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Kinematics Mathematical Modelling of Lower Limb Exoskeleton for Paralyzed Stroke Patients

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ABSTRACT

This paper presents the development of a lower limb rehabilitation robot to be used with bedridden patients. Strokes are one of the significant causes of death in 17% of the 109,155 medically certified death in 2020 in Malaysia. In most cases, stroke paralysis affects the opposite side of the damaged brain, and any part of the body can be affected. 90% of stroke patients get paralysis to some degree. Patients can recover from the disease and restore body motions by undergoing paralysis stroke physiotherapy, which involves numerous sessions with patients. There were several successful robotic rehabilitations in recent years; however, their design is inflexible and large, requiring the patient to sit or stand in a static position. This project will be built on a motor-driven parallel architecture that will offer motion assistance throughout the human's wide range of motion (ROM). This project development is divided into two parts: structure design and simulation. The design process for the lower limb devices used syncretization and mathematical analysis. The structure design is from the kinematic analysis. The mathematical models are then used to design in MATLAB simulation which is trajectory simulation. The outcome shows that the simulations that have been developed is compatible with the motion of human lower limb. This robot develops for bedridden use of lower limb rehabilitation exercises.

1. Introduction

The lower limb supports the body's weight and allows humans' gait [1]. Stroke is the second leading cause of death and the primary factor of adult disability. For full mobility to be achieved, early rehabilitation and movement aid are required.

Because the physiotherapist's undivided focus is required, these rehabilitation sessions are frequently performed one-on-one. Training exercises of the patient's lower limb during rehabilitation

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to execute the hip external/internal rotation, knee extension, and hip adduction/abduction are done during these sessions [2]. Thus, a robot-assisted rehabilitation device was proposed as a better solution to enable physiotherapists to deal with multiple patients simultaneously. Potentially, with this device, a physician can remote control the robots from a remote location.

Some research teams have illustrated the robotic solution's viability for helping patients regain lower limb mobility. However, most of this rehabilitation system is based on static platform designs [3,4]. These solve the patients' need to stand and are accompanied by bulky, non-portable devices [5,6].

Several research groups have proposed wearable designs of the lower limb exoskeletons and orthoses to overcome this limitation of the rehabilitation exercise [7-9]. However, these wearable rehabilitation systems are rigid and bulky, requiring additional weight support. The structures of the lower limb exoskeleton can be more flexible by using motor drive mechanisms.

Before analyzing the robot's design and the structure's kinematic analysis [10-12]. Should do deep research and understanding. Finally, operate before proceeding with production, it is also required to present the robot's functionality within the MATLAB software.

1.1 Joints of Exoskeleton

Exoskeletons are divided into groups according to the location of the robot's energy channel. Robot rehab equipment is frequently attached to human body parts. The purpose of this exoskeleton part is to move the user's joint. On each shank, the devices can be attached to one articulation, such as the pelvis, knee, or ankle; two articulations, such as the knee and ankle; or three articulations, such as the pelvis, knee, and ankle.

1.2 Pelvis Exoskeleton

The upper and lower limbs are attached by the pelvis. Human pelvises support three-dimensional (three DoF) motions such as extension, flexion, abduction, and adduction. These movements must be made by a human. Most studies have shown that exoskeleton users wear gadgets on their pelvis.

A device placed close to the user's pelvis was used to produce a pelvic orthotic by Giovacchini *et al.,* [13]. With the use of this exoskeleton, the patient may flex and extend their pelvis. Additionally, this wearable technology contains a passive actuator that enables the user to move within their range of motion (ROM), enhancing the welfare of the user [14]. HiPSO (hip ball screw orthosis) uses a ball screw in each foot to transmit energy generated by an actuator [13]. The movement of the actuation is sent to the thigh through a strap at the back of the ball screw. This structure performs additional motions in addition to flexion and extension. The HiPSO enables the patient to rotate both the thigh and waist in the abduction/adduction motion. The Powered Waist Exoskeleton, or PH-EXOS, is another wearable robot that includes abduction/adduction gait and internal and exterior revolute [15]. While abduction and adduction are passive movements, these gaits improve the fundamental flexion and extension movements. The patient's waist is used to secure the actuator, which is connected to the pulley by a Bowden Cable.

The Exosuit is an exoskeleton that was built [16]. The webbing straps are powered by a gear tread motor carried on the user's back. These straps are attached to the user's thigh and wraps function by compressing and inflating on the leg from heel strike to terminal stance.

During movements like walking, jogging, and other motions, human knees absorb impact. Additionally, the component is located on the side of the ankle and pelvis. The portion has a less difficult gait with flexion/extension and revolute manoeuvres when compared to the pelvis and ankle. Most of the exoskeleton research, however, has just included one DoF for the knee robot, which only relocates the flexion/extension movements, in the sake of simplicity.

An exoskeleton's actuator is a soft inflated cushion as shown in Figure 1 [17]. Behind the user's knee is where the expansion component is positioned. This part makes it possible to lighten the exoskeleton. The component is expanded and decompressed using a pneumatic system. During the swing phase of the gait motion cycle, the device expands, and during the other phases, it decompresses. Two DC motors are utilized to activate two Bowden cables [18].

(a) (b) (c) (d)

Fig. 1. (a) Exoskeleton Developed by Giovacchini *et al.,* [13], (b) Hipso (Hip Ball Screw Orthosis [14], (c) PH-EXOS [15], (d) Exosuit [16]

1.3 Ankle Exoskeleton

The ankle has the greatest torque during the walking stride when compared to other joints. As a result, most investigations have used ankle-based devices. Four pieces make up this articulation, which has three degrees of freedom (DoF). On the other hand, at the step cycle, plantar or dorsiflexion motion predominates. For this primary ankle motion, most studies had to reduce the robot's walk to only one DoF.

