International Journal of Innovative Research and Scientific Studies, 8(1) 2025, pages: 2855-2865

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

Development and prototyping of a stair-climbing wheelchair for lower limb disabled individuals

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Abstract

This research aims to develop a prototype of a stair-climbing wheelchair for individuals with lower limb disabilities. The research begins with designing the electric wheelchair using Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) principles. This technology allows for the simulation of the wheelchair's operation on a computer and the analysis of the structural strength of the electric wheelchair to calculate its robustness. After the design has been verified, the next step involves creating and assembling the stair-climbing wheelchair prototype. The performance testing of the prototype involves testing under conditions with three weight scenarios: 133 kg, 138 kg, and 149 kg. The results indicated that the wheelchair performed well in the first two cases, ascending and descending stairs efficiently. However, in the third case, with a total weight of 149 kg, the wheelchair failed to ascend stairs due to the motor's insufficient torque capacity, triggering an overload warning. The performance testing revealed differences in the time taken for stair climbing and stair descending, with the fastest time for climbing being approximately 4.84 seconds and descending at 5.02 seconds. The analysis of the Standard Deviation (SD) showed a low value of 0.07, indicating inconsistent weight distribution during testing. The ideal SD should exceed 1 for better consistency. User satisfaction was evaluated using a 5-point Likert scale, and the results showed that the average satisfaction score of the users was very satisfactory.

Keywords: Assistive devices for disabled individuals, Likert scale stair-climbing wheelchair.

DOI: 10.53894/ijirss.v8i1.5081
Funding: This study received no specific financial support.
History: Received: 12 January 2025 / **Revised:** 11 February 2025 / **Accepted:** 17 February 2025 / **Published:** 3 March 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Institutional Review Board Statement: Not applicable.
Acknowledgment: This work was supported by Bangkokthonburi University, Thawi Watthana, Bangkok, Thailand; Rajamangala University of Technology Suvarnabhumi, Nonthaburi, Thailand; and Rajamangala University of Technology Rattanakosin, Thailand.
Publisher: Innovative Research Publishing

1. Introduction

According to the 2024 National Statistical Office survey, Thailand has 1,134,380 individuals with mobility disabilities, accounting for 51.56% of the total disabled population (update 31, December 2024). Among them, 40,836 are individuals with lower limb disabilities. A person with lower limb paralysis refers to an individual who experiences a loss of motor function and sensation in the lower part of the body, including both legs. This condition results from spinal cord injury, leading to complete damage to the spinal nerve tissue. Therefore, medical devices that facilitate mobility for those with lower limb disabilities are essential and significantly important [1, 2]. Currently, 90% of individuals with lower limb disabilities use mobility aids such as wheelchairs, which are commonly recommended by doctors, especially for those who cannot walk normally. In Thailand, ramps or lifts for wheelchair users are limited, primarily available in hospitals, while other essential places often lack these facilities. This situation makes travel, daily life, and patient mobility challenging. Additionally, most homes have stairs, making it difficult for disabled individuals to move around easily [3-5].

One of the most significant challenges faced by wheelchair users is navigating stairs. Unlike flat surfaces, stairs pose a major obstacle for conventional wheelchairs, preventing independent movement and requiring assistance from others. Although electric stair-climbing wheelchairs exist, they are prohibitively expensive due to their complex mechanisms and high production costs. As a result, many low-income disabled individuals rely on standard wheelchairs, which cannot handle stairs. This limitation significantly impacts their independence, quality of life, and ability to access essential facilities, leading to a pressing need for an affordable and practical solution [6-9]. Furthermore, existing stair-climbing wheelchair solutions are not widely available in Thailand and often lack essential features such as real-time monitoring, safety enhancements, and adaptability to different stair sizes and inclinations. Additionally, many stair-climbing mechanisms are bulky, making them difficult to transport and integrate into daily life. These issues underscore the necessity of developing a cost-effective, compact, and efficient stair-climbing assistive device that enhances mobility without imposing financial burdens on users.

Electric wheelchairs designed to climb stairs are expensive to produce, resulting in high retail prices. This makes them inaccessible to low-income disabled individuals, who typically use conventional wheelchairs due to their affordability. However, conventional wheelchairs cannot navigate stairs, highlighting the difficulties faced by disabled individuals in stair environments without adequate facilities [6-9]. Computer-Aided Design (CAD) is used in the drawing and design process, creating geometric models focused on 2D and 3D modeling with Topology Optimization technology before actual production. The created parts, known as models, can be displayed in both 2D and 3D. CAD stands out as a highly accurate program specifically designed for production, capable of working with other manufacturing software like Computer-Aided Engineering (CAE) and Computer-Aided Manufacturing (CAM). Modern CAD supports Reverse Engineering, allowing real objects to be scanned and virtually replicated for accuracy checks. Additionally, it can connect to IoT devices for real-time design, inspection, and production progress monitoring, making it a valuable and interesting tool [9, 10].

