Kinematic Analysis of a Passive Sitting/Lying type Lower Limb Rehabilitation Robot

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Abstract

This paper addresses the working principal of a sitting/lying type passive lower limb rehabilitation robot (LLRR) where patients legs are connected with a passive serial manipulator(orthoses) which consists of three rotary joints serially connected in a plane (RRR), with an active feedback, driven by a three degrees of freedom (DOF) parallel manipulator looks like a symbol The Lambda. The kinematics of the proposed rehabilitation robot has been presented and discussed. Performance analysis of the proposed robot for basic therapeutic exercises has been analyzed on a virtual prototype with the help of multibody dynamic package (namely MSC ADAMS^{TM}) and discussed.

Keywords: Lower limb rehabilitation; rehabilitation robot; parallel manipulator; sitting/lying type rehabilitation robot; robotherapy

1 Introduction

Rehabilitation through robot physiotherapy has been quite successful in past few decades, helping patients and physios in getting faster recovery strategies. Persons undergone accidental disabilities, paralysis, lower limb dysfunction, stroke, spinal cord injuries (SCI) are being treated effectively by means of robots. It has been seen and proven that repetitive and intensive rehabilitation exercises with disabled limbs helping neuro-rehabilitation [1] [2]. Good results are obtained in case of the treatment of the incomplete paralyzisation of paraplegic and tetraplegic patients [3]. Rehabilitation robots can be classified into three major groups based on the need [4] and given as follows:

(i) to assist disabled people in special need with their daily activities

(ii) to support mobility;

(iii) to assist therapists performing repetitive exercise with their patients (clinical use).

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The LLRR comes under the group (iii) for clinical use these are divided into two categories : (a) sitting/lying type for leg, ankle and foot rehabilitation and (b) gait training along with a body weight support (BWS) system.

In sitting/lying category MotionMaker is a commercially available robot [5] while researchers also had proposed few other mechanisms for sitting /lying postures [6] [7] [8] [9]. For gait training Lokomat [10], LokoHelp [11], WalkTrainer [12], AutoAmbulator [13], Gait Trainer [14] are the commercially available rehabilitation devices, they use BWS to operate the patient at a standing position for treating the gait pattern and other artificial limb technologies.

Therapeutic exercises performed clinically are shown in Table 1.

Table 1: Clinical Therapeutic Treatments

Passive range of motion	For patients not having muscle strength; some regular cyclic motions are performed passively
Active assistive	Partial assistance provided by counter weights mechanisms or by the therapists manually to reduce patients' effort in performing motions.
Isokinetic	No motion of joints training patient to counteract a certain value of maximum resistance
Isotonic	Resistance to movement for enhancing ability of limbs Isometric: Contraction against fixed joint angles
Isometric	Contraction against fixed joint angles
Manual exercise	all kind exercises performed by a physiotherapist manually.

This paper presents a sitting/lying type passive LLRR based on a 3-DOF parallel manipulator along with lower limb guides. Commercially available mechanism namely Motion Maker [5] uses a serial manipulator to perform the rehabilitation tasks having a serial RRR configuration consist of joint rotation for hip joint, knee and ankle, while other robots uses passive mechanisms as in NeuroBike [8] and The Lambda [7] where ankle and feet are rested on the end-effector of the passive manipulator. The proposed LLRR structure is a modified and an improved version of the Lambda mechanism [7] along with the real time feedback from patients joint motions. Completely passive manipulator does not account the patients reflexes into account while serial manipulators face problem in repeatability while performing continuous cyclic tasks due to error accumulation [15]. Therefore by accounting the above mentioned limitations, in this study the following questions are attempted and addressed, namely

- Can a passive mechanism be used for taking account of reflexes of patients?
- Can a passive mechanism able to provide similar treatment in variability of limb size of patients?

The feature implemented in the present study has been done keeping the above questions in mind. This work displays the following features:

- Able to perform passive, active assistive, isometric, isokinetic, and isotonic type of therapeutic exercises.

