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PROTOTYPE OF AN ASSISTIVE DEVICE FOR LOWER LIMB MOTOR REHABILITATION.

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Abstract. *More than a billion people around the world live with some form of disability, among which about 200 million experience considerable motor functional difficulties. In the coming years, this type of physical disability will become an even greater concern because its incidence will have increased. This is mainly due to the aging of the population, as well as the global increase in chronic diseases such as diabetes, cardiovascular disease, cancer, and mental disorders. Also, it is due to injuries due to accidents and/or sports activities. In this sense, rehabilitation equipment as well as assistive technologies should enhance functional skills and provide autonomy and independence. In this way, this project presents a proposal for a study related to the construction and design of a prototype of a low-cost device for the rehabilitation of lower limb movements in patients with limited mobility, along with a process of motor recovery and assisted rehabilitation. by computer. The main objective of this work is to dimension and build the prototype of a mechanical device for the rehabilitation of the lower limbs for people with motor disabilities. The study intends to contribute and influence in the health sectors, and areas of biomechanics, as well as in academia and society. Thus, the characteristics of this study are generation of an assistive and economically accessible mechanical system to be used in the health system of the region; cost and time reduction in therapeutic sessions for the patient and encourage the use of assistive technologies in the population's health problems. The justification for this study seeks to meet the demand of the population with physical disabilities and thus promote social inclusion. The assistive technology device is adapted equipment used to rehabilitate the functional capacity of people with temporal impairment of the lower limbs. The mechanism transmits and controls the flexion and extension movements of the legs (quadriceps, knees, and ankles) through pneumatic actuators, movement sensors and interchangeable mechanical systems. The study is in progress and using the experimental, numerical, and analytical method based on data from works found in current scientific and academic bases. Experiments are necessarily made for the result, due to which the device should be the solution to the problem.*

Keywords: *Motor rehabilitation in the lower limbs*, *kinesitherapy*, *Mechanical Project*, *Prototype.*

1. INTRODUCTION

People with disabilities usually have physical problems and/or motor impairment, which manifests itself in any part of the body, whether in the legs, arms, etc. In these situations, there are different types of paralysis, either temporary or permanent. When it is permanent and depending on the severity of the problem, alternative help is sought, such as wheelchairs, canes, walkers, and even exoskeletons (Marizcal, 2017).

Clinical studies show that the essential type of rehabilitation, which restores mobility and efficient movement, is movement and exercise-based therapy (kinesiotherapy). Most of the time it is impossible to omit, but other types of treatment can also be of significant help. However, kinesiotherapy requires the involvement of highly qualified physiotherapists in the treatment process by performing appropriate exercises with the patient (Olinski et al., 2015). Also, there is robotic rehabilitation that helps the work of physiotherapists, in better coordination of rehabilitation exercises and greater accuracy in diagnosing injuries and measuring the evolution of patients (de Araújo et al., 2018).

When analyzing the dynamics of the lower limbs, quasi-static biomechanical models can describe the torques of the knee joints during the posture phase during gait and can provide a method to describe the mechanism of modulation of the maximum braking force. An advantage of this approach is that it results in a "snapshot" of parameters that can be interpreted more easily than a more comprehensive dynamic model (Prible et al., 2022).

Chaparro Rico et al. (2016), based their design on the parallel robot for knee rehabilitation. The robot was based on a five-bar mechanism and helped the physiotherapist in the realization of 4 basic rehabilitation exercises. The work was specifically with the characterization of the exercises, the position kinematics of the robot, and the final mechanical design. The robot can slide along a stretcher and the end effector is responsible for guiding the patient's leg to follow the characteristic path of each exercise.

Rehabilitation robots can be further delineated with respect to their mechanical design as either end-effector or exoskeleton systems. End-effector robots impose forces on the distal segments of the upper or lower limbs, but they cannot directly control individual joints since the contact between the patient and the robot is at limb endpoints (Chrif et al.,2017). The authors developed and evaluated control strategies for a novel lower-limb pediatric rehabilitation robot, based on linear-motor actuator technology and the leg-press exercise modality.

Cuevas-Vasquez et al. (2019), presented a mechanical design, the building, and the design of the control system of a robotic prototype for the rehabilitation of the wheel of intervened patients chirurgically in this joint. The authors used the methodology from the mechatronic design to generate the prototype. Applied analysis for the calculation of the kinematics and the control system, which is developed using logic diffuse. The exoskeleton was designed to be adjustable with the base in the anthropometry of the adult person.