The research team aims to design and develop a device to assist disabled individuals using conventional wheelchairs in climbing stairs. The device, which attaches to the back of a standard wheelchair, is designed to be portable, compact, low-cost, safe, and user-friendly. The stair-climbing wheelchair prototype will be designed using CAD. Once the prototype's performance is evaluated successfully on the computer, it will be constructed and tested for practical use. Upon completion of this research, the prototype can be further developed for commercial production.

2. Literature Review

Related research on Development and Prototyping of a Stair-Climbing Wheelchair for Lower Limb Disabled Individuals To be a guideline for developing the research to be created, the researcher has summarized the content of related research as shown in Table 1.

Table 1.
Details on the materials and equipment used in the research

Title	Short Summary	Reference
Design and Prototype a Stair-Climbing Wheelchair	This research proposes two new designs to increase the stair-climbing capability of electric wheelchairs. One concept is to use a curved spoke mechanism that can be transformed from a round wheel to a tricycle mechanism, allowing movement on flat ground and up stairs. The other concept is to use a tricycle mechanism with a planetary gear, which provides a unique stair-climbing capability. After analyzing the advantages and disadvantages of each concept, a tricycle mechanism with a planetary gear was selected for small-scale prototype construction and testing of the power transmission system on stairs. The prototype successfully moved up and down stairs in the stair-climbing mode and moved on flat or inclined ground in the translation mode.	Smith and Brown [11]
Design and Analysis of a Stair Climbing Wheel Chair	This research focuses on the design and analysis of a wheelchair capable of climbing stairs. Using a mechanism that allows disabled people to climb and descend stairs safely and efficiently.	Patel and Sharma [12]
Modeling and Design of a Stair Climbing Wheelchair with Pose	This research presents a new mechanism design for a wheelchair that can climb stairs, using a crawler system and posture control to	Nakamura, et al. [13]

Title	Short Summary	Reference
Control	make it smooth and safe to climb and descend stairs.	
Development of Stair Climbing Wheelchair with Legs and Wheels System	This study focuses on the development of a wheelchair that can climb stairs, using a system that combines legs and wheels, to assist disabled people with disabilities. This report describes the wheelchair's leg mechanism, principles for climbing and descending stairs. And the design of the prototype of the wheelchair.	Tanaka, et al. [14]
Design and Development of Multipurpose Wheelchair	This research aims to improve the quality of life of disabled people with lower extremities by enabling wheelchairs to climb stairs with the help of a single assistant. The designed stair-climbing system consists of 5 wheels and a slide plate. The 5 wheels are used for climbing stairs, and the slide plate is used to move the rear wheels of the wheelchair.	Verma, et al. [15]
Development and Practical Application of a Stair-Climbing Wheelchair	This research focuses on developing a wheelchair that can climb stairs. Using a two-part centipede system that can efficiently adapt to climb and descend large stairs.	Lawn and Sakai [16]
A Novel Approach for a Leg-Based Stair-Climbing Wheelchair	This research aims to develop a low-cost wheelchair that can climb stairs (according to Spanish building regulations), cross obstacles similar to steps, move on uneven surfaces such as cobblestone roads, and adjust the seat height.	Pereira, et al. [17]
Development of a Stair-Climbing Wheelchair Using a Wheel-Leg Mechanism	This research focuses on developing a wheelchair that can climb stairs using a mechanism that combines wheels and legs. To enable efficient movement on uneven surfaces and climbing stairs.	Shibaura [18]

3. Methodology

Under the research methodology section, the subtopics include: 3.1. Details on the materials and equipment used in the research, and 3.2. The design, development, and prototyping of a stair-climbing wheelchair for individuals with lower limb disabilities.

3.1. Details on the Materials and Equipment Used in the Research

The equipment used in the development of the stair-climbing wheelchair prototype for individuals with lower limb disabilities includes the following details in Table 2.

Table 2.
Details on the materials and equipment used in the research.

Details on the materials and equipment	Unit
1. Wheelchair	1
2. Stair-climbing wheelchair kit	1
3. Inverter	1
4. Battery	1
5. Battery charger	1
6. Operation control box	1
7. Electrical control box	1

3.2. The Design, Development, And Prototyping of a Stair-Climbing Wheelchair for Individuals With Lower Limb Disabilities

3.2.1. Calculation of Various Important Parameters

Research and study details about wheelchairs, including design structure and suitable materials for construction. Gather information on existing stair-climbing wheelchair kits from both domestic and international sources to use as references for the development, design, and construction of the stair-climbing wheelchair kit, as well as various calculation formulas. The details are as follows:

3.2.2. Calculation of Torque

The method for calculating the torque to select the gear reducer and 220 V electric motor for the stair-climbing wheelchair kit includes the following weight details needed for the calculation shown in Table 3.

