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Mechanical design and validation of an auxiliary active device for rehabilitation of the knee and quadriceps

Diseño Mecánico y validación de un dispositivo activo auxiliar en la rehabilitación de rodilla y cuádriceps

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Abstract

Motion difficulties, specifically the walk and displacement, are very common afflictions, mainly caused by some type of injury. The recurrent kind of rehabilitation treatments involve exercises of active and passive mobility. The success in the treatment and the early return to sports activity depends largely on the rehabilitation process. This should begin immediately after the production of the wound or the surgical process to repair the damage. The objective of this work is to develop a low-cost, easy manufacturing and assembly device, capable of providing exercises of active mobility. We designed an affordable and adaptable six-bar Watt linkage, coupled to a conventional leg extension machine. Structural and dynamic studies determine its safeness and its efficiency. The results of the kinematic and dynamic studies showed that the available range of motion for the different configurations goes from 24° to 109°. Its structural integrity was analyzed, pointing out that the weakest link had a Factor of Safety of 1.3, while the highest presents a value of 14.7, so that, the material overpasses the load needs. Based on the obtained results, a six-bar linkage is a viable option for the development of low-cost, therapeutic active devices.

Rehabilitation, Six bar linkage mechanism, Active exercise

Resumen

Los padecimientos de movimiento, específicamente la marcha y el desplazamiento, son muy comunes, principalmente causados por algún tipo de lesión. Los tratamientos de rehabilitación recurrentes implican ejercicios de movilidad activa y pasiva. El éxito en el tratamiento y el regreso a la actividad deportiva dependen en gran medida del proceso de rehabilitación. Éste debe comenzar inmediatamente después de la producción de la herida o del proceso quirúrgico para reparar el daño. El objetivo de este trabajo es desarrollar un dispositivo de bajo coste, fácil fabricación y montaje, capaz de proporcionar ejercicios de movilidad activa. Diseñamos un mecanismo Watt de seis barras adaptable, acoplado a una máquina convencional de extensión de piernas. Estudios estructurales y dinámicos determinan su seguridad y su eficiencia. Los resultados de los estudios cinemáticos y dinámicos mostraron que el rango de movimiento disponible va de 24° a 109°. Se analizó su integridad estructural, señalando que el eslabón más débil presenta un Factor de Seguridad de 1,3, mientras que el más fuerte presenta un valor de 14,7, superando las necesidades de carga. En base a los resultados obtenidos, un mecanismo de seis barras es una opción viable para el desarrollo de dispositivos activos terapéuticos de bajo costo.

Rehabilitación, Mecanismo de seis barras, Ejercicio activo

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1. Project Background

The injuries in any of the four major ligaments in the quadriceps, like anterior cruciate, posterior cruciate, medial collateral, and lateral collateral may adversely affect the biomechanical and functional stability of the knee. The success in the treatment and the early return to sports activity in the best way possible may depend largely on the rehabilitation process. This should begin immediately after the production of the wound or the surgical process to repair the damage (Legido, 2008).

For the year 2020, 6 million and 179 thousand 890 persons have some kind of disability, which represents 4.9% of the total population. Most of the disabled people have difficulties for walking or moving (60.4%). In this respect, there is no more specific data about people with difficulties because of their knees. Nevertheless, the percentage of this incapacity is high, compared with other types of disabilities such as visual, hearing, language, or mental (INEGI, 2020).

The recovery of the range of motion (ROM) is one of the main aspects of the postsurgical phase of the rehabilitation process. Early mobilization of the joint after surgery might decrease pain, reduce adverse changes of the articular cartilage, promote articular nutrition, improve wound healing, and prevent joint capsule contraction (Barber, 1993; Mackenzie, 1996; Siegel, 1998).

Among the most reviewed early-rehabilitation exercises in the literature are the knee passive flexion and extension in a sitting position. Depending on the patients' progress, this will go from slow and continuous repetitions until reaching a ROM of 90°, to faster and discontinuous repetitions until reaching 120° of motion (Legido, 2008; Damo, 2012; Coordinación, 2019).

