A 3-DOF Robotic Platform for the Rehabilitation of Reaction Time and Balance Skills of MS Patients

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ABSTRACT

We present the design, implementation, and experimental evaluation of a 3 DOF robotic platform to treat the balance disorder of the patients with MS. The robotic platform is designed to allow angular motion of the ankle based on the anthropomorphic freedom in the space. That being said, such a robot forces patients to keep their balance by changing the angular position of the platform in three directions. The difficulty level of the tasks are determined based on the data gathered from the upper and lower platforms responsible for patients’ reaction time against the unexpected perturbations. The upper platform instantaneously provides pressure distribution of each foot, whereas the lower platform simultaneously shares the center of mass of the patient. In this study, the kinematic and dynamic analyses, and simulation of the 3 DOF parallel manipulator is successfully implemented. The control of the proof of concept design is carried out by means of PID control. The working principle of the upper and lower platforms are verified by set of experiments.

Keywords: anticipatory postural adjustment, compensatory postural adjustments, multiple sclerosis, balance disorder, reaction time, robot-assisted rehabilitation

1 INTRODUCTION

The Multiple Sclerosis (MS) is one of the most common chronic neurological diseases in the young adult age group, affects around 2.5 million people in the world. It is the most common disease-causing disability due to neurological reasons and directly affects brain, the central nervous system, and spinal cord. Over seventy-five percent of the MS patients experience impaired balance symptoms (Mehravar et al., 2015). About sixty percent of MS patients experience at least one fall in 3 months, and over eighty percent of them report activity restrictions on their daily life. Such situations promote a sedentary lifestyle, reduce community and social participation, and lower the living standards of the patients (Tijms et al., 2017; Aruin et al., 2015).
MS patients with mild and moderate severity levels are recommended to receive regular rehabilitation therapy four times a week (Schilling et al., 2019). Research shows that currently, only thirty-one percent of the MS patients receive the rehabilitation services. It is quite essential to observe the influence of treatment way during the follow-up phase of the patients. Because untreated patients have to use a cane within 20 years and a wheelchair within 30 years from the onset of symptoms (Brown and Kraft, 2005). Physical therapy is necessary for MS patients to adapt to daily life more easily, but the number of patients requiring physical therapy and the number of physical therapists cannot match each other and the efficiency of the rehabilitation depends on the therapist’s personal knowledge and experience (Saglia et al., 2009a; Feys and Straudi, 2019).

Balance disorder, one of the prominent symptoms due to lesions in the sections of the brain responsible for movement and balance is common in MS patients (Feys and Straudi, 2019; Tossavainen et al., 2003; Cattaneo et al., 2014). In particular, reaching a stable gate pattern takes longer time for the patients and they inevitably do experience recurrent fall events. In healthy people, in order to maintain the balance of the whole body, central control of posture utilizes the anticipatory (feed forward) and compensatory (feedback) postural adjustments (APAs and CPAs) against the unexpected conditions, like postural perturbations. APAs take role in maintaining the equilibrium of the body by anticipating the perturbations as a means of postural muscles (Aruin et al., 2015; Aruin, 2016), whereas CPAs contributes to the posture control system by stabilizing the center of mass (CoM) of the body based on sensory feedback. The MS patients suffer from insufficient balance control due to their poor APAs and CPAs. When APAs was not able to ensure balance condition, body dependent only in CPAs. Hence, findings in literature state that perturbation-based rehabilitation programs can improve the balance and decrease the falling rate of the patients with MS (Aruin et al., 2015; Kanekar and Aruin, 2015).

The other common symptom to diagnose and follow up during the therapy and treatment phase of the MS patients is their reaction time against the intentionally provided external stimulation (Saito et al., 2014; Hoang et al., 2016). Basically, the reaction time is the period that elapses from the start time of the stimulus and the time interval from which the response begins. The reaction time is often used to assess the sensory-based motor disorders and also indicates the severity of the balance disorder. In particular, MS patient takes 1.5 times longer time to stabilize the posture and reaches safer condition in a longer period than their healthy pair, which causes inevitable falling (Cattaneo et al., 2014). As the longer reaction time is an indication of the loss of balance control, MS disease severity is evaluated and treated as a means of patients’ efforts to perturbations. Along these lines, some research groups (Tajali et al., 2018) have focused on the APA capability of the patients. In this particular, they conducted human-subject experiments on fallers and non-fallers MS patients and observe electromyography (EMG) activity of their leg muscles and distribution of center of pressure. The experimental evaluation reveals that the MS patients with fall history had weaker electrical activity, and accordingly required long reaction time to restore their balance by means of APA. The efficacy of the rehabilitation on MS patients was also proved with a task-based evaluation. In this study (Aruin et al., 2015), distortion of their center of mass (CoM) measured by means of the platform where the patients stood on and the EMG activity levels were evaluated while the patients were catching thrown ball randomly. After regular training, patients were able to keep their CoM in the close vicinity of the equilibrium point and regain their balance ability. Findings from this study provide a background for the development of perturbation-based rehabilitation programs to improve balance and prevent falling in patients.

The demands for therapeutic rehabilitation robots has increased and the research in this field has grown rapidly as robot-assisted rehabilitation can deliver efficient training and provide objective follow-up
assessment and evaluation relative to the conventional rehabilitation techniques (Saglia et al., 2009a). As for MS syndrome, the research on assistive devices has mainly focused on unilateral or bilateral upper limb dysfunctions since around fifty percent of people with MS suffer from impaired hand functions (Lamers et al., 2016, 2018). Some research groups (Feys et al., 2015; Maris et al., 2018) developed a robotic system, called Haptic Master accompanied with virtual learning environment (I-TRA VLE) for the MS rehabilitation of upper limb dysfunction. Patients forced their impaired arm by means of the assistive system and performed the tasks defined in virtual reality (VR) environment. Findings showed that motor control ability of the patients were improved and allowed to lift up their arm to higher level after regular training program. Upper limb exoskeletons was also proposed to assist MS patients with paresis (Gijbels et al., 2011). In the study, 5 DOF Armeo Spring (Hocoma AG, Zurich, CH) was employed to strengthen the muscle groups of the patients. This pilot study provided evidence that 8-week training with the Armeo Spring improved the upper limb muscle strengths and functional ability of the patients.