Table 3.
Weight details needed for the calculation.

Type of Weight	Weight (Kg)
Weight of the structure	60 kilograms
Weight of the wheelchair	8 kilograms
Weight of the person	80 kilograms
Total weight	148 kilograms

*** Note:** In the case of wanting to climb stairs 4 steps per minute, refer to the gear reduction and motor selection table.

- The calculated torque values are shown in Equation 1.

$$T = \frac{F \times r}{N} \quad (1)$$

When F is force(N), r is the radius of the stair-climbing leg (m) and N is the number of steps.

$$T = \frac{(148kg \times 9.81m/s^2 \times 0.167m)}{4}$$

$$T = 60.615\ Nm$$

- Calculation of maximum speed (V) Find the maximum speed as shown in Equation 2.

$$Speed = \frac{N \times t}{W} \quad (2)$$

When t is times (s) and, W is the weight of the structure.

$$Speed = \frac{4 \times 0.3}{60} = 0.02m/s$$

- The calculation of angular speed is shown by Equation 3.

$$\omega = \frac{V}{r} \quad (3)$$

When ω is the angular speed.

$$\omega = \frac{0.02}{0.167} = 0.119 rad/s$$

The conversion of angular speed to revolutions per second is equal to 1.136 rpm.

- The calculation of motor size is shown by Equation 4.

$$Horsepower\left(Hp\right) = \frac{safetyfactor \times 2\pi \times T \times rpm}{60 \times 746} \quad (4)$$

Use a safety factor of 1.6 to prevent vibrations.

$$Horsepower\left(Hp\right) = \frac{1.6 \times 2\pi \times 60.615 \times 1.136}{60 \times 746}$$

$$Horsepower\left(Hp\right) = 0.007$$

Therefore, use a motor size of 1/2 horsepower (Hp).

- Calculation of required battery size

The method to determine the required battery size is calculated using Equation 5, with details of the required battery size used in the calculation as shown in Table 4.

$$P = V \times I \quad (5)$$

When P is power (W), V is voltage(V) and, I is current (A).

Table 4.
The details of the required battery size used in the calculation.

Characteristic of battery
1. The battery has a voltage of 12 V
2. Battery capacity 50 Ah
3. Electric motor 370 W

From Table 4, the parameter values are used to calculate power:
Power Calculation:

P = 12 V×50 Ah = 600 Wh

Battery Usage Time:

$$= \frac{Battery\ capacity\ (Wh)}{Load\ (W)} = \frac{600\ (Wh)}{370\ (W)}$$

= 1.621 hours ≈ 1hour and 40 minutes

3.2.3. Analysis of 2D Equilibrium Free Body Diagrams

The forces involved in a Free Body Diagram (FBD) consist of three main components:

1. Forces due to the weight of the object
2. Forces due to external actions
3. Forces from supports (reaction forces)

The analysis of reaction loads is illustrated in Figure 1.

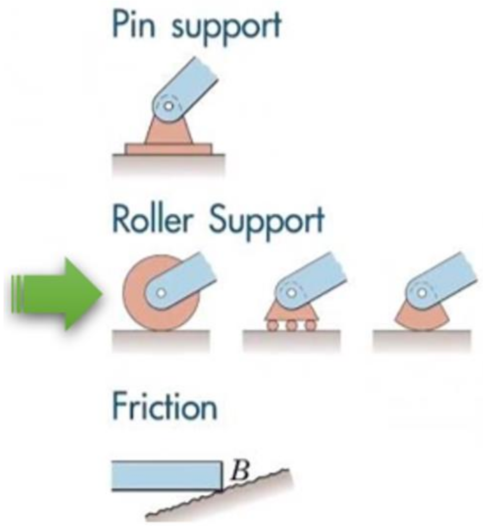

Figure 1.
Reaction Load.

Writing 2D Equilibrium (Free Body Diagrams)

From the reaction load diagram, the support is a roller support, characterized by a force acting perpendicular to the surface. This type of support allows horizontal movement along the X-axis but restricts movement along the Y-axis. As a result, a perpendicular reaction force, denoted as N (Normal), is exerted at the support.

The analysis of the Free Body Diagram involves a simulation where a student represents a test subject seated in a wheelchair moving up and down the stairs. In the first test example:

Weight of the person: 65 kg

Weight of the structure: 60 kg

Weight of the wheelchair: 8 kg

Total load acting at point G: 133kg

The support points C and D are free of ground forces. The focus of the analysis is to determine the vertical force required to lift the wheelchair up and down the stairs.