- A twice 3-DOF manipulator able to reach all required location for rehabilitation purpose.
- Passive RRR serial manipulator connected to the leg having joint at hip, knee and ankle gives feedback for proper control of joint motion.
- Hip joint can be adjusted according to the patients requirement
- Adjustable leg orthosis, to take care of variability in limb size.
- Active ankle control.

Patients facing lower limb disability are generally lack of control over their limbs. So it is difficult for them to use entirely passive robot [6] [8] which does not actively deal with their joints. Here the proposed system is providing leg supports which can be used as supporting structure for the disabled limb as well as feedback device for the active control. This proposed mechanism is more efficient on the terms of nullifying the chances of accidental effects of LLRR like the waist support does not allow the patient to change the reference position; providing supports to the waist; thigh and crus links are passively controlled by the parallel manipulator; ankle joint is actively controlled. All the joints of the passive manipulator are equipped with encoders and leg supports so as to prevent the patient from retaliation.

This paper consists of five sections including the introduction. In section II, it deals with a conceptual diagram of the proposed mechanism along with the mechanical design requirements of a therapeutic robot manipulator has been discussed. In section III, it deals with the implementation of kinematic solutions in trajectory tracking through the proposed mechanism. Section IV deals with how this mechanism is fulfilling the requirement and how this can be used for performing various therapeutic treatments. Finally, Section V gives the concluding remarks of this work.

2 The Proposed LLRR

In this section, basic design requirements of the sitting/lying type LLRR, a conceptual diagram of the proposed mechanism for passive type lower limb rehabilitation along with its kinematic solution are presented and discussed

2.1 Design Requirements

The design of sitting/ lying type LLRR need to follow certain aspect as follows:

- Manipulator should able to reach the desired locations according to the treatment necessities with largest possible limb length.
- Able to provide similar movements with variable loads as body weights may vary from person to person.
- Max force provided by the actuators should be sufficient enough to perform treatments at required maximum speed.

To meet all above mentioned design requirements, it is required to perform the kinematic and dynamic analysis of the mechanism. Therefore, in this paper the proposed mechanism's kinematic solutions obtained analytically and verified in thevirtual prototype along with its dynamic performance study with the help of a multibody dynamic analysis software namely MSC ADAMS^{TM}. A conceptual diagram of the proposed mechanism has been shown in Fig.1.

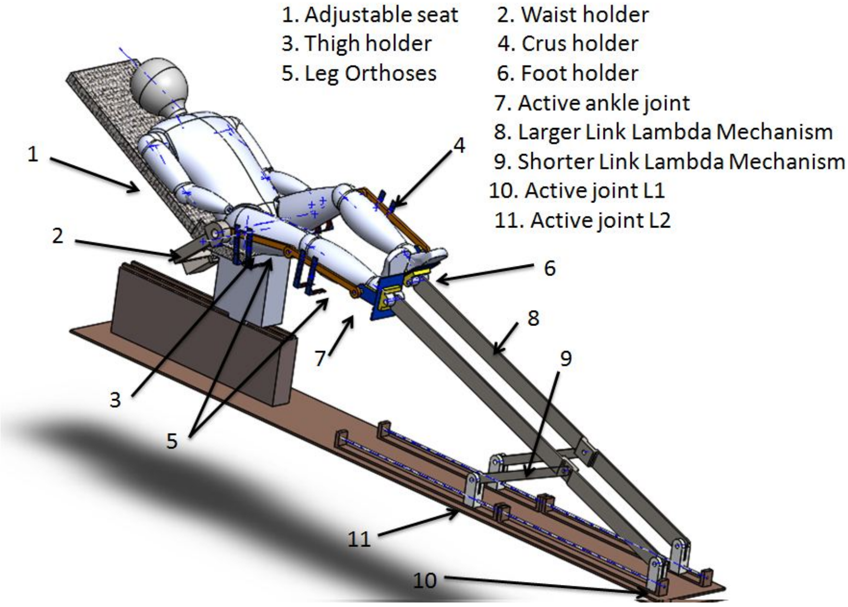

Figure 1: Conceptual diagram of the proposed mechanism.

