Graphical interactive user interface system for a stationary trainer to perform lower limb rehabilitation tasks

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Abstract. The graphical interactive user interface system of a stationary trainer for performing lower-limb rehabilitation tasks is presented in this article. The stationary trainer considered here for the interactive system development is based on a foot-plate operating system. The foot-plate is an end-effector of a parallel Cartesian manipulator. The interactive system primarily designed for the therapeutic tasks associated with passive range of motion (PROM) of the lower limbs. Further, the interactive system concentrated on the hip and knee joint motion therapies which include flexion/extension of knee and hip as well as abduction/adduction of hip. Various clinically suggested motions along with their working nature are designed in the interactive user interface. The suggested interface would generate the system settings (the various system parameters to be fixed during the real-time training) are generated based on the patient’s physical parameters such as limb length, patient’s weight, height, etc. The interactive simulator of the stationary trainer is demonstrated and verified using computer-based numerical simulations.

1. Introduction

People’s lifestyle has become poor with the increase in ageing population along with the diminishing environment quality. One of the major issues faced by the elderly population today is the dysfunction of the lower limb. The prime cause for the same is accounted by stroke which can culminate in neurological disorders or musculoskeletal malfunctions [1]. According to recent investigations, more than 80 million constitute to stroke survivors in the world [2, 3]. Stroke leaves behind behavioural disfunction as a consequence of cerebral disorder resulting in multiple dysfunctions of which the most common are the limb disorders. The limb disabilities are generally overcome by tedious therapeutic procedures which necessitate skilled physiotherapists. The difficulty of physiotherapists can be reduced with the help of mechanical assistive devices [4]. In this paper, we have developed a graphical interactive user interface system for a stationary trainer to perform lower limb rehabilitation tasks. The mechanical design of this stationary trainer consists of three parallel PRRR serial manipulators connected to the end effector. The stationary trainer considered here for the interactive system development is based on a foot-plate...
operating system. The foot-plate is an end-effector of the parallel Cartesian manipulator.

For each joint, specific range of motion (ROM) for lower limb tasks is suggested by the therapists. The range is chosen based on the patient’s condition like the presence of swelling, pain or stiffness. These tasks can be broadly classified as [5]:

- **Active range-of-motion (AROM):** Therapies are performed without any assistance.
- **Active assistive range-of-motion (AAROM):** Therapist/attendant helps the patient to perform the therapeutic task. This assistance is to support the weaker muscles and not to cause any discomfort to the patient during the procedure.
- **Passive range-of-motion (PROM):** The patient takes no effort in this. the task is completely performed either by the therapist or the equipment itself by moving the joints appropriately.

The interactive system primarily designed for the therapeutic tasks is associated with passive range of motion (PROM) of the lower limbs. Further, the interactive simulator concentrates on joint motion therapies of the hip and knee. The movements include flexion-extension of knee and hip as well as abduction-adduction of hip.

For the stationary trainer here, parallel manipulators are used. These are serial chains forming a closed loop, connecting the moving platform with the fixed base [6]. Here parallel manipulator is used due to its own advantages of higher payload capacity and good precision [7]. In comparison with serial, parallel manipulators posses lower inertia, thereby resulting in higher speed of working [8].

### 2. Mechanical Design and Model

#### 2.1. Conceptual Design

The conceptual design of the stationary trainer is given in our paper [4]. The mechanism has a 3-P_RRR parallel manipulator connected to the foot plate as shown in figure 1(a). There is a stationary fixed frame on which the Cartesian manipulator is attached. Each arm of the manipulator has active prismatic joints which slides along the guideways in the \( x, y \) and \( z \) axes. Each P joint is attached to RRR serial kinematic chain. All three arms are joined to the end-effector foot-plate where the load will be acting.

#### 2.2. Kinematic Model

Since the R (revolute) joints in the manipulator are passive, the configurational space variables of the mechanism will include only the motion of the active P (linear) joints, i.e \( r_1, r_2, r_3 \) as shown in figure 1(b). The inverse (indirect) kinematics gives the configuration of the mechanism with in task space variables with respect to the position and orientation of the end-effector.

\[
\mathbf{\xi} = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix} = \begin{bmatrix} P_x - a_x \\ P_y - a_y \\ P_z \end{bmatrix}
\]

where, \( \mathbf{\xi} \) represents the vector of the joint space displacements. \( a_x \) and \( a_y \) are the distances from the adjacent R joints to the end-effector position in \( x \) and \( y \) axes directions respectively. \( P_x, P_y \) and \( P_z \) represent the end-effector point location with respect to base frame in the cartesian coordinates. This itself denotes the end-effector positions. The same has been represented in figure 1(b).
2.3. Dynamic Model
The dynamic model is developed by forming the equation of motion using the Euler-Lagrange formulation, where the lagrangian gives the difference of the total kinetic energy and total potential energy of the manipulator.

Total Potential Energy: \( PE = \sum_{i=1}^{13} m_i g z_i \)

Total Kinetic Energy: \( KE = \frac{1}{2} \sum_{i=1}^{13} \left( m_i (\dot{x}_i^2 + \dot{y}_i^2 + \dot{z}_i^2) + I_i \dot{\theta}_i^2 \right) \)

Lagrangian: \( L = KE - PE \)

\( x_i, y_i, z_i \) give the coordinates of center of mass of the body. Similarly the angular velocity and linear velocities (along each axis) of the center of mass of the linkage are given by \( \dot{\theta}_i \) and \( \dot{x}_i, \dot{y}_i, \dot{z}_i \), respectively. Gravitational acceleration is represented by \( g \). The individual joint forces are given by Lagrangian formulation as

\( f_i = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{r}_i} \right) - \frac{\partial L}{\partial r_i} \)

3. Interactive Simulator
Based on this design of the stationary trainer, a graphical user interactive simulator is developed as an application in MATLAB® as shown in figure 2.

