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A PROTOTYPE OF ROBOT WITH ARTIFICIAL MUSCLES IN REHABILITATION OF THE LOWER LIMB

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Abstract: Rehabilitation is a process that takes a lot of time and money. The main reason is that it takes a long time to achieve good improvement in patient function and requires medical staff to spend a lot of time while providing/leading exercises. Lower limb rehabilitation robots can help patients perform reasonable and effective exercises to improve motor function of paralyzed limbs. The article provides a classification, comparison and overview of machine part structural designs, models and control strategies of lower limb rehabilitation robots in the reviewed literature. Finally, the study presents the future direction of robots for lower limb rehabilitation.
This article systematically presents the process of designing, manufacturing and testing a lower limb support robot model. A 3D CAD model of the details and assemblies of the robot has been completely built, allowing for kinematics and dynamics simulation, durability calculation, and design optimization to adjust the final result. structure before manufacturing.

Keywords: rehabilitation, lower limb, design, manufacturing, robot

1. INTRODUCTION

The process of rehabilitation is costly and time-consuming, [1–4]. The primary cause is that it takes a long time to see significant improvements in patient performance, and it takes a lot of time for medical personnel to conduct or provide exercises [5-8]. During rehabilitation, each patient has an individual treatment course and different exercises. Nevertheless, typical manual therapies like physical therapy primarily rely on the expertise of the therapist, posing challenges in fulfilling the demands of rigorous and repetitive exercise. [9-11]. Due to the severe shortage of physical therapists, treatment cannot be guaranteed. Therefore, there is an increasing demand for advanced rehabilitation devices that help patients perform exercises accurately, quantitatively and effectively [12-13].
As is often seen, robots have the ability to assist or replace any repetitive physical work or activity. Given that the majority of the rehabilitation equipment now in use consists of customized exercise machines, it is imperative to create robotic devices that streamline the procedure. This is why there is a lot of research aimed at developing modern robotic rehabilitation devices [14-22].
Rehabilitation robotics is a developing topic that holds promise as a means of automated training. In recent years, researchers and rehabilitation physicians have shown a growing interest in rehabilitation robots. [23-29]. Rehabilitation robots can alleviate doctors from arduous training duties, analyze robot data during training, and assess the patient's progress in recovery. Rehabilitation robots offer a precise and reliable method to enhance the results of stroke or post-surgical rehabilitation, making them highly advantageous. Hence, the involvement of rehabilitation therapists is indispensable in this process, although robotic devices can streamline their tasks by facilitating the repetition of exercises and rehabilitation procedures. Ongoing advancements in rehabilitation robotics are leading to the development of new technologies and lower prices, making rehabilitation robots more readily available to the general public.
Lower limb rehabilitation robots are specifically engineered robotic devices that aid in the rehabilitation process of individuals who have lower limb impairments resulting from conditions like stroke, trauma, or degenerative diseases. Study of the composition, properties, and behavior of matter. These robots are designed to improve a patient's motor function, strength, and mobility through focused and repetitive exercises, often with the guidance

of an expert. Lower limb rehabilitation robots exhibit diverse designs and functionalities, commonly employing a combination of motors, sensors, and software to deliver accurate and regulated movements. Nonetheless, this greatly complicates and increases the cost of producing a robot that can restore lower limb function. In a developing nation such as Vietnam, a patient has the ability to possess a robot of this nature is challenging.
This article systematically presents the process of designing, manufacturing and testing a lower limb support robot model. A 3D CAD model of the details and assemblies of the robot has been completely built, allowing for kinematics and dynamics simulation, durability calculation and design optimization to adjust the final result, structure before manufacturing.

2. METHODOLOGY

2.1. Overall structure

To fulfill the problem's requirements and ensure the robot's structure and function operate efficiently and safely, the article selected for a design plan for an artificial muscle robot that aids in lower limb rehabilitation. The plan includes the following technical criteria:
- Angle of hip rotation: from -30^0 to 90^0;
- Angle of knee rotation: from 0^0 to 90^0;
- Necessary upward force: from 75 N to 150 N.
- Variable height range for lower extremities: from 800 to 1350 mm.

