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Design of a 3-U$\underline{P}$S-R$\underline{P}$U Parallel Robot for Knee Diagnosis and Rehabilitation

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Abstract Nowadays, rehabilitation robots represent a field in which a variety of robotic devices have been proposed. One example of such devices is lower-limb rehabilitation robots. Specifically, the knee joint is one of the joints whose rehabilitation is foreseen as a potential task for a robot device. This paper describes the design of a robot for knee diagnosis and rehabilitation. First, we established the design specification by studying the mobility needed at the robot's end-effector to deal with diagnosis and rehabilitation treatments for knee injuries. The analysis led us to conclude that 4 degree of freedom (DoF), two translation (2T) and two rotational (2R), are needed in order to meet the design specifications. After that, we chose a parallel robot with a 3-U$\underline{P}$S/R$\underline{P}$U architecture from several conceptual designs of 4 DoF (2T2R) parallel robots. For the chosen robot, we developed the inverse kinematic model, and also we established the preliminary dimensions of the robot. Through simulations, we found the workspace of the robot showing that its end-effector is able to follow a prescribed task taken from studying the leg motion. Finally, we built a prototype, which is currently undergoing dynamic modelling, parameter identification and control design stages.

1 Introduction

Robot design has recently expanded into other non-traditional fields, mainly due to the emerge of new needs and demands; for instance, service robots addressing human and social needs (Alcocer et al., 2012). In the service robot field, rehabilitation robots are one such kind whose design and implementation focus on reducing the physical therapist's work, increasing the length of rehabilitation exercises, gathering information on the status of the patients recovery and, also enabling treatments to be done via teleoperation (telerobotics). However, the available devices are expensive and need appropriate protocols for therapy (Díaz et al., 2011), although some studies have reported evidence of the greater effectiveness of robotic therapy, as well as clear benefits in terms of reducing costs and the physical effort of the therapist (Alcocer et al., 2012). Most of the devices that have been developed focus on rehabilitation, without considering the task of diagnosis. In this respect, studies have shown that rehabilitation robots have great potential in term of precise diagnosis of the patient's injury, and they can also provide quantitative measures of the patient's recovery (Saglia et al., 2010). Diagnostic devices that are capable of performing rehabilitation tasks represent a potential field of research.

The various rehabilitation devices that have been developed differ in terms of the kind of treatment they focus on (Díaz et al., 2011). One of the major types of devices that has been proposed is the stationary type with many commercial and research prototypes having been developed. Some of them have undergone a great deal of development and others are basically still at an early stage. Yaskawa Electric produced a serial type robot for rehabilitation of the lower extremity called the TEM LX2 (Sakaki, 1999), which makes it possible to apply exercises that are usually controlled by a trained therapist. Akdoğan and Adli (2011) developed a stationary device for rehabilitation of the knee with the ability to collect information about forces and positions during therapy. The LAMBDA project developed by Bouri et al. (2009) consists of a robot with 3 degree of freedom (DoF) with one rotational (1R) and two translational (2T) motions. The robot provides motion to the lower extremity in the sagittal plane, and its advantage is that it can be used for training in sports activities. Bradley et al. (2009) developed a device that provides motion in the sagittal plane, the initial design of the robot is based on 2-DoF, but later the robot was modified to include 4-DoF. In addition, the device can be operated remotely; for instance, it can be used at home while the therapist can be in another place. All the above mention devices have a complex configuration and are task specific.

A wide variety of devices for knee rehabilitation have been proposed, but devices for the diagnosis of knee injuries, on the other hand, have barely been studied. We are interested in developing a robot that can carry out both tasks: rehabilitation and diagnosis. Therefore, the article presents the design of a robotic device based on a parallel robot configuration for knee diagnosis and rehabilitation. The next section presents the conceptual design of the robot including a review of the some of the current parallel robots accomplishing the required design specification. Section 3 presents the kinematic analysis of a 4-DoF robot. Section 4 presents the workspace of the proposed robot, including a task in which the end-effector is able to follow a prescribed trajectory taken from studying the leg motion. Finally, the conclusions and ongoing research are presented.

2 Conceptual Design

2.1 Design Specification

Two members of the multidisciplinary team involved in the project (Page and et all, 2013; Vallés et al., 2015) were assigned to research biomechanical aspects of the knee joint, and also to review current devices for knee rehabilitation and diagnosis. After a set of presentations and discussions involving most of the members of the project, we established the kinematic requirements, which are the DoF and the range of motion (RoM) required to accomplish both tasks: rehabilitation and diagnosis. For instance, the required RoM for diagnosis can be established according with the Pivot Shift Test (Wheeless, 1996). In term of rehabilitation requirements, the knee joint can rotate around the transverse axis and the vertical axis. Moreover, the knee can translate in the sagittal plane. Diagnosis and rehabilitation exercises generally occur in the plane and axis described above, therefore a robot with 2R2T DoF would cover a large number of procedures applicable to an injured knee.