Chaparro Cárdenas et. Al. (Chaparro, 2018) say that physiologic rehabilitation devices are classified into two large groups, active and passive devices. The first group consists mainly of links and springs, avoiding the use of electromechanical actuators with the intention of patients being capable of doing the exercises by themselves for their therapies, this is known as active mobility exercises.

Divergently, the active devices are focused on the use of electromechanical actuators, control devices, and signal processing, among others, to assist the patients in the precise generation of the necessary movements for their recovery, this is known as passive mobility. These devices are divided into three categories: treadmills, foot manipulators, and orthoses.

Passive mobility systems (with active devices) tend to present a bigger benefit than active mobility ones. Despite the relevant technological advances being done for active devices aimed at the rehabilitation of muscles and ligaments of legs plenty of them are not an option for most of the Mexican population, primarily due to the high cost that these devices involve (Chaparro, 2014). View Table 1.

This paper presents a proposal for a device that can be used as an auxiliary on knee rehabilitation exercises for people with this kind of injury. We obtained affordable, easy manufacturing, and adaptable linkage that is coupled to a conventional leg extension machine. Structural and dynamic studies determine the safety of the machine and its efficiency in terms of the use of material.

2. Current Advances in Knee Rehabilitation Devices

Knee rehabilitation devices are devices under current study, some of them try to implement complex control systems, last-generation fluids that change their behavior through variations of a magnetic field, or implementations of Human-machine interfaces with touchscreens. All of them achieve versatility of speed and range of motion but the materials, electronic components, and actuators are expensive and delicate. For this reason, these kinds of machines are not attractive to rehabilitation centers where patients cannot afford expensive treatments and heavy-duty work is necessary. Both active and passive devices are under continuous research in universities. Some related papers are discussed in the following.

The work of Paolo (Damo, 2012) presents the background of devices for different knee rehabilitation stages. There he explains the Kinetec spectra, a commercial device of Continuous Passive Motion (CPM) that breaks the inflammatory and traumatic cycle, reducing joint stiffness.

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It has a slider-crank mechanism assisted by electronic control. The work of Umchid (Umchid, 2016) shows on one side the development of a smart continuous passive motion device with control performed by an Arduino board and a touchscreen. In the work of Weinberg (Weinberg, 2007), they engineered an active device that is attachable to the legs of the patient. This device characterizes by its lightweight and use of electro-rheological fluids to control the stress developed in the knee.

The company Arthro-motion (Phoenix, 2022) developed a passive and low-cost machine called K.I.M (Knee in motion), it allows the patient to manually control the speed and range of motion and see their progress using three levers. It does not need a complex set-up or assembly because of the simplicity of the design. Li and colleagues (Li, 2021), proposed using a six-bar linkage mechanism to improve the treatment of patients with gait problems since this mechanism matches precisely with the gait trajectories. Table 1 collects the devices mentioned above and shows their main characteristics and an image for each machine.

3. Mechanical Fundamentals for the Knee Rehabilitator

In order to do a synthesis of a mechanism capable of performing flexion and extension motions, it is essential to know the principles of mechanism design, mainly Grashof conditions and vectorial loops. Kinematic and dynamic studies were done with the Solid-Works motion tool. The results are exported to a Finite Element Analysis tool where the dynamic load is tested against geometrical and material properties for every link in the machine.

3.1. Grashof condition

The Grashof condition is a simple inequality relation that predicts the rotational behavior of the inversions of a four-bar linkage. This condition is based on the length of the links. Depending on how the inequality is solved, the mechanism will be classified in one way or another.

If S is the length of the shortest link; L is the length of the longest link; P and Q are the lengths of the rest of the links, there are two main classes:

In Class *I*, $S+L \leq P+Q$, the mechanism is known as “Grashof” and at least one link will do a complete revolution with respect to the frame.

In Class *II*, $S+L>P+Q$, the mechanism is known as “Non-Grashof”, and no link is going to perform a complete revolution, this is also known as a triple rocker (Norton, 2013).

3.2. Watt six-bar linkage

Watt six-bar linkage essentially consists of two four-bar mechanisms, as it is shown in Figure 1, and it can be analyzed that way. The closed loop equations of the second mechanism are solved after the results of the first loop are applied as data for the second. The analysis for the four-bar linkage is applied twice in this kind of mechanism.