2.2 Mechanism

The proposed mechanical system consist of two mechanisms namely the leg orthosis and the improved lambda like parallel mechanism. The lambda like mechanism is similar to the mechanism has been proposed by et.al Bouri [6] but without any discusion on kinematics aspect. This paper is based on usage of the passive links to move patients limb the way serial manipulator would have done. The usage of parallel mechanism reduces the repeatability error in long time treatments. This approach of controlling a passive manipulator using an active planar parallel manipulator is a novel approach. The leg orthosis consist of three rotary joints (3R) serial link manipulator with joint corresponding to hip, knee and ankle. In these, the hip and knee joints are passive joints and used for active feedback for the passive manipulator, whereas the ankle joint is active with direct feedback. This orthosis is also with two passive and one active joint is also novel. The manipulator link lengths (i.e. links supporting the thigh and crus) are adjustable in order to accommodate the variability in the limb size of the patients. The parallel mechanism part is helping the orthoses to perform the directed tasks. Motion requirements like flexion-extension can be performed using kinematic solutions. For this mechanism must be capable of providing motion in X and Y direction in the sagittal plane having active ankle control which incorporate θ_z rotation in the sagittal plane. The leg orthoses are restricted not to go above 180; this makes mechanism possessing a unique solution with the provided constraints.

In sagittal plane, the proposed mechanism can be seen as the lambda like mechanism (shown in Fig.2) supporting the leg orthosis. The lambda like mechanism is having 2-PRR configuration while leg orthosis is having 3-R configuration.

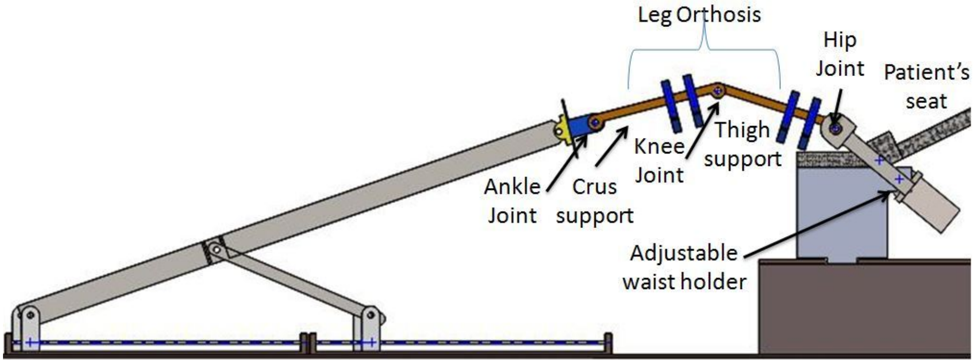

Figure 2: The proposed mechanism in the xy plane (with passive leg orthosis.

2.3 Kinematic Solution

The kinematic relations of the passive and active mechanisms are presented in this section. In the proposed LLRR, each of the leg movement is controlled by three actuator two in the lambda mechanism and one at the ankle joint so the control parameters are L_1 , L_2 and ϕ_3 as shown in Figs. 3 and 4.

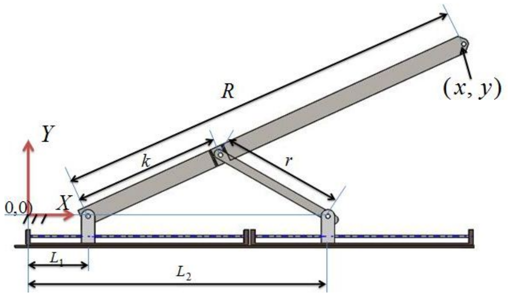

Figure 3: Lambda mechanism part in the sagittal plane

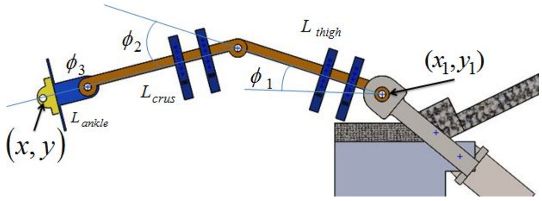

Figure 4: Leg orthosis in the sagittal plane.

