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A New Sitting-type Lower-Limb Rehabilitation Robot based on a Spatial Parallel Kinematic Machine

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Abstract

This paper proposes a lying/sitting type lower-limb rehabilitation robot based on a three degrees of freedom spatial parallel kinematic manipulator namely “The Orthoglide” along with an actuated rotational degree of freedom at the end-effector for the purpose of lower-limb rehabilitation treatments. This rehabilitation robot is an end-effector/foot-plate based mechanism which controls the ankle-joint movements to assist physiotherapists in performing therapeutic treatments along with a passive orthosis (supporting system). The conceptual and detail design of the rehabilitation device is presented along with its kinematics. Further, the functional validation of the proposed robot in terms of the kinematic motion capabilities to provide physiological motions like knee flexion-extension, hip adduction-abduction and hip flexion-extension are also investigated. The required safety features for the proposed rehabilitation robot in terms of mechanical constraints and non-actuated joints are also discussed.

Keywords: Lower limb rehabilitation robot; Orthoglide; foot-plate based; parallel manipulator; passive orthosis;

1 Introduction

Lower limb treatments using mechanized systems has improved the speed of recovery of patients from the bedridden state [1]. The lower limb impairments are caused by motor nerves dysfunction, which are generally caused by spinal cord injury (SCI), stroke and accidental disability. Continuous physical motion of the impaired limb, known as motor rehabilitation, required for this process [2]. These are done in numerous ways for example with a body weight support (BWS), using supportive orthosis, using foot-plate motion and limb motion in sitting/lying posture. The sitting/lying treatments are appropriate for the bedridden patients. Example of sitting/lying type systems are the ANKUR-LL2 [8], an improved Lambda [6], the Supine [4], Physiotherobot [3], the Lambda [5] and the ANKUR-LL1 [7].

Lower limb mechanisms with high mechanical advantage joints, outfits the system with a self-locking capability, which helps in case of emergency stop [9]. Structures of the mechanisms consist of bulky actuators and system appears dynamically heavy. To avoid such difficulty a passive light-weight orthosis, with no actuators, is used along with joint feedback sensors [6]. Here the orthosis is indirectly controlled.

Rehabilitation devices are generally having motion in sagittal plane[1]. Although many therapies need off-planar movements but complexity of the arrangement and

safety of the patient is major concern. In this direction a device namely Hipbot [10] is designed to give off-planar motions to the lower limbs, when the patient is in lying posture. Still Hipbot is having limitation that it can give adduction-abduction away from the body not towards the body because of physical limitations. To address this issue a new manipulator configuration is proposed. The major difficulty in off-planar movement is movement of the actuator assembly as they are mounted in single plane. So, here we have used a parallel manipulator based mechanism with passive orthosis which can render four degrees of freedom to the lower limb.

The rest of the paper is organized as follows: Section 2 discusses the architecture of the proposed rehabilitation robot and its geometrical aspects. Section 3 describes the system kinematics, Section 4 demonstrates the physiological motion validation of the proposed manipulator and section 5 concludes the paper with safety aspects and scope of future works.

2 Proposed Manipulator's Architecture

The proposed rehabilitation robot shown in Figure 1 consists of a driving mechanism and a passive orthosis. The driving mechanism is made using the concept of a parallel manipulator namely "The Orthoglide" [11]. Instead of an overhead structure a modified version with actuators on ground is taken for usage in rehabilitation purpose. Here three linear joints are placed orthogonally and three links with each leg having configuration PUU is connecting to the end-effector. The orthosis consists of three links corresponding to the thigh, crus and foot of the limb with a vertical hip joint. These three links are joined in series at the hip, knee and ankle positions, with rotary joint. The solid model of the proposed orthosis is shown in Figure 2. The passive orthosis can be seen in Figure 1. Forward kinematics for the passive orthosis is as follows:

$$\begin{aligned}
 x &= \left(L_{thigh} \cos \phi_1 + L_{crus} \cos(\phi_1 - \phi_2) \right) \cos \phi_3 \\
 y &= \left(L_{thigh} \cos \phi_1 + L_{crus} \cos(\phi_1 - \phi_2) \right) \sin \phi_3 \\
 z &= L_{thigh} \sin \phi_1 + L_{crus} \sin(\phi_1 - \phi_2)
 \end{aligned} \tag{1}$$

