Systematic Design of a Sitting-Type Lower Limb Rehabilitation Robot for Stroke Patient

Duc Luu, Trung Nguyen, and Tam Bui

Abstract This study presented the design of a sitting type robot to support the lower limb rehabilitation for patients after stroke during the early stages. The robot was designed based on the exoskeleton structure, with hip, knee, and ankle joints, and at the calf and thigh wraps. The segments' length can be adjusted to fit each patient object. The article presented the structure and operating principle of the joints. Kinetics and dynamics analysis were used to calculate and choose the power source for the device. Numerical and computational tests were used to check the safety of the structure. In addition, this paper uses a numerical simulation method to derive the motion trajectory of an ordinary person, which is the input data used in the device control process.

Keywords Lower limb rehabilitation · Exoskeletons robot · Sitting type · Gait cycle · Design engineering

1 Introduction

A stroke is a serious brain injury that occurs when blood flow to the brain is interrupted or a blood vessel in the brain bursts. Within minutes, brain cells begin to slowly die and cause many dangerous complications for the patient. In Vietnam, stroke is the leading cause of death with 200,000 new cases per year [1]. In which 50% of cases are fatal and 90% of survivors experience post-stroke sequelae such as cognitive disturbances, impaired mobility, and problems with communication and eating.

Rehabilitation for patients is to minimize sequelae, create equal opportunities, and soon bring patients back to integrate into family and social life. Rehabilitation for patients begins as soon as possible after a stroke. Especially in the early stages

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B. T. Long et al. (eds.), *Proceedings of the 3rd Annual International Conference on Material, Machines and Methods for Sustainable Development (MMMS2022)*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-57460-3_26

after severe stroke sequelae, patients must undergo passive exercises. This creates pressure and difficulties for doctors and family members in the treatment process.

With the importance of rehabilitation treatment, treatment support devices for patients are increasingly interested, especially in this study focusing on rehabilitation after stroke for the patient's lower extremities. In the world, there have been researches and publications about rehabilitation devices for lower extremities. However, each type of rehabilitation robot has its own characteristics and is suitable for each patient in each stage of the rehabilitation process. Some typical devices can be followed such as: robot MotionMaker, Lambda-robot, robot Lokomat [2–4]. These types of researched devices are expensive, cumbersome in structure and not really suitable for patient recovery at the early stages of therapy. Through researching and studying published documents, it shows that the rehabilitation process of patients in severe form in the early stages has not been interested and develop in accordance with social needs.

The objective of this study is to present the design of a device that supports rehabilitation for lower limbs in the form of sitting easily for patients, restoring movement for hip joints, knee joints, and ankle joints for patients with severe sequelae in the early stages of treatment. The device can be individually tailored for each patient with the ability to change links lengths and have exercises for each type of exercise. The mobility at the joints of the device corresponds to the joint range of motion in the lower limbs of normal people, helping the patient to feel the most comfortable when using.

2 Calculation and Structural Design of Rehabilitation System

2.1 Anthropometry

In the process of researching and designing, it is necessary to collect parameters of body size and joint range of normal people. Dimensional parameters are used as the basis for calculating and designing device. The size of the links in the robot is calculated to match the patient's lower limb size, they need to satisfy the correctness in rehabilitation and safety for the patient when used.

The mobility of each joint is characterized by the musculoskeletal and ligamentous structure of each joint. It is defined by the number of degrees of freedom (DOF) of the joint when moving separately in a 3-dimensional coordinate system. However, in fact regular daily activities are mainly: walking, climbing stairs, walking. During such operations, the lower limb moves only on a plane parallel to the sagittal plane. Meanwhile, to set up all the degrees of freedom of the lower extremities on the robot structure makes the robot structure more complicated but setting the entire degrees of freedom of the lower limbs is not really necessary for the process patient recovery in the early stages. Therefore, in this study for order to optimize the design and

Table 1 Range of angular in the lower limbs

No.	Joint	Movement	Min[°]	Max[°]
1	Hip	Extension—Flexion	−32	128
2	Knee	Extension—Flexion	0	142
3	Ankle	Dorsiflexion—Plantarflexion	−60	20

manufacturing costs, the focus will be on developing the device structure to meet the exercises for the lower limb operating on a plane. Therefore, the data in Table 1 have been obtained for solving the operation of 3 joints only on the sagittal plane.