Figure 1 illustrates the comprehensive design of the artificial muscle robot used for lower limb rehabilitation. The system consists of two main components, a robot with integrated artificial muscles suspended on a fixed frame. The robot will be attached directly to the patient's lower limb, through a connection with the frame, it will create the necessary movements for exercise.

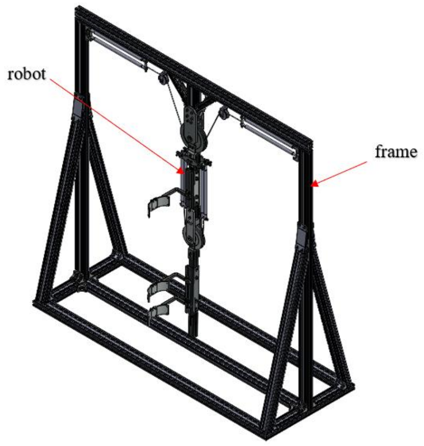

Fig. 1. 3D structure model for lower limb rehabilitation

2.2. Artificial muscle model

The pneumatic artificial muscle model is connected to function as a transmission mechanism for the rotating joint of the robot, as depicted in Figure 2.

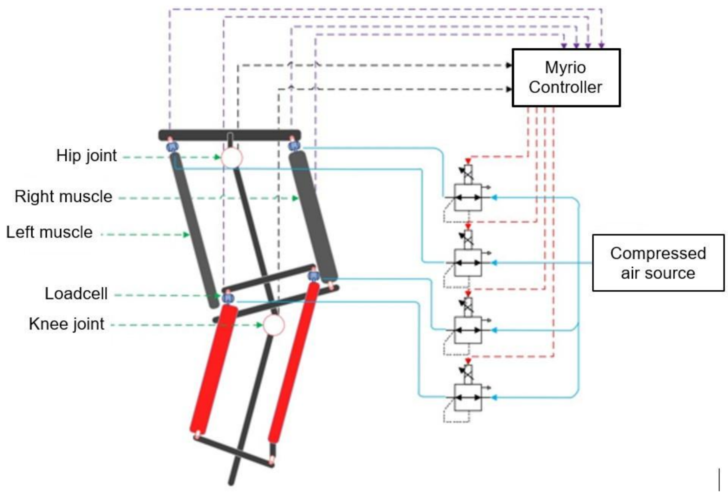

Fig. 2. Working principle of lower limb rehabilitation robot

The lower limb rehabilitation robot model consists of two joints called the hip joint and the knee joint. The pneumatic mechanism used is the McKibben artificial muscle with a diameter of 25.4mm, which is attached to each joint of the robot model, and can be stretched up to 30%. The parameters of the artificial muscle are listed in Table 1.

Table 1. Muscle parameters of lower limb rehabilitation robot

Robot structure	Original length (mm)		Initial pressure (kPa)	
	Anterior muscle	Posterior muscle	Anterior muscle	Posterior muscle
Hip joint	340	340	2	2
Knee joint	350	300	2	0.6

The experimental transmission model using pneumatic mechanics that this report studies has the structure of the Mc Kibben mechanical model, and is shown in detail as shown in Figure 3.

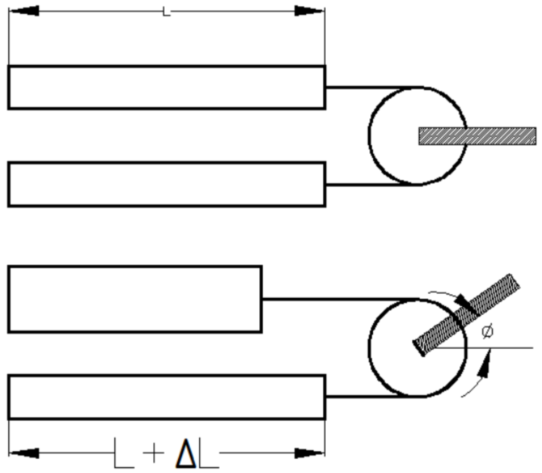

Fig. 3. Model of artificial muscle transmission

Working principle: when there is a difference in air pressure applied to the two muscles, two forces will form that act on the two muscles in two different directions. Because the pressure in the two muscles is not equal, one muscle will contract and one muscle will relax, which will cause the robot's rotary joint to rotate a corresponding angle. The rotation angle of the joint causes the length of the muscles to change accordingly.