The reason why the synthesis for this kind of mechanism is realized instead of a simple four-bar mechanism is that these could not meet the geometrical necessities, in which the requirement of a machine reaches a blocking position in the output link when there is motion in the input of the mechanism (Norton, 2013).

3.3. Finite Element Analysis (FEA)

The finite element method is a computational numerical technique that allows the description of the behavior of a system under certain work conditions. This technique consists of the discretization of a body in n parts, such parts are denominated elements, and their connections are known as nodes. These are studied under Hooke’s law, which says that the deformation of a body is directly proportional to the applied stress, as long as the stress is inside the elastic region of the material. To provide accurate results, matrix calculations were done by programming them in a high-level language. The objective is to determine the nodal displacements with the stiffness matrix and the nodal forces as in equation (1).

$$\{f\} = [k]\{u\} \quad (1)$$

Where:
$\{f\}$: Nodal forces
$[k]$: Stiffness matrix
$\{u\}$: Nodal displacements

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The stiffness matrix is defined by the geometrical and material characteristics of the body, whereas the nodal forces matrix is governed by the mechanical loads in the system. When the displacements are gotten, these are substituted in the equations of the solid mechanics that establish the relation between strain and stress, equation (2).

$$\varepsilon = \frac{\Delta L}{L_0} \qquad \sigma = E\varepsilon \tag{2}$$

Where,
ΔL: Elongation.
L_0: Original length.
ε: Strain.
E: Elasticity Modulus.
σ: Stress

Previously it was mentioned that the matrixes are larger depending on the number of degrees of freedom and the way that discretized elements are connected. In addition, the calculations of stresses are performed as many times as necessary according to the existing elements in the body. This method may be a bit impractical if it is intended to be done step by step. Today exists a wide variety of software selections that helps the engineering job, implementing the finite element analysis inside the design spaces with a friendly-user interface in an intuitive post-processing product based on the color scale. Some of the most used software are SolidWorks Simulation, Nastran, Algor, and Ansys Workbench. The use of any of these reduces to a great extent the time and cost of the prototype design (Budynas, 2015).

4. Mechanical Design of the Knee Rehabilitation Machine

A conventional gym machine is adapted to accommodate an articulated linkage that generates a maximum range of motion as close as possible to 120°; this mechanism must be adjustable to adapt to the different stages of knee-injured patients' rehabilitation. The input motion will be delivered by a compact DC motor. SolidWorks 2020 package was used for the mechanical design of the linkage, Motion, and Simulation plugins were used to perform the kinematic, dynamic, and structural analysis. The complete goal and established conditions are shown in Table 2, and the model of the gym machine is represented below in Figure 2.

4.1. Synthesis of the mechanism

Due to reduced space, the structure of the frame, and big outputs of motion, it was decided to do the synthesis of a Watt six-bar linkage. As mentioned previously, this configuration can be analyzed and characterized by separating the mechanism into two closed loops of a four-bar linkage.

The geometrical parameters for the synthesis of the mechanism were defined, firstly, to achieve an angular displacement as near as possible to 120°. Then, some drill holes were done to adjust the connections of the mechanism, thus, obtaining different ranges of motion. Additionally, it can be seen in Figure 3 that link 3 (DCE) joins both vectorial loops to conform to the mechanism, and because of its configuration, saves space and material for that linkage. In Table 3, the lengths of each link to fulfill a maximum range of motion are presented.

4.2. Modelling of components

We considered the use of a steel strip of 1½" in width and ¼" to ½" thickness of ASTM A36 steel for the design, plus a steel bar of 1" in diameter. This material was chosen because of its wide use in structures, good ductility, high strength to fatigue, and affordable cost. Some of its mechanical properties are shown below:

– Elastic Modulus (E) = 200 GPa
– Yield strength (Sy) = 250 MPa

Several ranges of motion can be reached just by connecting links in different drill holes. In Figure 4 the design of the linkage can be seen. Another need was to design a speed reducer transmission. From the datasheets of the DC motor and the geared motor, this one reaches a minimum speed of 90 RPM (revolutions per minute). To reach an adequately low speed for patients that are in their last stages of recovery is necessary to decrease that speed to 30 RPM. Taking into consideration standard AGMA sizes of gears, a diametral pitch of 10, and a 15 teeth gear in the input. Below are the calculations in equations (3)-(4) and the model of the transmission is presented in Figure 5. The assembled mechanism is shown in Figure 6.