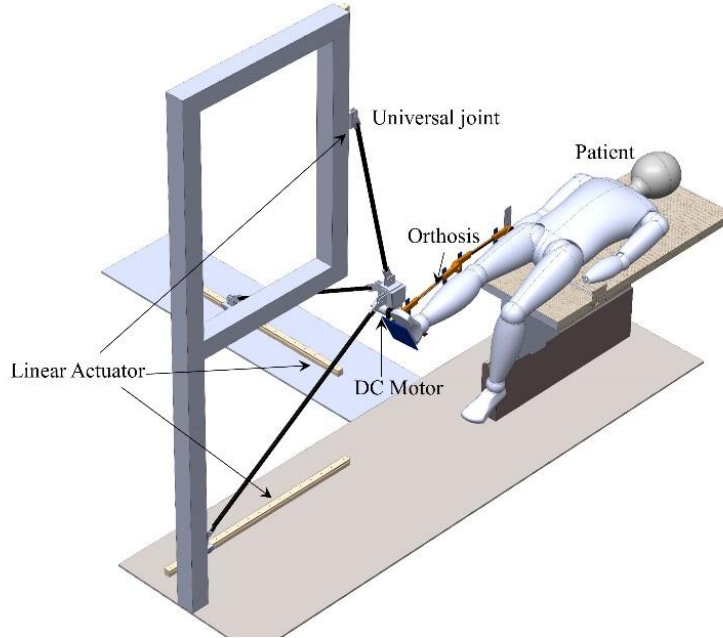


Figure 1: Proposed Lower limb rehabilitation robot

Here ϕ_1 , ϕ_2 and ϕ_3 are the hip flexion-extension, knee flexion-extension and hip adduction-abduction angles, which are shown in Figure 2. L_{thigh} and L_{crus} are the length of the thigh support and crus support. Where (x, y, z) are the coordinate location of the ankle joint. The required workspace based on the physiological motion specifications are plotted and shown in Figure 3. Here the reachable workspace is shown by considering the hip flexion-extension joint as origin. The possible joint movements on the sagittal plane for the human limbs are as: $-30^\circ \leq \phi_1 \leq 60^\circ$, $0^\circ \leq \phi_2 \leq 105^\circ$ and $-15^\circ \leq \phi_3 \leq 15^\circ$. In the Figure 3, $\theta_s = \phi_1 - \phi_2$, shows orientation of the crus link at the ankle joint. Here, the ankle rotation is controlled by an independent actuator which is placed at the ankle joint. the angle requirement for the foot link at the end effector is. $\theta_s + \phi_{ankle}$.