Fig. 4. Experimental pneumatic artificial muscles

Pneumatic mechanics have a rubber inner tube inside and a cylindrical shell made of braided fibers that have the ability to stretch. The two ends are sealed and have a mechanical part that can be permanently suspended as well as attached to the Loadcell sensor head, one end is attached with an air inlet pipe. When the rubber tube is filled with air and inflated, the entire muscle will shorten. The relationship between the three components of force - pressure - contraction depends on geometric parameters (length and diameter of the muscle tube when not elastic, angle of the braid when not elastic), material of the intestine inner tube, air pressure value and external tension forces acting on the muscle.

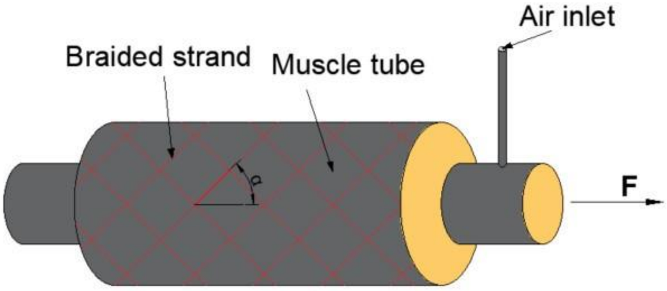

Fig. 5. General view of the basic structure of artificial muscles

Figure 5 illustrates the operational concept of an artificial muscle, assuming that the alteration of pressure within the muscle occurs in a closed system without any temperature variation or dissipation to the surroundings. The work produced in this process will be:

$$F = -P\frac{dV}{dL} \quad (1)$$

where: F-force generated by muscles, [N]; P-compressed air pressure is pumped into the muscle, [MPa]; V-muscle volume, [mm^3]; L-muscle length, [mm].

The muscle mass is composed of muscle fibers wrapped n turns along the cylindrical muscle tube, considering the length of each muscle fiber as b. Cutting the muscle mass along the muscle fiber while stretching the muscle fiber on the plane, we will obtain a right triangle as shown, with θ being the braid angle, as depicted in Figure 6.

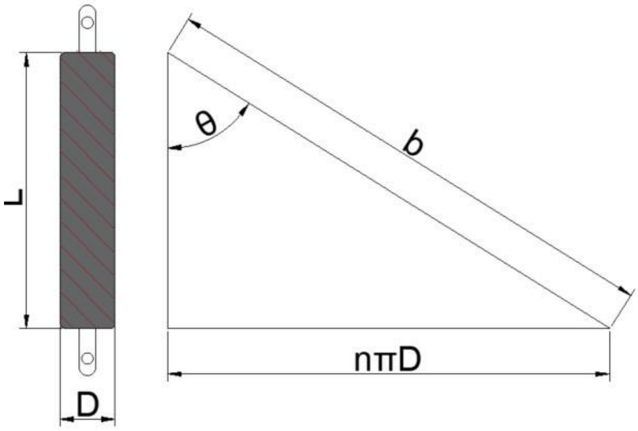

Fig. 6. Geometric structure of artificial muscles

Muscle mass volume $$V = \pi\left(\frac{D}{2}\right)^2 L = \frac{b^3}{4\pi n^2}\sin^2\theta \cdot \cos\theta \quad (2)$$

Muscle length $$L = b.\cos\theta \quad (3)$$

Diameter of artificial muscle $$D = \frac{b.\sin\theta}{\pi n} \quad (4)$$

And then we have $$F = -P\frac{b^2[2\cos^2(\theta) - \sin^2(\theta)]}{4\pi n^2} \quad (5)$$

$$\text{or } F = -P\frac{\pi {D_0}^2(L^2 - b^2)}{4b^2}$$

Based on the observation and consideration that in the small length change dL, the compressed air pressure does not change, the stiffness of the mechanical spring can be calculated as follows:

$$K = \frac{dF}{dL} = K_p P \quad (6)$$

and then: $F = K_p P(L - L_{min})$ (7)

where: $Lmin$ is the length of the shortest muscle, [mm].

