DISPOSITIVO MODULAR DE REHABILITACIÓN DE RODILLA: CONFIGURACIÓN Y ESPACIO DE TRABAJO DE LAS RUTINAS DE TERAPIA FÍSICA ASISTIDA

ANDRES FELIPE GUATIBONZA ARTUNDUAGA

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Director:

ING. ALEXANDRA VELASCO VIVAS, Ph.D

UNIVERSIDAD MILITAR NUEVA GRANADA

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Modular Knee-Rehabilitation Device: Configuration and Workspace of assisted physical therapy routines

Marianne Romero-Acevedo
Mechatronics Engineering
Universidad Militar Nueva Granada
Bogotá-Colombia
tmp.marianne.romero@unimilitar.edu.co

Andrés Guatibonza
Mechatronics Engineering
Universidad Militar Nueva Granada
Bogotá-Colombia
u1802425@unimilitar.edu.co

Alexandra Velasco-Vivas
Mechatronics Engineering
Universidad Militar Nueva Granada
Bogotá-Colombia
alexandra.velasco@unimilitar.edu.co

***Abstract*—Knee injuries are common in people of all ages, due to physical activity and other reasons. In all cases, physical therapy is prescribed but it will depend on the type of injury suffered. Latest research in robotics has developed assistive devices to contribute to improving the patient's quality of life. In this paper, we propose a five-bars-linkage knee rehabilitation device, which is reconfigurable according to the patient's height. We present the kinematic modeling of the device to show that it can reproduce certain exercises or routines prescribed at physiotherapy during the knee rehabilitation according to a processor developed. For this, we show the corresponding workspace and the required mechanical configuration of the five-bars-linkage system. To validate the functionality of the processor and of the mechanism, we implement a real case routine performed by a healthy subject. We use the hip and knee angular positions to process them and show the feasibility of the system, obtaining and comparing the corresponding workspaces.**

I. INTRODUCTION

According to [19], knee injury is one of the most common causes of occupational and physical medicine consultation. Furthermore, the knee joint is more exposed to traumas due to physical activity [11]. In all cases of knee injury, after reducing pain and swelling, physical therapy is prescribed to promote tissue repair, restoring mobility or maintaining the remaining functions of the joint [13]. However, the patients sometimes do not follow the recommended regimes appropriately [12]. On the other hand, in a long-term physiotherapist may develop some occupational diseases because of the activities they must perform with patients [4]. On this basis, the interest in the research on robotic assistive devices has recently increased with the aim of improving patients' and therapists' quality of life.

There are already several devices designed for rehabilitation purposes. Some of these devices have limits regarding the routines that can be reached to contribute to patient's rehabilitation (see for example [1], [14] and [18], [15]). Other devices are heavy and non-portable as presented in [2] and [6]. On the other hand, there are portable devices like exoskeletons, as [6], [7], [9], [20], that have a disadvantage in terms of their weight, because of that the patient must support it. In some cases, this can be counterproductive for the patient's rehabilitation. Furthermore, some differences among these devices are the control strategy, the device structure, the actuation system, and the injuries covered.

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Fig. 1. Knee rehabilitation five-bars-linkage system.

Regarding knee physiotherapy, the procedure depends on the diagnosis, i.e. there are specific rehabilitation treatments according to the injury and to the patient's periodic improvement. The differences in the treatments consist of when to start the training, the number of sessions recommended, the number of trials and the muscles that need to be stretched or strengthened. However, from the therapy point of view, these routines can be part of a physiotherapy treatment for several knee injuries. The aim of the training is to recover mobility and to recover and enhance muscular strength [3].

In this paper, we tackle the possibility of performing different exercises, using the proposed assistive device (see Fig. 1), as part of physical therapy treatments. We present a five bars-linkage knee rehabilitation device which can perform several routines for stretching and strengthening the muscles that are involved in the knee stability and motion. This device is modular, portable, supported on a base to avoid loading on the patient and allows to perform different routines in comparison with other devices. The design of this five-bars-linkage soft device was already presented in [17]. To reproduce physiotherapy routines on the proposed device, we first introduce the model of the five-bars-linkage rehabilitation system. Afterward, we analyze some important knee rehabilitation routines, showing the required workspace (WS) and obtaining the corresponding signals to control the actuators in each case, to reproduce the exercises with the proposed device. Finally, we present one case study, in which we measure the hip and knee angular positions when a subject is performing a specific not-assisted routine. We treat the signals obtained in a processor where the inverse kinematics are calculated to determinate the actuating signals. These results generate the WS for the proposed device which is compared with the acquired signals to validate the processor's action. Results show