The 2D Equilibrium Free Body Diagram is illustrated in Figure 2.

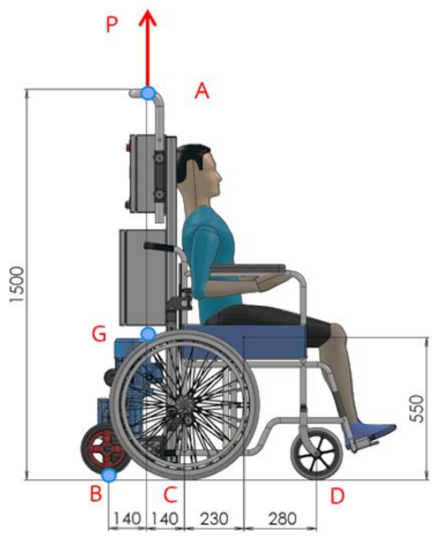

Figure 2.
2D Equilibrium (Free body Diagrams).

3.2.4. Design of a Stair-Climbing Wheelchair

The prototype design for the development of a stair-climbing wheelchair was created using CAD technology with the SolidWorks® software. Upon completing the design process, the stair-climbing wheelchair model was generated and is illustrated in Figure 3.

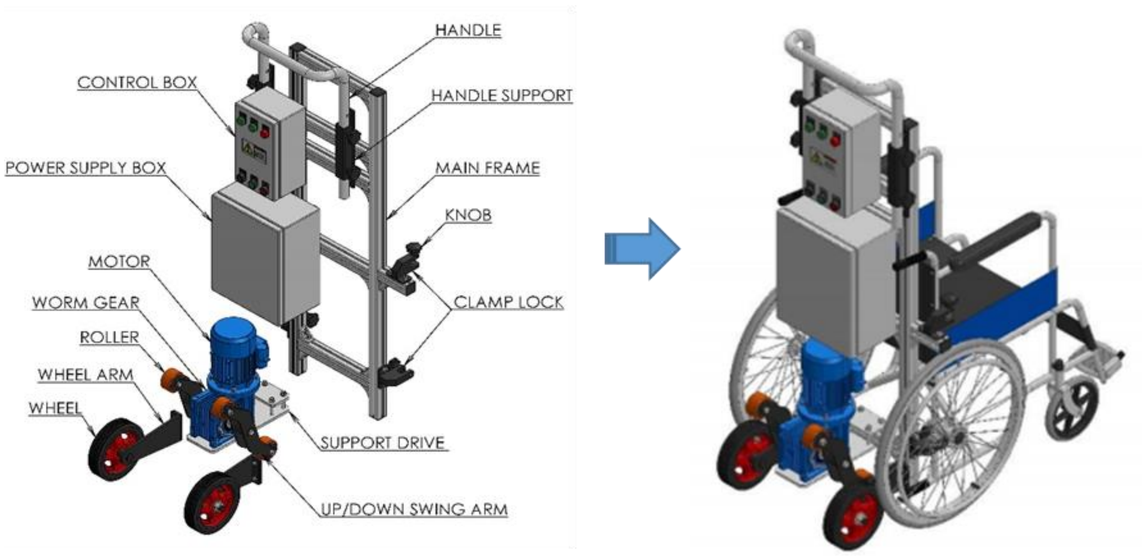

Figure 3.
Design of the Stair-Climbing Wheelchair Structure.

3.2.5. Electrical and Control System Integration

The circuit diagram for the control system is presented in Figure 4, detailing the connections and components of the control circuitry.

