Exoskeleton Design Using Kinematics Analysis for Upper Limb Rehabilitation in Post-Stroke Patients

Eko Wahyu1, Susy Sumartini2, Pringgo Widyo3, Lobes Herdman3

Abstract. Robotic technology in the last decade has developed to support the rehabilitation of post-stroke patients. This paper aims to analyze the kinematics of the exoskeleton and simulate movements during the upper limb rehabilitation process. The exoskeleton model must meet the convenience and adjustment of the rehabilitation robot. In the last decade, several studies have shown the development of rehabilitation robots to help post-stroke patients [10], [11]. The result was due to the different mechanical structures and rehabilitation principles. Vetrice et al., [12] structural and kinematic robot arm for upper limb rehabilitation needs, the simulated design is identical to the human arm structure. Pilea et. al. [13] analyzed the conceptual model of a medical rehabilitation robotic system to achieve the following movements: flexion/extension of the elbow, supination/pronation of the forearm and extension/flexion and adduction/abduction of the wrist, which is based on exoskeleton design (ReExRob) to meet the rehabilitation needs of post-stroke patients. The second approach adds passive degrees of freedom to link the two kinematic chains.

According to Schiele et al. [9] the exoskeleton kinematic model can be done through an approach; the first approach is by making an outer frame adapted to the robotic segments, such as the length of the robot's arm and the design used. The second approach adds passive degrees of freedom to link the two kinematic chains.

The exoskeleton model must meet the convenience and adjustment of the rehabilitation robot. In the last decade, several studies have shown the development of rehabilitation robots to help post-stroke patients [10], [11]. The result was due to the different mechanical structures and rehabilitation principles. Vetrice et al., [12] structural and kinematic robot arm for upper limb rehabilitation needs, the simulated design is identical to the human arm structure. Pilea et. al. [13] analyzed the conceptual model of a medical rehabilitation robotic system to achieve the following movements: flexion/extension of the elbow, supination/pronation of the forearm and extension/flexion and adduction/abduction of the wrist, which is based on exoskeleton design (ReExRob) to meet the rehabilitation needs of post-stroke patients. The second approach adds passive degrees of freedom to link the two kinematic chains.

1 Introduction

The design and development of medical rehabilitation products are still open to researchers and engineers in the industrial sector. The development of post-stroke rehabilitation has been heavily influenced by research examining the field of human-robot interaction (HRI) [1]. The intuitive control mechanism via HRI allows the robot to help improve rehabilitation performance [2]. HRI's contribution in its development has helped many people perform tasks in everyday life, such as service robots and robots for clinical applications [3]. HRI research has shifted towards robotic systems designed for rehabilitation, especially exoskeleton-based robots [4]. The design of the exoskeleton relies on replicating the kinematics of the human arm anatomy. Schiele [5] in his research, modelled explicitly to predict and analyze forces by considering 3 DoF kinematic through tissue in bone anatomy.

Replication of the exoskeleton kinematics model makes it possible to increase the precision of arm movements during the upper limb rehabilitation process by adjusting the needs of human arm anatomy [6], [7]. The dynamics perspective of motor control interaction is based on a model of the developing nervous system and represents a paradigm shift that has occurred [8].
exoskeleton's kinematics to achieve the stability of the flexion/extension and supination/pronation movements required for the upper limb rehabilitation process for poststroke patients. This research is essential because kinematic analysis allows the exoskeleton to avoid excessive robot movement angles and avoid more angular movements than necessary to cause the same direction. The structure of the exoskeleton design used refers to the patient's arm size anthropometric data. Modelling of the exoskeleton prototype mechanism was carried out with the RoboAnalyzer software. This design and simulation were carried out as a preliminary study as a planning exoskeleton design used for upper limb rehabilitation in post-stroke patients.

2 Kinematic modeling of the exoskeleton structure

Kinematic models were developed to verify the dynamic and kinematic equations that govern the motion of mechanisms and are used to study exoskeleton performance [14]. Modeling using kinematics is the science that studies how motion can occur, allowing the exoskeleton to avoid excessive robot movement angles and avoid more angular movements than necessary, causing the same direction [15]. In addition, it is necessary to solve the kinematic and dynamic equations that govern the mechanism's motion to obtain the driving torque on the exoskeleton [16]. The proposed exoskeleton has a 3 DoF joint mechanism. The exoskeleton mechanism is then transformed into the Denavit-Hartenberg (DH) method. The DH parameter is used to identify the robot configuration through the Jacobian equation (citation). The time derivative of the exoskeleton kinematics equations gives the Jacobian, which relates the velocity of each joint to the linear and angular velocity of the end effector. Furthermore, dynamic analysis is carried out through forward kinematics calculations enabling the displacement and speed of the joints to be carried out precisely. Dynamic analysis can be performed using the Newton-Euler method (citation). The emotional equation of the exoskeleton is used to control the motion of the exoskeleton. Figure 1 is a schematic diagram of a kinematic exoskeleton test for post-stroke rehabilitation.

