Journal of the Brazilian Society of Mechanical Sciences and Engineering (2018) 40:245
https://doi.org/10.1007/s40430-018-1172-y

TECHNICAL PAPER

Cable-driven lower limb rehabilitation robot

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Received: 17 May 2017 / Accepted: 5 April 2018 / Published online: 16 April 2018

Abstract

This paper describes a low-cost cable-driven manipulator robot for lower limb rehabilitation, designed for the population with gait impairments, such as those with cerebral palsy or stroke. The robot is composed by a fixed base and a mobile platform (orthoses) that can be connected to one cable, or at most six, and can perform the individual movements of the hip, the knee, and the ankle. It starts with a review of the different mechanical systems developed and applied for lower limb rehabilitation. After, the proposed structure is detailed. Finally, the numerical and experimental tests of the cable-driven parallel structure for lower limb rehabilitation movements are outlined, showing the viability of the proposed structure.

Keywords Cable-driven manipulator · Lower limb · Rehabilitation · Robots

1 Introduction

For every 1000 children born, 2–3 will have cerebral palsy (CP) [1], which accounts for about 8000–10,000 new cases per year in the United States [2]. CP refers to brain irregularities or injuries which may result in movement impairment which occurs before the age of 2 and is often due to developmental defects or trauma.

Stroke, like cerebral palsy, is a static (non-progressive) brain injury. Presently, Estimated 6.6 million Americans have survived a stroke [3]. Projections from the American Heart Association suggest that this number will increase by an additional 3.4 million people by 2030 [3], with the majority of stroke survivors experiencing some residual motor impairment [4].

At this stage, neurorehabilitation for both CP and stroke is limited to physical or occupational therapy delivered by clinicians (and potentially augmented by robotic tools [4]) to facilitate neuro-recovery and reduce the consequences of central nervous system injury. Many of those diagnosed with CP [5] and a proportion of patients with stroke [6] will endure further debilitating secondary impairments throughout their lifespan, as a result of their poor gait pattern. It is, therefore, vital to explore methods for improving gait rehabilitation and the clinical outcomes for those living with CP or stroke.

One such method for providing or augmenting gait rehabilitation is robotic therapy. Many different gait rehabilitation robotic systems have been proposed over recent years [7–11]. Nonetheless, the results of the Locomotor Experience Applied Post-Stroke (LEAPS) study suggest that continued development of the design and the purpose of these devices are required for effective gait retraining [12–15].

The Hocoma's Lokomat system (http://www.hocoma.com/) is the most commercial successful example of gait rehabilitation. The Lokomat uses two actuators, at the hip and the knee, to move the patient lower limb through a neurologically healthy kinematic path. Other similar exoskeletons include the LOPES [16] and ALEX [17]. Some authors have been using orthoses/exoskeletons with pneumatic muscle-type actuators. Dzahir and Yamamoto [8] presented a survey of these mechanisms. The major issue of these mechanisms is the development of a more effective control algorithm.

Another type of robots used in rehabilitation is the foot plate robots [10] that include the MoreGait [18], the Gait Trainer [19], Haptic walker [20], and the G-EO system [21]. These systems simulate the walking from an end-

Technical Editor: Victor Juliano De Negri.

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effector that stays with the foot during the full cycle of walking.

The cable-driven parallel manipulators are another alternative that has been studied over the past few years to be applied in human rehabilitation. These structures consist on a fixed base and a moving platform (end-effector) connected by multiple cables that can move the end-effector by changing the cables lengths while prevent any cable from slackening [22, 23].

These structures can be suitable for rehabilitation process, because they have a large reconfigurable workspace which may be adapted to different patients and rehabilitations protocols. Besides that, the mechanical structure is easy to assemble, disassemble, and to transport. In the clinical point of view, the use of robot with cables, instead of exoskeleton or rigid links, makes the patient feel less constrained which is important to the patient accept the new rehabilitation technology [9, 15]. The major drawback related to the use of cable-driven manipulator is the control problem to remain all the cables tensioned [18].

There are few cable-driven robots applied in medical/rehabilitation. The CALOWI (Cassino Low-Cost Wire System) has four cables disposed in a 4-4 architecture that can be used to helping elderly and patients with lower limb injuries for sitting and getting up, or moving patients in hospital rooms [24].

Surdilovic and Bernhardt [25, 26] presented a robotic system for supporting gait rehabilitation and restoring of motor functions, called STRING-MAN, developed at Fraunhofer IPK-Berlin. The system is designed to support gait restoration for several kinds of injury [26].

Wu et al. [27] presented a cable-driven robotic gait system that works with a treadmill and body weight support system. The system has four cables driven by four motors, pulleys, and cable spools which were used to apply controlled resistance/assistance loads to the legs. Another cable-driven parallel robot for gait rehabilitation was developed by Harshe [28]. The objective of this device is analyzing the gait and aiding a medical practitioner to identify gait patterns (measurement) and diagnose injuries.