Lower limb rehabilitation is becoming more and more necessary due to the severe aging trend in China. Although there are plenty of products aiming to address the demand, problems like cost and pertinence still exist (Xu, 2022). The author presented a design of the Lower Limb Rehabilitation Robot (LLRR) a new model and economical design considering the existing products, the body size of the Chinese, and the application prospects of the LLRR. The LLRR mainly consists of the seat device, the lower limb exercise device, and the structures which provide the whole device good mobility. The lightweight design and specific material selection reduce the LLRR´s weight while ensuring strength. At the same time, the backrest mechanism and the exercise mechanism realize the functions of backrest angle adjustment and the patient's lower limb rehabilitation exercise.

Dao Minh et al. (2021), developed a device to support lower extremity rehabilitation for stroke patients. The equipment was controlled by control and monitoring software, which is designed from Visual Basic software. The control circuit was built with an Arduino 2560 circuit, responsible for receiving the angle sensor signal and measuring the current during operation. The control signals to the actuator and communicates with the software using the rs232 cable. Finally, an experiment on volunteers was conducted, and the results showed that the device was stable and safe to operate.

Zhang et al. (2022), designed a lower limb rehabilitation robot for MMT-2 level patients. It balanced the gravity of the patient's leg to a certain extent so that the patient could make a full joint range of motion. After determining the operation range of each joint in the human lower extremity and the average gravity of the leg, the authors did the overall static and kinematic analyses to verify that the stiffness and strength of the structure met the requirements and could achieve the required range of motion.

In this way, the objective of this proposal consists of the design and dimensioning of the mechanical system for the rehabilitation of people with motor disabilities in the lower limbs, which basically should allow flexion and extension movements.

2. METHODOLOGY

A detailed methodology must be used in obtaining the structure of the device to allow for performing the functions required for the purposes of rehabilitation of the lower limbs. The application process of the various techniques must be considered to define the device, considering mainly the requirements for the engineering project and/or the machine project, which deals with the creation of a machine that works safely and reliably (Norton, 2013).

2.1 MECHANISM OF THE KNEE REHABILITATOR

The articular behavior of each exercise corresponds to the angles formed in the leg and shown in the geometric model of the leg as the Figure 1, and the Cartesian behavior corresponds to the trajectory generated by the ankle in the Cartesian plane, in this case only the trajectory of the ankle is necessary because it is the one that the mechanism will have to reproduce.

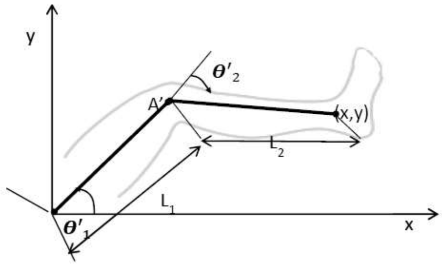

Figure 1. Geometric representation of the leg. Reference image (Chaparro-Rico, 2016).

Figure 2, shows the geometric representation of the leg by means of a two-link serial configuration mechanism with two degrees of freedom, where link L_1 represents the femur and link L_2 represents the tibia:

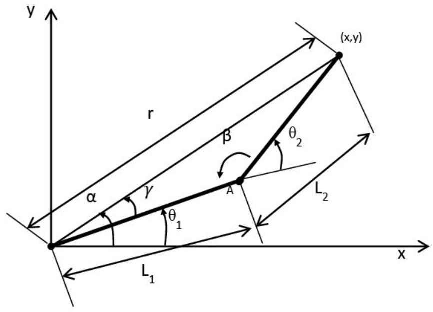

Figure 2. Geometric representation of the lower limb. Reference image (Chaparro-Rico, 2016).

The inputs to the system are (x, y) and the unknowns are the angles θ_1 and θ_2. The equations of the inverse geometric model are proposed and developed.

From Figure 2 it is calculated,

$$\alpha = tan^{-1}\frac{y}{x}, \tag{1}$$

By the law of cosines,

$$L_1{}^2 + L_2{}^2 - 2L_1L_2\cos\beta = r^2, \tag{2}$$

By the Pythagorean theorem,

$$r^2 = x^2 + y^2, \tag{3}$$

Substituting equation 3 in equation 2,

$$L_1{}^2 + L_2{}^2 - 2L_1L_2\cos\beta = x^2 + y^2, \tag{4}$$

Solving for β,

$$\beta = \cos^{-1}\frac{L_1{}^2 + L_2{}^2 - x^2 - y^2}{2L_1L_2}, \tag{5}$$

From Figure 2 it can be seen θ_2,

$$\theta_2 = \pi - \beta, \tag{6}$$

Substituting equation 5 in equation 6 one can find θ_2

$$\theta_2 = \pi - \cos^{-1}\frac{L_1{}^2 + L_2{}^2 - x^2 - y^2}{2L_1L_2}, \tag{7}$$