In the literature, some research groups have also focused on lower limb rehabilitation of people with MS. For instance, ankle rehabilitation is considered as an effective way to improve walking performance, muscle strength (Saglia et al., 2009a) as well as range of motion of the ankle of MS patients (Lee et al., 2017). To address the problem, researchers mainly have utilized two fundamental concepts developed in robotic rehabilitation. Lower limb exoskeletons have been employed for years to treat the neurological disorders. In the study (Puyuelo-Quintana et al., 2020), the exoskeleton together with the assist-as-needed concept was used to explore the efficacy of MAK exoskeleton for gait rehabilitation of MS patient. Results showed that MAK exoskeleton improved the gait performance of the patients to a some extend; however loss of stability was observed during the training. In the other side of the ankle rehabilitation, the robotic platforms have served to improve walking patterns of MS patients. In the study (Gonçalves et al., 2014), 1 DOF robotic platform (RePAiR) allows to realize dorsiflexion and plantar flexion movements of the post-stroke patients. The comparison between the patients and the control group revealed that the device availed to increase the muscle strength, improved motor control, sensory-motor coordination of patients and accordingly walking patterns. A 2 DOF robotic platform (Saglia et al., 2009b) was also proposed to train ankle in plantar/dorsiflexion and inversion/eversion directions. However, such platforms specifically designed for the ankle rehabilitation and do not treat the balance dysfunction in MS.

Posturography, the expression of postural balance or sway, is evaluated basically by means of platforms with integrated load cells that can provide pressure/force measurement. Such evaluation can be implemented either static or dynamic means. For the static case, it is expected from patients to stand on the fixed platform and fulfil the required tasks displayed in VR environment in order to evaluate their center of mass and pressure distribution (Prosperini and Pozzilli, 2013). Some commercially available platforms (Hubbard et al., 2012; Park and Lee, 2014; Wii, 2021; Tyr, 2021) exist to assess the performance of the patients under static conditions. Such devices have been put into the services of patients together with the VR environment to give visual feedback and commands, and accordingly prolong the training period (Feys and Straudi, 2019). Although it has been stated that training with static balance platforms is effective in the regulation of pressure distribution in patients in a longer time (Held et al., 2018), the findings indicate that rehabilitation of balance disorder in dynamic conditions contributes significantly to the recovery of motor functions (Hubbard et al., 2012).

Dynamic platforms have been designed to treat balance disorder, like the static ones; however such systems require instantaneous dynamic action of the patients by forcing them to regulate their balance even under perturbations. Various studies have been performed to regulate the balance stability of people. For instance, balance boards (Bal, 2021) have been developed either electronically or by wood plate placed on
a roller to train the people. The ones including load cells are able to measure the pressure of the foot and center of gravity of the patient (Gea, 2021; bob, 2021; CoR, 2021; Tym, 2021). Another solution to train the patient has been proposed by GRAIL (GRA, 2021), which is a dynamic treadmill working in harmony with the VR environment. Some commercially available robotic platforms (Tec, 2021; Mul, 2021) have been produced to address the post-traumatic, orthopedic or neurological problems by training hip, ankle and shoulder joints. Depending on the instruction given by the therapist to the robot, the robotic system can intentionally expose patients to an unbalanced state and expect them to strive against the instability. Such systems are able to measure the pressure distribution of each foot and evaluate balance level by means of the the center of mass of the body. Human - subject experiments provided evidence that dynamic force platforms help to regain dexterity of the limbs and postural stability than the traditional treatment group (Saglia et al., 2019). Despite the benefits of the platforms, there is no study conducted in the literature to investigate the ability to control APAs and CPAs, accordingly the reaction time of the patients, and regulate the control strategy of the platform based on such information. Moreover, aforementioned robotic platforms were designed as a series of links connected by motor-actuated joints. Despite it is easier to solve dynamics and model the serial manipulators, preferring parallel manipulator in such an application provides advantages in terms of achieving high load carrying capability, better dynamic performance and precise positioning. Considering the efficacy of the parallel manipulator, to the best of our knowledge, there is no such study developed as a parallel manipulator to carry out balance training in the literature.

In this study, we present the design, fabrication and evaluation of a 3DOF robotic platform to rehabilitate the balance dysfunctions of the MS patients. The proposed platform is basically composed of three main parts: 3 DOF parallel manipulator, upper and lower platforms. The 3DOF parallel manipulator provides rotational motion in the space and accordingly leads to destabilizing the human body by means of perturbations to force them to regulate their balance. The reaction of the patients to the action of the 3DOF manipulator is evaluated by means of the upper and lower platforms. The upper platform is responsible for the pressure distribution of two feet of the patient to follow up their balance level and reaction time against the perturbation. The lower platform designed to analyze center of mass of the patients in real-time points out the severity of the MS patients. Moreover, the information acquired from the upper and lower platforms is employed as biofeedback to adjust the assistance coefficient of the assist-as-needed paradigm used in the platform.

The rest of the manuscript is organized as follows: Section II introduces the design objectives of the robotic platform, presents kinematic and dynamic analyses of the 3DOF parallel manipulator and its simulation, and also details the design of the upper and lower platform of the robot, while Section III evaluates the manipulator’s performance and capability of the upper and lower platforms to analyze center of mass and pressure distribution of the objects in both static and dynamic conditions. Finally, Section IV concludes the paper and presents the discussion and future work.

2 MATERIALS AND METHODS

2.1 Design Objectives of 3 DoF Robotic Platform

The electromechanical design of robotic platform is mainly composed of the moving part mobilized by linear actuators and the upper and lower platforms integrated with the load cells.

- The upper platform contains eight load cells that allow the forces applied to different regions of the foot to be taken independently of each other, used for calculating the reaction time, and also helping to monitor the patient’s postural deformity and recovery process.
• Load cells are used to measure the reaction time of the sudden force change that occurs on the sole of the foot applied by the patient during the changes that occur during the virtual reality game. This is done by transmitting data in real-time to a microprocessor after connecting to the amplifier with an analog to digital converter.

• The rail system was used to adjust the load cells according to the coordinates of the foot lengths of the patients.

• The lower platform contains three load cells, positioned to form an equilateral triangle, used to determine the position of the center of mass in the x-y plane.