Based on statistics from the group of survey subjects, the group of patients suitable for the studied device has a height of 1350 mm to 1850 mm and a maximum weight of 80 kg [5]. From the height of the group of patients determined above, based on the ratio coefficient obtained from the book [6], a table can be calculated to solve the size value of the sutures in the lower extremities.

2.2 Proposed Rehabilitation Robotic

The device to support lower limb rehabilitation for patients with sequelae after stroke has had a few published studies and design models. However, each design model can only meet a few specific rehabilitation exercises for each patient. In general, rehabilitation devices are designed based on basic principles. In this study, the focus is on rehabilitation for the lower extremities, so we synthesize and classify the structures into basic groups as diagrams (Fig. 1).

With the goal of the robot sitting and restoring movement for the joints in the lower extremities, and the ability to follow the exercises. With each different exercise, the trajectory of joint movement will be different, so the design principle according to the exoskeleton structure is the most reasonable. The exoskeleton is a frame-like structure that covers the lower extremities, including the structure of the suture and the joint. Because the patient will be in a sitting state, the hip joint will have a reduced range of motion compared to the standard position, so the structure of the recliner to help the patient recline is the best solution. It helps to increase the trajectory of the joint, reduce the body load on the robot skeleton and at the same time help the patient have a more comfortable posture.

2.3 Design Robot Structural

The sitting limb rehabilitation device for stroke patients has been designed based on anthropometric data. The device model structure is described as follows (Fig. 2).

The model structure includes:

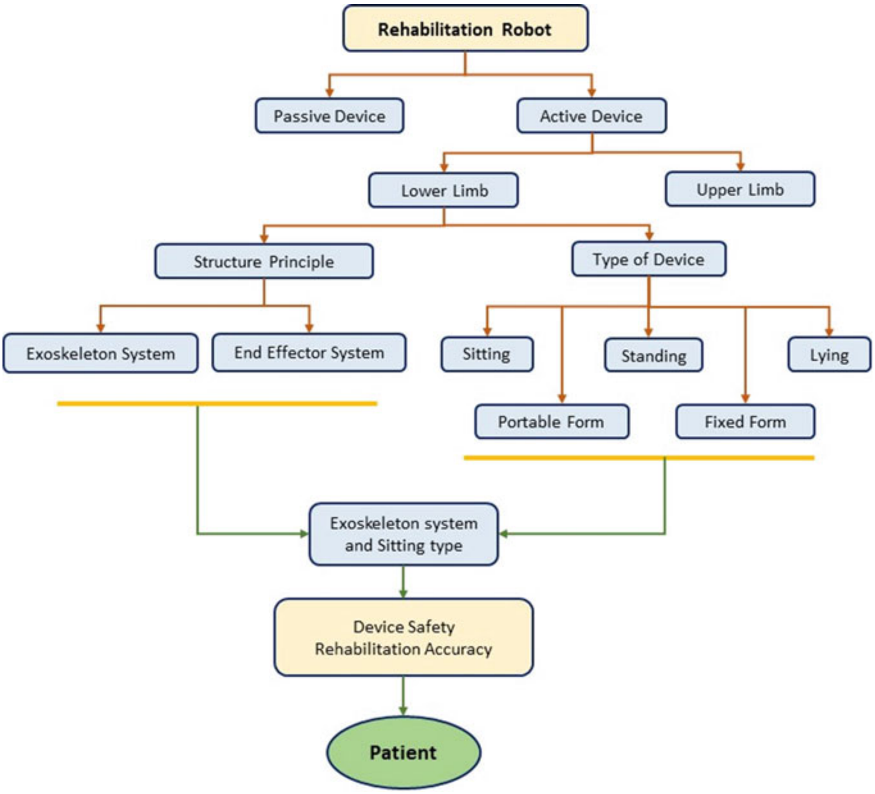

Fig. 1 Classification of rehabilitation equipment and proposed model principle

1. Patients
2. Recliner
3. Base links
4. Counterweight system
5. Hip joint motor block
6. Hip joint encoder
7. Knee joint motor block
8. Thigh adjustment motor
9. Fixed thigh links
10. Movable thigh links
11. Fixed calf links
12. Calf adjustment motor
13. Movable calf links
14. Ankle joint motor block
15. Base of foot
16. Ankle joint encoder

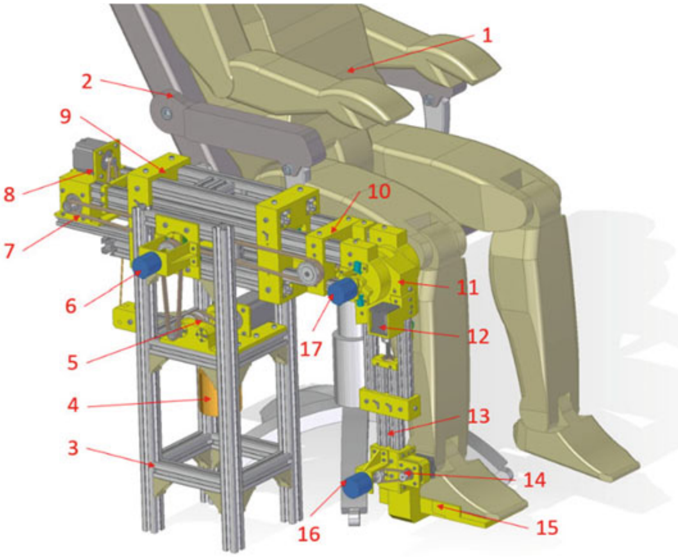

Fig. 2 Proposed rehabilitation robotic

17. Knee joint encoder.

The structure of the rehabilitation device is made in the form of an exoskeleton including 4 links and 3 joints. The separate seat section offers flexible patient mobility, including the ability to recline at an angle to reduce the load on the robot frame. In which there are 2 main parts, which are thigh links and calf links, which can adjust the length and size according to the patient's height. The device model has 3 rotary joints: hip joint, knee joint, ankle joint. The transmission used for rotary joint motion is a toothed belt transmission combined with a tooth pulley, although the structure of the transmission is compact, the transmission ratio is not high. Therefore, the ability to increase engine torque will decrease, so a large torque motor is required. The motor used is a stepper motor, capable of moving in the form of micro step, so the accuracy of the rotation angle output at the joint can meet the treatment exercise. The transmission used for the length adjustment of the thigh and leg links uses a lead screw type transmission, which converts the rotation of the motor into a reciprocating motion so that the movable part of the suture slides over the fixed part determined. At each output angle on the 3 joints, 3 additional rotary encoders are installed to feedback the current position of each joint, helping to determine the accuracy when controlling the robot.

3 Analysis of the Robot's Working Trajectory

3.1 Workspace of Robot

After the robot design and calculation process, once the robot structure and motion transmitter have been obtained, it is necessary to define the robot workspace.

Analyzing the robot's workspace helps determine the limits of movement, the trajectory of the exercises will be in the workspace of the machine. Here consider on the descartes coordinate system with X, Y axes being the axes of the point coordinates in space. The robot's workspace is all the point coordinates that the robot can generate when operating within the established angle limits. The stroke of the stitches will be determined based on the change of angle at each inner joint as shown in Table 2.