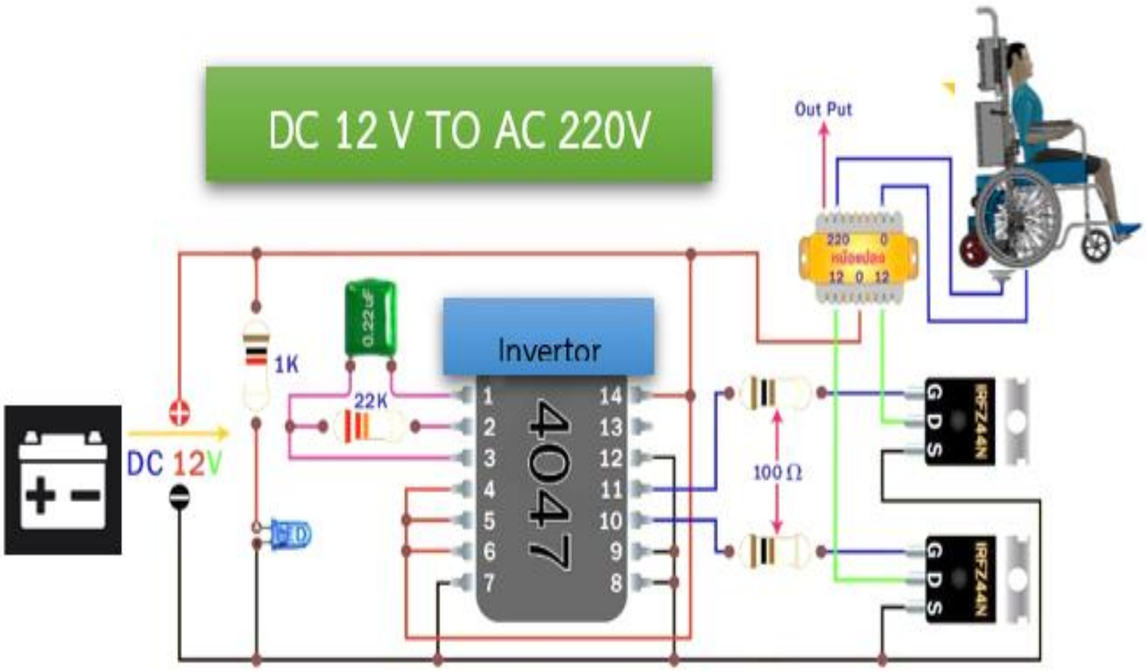

Figure 4.
Circuit Diagram for the control system of the Stair-Climbing Wheelchair Structure

The Control Box is a device designed to manage the electrical current within the system and divide control into sub-circuits. It provides safety measures against short circuits and overcurrent while ensuring proper operation. The Control Box structure is depicted in Figure 5, and the control circuit diagram is shown in Figure 6, providing a detailed representation of the system's wiring and connections for effective functionality and safety.

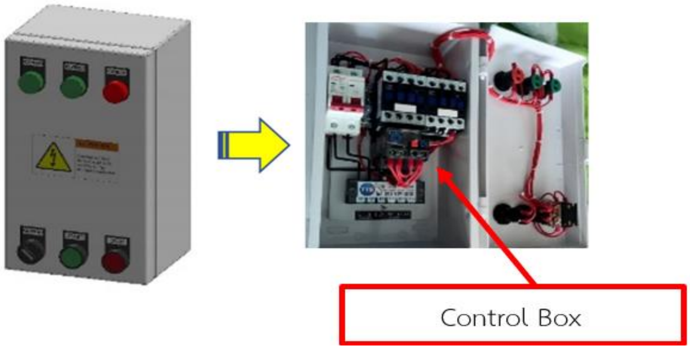

Figure 5.
Control Box Circuit of the Stair-Climbing Wheelchair Structure.

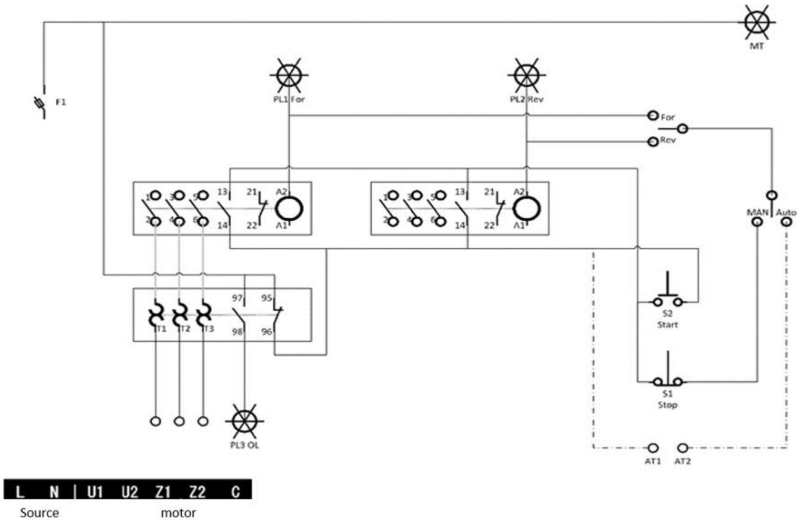

Figure 6.
Control Box Circuit Diagram of the Stair-Climbing Wheelchair Structure

The Power Supply Box houses a 12.6V 50Ah lithium-ion battery, which is connected to a 1000W SUOER Pure Sine Wave Inverter (FPC-1000A). The inverter's primary function is to convert the direct current (DC) from the battery into alternating current (AC), which is required to power the electric motor. This AC power is then used to drive the gearbox for the operational movement of the wheelchair.

The Power Supply Box design is shown in Figure 7, while the circuit diagram of the inverter system is illustrated in Figure 8, providing a detailed representation of how the electrical components work together to power the stair-climbing wheelchair.