Again, by law of cosines

$$L_1{}^2 + r^2 - 2L_1r\cos\Upsilon = L_2{}^2, \tag{8}$$

Substituting equation 3 in equation 8

$$x^2 + y^2 + L_1{}^2 - 2L_1r\cos\Upsilon = L_2{}^2, \tag{9}$$

Therefore Υ

$$\Upsilon = \cos^{-1}\frac{L_1{}^2 - L_2{}^2 + x^2 + y^2}{2L_1r}, \tag{10}$$

And from Figure 2 it can be that,

$$\theta_1 = \alpha - \Upsilon, \tag{11}$$

Substituting equation 1 and equation 10 in equation 11 one can find,

$$\theta_1 = tan^{-1}\frac{y}{x} - \cos^{-1}\frac{L_1{}^2 - L_2{}^2 + x^2 + y^2}{2L_1L_2}, \tag{12}$$

Now, as in the case of the human leg, the knee is always up and not down, since hyperextension would otherwise occur, the analysis is made for this case, the representation is observed in Figure 3.

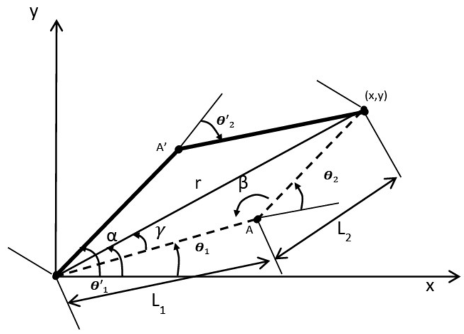

Figure 3. Geometric representation of the leg with the knee above. Reference image (Chaparro-Rico, 2016).

For this case,

$$\theta'_1 = \theta_1 + 2\Upsilon, \tag{13}$$

$$\theta'_2 = -\theta_2, \tag{14}$$

Next, the equations of the direct geometric model of the leg are developed, so the graphic representation of the leg is resumed, the known data are the angles θ'_1 and θ'_2, and the dimensions of the bars.

Figure 3. shows that,

$$\theta_1 = \theta'_1 + 2\Upsilon, \tag{15}$$

$$\beta = \pi - \theta_2, \tag{16}$$

$$\theta_2 = -\theta'_2, \tag{17}$$

$$\alpha = \theta_1 + \Upsilon, \tag{18}$$

By the law of cosines, equation 2 and equation 8 are retaken, and from equation 8 change Υ,

$$\Upsilon = \cos^{-1}\frac{{L_1}^2 - {L_2}^2 + r^2}{2L_1 r}, \tag{19}$$

From equation 2, we obtain the value of r,

$$r = \sqrt{{L_1}^2 + {L_2}^2 - 2L_1L_2\cos\beta}, \tag{20}$$

Replacing equation 19 in equation 15

$$\theta_1 = \theta'_1 - 2\cos^{-1}\frac{{L_1}^2 - {L_2}^2 + r^2}{2L_1 r}, \tag{21}$$

Equation 21 and equation 19 are replaced in equation 18.

$$\alpha = \theta'_1 - 2\cos^{-1}\frac{{L_1}^2 - {L_2}^2 + r^2}{2L_1 r} + \cos^{-1}\frac{{L_1}^2 - {L_2}^2 + r^2}{2L_1 r}„ \tag{22}$$

Finally

$$x = r\cos(\alpha), \tag{23}$$

$$y = r sin(\alpha), \tag{24}$$

The angular behavior is the same for any height, since approximately the same size relationship is maintained between L_1 and L_2 according to Figure 1, for the execution of each movement (Cartesian trajectory) it is necessary to use the maximum and minimum height that the mechanism will handle. Therefore, based on the information obtained of the Brazilian Institute of Geography and Statistics (IBGE, 2011). The average height of Brazilians falls with age. Among men aged 20 to 30, the average was 1.74 m., among those aged 70 to 80, it was 1.62m., And among women aged 20 to 30, the average was 1.62 m., while in the 70 to 80 age group, it was 1.53 m. Based on these heights, the height reconstruction formulas these being the formulas closest to the Brazilian population that allow us to obtain an approximate value of these two bones of the lower limb. In the Table 1, show the values of femur and tibia for women and men according to ages. Next for exercises in the knee, once the dimensions of the tibia and femur were obtained for the maximum and minimum height, where the femur corresponds to the L_1 bar and the tibia to the L_2 bar, by means of the geometric model of the leg, the angular behavior of each exercise was obtained and from the angular behavior the trajectories of the different heights were reproduced, obtaining the Cartesian behavior for the minimum to maximum height where the space required for the reproduction of each movement can be observed. In Figure 4 the angular trajectories of exercise A are observed, the black trajectory describes the angles reached by the femur with respect to the plane (angles of the hip "theta1 primal") during the execution of the out and back exercise, and the red trajectory describes the angles reached by the tibia with respect to the femur (angles of the knee "theta2 primal"). In this case the angles reached by the hip increase when the patient's leg is raised and decrease when the leg is lowered, while the knee angles remain constant since there is no knee flexion extension in this exercise.