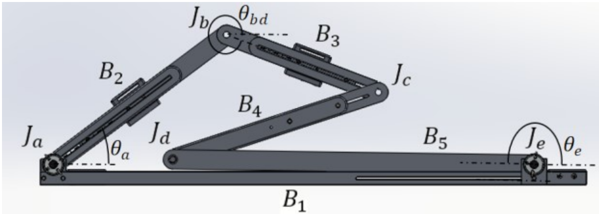

Fig. 2. Linkages of Knee rehabilitation five-bars-linkage system.

TABLE I
POSITION JOINTS EQUATIONS FOR FIVE-BARS LINKAGE SYSTEM

Joint	x Axis	y Axis
J_a	0	0
J_b	$l_2\ cos(\theta_a)$	$l_2\ sin(\theta_a)$
J_c	$B_x + l_3\ cos(\theta_{b_d})$	$B_y + l_3\ sin(\theta_{b_d})$
J_d	$E_x + l_5\ cos(\theta_e)$	$l_5\ sin(\theta_e)$
J_e	l_1	0

that we can reproduce the desired exercise using the proposed device, respecting the mechanical limits of the mechanism to guarantee the patient's safety.

II. FIVE-BARS-LINKAGE SYSTEM MODEL

Let us now consider rehabilitation treatments that include routines in sitting and lying position. We present in this section the kinematic modeling of the five-bars-linkage system, to perform such routines. The system has two actuated joints, J_a (hip) and J_e (auxiliary) on the fixed body B_1. Then, θ_a is the angular position of the thigh B_2 at joint J_a; θ_b is the angular position the calf B_3 at joint J_b; and θ_e is the angular position of the body B_5 (auxiliary) at joint J_e, as shown in Fig.2. Notice that at the knee joint J_b there is no actuation. To move the knee joint it is necessary to calculate the relation between J_b and the actuated joints J_a and J_e. This modeling can be obtained by Davies' method, which is based on screw theory, Assur's virtual chains and Kirchhoff laws. Depending on the requirements, we obtain static, kinematic or kinetostatic equations, as defined in detail in [16], [5]. In this case, we derive kinematic equations to validate the model. To obtain the dynamics equations for control we need to derive the static equations and define the load torque to replace it in the actuators model, as explained in [17]. The motion of the five-bars-linkage system proposed (Fig.1) can be represented by position equations of joints J_a, J_b, J_c, J_d and J_e, taking into account the angles θ_a, θ_b and θ_e measured according positive x-axis, and the lengths l_1, l_2, l_3, l_4 and l_5 of each body B_1, B_2, B_3, B_4 and B_5 respectively, as shown in Table I[1]. A detailed description of this modeling is explained in [17].

Defining ω_a and ω_e as the angular velocities of joints J_a and J_e respectively, we obtain the angular velocity equations ω_b at J_b from Davies' Method as

$$w_b = -w_e\, k_r + \frac{w_a\,(C_x\, D_y - C_y\, D_x) k_r}{C_x\, D_y - C_y\, D_x - C_x\, E_y + C_y\, E_x + D_x\, E_y - D_y\, E_x}; \quad (1)$$

where k_r is an auxiliary term defined as,

$$k_r = \frac{C_xD_y - C_yD_x - C_xE_y + C_yE_x + D_xE_y - D_yE_x}{B_xC_y - B_yC_x - B_xD_y + B_yD_x + C_xD_y - C_yD_x}; \quad (2)$$

In (1) and (2), B, C, D, E, denote the system joints and the sub-indices x and y indicate the joint's position component in the corresponding axis.

The static equations are defined by the load torque of the entire system in the knee joint Tb, which means that the actuation torque Ta at the hip joint is defined by

$$T_a = \frac{T_b(C_xD_y - C_yD_x)}{B_xC_y - B_yC_x - B_xD_y + B_yD_x + C_xD_y - C_yD_x}, \quad (3)$$

and the actuation torque T_e at joint J_e is

$$T_e = -\frac{T_b(C_xD_y - C_yD_x - C_xE_y + C_yE_x + D_xE_y - D_yE_x)}{B_xC_y - B_yC_x - B_xD_y + B_yD_x + C_xD_y - C_yD_x}. \quad (4)$$

Using the values of torque T_b in (3) and (4), we obtain the dynamic behavior of the system for control; however, this procedure is not reported here because it is out of the scope of this paper; it will be reported in future work regarding the control strategy for this system.