From the long size and angular limit of each joint, the simulation of the number of trajectories on Matlab software obtains all the points in the robot's workspace. The end point of the previous links will be the position of the next joint, so the end point of the link is determined by the point coordinates of the next joint on the robot workspace. Figures 3 and 4 show the workspace of each joint and the main workspace of the robot. Since the hip joint is determined to be stationary with the patient's sitting or lying position, the position of the hip joint is considered as the origin in the orbital space of the robot. The red line shown in Fig. 3 is the working trajectory of the thigh's link when the hip joint rotates within the angular range (from −20° to 40°), which is the orbital curve of the knee joint. The blue point cloud is the set of all the trajectories of the calf link produced when the hip joint (−2° to 40°) and knee joint motion (from 0° to 110°) are combined works at the same time. The end point of the calf link is the ankle joint, so the blue point cloud is the working space of the ankle joint. Figure 4 shows the purple point cloud, which is the collection of all the trajectories of the foot suture created when all 3 joints move simultaneously: hip joint (from −20° to 40°), knee joint (from 0° to 110°) and toe joints (from −60° to 20°). Considering the foot length is calculated as the toe joint, so the end point of the foot stitch is the toe joint, and the robot's end point. So, the purple point cloud set in Fig. 4 is the robot workspace in 2-D space. The motion trajectories of all exercises will be within the working space of the given joints. See that there are no singularities in the robot workspace.

