DESIGN AND ANALYSIS OF A LOWER LIMBS HORIZONTAL ROBOT FOR FEMORAL SHAFT FRACTURE REHABILITATION USING LINEAR ACTUATORS

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ABSTRACT

This paper presents a horizontal rehabilitation robot based on parallel mechanism used after the femoral shaft fracture of hip. It can help patients to do passive exercises of hip. The system consist of three degrees of freedom actuated with linear actuators. The kinematics and dynamics of the mechanism is analyzed. The mechanical design of the robot is described. The forward and inverse kinematics solution of the robot is given. The working space and the trajectory planning is studied. Based on the Lagrangian method, the dynamic equation of the robot is deduced and the dynamics simulation is carried out using MATLAB. A PD controller is proposed for trajectories tracking.

KEYWORDS: *Rehabilitation Robotics, Femoral Shaft Fracture, Biomechatronics, Patient Rehabilitation.*

I. INTRODUCTION

The femur is the longest and strongest bone of the human body. This bone, requires a high impact or collision to break it. The longest straight part of the femur is called the femoral shaft, see Figure 1. When there is a break in this part, is called femoral shaft fracture, see Figure 2a. The femoral shaft fracture is one of the most painful injuries in the hip usually caused by car accidents [1]. The femoral shaft fracture impedes the move of the patient's leg due to severe pain. Surgery is the only solution to stop the patient's pain and recover the movement, see Figure 2b. Generally the elderly people are more prone to this type of fracture due to osteoporosis [2].

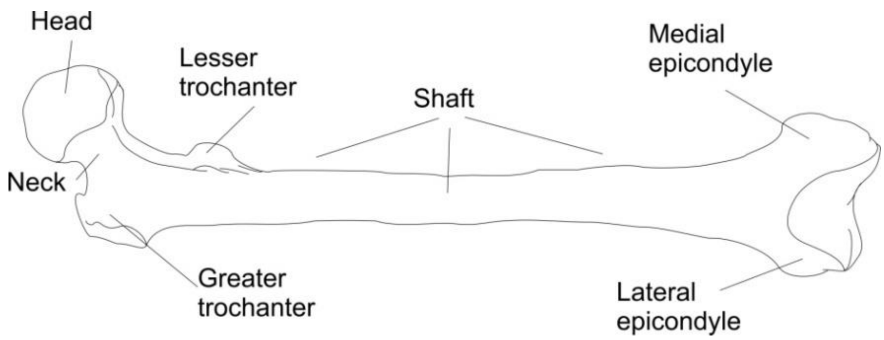

Figure 1. Parts of the femur

a) b)

Figure 2. Femoral shaft fracture. a) Radiograph of the patient's broken femur, b) Doctor lifting the patient's broken leg.

Today, the method that most surgeons use to treat a femoral shaft fracture is implanting an intramedullary nail (IM nail) [3], see Figure 3a. During this procedure, a titanium metal rod is specifically designed to be inserted into the femur. This rod passes through the fracture and is fixed with screws, see Figure 3b. An intramedullary nail can be inserted making three small incisions in the patient's leg. To fix the rod to the bone, some screws are necessary in both ends of the femur, see Figure 3c. The intramedullary nail and bone are fixed during the rehabilitation process.

a) b) c)

Figure 3. Intramedullary nail. a) Set of screws and IM nails, b) Two screws inside the leg of the patient, c) The doctor introduces the screws into the IM nail

Generally, after surgery, the size of the wound cause pain. The patient can not touch or move the leg, see Figure 4a. Moreover, such operations can cause discomfort to the patient. Once the patient is in the recovery room begins the healing process. Due to the size and number of injuries is sometimes not possible the free movement of the leg, see Figure 4b. Early rehabilitation and mobilization of the leg is necessary for the patient.

a) b)

Figure 4. After a femur shaft fracture. a)Sewing the wound, b) Four scars

After surgery of femoral shaft fracture, rehabilitation is required every day. Recovery takes regularly for 4-6 months and its duration depends on the severity of the fracture [4].The hip joint, also known as hip, has mobility in three axes in space, that is, this type of movement is known as a ball and socket joint. The hip joint is formed primarily by femoral head and acetabulum as a ball joint. The importance of the hip is to support bodyweight and perform locomotion [5]. In passive rehabilitation exercises after a femoral shaft fracture, there is one basic movement. This is flexion and extension, see Figure 5. The proposed prototype in this study is able to perform the basic movements of the hip after a femoral shaft fracture.