For the human lower limb rehabilitation, there are a few studies that consider the rehabilitation of all the joints movements in isolation or combined form. In part, this is due to size, weight, and complexity of the movements of the lower limb. Thus, the development of a low-cost robotic device applied to the rehabilitation of the lower limbs of the human body, capable of reproducing the movements of all joints in an isolated manner or combined, even assisting in rehabilitation of human gait has great applicability, by constituting the main contribution of this paper.

This paper presents a cable-driven parallel manipulator for rehabilitation of the lower limb human movements. The structure can be assembled from one to six cables that allow the individual movements of the hip, the knee, the ankle, and the human gait simulation, with different limits and speeds. This paper focuses on the rehabilitation of the individual movements of the joints.

This paper details the following: Sect. 2 presents the proposed device and the mathematical model. Section 3 presents the numerical and experimental tests of the cable-driven robot for lower limb rehabilitation. Finally, Sect. 4 presents the discussion and conclusion of this paper.

We should point out that the aim of the developed cable-driven robot is to assist the health professionals and not to replace them.

2 Proposed device

The design of cable-driven rehabilitation robot presents a number of challenges, like working with patients with different backgrounds. The repetitive movements of the lower limb constitute part of the rehabilitation process and the physiotherapist moving the limb in a desired trajectory and providing assistance for resistance to motion, as well as purely passive movement, depending on the patient level of muscle activity. The device proposed in this paper has the requirements: it will be worked in patients that are passive, i.e., the movement needs to be made by another person or a robotic device; the proposed device will be used in clinics and permits recording the data to monitoring the progress and facilitate the feedback to the patient; the mechanism is low cost, compared to other commercial solutions and easy to fix to the patient, using Velcro tape; finally, the physiotherapist can control the number of repetitions and the speed.

The proposed cable-driven manipulator can be assembled from one to six cables. Figure 1a shows the elements of the proposed structure to the case of using two cables. The structure consists of sets formed by 24 V × 45 Nm DC motor (Bosch gear motors model F006WM0310), encoder with 500 pulses per revolution, pulley, load cells (model CSA/ZL—20 kgf), and stretcher. The control system was performed using PIC18F4550 microcontrollers, one for each cable. The microcontrollers communicate with the computer via the USB interface [29].

Figure 1b shows the built prototype. In the numerical and experimental tests, a 1.80 m-tall anthropometric wooden puppet was used, Fig. 1b.

The number of cables used is directly linked to the complexity of the desired movement. Only one actuator/cable can be used for single and simple movements, e.g., the execution of ankle dorsiflexion or the flexion/extension of the knee. As the movements become more

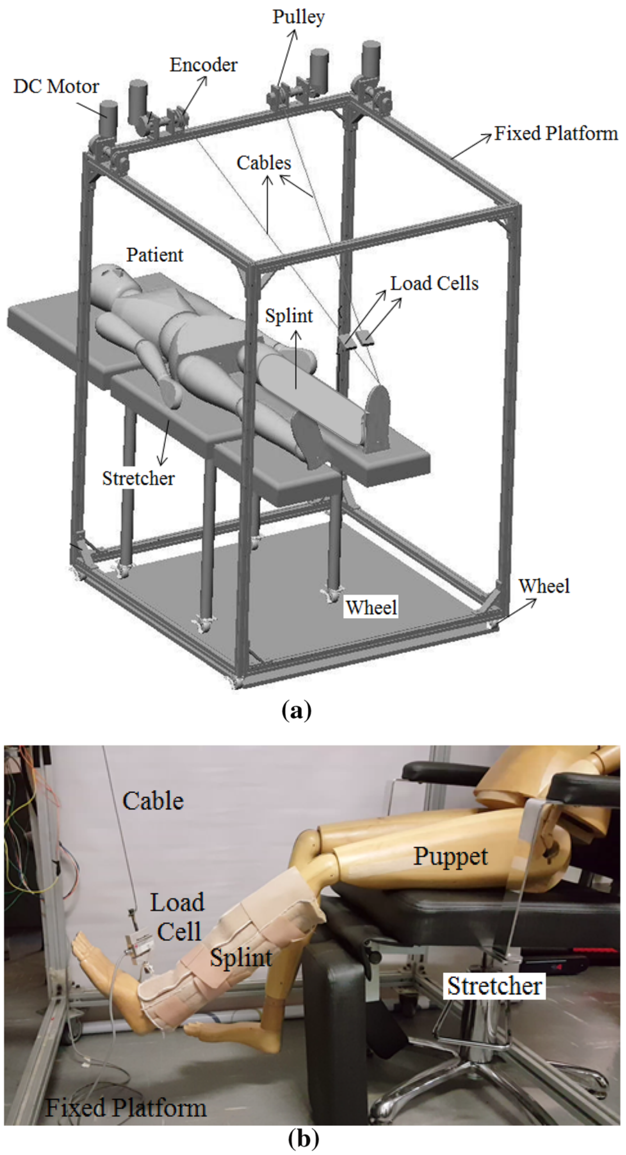


Fig. 1 **a** Scheme of the proposed device with two cables. **b** Prototype build at Federal University of Uberlândia

complex, the amount of cables may be increased to accomplish the movement.

The numerical simulation of gait rehabilitation, using six cables, was presented in [9, 30, 31].