Table 2 Limiting movement of joints in robots

Joint	Range of motion
Hip	−20° to 40°
Knee	0° to 110°
Ankle	−60° to 20°

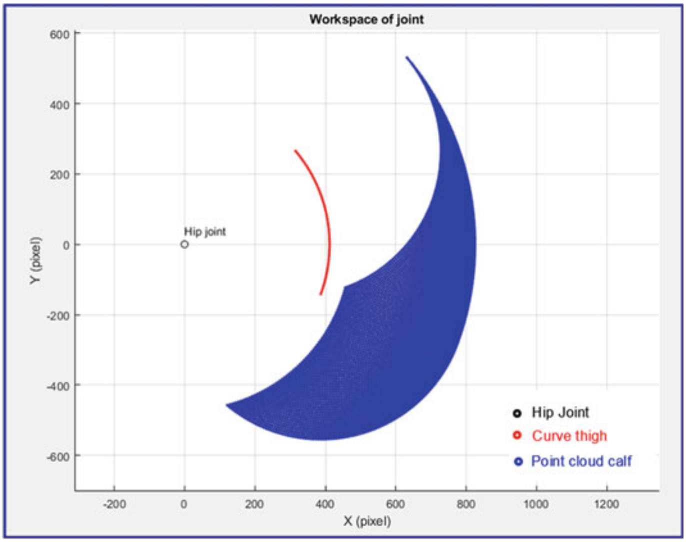

Fig. 3 Workspace of knee, ankle joint

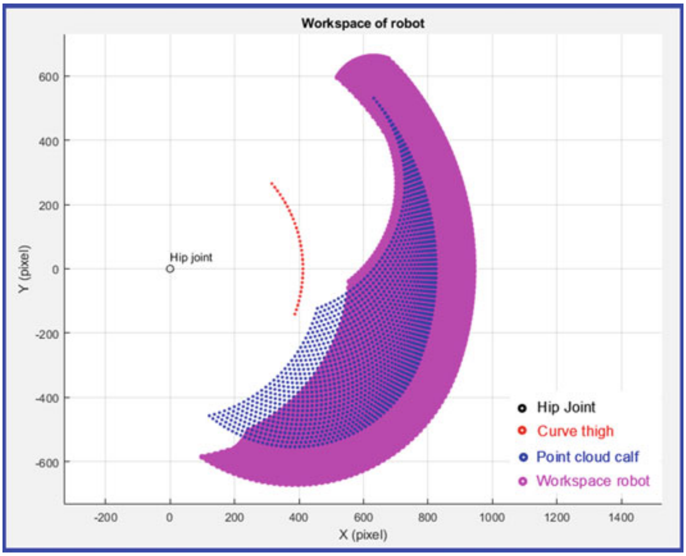

Fig. 4 Workspace of robot

3.2 Data Analysis of Robot Exercises

After analyzing the robot's workspace, it is very important to build exercises for the robot to work. Rehabilitation exercises will directly affect the patient, affecting the recovery process during the period. In this study, set up two basic exercises for the robot to work. The exercises are referenced in [7, 8], including single-joint exercises and exercises that combine joints to work at the same time. The trajectory of the exercises will always be in the workspace of the robot. As a result of the operation simulation, the angle values of the joints are obtained according to the progress of the exercise. With a single exercise for each hip joint (Fig. 5), knee joint (Fig. 6), and ankle joint (Fig. 7). Proceed to rotate the link according to the rotation angle of the joint, obtain the total motion trajectory of the robot and solve the angle value over time. At the exercise combining the joints at the same time, we choose the cycling exercise in a circle (Fig. 8). The trajectory of the exercise is in the robot's workspace, approximated to 24 points on the trajectory. The angle values of the 3 joints are distributed according to 24 points as shown in the graph (Fig. 8). The angle value convention is followed by the anthropometric convention mentioned above. We get the following results from the analysis:

The simulation results show that in the separate exercise of each joint, only the joint is regulated to move, the other joints are stationary, satisfying the correctness of the individual recovery for each joint.

The exercise combining joints in a circular orbit gives the results that the values of all joints are within the given limit. The matching value varies evenly, the distribution curve is smooth, and the start and end points in the value cycle coincide.