Consider the transmission system of a joint, as depicted in Figure 7.

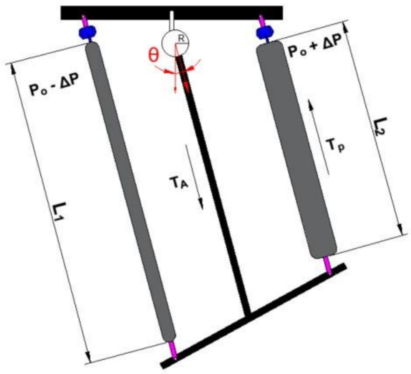

Fig. 7. Dual muscle pair configuration

Initially, we introduce a gas with a pressure $P0$ into both muscles to ensure that they are equal in size. At this point, the rotation angle θ_0 is set to 0 degrees, and the length of the muscle connected to the system is L_0. Alterations in muscle pressure result in changes in muscle length, which in turn induce a rotation of the joint by an angle θ. To induce rotational motion in the muscle, we will inject a specific quantity of air into one muscle, increasing pressure (ΔP). Simultaneously, the other muscle will extract a certain amount of air, leading to a decrease in pressure (ΔP).

Muscle mass length can be calculated using the formula

$$L = L_0 \pm r\theta \quad (8)$$

and then: $$F = K_p(P_0 \pm \Delta P)(L_0 \pm r\theta - L_{min}) \quad (9)$$

where: K-stiffness coefficient of muscle; P-Pressure at the present time, [MPa]; $P0$-Pressure of initial gas injected into the muscle, [MPa]; ΔP-Pressure difference at the current time compared to the initial pressure, [MPa]; $L0$-Initial muscle length, [mm]; L-Muscle length at current time, [mm]; $Lmin$- Shortest muscle length, [mm]; K-Stiffness coefficient of muscle.

The rehabilitation robot using artificial muscles in this report consists of two rotating joints: The first joint is the hip joint and the second joint is the knee joint. The transmission system that controls the rotation angle of each joint consists of two artificial muscles connected in parallel with one end fixed and the other end attached to the rotating joint as shown in Figure 8.

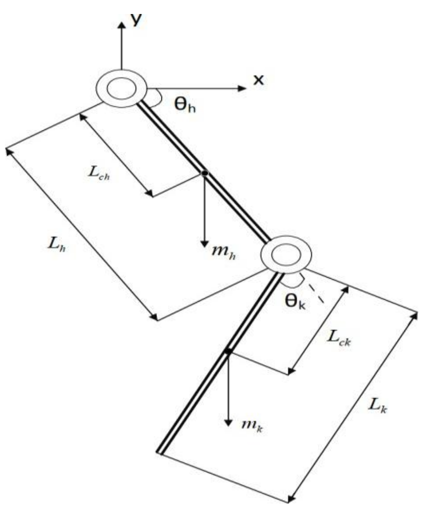

Fig. 8. Robot model in Cartesian coordinate system

In figure 8 i is the coefficient (h: hip joint, k: knee joint); m-mass of joint and connecting rod i; θ_i-rotation angle of joint i; L_{ci}-position of center of gravity of joint and connecting rod i; L_i-length of connecting bar i.

Equation of relationship between rotational torque of rotating joints with position, velocity and acceleration

$$M_i = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q_i}}\right) - \frac{\partial L}{\partial q_i} \qquad (10)$$

where: i-coefficient (h: hip joint, k: knee joint); M-rotational moment of joint I; $L = K - P$: Lagrangian of robot; K-total kinetic energy of the robot; P-total potential energy of the robot; qi-rotation angle of joint I; $\dot{qi}$-rotation speed of the joint.

Equation of rotation of a robot transmission system using artificial muscles:

$$M = (F_1 - F_2)r = H.\ddot{\theta} + V\dot{\theta} + G.\theta \qquad (11)$$

where: F_1-pulling force of the anterior muscle; F_2-pulling force of the posterior muscle.

2.3. Static load analysis

The mechanism's shaft is constructed from 6063 aluminum. The simulation calculation outcomes are depicted in Figures 9 and 10.