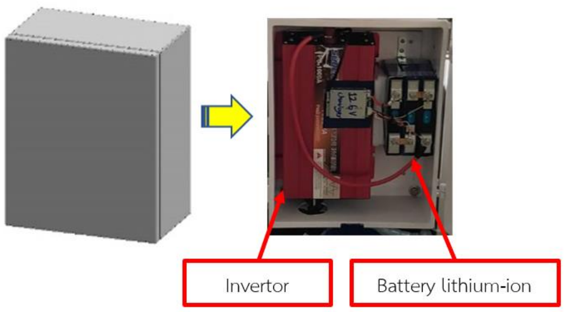

Figure 7.
Power Supply Box.

Figure 8.
Circuit diagram of the inverter system of the Stair-Climbing Wheelchair Structure.

Analyze the structural strength of the wheelchair up-and-down stairs using CAD technology to simulate the movement of the wheelchair up-and-down stairs and perform a simulation of the operation of the wheelchair up-and-down stairs, allowing for precise design of parts. If any errors are found, they can be corrected before creating a prototype.

Create a prototype of the wheelchair up-and-down stairs by starting with creating a structure that looks like the design in the SolidWorks® program, as shown in Figure 9. After creating the prototype, proceed to check the prototype creation in the next step.

a. b.

Figure 9.
The prototype of the wheelchair up-and-down stairs that has been developed.
Note: a. Front of the prototype of the wheelchair up-and-down stairs.
b. Back of the prototype of the wheelchair up-and-down stairs.

3.3. Check the Integrity of the Wheelchair Up-and-Down Stairs.

Check the prototype creation by examining various fastening points in the workpiece, all welds in the workpiece, assessing the strength of the structure, and ensuring safety by checking the electrical system, the control system, and everything else. If any errors are found, correct the workpiece before testing its actual efficiency.

3.3.1. Test The Efficiency of Use.

The experiment was repeated five times, and the data was recorded for all five instances to summarize the actual performance of the stair-climbing wheelchair. The stair-climbing characteristics are shown in Figure 5.

4. Result and Discussion

4.1. The testing wheelchair Stair Climbing Capability Characteristics

The testing of a stair-climbing wheelchair powered by a lithium battery was conducted based on the conditions shown in Figure 10.

The test was divided into three cases:

Case 1: The user weighs 65 kg, the structural weight is 60 kg, and the wheelchair weight is 8 kg, resulting in a total weight of 133 kg.

Case 2: The user weighs 70 kg, the structural weight is 60 kg, and the wheelchair weight is 8 kg, resulting in a total weight of 138 kg.

Case 3: The user weighs 81 kg, the structural weight is 60 kg, and the wheelchair weight is 8 kg, resulting in a total weight of 149 kg.

The testing was carried out at the Faculty of Engineering building, Bangkok Thonburi University, Thailand. A total of 5 tests were performed. The results are presented in Table 5.