2.1 Mechanical design

The developed exoskeleton design is used for forearm rehabilitation in post-stroke patients. The exoskeleton is designed with two active DoF with the range of motion (ROM) exoskeleton flexion/extension type of movement/extension of the elbow and wrist described in Table [13].

<table>
<thead>
<tr>
<th>Types of motions</th>
<th>Anatomical range</th>
<th>Proposed device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>145°</td>
<td>120°</td>
</tr>
<tr>
<td>Extension</td>
<td>15°</td>
<td>0°</td>
</tr>
<tr>
<td>Pronation</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>Supination</td>
<td>85°</td>
<td>75°</td>
</tr>
</tbody>
</table>

ROM of the shoulder during flexion/extension and pronation/supination of the wrist is described in Figure 2.

![Figure 2](image)

Fig. 2. The interval of arm movement by flexion/extension (a), pronation/supination (b)

Table 1. Range of elbow motion on the arm

<table>
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</tr>
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<td>85°</td>
<td>75°</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic of the Kinematic Exoskeleton Testing Diagram

![Figure 1](image)

Fig. 3. Schematic of the exoskeleton design (a) Schematic of the kinematics of the exoskeleton system for arm mobilization.

![Figure 3](image)

Fig. 4. Kinematics of the exoskeleton system
The design of the exoskeleton is based on human anthropomorphic structures; the exoskeleton consists of 3 links and two drive units. The forearm is connected to the wrist rest exoskeleton, which supports the forearm. The wrist brace has free space with a support link that requires a flexion/extension angle to form a pronation/supination movement carried out by grasping the tip of the exoskeleton.

2.2 Direct kinematics

The basic principles of mathematical modelling in robotic systems are explained in Figure [17]

![Figure 5](image)

Fig. 5. Schematic Blog diagram of the robotic system

The mechanism of G(s) is a mathematical equation of the controller. H(s) is the physical equation of the robot system, including actuators and electronic systems. The components of X(s) are the input reference position and reference speed. Component E(s) is an error or error, while U(s) is the controller's output. Y(s) is the robot's motion function which is always expected to be the same as the reference defined at the input X(s).

The kinematic transformation of the schematic from the Blog diagram is explained in Figure 6 [17].

![Figure 6](image)

Fig. 6. Schematic Blog kinematics diagram of a robotic system

The input mechanism used is in the form of position and orientation vector coordinates P(x,y,z), and the output is in the form of θ (θ₁, θ₂…θₙ) where n is the number of DoF. The result is measured from the robot's motion with the angular domain from joint to joint. The robot control system requires the user to program or workspace the robot by determining the position expressed by coordinates. To determine the place, it is necessary to transform the coordinates between the Cartesian space and the angular space described in inverse and forward kinematics. Kinematic controller through a combination between P to θ is done with G(s) so that it produces controller output u, which works in joint space u (θ₁, θ₂…θₙ).

The direct kinematics exoskeleton takes input data from the active joint values described in Figure 7.

![Figure 7](image)

Fig. 7. Schematic of setting the coordinate frame (a) active joint design (b) pronation/supination involved joint (c) active flexion/extension

The joint coordinate mechanism is transformed into the Denavit-Hartenberg (DH) parameter table to obtain kinematic equations. DH parameter data in this study are described in Table 2.

<table>
<thead>
<tr>
<th>i</th>
<th>ai - 1</th>
<th>ai - 1</th>
<th>di</th>
<th>θi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>π/2</td>
<td> </td>
<td>d2</td>
<td>θ1</td>
</tr>
<tr>
<td>2</td>
<td>π/2</td>
<td> </td>
<td> </td>
<td>θ2</td>
</tr>
</tbody>
</table>

DH parameters, according to Ding et al. [18] used to determine the corner coordinates of the end-effector (X; Y; Z), namely ψ, θ and φ where i is the number of joints, Zi is the coordinate of each joint, ai is the distance from Zi to Zi+1 measured along Xi, ai is the angle between Zi to Zi+1 measured by Xi estimate, di is the distance between Xi - 1 to Xi measured along Zi and θi is the angle Xi - 1 to Xi measured by Zi estimate. The DH parameters in this study are shown in Table 2. The coordinate values of the DH parameters are then entered into the total transformation matrix (3T₀) by adjusting the exoskeleton framework in Figure 4. The complete transformation matrix (3T₀) is calculated by equation 1 as follows [19]:

\[
\begin{bmatrix}
\cos \theta_1 & -\sin \theta_1 & 0 & a_1 \\
\sin \theta_1 & \cos \theta_1 & 0 & d_2 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]

A total transformation matrix equation (3T₀) is performed to determine the singularity configuration of the exoskeleton, enabling the exoskeleton to avoid excessive robot motion angles and avoid more than necessary angular motions to cause the same movement [20]. Robot Singularity configuration refers to the design of the robot tip effector motion blocked in a specific direction so that the joints can be determined to move at a particular nominal speed in Cartesian space. The primary function of exoskeleton singularity ICIMECE 2023 https://doi.org/10.1051/e3sconf/202346502027E3S Web of Conferences 465, 02027 (2023)
3 Result and simulation

The Exoskeleton model was developed to analyze HRI with drive mechanisms and verify the dynamic and kinematic equations of the mechanical movement of exoskeleton performance. Mechanical design is done with SolidWorks software. Anthropometric data is needed to determine the parameters of the subject's arm mechanism, which is used to support the exoskeleton model that matches the size of the Indonesian arm [24]. While the data on arm weight found that the percentage distribution of human arm mass is 3.2% of body weight (kg) which is assumed to be 70kg, and the arm weight is 2.45 kg [25]. Table 3 describes the parameters of the mechanism of the human arm, and Table 4 describes the parameters of the exoskeleton mechanism.