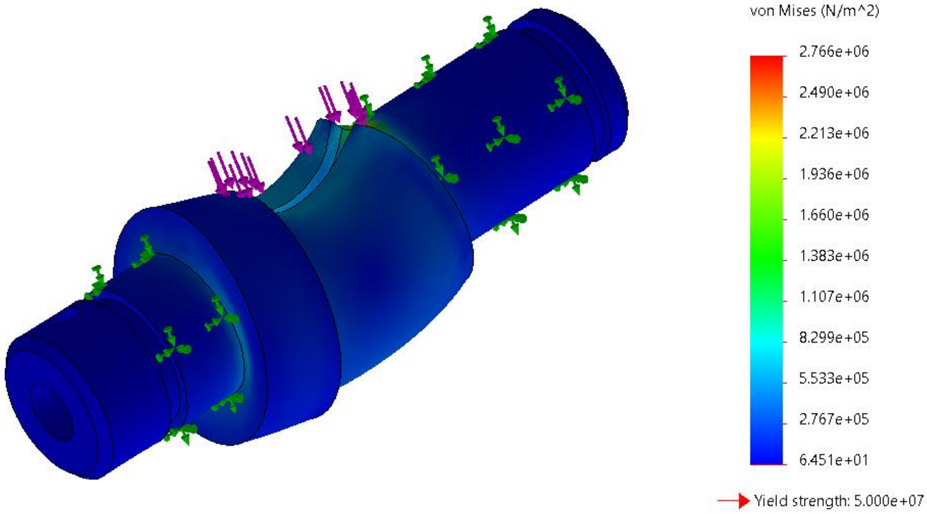

Fig. 9. Simulation results of shaft strength

The results show that the shaft is exceptionally resilient. The maximum stress occurs at $\sigma_{max} = 2.7 \cdot 10^6$(Pa), which is below the yield strength of $S_{yt} = 5 \cdot 10^7$ (Pa).

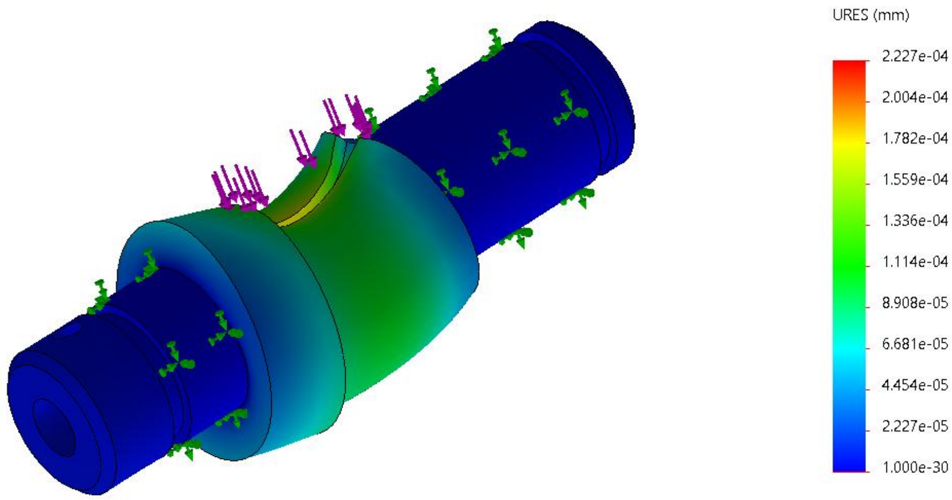

Fig. 10. Displacement simulation results

Based on the simulation results, it is evident that the shaft experiences a maximum displacement of 0.23µm. This displacement, although small, falls within acceptable limits, thereby confirming the shaft's rigidity during operation.

