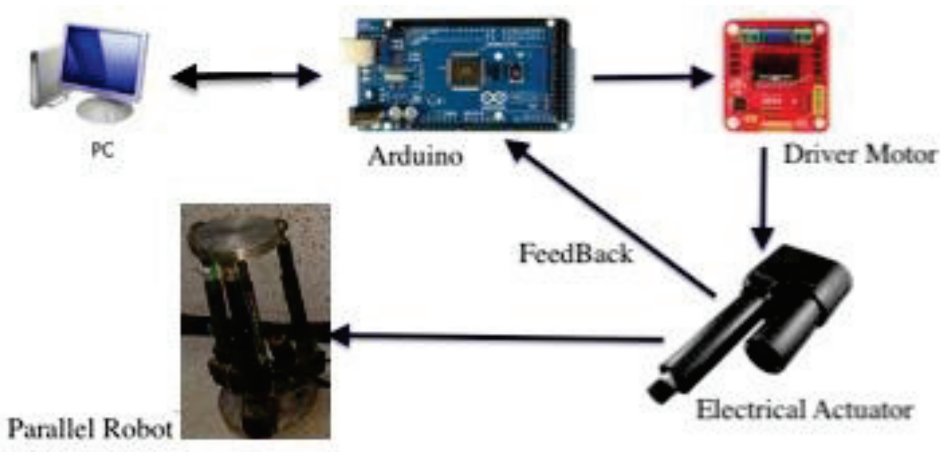

Fig (5) the overall system

The force sensor (FSR) is used to measured the external force exerted by the patient's foot on the moving platform but the angle sensor (EM-3242) is used to be as feedback for the angle.

5.The Simulation Model

The simulation model for the robot and the controller is shown in Figure (6)

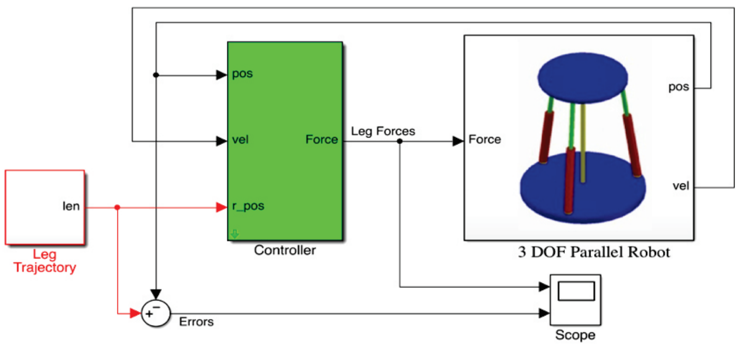

Fig (6) The simulation model of the 3 DOF parallel robot with controller

The input of the system will be the number of exercise; according to the exercise's number, the actuator desired length would be specified. The block diagram of the control with PID controller for all the system is shown in Figure (7).