• The cylindrical rod has been used to increase the safety of the person on the platform and the robustness of the device.

• The position schedules are used to detect and control the position change of linear motors.

• Linear motors are used to change the roll, pitch, and yaw angles of the upper platform on which the patient is, allowing the robotic platform to move at different angles in three-dimensional space and to rise and descend at different angles.

The maximum angle changes data of the human wrist are $0 - 20^\circ$ dorsiflexion, $0 - 50^\circ$ plantar flexion movements, $0 - 10^\circ$ adduction, $0 - 5^\circ$ abduction, $0 - 20^\circ$ eversion and $0 - 35^\circ$ inversion values. The maximum angle changes of the platform are limited to prevent the patient from being hurt, and the movement capacity of the joints chose accordingly which are in the range of $0 - 18^\circ$. The maximum stroke length is chosen as 20 cm and motor placement is done $0 - 70^\circ$ with the base. For a comfortable exercise movement, the working area is designed according to the ankle change of the person. These values were used to determine the maximum and minimum values of roll, pitch, and yaw values, which are the angles to be made by the end effector.

The system must carry the average human weight and the weight of the moving platform, so the power of each motor has been selected as a minimum of 900 N. Linear motors are placed at equal distances under the platform so that the same amount of imbalance can be achieved from each angle. The position of linear motors are measured by linear position schedules. Motors controlled with VNH2SP30 motor driver, Arduino, and Simulink environment, so that the speed and platform angle can be adjusted according to the patient.

Robotic platform shown in Figure[1] is specifically designed to be used in the rehabilitation process and follow-up of the neurological or neuromuscular disorders of patients. The necessary kinematic and dynamic analysis of the platform system, which has 3 degrees of freedom, was made and simulated in MATLAB/SIMULINK. As a result of the kinematic analysis, angular equations and relations were found for the parameters of the mechanism such as position, velocity, and acceleration. The platform’s matched with a virtual game design. The targets defined for the patient will be reached by the stability movements that the patient tries to provide on the platform. Depending on the disease degree of the patient, the difficulty level of the game is automatically detected and adjusted by the platform. In addition to that, the platform can support the patient to be successful, or if the patient’s health is improving, patients are expected to reach the goal with their own effort.

Figure[2]

The virtual reality game of the system will be used to increase treatment efficiency and make it interesting during rehabilitation and arrangement shown in Figure[2a]. The virtual reality environment to be used for rehabilitation treatment is created with the MATLAB® VR toolbox and shown in Figure[2b]. The game
will create an imbalance at different angles for each imbalance change data on the sole of the patient’s foot will be taken and at the end, the total reaction time and pressure will be calculated. It is aimed to provide learning in anticipatory postural adjustment with different imbalances which is intended to protect the patient’s vertical posture. In this way, the patient can react to subsequent imbalances more steadily, and the reaction time may decrease because these control strategies are mostly achieved through learning and can improve the response of anticipatory postural adjustment based on previous disorder experience.

Figure 3

The feasibility of the platform is tested with finite element analysis under the overload of the average human weight and weight of the platform (1000N). Figure 3 demonstrate the response of the bodies under static nodal stress. Negligible deformations with less than 1mm show that the proposed system is safe to use.

2.2 Kinematic and Dynamic Analyses of 3DOF Parallel Manipulator

2.2.1 Kinematics Analysis of the Manipulator

Kinematics is the analysis of motion without considering forces and there is only need geometric properties such as frame relationship. Forward and inverse kinematics model involves deriving equations to describe an analytical relationship between the link parameters and orientation/position of the moving platform.

The kinematic analysis of the platform was solved by forming equilateral triangles from position of linear motors’ points in base and upper platform, then unit vectors for each connection element were defined, the naming of the frame is shown in Figure 4. Symbol r represent the distance between upper platform and upper joints, symbol li is the length of each motor for, the angle between the base frame and the motors showed by symbol \( \theta_i \), it is fixed to 70 degrees. Symbol X and u is the center point of base and upper platform, respectively.

Figure 4

A fixed coordinate frame was established in the base naming x, y z. Coordinate of the points A1, A2, and A3 with respect to this fixed frame are:

\[
A_1 = \begin{bmatrix} R & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -1/2R & \sqrt{3}/2R & 0 \\ \sqrt{3}/2R & -1/2R & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad A_3 = \begin{bmatrix} -1/2R & \sqrt{3}/2R & 0 \\ -\sqrt{3}/2R & -1/2R & 0 \\ 0 & 0 & 1 \end{bmatrix}
\] (1)

\[
b_1 = \begin{bmatrix} r \\ 0 \\ 0 \end{bmatrix}, \quad b_2 = \begin{bmatrix} -1/2r \\ \sqrt{3}/2r \\ 0 \end{bmatrix}, \quad b_3 = \begin{bmatrix} -1/2r \\ -\sqrt{3}/2r \\ 0 \end{bmatrix}
\] (2)

End effector frame ‘u’ can be express in fixed base frame by using Euler matrix roll, pitch, and yaw angles. Then coordinates of the point \( b_1 \), \( b_2 \), and \( b_3 \) can express in fixed frame by using equation 4.

\[
T = \begin{bmatrix} C_\alpha C_\beta & C_\alpha S_\beta S_\gamma - S_\alpha C_\gamma & C_\alpha S_\beta C_\gamma + S_\alpha S_\gamma & X_u \\ S_\alpha C_\beta & S_\alpha S_\beta S_\gamma + C_\alpha C_\gamma & S_\alpha S_\beta C_\gamma - C_\alpha S_\gamma & X_u \\ -S_\beta & -\sqrt{3}/2r & C_\beta S_\gamma & Y_u \\ 0 & 0 & C_\beta C_\gamma & Z_u \\ 0 & 0 & 1 & 1 \end{bmatrix}
\] (3)
\[
\begin{bmatrix} B_1 \end{bmatrix} = [T] \cdot \begin{bmatrix} b_i \end{bmatrix}
\]  
\[B_1 = \begin{bmatrix} r.C_{\alpha}C_{\beta} + X_u \\ r.S_{\alpha}C_{\beta} + Y_u \\ -r.S_{\beta} + Z_u \end{bmatrix}
\]