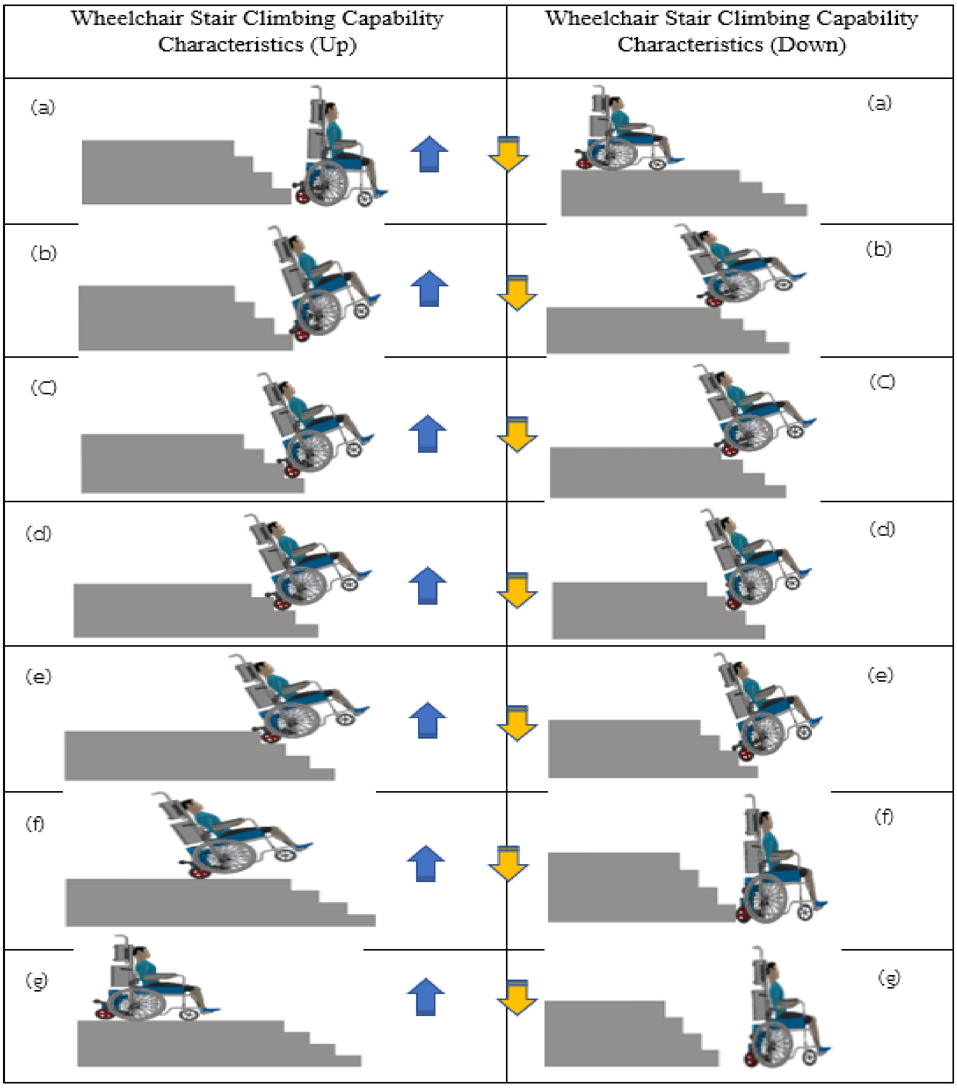

Figure 10.
Wheelchair Stair Climbing Capability Characteristics.

Table 5.
Activity and Test Results.

Activity	**1**	**2**	**3**	**4**	**5**	**Summary**
1. Stair-climbing test for user 1: User weight: 65 kg, structure weight: 60 kg, wheelchair weight: 8 kg, total weight: 133 kg.	✓	✓	✓	✓	✓	Passed
2. Stair-climbing test for user 2: User weight: 70 kg, structure weight: 60 kg, wheelchair weight: 8 kg, total weight: 138 kg.	✓	✓	✓	✓	✓	Passed
3. Stair-climbing test for user 3: User weight: 81 kg, structure weight: 60 kg, wheelchair weight: 8 kg, total weight: 149 kg.	x	x	x	x	x	Failed
4. Stair-descending test for user 1: User weight: 65 kg, structure weight: 60 kg, wheelchair weight: 8 kg, total weight: 133 kg.	✓	✓	✓	✓	✓	Passed
5. Stair-descending test for user 2: User weight: 70 kg, structure weight: 60 kg, wheelchair weight: 8 kg, total weight: 138 kg.	✓	✓	✓	✓	✓	Passed
6. Stair-descending test for user 3: User weight: 81 kg, structure weight: 60 kg, wheelchair weight: 8 kg, total weight: 149 kg.	x	x	x	x	x	Failed
7. Charging duration test: One cycle (12.5V, 50Ah) within 3 hours.	✓	✓	✓	✓	✓	Passed

From the results of five experiments with different weights, arranged from most to least, using the criteria for testing going down the stairs, the first person weighs 65 kg, the structure weighs 60 kg, the wheelchair weighs 8 kg, resulting in a total weight of 133 kg. The second person weighs 70 kg, the structure weighs 60 kg, the wheelchair weighs 8 kg, resulting in a total weight of 138 kg. The third person weighs 81 kg, the structure weighs 60 kg, the wheelchair weighs 8 kg, resulting in a total weight of 149 kg. The timing for going down eight steps of stairs from the ground until reaching the resting point was recorded. The experimental results found that in the case of person 1, who weighed a total of 133 kg, it took an average of 33.24 seconds to go down the stairs quickly. In the case of person 2, who weighed a total of 138 kg, it took an average of 36.40 seconds to go down the stairs quickly. In the case of person 3, who weighed a total of 149 kg, it was unable to go down the stairs because the weight was too high (the design specified that the user's weight should not exceed 70 kg), causing the control box to display the operation of the red switch button above as an overload warning.

4.2. Satisfaction Testing for the Use of the Stair-Climbing and Descending Wheelchair

The user satisfaction test was conducted with a sample group to evaluate the usability of the stair-climbing and descending wheelchair. The sample group consisted of 3 males and 2 females. The participants assessed the wheelchair's efficiency and rated their satisfaction using a Likert scale [19] as follows:

1: Very dissatisfied
2: Somewhat dissatisfied
3: Neutral
4: Somewhat satisfied
5: Very satisfied

The results of the evaluation are presented in Table 6.

Table 6.
User Satisfaction Testing (n=5).