III. MECHANISM CONFIGURATION FOR REHABILITATION ROUTINES

The rehabilitation therapy is determined by an expert, e.g. a physiotherapist, according to the knee injury. Among the most common routines, the physical programs include exercises as the Unilateral hamstring stretch in supine, the Assisted unilateral hamstring stretch in supine, and passive hip and knee movements [8]. In this section, we show the requirements of these routines from the mechanical point of view. For each case, we show the corresponding WS and the implementation of the routine using the proposed device. To carry out these exercises in an assisted way, using the proposed device, it is necessary to consider some anatomical parameters, i.e. the patient's height and the proportions of the legs segments. To meet patients' requirements, the most important mechanical characteristic of the system is reconfigurability. We consider that the system can be configured for patients' heights between 1.40 m and 1.90 m, according to mean adult population. Likewise, we seek to attend different rehabilitation routines as required in each case. The repetitive motions for the knee (joint J_b) required for each routine are achieved by actuating the joints J_a and J_e on the fixed body B_1, as in Fig. 2, reducing the actuation torques and unwanted loading in the knee.

In this way, for each routine we obtain experimentally a defined mechanism configuration. Consider a subject of height h; for the sake of analysis and according to the anatomy proportions [10], the length ratio of the leg segments B_2 and B_3 with respect to the height h is $l_2 = h/3.75$ and $l_3 = h/5$ respectively, therefore the length of B_1 is $l_1 = l_2 + l_3$.

[1] Notice that the equation for C_y is used to determinate the coordinates of joint J_c knowing the desired angular position θ_{b_d}.

In addition, we implement a processor (see Fig. 3) in two steps, to calculate the inverse kinematics for the actuated joint J_e, from a known behavior of the hip θ_a and a desired motion of the knee θ_{b_d}. This is done considering the mechanical restrictions, to prevent the motors the generation of movements outside the limits of the mechanism, avoiding collisions with the ground avoiding motions that could hurt the patient. First, the range of motion of the knee and hip constrain the inputs as $0° \leq \theta_a \leq 120°$ and $-30° \leq \theta_b \leq 90°$. These signals depend on the routine that will be implemented, then the aim of this step is to determine θ_e, as

$$\theta_e = (\pi - \eta) + \rho, \quad (5)$$

which is the actuation signal of joint J_e, where

$$\rho = \arccos((p^2 + l_5^2 - l_4^2)/(2\,p \setminus l_5)),$$
$$\eta = \arccos((p^2 + l_1^2 - x^2)/(2p \setminus l_1)),$$

which depend on the lengths l_1, l_4 and l_5 of the corresponding links, and on the auxiliary variables x and p defined as

$$x = \sqrt{C_x^2 + C_y^2},$$
$$p = \sqrt{(E_x - C_x)^2 + C_y^2},$$

where C_x, C_y and E_x are defined in Table I, and these are calculated using θ_a and θ_b respectively.

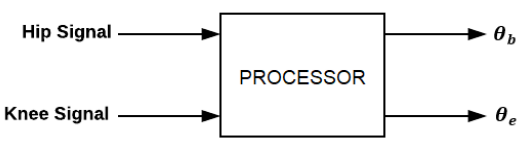

Fig. 3. Inputs and outputs for the inverse kinematics processor of the five-bars-linkage system.

Second, we use the signal θ_e obtained in the first step to calculate the resulting motion for the knee θ_b at joint J_b as

$$\theta_b = \arcsin((C_y - B_y)/l_3), \quad (6)$$

where B_y is defined in Table I. Instead, C_y will depend of angular position θ_d at joint J_d according to[2]

$$C_y = D_y + l_4 sin(\theta_d),$$

then,

$$\theta_d = \begin{cases} \pi - \rho - \sigma,\ for\ C_x < D_x\ or\ \ C_x > D_x\ and\ B_x > D_x \\ \rho = \arcsin\left(\dfrac{B_y - D_y}{r}\right), \\ \rho - \sigma,\ for\ \ C_x > D_x\ and\ B_x < D_x \\ \rho = \arccos\left(\dfrac{B_x - D_x}{r}\right). \end{cases}$$