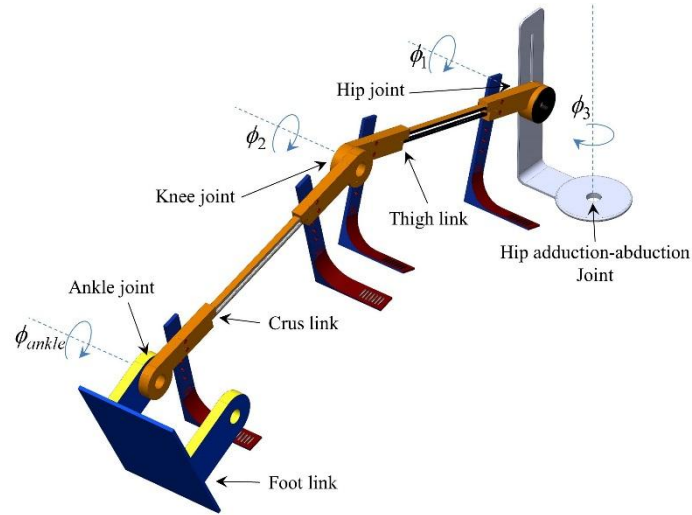


Figure 2: Passive orthosis

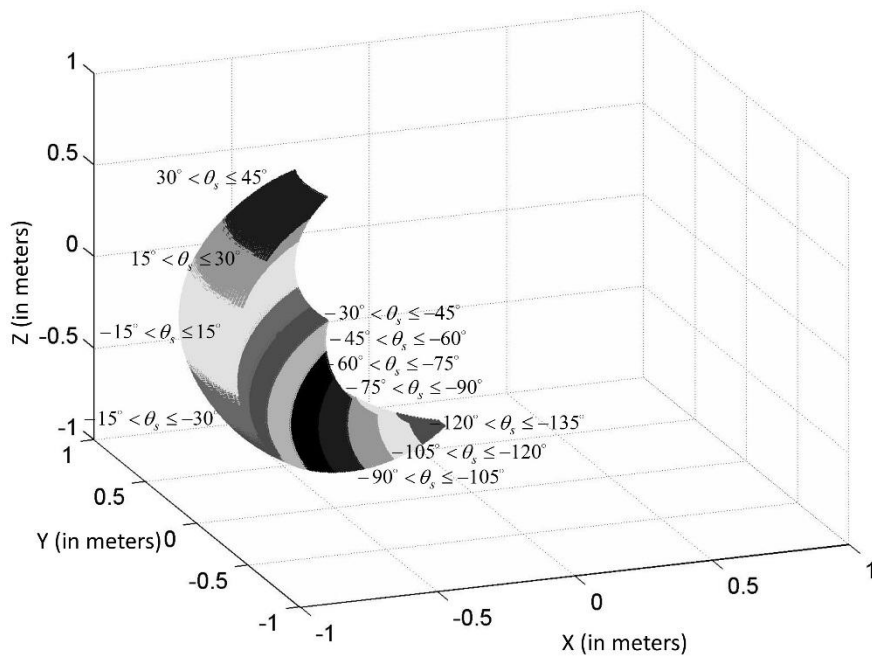


Figure 3: Distribution of the required workspace area for ankle joint

Figure 4 shows the junction end-effector arrangement for the system, where the orthosis ankle joint and Orthoglide's end-effector is connected. The orthosis ankle joint is mounted on a body. This body has a passive vertical rotary joint at the bottom

of the Orthoglide's end-effector's cube. This enable the orthosis not to hinder the hip adduction-abduction motion.

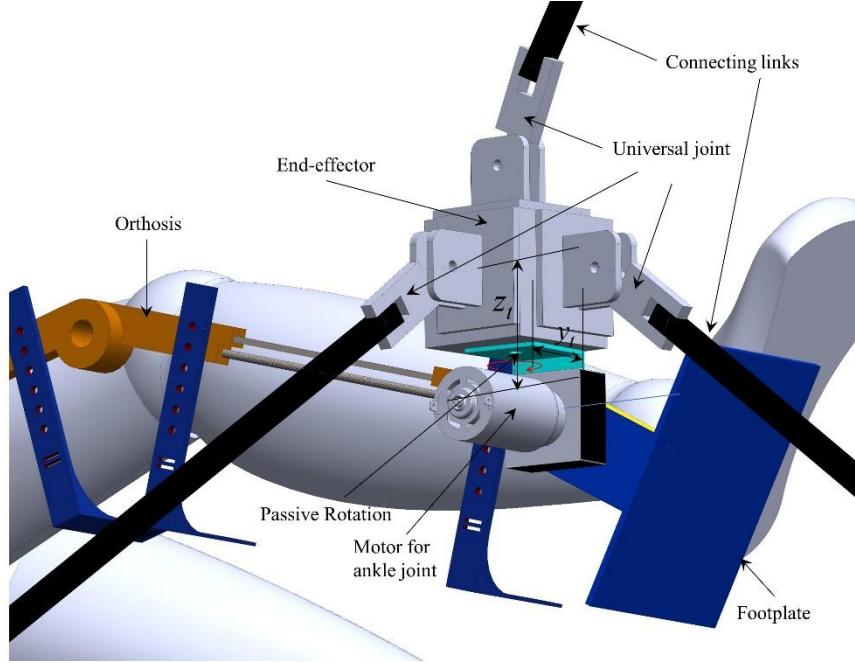


Figure 4: End-Effector orientation arrangement

3 Manipulator Kinematics

For the Orthoglide kinematic solution can be determined by the following relations

$$\begin{aligned} (x - x_1)^2 + y^2 + z^2 &= l^2 \\ x^2 + (y - y_2)^2 + z^2 &= l^2 \\ x^2 + y^2 + (z - z_3)^2 &= l^2 \end{aligned} \quad (2)$$

Here, $x_1 = r_1 - d_1$, $y_2 = r_2 + d_2$ and $z_3 = r_3 + d_3$. Where r_1 , r_2 and r_3 are the joint space variable. Hence our joint space vector consist of $[r_1 \ r_2 \ r_3 \ \theta_{ankle}]^T$ and task space consists of $[\phi_1 \ \phi_2 \ \phi_3 \ \phi_{ankle}]$

Inverse kinematics for the Orthoglide part can be written as follows:

$$\begin{aligned} r_1 &= \sqrt{l^2 - y_o^2 - z_o^2} + x_o + d_1 \\ r_2 &= \sqrt{l^2 - x_o^2 - z_o^2} - y_o - d_2 \\ r_3 &= \sqrt{l^2 - x_o^2 - y_o^2} + z_o - d_3 \end{aligned} \quad (3)$$

Where the x_o , y_o and z_o are the Orthoglide end-effector point.