2.2 Parallel robot with 2T2R Degree of Freedom

Current research on parallel robots with 2T2R motions turns out to be limited. Chen et al. (2002) introduced a novel 4-DoF parallel robot with base mounted prismatic actuators and 2$\underline{P}$RS-2$\underline{P}$US configuration. Fan et al. (2011) proposed a robot with four limbs containing two adjacent R$\underline{P}$U limbs and two adjacent S$\underline{P}$S limbs, connecting the base to the moving platform.In the aforementioned robots two of their arms form a plane, which limits the leg motion, so the 4-DoF available are two displacements (y and z) and two rotations (x and y axis). Other parallel robots with 2T2R have been proposed, but they present some difficulties from an assembly point of view, or they have been designed for very specific tasks. To sum up, Fig. 1 shows four conceptual designs which are based on Chen et al. (2002) and Fan et al. (2011), and our own design analysis.

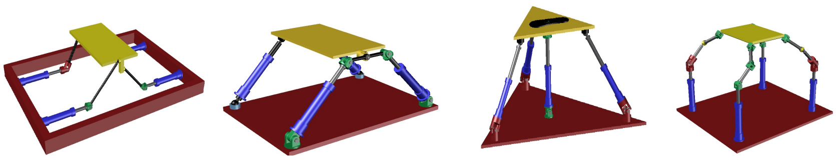

Figure 1. From left to right 2PRS+2PUS modified Chen et al. (2002), 2RPU+2SPS modified (Fan et al., 2011), 3UPS-RPU, and 2PRRR+2PUSR.

Of the four conceptual design shown in Fig 1, the 3UPS-RPU presents the following advantages: 1) High load-to-weight ratio thanks to the central strut, which represents an important factor for selecting the robot since it has to be able to hold in some cases up to the entire weight of the human body. 2) The central strut includes a revolute joint constraining the end-effector's motion to the sagittal plane (which is the required motion), the joint can also provide a wide rotational motion in the plane in which the translational motions occur. Therefore, we selected the 3UPS-RPU as the architecture for the knee diagnosis and rehabilitation robot.

3 Kinematic Analysis of the 3UPS-RPU Parallel Robot

A global coordinate system O_F is attached to the center of the fixed platform, while a local coordinate system is attached at the center of the mobile platform O_M, both the O_F and O_M can be related through the (X, Y, Z) coordinates and the Euler angles (δ, γ, ϕ) by the following rotational matrix,

$$^{F}R_M = \begin{bmatrix} c_\gamma c_\phi & -c_\gamma s_\phi & s_\gamma \\ s_\delta s_\gamma c_\phi + c_\delta s_\phi & -s_\delta s_\gamma s_\phi + c_\delta c_\phi & -s_\delta c_\gamma \\ s_\delta s_\gamma c_\phi + s_\delta s_\phi & c_\delta s_\gamma s_\phi + s_\delta c_\phi & c_\delta c_\gamma \end{bmatrix} \tag{1}$$

where $s_* = \sin(*)$ and $c_* = \cos(*)$

For the position analysis of each leg the D-H notation is used, Fig. 3 shows the parameters for the central strut, the U joints are considered as 2 consecutive revolute joints.

The position of the O_M with respect to the O_F can be found as follow,

$$\vec{r}_{F,M} = \vec{r}_{F,1} + {}^{0}R_1 {}^{1}\vec{r}_{1,2} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} c_1 & -s_1 & 0 \\ 0 & 0 & 1 \\ -s_1 & -c_1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ -d_1 \\ 0 \end{bmatrix} \tag{2}$$

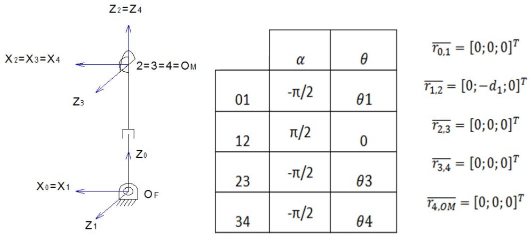

Figure 2. D-H parameters for position analysis of the central strut (R$\underline{\text{P}}$U)

$$\begin{bmatrix} X & Y & Z \end{bmatrix}^T = \begin{bmatrix} s_1 d_1 & 0 & c_1 d_1 \end{bmatrix}^T \tag{3}$$

From equation 3 $Y = 0$ which means that the end-effector is constrained to move in the sagittal plane. In addition, we are interested in the inverse kinematics problem, thus, the actuator displacement d_1 can be found as follows,

$$d_1 = \sqrt{X^2 + Z^2} \tag{4}$$

The U joint of the central strut also introduces another restriction which is that the end-effector rotation of the platform around O_F x axis is equal to zero. The second component of the vector normal to the mobile platform is null. This constraint can be written as follows,

$$-s_\delta c_\gamma {r_m}^2 s_{\beta_2} = 0 \tag{5}$$

where β_2 represents the angle between the line defined by the center of the platform and one of the spherical joint and X_m, and r_m represents the radio of the mobile platform. From equation 5, $\delta = 0$.