\[
B_2 = \begin{bmatrix}
-\frac{r.C_{\alpha}C_{\beta} + \sqrt{3}.r.(C_{\alpha}S_{\beta}.S_{\gamma} - S_{\alpha}.C_{\gamma})}{2} + X_u \\
-\frac{r.S_{\alpha}C_{\beta} + \sqrt{3}.r.(S_{\alpha}.S_{\beta}.S_{\gamma} + C_{\alpha}.C_{\gamma})}{2} + Y_u \\
\frac{r.S_{\beta} + \sqrt{3}.r.C_{\alpha}.S_{\gamma}}{2} + Z_u
\end{bmatrix}
\]

\[
B_3 = \begin{bmatrix}
-\frac{r.C_{\alpha}C_{\beta} - \sqrt{3}.r.(C_{\alpha}S_{\beta}.S_{\gamma} - S_{\alpha}.C_{\gamma})}{2} + X_u \\
-\frac{r.S_{\alpha}C_{\beta} - \sqrt{3}.r.(S_{\alpha}.S_{\beta}.S_{\gamma} + C_{\alpha}.C_{\gamma})}{2} + Y_u \\
\frac{r.S_{\beta} - \sqrt{3}.r.C_{\alpha}.S_{\gamma}}{2} + Z_u
\end{bmatrix}
\]

Where symbols c and s represent cosine and sine functions, respectively. The motor link position imposed constrained equation to the system when \( y = 0 \), \( y = -\sqrt{3}.x \) and \( y = \sqrt{3}.x \) planes, shown in Figure 6a.

Figure 5

\[
y = 0 \rightarrow r.S_{\alpha}C_{\beta} + Y_U = 0
\]
\[
y = -\sqrt{3}.x \rightarrow \frac{\sqrt{3}.r.(S_{\alpha}.S_{\beta}.S_{\gamma} + C_{\alpha}.C_{\gamma}) - r.S_{\alpha}C_{\beta} + 2Y_U}{2} = \ldots
\]
\[
-\sqrt{3} \left( \frac{-r.C_{\alpha}C_{\beta} + \sqrt{3}.r.(C_{\alpha}S_{\beta}.S_{\gamma} - S_{\alpha}.C_{\gamma}) + 2X_U}{2} \right)
\]
\[
y = \sqrt{3}.x \rightarrow \frac{-r.S_{\alpha}C_{\beta} + \sqrt{3}.r.(S_{\alpha}.S_{\beta}.S_{\gamma} + C_{\alpha}.C_{\gamma})}{2} + Y_U = \ldots
\]
\[
+\sqrt{3} \left( \frac{-r.C_{\alpha}C_{\beta} - \sqrt{3}.r.(C_{\alpha}S_{\beta}.S_{\gamma} - S_{\alpha}.C_{\gamma})}{2} + X_U \right)
\]

By adding and subtracting equation 9 and 10 each other respectively equation 11 and 12 can be obtained.

\[
S_{\alpha}C_{\beta} = C_{\alpha}S_{\beta}.S_{\gamma} - S_{\alpha}.C_{\gamma}
\]

\[
X_U = \frac{r.(C_{\alpha}C_{\beta} - S_{\alpha}.S_{\beta}.S_{\gamma} - C_{\alpha}.C_{\gamma})}{2}
\]

Equation 11 is satisfied when \( \alpha + \gamma = n.\pi \) but only \( n = 0 \) is physically making sense so constraint equations become,

\[
\alpha + \gamma = 0
\]

\[
X_U = \frac{-r.(1 - C_{\beta}^2)C_{2\alpha}}{2R}
\]
To find dynamic equation, closed loop equation and link lengths are redefined by using unit vector as,

\[ L_1 = \sqrt{(B_1x - A_1x)^2 + (B_1y - A_1y)^2 + (B_1z - A_1z)^2} = \sqrt{(r.C_\alpha.C_\beta + X_U - R)^2 + (r.S_\alpha.C_\beta + Y_U)^2 + (-r.S_\beta + Z_U)^2} \] (16)

\[ L_2 = \sqrt{(B_2x - A_2x)^2 + (B_2y - A_2y)^2 + (B_2z - A_2z)^2} = \sqrt{(r.C_\alpha.C_\beta + \sqrt{3}.r.(C_\alpha.S_\beta.S_\gamma - S_\alpha.C_\gamma) + X_U + \frac{R}{2})^2 + (r.S_\alpha.C_\beta + \sqrt{3}.r.(S_\alpha.S_\beta.S_\gamma + C_\alpha.C_\gamma) + Y_U - \frac{\sqrt{3}R}{2})^2 + (r.S_\beta + \sqrt{3}.r.(C_\beta.S_\gamma) + Z_U)^2} \] (17)

\[ L_3 = \sqrt{(B_3x - A_3x)^2 + (B_3y - A_3y)^2 + (B_3z - A_3z)^2} = \sqrt{(r.C_\alpha.C_\beta - \sqrt{3}.r.(C_\alpha.S_\beta.S_\gamma - S_\alpha.C_\gamma) + X_U + \frac{R}{2})^2 + (r.S_\alpha.C_\beta - \sqrt{3}.r.(S_\alpha.S_\beta.S_\gamma + C_\alpha.C_\gamma) + Y_U + \frac{\sqrt{3}R}{2})^2 + (r.S_\beta + \sqrt{3}.r.(C_\beta.S_\gamma) + Z_U)^2} \] (18)

Coordinate of each linear motor,

\[ X_{u1} = R - l_1 \cos(\theta_1), \quad Y_{u1} = 0, \quad Z_{u1} = l_1 \sin(\theta_1) \] (19)

\[ X_{u2} = \frac{-R + l_2 \cos(\theta_2)}{2}, \quad Y_{u2} = \sqrt{3(R - l_2 \cos(\theta_2))}, \quad Z_{u2} = l_2 \sin(\theta_2) \] (20)

\[ X_{u3} = \frac{-R + l_3 \cos(\theta_3)}{2}, \quad Y_{u3} = \sqrt{3(-R + l_3 \cos(\theta_3))}, \quad Z_{u3} = l_3 \sin(\theta_3) \] (21)

