Post-stroke rehabilitation robot for knee: a compact design and manufacture

Herianto¹, Ilham Adityarsena Febryantho², Hasan Mastrisiswadi³

¹,²Department of Mechanical and Industrial Engineering, Universitas Gadjah Mada, Indonesia
³Department of Industrial Engineering, UPN Veteran Yogyakarta, Indonesia

E-mail: herianto@ugm.ac.id

Abstract. The number of stroke patients is increasing every year. Many studies have been carried out to rehabilitate post-stroke patients; one of them is using robotic assistance. However, rehabilitation robots, especially for lower limbs, are usually large, so they are less active. This study aims to design and manufacture compact lower limb rehabilitation robots, which focus on the knee so that the rehabilitation process can run effectively. After being designed and manufactured, the rehabilitation robot is also tested whether it can run well. Based on measurements between the motion sensor and the actual movement, there is almost no difference in distance. Besides, from the graph of position, speed, and acceleration, the rehabilitation robot runs well.

1. Introduction
In 2014, around 7.2 million people in America over the age of 20 suffered a stroke, and every year, approximately 795,000 people experience these symptoms[1]. Many strokes that occur can affect both men and women. Even worse, this disease can lead to death[2]. About 1 in 19 deaths in America are caused by stroke. On average, every 3 minutes 45 seconds, someone dies of a stroke[1].

Stroke is a disease that causes sufferers to experience disability[1–5]. To get normal activities, patients need routine post-stroke rehabilitation. Various ways of treatment and rehabilitation have been developed, one of which is the rehabilitation process with the help of robots[5–10]. The use of robots as a rehabilitation aid is needed[6]. So far, the rehabilitation process has been done manually and is in great need of human labor[5,6]. Meanwhile, therapists who have expertise and experience are very limited in number.

Identification of the need for rehabilitation robots for stroke patients has been carried out[5,11–13], one of them is a compact shape[6,9]. So far, the form of rehabilitation robots is enormous and takes place, especially robots for lower limb rehabilitation such as the knee[6]. It causes the rehabilitation process only to be carried out in hospitals or rehabilitation centers. Meanwhile, many patients have difficulty going to that place. Also, the costs required are relatively large. With the existence of a compact rehabilitation robot, patients are expected to be able to carry out the rehabilitation process independently with more frequent exercise. It is considered more effective and cheaper. This study aims to design a robotic rehabilitation of a patient's knee after a compact stroke.
2. Methods

2.1. Design
The design process is based on the need for kinematic movements and structural strength. This kinematic movement is used to determine the mechanical system of a robot. Kinetic movement data in the form of a range of motion and movement of the knee and ankle. Meanwhile, the strength of the structure is determined by conducting a force simulation that works on a mechanical robot. Besides, the design process also considers anthropometric data so that the resulting tool is more ergonomic.

2.2. Manufacture
The manufacturing process begins with the selection of components and materials. The elements in this process consist of mechanical and electronic components. Mechanical components used include bearings, linear guides, couplings, timing belts, pulley timings, and hinges. The electronic components used are stepper motors, rotary encoders, limit switches, pushbuttons, power supply, Arduino, and motor drivers. Also, for the body and other devices that must be made using aluminum alloy, brass, and cast steel.

2.3. Assembly
The assembly process is based on the entity-relationship diagram that can be seen in Figure 1. The entity-relationship diagram aims to provide an overview of the relationships between the main parts of the rehabilitation robot. The assembly process uses a connection in the form of a bolt symbolized by the letter "J". The use of bolts is chosen because it is more flexible. Connecting with bolts is a type of non-fixed connection that is strong but easy to disconnect.

2.4. Robot testing
The testing process is conducted on one of the patient's knees. The operator controls the movement of the rehabilitation robot on the control panel. The method of controlling motor speed is done by using a potentiometer in the form of PWM. Control in this way is more comfortable to adapt to patient needs.

Data that taken in this testing process is the distance of the sensor to the actual range and profile of the position, speed, and acceleration. This data is used to find out whether the rehabilitation robot provides the same output as input.

![Figure 1. Entity-relationship diagram for assembly](image-url)
3. Result and Analysis

3.1. Rehabilitation robot

Research on the design of rehabilitation robots for lower limbs has been carried out. [14] has designed a robot for rehabilitation of limbs using 5 DOF. However, the robot with the name HipBot has a large size (Figure 2a), so it requires a particular space to carry out the therapy. In the same year, [15] made a design of continuous passive movement (CPM) rehabilitation robot (Figure 2b). This robot is using the constraint-induced movement therapy (CIMT) rehabilitation technique. However, patients must do it while lying down. In this study, a rehabilitation robot will be designed that can not only be done while lying down but also sitting, flexible, and compact.