The location of coordinate (x, y) and (x_1, y_1)in Fig.4 is with respect to the reference mentioned in the Fig.3. According to the diagram of leg orthosis the coordinate x and y can be written as:

$$\begin{aligned} x = &\quad x_1 - L_{thigh} cos\phi_1 - L_{crus} cos(\phi_1 + \phi_2) - L_{ankle} cos(\phi_1 + \phi_2 + \phi_3) \\ y = &\quad y_1 + L_{thigh} sin\phi_1 + L_{crus} sin(\phi_1 + \phi_2) + L_{ankle} sin(\phi_1 + \phi_2 + \phi_3) \end{aligned} \tag{1}$$

Here, x_1 and y_1 are the coordinate of the hip joint which are fixed with respect to the reference frame in Fig.3, while L_{thigh} , L_{crus} and L_{ankle} are the patients limb sizes corresponding to the length of the thigh, crus and ankle, respectively. For any kind of therapeutic rehabilitation treatment the data values for ϕ_1 , ϕ_2 and ϕ_3 are

known which are the joint angles corresponding hip, knee and ankle, respectively. So using (1) the values of x and y are known, to follow the desired path the

parameters L_1 and L_2 need to be determined as shown in Fig.3. The solution for L_1 and L_2 are as follows:

$$\begin{aligned} L_1 &= x - \sqrt{R^2 - y^2} \\ L_2 &= x - \sqrt{R^2 - y^2} + kx/R + \sqrt{r^2 - k^2 + k^2 x^2/R^2} \end{aligned} \tag{2}$$

Here R , r and k are lengths corresponding to larger link of Lambda mechanism, shorter link and actuator joint to the shorter link joint of the larger link, respectively.

3 Trajectory Tracking through simulation

To validate the kinematic solutions joint response for a given trajectory tracking task has been traced. For simulation purpose a cyclic pedal motion has been taken, which is a circular trajectory with diameter of 200 mm. The actuators L_1 and L_2 are given

time based motion and the response of the actuator joints and leg orthoses are recorded. The trajectory at the end effector of lambda mechanism is given as:

$$\begin{aligned} x(t) &= 1890 - 100cos(2\pi t/5) \\ y(t) &= 660 - 100sin(2\pi t/5) \end{aligned} \tag{3}$$

The actuator input to follow the given trajectory can be obtained by substituting values in (2). The parameter for simulation in the multibody dynamics software ADAMS are the length of the larger link of the lambda mechanism R=190.50 mm ,shorter link r=63.50 mm and pivot distance k=63.50 mm . For the leg orthosis: L_{thigh}=460 mm , L_{crus}=490 mm and L_{ankle}=80 mm are the assumed limb sizes, although mechanism has been designed to accommodate limb size L_{thigh}= L_{crus}= L_{ankle}=1050 mm and minimum limb size L_{thigh}= L_{crus}= L_{ankle}=500 mm .

The end effector velocity components for leg orthoses and the lambda mechanism would be same with respect to time, as:

$$\begin{aligned} \dot{x}(t) &= 40\pi sin(2\pi t/5) \\ \dot{y}(t) &= 40\pi cos(2\pi t/5) \end{aligned} \tag{4}$$

So the actuator joint velocities can be written as:

$$\begin{aligned} \dot{L}_1 &= \dot{x}(t) - \frac{y(t)\dot{y}(t)}{\sqrt{R^2 - y^2(t)}} \\ \dot{L}_1 &= \dot{x}(t) - \frac{y(t)\dot{y}(t)}{\sqrt{R^2 - y^2(t)}} + \frac{kx(t)}{R} - \frac{k^2x(t)\dot{x}(t)}{R^2\sqrt{r^2 - k^2 + (k^2x^2(t)/R^2)}} \end{aligned} \tag{5}$$

Total time for the simulation is 15 seconds which allows the mechanism to take three cycles of flexion-extension kind of therapeutic exercise. The performance analysis of the proposed mechanism is demonstrated in the virtual prototype through the help of ADAMS software and the proposed mechanism in the ADAMS environment is shown in Fig. 5.