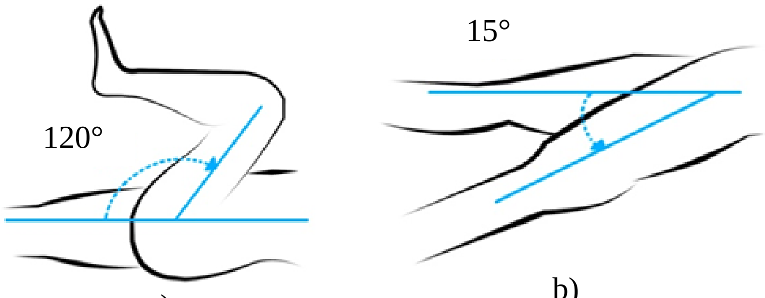

Figure 5. Basic movements after a femoral shaft fracture. a) flexion (120°), b) extension (-20°)

Physical rehabilitation, in a general sense, aims to maintain, restore and develop the human body movement through physical therapy. Rehabilitation therapies are procedures to return a person to their activities of daily living. The physiotherapist is the expert to provide rehabilitation exercises. There are two types of rehabilitation: active and passive [6]. In the first, the patient can perform the exercises voluntarily by himself, is divided into: assisted, free and resisted. In the second, the therapist is the one who moves the extremities without any effort of the patient.
The feature that distinguishes a femoral shaft fracture compared to others, in terms of rehabilitation, is to guarantee secure movements due to condition of the patient after the surgery. On the other hand, to rehabilitate the joints of a person with a femoral shaft fracture is necessary to know: (a) characteristics and limitations of each patient, (b) the maximum range of motion, (c) the duration and type of exercise. After a surgery the patient need to perform passive exercise on the bed to maintain the joints moving, otherwise, a prolonged immobilization can cause muscle atrophy.
After the Second World War, rehabilitation devices have been developed in research centers. Today, advances in medicine seek to improve the speedy recovery of the patient to provide a better quality of life. Devices called "continuous passive motion (CPM)" are machines used in passive rehabilitation. The CPM concept was introduced in 1970 by [7]. Today, CPM devices for lower limbs facilitate the rehabilitation of the patient, see Figure 6. These machines perform passive exercises automatically in a given interval of time.

Figure 6. CPM machine for knee rehabilitation.

In [8], [9] demonstrate that using a CPM machine is promising because of the benefits it offers, especially in patients who have suffered postoperative orthopedic surgery. Among the many benefits it offers, mainly reduces pain, risk of thrombosis and accelerates the healing process.
Moreover, robotics has pushed the field of rehabilitation with the purpose of automate the therapies. Several robots for passive lower limbs rehabilitation have been developed [10], [11], [12], [13], [14], [15], [16], [17], [18]. The first machine of therapeutic exercise for hip and knee mobilization of spastic patients was developed in [19]. Later, a commercial therapeutic exercises machine was proposed by [20]. The disadvantage is that the patient does not feel safe due to the configuration of the articulated arm manipulator for rehabilitation purposes.
A system using a parallel cable mechanism was applied in [21] to increase the degrees of freedom for hip rehabilitation. This device was able to perform leg movements to help medical personnel. Continuing along the same line, a new system for lower limbs rehabilitation was proposed by [22]. The system can move in the XY plane, has an interface in Labview and is actuated by pneumatic pistons. A robot of three GDL for therapeutic exercises was proposed in [23] for lower limb requiring rehabilitation after spinal cord injury, muscular disorder or surgery. Finally, a horizontal robot for lower limb rehabilitation was proposed in [24], [25]. The system focuses on mobilizing both legs of the patient with predetermined cyclic movements, see Figure 7.