The auxiliary terms $r = \sqrt{(B_y - D_y)^2 + (D_x - B_x)^2}$ and $\sigma = \arccos((l_4^2 + r^2 - l_3^2)/(2 l_4 r))$ relate geometrically the link lengths l_3, l_4, and the coordinates B_x, B_y of joint J_b and D_x, D_y of joint J_d. These values depend on θ_a and θ_e, as shown in table I. Notice that θ_b is different from the input signal θ_{b_d}, because according to the mechanism configuration and the mechanical constraints this signal will be adjusted to the levels that can be attended by the proposed mechanism. In this way, the signals θ_a and θ_b define the hip and the knee motion for each routine introduce below. Then we obtain the signal θ_e required to control the actuator placed at joint J_e, which will cause the desired motion for the knee on θ_b at joint J_b, according to the mechanism characteristics and configuration. The output of the processor in Fig. 3 includes the maximum and minimum values of θ_a and θ_e that can be attended for a desired angular position θ_{b_d} at the knee. It is worth noting that the signal imposed to both actuated joints J_a and J_e depend on the subject's height and the length of the base link B_1. In that way, we can determine the WS and the resulting motion of θ_b for each of the routines presented in this paper.

[2] Notice that the equation below is used when we want to determinate the coordinates of joint J_c (this is C_y) knowing the angular position θ_e of joint J_e, and without knowing θ_b.

A. *Unilateral hamstring stretching in supine*

This rehabilitation routine aims to stretch the hamstrings. For this, the patient is in a supine position with the leg flexed at the hip. Without any assistive device, the patient should place the hands on the thigh for support and then straighten the knee as shown in Fig.4.a. There are two advanced options, i.e. the first is to bring the leg towards the hip flexion and the second is to add dorsiflexion. To perform this routine with the five-bars-linkage system proposed, we determine the values of the segments and joints experimentally. In this case, we define $h = 1.80m$, $l_4 = 0.57\,m$ and $l_5 = 0.62\,m$. The WS for this configuration and the requirements for this rehabilitation routine is obtained as follows. We use a constant signal θ_a of $\pi/2$ at joint J_a and a sinusoidal signal of amplitude $1\,rad$ and bias of $1.17\,rad$ at joint J_b. These signals are entered to the first step of the processor. Here, the inverse kinematics is calculated, getting the angular position for J_a and J_e. The processor does not only calculate the inverse kinematics, but it also limits and adapts the signal for the motors at J_a and J_e according to the mechanical constraints of the mechanism. Then, in Fig.5, we show how the angular position signal for joint J_e changes. Nevertheless, after carrying out the second step of the processor, the final signal for J_b is different of the entered

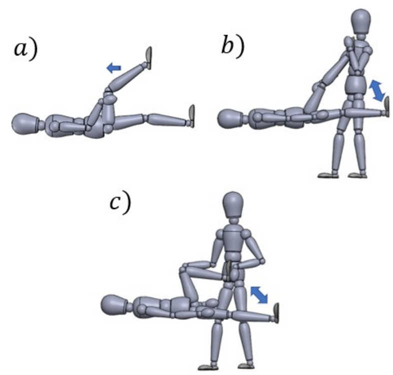

Fig. 4. Routines for knee rehabilitation: a) Unilateral hamstring stretch in supine, b) Assisted unilateral hamstring stretch in supine, c) Passive hip and knee movements.

signal, because the initial signal has an amplitude greater than the one that can be reached by the mechanism. The resulting WS allows extending the leg completely to 180° and to flex it to 102° defined as shown in Fig.6, with the hip at 90°.