Mooney and Herr [18] created a one-DoF device. The equipment was made to support the patient's weight while assisting with gait. The equipment was created to make it easier for the user to walk while carrying weight. A brushless DC motor (BLDC) is used in the apparatus, which is worn in the user's shank. The motor controller and power supply are stored in the user's clothes. A fiberglass strut that is fastened to the shoe straps at the patient's joint thanks to tools. Asbeck *et al.,* [19] developed another idea dubbed a soft exosuit. This apparatus is designed to help patients navigate while carrying weight. Its exoskeleton, which is kept in a backpack together with the motor, power source, and controller, is propelled by an electric motor. This motor is connected by a Bowden cable, and the cable's function is to yank the user's heel. The wires work similarly to the calf muscle in humans. Bai *et al.,* [20] created yet another exoskeleton. Patients who have sustained ankle injuries are treated with the use of this device. With the motor control and power source mounted on the patient's hip, an electric motor is fastened to the subject's shinbone. The gadgets receive motor movement through the belt. The procedure is what makes the subject's ankle move. Shorter *et al.,* [21] developed a pneumatically propelled ankle exoskeleton. A rotary pneumatic actuator controls the subject's ankle movement. The user's ankle is where this device is attached. The air supply for this exoskeleton, which has two valves, comes from the subject's waist. The potential gap from the literature shows that kinematics for bedside rehabilitation is required as most of the available literature on exoskeletons focuses more on assisted walking. This study contributes regarding kinematics of the proposed lower limb exoskeleton for bedside rehabilitation.

2. Methodology

2.1 Desired Gait

The collection of gaits for help in a narrower array is mainly considered for rehab and helping the senior citizen. The desired structure and process consider the gait the lower limb must do. The desired lower limb movements would be entirely passive.

2.2 Structure Characteristic

Rehab robots are humanoid mechanical devices worn by a controller that conforms to the patient's gait and functions in concert with it. Among the primary characteristics of an exoskeleton to be considered during design are:

(i) Structure must be humanoid: The shape of history's structure is strange. Another problem with devices is the lack of direct information exchange between the human nervous system and the exoskeleton worn. The user's health condition and wishes must be recognized and evaluated before generating gait intentions.
(ii) Structure must be flexible: Adjustable thigh, shank, and waist lengths are recommended. Ordinary people with heights ranging from 1.60 m to 1.80 m have a 6 cm range in thigh and shank length. The leg size is approximately 0.246 times the stature, whereas the thigh size is about 0.245 times the stature.
(iii) Rise articulator strength: Rehab robot does not transfer substantial weights to the land, but instead increases joint tension. This consideration may reduce joint pain or increase articulator strength in paralyzed or weak joints.
(iv) Motion degree of freedom (DoF): The robot must respond to joint motion. Degrees of freedom (DoF) of a lower limb exoskeleton are shown in Table 1.
(v) The exoskeleton devices should have a large output power-to-weight ratio and characteristic of low inertia, fast response, high precision, etc.

Table 1
Array of Gait for the Lower Limb

Joint	DOF(s)	Motion form	ROM
Hip	3	Hip Internal/External (HIE) Hip Extension/Flexion (HEF) Hip Abduction/Adduction (HAA)	-120°/65° -15°- -30°/60° -30° - -35°/40°
Knee	1	Knee Flexion/Extension (KEF)	-120°- -160°/0°

2.3 Kinematics

Kinematics is the connection between the joint space and the robot's end effector. The method is used for generating position and setting joint actuator control. The kinematic analysis findings are shown in Figure 2.

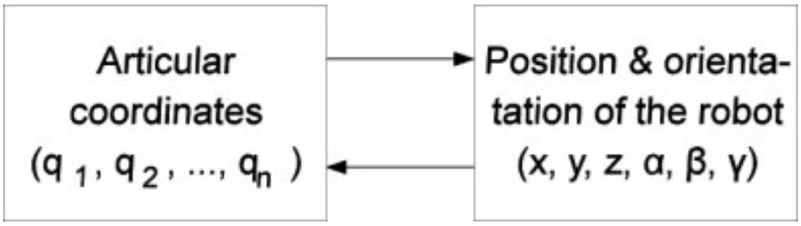


Fig. 2. Example of Allocation of reference axes on the lower limb exoskeleton used in Kinematics

2.3.1 Forward kinematic

The suggested exoskeleton features four degrees of freedom in its forward kinematic. Every part is rotated, placement of DoF when the robot is displaced in the sagittal plane is as follows:

(a) 2 DoF in each side of the pelvis
(b) 2 DoF one for each ligament in the knees

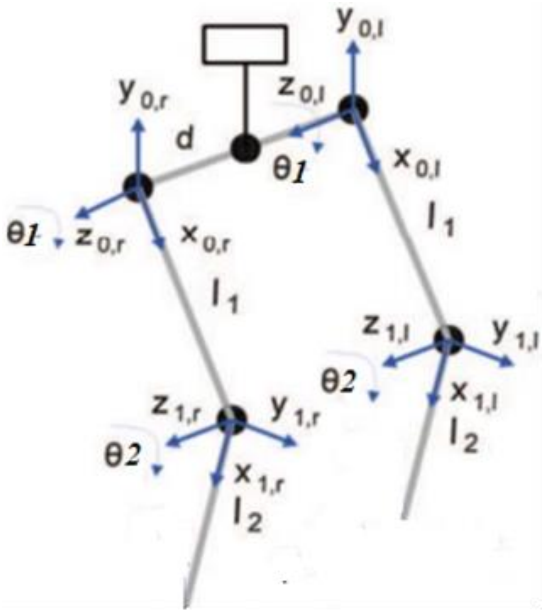


Fig. 3. Distribution of Reference Planes on the Exoskeleton of the lower limb [22]

$$\begin{aligned}
x &= f_x(q_1, q_2, \ldots\ldots q_n) \\
y &= f_y(q_1, q_2, \ldots\ldots q_n) \\
z &= f_z(q_1, q_2, \ldots\ldots q_n) \\
\alpha &= f_\alpha(q_1, q_2, \ldots\ldots q_n) \\
\beta &= f_\beta(q_1, q_2, \ldots\ldots q_n) \\
\gamma &= f_\gamma(q_1, q_2, \ldots\ldots q_n)
\end{aligned} \tag{1}$$

Figure 4 shows the axes placed on each exoskeleton joint the Denavit-Hartemberg (DH) algorithm is used [14]. Table 2 shows the parameter for each robot link.