Figure 7. The model machine of horizontal lower limbs rehabilitative robot [24].

All these robots use direct current motors or pneumatic pistons to move the patient's leg. However, do not ensure the safety and comfort of the therapies because they are systems that are not designed to treat fractures of the femoral shaft. In addition, these systems cause pain to the patient because they put pressure on the leg. On the state of the art, there are not related investigation with robots specially designed for femoral shaft fracture rehabilitation. In this paper a new robot is proposed, the main advantage of this system is that no cause pain in rehabilitation therapies after a femoral shaft fracture.
The proposed system has the following advantages:

- Comfortable and safe
- The weight of the legs do not affect the movements
- Perform smooth and controlled movements for reduce pain during the therapies
- The therapist can program different movements for each patient

With the above, this paper discusses the design and analysis of a lower limb horizontal robot for femoral shaft fracture rehabilitation using linear actuators. The objective of this paper is to present a new robot to reduce the patient's pain during rehabilitation therapies. To achieve this, it is necessary a kinematic and dynamic analysis to determine whether the robot can perform basic rehabilitation movements of the lower limbs after a femoral shaft fracture. Some simulations can be carried out to verify the performance of the robot.
This paper is organized as follows: Section II presents the mechanism and structure of the robot. Section III presents the kinematics of the robot using Denavit Hartemberg parameters. Section IV presents the dynamic model using the Lagrangian method. Section V shows the results of simulation using a proportional derivative controller to follow smooth trajectories. Finally, Sections VI and VII show the conclusions and future work, respectively.

II. MECHANISM AND STRUCTURE OF THE ROBOT

The proposed horizontal robot aims to achieve the maximum range of movement of the hip joint. In this paper a parallel mechanism actuated by linear actuators to support the weight of the leg is proposed, see Figure 8. The system comprises a horizontal linear actuator to move a cross slide. This actuator is positioned by a screw and nut. Moreover, two commercial linear actuators that allow the patient's foot move in any desired position are proposed. When there is a height difference between the linear actuators movement is possible obtain different angles in the foot.

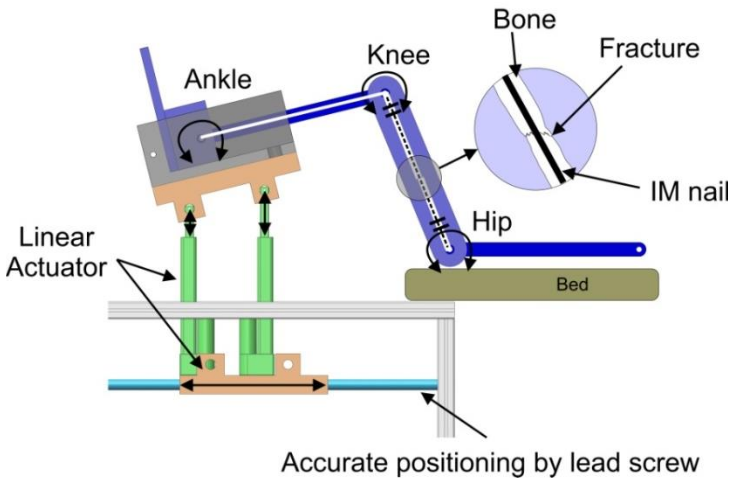

Figure 8. Proposed structure of the robot

III. KINEMATICS ANALYSIS

To analyze the kinematics of the rehabilitation robot, the coordinate system is established as shown in Figure 9. The linear actuators are connected to the patient's foot and do not have contact with the scars of the leg.