B. Assisted unilateral hamstring stretch in supine

This rehabilitation routine aims to stretch the hamstring muscle. For this, the patient should be in supine with the hip flexed, the knee extended, and the leg raised and resting, as shown in Fig.4.b. Then the therapist applies a gentle upward pressure to the leg to push the hip into further flexion, making sure that the knee remains straight. There are two advanced options. First, to push the leg further into hip flexion; second, to add dorsiflexion to the ankle, i.e. flex the ankle joint so that the lower part of the foot turns towards the shin. To implement this routine, we determine experimentally that the system must be configured with $h = 1.80m$, $l_4 = 0.57\,m$ and $l_5 = 0.62\,m$. The WS for this configuration and the requirements for

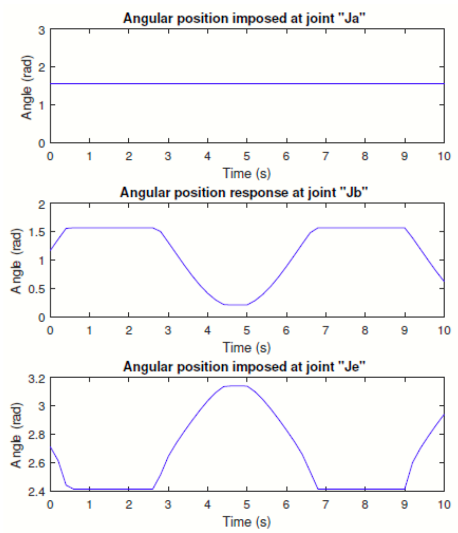

Fig. 5. Angular position response at joints "J_a", "J_b" and "J_e" for Unilateral Hamstring Stretch in Supine routine

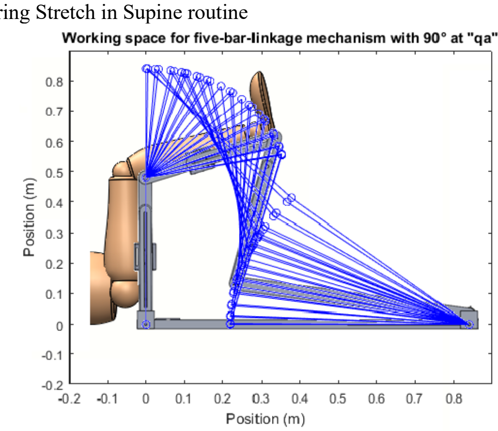

Fig. 6. WS for Unilateral Hamstring Stretch in Supine routine.

the rehabilitation routine, are determined by a sinusoidal signal θ_a at joint J_a of amplitude of 0.495 rad and bias of 1.0708 rad and a sinusoidal signal θ_{b_d} at joint J_b of amplitude of 0.6 rad and bias of 1.17 rad. With these signals, the first step of the processor calculates the inverse kinematics, obtaining the angular position for J_a and J_e . Fig.7, shows the angular position signal adequate for joint J_e. Nevertheless, after carrying out the second step of the processor, the signal for J_b is exactly same of the entered signal. This configuration gives a WS with a maximum value for the hip of 90° and a minimum value of 33°

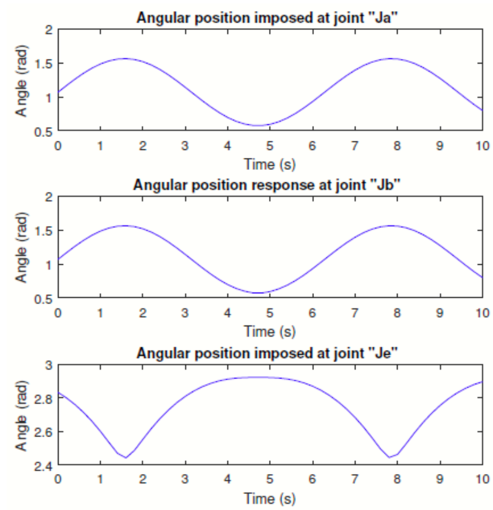

Fig. 7. Angular position response at joints "J_a", "J_b" and "J_e" for Assisted Unilateral Hamstring Stretch in Supine routine.

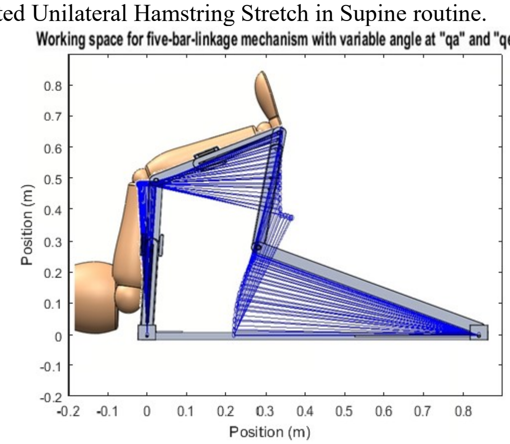

Fig. 8. WS for Assisted Unilateral Hamstring Stretch in Supine

that allows extending the leg completely in 180° for any position of the hip, as shown in Fig.8.