Table 1. Average Sizing of tibia and femur of Brazilian people according to ages and gender.

People	**Age (20 to 30 years)**			**Age (70 to 80 years)**		
	Height (m)	**Femur (m)**	**Tibia (m)**	**Height (m)**	**Femur (m)**	**Tibia (m)**
Women	1,62	0,433	0,361	1,53	0,399	0,328
Men	1,74	0,476	0,410	1,62	0,423	0,348

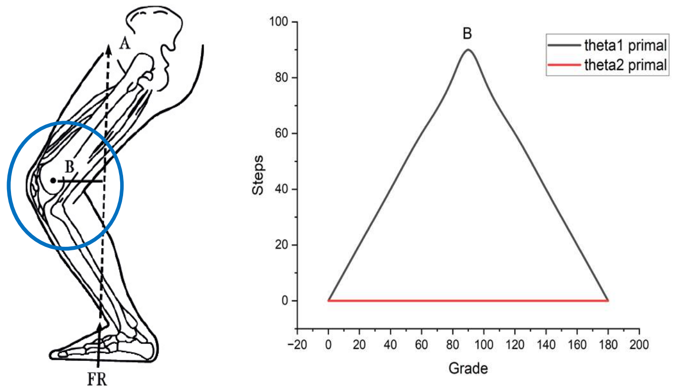

Figure 4. Angular trajectory (grade) of the knee exercise while straight leg raises (steps).

In Figure 5, the Cartesian trajectory followed by executing knee exercise is graphed to four cases of people, the trajectories produced by the lower limbs of dimensions, which the average longest leg is for males between 20 and 30 years old and the average shortest leg for women between 70 and 80 years old.

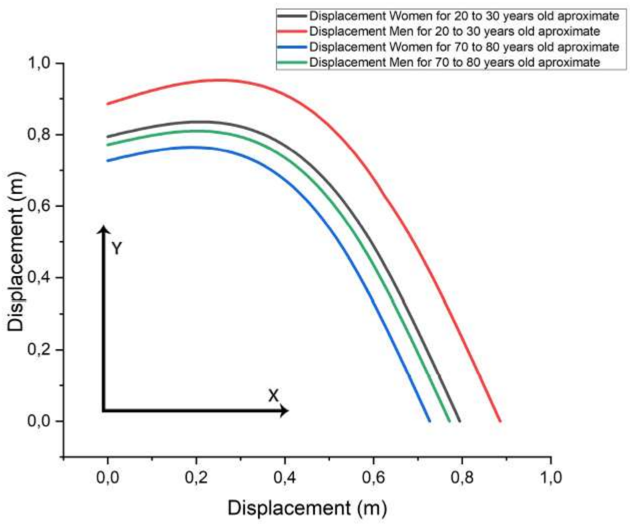

Figure 5. Cartesian displacement of the knee exercise in the axis "x" while straight leg raises in the axis "y".

2.2 MECHANISM OF THE HIP REHABILITATOR

The hip joint is responsible for the movement of the leg (thigh, shin, and foot). In a healthy individual it performs lateral abduction and adduction movements of the leg, frontal plane as showed in the figure 6.a; extension and forward flexion movements of the leg, sagittal plane; as the figure 6.b.

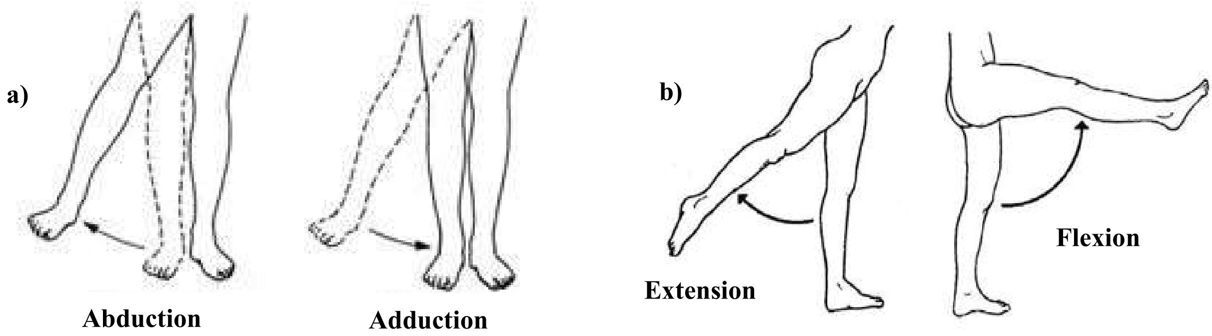

Figure 6: 6.a) Abduction and adduction movements of the leg in the frontal plane. 6.b) Leg extension and flexion in the sagittal plane. Reference images (de Araújo, 2010).