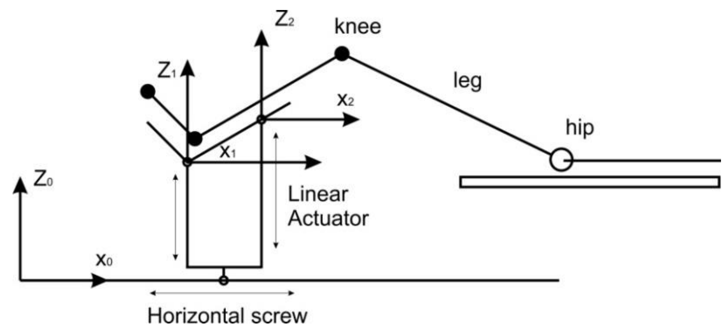

Figure 9. Coordinate system of the robot

For the kinematic model of the robot, first we have to assign frames to each link, starting from base to end effector. Table 1 shows the geometric parameters of the robot according to Denavit-Hartenberg convention [26]. Where: i represents the number of the joint, a_i represents the distance along the axis x_i, α_i is the angle between the axes z_i and z_{i+1}, d_i represents the distance between z_i and finally axis represents the angle θ_i with respect to xi and x_{i+1} axis.

Table 1. DH Parameters

i	a_i	α_i	d_i	θ_i
1	a ± distance	0	d ± distance	0

As we have two linear actuators located at the same distance from the transverse carriage is possible to simplify the positioning of the coordinate system. The direct geometric model (DGM) calculates the position and orientation of the leg based on their joint angles. To find it, is necessary to calculate the homogeneous transformation matrix i-1Ti each joint using (1).

$$^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where: $S\theta_i = Sin\theta_i$, $C\theta_i = Cos\theta_i$ y $S_{23} = Sin(\theta_1 + \theta_2)$
Finally, the transformation matrix is as follow:

$$^{i-1}T_i = \begin{bmatrix} 1 & 0 & 0 & \text{a} \pm \text{distance} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & \text{d} \pm \text{distance} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

IV. DYNAMICS ANALYSIS

The dynamic model is useful in the simulation of motion of the robot, the design and evaluation of its mechanical structure and the dimensioning of the actuators. Figure 10 shows a simplified diagram of the location of the concentrated mass.

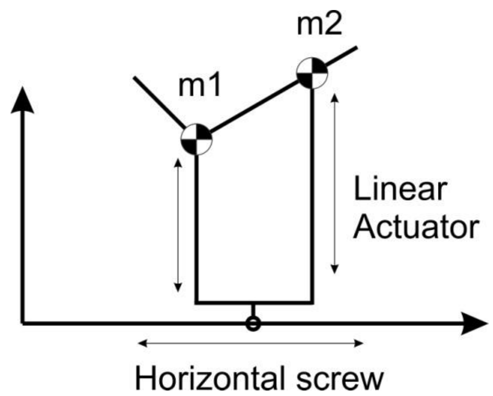

Figure 10. Dynamic model of the robot

The dynamic model of the robot according to the Euler-Lagrange method [27] is expressed by (3)

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = Q_i \quad (3)$$

Where,

L: Lagrangian
K: total kinetic energy of the system
V: total potential energy of the system
D: Power Dissipation
qi: generalized coordinate: each degree of freedom of the system is expressed by a generalized coordinate.
Qi: external forces applied to the system
The total kinetic energy of the robot shown in (4).

$$K = \frac{1}{2}mv^2 = \frac{1}{2}m(\dot{x}^2 + \dot{z}^2)^2 \quad (4)$$

The total potential energy of the robot is shown in (5).

$$\text{V} = \text{mgz} \quad (5)$$

The Lagrangian (L = K-V) is shown in (6)

$$\text{L} = \frac{1}{2}m\left(\dot{x}^2 + \dot{z}^2\right)^2 + mgz \quad (6)$$

The dynamic model of the robot is shown in (7)

$$F_1 = m_1\ddot{x} + m_2\ddot{x}$$
$$F_2 = m_1\ddot{z} + m_1 g \quad (7)$$
$$F_3 = m_2\ddot{z} + m_2 g$$

V. SIMULATION RESULTS

This research work seeks to introduce a new mechanism that is capable of providing rehabilitation exercises after a femoral shaft fracture. Figure 11 shows a simulation of the robot kinematics. The system moves the patient's leg (green line) without contacting wounds due to surgery (red line) through a planned trajectory (blue line). The movement of the leg is smooth and do not cause pain to the patient. The leg goes from an initial position to a final position.