This paper focuses on the structure with one to three cables to make single movements of the lower limb joints and expands the previous ones [9, 31, 32] presenting experimental results compared to the mathematical model presented in [9, 31, 32].

Thus, to perform the individual movements of flexion/extension of the hip, the knee, or the ankle, there are used from one up to three cables. The use of one cable is enough to perform the individual movements of flexion and the weight of the lower limb assists in extension movement. The use of two/three cables aims to minimize/optimize the tension applied to the cables.

The system runs using the "teaching by showing", where the control is performed in two steps: the first one labeled "teaching" in which the therapist "teaches" the movements to be performed by the cable-driven robot, and the other step labeled "playing" in which the robot runs the predefined movement.

In the "teaching" mode, the acquisition of position data and speed of each motor shaft is done through digital encoders. The therapist movements in the splint are controlled by a loop that maintains the tension of the cables so as to cause the movement of the actuator when the therapist moves the splint. The signal of load cells attached to the cables is used as a control variable and the PWM signal of microcontrollers make the actuators rotation. The position and angular speed of each actuator are saved to be replayed during the "playing" mode. In this way, the position control is used in this paper.

A graphical interface for PC was developed to control in which mode of operation that the device should run. To ensure the safe operation, emergency buttons are installed and the maximum allowable forces acting on the cables are set to prevent injuries involving patients. The control system is explained in [29, 31].

The kinematic model of the proposed cable-driven robot can be obtained similar to the traditional parallel structures [33], Fig. 2.

The inverse kinematic model permits to find the cables lengths, ρ_i, as function of the end-effector pose, Eqs. (1)–(5). In Eq. (5), the function sine is abbreviated by s and cosine by c:

$$\rho_i = \|(\mathbf{c} + Q\mathbf{v_i} - \mathbf{p_i})\|. \tag{1}$$

Equation (1) can be rewrite by:

$$\rho_i^2 = (\mathbf{c} + Q\mathbf{v_i} - \mathbf{p_i})^{\mathrm{T}} \cdot (\mathbf{c} + Q\mathbf{v_i} - \mathbf{p_i}). \tag{2}$$

The development of Eq. (2) leads to:

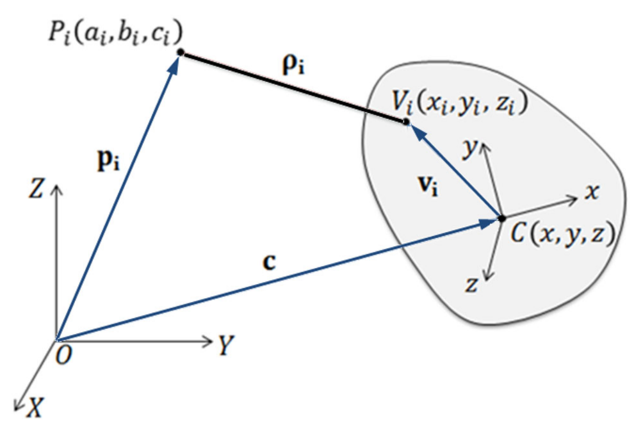


Fig. 2 Kinematic parameters

$$\rho_i^2 = \mathbf{c}^{\mathrm{T}}\mathbf{c} + 2\mathbf{c}^{\mathrm{T}}Q\mathbf{v_i} - 2\mathbf{c}^{\mathrm{T}}\mathbf{p_i} + \mathbf{v_i}^{\mathrm{T}}\mathbf{v_i} - 2\mathbf{p_i}^{\mathrm{T}}Q\mathbf{v_i} + \mathbf{p_i}^{\mathrm{T}}\mathbf{p_i}. \tag{3}$$

Thus, the cable length can be found by Eq. (4):

$$\rho_i = \sqrt{\mathbf{c}^{\mathrm{T}}\mathbf{c} + 2\mathbf{c}^{\mathrm{T}}Q\mathbf{v_i} - 2\mathbf{c}^{\mathrm{T}}\mathbf{p_i} + \mathbf{v_i}^{\mathrm{T}}\mathbf{v_i} - 2\mathbf{p_i}^{\mathrm{T}}Q\mathbf{v_i} + \mathbf{p_i}^{\mathrm{T}}\mathbf{p_i}}. \tag{4}$$

Q is calculated by Eq. (5):

$$Q = \begin{bmatrix} c\beta\, c\gamma & -c\beta\, s\gamma & s\beta \\ s\theta\, s\beta\, c\gamma + c\theta\, s\gamma & -s\theta\, s\beta\, s\gamma + c\theta\, c\gamma & -s\theta\, c\beta \\ -c\theta\, s\beta\, c\gamma + s\theta\, s\gamma & c\theta\, s\beta\, s\gamma + s\theta\, c\gamma & c\theta\, c\beta \end{bmatrix}. \tag{5}$$

In Eq. (1), i varies from 1 to n (number of cables), where: $\mathbf{p_i}$ is the position vector of point P_i in relation to a fixed reference frame, $\mathbf{v_i}$ is the position vector of point V_i related to the moving frame, $\mathbf{c}$ (c_x, c_y, c_z) is the position vector of the center of gravity of the moving platform, and Q is the rotation matrix between fixed and moving frames obtained by a rotation of θ about x-axis followed by a second rotation β about the new y-axis and a third rotation γ about the new z-axis. The length of cable i is the distance between points P_i and $V_i = \rho_i$.