A mathematical model of abductor moment arm, defined by anatomical coordinates of the origins and insertions of the gluteus medius and minimums and the femoral head center, was derived using anatomical measurements published previously in the Figure 7. The straight-line method of approximating the path of muscle pull was used for this study since the broad attachments of the gluteus medius and gluteus minimums do not facilitate definition of the transverse sections required for the centroid line model.

Derivation of the mathematical model began with the equation for moment arm according to the Equation 1. Moment arm was calculated by defining the lever arm (r) in terms of the femoral head and abductor muscle insertions about the Equation 2 and defining the angle of pull (θ) in terms of the femoral head, muscle origins, and insertions in the Equation 3. The moment arm could therefore be calculated and plotted for all values of a muscle's origin, insertion, and joint center in the Equation 4. Modifications of the moment arm equation were required for this analysis with Equation 5 and Equation 6. An additional modification of the moment arm equation was required for this analysis in the Equation 7 and Equation 8. The final analysis examined the effect of medialization of the proximal femur on abductor moment arm.

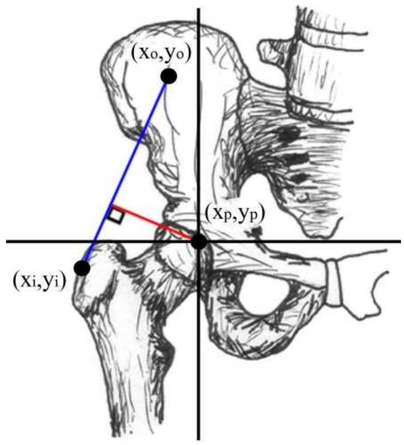

Figure 7. Coronal view of hip demonstrating hip abductor moment arm, (red line). Coronal view of hip demonstrating hip abductor moment arm, defined as the length of a line originating at the joint center (red) which forms a 90˚ angle with the line of action (blue). Reference image (Henderson et al, 2011).

$$\mathrm{r}_{\perp} = r \sin\theta, \tag{25}$$

Where r is the lever arm length defined as the femoral head-to-abductor insertion point distance in the case of the hip, and θ is equal to the angle between r and the line of muscle pull.

$$r = [(X_p - X_i)^2 + (Y_p - Y_i)^2]^{0,5}, \tag{26}$$

$$\theta = [\arctan[(Y_o - Y_i)/(X_o - X_i)] - \arctan[(Y_p - Y_i)/(X_p - X_i)]], \tag{27}$$

$$\mathrm{r}_{\perp} = \left[[(X_p - X_i)^2 + (Y_p - Y_i)^2]^{0,5}\right] * \sin\left[\arctan\left[\frac{Y_o - Y_i}{X_o - X_i}\right] - \arctan[(Y_p - Y_i)/(X_p - X_i)]\right], \tag{28}$$

$$X_i = r\cos(\alpha - \beta), \tag{29}$$

$$Y_i = r\sin(\alpha - \beta), \tag{30}$$

Where (r*cosα) and (r*sinα) are polar coordinate equivalents for X_i and Y_i, respectively, and β is the angle of abduction. These substitutions were made for Equation 29 and a plot was generated of r⊥ as a function of β.

$$X_{oi} = [(X_o - X_p)^2 + (Y_o - Y_p)^2]^{0,5} * \cos(X - \delta), \tag{31}$$

$$Y_{oi} = [(X_o - X_p)^2 + (Y_o - Y_p)^2]^{0,5} * \sin(X - \delta), \tag{32}$$

Where *X* is the polar coordinate angle for the muscle origin with 0° pelvic tilt and δ is the angle of pelvic tilt. Again, these substitutions were made for equation 29 and a plot was generated of r⊥ as a function of δ, whose values ranged from 0° to 30°.

2.3 MECHANISM OF THE ANKLE REHABILITATOR

The ankle joint is responsible for transmitting the irregularities felt by the feet to the rest of the leg, giving the body the necessary adaptation to balance on the feet. The ankle is responsible for the union between the shin and the foot, being able to perform movements in the frontal plane, flexion, and extension, showed in the figure 7.a. Also, the ankle movements are the plantar flexion and dorsiflexion of the foot. Plantar flexion is the motion that decreases the angle between the sole and the back of the foot, while dorsiflexion is the opposite motion by that the toes are brought towards the shin, showed in the figure 7.b.