Table 2
Parameter for the Robot

Right Side	a_i	a_i	d_i	θ_i	Left Side	a_i	a_i	d_i	θ_i
1	l_1	0	0	θ_1	4	l_4	0	0	θ_1
2	l_2	0	0	θ_2	5	l_5	0	0	θ_2

$$T = \begin{pmatrix} C(\theta_1+\theta_2) & -S(\theta_1+\theta_2) & 0 & l_1 C\theta_1 + l_2 C(\theta_1+\theta_2) \\ S(\theta_1+\theta_2) & C(\theta_1+\theta_2) & 0 & l_1 S\theta_1 + l_2 S(\theta_1+\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2)$$

where of the S(Θi) is the sine variable joint I and C(Θi) is the cosine of the variable joint i.

The fourth column of matrix T in Eq. (2) indicates the position of the right limb's third link (2) The xy plane is used for the analysis to obtain Eq. (2). (Sagittal plane). As a result, the forward kinematic equations for the right limb are altered.:

$$\begin{aligned} xd &= l_1 C(\theta_1) + l_2 C(\theta_1+\theta_2) \\ yd &= l_1 S(\theta_1) + l_2 S(\theta_1+\theta_2) \\ z\,d &= -\,d \end{aligned} \quad (3)$$

2.3.2 Inverse kinematic

Inverse kinematic provides the values of the articular variable (q=[q1,q2,...,qn]T) at a specific position in the space of the final link of a kinematic chain in a robot [x,y,z,α,β,γ]T. The following are the definitions of inverse kinematics equations.

$$\begin{aligned} q_1 &= f_1(x,y,z,\alpha,\beta,\gamma) \\ q_2 &= f_2(x,y,z,\alpha,\beta,\gamma) \\ q_n &= f_n(x,y,z,\alpha,\beta,\gamma) \end{aligned} \quad (4)$$

The geometric method is used to get the inverse kinematics equations for the lower limb exoskeleton. The analysis is most widely accomplished in the sagittal plane, as shown in Figure 4.

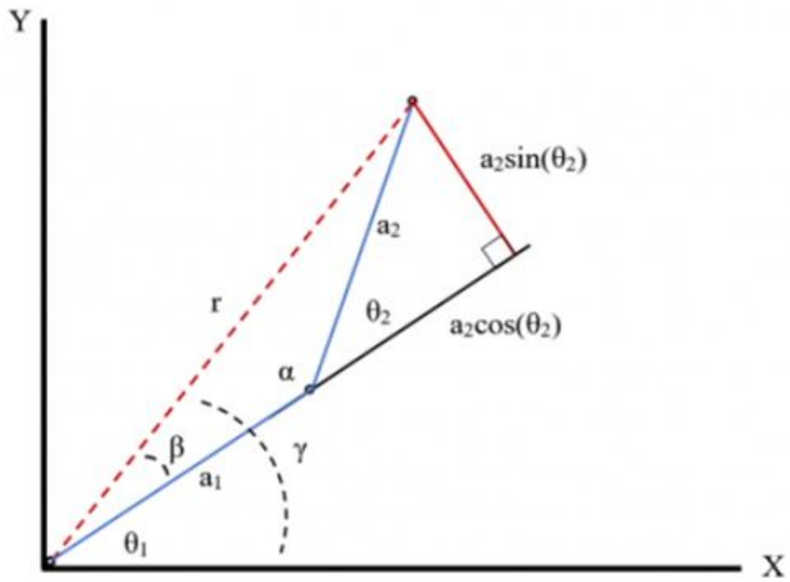


Fig. 4. Geometric Equations

The variables for Figure 4 are:

Final link position = [x, y]
Links length = a1, a2

Using triangle laws and cosine rule:

$$r^2 = a_1^2 + a_2^2 - 2a_1a_2\cos(\alpha)$$
$$\alpha = \pi + \theta_2$$
$$cos(\alpha) = \frac{a_1^2 + a_2^2 - r^2}{2a_1a_2} \quad (5)$$
$$cos(\theta_2) = -\cos(\alpha)$$

$$sin(\theta_2) = \sqrt{(1-\cos(\theta_2)^2)}$$
$$\gamma = \text{atan}\left(\frac{y}{x}\right) \quad (6)$$
$$\theta_1 = \gamma - \beta$$

By substituting variable:

$$\theta_1 = \text{atan}\left(\frac{y}{x}\right) \mp \text{atan}\left(\frac{a_2\sin(\theta_2)}{a_1 + a_2\cos(\theta_2)}\right) \quad (7)$$
$$\theta_2 = \text{acos}\left(\frac{x^2 - y^2 - a_1^2 - a_2^2}{2a_1a_2}\right)$$

3. Results

3.1 Selected Structure for the lower Limb Exoskeleton

The lower extremity exoskeleton gives the lower limb six rotational degrees of freedom. The sagittal plane rehab robot is as follows. Which has two degrees of freedom on each side of the pelvis, two degrees of freedom in the knees, and one part each of the knee articulators. The structure of the lower limb is a parallel robot that has a joint with two DoF for each side of the lower limb.

3.2 Generated MATLAB Model from the Structure

A model for the lower extremity exoskeleton robot's suggested devices is created. This model was created using the Inverse Kinematics procedure. The actuation motor is positioned at each part of the joint of the exoskeleton which allows movement of the hip and knee of the patient. This motor-driven mechanism can move the femur in flexion/extension and abduction/adduction directions and the knee in flexion/extension directions.