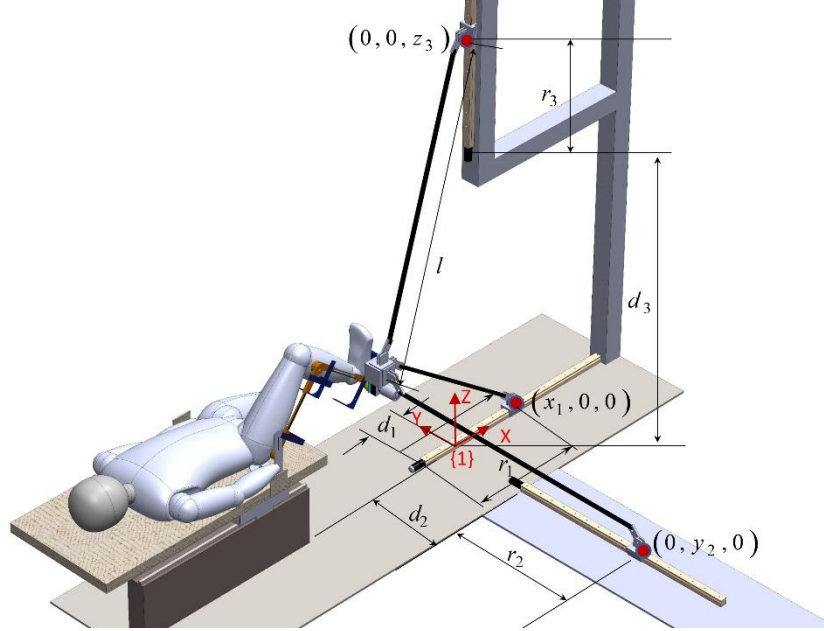


Figure 5: Kinematic parameters of Orthoglide

Kinematics of the orthosis system is shown in eq. (1) relation between the orthosis coordinates to the to the end-effector coordinates of the Orthoglide can be written as

$$\begin{aligned} x_o &= x - p_x - y_t \sin \phi_3 \\ y_o &= y - p_y - y_t \cos \phi_3 \\ z_o &= z + p_z - z_t \end{aligned} \quad (4)$$

By substituting eq. (4) and eq.(1) in eq. (3) we can obtain complete inverse kinematics relation for the assembly. The parameters y_t and z_t are shown in Figure 4. The point (x, y, z) is with respect to (w.r.t.) frame {2}, while (x_o, y_o, z_o) is w.r.t. frame {1}. To bring all the points to one coordinates system linear transformation is applied to the frames the distances $[p_x \ p_y \ p_z]$ are the linear transformation for the coordinates. In motion assembly, the parameters $[r_1 \ r_2 \ r_3] = f(\phi_1, \phi_2, \phi_3)$ while the ankle joint is having independent actuator whose actuation is represented by ϕ_{ankle} which is a function of hip and knee adduction-abduction angle, $\theta_{ankle} = f(\phi_1, \phi_2, \phi_{ankle})$.

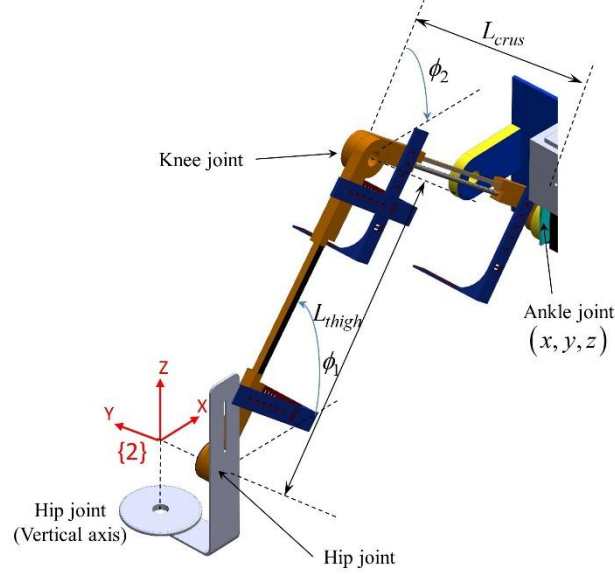


Figure 6: Passive orthosis

4 Physiological Motions

Physiological motions are decided by the therapist according to rehabilitation status of the patient. Here in this section basic physiological motions are shown to validate the kinematics of the proposed system. Each individual joint are given motion according to the angular limits used in therapeutic treatments [12].