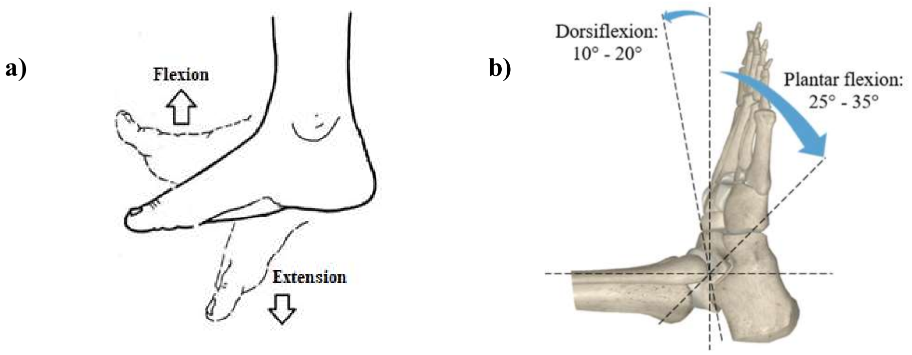

Figure 7: 7.a) Flexion and extension of the screw in the sagittal plane. 7.b) Motions of the ankle. Reference images (Zeghloul, 2020).

The geometrical model is show in the figure 8, shows the variation of angles φ_1 and φ_3 as well as the limits of the stroke carried out by point D.

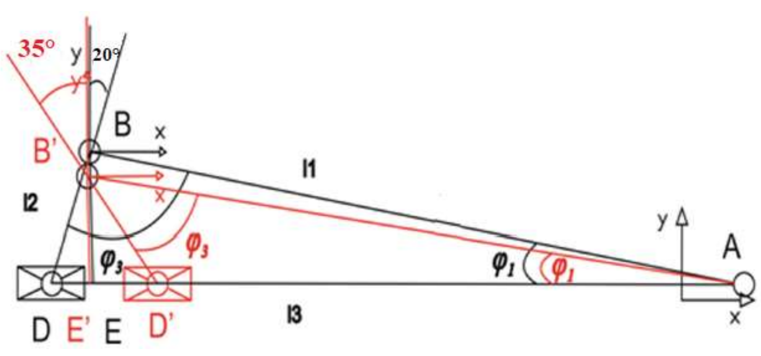

Figure 8. Kinematic diagram of the rehabilitation model.

Using the notations of figure 8, the hip rotation angle φ_1 is calculated with Equation (33):

$$\varphi_1 = \arccos\left(\frac{l_3^2 + l_1^2 + l_2^2}{2 l_3 l_1}\right), \tag{33}$$

And angle φ_3 is:

$$\varphi_3 = \arccos\left(\frac{l_1^2 + l_2^2 - l_3^2}{2 l_1 l_2}\right), \tag{34}$$

3. RESULTS AND DISCUSSION

This section of the study focuses on the diagram and modeling of a prototype designed for lower limb rehabilitation. The prototype offers a range of rehabilitation exercises. It is mentioned that the study is currently in progress, and a full-scale experiment will be conducted using the mechanisms described in item 2 of the methodology.

One important consideration is that the maximum weight of a human leg is approximately 16% of the total body weight. Taking into account the highest average weight in Brazil, which is around 120 kg, the maximum weight of the leg would be 19.2 kg.

Figure 9 only presents a diagram of the pneumatic actuation. The system includes: a pneumatic muscle actuated by a proportional directional control valve, a resistive position transducer attached to the slide, an Arduino Uno controller for programming and saving the working positions, the types of motion, and their sequence, and electronic elements for transmitting information from the transducer to the controller, which is connected to a relay.

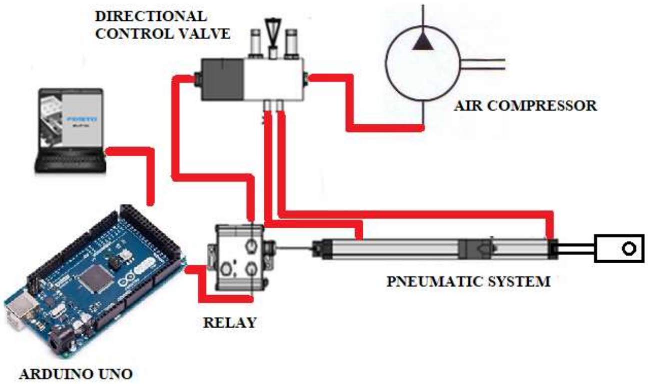

Figure 9. Pneumatic actuation diagram of the rehabilitation equipment.

Figure 10 presents the model of the developed prototype made of 6063-T5 anodized aluminum material. This material has a yield strength of 105 MPa, allowing it to withstand over 1000 kg of weight. The prototype features a chair that can be converted into a therapeutic stretcher, equipped with safety bars to ensure the stable and secure positioning of the patient. The first level of this mobile equipment incorporates pneumatic actuators, generating linear movements in both the longitudinal direction, facilitating lower limb extension and flexion exercises, and the transverse direction, allowing for abduction and adduction exercises.