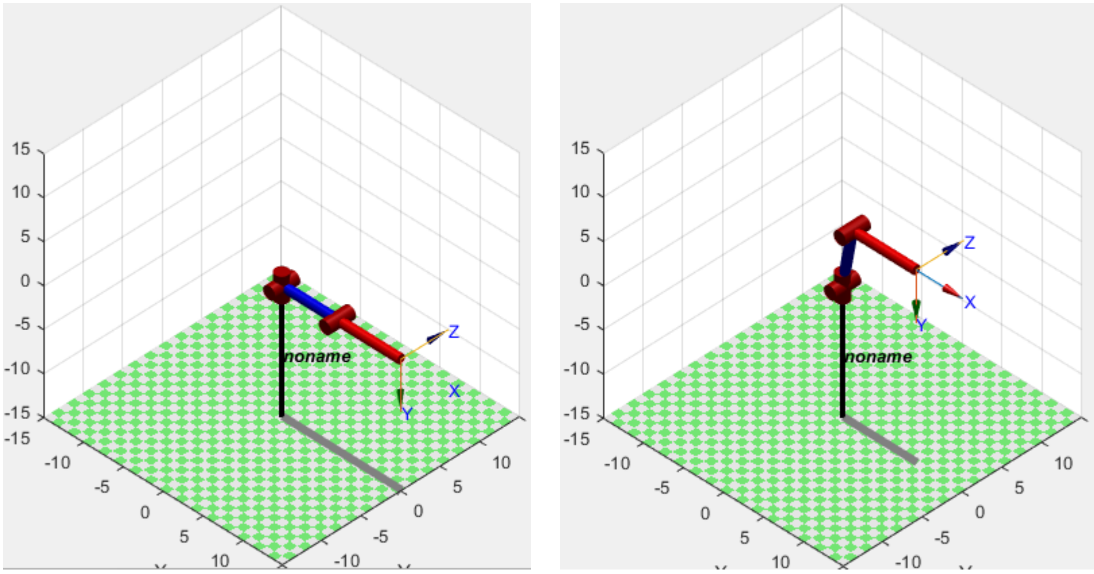
3.3 Kinematic Simulation

The Kinematic simulation uses the Robotics Toolbox for the MATLAB Model of the lower limb exoskeleton. The MATLAB model is to apply the degree for each of the joints of the exoskeletons and gets the position of the end-effector. Figure 5 shows the result of applying based on the required array of gait (ROM) exercises that are successful for lower limb rehabilitation. For the kinematic simulation, the second link is located at which is the knee joint:

[9.216, 0.001,6.894]

The degree apply at the joint are:

$\theta_1 = -80, \theta_2 = 80$

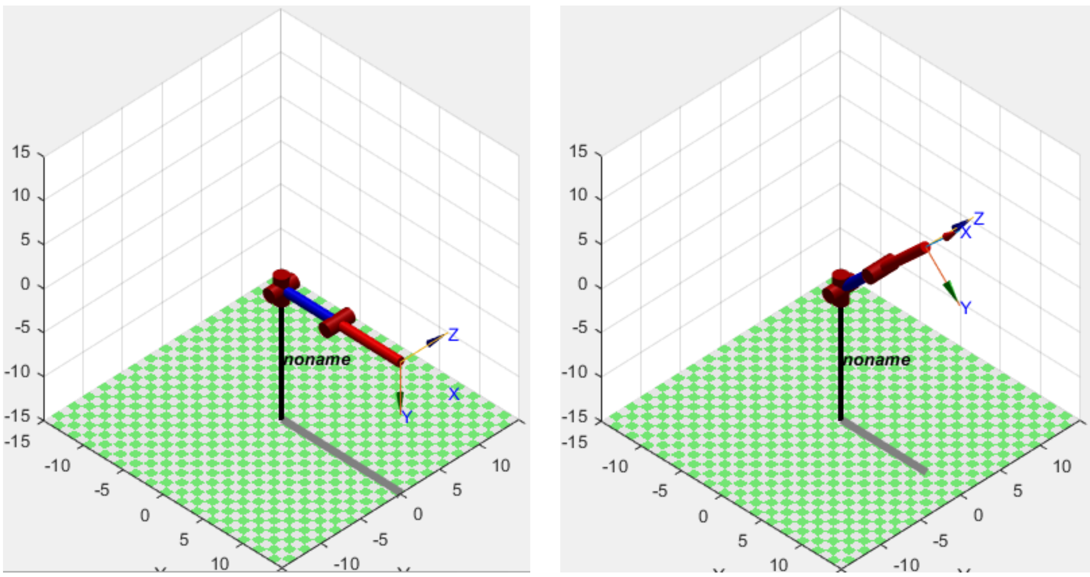


(i) (ii)

Fig. 5. (i) Forward kinematic simulation; (ii) Inverse kinematics simulation

3.4 Exercise for the Lower Extremity of Bedridden Patient

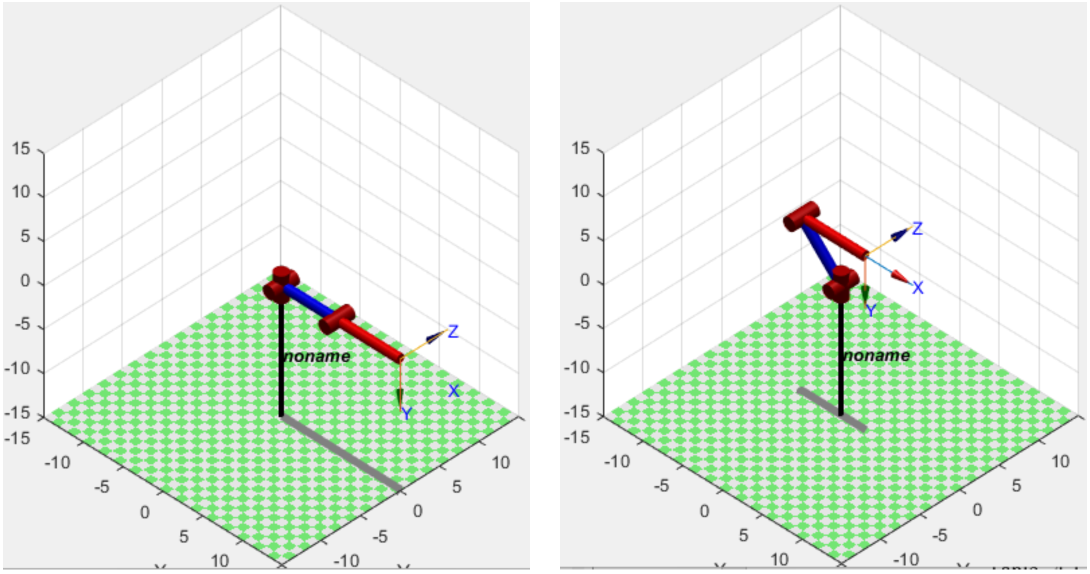
Figure 6 shows the result of applying based on the required array of gait (ROM) exercises that are successful for lower limb rehabilitation base on Straight Leg Lift.