<table>
<thead>
<tr>
<th>Link</th>
<th>Link length (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>26</td>
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<td>26</td>
<td>0.023</td>
</tr>
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</table>

The joint model is simulated based on Figures 4 (b) and 4 (c) design. The exoskeleton prototype mechanism was modelled with the RoboAnalyzer software according to the designed exoskeleton simulator link length. Verify the kinematic equations; the developed model is given a set of inputs and compares the results of solving the analytical equations. System input \( \theta_1 = 45^\circ, \theta_2 = 115^\circ, \theta_3 = 75^\circ \). Kinematic equation verification with RoboAnalyzer software is obtained as follows:

\[
\mathbf{O}_{\theta_1} = \begin{bmatrix} -0.422618 & -0.906308 & 0 & -0.126785 \\ -0.906308 & -0.422618 & 0 & 0.271892 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

\[
\mathbf{O}_{\theta_2} = \begin{bmatrix} 1 & 0 & 0 & 0.08 \\ 0 & 0.258819 & -0.965926 & 0 \\ 0 & 0.965926 & 0.258819 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

The link dimensions and angle sizes that have been determined using the RoboAnalyzer software are obtained from the forward kinematic calculation simulation results as follows:

\[
\mathbf{O}_{\theta_2,3} = \begin{bmatrix} 0.9396 & -0.0885 & -0.0885 & 0.2510 \\ 0.34202 & 0.24321 & -0.907673 & 0.236034 \\ 0 & 0.965926 & 0.258819 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

The initial movement position of the exoskeleton according to Denavit Haternberg-Parameter is explained in Figure 8(a), and the end motion position is described in Figure 8(b) where the blue line represents the Z axis coordinates, the red line represents the X axis coordinates, and the green line represents the Y-axis coordinates.

Table 3.

<table>
<thead>
<tr>
<th>Arm length</th>
<th>Forearm length</th>
<th>Forearm weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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The simulation results of exoskeleton movement, parameter values, and joint angles are used to analyze the suitability of movement for upper limb rehabilitation needs for post-stroke patients. Analysis of the end effector position points from the simulation results is explained in Figure 9.

Fig. 9. Simulation results of changes in the position of the elbow exoskeleton link (a) X coordinate value, (b) Y coordinate value, (c) Z coordinate value. The initial position of the end effector on the X axis is at coordinate 0 at the base of the 45° joint shoulder, then the rotational movement at the elbow is 115°; in the wrist position, the action is supination and pronation because the joint is parallel to the elbow so that the coordinates of the x and y axis rotation changes following the elbow coordinates. Changes in the joint angle are described in Figure 10.

Fig. 10. Results of changes in the exoskeleton joint angle. The graph of changes in joint angle in Figure 7 describes the final position of the end effector, which is analyzed using the RoboAnalyzer. This chart moves to fluctuate and indicates the initial coordinates of the exoskeleton manipulator and then goes to the final coordinates of the end effector. The movement of the exoskeleton of the manipulator is 1 second, so on the graph, the maximum X angle movement value is 1; it represents the whole time that needs to be taken by the manipulator robot to move to the desired position, namely at the initial part of the end effector on the X axis at coordinate 0 at the base 45° joint shoulder, then a rotational movement at the elbow of 115°.

Analysis The exoskeleton simulation used for rehabilitation refers to the performance structure of the post-stroke patient’s arm. The RoboAnalyzer device is used to simulate and analyze the motion stability of the exoskeleton to optimize the exoskeleton structure according to the rehabilitation needs of the upper limb. Movement of the exoskeleton is affected at a constant speed to study the state of motion of the forearm joint, namely flexion/extension and supination/pronation.

4 Conclusion

The results of the kinematic analysis of the exoskeleton design show that the exoskeleton simulated movement using the RoboAnalyzer moves to the desired position to achieve movement stability, namely flexion/extension and supination/pronation according to the needs of the upper limb rehabilitation process for post-stroke patients. The infinity number in the completion of the inverse kinematics generates the angle values at each joint that form the X, Y, and Z coordinate values with a simulation that represents a maximum time of 1 second to complete the exoskeleton movement to the desired position, namely at the initial part of the end effector on the X axis. At coordinate 0 at the base of the 45° joint shoulder, the rotational movement at the elbow is 115°. The simulated exoskeleton design adapts to anthropometric data on the size of the Indonesian arm so that the movement stability mechanism in the component can be simulated and adjusted to the angle requirements during the rehabilitation movement. For future research, the authors plan to build a prototype exoskeleton for testing and practical implementation.

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