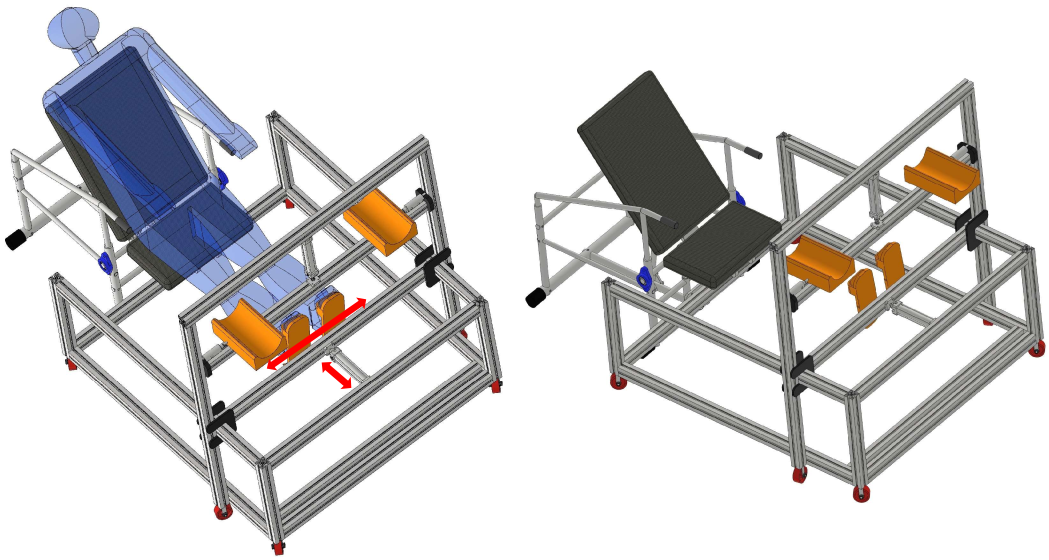

Figure 10. First level of the prototype assistive device for the limb lowers.

In Figure 11, the prototype is turned into a therapeutic stretcher, in which the patient is lying down safely. The second level of the mobile equipment has pneumatic actuators that generate linear movements in the longitudinal direction for lower limb extension and flexion exercises, elevation for flexion exercises, and transverse direction for abduction and adduction exercises.

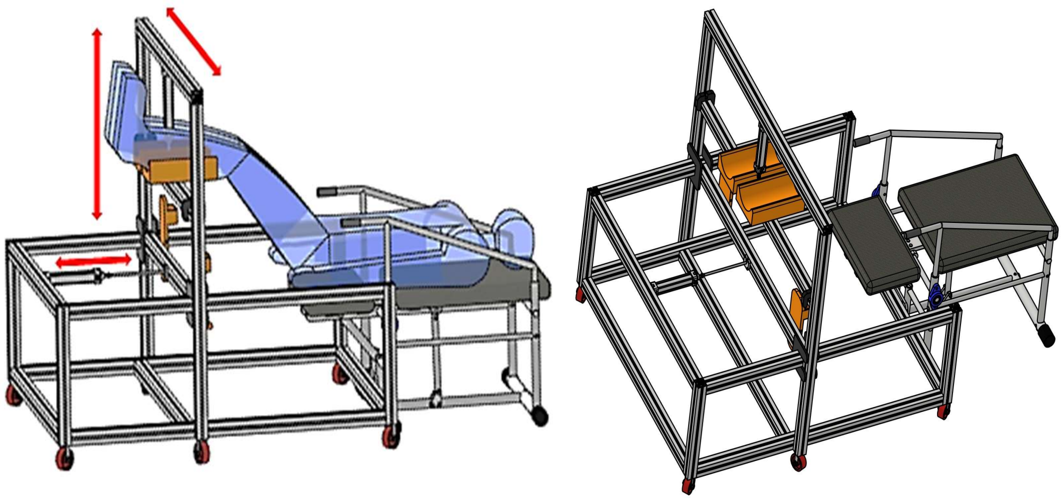

Figure 11. Second level of the prototype assistive device for the limb lowers

The outcomes of this research have provided insight into the proposed prototype of an assistive device for lower limb motor rehabilitation in relation to the actual and existing prototypes of assistive devices for this kind of rehabilitation around the world. However, the results should be interpreted with caution due to the limitations of the current research. This chapter provides a reflection on the research process. The limitations and potential consequences of the design are discussed, as well as the implications for the interpretation of the results. The chapter ends with recommendations for future research.

4. CONCLUSION

A prototype model for lower limb rehabilitation, encompassing multiple exercises for adults who need to exercise their lower limbs, has been developed.

The ensuing process will be assessed through experimentation, which is essential for obtaining results. Subsequently, the device will need to be patented as a solution to the previously mentioned problem.