(i) (ii)

Fig. 6. (i) Initial position (ii) Straight Leg lift

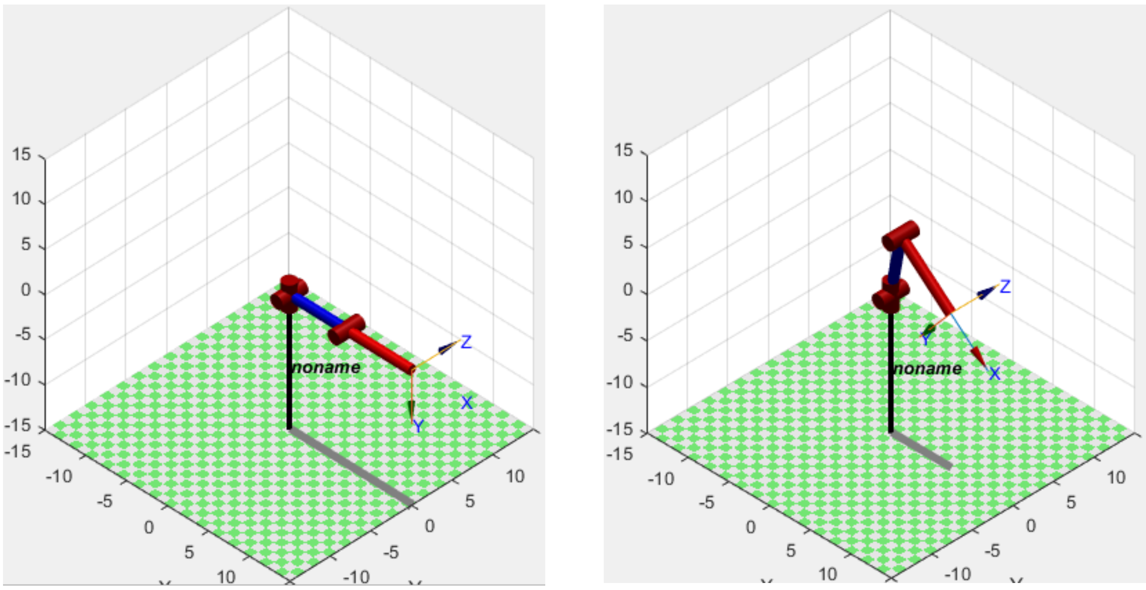
Figure 7 shows the result of applying based on the required array of gait (ROM) exercises that are successful for lower limb rehabilitation base on Reverse Crunch.



(i) (ii)

Fig. 7. (i) Initial position (ii) Reverse Crunch

Figure 8 shows the result of applying based on the required array of gait (ROM) exercises that are successful for lower limb rehabilitation base on Heel Slide.



(i) (ii)

Fig. 8. (i) Initial position (ii) Heel Slide

The kinematic simulation can get the end-effector's position for the exoskeleton. Based on the different types of exercise for rehabilitation. Each type of exercise is for strengthening the patient's muscles so that the patient can get mobility to move on their own. For straight leg lift for the hip, reverse crunch for the knee and hip, and heel slide for the knee and hip.

3.5 Position for the End Effector

Table 3 is the simulation of the kinematics structure that can do rehabilitation exercises of the exoskeleton to do a straight leg lift, this shows the degree applied at the hip of the exoskeleton after using the exercise, which get the end effector position for each degree applied at the joint.

Table 3
Rise leg Exercise angle the position end effector

Joint	Rise leg Exercise angle	x	y	z
Hip	0°	15	0	0
	-5°	14.943	0	1.307
	-10°	14.772	0.001	2.605
	-15°	14.489	0.001	3.882
	-20°	14.095	0.001	5.13
	-25°	13.595	0.001	6.339
	-30°	12.990	0.002	7.5
	-35°	12.287	0.002	8,604
	-40°	11.491	0.002	9.642
	-45°	10.607	0.002	10.607

Table 4 is the simulation of the kinematics structure that can do rehabilitation exercises of the exoskeleton to do a reverse crunch for Hip.

Table 4
Reverse crunch Exercise angle the position end effector for Hip

Joint	Reverse crunch Exercise angle	x	y	z
Hip	0°	7	0	0
	-15°	6.761	0	1.812
	-30°	6.062	0.001	3.5
	-45°	4.95	0.001	4.950
	-60°	3.5	0.001	6.062
	-75°	1.812	0.001	6.761
	-80°	1.216	0.001	6.894
	-95°	-0.610	0.001	6.973
	-110°	-2.394	0.001	6.578
	-135°	-4.95	0.001	4.95

According to Figure 9, the initial position of the end effector for the hip joint for the exercise reverse crunch is in the x-axis, y-axis, and z-axis. For the position for x axis decrement rapid until angle -75°. For z axis increment until -75° while for y axis have almost the same value.