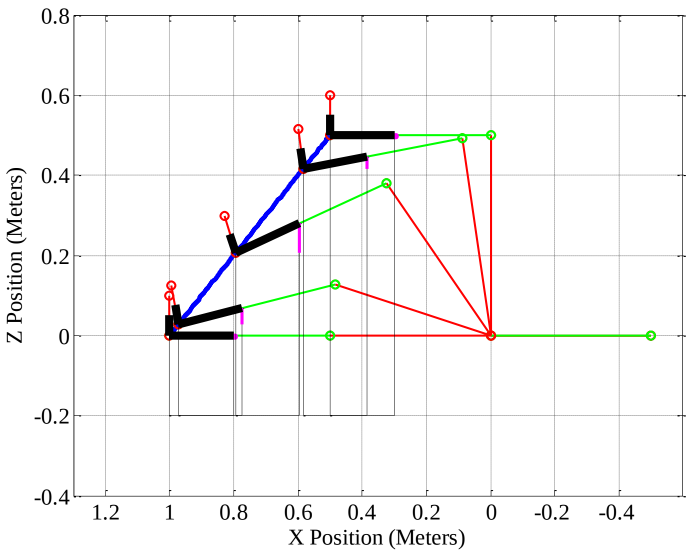

Figure 11. Coordinate system of the robot

To simulate the dynamics of the system (7), a Proportional Derivative controller to bring the error dynamics to zero is proposed. The simulation was developed in Simulink. The block diagram is shown in Figure 12.

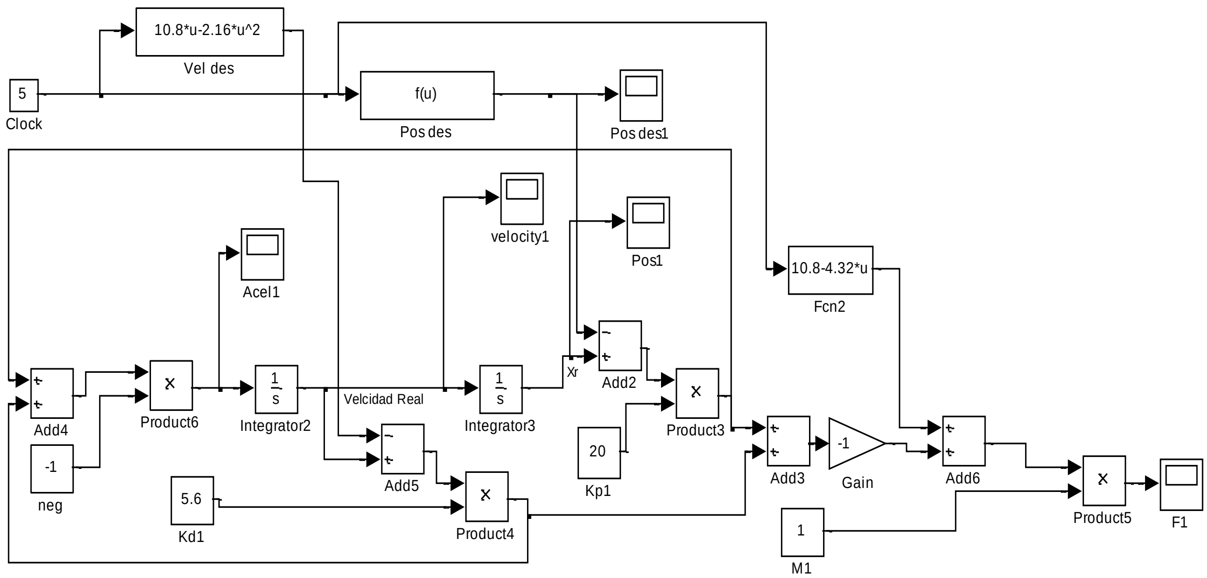

Figure 12. Block diagram of the robot.