Since three motors placed at equal distance, coordinate of platform with respect to base frame can be found as,

\[ X_c = \frac{X_{u1} + X_{u2} + X_{u3}}{3}, \quad Y_c = \frac{Y_{u1} + Y_{u2} + Y_{u3}}{3}, \quad Z_c = \frac{Z_{u1} + Z_{u2} + Z_{u3}}{3} \] (22)

2.2.2 Dynamic Analysis of the Manipulator

The general form of dynamic equation is,

\[ M(X) \dot{\ddot{X}} + C(X, \dot{X}) + G = F \] (23)

To find dynamic equation, closed loop equation and link lengths are redefined by using unit vector \((\hat{s}_i)\) along motor direction.
\[ X_c = a_i + l_i \hat{s}_i - B_i \]  
\[ L_i = \| X_c + B_i - a_i \|_2 \]  
where,
\[ \hat{s}_i = \frac{X_c + B_i - a_i}{l_i} \]  

An intermediate variable \( x_i \) is defined as position of the \( B_i \) points to make analysis easy. This variable can be express two different ways and shown in (26),
\[ x_i = X_c + B_i \]  
\[ x_i = a_i + l_i \hat{s}_i \]  

By differentiation equation 27 and 28, velocities of intermediate variable can be found as,
\[ \dot{x}_i = \dot{X}_c + w_i \times B_i \]  
\[ \dot{x}_i = a_i + l_i \hat{s}_i \]  

where \( w_i \) represent angular velocity of intermediate variable \( x_i \). Again, by differentiation equation 29 and 30, acceleration of intermediate variable can be found as,
\[ \ddot{x}_i = \ddot{X}_c + w_i \times B_i + w_i \times (w_i \times B_i) \]  
\[ \ddot{x}_i = \ddot{X}_c + w_i \times B_i + l_i \dot{w}_i \times \hat{s}_i + l_i \dot{w}_i \times \dot{s}_i + \dot{l}_i w_i \times \hat{s}_i + \dot{l}_i \dot{w}_i \times \hat{s}_i \]  

Then by applying dot product between equation 29 and \( \hat{s}_i \),
\[ l_i = \dot{x}_i \hat{s}_i = [\dot{X}_c + w_i \times B_i]^T \hat{s}_i \]  

Applying cross product procedure in equation 29 and 30 to \( \hat{s}_i \) yield,
\[ w_i = \frac{\hat{s}_i \times \dot{x}_i}{l_i} = \frac{\hat{s}_i \times (\dot{X}_c + w_i \times B_i)}{l_i} \]  

In order to make calculations easier, dynamic analysis of the motors and moving platforms were done separately and later combined with the Jacobian matrix.

### 2.2.2.1 Dynamic Analysis of Actuators

Linear motors were analyzed by dividing it into two parts. The first is the non-moving piston part, the second is the stroke part that can move to change the length of the motor.

Symbol \( m_{i1} \) and \( c_{i1} \) represent mass and half length of the piston part, respectively. Whereas symbol \( m_{i2} \) and \( c_{i2} \) represent mass and half length of the stroke part, respectively.
\[ c_{i1} = a_i + c_{i1} \hat{s}_i \]  
\[ c_{i2} = a_i + (l_i - c_{i2}) \hat{s}_i \]
Time derivative of equation 35 and 36 yields velocities of piston and stroke part,

\[ v_{i1}^2 = c_{i1} \left( w_i \times \hat{s}_i \right) \] (37)

\[ v_{i2}^2 = \hat{l}_i \hat{s}_i + (l_i - c_{i2}) \left( w_i \times \hat{s}_i \right) \] (38)

Again, by taking time derivative of equation 37 and 38, acceleration of piston and stroke part can be found as,

\[ a_{i1}^2 = c_{i1} \left( \dot{w}_i \times \hat{s}_i - \left| w_i \right|^2 \hat{s}_i \right) \] (39)

\[ a_{i2}^2 = \hat{l}_i \hat{s}_i + (l_i - c_{i2}) \left( w_i \times \hat{s}_i - \left| w_i \right|^2 \hat{s}_i \right) + 2 \hat{l}_i \left( w_i \times \hat{s}_i \right) \] (40)

The skew-symmetric matrix method is used to calculate the equations more easily. The skew-symmetric matrix form of a vector 'a' is represented by the symbol 'S (a)'. Equations using cross product are reconstructed using a skew symmetric matrix.

\[ w_i = \frac{S \left( \hat{s}_i \right) \dot{x}_i}{l_i} \] (41)

\[ \ddot{w}_i = \frac{S \left( \hat{s}_i \right) \dot{x}_i - 2l_i \dot{w}_i}{l_i} \] (42)

\[ \ddot{v}_{i1} = \frac{-c_{i1}}{l_i} \left( S \left( \hat{s}_i \right) \dot{x}_i \right) \] (43)

\[ \ddot{v}_{i2} = \left( \frac{l_i - c_{i2}}{l_i} S \left( \hat{s}_i \right) \left( \hat{s}_i \right) \right) \dot{x}_i \] (44)

Dynamic equation of each limb,

\[ M_i \ddot{x}_i + C_i \dot{x}_i + G_i = F_i \] (45)

Kinetic of the linear motor,

\[ K_i = \frac{1}{2} x_i^T M_i x_i = \frac{1}{2} v_{i1}^T m_{i1} v_{i1} + \frac{1}{2} v_{i2}^T m_{i2} v_{i2} + \frac{1}{2} w_i^T (I_{c1} + I_{c2}) \ddot{w}_i \] (46)

Where \( I_{c1} \) and \( I_{c2} \) represent the moment of inertia of piston and stroke part, respectively. By substituting above equations and simplifying,

\[ K_i = \frac{1}{2} x_i^T \left[ \frac{-S \left( \hat{s}_i \right) \left( I_{c1} + I_{c2} \right) S \left( \hat{s}_i \right)}{l_i^2} + \left( m_{i1} c_{i1}^2 + m_{i2} (l_i - c_{i2})^2 \right) S \left( \hat{s}_i \right)^2 + m_{i2} \hat{s}_i \hat{s}_i^T \right] \dot{x}_i \] (47)

\[ M_i = \frac{-S \left( \hat{s}_i \right) \left( I_{c1} + I_{c2} \right) S \left( \hat{s}_i \right)}{l_i^2} + \left( m_{i1} c_{i1}^2 + m_{i2} (l_i - c_{i2})^2 \right) S \left( \hat{s}_i \right)^2 + m_{i2} \hat{s}_i \hat{s}_i^T \] (48)