$$\frac{\omega_2}{\omega_3} = \frac{N_3}{N_2} \tag{3}$$

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Where:
ω_2 and N_2: Angular velocity and number of teeth in the input.
ω_3 and N_3: Angular velocity and number of teeth in the output.

$$N_3 = \frac{\omega_2}{\omega_3} N_2 = 45\, teeth \tag{4}$$

5. Mechanical Analysis

In the study of the mechanics of the system, first is needed to calculate kinematics aspects such as velocity, acceleration, and angular displacement, this latter must be as close as possible to 120° in the configuration that provides the highest range of motion. Afterward, knowing the torque needed to generate the desired amount of movement is crucial to ensure that the electric motor proposed is suitable for the task. Lastly, the dynamic analysis should be done with Finite Element Methods to appreciate how the stresses are distributed throughout the components and if they can support the dynamic loads.

5.1. Kinematic analysis

Velocity and extent of the range of motion are crucial for a successful recovery in physiotherapeutic patients. Hence, for purposes of the motion analysis, an input of uniform circular movement on the crank of 30 RPM was established, which means doing an exercise of flexion or extension every two seconds, no matter the range of movement selected. To simulate a real leg load from a patient, it was also defined as a load that will oppose the motion in half of a duty cycle, and it would help motion on the other half. Besides, the standard value for gravity acceleration was set up to fill the necessary boundary conditions for the study. Next in Table 4, the conditions that were established in the software are described.

As mentioned earlier, the drill holes in the piece that joins both loops and in the second coupler, help to provide a wider range of motion on the machine. The number of possible combinations is quite large, however, for purposes of this paper, eight of them were analyzed, as may be seen in Figure 7.

It should be mentioned that the weight of the links also generates loads for the mechanism, so they were already calculated from the tridimensional design of the elements.

The trace path of the last link on the mechanism is shown in Figure 8. Figure 9 shows that configuration (a) is the one that provides the biggest range of motion with an angular displacement of 109°, while the other configurations show reductions of 10° to 15° until reaching the minimum ROM, which is 24° in configuration (h).

5.2. Torque

Motor torque is a physic magnitude that measures the rotational force applied to a shaft, causing a rotational movement. In the studied mechanism, knowing this magnitude is significant to adequately select a motor that can perform the task or process it. The torque analysis intends to validate the use of the proposed motor.

It was detected a direct relationship between the amount of angular displacement and the necessary torque to execute it, because once again, configuration (a) required the most amount of torque (25.4 N.m), whereas the configuration that needed the lowest amount of torque to perform its ROM was the configuration (h), with 6.3 N.m. The outcomes can be seen in Figure 10.

According to the Maxon motor data sheet, the maximum amount of intermittent torque is 22.5 N.m, so when executing the work directly it would not be able to carry out the largest angular displacements. However, when implementing a speed reduction transmission, it will also be a torque multiplier in the same proportion that it reduces speed. In other words, the proposed transmission also helps to not strain the engine in its functioning.

5.3. Dynamic analysis of stresses

It was decided to analyze the configuration (a) from Figure 10, due to being the one that requires the most torque among the others for its working, besides providing the highest angular displacement, therefore, suffers the highest dynamic loads. With the aid of Solidworks Motion and Simulation plugins, it was possible to do a Finite Element Analysis for the dynamic loads present in the mechanism. This study is complemented with the maximum distortion energy criterion, where the outcome of the general state of stresses is known as Von Misses stress, and is given by equation 5.

This kind of stress is compared with the yield strength of a material to obtain the corresponding factor of safety as in equation 6.

$$\sigma_{VM} = \left[\frac{(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2+6(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)}{2}\right]^{\frac{1}{2}} \quad (5)$$

$$n = \frac{S_y}{\sigma_{VM}} \quad (6)$$

Where,
$\sigma_x, \sigma_y, \sigma_z$: Normal components of the general state of stress.
$\tau_{xy}, \tau_{yz}, \tau_{zx}$: Shear components of the general state of stress.
σ_{VM}: Von Mises stress.
n: Factor of Safety (FoS).
S_y: Yield strength.