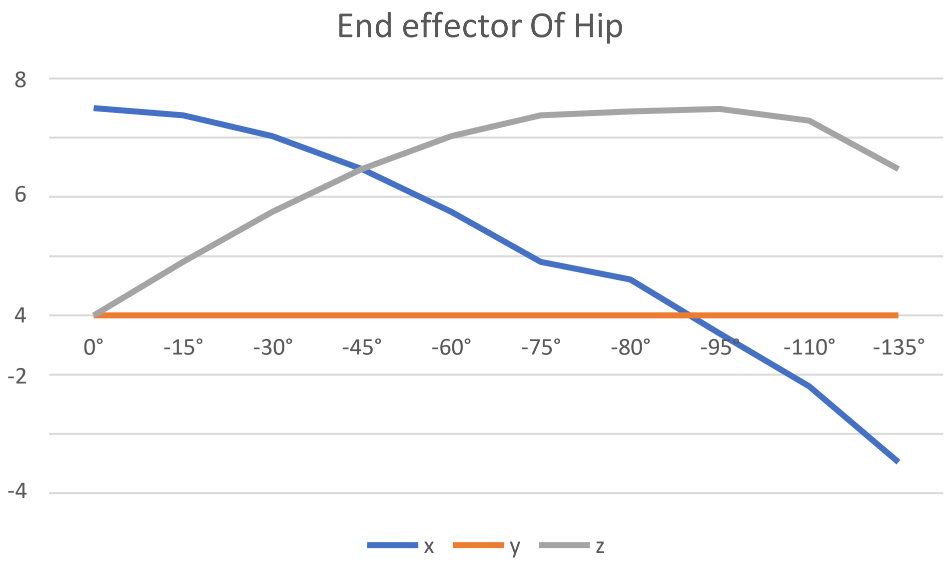


Fig. 9. Graph illustrating the position of the hip end effector during the reverse crunch exercise

Table 5 is the simulation of the kinematics structure that can do rehabilitation exercises of the exoskeleton to do a reverse crunch for Knee.

Table 5
Reverse crunch Exercise angle the position end effector for Knee

Joint	Reverse crunch Exercise angle	x	y	z
Knee	0°	15	0	0
	15°	14.761	0	1.812
	30°	14.062	0.001	3.5
	45°	12.95	0.001	4.950
	60°	11.5	0.001	6.062
	75°	9.812	0.001	6.761
	80°	9.216	0.001	6.894
	95°	7.390	0.001	6.973
	110°	5.606	0.001	6.578
	135°	3.050	0.001	4.95

According to Figure 10, the initial position of the end effector for the knee joint for the exercise reverse crunch is in the x-axis, y-axis, and z-axis. For the position for the x-axis decrement rapidly until the angle is -75°. For z-axis increments, until -75° while y y-axis has almost the same value.

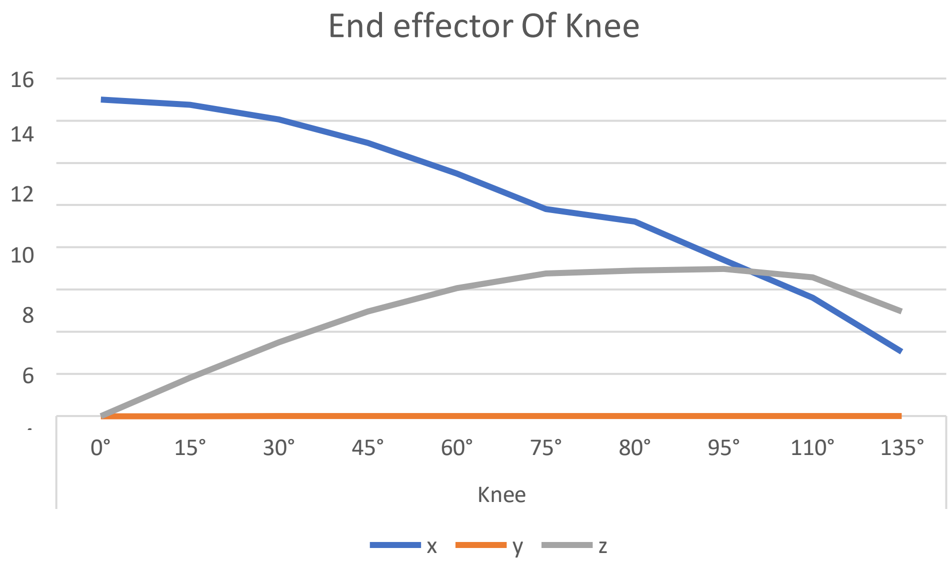


Fig. 10. Graph illustrating the position of the knee's end effector during the reverse crunch exercise

Table 6 is the simulation of the kinematics structure that can do rehabilitation exercises of the exoskeleton for Hip.

Table 6
Heel slide Exercise angle the position end effector for Hip

Joint	Reverse crunch Exercise angle	x	y	z
Hip	0°	7	0	0
	-8°	6.932	0	0.974
	-16°	6.729	0.001	1.929
	-24°	6.395	0.001	2.847
	-32°	5.936	0.001	3.709
	-40°	5.362	0.001	4.5
	-48°	4.684	0.001	5.202
	-56°	3.914	0.001	5.803
	-64°	3.069	0.001	6.292
	-72°	2.163	0.001	6.657

According to Figure 11, the initial position of the end effector for the hip joint for the exercise heel slide is in the x, y, and z axis. For the position for x-axis decrement rapid at the angle -24°. Z axes increment rapidly until -40° while y axis have almost the same value.

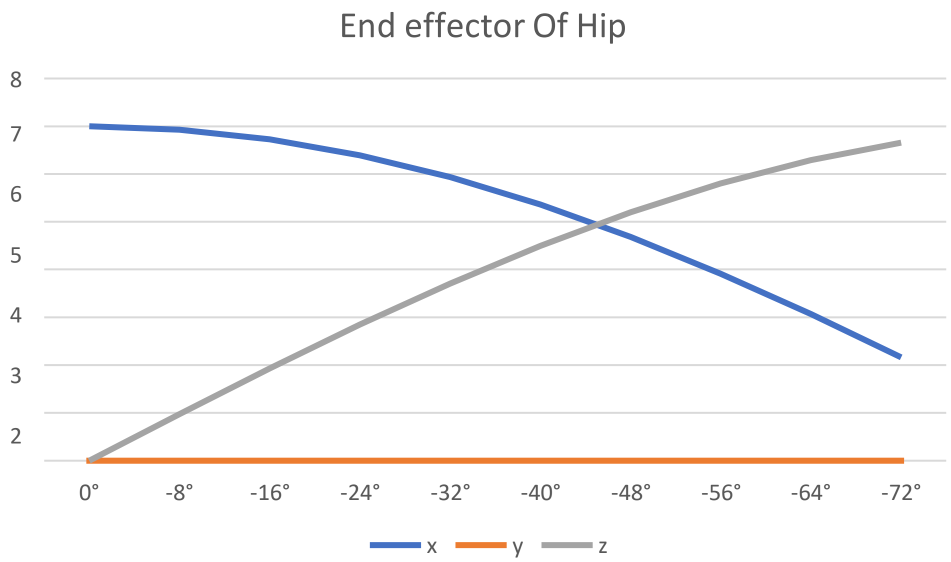


Fig. 11. Graph illustrating the position of the Hip end effector during the heel slide exercise

Table 7 is the simulation of the kinematics structure that can do rehabilitation exercises of the exoskeleton for Knee.