Potential energy of the linear motor,

\[ P_i = -g^T \left( m_{i1} c_{i1} \hat{s}_i + m_{i2} (l_i - c_{i2}) \hat{s}_i \right) \] (49)
where $g$ is gravity constant, $g = [0,0,9.8]$.

$$G_i = \frac{\partial P_i}{\partial x_i} = \left[ \frac{m_i c_{l1}^2 + m_i (l_i - c_{l2})^2}{l_i} S(\hat{s}_i)^2 - m_i \ddot{s}_i \dot{s}_i^T \right] g$$ (50)

$$C_i x_i = M_i \ddot{x}_i - \frac{\partial \left( x_i^T M_i \dot{x}_i \right)}{2 \partial x_i}$$ (51)

$$C_i = \frac{-m_i c_{l2} \hat{s}_i x_i^T S(\hat{s}_i)^2}{l_i^2} - \frac{w_i \dot{s}_i^T (I_{c1} + I_{c2}) S(\hat{s}_i)}{l_i^2} \delta$$

$$\ldots + \frac{2i}{l_i^3} \left( \frac{m_i c_{l1}^2 + m_i (l_i - c_{l2})^2 - m_i l_i (l_i - c_{l2})}{l_i} S(\hat{s}_i)^2 + (\hat{s}_i) (I_{c1} + I_{c2}) \right) (\hat{s}_i)$$ (52)

### 2.2.2.2 Dynamic Analysis of Moving Platform

Dynamic equation of moving platform,

$$M_p \left( X \right) \ddot{X} + C_p \left( X, \dot{X} \right) + G_p = F_p$$ (53)

where $X = [x; y; z; \alpha; \beta; \gamma]$ and $\dot{X} = [\dot{x}; \dot{y}; \dot{z}; \dot{\alpha}; \dot{\beta}; \dot{\gamma}]$. These vectors represent position and velocity level variable of the moving platform with respect to base frame. However, while finding kinematic equations, angle changes were expressed according to the fixed frame. The ‘$T_{\text{reverse}}$’ matrix used to express these variables to its own frame and derivative of this symbol is represented with ‘$T_{\text{reverse}}$’

$$T_{\text{reverse}} = R_z(\gamma)^T R_x(\alpha)^T R_z(\beta)^T = \begin{bmatrix} C_\gamma & C_\alpha S_\gamma & C_\alpha S_\beta C_\gamma & C_\alpha S_\beta S_\gamma - C_\alpha S_\beta C_\gamma & -S_\alpha & S_\alpha S_\beta C_\gamma & S_\alpha S_\beta S_\gamma - C_\alpha S_\beta C_\gamma \alpha \\ -S_\gamma & C_\alpha C_\gamma & C_\alpha S_\beta C_\gamma & C_\alpha S_\beta S_\gamma - C_\alpha S_\beta C_\gamma & -S_\alpha & S_\alpha S_\beta C_\gamma & S_\alpha S_\beta S_\gamma - C_\alpha S_\beta C_\gamma \beta \\ 0 & S_\alpha & -S_\alpha & S_\alpha S_\beta C_\gamma & S_\alpha S_\beta S_\gamma - C_\alpha S_\beta C_\gamma \gamma \end{bmatrix}$$ (54)

$$w = T_{\text{reverse}} \cdot \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix} + T_{\text{reverse}} \cdot \begin{bmatrix} \ddot{\alpha} \\ \ddot{\beta} \\ \ddot{\gamma} \end{bmatrix}$$ (55)

$$\dot{w} = T_{\text{reverse}} \cdot \begin{bmatrix} \ddot{\alpha} \\ \ddot{\beta} \\ \ddot{\gamma} \end{bmatrix}$$ (56)

$$M_p = \begin{bmatrix} m_p I_{3x3} & 0 \\ 0 & T_{\text{reverse}} \cdot T_{p} \cdot T_{\text{reverse}} \end{bmatrix}$$ (57)

$$C_p = \begin{bmatrix} 0 & 0 \\ 0 & T_{\text{reverse}} \cdot T_{p} \cdot T_{\text{reverse}} + T_{\text{reverse}} \cdot S(w) I_{p} \cdot T_{\text{reverse}} \end{bmatrix}$$ (58)

$$G_p = \begin{bmatrix} -m_p g \\ 0 \end{bmatrix}$$ (59)
2.2.2.3 Dynamic Analysis of the Overall System

The final dynamic equation is obtained by converting the intermediate variable \((x_i)\) to the task space variable \((X)\). This transformation can be done with the Jacobian matrix.

\[
J_i = \begin{bmatrix} I_{3x3} & -S(B_i) \cr S(B_i) & I_{3x3} \end{bmatrix}
\]

(60)

\[
M_{all} = M_p + \sum_{i=1}^{3} J_i^T \cdot M_i \cdot J_i
\]

(61)

\[
C_{all} = C_p + \sum_{i=1}^{3} (J_i^T \cdot M_i \cdot J_i + J_i^T \cdot C_i \cdot J_i)
\]

(62)

\[
G_{all} = G_p + \sum_{i=1}^{3} J_i^T \cdot G_i
\]

(63)

Final dynamic equation,

\[
M_{all} (X) \cdot \ddot{X} + C_{all} (X, \dot{X}) + G_{all} = F_{\text{system}}
\]

(64)

2.2.2.4 Simulation of the Kinematics and Dynamics of the Robot

The kinematic and dynamic simulations of the system were transferred to the Simulink program and the accuracy of the equations was tested as shown in Figure 6 algorithm.

First, three of the six reference rotation and orientation values were generated as references. Then constraint equations 13,14, and 15 were used to find the remaining variables and by taking their derivatives, velocity and acceleration level references were found. The task space reference variables have been converted to joint space variables with inverse kinematics equations. After that forward kinematics equation was solved and converted into force and moment values in forward dynamic by equations 61,62, and 63. Finally inverse dynamic analysis computes the trajectory of end effector (position, velocity, and acceleration) from required joint actuator torques and forces. Since it is in a closed loop structure, it minimizes the error in the calculation of rotation and orientation values. The comparison of the values obtained in the simulation results with the reference position and rotation values and the RMS error graph are shown in Figure 7a, 7b, and 7c, respectively.