4.1 Hip flexion-extension

Hip flexion-extension motion refers to motion of hip joint about the sagittal plane. To visualize this motion the values input is shown in Table 1.

Table 1: Task-space for validation of hip flexion-extension motion

| Joint | ϕ_1 | ϕ_2 | ϕ_3 | ϕ_{ankle} |
|-------|--|------------|-----------|----------------|
| Value | $\left(\frac{60(168.75 - (t-15)^2)}{225} \right)^\circ$ | 10° | 0° | 0° |

To validate the motion possibility each joint is simulated for a 30 second motion trajectory. Here in this case the hip flexion-extension, $-15^\circ < \phi_1 < 45^\circ$ is simulated the geometric parameters are taken as: $L_{thigh} = 0.42$ m, $L_{crus} = 0.4$ m, $l = 1.4$ m, $d_1 = 0.28$ m, $d_2 = 0.4$ m, $d_3 = 1.6$ m, $p_x = 1.2$ m, $p_y = 0.14$ m, $p_z = 0.917$ m, $y_t = 0.05$ m and $z_t = 0.1$ m.

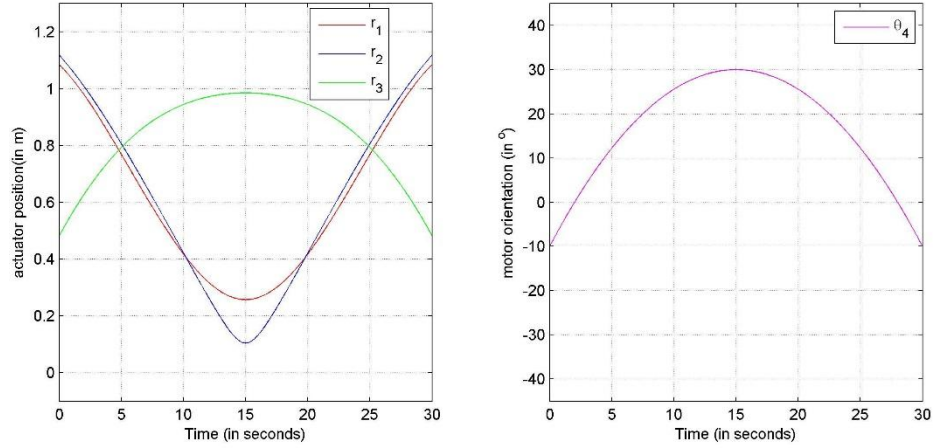


Figure 7: Hip flexion-extension joint space movement

The joint-space movement shown in Figure 7. shows that the motion is possible and mechanism is not encountering any singularities while performing the task. Parallel singularity can be avoided by regulation the parameter l , higher values are more stable, which is the length of the connecting link from the actuator to end effector with universal joints. Furthermore, optimization can be done as this parameter. The stroke length of the linear actuator is taken as 1.2 m. Hence, during the motion system is not overruling the limits.

4.2 Hip adduction-abduction

The trajectory taken for hip adduction-abduction is shown in Table 2. Here we have given motion to ϕ_3 as, $-15^\circ < \phi_3 < 15^\circ$ using as sinusoidal function with a time period of 30 seconds. The trajectory would be a circle in transverse plane as the patient is in lying posture.

Table 2: Task-space for validation of hip adduction-abduction motion

| Joint | ϕ_1 | ϕ_2 | ϕ_3 | ϕ_{ankle} |
|-------|------------|------------|----------------------|----------------|
| Value | 30° | 20° | $15 \sin(12t)^\circ$ | 0° |