The use of the two plugins simultaneously facilitates calculations since the magnitudes of the dynamic loads change throughout the work period. The maximum stresses and minimum FoS of each link on the six-bar mechanism are presented below in Table 5. In the results, it can be seen that the lower FoS for a part in the entire work cycle of the mechanism is 1.3 for the rocker that joins both vectorial loops on the six-bar linkage. This Factor of Safety shows efficient use of both surface area and material, likewise of certainty on the structural integrity of the element. Besides, the highest Factor of Safety with a value of 14.7, is due to the coupler of the second loop, this means that the material overpasses the work needs by a wide margin.

6. Discussion

The proposed machine is capable of delivering ranges of motion from 20° to 109° with increments of 15° average between each configuration. The needed torque to perform the duty cycle is considerably lower on the electric motor than on the mechanism due to the use of a 1/3 speed reducer transmission, thus the Maxon motor selected previously will be under safe stress conditions. These conditions confirm the versatility of the apparatus for the different patients' rehabilitation stages. However, only a few configurations were tested and certainly, some of them will get to a blocking position leading to a high state of stress for all the components, which could be harmful to the machine and patient. These configurations should be identified to avoid accidents.

As mentioned earlier, every link in the mechanism has an elastic behavior in the work period, with the weakest link reaching a factor of safety of 1.3. The stress distribution on the material shows that the maximum stress is located on the joint of coupler 1. In the rest of the element, the stresses are significantly lower, so a topology optimization is viable to improve the use of the area in the whole element.

The weight and needed torque in the machine can be reduced by not only topology optimization, change of the material is structurally viable (for a much lighter and less resilient one) for pieces with a safety factor above four. These recommendations for the optimization of elements are subject to economic aspects because they involve material and manufacturing additional costs.

This device, compared to other developed previously by different institutions, has several benefits in terms of adaptability, versatility, and cost. The range of motion is not as good as models like Kinetec (Damo, 2012) or SCPM (Umchid, 2016), but these devices are only capable of using one leg at a time, while the machine designed in this paper can exercise both legs simultaneously. Besides, the adjustment in the ROM is mechanical instead of electronic, which reduces the costs and number of parts.

Another benefit of the designed mechanism is the low fabrication cost, since its base is a commercial gym machine, the mechanism is made of standardized steel and no complex cuts or specialized tools are needed. The transmission is designed under AGMA standards, so the gears can be found in catalogs. These characteristics make mass production feasible to decrease the final price and offer an affordable product for small rehabilitation clinics. When compared to the device proposed by Weinberg (Weinberg, 2007), which uses rheological fluids and personalized frames, those aspects involve a higher fabrication cost making mass production impractical.

The six-bar mechanism has been little studied for rehabilitation devices. Li in his works (Li, 2021) focuses on using this kind of linkage to design a low-cost prototype able to simulate a gait trajectory in patients with orthopedic impairments.

This study also focuses on patients with walking difficulties, specifically in the knee, so these two devices solve different problems but depending on which stage of rehabilitation the patients are at, both machines can be used together to improve patient outcomes.

7. Conclusions

In this paper, the design for a novel Watt six-bar linkage for the physical rehabilitation of knee-injured patients is proposed. The results shown in this study prove that the proposed machine met the task of providing a wide variety of ranges of motion that cover from the early to last stages of physical rehabilitation. The obtained data shows that the links conforming to this mechanism could bear the necessary dynamic loads for its working. Nevertheless, it was also observed that reductions in weight, material changes, and topology optimizations, could be done, and consequently, the reduction of the necessary torque. This can be a matter of study for future investigations to validate the cost/benefit of these changes.

Based on the design and simulation results, future studies related to this project will focus on the implementation of the mechanism, on field tests to determine the stress produced on the knees, and on evaluation with health workers to establish its clinical relevance on patient rehabilitation.