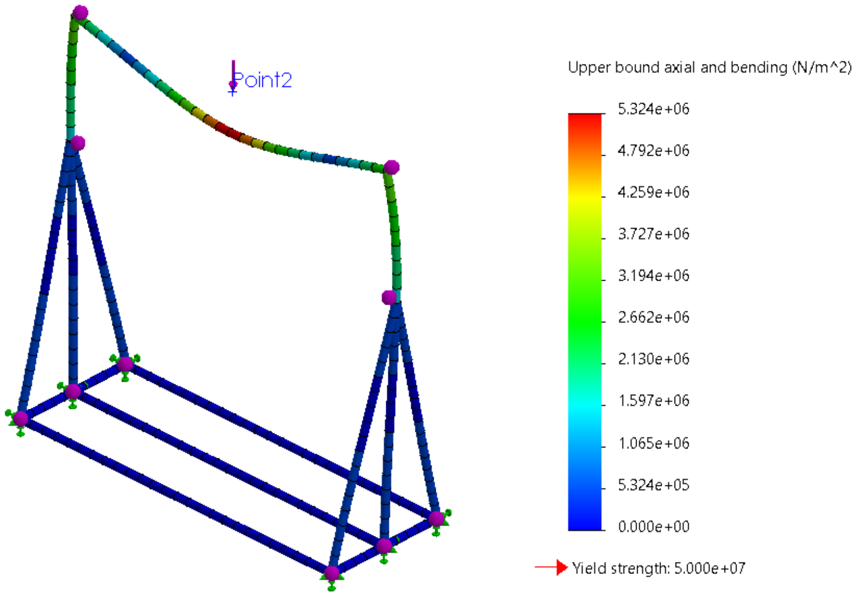

Fig. 11. Results of stress simulation on the frame system

The stress simulation results in Figure 11 indicate that the maximum stress observed on the frame is δmax = $5.32 \cdot 10^6$(Pa), which is below the yield strength of $5 \cdot 10^7$ (Pa). The frame is sufficient in strength.

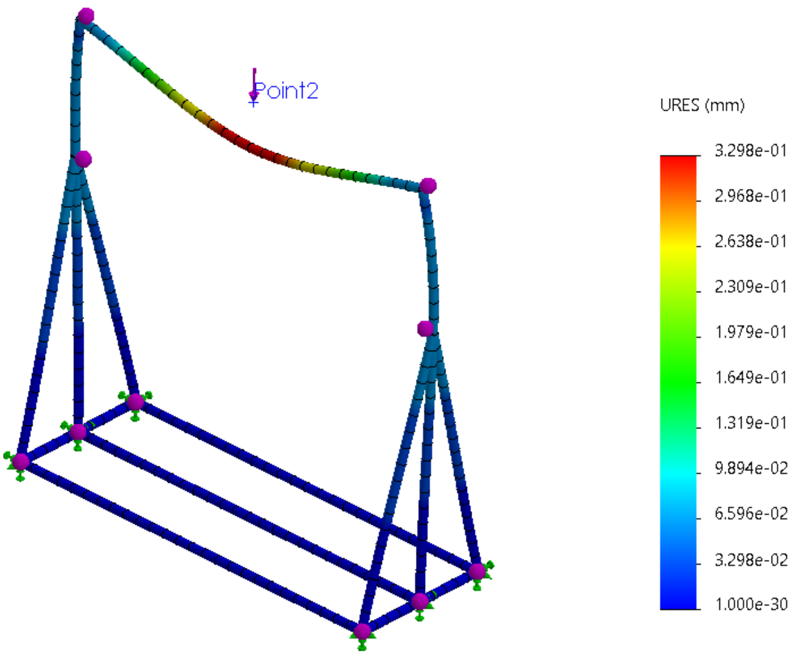

Fig. 12. Simulate displacement on the frame system

Figure 12 displays the estimated displacement of the machine frame system, with the maximum displacement measuring 0.32 mm. This displacement is considered small and falls within an acceptable range for actual operation.

3. RESULTS AND DISCUSSION

Figure 13 depicts the lower limb support robot that was constructed and subjected to testing. Prior to manufacturing, this model underwent simulations for kinematics, dynamics, and durability calculations in order to fine-tune and optimize its structure. The parametric design function of CAD allows for convenient and effortless adjustment of the model's size, shape, and mass parameters.