C. Passive hip and knee movements

This rehabilitation routine aims to stretch or maintain the range of motion of the hip and knee joints. For this, the patient must be in supine with the legs extended. Then, passively move the hip and knee joints through their full range of motion, as shown in Fig.4.c. To implement this routine, the five-bars-linkage system proposed in this paper is experimentally configured with $h = 1.80m$, $l_4 = 0.4\ m$ and $l_5 = 0.4\ m$. It is important to highlight that performing this routine with the device, will not strengthen the abdominals. The WS and the requirements for this rehabilitation routine, are obtained by using a sinusoidal signal θ_a of amplitude of $0.94\ rad$ and bias of $0.94\ rad$ at joint J_a, and a sinusoidal signal θ_{b_d} of amplitude of $-0.1\ rad$ and bias of $-0.1\ rad$ at joint J_b . Calculating the inverse kinematics with the first step of the processor, we obtain the angular position for J_a and J_e, which is presented in Fig.9. Notice that the signal for J_b is exactly same of the entered signal. This configuration gives a WS with a maximum value for the hip of 107.7° and a minimum value of 0°, that allows extending the leg at a maximum value of 180° and flexing the leg at a minimum value of 78.5° defined as shown in Fig.10.

IV. RESULTS

To validate that the processor can be implemented for a defined routine, we obtain the WS and reference signals for the

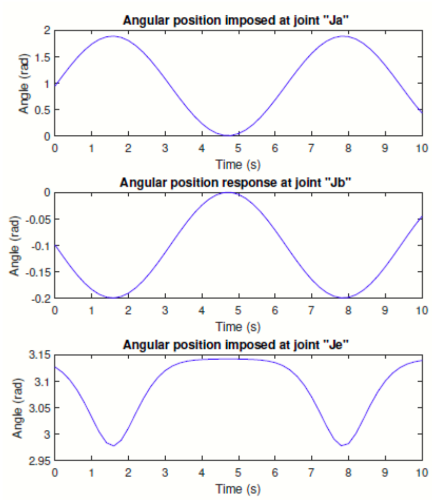

Fig. 9. Angular position response at joints "J_a", "J_b" and "J_e" for rehabilitation routine Passive Hip and Knee motions.

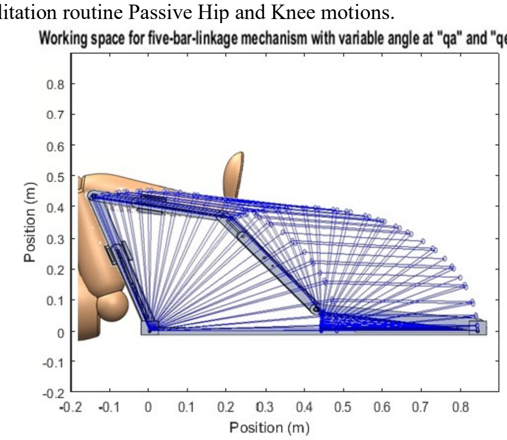

Fig. 10. WS for rehabilitation routine Passive Hip and Knee motions.

Fig. 11. Measurement device to acquire knee and hip angular positions when performing rehabilitation routines.

actuated joints J_a and J_e, considering the mechanical restrictions of mechanism. For this, we built an auxiliary two-linkage device as shown in Fig.11., with the purpose of measuring the hip and knee angular positions when performing the Unilateral hamstring Stretch in supine routine. To reduce errors and to have repeatability, we use respectively a potentiometer and a Gyroscope MPU6050 to measure the angular position of joints at knee and hip. Data are collected using an Arduino Mega2560 and processed Using a low-pass filter with Matlab®.
Without any assistance, the subject should place the hands behind the thigh and must extend the knee. After carrying out the routine five times for 10 seconds each time, we filter and process data. The resulting signals of the hip and knee are

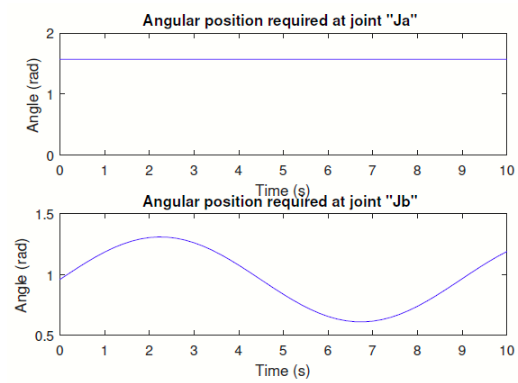

Fig. 12. Measured angular position signal of joints "J_a" and "J_b" for Unilateral Hamstring Stretch in Supine routine.