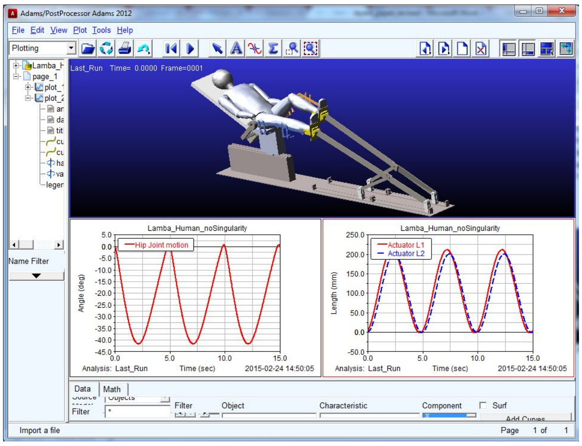

Figure 5: Simulation environment of the proposed mechanism in ADAMS

4 Results and Discussions

4.1 Mechanism aspect

Therapeutic treatments depend on the providing controlled motion to the limb orthoses. The Simulation results validate the usage of the manipulator for controlled motion purpose. This clarify that the above equations are governing the motions. Variation of hip and knee angle with respect to time (time histories) are shown in Fig.6, this is key information while deciding the limits and capability of therapeutic treatment. Here the reference angle which is shown here as 0^o is the when the leg orthosis are in a straight line parallel to the horizontal axis. Deviation from this mean point has been plotted here with joints moving upward as positive. It can be easily realized by seeing the negative values in the graph of Fig.6. Adding 180^o to the knee joint values will give angle between the thigh and crus. Here blue dashed line shows the variation in the hip joint while the red line shows the variation in the knee joint.

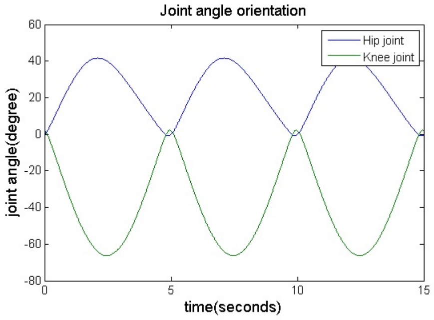

Figure 6: Variation in Joint angles of leg orthosis (right).

Figure 7 shows the variation in the joint angular velocity of hip and knee joints taken from the data of orthoses joints through ADAMS software

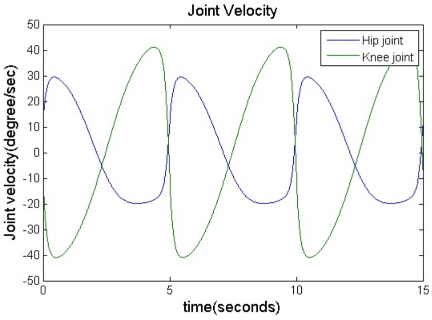

Figure 7: Variation in joint angle velocities of the passive mechanism..

It represents the variation in velocity of leg orthosis, in therapeutic treatment the maximum speed of the joints are decided based on the condition of the extremities. Here the max velocity can be achieved by the applying sufficient forces and the time histories of the required forces of each actuator are plotted in Fig.8.

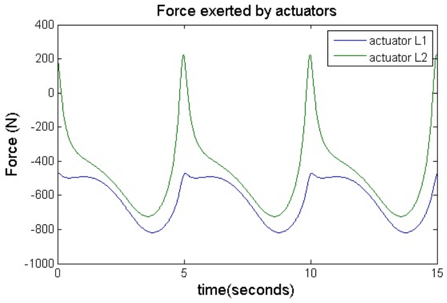

Figure 8: Input force variation in actuators.

For input actuation the force required by the actuator are reasonably approachable as this amount of forces can easily be provided by the commercial actuators. Maximum force requirement is an important data for selection of actuators. Here we can see the how much force must be provided by the actuator joints to perform this task and it has been shown the force corresponding to joint parameters L_1 and L_2 are represented by the blue and green line, respectively. Average industrial linear actuators gives max push and pull limit of 5 kN. As shown in the graph the maximum force required is well under the commercially available range .