During the lower limb rehabilitation sessions, the patient limb movement speed should be reduced to avoid pain and discomfort to the patient. In this way, the static model of the proposed device is presented using the Jacobian static force analysis [9, 30–32]. The static force analysis is important to determine if the cables are in tension under the load to obtain a feasible workspace.

The relation between the cables forces vector, **F**, and the external efforts **W**, which are the limb and the splint weight, can be obtained by Eq. (6) in matrix form. J is the Jacobian matrix of the structure:

$$[J]^{\mathrm{T}}[\mathbf{F}] = [\mathbf{W}]. \tag{6}$$

The Jacobian matrix can be written as (7) for the structure with i cables, and $\hat{\rho}$ is the unitary vector defining the cable direction to the actuator:

$$J = \begin{bmatrix} \hat{\rho}_1 & \hat{\rho}_2 & \cdots & \hat{\rho}_i \\ \hat{\rho}_1 \times Q\, v_1 & \hat{\rho}_2 \times Q\, v_2 & \cdots & \hat{\rho}_i \times Q\, v_i \end{bmatrix}. \tag{7}$$

Equation (6) is used to evaluate the cable tension for a given trajectory, rehabilitation movement, in respect to the kinematic of the cable-driven architecture. One important requirement to develop the cable-driven rehabilitation robot proposed in this paper is the workspace of the lower limb joints. This workspace is obtained in function of range movements of hip and knee. The ankle joint movements was neglected to simplify the model.

The lower limb includes the hip, knee, and ankle joints [34].

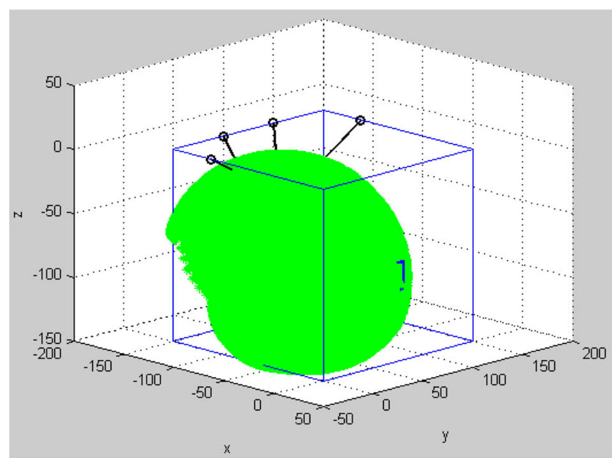
The hip has three degrees of freedom and works like a ball-and-socket joint. The hip motions are the flexion/extension (− 120° to 10° when the knee is flexed), adduction/abduction (− 45° to 30°), and lateral/medial rotation (− 30° to 60° when the knee is flexed).

The human knee has two degrees of freedom, one is the flexion and the extension, and another is the rotation that is possible with the knee flexed. When the knee is flexed, the range of rotation is − 32° to 42°. The knee flexion when the hip is flexed, the range is of 0° to 140° [30, 34].

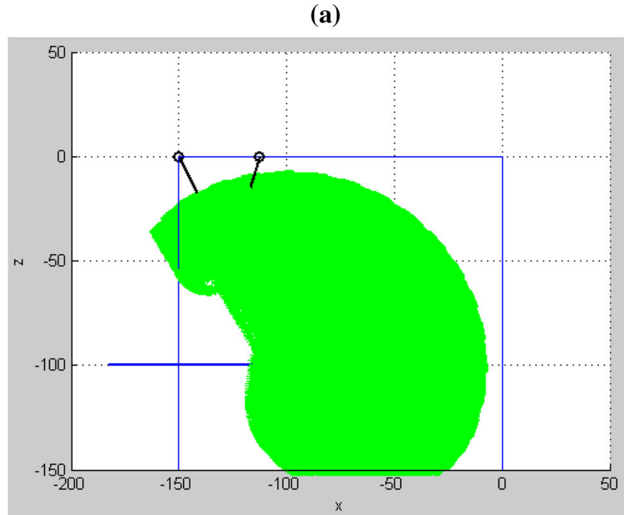
The complete details of lower joints movements and lower limb dimensions can be found in [30, 34].

Figure 3 shows the obtained workspace considering a subject with 1.75 m tall. From the analysis of the workspace, it was verified the necessity of fixed platform, Fig. 1a, in cubic format with edge of 2 m to satisfy all the lower limbs movements.

More details about the Jacobian static force analysis and the workspace optimization procedure to obtain an end-



(a)



(b)

Fig. 3 Lower limb workspace (cm). **a** Tridimensional view; **b** side view effector controllable with positives tensions in cables can be found in [9, 30–32].

3 Experimental tests

Experimental tests were conducted with different configurations to verify that the cable-driven robot proposed is able to perform the movement's rehabilitation and to record force and length cables coherent with the numerical model. The experimental tests were made using an anthropometric wooden puppet with 1.80 m tall. Movements were carried with the puppet knee joint being flexion/extension with one and two cables, and rotational hip, with three cables. In all tests, the puppet hip was flexed at 90°.