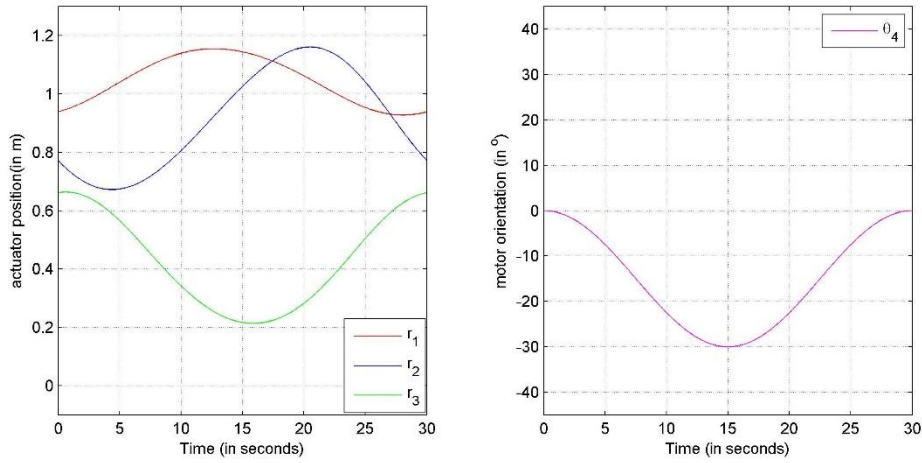


Figure 8: Hip adduction-abduction joint space movement

This joint-space in Figure 8 clearly shows that mechanism is able to provide bidirectional adduction and abduction which was not possible in case of Hipbot. Only one condition is to be verified that the lower limb under treatment is should not hit the other limb which is not being treated.

4.3 Knee flexion-extension

For knee flexion-extension the ϕ_2 angle is to be varied, this angle cannot be less than zero as it is constrained by human body constraints, also a safety feature in the knee joint is also required which stops the orthosis to go less than zero physically, for this simulation the task-space is shown in Table 3 and the joint-space output is shown in Figure 9. Here we have taken $0 < \phi_2 < 40^\circ$ using a polynomial equation.

Table 3: Task-space for validation of knee flexion-extension motion

| Joint | ϕ_1 | ϕ_2 | ϕ_3 | ϕ_{ankle} |
|-------|------------|---|-----------|----------------|
| Value | 10° | $\left(\frac{40(225 - (t-15)^2)}{225} \right)^\circ$ | 0° | 0° |

All the joint must be protected by physical restriction and numerical restriction through integrated software. Other than this two emergency switches must be installed. One near patient's hand and another with the physiotherapist. These treatments must be provided in presence of a therapist. These devices are supportive devices which increases the efficiency of the therapist to give long duration treatments without making the therapist tired.

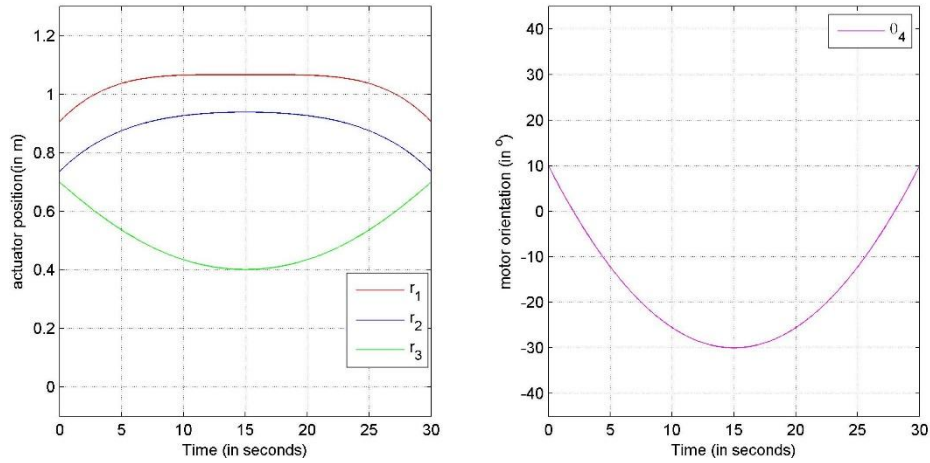


Figure 9: Knee flexion-extension joint space movement

5 Conclusions

Lower limb rehabilitation techniques are designed in order to provide continuous therapy for a longer period of time at a stretch. For such purpose the mechanisms should perform continuous operation without facing any kind of singularity and joint space limitations. Also, it should be safe for the patient and the therapist. The proposed system is designed to provide an additional dimension to the therapists that is hip adduction-abduction which is not present with proper features in other devices. The design and kinematics is explained in order to realize the system. The basic physiological motions are kinematically simulated to verify the manipulator behavior towards the joint input. This architecture has potential to provide a wide range of rehabilitation treatments. In future we would like to find dynamic based control schemes and real-time validation on human subject.

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