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Annexes

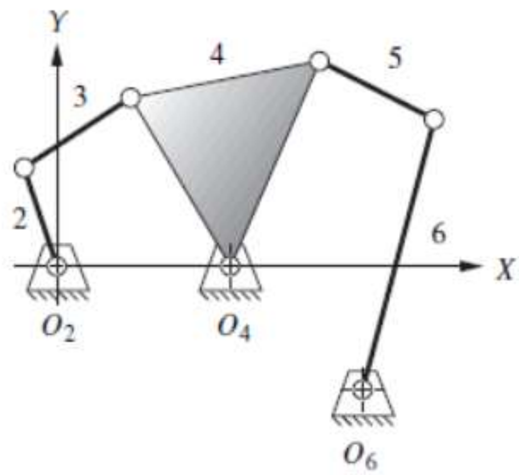

Figure 1 Schematic model of the six-bar Watt linkage mechanism that contains the five mobile links (2, 3, 4, 5, 6), and three fixed ones (O2, O4, O6), with O2 centered in (0, 0).

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Figure 2 SolidWorks model of the original extension machine where is possible to see that it depends on the person to generate the movement.

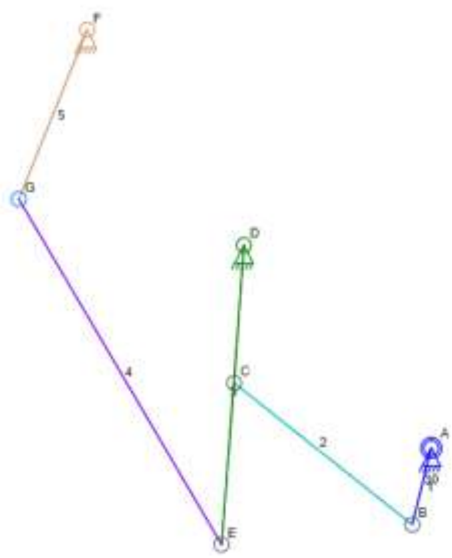

Figure 3 The solid works scheme presents fixed points F, D, and A; the mobile links are B, C, E, and G. The link A is where the motor should be placed to start the movement

Figure 4 SolidWorks design for the six-bar Watt linkage mechanism is presented. It is important to notice that the smallest link at the right corresponds to the motor connection. The link on the left generates the leg movement. The holes in the middle links allow reconfiguring to have a smaller range of motion.

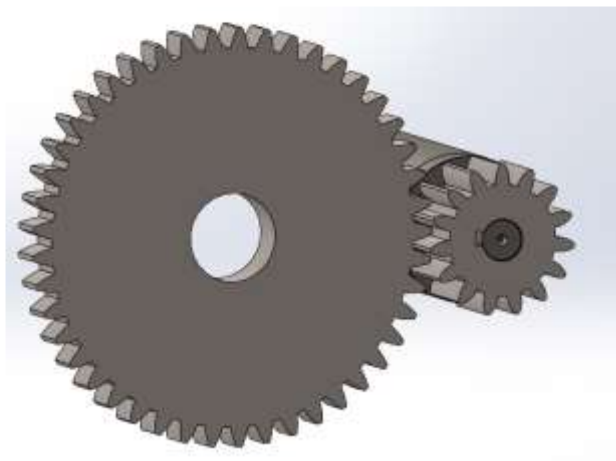

Figure 5 A transmission was designed to reduce the motor speed and increase its torque. It is important to notice that the transmission uses a factor of 3:1. It was built using nylamid and water jet cut.

Figure 6 The assembly is presented with the six-bar Watt linkage placed into the machine. Notice that a rowlock is the support for the transmission gear, while the motor is fixed with an iron base