The point *O* was used as the inertial frame to perform the numerical simulations and experimental tests, Fig. 4.

The cable attachment is made directly on the patient́s limb with the aid of a Velcro tape.

Loads cells were previously calibrated to determine the forces in the cables during the experimental tests. The load cell has a 0.25 N resolution and 0.195 kilos mass. It is place directly in the cable, Fig. 1. A digital inclinometer was used to measure the angle of the lower limb. It has a 0.1-degree resolution and 0.230 kilos mass, and it was positioned on the puppet's leg, Fig. 1b. The puppet shin and foot mass is 1.034 kilos and the shin length is 0.35 m. Static tests were done where, for each angle value obtained by a digital inclinometer, there were collected values of the cable tension (force) obtained by a load cell. To the numerical calculus of cable force and length, Eqs. (6) and (4) were used, respectively.

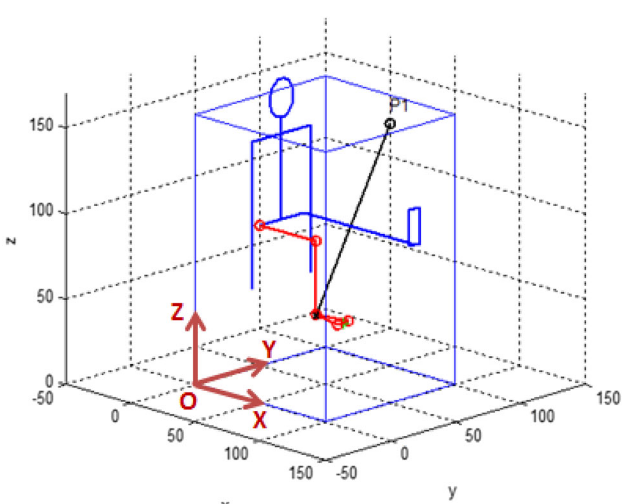


Fig. 4 Inertial frame

3.1 Flexion/extension of the knee using one actuator/cable

For this test, the actuator was positioned aligned with the puppet, and the coordinates are shown in Table 1.

The puppet position remained always the same for all experimental tests.

Figure 5 shows the flexion/extension test carried out on the wooden puppet. The initial condition established is when the lower limb is stretched parallel to the ground and the angle value equals 0°. In this experimental setup, it is possible to make the knee movement between 0° to 90°. To reach the maximum flexion range of 140°, it is necessary another setup showed in [30, 34], using more cables.

Figure 6 shows forces graph as angle function for flexion/extension of the knee, using one cable, and Table 2 presents the errors.

The largest errors were found for knee flexion angles near 90°, Fig. 5. This fact is due to the low values of the forces in these configurations.

The cable lengths along the movement were also calculated for this test, as shown in Fig. 7.

The cable length errors along the movement are small (less than 2%) and can be associated to measuring errors and the puppet positioning error inside the structure.

3.2 Extension of the knee using two actuators/cables

The puppet position was maintained for this test. Table 3 presents the actuators position.

Figure 8 shows the scheme of the extension test with two cables and the foot trajectory.

Figure 9 shows forces graph as angle function for extension of the knee using two cables, and Table 4 presents the errors. Again, the larger errors are close to 90°, due to low cables' tension.

The cables lengths along the movement were also obtained for this test, as shown in Fig. 10. The cable length errors along the movement are small and can be associated to measuring errors and the puppet positioning error inside the structure. The error values are presented in Table 5.

Table 1 Puppet and actuator coordinates to test with one cable

Position	*OX* axis (cm)	*OY* axis (cm)	*OZ* axis (cm)
Hip puppet	0	50	82
Actuator	100	50	163.5

Fig. 5 Knee flexion/extension experimental test with one cable

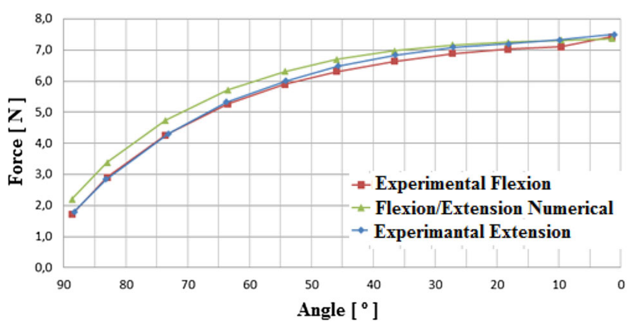


Fig. 6 Knee flexion/extension experimental test results with one cable

3.3 Rotation of the hip using three actuators/cables

The puppet's knee was flexed at 64° for this test, Fig. 11, and three cables were used to carry out the movement. Figure 11a presents the numerical simulation scheme, and Fig. 11b presents the experimental test.

Table 6 presents the position motors.

The knee flexion was always kept close to 64°, since it was very difficult to maintain this exact inclination at all points of data collection.

Table 7 shows the force results in the cables, and Table 8 shows the errors found between the experimental tests and numerical tests. Tables 9 and 10 show the cables lengths and the errors found, respectively.