Table 7
Heel slide Exercise angle the position end effector for Knee

Joint	Reverse crunch Exercise angle	x	y	z
Knee	0°	15	0	0
	14°	14.888	0	0.138
	28°	14.554	0	0.266
	42°	14.003	0	0.375
	56°	13.245	0	0.456
	70°	12.291	0	0.5
	84°	11.156	0	0.5
	98°	9.860	0	0.45
	112°	8.422	0	0.346
	126°	6.865	0	0.185

According to Figure 12, the x-axis, y-axis, and z-axis for the exercise heel slide are the initial positions of the end effector for the knee joint. The position for the x-axis decrements rapidly until the angle is 56°. For the z-axis increment until 70°, then decrement, while for the y-axis have almost the same value.

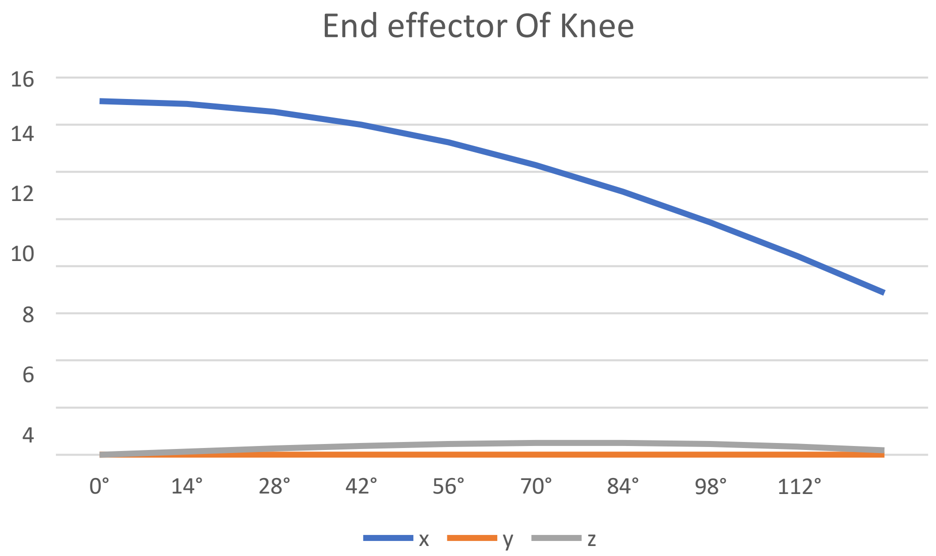


Fig. 12. Graph illustrating the position of the Knee end effector during the heel slide exercise

3.6 Discussion on the Results

While developing the Kinematic Mathematical Modelling of the lower limb exoskeleton for paralyzed stroke patients, multiple approaches and troubleshooting were involved in achieving the desired objective of the project. This part discusses the process of troubleshooting the problem faced.

The first problem faced in developing the mathematical modelling was the kinematic analyses for the forward kinematic and inverse kinematic. For kinematics can use trigonometry or Denavit-Hartenberg parameter or screw theory. Need to choose the forward kinematic and inverse kinematic that is suitable for the lower limb exoskeleton. Which for the forward kinematic using the Denavit-Hartenberg for the inverse kinematic uses the geometric.

The next problem is to create the mathematical modelling for generated the model in MATLAB based on the kinematic analysis of the lower limb. MATLAB model can be made using Simulink or using a robotic toolbox. To make the mathematical modelling using the robotic toolbox which is PETER CORKER robotic toolbox using the DH method to create the model and can control the angle that is applied at the joint. The robotic toolbox shows the position of the end effector.

The problem is analyzing the data from the rehab exercise executed from the mathematical modelling. Because there is no research about the effectiveness of the rehab exercise for paralyzed stroke patients and the range of motion that is applied for the rehab. Then, there is no comparison between the mathematical model from the rehab exercise.

4. Conclusions

Kinematics mathematical modelling of lower limb exoskeleton for paralyzed stroke patients is a wearable solution for various patients to execute different exercise types. Moreover, this project is limited to the lower limb paralyzed stroke patients which can participate in self-treated therapy with less observation from the caretaker, therapist, and medical consultants. The forward and inverse kinematic models were then developed to integrate the mathematical model into MATLAB. This simulation was created to test the feasibility of using a lower limb exoskeleton to perform a range of motion exercises on the hip and knee. For the sustainability of the complete human- machine system, the subject should be in symbiosis with the exoskeleton. The efficiency of the exoskeleton is critical for human safety, as it reduces effort while enhancing performance.