In the first simulation, the transverse carriage moves from an initial position to a final position, 0 to 0.5 Meters, respectively, see Figure 13a. In the second simulation, a smooth trajectory planning is proposed. This requires an initial position and a final position. The leg goes from 0.3 to 0.75 meters in a final time of 5 seconds, see Figure 13b. Using a third order polynomial, the equation obtained for the trajectory tracking is (8).

$$\begin{gathered} x(t) = 30 + 5.4t^2 - 0.72t^3 \\ \dot{x}(t) = 10.8t - 2.16t^2 \\ \ddot{x}(t) = 10.8 - 4.32t \end{gathered} \tag{8}$$

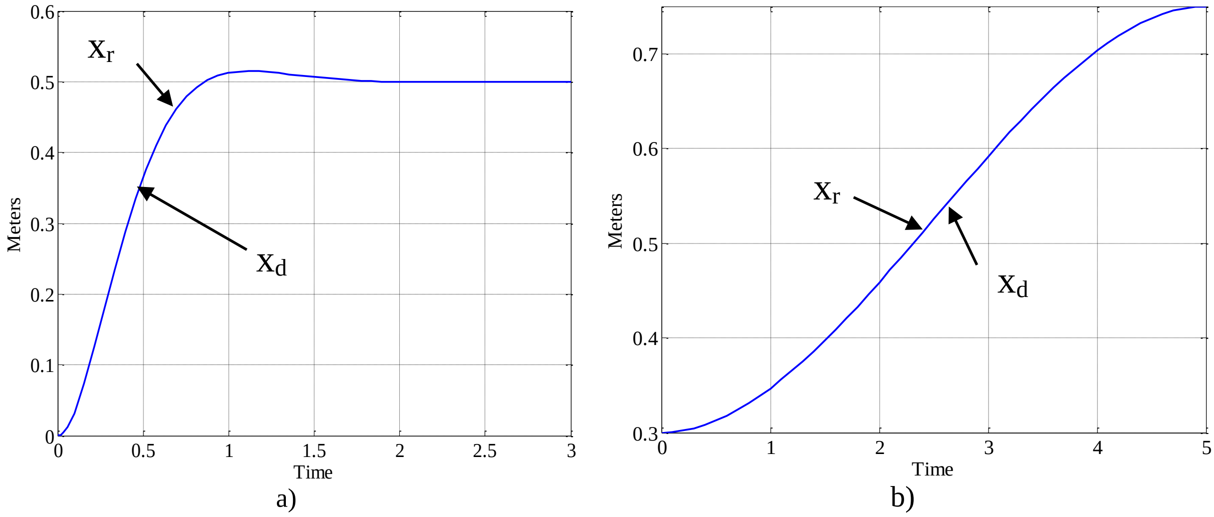

Figure 13. Simulation results, a) Simulation of the transversal slide, b) Simulation from 0.3 to 0.75 meters

VI. CONCLUSIONS

Lower limbs horizontal robot for femoral shaft fracture rehabilitation can be designed using a simple mechanism in parallel with linear actuators. The robot can easily be controlled using a proportional derivative controller. The precision of the output of the robot for effective positional tracking trajectories can be validated from the simulation results. On the other hand, to realize the passive exercises of the therapy in Cartesian space one has to solve the inverse kinematics. The methodology presented here can be used for trajectory planning based on positional analysis with real world disturbances. The present paper can be a tool to facilitate the work of rehabilitation after a femoral shaft fracture and do not intend to replace the work and experience of the therapist.

VII. FUTURE WORK

There are a numerous opportunities to extend or continue this work. First, the number of degrees of freedom can be increased to more than three. A new mechanism can be develop for hip abduction/adduction rehabilitation movements. An impedance controller and a complete dynamic model can be proposed to increase the security of the therapy during rehabilitation. Second, the design, construction and implementation can be carried out. Finally, the prototype can be tested initially on healthy patients to verify the correct operation.

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