Figure 2 lower limb rehabilitation robot: (a) HipBot and (b) CPM

In the process of designing a rehabilitation robot, anthropometric data is used. The use of anthropometric information aims to make the robot produced more ergonomic. Anthropometric data is the overall size of the human body, both static and dynamic. The anthropometric data used were the results of research [16], including buttock-knee length, buttock-popliteal length, knee height, foot length, foot breadth, popliteal height, and lower limb weight.

Figure 3. Rehabilitation robot design

The results of the design of the rehabilitation robot can be seen in Figure 3. This rehabilitation robot consists of several parts namely manipulator frame module, frame, linear guideway holder, footrest, coupling-like system, motion rehabilitation system module, belt and pulley, motor mounting, bearing housing, shafts, flexible coupling, and mounting encoder. The design of this rehabilitation robot is used to train the movement of flexion-extension on the knee. In designing this rehabilitation robot, compact factors are very much considered. The design of the rehabilitation robot must also be flexible so that it can be used independently.
After the visual design is done, the next step is to calculate the required torque. Calculation of motor torque requirements is done by calculating the amount of torque received by the motor. Data was taken through a pilot study of five healthy people. The data taken is the maximum resistance force during flexion-extension movements. This data can be seen in Table 1. Based on Table 1, the maximum motor torque requirement is 15 Kg. So that the total mass of the load that must be moved by the motor following (1) is:

\[
\text{Resistance force} = \text{Resistance load} \times 10 \text{ (Newton)}
\]

\[
= 15 \text{ kg} \times 10 \text{ m}^2/\text{s} = 150 \text{ Newton}
\]

After getting the resistance force, the next step is to calculate the torque on the motor. The motor torque calculation scheme used can be seen in Figure 4. From the data, the amount of torque that works on the stepper motor can be calculated according to (2) as follows:

\[
\text{Torque (T)} = \text{Fmotor} \times \text{Distance axis motor to the load}
\]

\[
= 15 \text{ Kg} \times 1.25 \text{ cm} = 18.75 \text{ Kg.cm}
\]
From the calculation results, the maximum torque value that works on the motor is 18.75 Kg.cm. Based on the results of this calculation, the Nema 23 stepper motor with a torque stall 23 Kg.cm at 24 V voltage is selected.

After calculating the torque requirements, the next step is to carry out stress analysis on the footrest as well as the mainframe. Stress analysis is carried out with Autodesk inventor professional 2016. Stress analysis is done using two types, Von Mises and Displacement. The results of the stress analysis can be seen in Figure 5.

![Stress Analysis of (a) Footrest using Von Mises, (b) footrest using displacement, (c) mainframe using Von Mises, and (d) mainframe using displacement](image)

From the simulation stress analysis result, the mainframe has the highest displacement and Von Mises value. Von Mises value of stress on the mainframe is 18.25 Mpa and displacement is 0.02819 mm. The amount of this stress is still below the yield strength of the material (aluminum: 275 Mpa, brass: 13.4 Mpa, and cast steel: 690 Mpa) used. The displacement value, which is only 0.02819 mm, does not significantly influence the structure. It can prove that the design is strong enough to support the patient's legs, so no modification is needed to the design that has been made. The results of the manufacturing process and assembly can be seen in Figure 6.
The rehabilitation robots programming with different movement variations and intervals are based on the distance and angle limits inputted. Also, the speed of movement can be adjusted so that it is easy to use.

3.2. Result of the test
The test is conducted five times with different distance intervals. Each test starts from zero to close to the maximum distance. The actual distance test results and sensor readings can be seen in Figure 7. In Figure 7, it can be seen that there is almost no deviation between the actual data and the sensor readings. It means the movement process is going well.

![Figure 7. Actual distance and sensor reading for (a) 100 RPM, (b) 200 RPM, and (c) 300 RPM](image)

The test and retrieval of the next data is a graph of position, velocity, and acceleration profiles. Data retrieval is done using Arduino mega 2560. It is conducted when the robot is run continuously from a distance of 0 to 44 cm. As for this test, data can be seen in Figure 8. From Figure 8, it can be seen that the position profile shows a linear graph, the velocity profile shows constant movement, while the acceleration profile increases at the beginning of the period then decrease with increasing time. The initial acceleration process occurs to reach the desired speed. After the desired speed is reached, the acceleration decreases over time.

![Figure 8. Graph of (a) position, (b) speed, and (c) acceleration](image)
4. Conclusion

Based on the results of this study, it can be concluded that the design and manufacturing of rehabilitation robots are running well. Rehabilitation robots are also designed with compact and flexible, easy to assemble due to the type of connection used using bolts. The results of the tests conducted indicate that the rehabilitation robot is running well. Besides, rehabilitation robot designs are also made with anthropometric data so that it is more ergonomic. Research on the usability level of rehabilitation robots is needed to support product success.