Through Tables 7, 8, 9, and 10, it can be seen that even with an increased number of cables, the forces values found by numerical and experimental tests are similar and the errors in the cables lengths are small. It can also be highlighted that the increased number of cables was followed by an increase in the error of the force values.

Table 2 Errors between numerical and experimental results to flexion/extension with one cable

Angle (°)	Numerical (N)	Experimental	Error (%)
Extension			
1.1	7.366	7.499	− 1.8
9.9	7.311	7.328	− 0.2
18.1	7.257	7.205	0.7
27.1	7.159	7.091	1.0
36.5	6.982	6.833	2.1
45.7	6.702	6.482	3.3
54.1	6.324	6.006	5.0
63.7	5.698	5.325	6.5
73.1	4.800	4.315	10.1
83.2	3.343	2.844	14.9
88.3	2.302	1.804	21.6
Flexion			
Angle (°)	Numerical (N)	Experimental	Error (%)
1.5	7.363	7.428	− 0.9
9.7	7.312	7.105	2.8
18.3	7.255	7.021	3.2
27.2	7.158	6.886	3.8
36.6	6.980	6.631	5.0
45.9	6.695	6.314	5.7
54.3	6.314	5.900	6.6
63.5	5.713	5.265	7.8
73.6	4.742	4.267	10.0
83.0	3.379	2.900	14.2
88.7	2.208	1.707	22.7

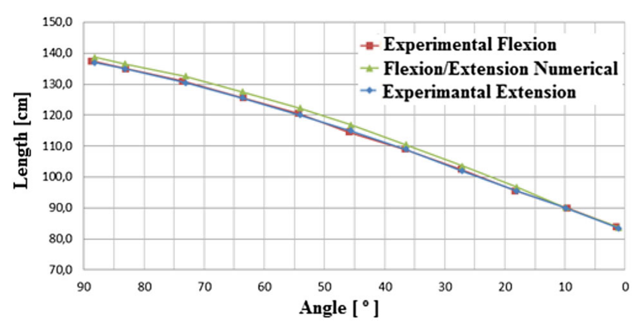


Fig. 7 Cable length along the movement

4 Conclusions and discussion

This paper outlined the mechanical design and development of a low-cost cable-driven lower limb rehabilitation robot. The device proposed is conceptually simple to obtain a low-cost device to be used in countries with lower

Table 3 Actuator coordinates to test with two cables

Position	*OX* axis (cm)	*OY* axis (cm)	*OZ* axis (cm)
Actuator P1	100	34.5	163.5
Actuator P2	100	65.5	163.5

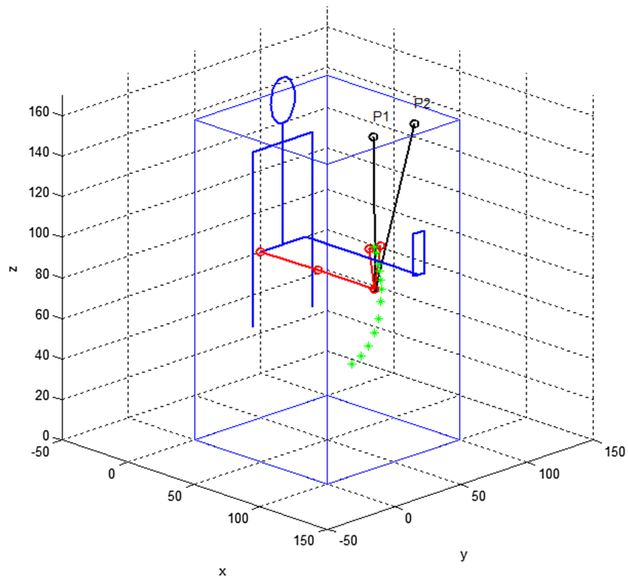


Fig. 8 Flexion/extension of the knee using two cables

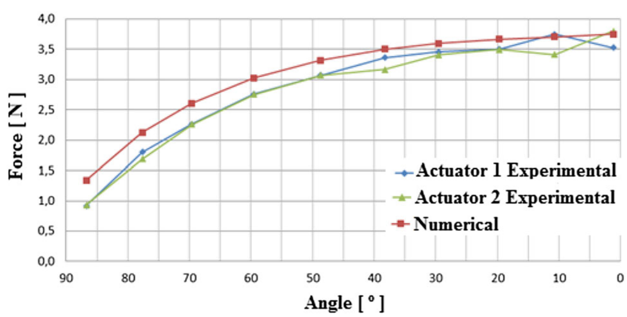


Fig. 9 Knee extension experimental test results to two cables

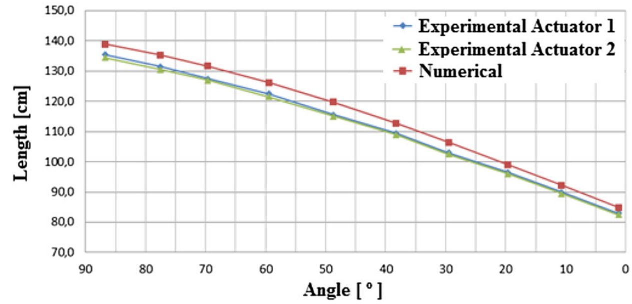


Fig. 10 Cable length along the extension movement for two actuators

incomes. Injuries of the central nervous systems like the cerebral palsy and stroke often affect the survivor's ability to move, and the proposed structure can help in the lower limb rehabilitation procedures.