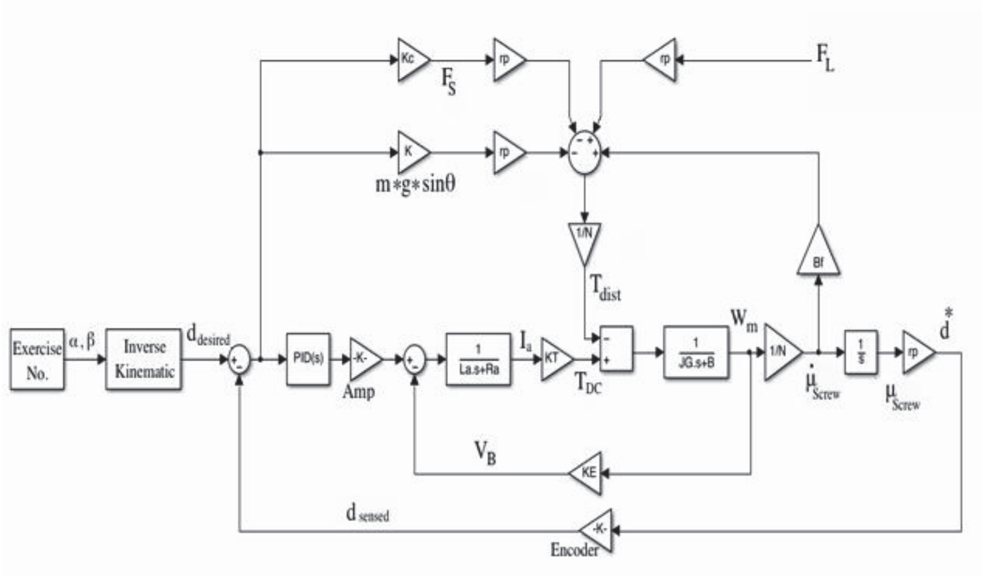

Fig (7) Block Diagram of actuators with disturbance action and feedback.

6. Results And Discussion

After complete the implementation the robotics system and compare the results of the experimental with the result of a simulation.

The different between the simulation and the experimental results is shown in the figure (8)

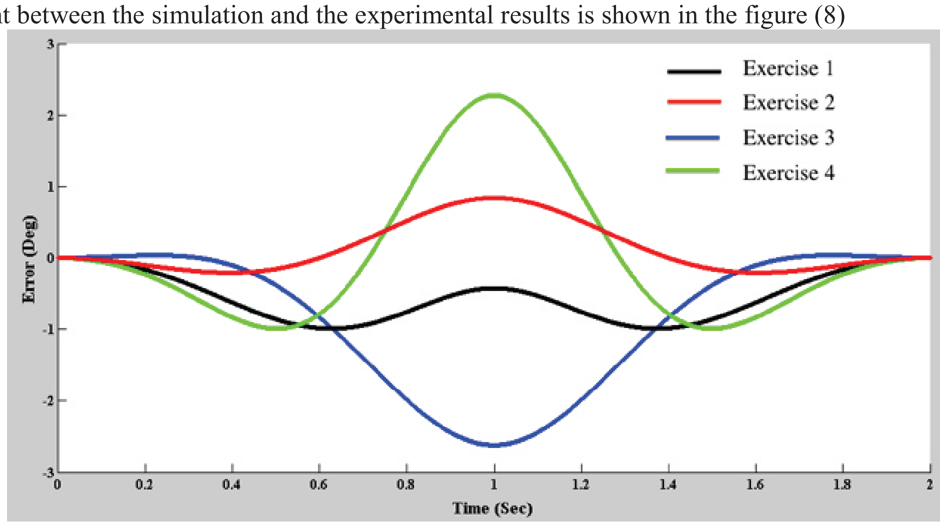

Fig (8) Errors of the exercises

The exercises 1 and 3 are with positive angles, the error of them in negative, which means the experimental result less than the simulation result. On other hand, the exercises 2 and 4 are with negative angle, for that the difference between the simulation and experimental result in positive because the experimental less than the simulation.The maximum error happens with exercise 3, which it is rotation by 46^0 as shown in table (3). The error of this rotation is not exceeding 5.6%, which it is acceptable ratio medically.

7. Conclusions

The suggested system has the following features:

- The suggested robotics system for ankle rehabilitation based on a parallel mechanism with 3 DOF controlled by Arduino microcontroller system covers the full range of motion of the human ankle with minimum number of DOF, and simple control approach.
- The robot workspace is within the limits that make the system able to implement different motion scenarios for the upper platform with the required forces for Four Physical therapy exercises for foot drop treatment.
- The suggested robot system can be easily deployed in several simple clinics to offer physical therapy for foot drop patients with low cost and efforts.

8. Recommendations for Future work

- Using fuzzy or neural network to implement the control algorithm**.**
- Designing a remote control system to control the real robot through a wireless link, LAN protocols or via Internet protocols or by cell phone using a SMS.
- Adding more sensors and sound system to implement the exercises or stop it for more safety.
- Capability to change the design to implement other exercises for other joints of human body for treatment for low back pain, or knee, or shoulder, or cruciate ligament.

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