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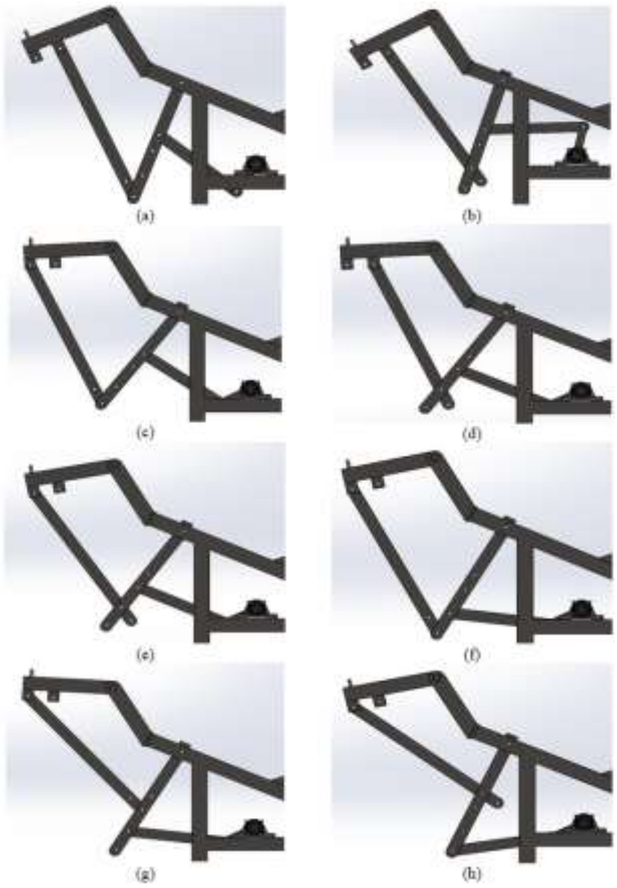

Figure 7 The different mechanical configurations that can be used to modify the range of motion (***a*** to ***h***). Being ***a*** the widest with a ROM of 109.28°, and the shortest path is given by ***h*** with 24.23°.

Figure 8 Trace path of the configurations with the widest (***a*** – 109.28°) and shortest (***h*** – 24.23°) range of motion, respectively. Notice the variation in the last link from left, it causes to have a greater effort in the case ***a***.

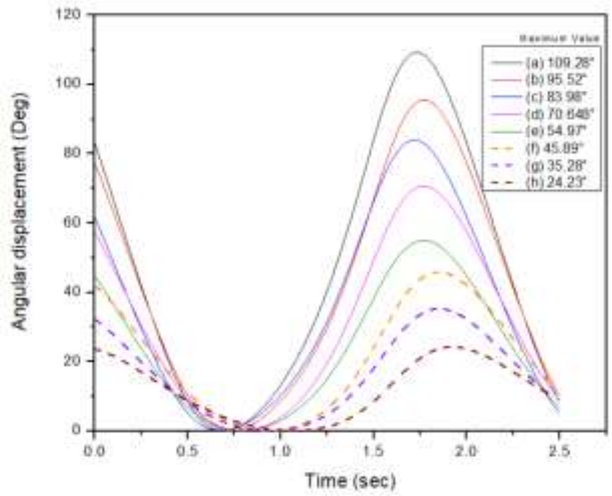

Figure 9 Plot of motion for the different configurations tested (***a*** to ***h***). It is noticeable that the wider path is realized by ***a*** rather than by ***h***. Intermediate configurations are useful for midway rehabilitation movements.

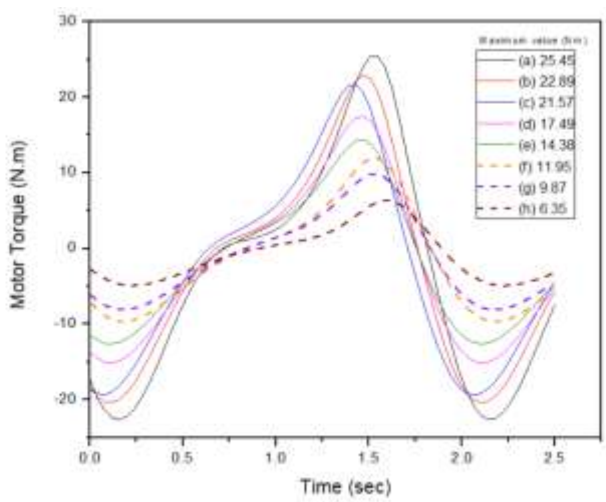

Figure 10 Plot of torque for the different configurations tested (***a*** to ***h***). It is noticeable that while ***a*** realizes the wider path it requires more torque. The case of ***a*** requires 25.45Nm, while the ***h*** case requires 6.35 Nm.