2.3 Upper and Lower Platform Design of the Rehabilitation Robot

In the upper part of the device, four load cells are used for each foot in order to receive data independently from different regions located on the sole of the foot. Placements of load cell points are determined as the parts where the pressure data are the most intense at the base of the foot as can be seen in table 1. However, the length of the feet varies from person to person so that coordinates of these points change to overcome this problem, the heel of the foot is accepted as a fixed point and a rail...
system is placed under other load cells. By this customization, the most appropriate data will be read. Also, the moving capacity of the rail systems was decided by using the average anthropometric data of people as can be seen in table 2 (Gordon, 1988; Openshaw et al., 2006; ANT, 2021). The sudden force change that occurs on the sole of the foot applied by the patient to the changes that occur during the virtual reality game will be used to determine the reaction time. Three load cells on the lower platform are placed to form a triangle and the pressure and mass center of the person are calculated with mathematical manipulations.

Table 1.
Table 2.

2.3.1 Center of Mass

The lower and upper platforms are produced symmetrically. Therefore, the center point created without applying weight is the direct starting point (0,0). When weights imposed to the system, equations 65 and 65 are used to calculate the center point.

\[
COM_x = \frac{weight_9 - r \cdot \cos(30^\circ) \cdot weight_{10} + r \cdot \cos(30^\circ) \cdot weight_{11}}{weight_9 + weight_{10} + weight_{11}}
\]

\[
COM_y = \frac{r \cdot weight_9 - r \cdot \sin(30^\circ) \cdot weight_{10} + r \cdot \sin(30^\circ) \cdot weight_{11}}{weight_9 + weight_{10} + weight_{11}}
\]

2.3.2 Center of Mass

Center of pressure points in static condition can be calculated by equation 67.

\[
COP = \frac{M_x - ((3cm)F_y)}{F_z}
\]

Where Mx is the moment in x axis and Fy and Fz are reaction force in y and z axis, respectively. The height of the moving platform is equal to 6 cm so distance from origin of base to ground equal to 3 cm

3 RESULTS

3.1 Experimental Evaluation of the System Performance

Closed-loop control is a process that provides feedback from operating mechanisms and is used to stabilize the system. In robotic applications, the control of the robot changes the plant of the manipulator and determines its behavior by finding the appropriate mathematical model. Since there will always be an external disturbance in real-time systems, the designed controller optimizes the system according to all parameters. In this study, proportional-integral-derivative (PID) controller type was used. All 3 DC motors are controlled and tuned separately with a closed-loop controller. The feedback information of each motor is obtained from the linear positioning schedules which are mounted next to it. The real-time modeling of the system was done through the MATLAB/Simulink program. Step and sine performance of the system is shown in Figure 9a and Figure 9b, respectively. The step signal position tracking accuracy of the first, second, and third motor is 94.6%, 96.86%, 96.8%, respectively. Additionally, the sine wave position tracking accuracy of the first, second, and third motor is 89.8%, 88.8%, 84.3%, respectively.

Figure 9
3.2 Evaluation of Balance Skills and Reaction Time Measurement

Healthy load distribution in the sole of the foot depends on the ability of the foot to perform its stabilization and mobilization tasks together. In order to determine the effectiveness of the load cells used in the study, loads suitable for the load distribution of the human foot was created (Price, 2014). Then, the platform was tested in static and dynamic conditions using these designed loads. There are 8 load cells on the upper platform and their maximum load capacity is 10 Kg. Likewise, the load capacity of lower platforms’ load cells is 40 kg. These values are determined by average human weights and pressure disturbance in the sole of the foot.

The static evaluation conducted in three cases. In the first case, the prepared loads are placed separately on the left (Region 1,2,3, and 4) and right (Region 5,6,7, and 8) parts while the platform is placed at a fixed level. In the second case, some of the prepared loads were positioned in front of the platform so that the pressure ratios in regions 1,2,5, and 6 were increased. Finally, loads were transferred to the rear of the platform, this cause the pressure ratio in regions 4 and 8 to increase. Each case was continued for 2 minutes and 200 data values were recorded and mean values of the experiment are given in Table 3. The aim of this experiment is to test the prepared loads and understand whether it can mimic the load distribution of the feet in different conditions.

Table 3.

The dynamic evaluation was done in four-step the prepared loads were placed on the platform and after waiting for 10 seconds, the plantar flexion movement was applied first. Then follow by dorsiflexion and inversion movement and finally, the eversion movement was performed each step continued for 1 minute and 100 data values were recorded. Load and Center of mass distribution invariant condition and region are given in Figure [10]a. and Figure [10]b, respectively. The purpose of this experiment is to understand how loads are distributed in a dynamic environment.

Figure [10]

4 DISCUSSION

Multiple Sclerosis (MS) is one of the most common chronic neurological diseases and directly affects the brain and central nervous system. It was stated that MS patients showed signs of impaired balance and had a history of falls but through physical therapy symptoms and the quality of daily activities can improve. Rehabilitation therapy for MS patients typically includes cardiovascular strength and balance training, and numerous clinical studies have demonstrated the benefits of these exercise interventions. Therapy is usually done in two main types, conventional rehabilitation, and robotic rehabilitation. Worldwide research in robotic rehabilitation has increased significantly in recent years both as an industrial product and as a research project. It was emphasized that robotic devices have a positive effect on the patient in terms of precise measurement of kinematic and dynamic parameters and provide objective evaluations that complement existing clinical environment treatments. Nevertheless, existing robot devices have been criticized for taking up a lot of space in clinical settings, limited accessibility, and working with the same difficulty level in all patients. In the studies conducted so far, there is no medical robotic device that allows determining the reaction times of the patients against the actions and aimed at lower extremity-focused strength balance training. Also, due to the sparseness of studies and the scarcity of physical therapists, the optimal duration and type of treatment in MS patients has not been determined.
This study includes platform design and virtual reality specific to MS patients. When performing situations of instability from different angles, the patient’s reaction time, the center of mass, and pressure will be determined, and progress will be observed in the patient’s adjusted postural adjustment. It is aimed to perform the daily activities of the patients more consistently and to perform fewer falling actions. Moreover, it can objectively evaluate patient performance and present the recovery and follow-up process with quantitative variables. Besides, it uses treatment-based, task-oriented virtual reality games to increase the patient’s interest and provide continuity in treatment. The patient’s reactions will be evaluated, and the movements of the platform and the speed and difficulty of the virtual reality game will be adjusted accordingly. The freedom of movement of the platform in three-dimensional space encourages all body muscles to work, especially the muscle groups in the back, waist, and lower extremities.