Through the experiments with the wooden puppet, it could be verified consistency between the numerical model and the experimental tests for most movements analyzed, shown by the acceptable values of errors found.

Good levels of correlation between the numerical and experimental models can be observed for the cable length with errors less than 5%. One requirements of the device proposed in this paper is that will be worked in patients that are passive, i.e., the movement needs to be made by physiotherapist or a robotic device. The goal of the physiotherapist in this process is to help patients achieve normal standards of range of motion and to strengthen their muscles [35]. The manual movements of the physiotherapist have inaccuracies related to the clearance in the human joint complexes as presented in [35–42] that cause less precise/repetitive movements. Thus, the proposed device can make the rehabilitation movements proposed in this paper better than manual treatments.

The found errors in the experiments with the wooden puppet can be caused by various factors, such as difficulty in obtaining the exact center of mass position of the lower limb puppet, and the coordinates position of the puppet inside the device. Another error source is the reaction

Table 4 Errors between numerical and experimental results to extension with two cables

Angle (°)	Numerical (N)	Motor 1 (N)	Motor 2 (N)	Error motor 1 (%)	Error motor 2 (%)
86.7	1.337	0.919	0.933	31.29	30.27
77.6	2.129	1.804	1.688	15.27	20.69
69.6	2.605	2.264	2.256	13.09	13.39
59.5	3.024	2.759	2.751	8.76	9.02
48.7	3.319	3.072	3.069	7.46	7.52
38.3	3.502	3.360	3.163	4.03	9.66
29.5	3.600	3.457	3.409	3.96	5.30
19.7	3.667	3.503	3.494	4.48	4.70
10.7	3.706	3.748	3.413	− 1.14	7.92
1.2	3.746	3.529	3.797	5.77	− 1.37

Table 5 Errors between numerical and experimental results cables' length to extension with two cables

Angle (°)	Numerical (cm)	Experimental motor 1 (cm)	Experimental motor 2 (cm)	Error motor 1 (%)	Error motor 2 (%)
86.7	138.90	135.50	134.50	2.4	3.2
77.6	135.33	131.50	130.50	2.8	3.6
69.6	131.63	127.50	127.00	3.1	3.5
59.5	126.26	122.50	121.50	3.0	3.8
48.7	119.74	115.50	115.00	3.5	4.0
38.3	112.79	109.50	109.00	2.9	3.4
29.5	106.49	103.00	102.50	3.3	3.7
19.7	99.14	96.50	96.00	2.7	3.2
10.7	92.22	90.00	89.50	2.4	2.9
1.2	84.89	83.00	82.50	2.2	2.8

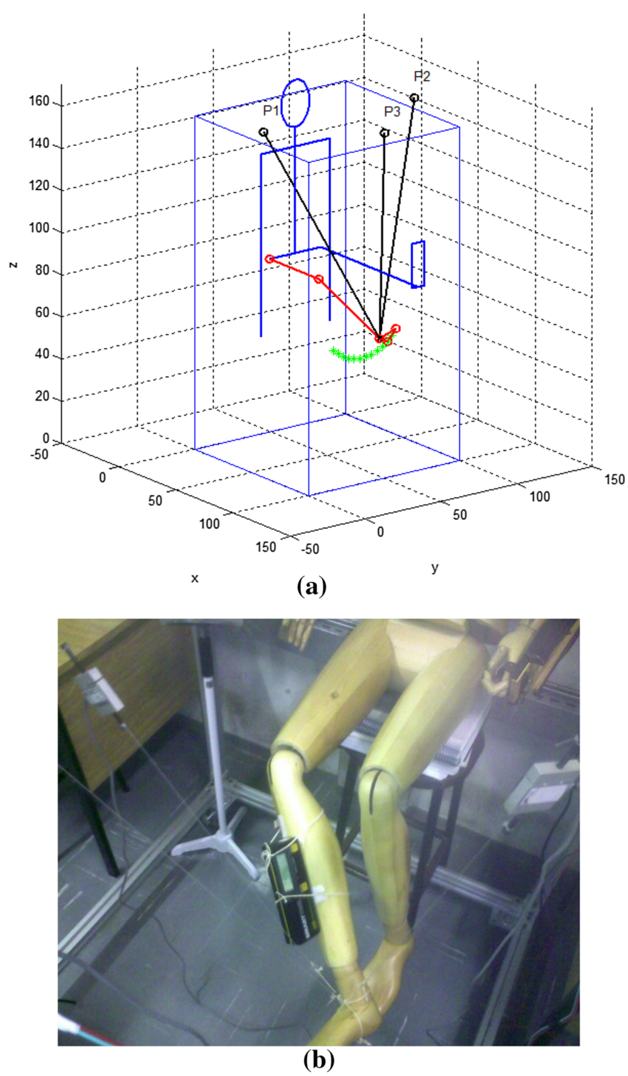


Fig. 11 **a** Actuator positions; **b** experimental test with three cables

Table 6 Actuator coordinates to test with three cables

Position	*OX* axis (cm)	*OY* axis (cm)	*OZ* axis (cm)
Actuator P1	60.5	0	163.5
Actuator P2	60.5	100	163.5
Actuator P3	100	50	163.5