A rehabilitation device, based on a mechanism module, is proposed to help physiotherapists with lower limb rehabilitation tasks. Five exercises generally used in knee rehabilitation were identified and characterized; they were used to establish workspace and mobility requirements. The position kinematics of the mechanism as well as its workspace are presented.

A prototype was dimensionally designed and built to validate that the requirements of mobility and workspace are met. The mechanism can accommodate different leg sizes and can also facilitate other exercises that occur in the vertical plane.

This prototype is the first proposal version; new versions will include advanced technologies such as AI (Artificial Intelligence), with a cloud database for rehabilitation treatments for each patient. Finally, the authors invite all stakeholders to participate in future research on the topic.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Chaparro-Rico, B. D. M., & Castillo-Castaneda, E. ,2016. Design of a 2DOF parallel mechanism to assist therapies for knee rehabilitation. Ingenieria e Investigacion, 36(1), 98–104. https://doi.org/10.15446/ing.investig.v36n1.53191

Chrif Farouk, Hubertus J.A. Van Hedel, Mauro Vivian, Tobias Nef, and Kenneth J. Hunt. 2022. Usability evaluation of an interactive leg press training robot for children with neuromuscular impairments. Technology and Health Care, 30, pp. 1183–1197.

Cuevas-Vasquez C.N., Lugo, E., Profile, S., Arias-Montiel, M., & Tapia-Herrera, R. (n.d.). 2019. Desarrollo de un prototipo para rehabilitaci´on de rodilla utilizando un robot paralelo 5R de 2 GDL.A review on sun position sensors used insolar applications View project Ballbot Lego NXT control View project. https://www.researchgate.net/publication/337366953.

de Araújo, M., 2010. Desenvolvimento de Uma Órtese Ativa Para os Membros Inferiores Com Sistema Eletrônico Embarcado. Ph.D. Thesis, Federal University of Rio Grande do Norte. https://repositorio.ufrn.br/bitstream/123456789/15313/1/MarcioVA_DISSERT.pdf

Dao Minh Duc, Pham Dang Phuoc, and Tran Xuan Tuy. 2021.Study on the Lower Extremity Rehabilitation Device RHleg. International journal of online and biomedical engineering, 17, pp. 141–156.

Harzheim, E., Felipe Pinto, L., D'Avila, O. P., & Hauser, L. (2019). Following the legacy of professors Barbara Starfield and Leiyu Shi in Brazil as health policy: The National Health Survey (PNS), led by the Brazilian National Institute of Geography and Statistics (IBGE) and the Primary Care Assessment Tool (PCAT). In International Journal for Equity in Health (Vol. 18, Issue 1). BioMed Central Ltd. https://doi.org/10.1186/s12939-019-1083-2.

Henderson, E. R., Marulanda, G. A., Cheong, D., Temple, H. T., & Letson, G. D.,2011. Hip abductor moment arm – a mathematical analysis for proximal femoral replacement. Journal of Orthopaedic Surgery and Research, 6(1). https://doi.org/10.1186/1749-799X-6-6.

Marizcal Castro, Jesus. 2017. Diseño de un exoesqueleto para terapias de rehabilitación. Tesis de mestrado [s. l.], p. 221. TECNOLÓGICO NACIONAL DE MÉXICO. www.itlp.edu.mx.

Olinski M., Lewandowski B., and Gronowicz A., 2015. The evolution of devices and systems supporting rehabilitation of lower limbs. International Journal of Applied Mechanics and Engineering, 20, pp. 147–158.

Prible, D., Fey, N. P., & Yuan Hsiao, H., 2022. Biomechanical mechanism of peak braking force modulation during increased walking speed in healthy young adults. Journal of Biomechanics, 144. https://doi.org/10.1016/j.jbiomech.2022.111311.

Norton, R. 2013.Projeto de máquinas: uma abordagem integrada. 4. ed. Porto Alegre: Bookman, Brasil.

Xu, Ruidi, 2020. A novel design of the lower limb rehabilitation robot. Proceedings - 2020 6th International Conference on Mechanical Engineering and Automation Science, ICMEAS 2020, 1, pp. 254–259.

Zhang Zhen, Taisheng Zhang, Yanpeng Kan, and Manman Xu., 2022. Research on lower limb rehabilitation training device based on gravity balance. 2022 12th International Conference on CYBER Technology in Automation, Control, and Intelligent Systems, CYBER 2022, pp. 817–820.

Zeghloul Said, Med Amine Laribi, Juan Sebastian Sandoval Arevalo Editors, S. (n.d.), 2020. Advances in service and industrial robotics Mechanisms and Machine Science. vol 84. http://www.springer.com/series/8779. France. https://doi.org/10.1007/978-3-030-48989-2.

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