The 3-DOF Platform consists of different sub-parts. In the upper platform, eight load cells will be used in different areas, with these, the pressure and reaction time on the sole of the foot can be calculated. On the lower platform, three load cells are placed to form an equilateral triangle, and these used in the calculation of the center of mass. Each load cell transmits data to the Arduino microprocessor in real-time after connecting to the HX711 amplifier, which has an analog-to-digital converter. The configuration of the platform in space is carried out by three linear motors placed under the platform. Linear position schedules are used to detect and control the position of linear motors.

The most important design criterion of the system is production in accordance with the ankle parameters of the human body. These parameters are used in the mechanical restraint of the system so that the patient is not harmed. For example, the maximum angle that the joint connecting the motors to the moving platform can make is limited to 18 degrees, a cylindric rod is placed in the middle to support the weight of the system, and a support environment will be placed around the system in the rehabilitation application as shown in Figure 2a. In addition, the power of the each linear motors was selected as 900 because it is bearing the average human weight and the weight of the moving platform. Placement of the motors is done at equilateral triangle shape therefore the same amount of change is provided in each axis. Furthermore, the result of FEA has been proven that the platforms do not show deformation when 1000N is applied to the system.

Kinematics equations for the 3-Dof robotic platform are driven to analyze the motion profile of the system. The equations were obtained analytically by using the vector loop technique between the link parameters and the orientation/position of the moving platform. Dynamic analysis is derived to examine the torque and force of the robotic platform. The mathematical model of the robotic platform is defined by kinematic and dynamic analysis which is called the plant of the system. Motor and disturbances can be controlled by using this modeling. The accuracy of the mathematical model was tested in the MATLAB/Simulink and shown in Figure 7. The minimum accuracy percentage is 96.2975% and these values prove the correctness of the plant. Step and sine signals are given as reference to determine the accuracy of PID parameters and system modeling. The serial port communication between the workstation and the hardware is executed with the Arduino microprocessor and VNH2SP30 motor drivers, but the Arduino processes the data with a delay, and the motor itself is under influence of a very large gravity force and must be overcome by static and kinetic friction force. Due to the reasons mentioned above, delay and noise reading have occurred in the real-time control of the robotic platform. The minimum accuracy percentage of step and sine responses are 94.3% and 84.3%, respectively. These values will be improved in future studies by using a data acquisition card, which can process data without delay.

The foot carries the body weight and provides a secure posture by spreading the weight on the floor. In standing posture, 50% of the body weight is transferred to the heel, while the remaining 50% is transferred
to the toes and metatarsals. In order to test the usability of the load cells on the upper and lower platforms, weights that mimic the load distribution mentioned above were designed. The evaluation was made under two sub-headings. The first one has done in a static state, it was checked whether the design load imitates the foot distribution. As seen in Table 3, case 1, the designed loads mimic the distribution of the sole of the foot. Besides, as seen in cases 2 and 3, the load cells are able to follow the change in weight distribution. The second situation was performed in the dynamic state, where the movements of the ankle dorsiflexion, plantar flexion, eversion and inversion were applied. Pressure distributions resulting from these movements and the calculation of the center point are shown in Figure [I0]

**AUTHOR CONTRIBUTIONS**

EH found the research contribution of the study. TE implemented the kinematic and dynamic analyses and simulation of the 3 DOF parallel manipulator. Both authors designed the experiments and equally efforted to discuss the results. TE implemented real-time experiments of the robotic platform and EH finalized overall paper editing and scientific representation.

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Figure 1. (A) Prototype and (B) Illustrative representation of proposed 3-DOF platform

Figure 2. Illustrative representation of virtual reality (A) system set-up and (B) game environment

Table 1. Average footpad pressure ratios

|       | Toes  | Metatarsals | Middle Foot | Heel of Foot |
|-------|-------|-------------|-------------|--------------|
| Right | 3.54  | 28.24       | 0.97        | 12.42        |
| Left  | 3.16  | 23.85       | 1.19        | 12.51        |

Table 2. Anthropometric Values

|       | Women | Men  |
|-------|-------|------|
| Height(cm) | 162.94 | 175.58 |
| Weight(Kg)  | 67.12  | 74.74 |
| Foot Length(cm) | 23.62  | 26.15 |
| Foot Width(cm)  | 9.17   | 10.28 |
Figure 3. Von Mises result under the static nodal stress for (A) Upper platform, (B) Lower platform, and (C) Linear motor

Figure 4. Representation of Frame Placement
Figure 5. Illustrative representation of (A) constrain planes and (B) closed loop

Figure 6. Representation of the Simulink environment

Figure 7. Comparison between reference and simulation result of (A) position and (B) rotation values and (C) RMS error of simulation test
Figure 8. Illustration of the load cell placement on (A) Upper and (B) Lower platform

Figure 9. (A) Step and (B) Sine performance of the system

Table 3. Evaluation of Load Cell in Static Condition

| Pressure (N/cm²) | Case 1     | Case 2     | Case 3     |
|-----------------|------------|------------|------------|
| Region 1        | 49.02±0.086| 81.52±0.872| 19.97±0.062|
| Region 2        | 43.51±0.066| 83.18±1.872| 28.53±0.186|
| Region 3        | 10.67±0.058| 10.54±0.195| 10.39±0.051|
| Region 4        | 130.82±0.102| 64.07±1.028| 163.76±0.041|
| Region 5        | 46.79±0.533| 74.4±0.488  | 26.84±0.443|
| Region 6        | 44.08±0.124| 72.17±0.563| 19.68±0.426|
| Region 7        | 9.56±0.489 | 4.02±0.095 | 3.82±0.223 |
| Region 8        | 133.79±0.241| 65.57±0.172| 159.35±0.858|
Figure 10. Evaluation of (A) Load Cell and (B) Center of Mass in Dynamic Condition