forces existing in the joints of the puppet during movement and the friction joints which are not considered in the numerical model. The device proposed has the limitation of not allowing small forces to be read as the load cell used is placed directly on the cable. Since the load cell has a considerable mass of 0.195 kilos and needs to be tensioned to indicate reliable measures, values close to its mass presented considerable measurement errors according to Tables 2, 4, and 8. With the use of three cables, Fig. 11, the load is divided and the force values are close to the mass of the load cell with considerable errors according to Table 8.

In the cases that the proposed structure is not working with value near of load cell mass, the force errors are less than 10%. From the literature, the errors forces found are similar to other prototypes rehabilitation devices [43–47] with errors less than 10% when using PID/trajectory control or impedance control. To compare, the commercial version of InMotion Arm Robot has a force resolution of 0.05 N [48] and a cost of more than USD 100,000 [49].

The device proposed in this paper can work on different movements of the rehabilitation process, from simple and pure rehabilitation movements, e.g., varying only the angle of a single joint in a certain direction. However, the proposed device needs the gravity to make the return movements and has problems if the carry load is low (near of the mass of load cell).

Table 7 Forces in the three cables

Angle (°)	Numerical (N)			Experimental (N)		
	Cable 1	Cable 2	Cable 3	Cable 1	Cable 2	Cable 3
− 32.4	4.884	2.476	0.631	4.678	3.135	0.949
− 25.6	4.653	2.654	0.660	4.463	3.625	0.779
− 18	4.302	2.887	0.749	3.931	3.417	1.139
− 7.8	3.837	3.234	0.848	3.809	3.723	1.085
2.4	3.428	3.611	0.879	3.243	4.226	1.102
13.5	3.028	4.007	0.897	3.033	4.557	1.032
22	2.763	4.432	0.755	2.953	4.904	0.714
30.2	2.544	4.636	0.779	2.574	5.043	1.087
42	2.265	5.202	0.549	2.480	5.390	0.638

Table 8 Force errors in the three cables

Angle (°)	Error cable 1 (%)	Error cable 2 (%)	Error cable 3 (%)
− 32.4	4.23	− 26.61	− 50.41
− 25.6	4.09	− 36.58	− 18.00
− 18	8.61	− 18.34	− 52.10
− 7.8	0.72	− 15.12	− 27.88
2.4	5.37	− 17.04	− 25.28
13.5	− 0.17	− 13.73	− 15.07
22	− 6.91	− 10.64	5.43
30.2	− 1.22	− 8.79	− 39.49
42	− 9.51	− 3.61	− 16.08

Table 9 Length of the three cables

Angle (°)	Numerical (cm)			Experimental (cm)		
	Cable 1	Cable 2	Cable 3	Cable 1	Cable 2	Cable 3
− 32.4	118.70	135.52	123.64	120.5	129.0	118.5
− 25.6	122.33	135.85	125.90	123.5	129.0	121.5
− 18	125.51	135.06	126.93	125.0	129.0	122
− 7.8	128.88	133.00	127.22	128.0	127.5	123
2.4	131.58	130.31	127.06	129.0	126.0	123
13.5	133.12	126.12	125.31	130.5	122.0	122
22	135.04	123.50	125.64	132.0	120.0	122
30.2	134.23	118.89	122.18	131.0	116.5	119
42	134.60	113.30	120.25	131.0	112.5	117

Table 10 Length errors of the three cables

Angle (°)	Error cable 1 (%)	Error cable 2 (%)	Error cable 3 (%)
− 32.4	− 1.5	4.8	4.2
− 25.6	− 1.0	5.0	3.5
− 18	0.4	4.5	3.9
− 7.8	0.7	4.1	3.3
2.4	2.0	3.3	3.2
13.5	2.0	3.3	2.6
22	2.3	2.8	2.9
30.2	2.4	2.0	2.6
42	2.7	0.7	2.7

The number of cables used is directly linked to the complexity of the desired movement. Only one actuator/cable can be used for single and simple movements, e.g., the execution of ankle dorsiflexion. As the movements become more complex, the amount of cables may be increased to accomplish the movement.

The robot presented in this paper allows a quick adjustment to the patiens limb from the use a Velcro tape. No length adjustments or joint alignment are required as in the case of the robotic exoskeletons. The cost of the equipment is very low compared to other commercial solutions, like Anklebot [50] and Hocoma's Lokomat.

The structure proposed in this paper is quite friendly for patients, as they are often already familiar with therapies using ropes/cables.

Moving forward, we plan to finalize the impedance control [51], and to commence a large set of clinical studies with healthy and impaired subjects.

Acknowledgements This work was supported in part by CNPq, UFU, CAPES, and FAPEMIG.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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