Model	Type of Device	Characteristics	Image
Kinetec Spectra (Damo, 2012)	Active	Slider-crank mechanism. Adults or pediatric patients. Manually adjustable ROM from -10 to 120°	
SCPM (Umchid, 2016)	Active	Adjustment of ROM, speed, and time. Controlled by Arduino, encoders, and switches. Microcontroller ARM9 with built-in touch screen color LCD display.	

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AKROD (Weinberg, 2007)	Passive	Lightweight design. Multiplies torque by implementing a compact planetary gear system. Use of electro-rheological fluids to facilitate knee flexion.	
K.I.M (Phoenix, 2022)	Passive	Allows the patient to control manually ROM and speed. User friendly.	
Six-bar Mechanism (Li, 2021)	Active	Produce accurate gait trajectories. Use only a constant speed motor to produce motion. Low cost.	

Table 1 Devices for knee and leg rehabilitation

Condition	Specifications
Frame	Structure of a leg extension machine made on steel RHS 2”x2” gauge 10
Motor DC	Maxon EC-i 40, 18 V, 5.46 A, with geared motor Maxon GP 42C, maximum discontinuous torque 22.5 Nm
Speed	30 RPM
ROM	from 20° to 120°
Links	Designed in A36 steel
Supports	Steel RHS on A36 steel 2”x2” gauge 14
Transmission	Gears on Nylamid, width face of 1”, Diametral pitch 10

Table 2 Specifications of the system

	No. of link	Kind of link	Length (mm)
4-bar linkage Crank-rocker	1	Crank (Input)	115
	2	Coupler 1	320
	3-C	Rocker	200
4-bar linkage Triple rocker	3-E	Rocker	435
	4	Coupler 2	580
	5	Rocker (Output)	200

Table 3 Theoretical lengths of the scheme of the mechanism for a maximum range of motion

Load	Description
Motor	Constant speed motor of 30 RPM applied to the crank
Point load	Load of 7 Kgf that simulates the weight of the legs, applied in the edge of the legs support of the original machine
Gravity	$9.81\,\frac{m}{s^2}$ in the negative Y axis

Table 4 Conditions for the motion generation.

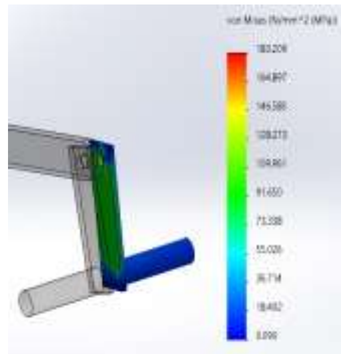
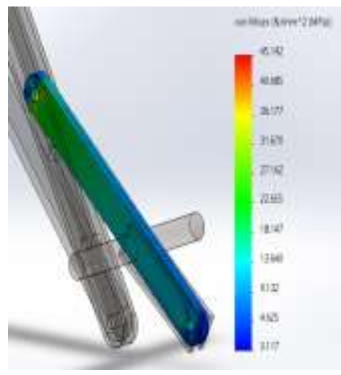
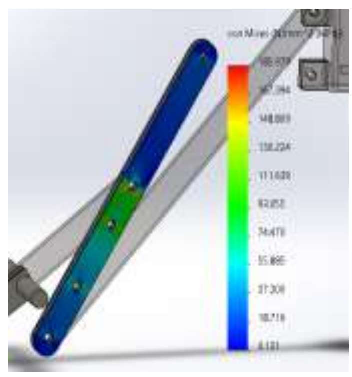
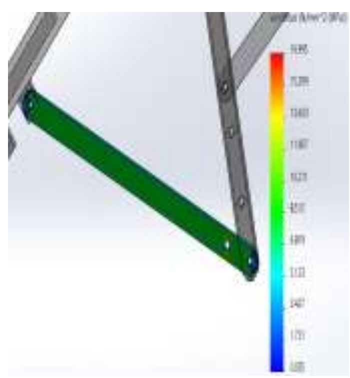
Type of link	$\sigma_{VM,max}$ (MPa)	Factor of Safety , n	Picture
Crank	183.2	1.4	
Coupler 1	45.2	5.5	
Rocker	186	1.3	
Coupler 2	17.0	14.7	

Table 5 Stresses and safety factor for the elements of the mechanism