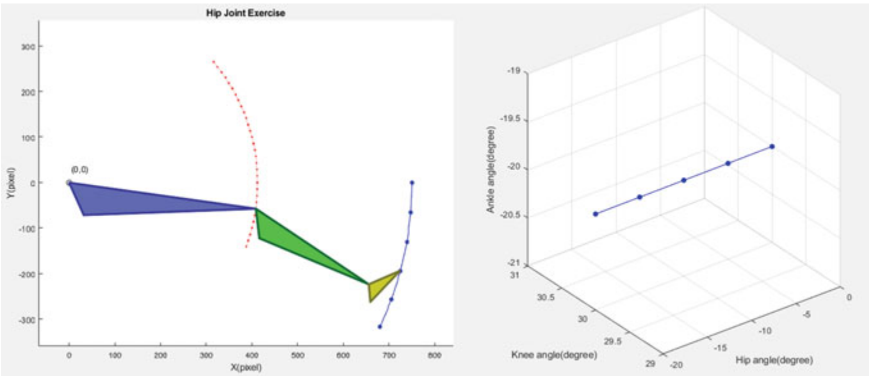

Fig. 5 Analysis of the exercise trajectory for the hip joint

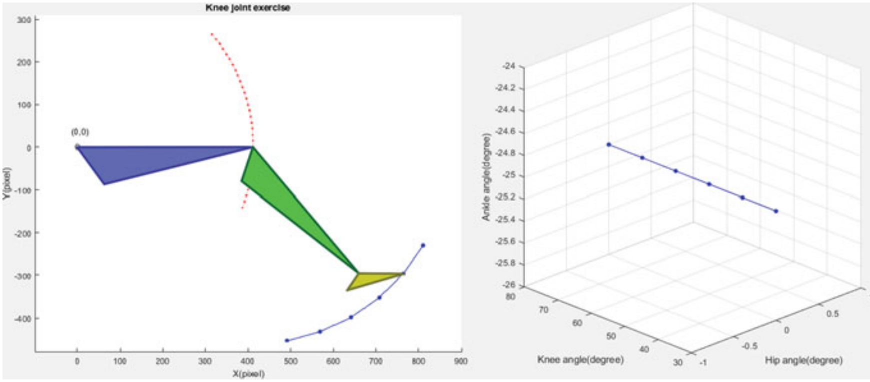

Fig. 6 Analysis of the exercise trajectory for the knee joint

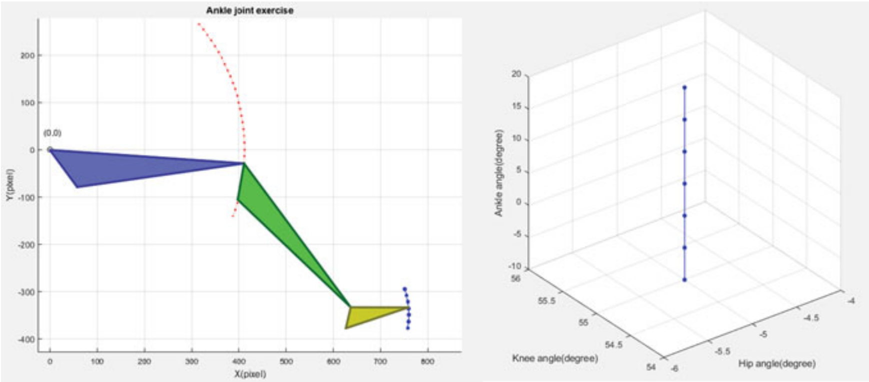

Fig. 7 Analysis of the exercise trajectory for the ankle joint

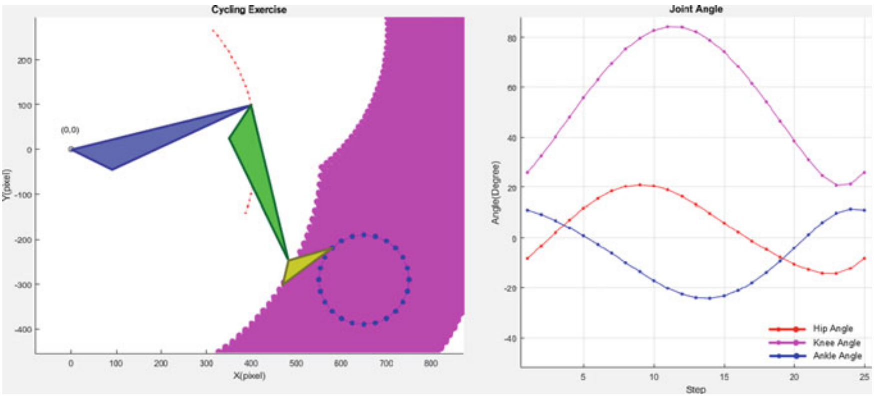

Fig. 8 Trajectory analysis of joint exercises

4 Result and Discussion

After the process of researching and designing a sitting rehabilitation device for patients after a stroke at an early stage. The initial prototype model has been successfully built and put into trial operation. The initial operation process is too simple exercises such as rotating each joint, combined with slow walking, showing that the device runs stably and safely for the patient. Besides, the compact weight is easy to transport and disassemble, making the robot more flexible. Regarding the correctness in rehabilitation therapy, the robot can respond to basic exercises such as movement of each joint, stable operation with exercises such as walking steadily. The device can be used in both sitting and reclining positions. The ability to safely recover at an early stage after a stroke, and the low cost give the device a prominent advantage over conventional devices. However, at present the prototype model only stops rehabilitation for one side of the lower limb and does not have high aesthetics. The next direction of future research is to improve the design to help restore the disease for both lower limbs, and at the same time commercialize the product in the future. Through the above research paper, it will be the basis for further development of research and design of assistive devices for humans.

5 Conclusion

In the above study, a systematic design sitting type of a lower limb rehabilitation robot for post-stroke patients was presented in the early stages of treatment. The study also goes into the analysis of human anthropometry, which is the basis for calculation and device design. The design calculations of the study are based on meeting the goal of a compact, easy-to-use, low-cost device. Endurance testing for the device shows that the device is safe for patient use. At the same time, the ability to exercise exercises for each joint separately or exercises to combine joints together helps the patient's recovery training process become better. The angular position feedback sensor system provides feedback on the exercise trajectories, ensuring the accuracy of the exercises performed. Next, the research will develop a rehabilitation system for the other leg that is similar in structure and kinematics, and will research and develop rehabilitation exercises for the patient that are suitable for the structure and workspace of robot.

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