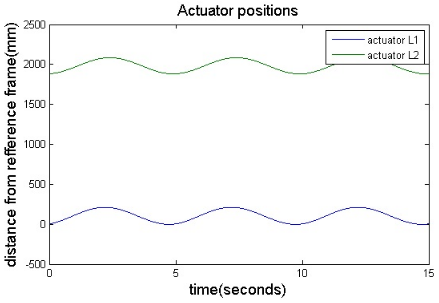

Figure 9: Displacement variation in actuator joints

By performing different kind of treatment patterns in simulating environment on the virtual prototype of the mechanism, the actuators maximum speed specifications can be determined Figs. 9 and 10 shows the joint space variation and the velocities of the actuators. Position and velocity is again one of the major parameter in deciding the stroke length and maximum speed of actuation system which can be decided according to the max hip and knee joint angular velocity requirements of the therapy.

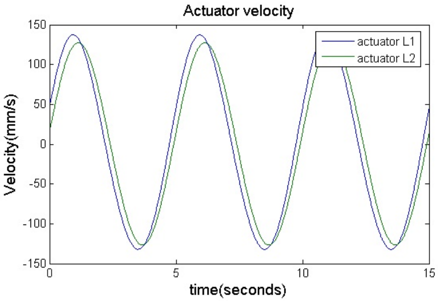

Figure 10: Velocity of actuator joints

4.2 Robotherapy aspect

This robot mechanism is showing the capability of fulfilling various kinematic motion requirements in the therapeutic treatment. Now let us analyze how it can perform different type of therapeutic treatments.

(i) Passive range of motion (ROM): For bed ridden patients not having sufficient muscle strength, for them directed continuous cyclic motions are provided passively so as to activate the motor nerve action in the nervous system, this process is known as motor recovery. This task can be easily performed by the position control based on kinematic solutions and simple PID control. Although these treatments can be verified before treating the patients and chances of error can be minimized by the active feedback from the knee and hip joints still seeing the safety perspective emergency stop button must be provided for both patient and the therapist while performing these treatments.

(ii) Active assistive: Here partial assistance is provided by the mechanism which can be implemented by the fusion of force sensor into the system, which can measure the effort, put on by the patient and can be magnified by controller to perform this kind of therapy.

(iii) Isotonic: These exercises enhance ability of limbs, performed by providing resistance to the movement of limbs. It can be seen just apposite of the active assistive task. Now again by implementing force sensor, the measured value of the force instead of magnifying we need to diminish the value of the applied force through the help of controller which help to perform these therapies.

(iv) (iv) Isometric: At fixed joint angles we need provide load on the limb which is according to the physical need of the patient. This is performed by providing motion just apposite to the direction of the force. In this treatment variation of 10 degrees on either side is allowed. Although manipulator will always try to keep the mechanism at the required position, still sometime due to fluctuating values of patients input joint is allowed to move within 10 degrees. With force estimation the joint toque requirement can judged.

(v) Isokinetic: Here, by measuring the joint forces, movement is not allowed till a certain force value is reached. In this task the goal is to improve the strength and reflexes, the measured value of the orthoses joint and force will determine whether movement is allowed or not. The value of force is not very high in these cases.

5 Conclusion and future aspects

In this paper, the use of passive manipulator for the lower limb rehabilitation purpose has been shown and discussed. If the manipulators inverse kinematics is known the passive lower limb rehabilitation mechanism can be run and utilized for rehabilitation purpose as well as the use of feedback from the active joint can enhance the performance of the system by taking advantage of using passive links which takes patients immediate response into account. In addition, other sensors like encoders and force sensors can be mounted on the mechanism to generate live information during therapy. In this work, the Lambda mechanism is used as a helping mechanism to show this concept, this hold true for the other mechanisms

also those which can provide XY and θ_z movements in a plane.

To verify the Design and to work on advance control strategy we are working to make physical prototype of the system. So that the validity of the mechanism for the purpose of rehabilitation can be established.

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