References

[1] Benjamin E J, Virani S S, Callaway C W, Chamberlain A M, Chang A R, Cheng S, Chiuye S E, Cushman M, Delling F N, Deo R, De Ferranti S D, Ferguson J F, Fornage M, Gillespie C, Isasi C R, Jiménez M C, Jordan L C, Judd S E, Lackland D, Lichtman J H, Lisabeth L, Liu S, Longenecker C T, Lutsey P L, MacKey J S, Matchar D B, Matsushita K, Mussolino M E, Nasir K, O’Flaherty M, Palaniappan L P, Pandey A, Pandey D K, Reeves M J, Ritchey M D, Rodriguez C J, Roth G A, Rosamond W D, Sampson U K A, Satou G M, Shah S H, Sparto N L, Tirschwell D L, Tsao C W, Voeks J H, Willey J Z, Wilkins J T, Wu J H Y, Alger H M, Wong S S and Muntner P 2018 Heart disease and stroke statistics - 2018 update: A report from the American Heart Association Circulation

[2] Katan M and Luft A 2018 Global Burden of Stroke Semin. Neurol.

[3] Lallukka T, Ervasti J, Lundström E, Mittendorfer-Rutz E, Friberg E, Virtanen M and Alexanderson K 2018 Trends in diagnosis-specific work disability before and after stroke: A longitudinal population-based study in Sweden J. Am. Heart Assoc.

[4] Bright F A S, Kayes N M, McPherson K M and Worrall L E 2018 Engaging people experiencing communication disability in stroke rehabilitation: a qualitative study Int. J. Lang. Commun. Disord.

[5] Stephenson A and Stephens J 2018 An exploration of physiotherapists’ experiences of robotic therapy in upper limb rehabilitation within a stroke rehabilitation centre Disabil. Rehabil. Assist. Technol.

[6] Diaz I, Gil J J and Sánchez E 2011 Lower-Limb Robotic Rehabilitation: Literature Review and Challenges J. Robot.

[7] Kim M S, Kim S H, Noh S E, Bang H J and Lee K M 2019 Robotic-Assisted Shoulder Rehabilitation Therapy Effectively Improved Poststroke Hemiplegic Shoulder Pain: A Randomized Controlled Trial Arch. Phys. Med. Rehabil.

[8] Ang K K, Chua K S G, Phua K S, Wang C, Chin Z Y, Kuah C W K, Low W and Guan C 2015 A Randomized Controlled Trial of EEG-Based Motor Imagery Brain-Computer Interface Robotic Rehabilitation for Stroke Clin. EEG Neurosci.

[9] Polygerinos P, Wang Z, Galloway K C, Wood R J and Walsh C J 2015 Soft robotic glove for combined assistance and at-home rehabilitation Robotics and Autonomous Systems

[10] Louie D R and Eng J J 2016 Powered robotic exoskeletons in post-stroke rehabilitation of gait: A scoping review J. Neuroeng. Rehabil.

[11] Matriasiswadi H and Herianto H 2015 Identifikasi kebutuhan konsumen robot rehabilitasi pasien pasca stroke dengan menggunakan metode Quality Function Deployment ( QFD ) SEMINAR NASIONAL TEKNIK INDUSTRI UNIVERSITAS GADJAH MADA 2015 ed B M Sopha and T Wijayanto (Yogyakarta: Universitas Gadjah Mada) pp 27–36

[12] Matriasiswadi H and Herianto H 2017 Identifikasi Kepentingan Relatif Konsumen Terhadap Robot Rehabilitasi Pasien Pasca Stroke dengan Menggunakan Conjoint Analysis J@ti Undip J. Tek. Ind. 12 35

[13] Matriasiswadi H and Herianto H 2017 Analisis Kebutuhan Robot Rehabilitasi Pasien Pasca Stroke dengan Menggunakan Metode Kano J. Ilm. Tek. Ind. Vol 15, Iss 2, Pp 151-156 VO - 15
[14] Guzmán-Valdivia C H, Blanco-Ortega A, Oliver-Salazar M A, Gómez-Becerra F A and Carrera-Escobedo J L 2015 HipBot - The design, development and control of a therapeutic robot for hip rehabilitation *Mechatronics*

[15] Hsieh M-S, Chen C-S and Chien K-S 2013 Intelligent passive control for lower limb rehabilitation system *Trans. Can. Soc. Mech. Eng.* 37 1023–33

[16] Huston R 2008 *Principles of biomechanics* (CRC press)