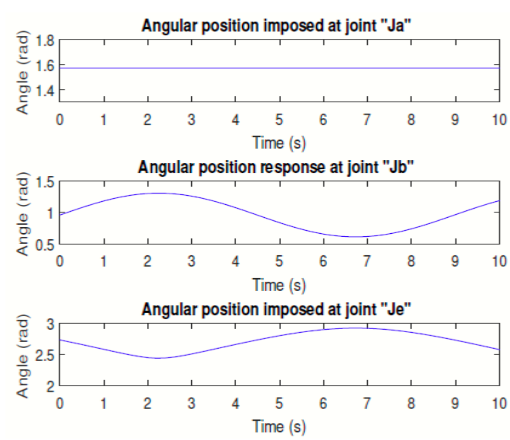

Fig. 13. Angular position -joints "J_a", "J_b" and "J_e" for Unilateral hamstring stretch in supine routine according to measurements.

shown in Fig.12. Observe that the range of motion of knee is between $0.6113\,rad$ and $1.309\,rad$. We use these signals as inputs for the processor, to calculate the inverse kinematics of mechanism proposed, which is configured with $l_4 = 0{,}5\,m$ and $l_5 = 0.6\,m$. In this way, we obtain the angular position signals that will be used to control the actuators at joints J_a and J_e of the five-bars-linkage mechanism. We use these signals to calculate the second step of processor, to verify the inverse kinematics for joints J_a and J_e. Let us calculate the resulting position for J_b to attend the same routine done by the patient as shown in Fig.13. These signals allow to reproduce the behavior of the mechanism and compare the WS generated by Matlab® (Fig.14) with the routine carried out by the subject. Comparing the WS proposed in Fig.6 with the WS in Fig.14, we can point out that the movement required for a physiotherapy routine can be carried out with the prototype proposed. Finally, this prototype will let the patient carry out passive exercise with the aim of recovering the flexibility of tendons and muscles that are involved in the proper functioning of the knee. This could substitute to some extent the physical assistance in rehabilitation, provided by a physiotherapist, as well as and the use of elastic bands in the process of stretching the muscles.

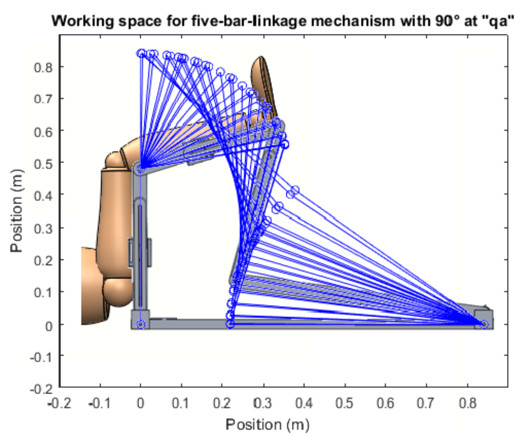

Fig. 14. WS for rehabilitation routine Unilateral Hamstring Stretch in Supine using measured positions.

V. CONCLUSIONS

In rehabilitation prototypes, it is possible to find several possibilities to solve some of the most frequent injuries. In this paper, we present a solution for a knee rehabilitation device. We have presented some of the most commonly used routines, i.e. Unilateral hamstring stretch in supine, assisted unilateral hamstring stretch in a supine position, and passive hip and knee movements. According to the mechanical configuration requirements, it is possible to attend all the routines proposed considering the mechanical restrictions of the prototype. To prove this, we have shown the WS in each case. Furthermore, we measured the hip and knee position of a healthy subject when performing a chosen routine. From this, we determine that the motion performed by a healthy patient is inside of the WS that can be attended by the prototype in the proposed configuration. Future works will be focused on the physical implementation of the proposed device, studying all the configurations to choose a complete rehabilitation program, and controlling the soft actuated device.

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