Table 2 shows the technical specifications of the robot. The robot can be adjusted to fit leg lengths from 1100 to 1250 mm, this is the common leg length of adults in Vietnam. Hip joint opening ranges from -28.9 to 87 degrees. Knee joint opening ranges from o to 87.8 degrees. In general, it fully meets the basic movements of the lower limbs to help patients practice

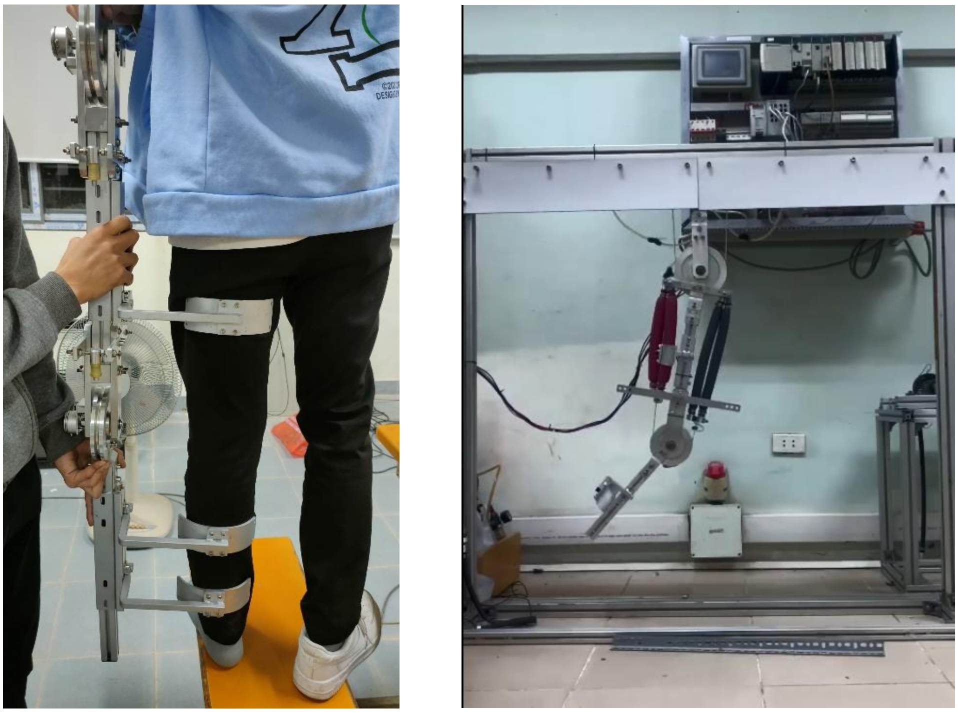

Fig. 13. Model of robot prototype

Table 2. Specifications for the robot prototype

Leg height is adjustable, [mm]	1100 – 1250
Robot Weight, [kg]	15
Hip rotation angle, [°]	$-28.9 \rightarrow 87$
Knee rotation angle, [°]	$0 \rightarrow 87.8$
Required lifting force, [N]	$72.49 \rightarrow 149.79$
Compressed air pressure, [KPa]	0.6 – 2

Experiments testing the robot's movement support capabilities have been conducted in the laboratory, both with and without a load. In the treeb zero step experiment, the robot is suspended on a shelf and carries out a walking process without any load. The robot's movement is controlled using the kinematic data obtained from the walking process of an actual person.

This experiment primarily assesses the robot's kinematic capabilities, step control algorithms, and movement rules. During the subsequent experiment, the robot acquired the ability to autonomously navigate along the shelf. This is the mode where the test is conducted without any load, and it is used to execute the control program.

At last, the robot's interaction with humans is evaluated. The robot is connected to the individual and carries out deliberate motor actions at a leisurely pace. The tester fully relaxes the lower extremities to allow the robot to execute its supportive role.

4. CONCLUSIONS

The article methodically outlines the procedure for designing, fabricating, and evaluating prototypes of robots that aid in mobility and rehabilitation for individuals with motor impairments. The design and structural selection process has been carried out in accordance with the requirements and research findings.

The Robot's 3D CAD model has been fully constructed, enabling simulation of kinematics, dynamics, calculation, durability testing, and design optimization for precise adjustment and refinement of the structure prior to manufacturing. Based on this premise, a support robot prototype was developed and independent movement trials were carried out, both with and without human involvement. The experimental results demonstrate that the robot has successfully fulfilled the specifications for designing and fabricating a prototype model in relation to kinematics, dynamics, and structure. This model serves as a physical platform for testing control algorithms. Manage, facilitate locomotion, and reinstate functionality for patients.

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