This interactive system primarily focuses on the motion under passive range of motion (PROM). This app allows the user to customize the following features:

- Hip Angle: The user can change the hip angle using a slider provided. The live simulation of the same will occur on the screen and the angle will be displayed in the text box provided.

Figure 1. Mechanical design and kinematic arrangement of the trainer
4. Results and Discussions

Using the interactive simulator developed, the maximum range of motion possible for the manipulator was analyzed.

4.1. Limb interference along sagittal plane

For designing the limb, thigh width(thickness), crus width(thickness) near ankle, thigh height and crus height near ankle are taken as 0.1 m, 0.05 m, 0.2 m and 0.1 m respectively. For analysis, the footplate dimensions are chosen as $a_x = 0.1m$ and $a_y = 0.1m$. The maximum knee angles obtained for various footplate heights for respective hip angles of $0^\circ$, $-30^\circ$ and $45^\circ$ are given in table 1.

It can be seen that, for the initial increase in the footplate length there is significant increase in the maximum knee angle. Thereafter, the increase is not very significant. Beyond maximum angle, the footplate will interfere with the limb motion and obstruct the movement of crus.

All the data presented above are for the manipulator with footplate below the supporting links.
Table 1. Variation of maximum knee angle with footplate height.

| Footplate Height | Maximum Knee Angle for Hip Angle 0° | Hip Angle −30° | Hip Angle 45° |
|------------------|-------------------------------------|----------------|--------------|
| 0.1 m            | −32°                                | −5°            | −75.39°      |
| 0.2 m            | −66.57°                             | −36.87°        | −112.3°      |
| 0.3 m            | −76.18°                             | −46.37°        | −120.6°      |
| 0.4 m            | −79.78°                             | −49.72°        | −124.3°      |

The results show that there is interference along the sagittal plane when the footplate is below the supporting links. But for this manipulator, there was not any interference along the frontal plane. Sagittal plane interference can be avoided by making the footplate above the supporting links.

4.2. Limb interference along frontal plane

The analysis is done for hip angle 0° and knee angle −30°. The plate dimensions used are 0.2 m along X direction and along the Y direction, the length is varied from 0.2 m to 0.5 m. The variation of the maximum frontal (lateral) angle that can be achieved with variation in the length of the footplate is given in table 2, observed with the help of the interactive simulator.

Table 2. Variation of maximum lateral angle with footplate length.

| Footplate Length | Maximum Frontal Angle |
|------------------|-----------------------|
| 0.2 m            | 4.146°                |
| 0.3 m            | 9.024°                |
| 0.4 m            | 13.9°                 |
| 0.5 m            | 18.22°                |

The analysis of interference of the crus in the limb with the supporting links in the frontal plane is done when the footplate is above the links. From observation, there is a linear increase in the maximum frontal limb angle achieved with increase in the footplate length. The movement of the limb in this case is along the frontal (lateral) plane. Hence, the change in hip angle will not differ the results. But, change in knee angle may change the results as the crus is considered to be a sloping region. However, the variation can be safely ignored as the slope is very less. The results show that there is interference along the lateral plane when the footplate is above the supporting links. But for this manipulator, there was not any interference along the sagittal plane.

5. Conclusion

Changing lifestyles have increased the rate of neurological disorders. Stroke has been the most common. A stationary trainer has been designed to perform the therapeutic procedures. In this paper, graphical interactive user interface system for this mechanism has been presented. This interactive simulator is developed as an application with which the maximum range of motion for the manipulator is found out. This interactive simulator is highly useful as knowing the
maximum range of motion is necessary to find any interference of the limb with the links. From the results, it could be seen that there is interference in the sagittal plane when the footplate of the manipulator is below the supporting links and there is interference in the frontal or lateral plane when the footplate is above. There is scope for future work in finding modifications of the manipulator so as to eliminate both the interferences in a single configuration of the manipulator.

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References
[1] Faizura W W, Luqman M, Hafiz O M, Naim M S, Armin S A and Irraivan E 2020 Journal of Physics: Conference Series vol 1532 (IOP Publishing) p 012026
[2] Jiang D, Shi G, Pang Z, Li S and Tian Y 2020 Journal of Physics: Conference Series vol 1622 (IOP Publishing) p 012119
[3] Kurmashev S, Ospanov S, Malik A, Xydas E and Mueller A 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference vol 51807 (American Society of Mechanical Engineers) p V05AT07A058
[4] Mohan S, Sunilkumar P, Rybak L, Malyshev D, Khalapyan S and Nozdracheva A 2020 International Conference on Robotics in Alpe-Adria Danube Region (Springer) pp 345–355
[5] Marek S M, Cramer J T, Fincher A L, Massey L L, Dangelmaier S M, Purlayastha S, Fitz K A and Culbertson J Y 2005 Journal of Athletic Training 40 94
[6] Sunilkumar P, Choudhury R, Mohan S and Rybak L 2020 European Conference on Mechanism Science (Springer) pp 103–111
[7] Briot S, Arakelian V and Guégan S 2009 Mechanism and Machine Theory 44 425–444
[8] Briot S and Bonev I A 2007 Transactions of the Canadian Society for Mechanical Engineering 31 445–455