Considering a similar approach for the remaining leg the following set of equation can be found,

$$d_2 = \sqrt{\left(X + c_\gamma c_\phi r_m - r_f\right)^2 + s_\phi^2 {r_m}^2 + \left(Z - s_\gamma c_\phi r_m\right)^2} \tag{6}$$

$$\begin{aligned} d_i = \Bigg[& \left(X + (-1)^{(i-1)} c_\gamma c_\phi c_{\beta_{i-1}} r_m + (-1)^i c_\gamma s_\phi s_{\beta_{i-1}} r_m c\beta_{i-1} r_f\right)^2 \\ & + \left(-s_\phi c_{\beta_{i-1}} r_m + (-1)^{(i-1)} c_\phi s_{\beta_{i-1}} r_m + (-1)^i s_{beta_{i-1}} r_f\right)^2 \\ & + \left(Z + s_\gamma c_\phi c_{\beta_{i-1}} r_m + (-1)^{(i-1)} s_\gamma s_\phi s\beta_{i-1} r_m\right)^2 \Bigg]^{1/2} \end{aligned} \tag{7}$$

for $i = 3, 4$, where r_f is the radius of the fixed platform.

The velocity of the actuated joints with respect to the end-effector velocity can be found by deriving equations 4, 6, and 7. That is,

$$\dot{\vec{d}} = \mathrm{J} \begin{bmatrix} \dot{X} & \dot{Z} & \dot{\phi} & \dot{\gamma} \end{bmatrix}^T \tag{8}$$

where J represents the jacobian matrix.

4 Workspace Analysis

Equations 4, 6 and 7 can be used to develop the workspace of the 3R$\underline{\text{P}}$S-R$\underline{\text{P}}$U parallel robot. The kinematics dimensions of the robot are found based on the required Range of Motion. The workspace has to be able to include motion allowing one leg to be moved along a normal walk. After a trial and error approach the following dimensions were found: $r_f = 0.4$ and $r_M = 0.2$ meters, and $\beta_2 = 40$ and $\beta_3 = 50$ degrees. The displacement of the prismatic joints are set to 0.60 to 0.90 meters. An asymmetrical design (β_i are different) of the mobile platform was selected in order to eliminate a particular singularity of the robot that occurs when the β_i are similar. Fig. 4 shows the workspace of the robot which was found by considering the motion in the X and Z direction ($Y = 0$), and 5 degree intervals for rotation around the Z axis.

On the other hand, we simulate the case in which the robot is able to follow a prescribed taks taken from studying the leg motion. Major rotations that occur in the joints of the ankle, knee and hip were determined in Andriacchi et al. (1997). Thus, the task to study correspond to a trajectory following the central point of the foot, whereas knee displacement and hip displacement are fixed. Fig. 4 shows how the robot is capable of accomplishing the defined task.

Fig 4 shows the actual prototype which is currently undergoing dynamic modeling, parameter identification and control design stages.

5 Conclusion

In this paper we have presented the design of a robot for knee diagnosis and rehabilitation. The design specification was developed by studying the mobility needed at the robot end-effector to deal with diagnosis and rehabilitation treatments for knee injuries. Four degrees of freedom were established to accomplishing the design specification, in which two are translation (2T) and two rotational (2R). A 3-U$\underline{\text{P}}$S/R$\underline{\text{P}}$U architecture was selected from several conceptual designs of 4 DoF (2T2R) parallel robots. Then, the in-

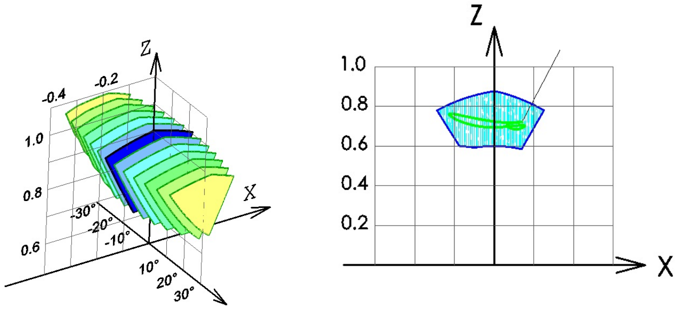

Figure 3. 3 UPS - RPU workspace, and a rehabilitation task performed within the workspace

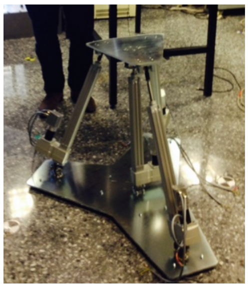

Figure 4. Prototype of the 3U$\underline{\text{P}}$S-R$\underline{\text{P}}$U for knee diagnosis and rehabilitation

verse kinematic model was developed, and the preliminary dimensions of the robot were found by trial an error. In addition, the workspace of the robot representing the end-effector X,Z and rotation around Z motion was developed through simulations. Moreover, a prescribed task taken from studying the leg motion was also analyzed. Finally, a first prototype of the robot has been built. Further work, which is currently being undertaken, focuses on dynamic modelling, parameter identification and control design of the robot. After that, clinical research will be carried out with patients.

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