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References
[1] Lumen Learning. "The Lower Limb | Boundless Anatomy and Physiology." *Lumen Learning Pressbooks*. Accessed April 1, 2022. https://courses.lumenlearning.com/boundless-ap/chapter/the-lower-limb/.
[2] Flint Rehab. "10 Outstanding Leg Exercises for Stroke Patients." *Flint Rehab*. Accessed April 1, 2020. https://www.flintrehab.com/leg-exercises-for-stroke-patients/.
[3] Ramli, Nik Nasihah Nik, Amhsavenii Asokan, Daniel Mayakrishnan, and Hariharasudan Annamalai. "Exploring stroke rehabilitation in Malaysia: are robots better than humans for stroke recuperation?." *The Malaysian Journal of Medical Sciences: MJMS* 28, no. 4 (2021): 14. https://doi.org/10.21315/mjms2021.28.4.3
[4] Nam, Ki Yeun, Hyun Jung Kim, Bum Sun Kwon, Jin-Woo Park, Ho Jun Lee, and Aeri Yoo. "Robot-assisted gait training (Lokomat) improves walking function and activity in people with spinal cord injury: a systematic review." *Journal of Neuroengineering and Rehabilitation* 14, no. 1 (2017): 1-13. https://doi.org/10.1186/s12984-017-0232-3
[5] De Keersmaecker, Emma, Nina Lefeber, Ben Serrien, Bart Jansen, Carlos Rodriguez-Guerrero, Nilofar Niazi, Eric Kerckhofs, and Eva Swinnen. "The effect of optic flow speed on active participation during robot-assisted treadmill walking in healthy adults." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 28, no. 1 (2019): 221-227. https://doi.org/10.1109/TNSRE.2019.2955804
[6] Cespedes, Nathalia, Marcela Munera, Catalina Gomez, and Carlos A. Cifuentes. "Social human-robot interaction for gait rehabilitation." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 28, no. 6 (2020): 1299-1307. https://doi.org/10.1109/TNSRE.2020.2987428
[7] Sapiee, M. R., M. H. M. Marhaban, M. F. Miskon, and A. J. Ishak. "Walking simulation model of lower limb exoskeleton robot design." *Journal of Mechanical Engineering and Sciences* 14, no. 3 (2020): 7071-7081. https://doi.org/10.15282/jmes.14.3.2020.09.0554
[8] Law, Khuan Foo, Dalbir Singh, and Zaidi Mohd Ripin. "Development of a lower limb stroke rehabilitation machine." In *MATEC Web of Conferences*, vol. 217, p. 02004. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201821702004
[9] Wang, Yuefei, Zhen Liu, and Lei Shi. "Development of an Exoskeleton Rehabilitation Robot Framework for the Knee Joint Based on Predictive Assessment." *IEEE Access* 9 (2021): 168794-168805. https://doi.org/10.1109/ACCESS.2021.3136919
[10] Lv, Ge, Jianping Lin, and Robert D. Gregg. "Trajectory-free control of lower-limb exoskeletons through underactuated total energy shaping." *IEEE Access* 9 (2021): 95427-95443. https://doi.org/10.1109/ACCESS.2021.3094979
[11] Liu, Yang, Shi-guo Peng, Yu-xiao Du, and Wei Hsin Liao. "Kinematics modeling and gait trajectory tracking for lower limb exoskeleton robot based on PD control with gravity compensation." In *2019 Chinese Control Conference (CCC)*, pp. 4504-4511. IEEE, 2019. https://doi.org/10.23919/ChiCC.2019.8865916
[12] Vantilt, Jonas, Chetan Giraddi, Erwin Aertbeliën, Friedl De Groote, and Joris De Schutter. "Estimating contact forces and moments for walking robots and exoskeletons using complementary energy methods." *IEEE Robotics and Automation Letters* 3, no. 4 (2018): 3410-3417. https://doi.org/10.1109/LRA.2018.2852776
[13] Giovacchini, Francesco, Federica Vannetti, Matteo Fantozzi, Marco Cempini, Mario Cortese, Andrea Parri, Tingfang Yan, Dirk Lefeber, and Nicola Vitiello. "A light-weight active orthosis for hip movement assistance." *Robotics and Autonomous Systems* 73 (2015): 123-134. https://doi.org/10.1016/j.robot.2014.08.015
[14] Yasuhara, Ken, Kei Shimada, Taiji Koyama, Tetsuya Ido, Keishiro Kikuchi, and Yosuke Endo. "Walking assist device with stride management system." *Honda R&D Technical Review* 21, no. 2 (2009): 54-62.
[15] Baud, Romain, A. Ortlieb, J. Olivier, M. Bouri, and H. Bleuler. "HiBSO hip exoskeleton: Toward a wearable and autonomous design." In *New Trends in Medical and Service Robots: Design, Analysis and Control* 5, pp. 185-195. Springer International Publishing, 2018. https://doi.org/10.1007/978-3-319-59972-4_14
[16] Wu, Qingcong, Xingsong Wang, Fengpo Du, and Xiaobo Zhang. "Design and control of a powered hip exoskeleton for walking assistance." *International Journal of Advanced Robotic Systems* 12, no. 3 (2015): 18. https://doi.org/10.5772/59757

[17] Asbeck, Alan T., Kai Schmidt, and Conor J. Walsh. "Soft exosuit for hip assistance." *Robotics and Autonomous Systems* 73 (2015): 102-110. https://doi.org/10.1016/j.robot.2014.09.025
[18] Mooney, Luke M., and Hugh M. Herr. "Biomechanical walking mechanisms underlying the metabolic reduction caused by an autonomous exoskeleton." *Journal of Neuroengineering and Rehabilitation* 13, no. 1 (2016): 1-12. https://doi.org/10.1186/s12984-016-0111-3
[19] Asbeck, Alan T., Stefano MM De Rossi, Kenneth G. Holt, and Conor J. Walsh. "A biologically inspired soft exosuit for walking assistance." *The International Journal of Robotics Research* 34, no. 6 (2015): 744-762. https://doi.org/10.1177/0278364914562476
[20] Bai, Yang, Xueshan Gao, Jun Zhao, Fei Jin, Fuquan Dai, and Yunqi Lv. "A portable ankle-foot rehabilitation orthosis powered by electric motor." *The Open Mechanical Engineering Journal* 9, no. 1 (2015). https://doi.org/10.2174/1874155X01509010982
[21] Shorter, K. Alex, Géza F. Kogler, Eric Loth, William K. Durfee, and Elizabeth T. Hsiao-Wecksler. "A portable powered ankle-foot orthosis for rehabilitation." *Journal of Rehabilitation Research & Development (JRRD)* 48, no. 4 (2011): 459-472. https://doi.org/10.1682/JRRD.2010.04.0054
[22] Minchala, Luis I., Fabián Astudillo-Salinas, Kenneth Palacio-Baus, and Andrés Vazquez-Rodas. "Mechatronic design of a lower limb exoskeleton." *Mechatronic Systems in Engineering: Design, Control and Applications* (2017): 111-134. https://doi.org/10.5772/67460