Category	Tester Scores					Average Score	SD
	1	2	3	4	5		
1. Usability							
1.1 Speed of movement	5	5	5	4	4	4.6	0.55
1.2 Suitability for all-day use	5	5	5	5	5	5.0	0
1.3 Simplicity and flexibility in operation	4	4	5	5	4	4.4	0.55
1.4 Self-installation capability	3	3	3	4	4	3.4	0.55
1.5 Ease of use and assembly	4	3	4	3	4	3.6	0.55
1.6 Suitability for Mobility	5	5	4	4	5	4.6	0.55
Average (Usability)						4.27	0.63
2. Design and Appearance							
2.1 Modern and attractive design	5	5	4	5	4	4.6	0.55
2.2 Material appropriateness	5	4	4	4	5	4.4	0.55
2.3 Suitability for disabled users	4	5	5	5	4	4.6	0.55
2.4 Structure safety and fit	3	3	3	4	4	3.4	0.55
2.5 Structural durability	5	4	5	5	4	4.6	0.55
Average (Design)						4.32	0.52
3. Cost and Material Suitability							
3.1 Cost of development		5	5	5	5	5	5.0
3.2 Material durability		4	5	4	5	4	4.4
3.3 Market price comparison		5	5	5	5	5	5.0
3.4 Ease of maintenance		5	5	5	5	5	5.0
3.5 Quality and modernity		5	5	4	4	5	4.8
3.6 Social integration		5	5	5	4	4	4.8
3.7 Overall satisfaction		4	4	4	4	4	4.0
Average (Cost)						4.71	0.38

From the results of the satisfaction assessment for testing the stair-climbing wheelchair set, it was found that the highest satisfaction score was in the categories of suitability, price, and materials, with an average score of 4.7. The operational procedure category received an average score of 4.4, which is considered moderate, while the design and appearance category received the lowest average score of 4.3. Specifically, the bar graph indicates that the suitability and price categories scored 4.7, showing the highest user satisfaction compared to imported products, which are significantly more expensive.

For the operational procedure category, the score of 4.4 reflects moderate satisfaction, mainly due to the lengthy time required to install the stair-climbing wheelchair set onto a standard wheelchair. The design and appearance category received the lowest score of 4.3, indicating a need for further development in aesthetics and modernity.

In summary, the satisfaction assessment for the stair-climbing wheelchair set showed a maximum score of 5.00, a minimum score of 3.46, an average score of 4.46, and a standard deviation of 0.52. The relatively low standard deviation suggests a consistent level of feedback; however, improvements should focus on usability and design.

The most critical factor contributing to the lowest scores is safety concerns for disabled users. Specifically, the lack of a safety belt installation in the stair-climbing wheelchair set significantly impacts user confidence during testing.

5. Conclusion

The current problem is that the import of medical equipment from abroad for the disabled is expensive. Therefore, the idea is to create equipment that helps disabled individuals with physical movement issues to go up and down stairs like normal people by developing a set of wheelchairs designed for this purpose. The process begins with researching the fundamentals of wheelchairs and the design structure of the stair-climbing wheelchair set using CAD technology for simulation and analysis. The strength of the structure is evaluated with CAE technology using the FEA method as designed. Once the prototype is complete, various fixing points are checked, and the electrical system is ensured to be safe. Then, testing of the efficiency of actual use begins.

The efficiency test of the wheelchair set to go up and down the stairs can be summarized, and the recommendations are as follows: Summary of the results of the wheelchair ability test to go up the stairs (Up) and the results of the wheelchair ability test to go down the stairs (Down) passed all 5 tests. Case 1: Weight + machine total 133 kg. Case 2: Weight + machine total 138 kg. Can go up the stairs normally. Case 3: Weight + machine total 149 kg. Cannot go up the stairs because the weight is too high. From the test results of the wheelchair to go down the stairs, it was shown that Case 1 had a total weight of 133 kg. Case 2 had a total weight of 138 kg, which is approximately 5 kg apart. It can be seen that the time it takes for the wheelchair to move up and down the stairs is significantly different. In the case of the wheelchair going up the stairs (Up), the maximum speed is approximately (Min) 4.84 seconds, and it is clearly seen in the case of the wheelchair going down the stairs (Down) with a maximum speed of approximately (Min) 5.02 seconds. In Case 3, the total weight is 149 kg, which is more than the load for the speed reduction motor to work. Therefore, the control box displays the operation of the red switch above to warn of overload. The analysis of the SD or Standard Deviation value shows that each data point has an unequal distribution, and the time is clearly different. The problem is that the SD value has a minimum value of 0.07 because the weights in the test are too far apart, causing the SD value to be not as good as the standard value, which must be greater than 1. The satisfaction assessment result of the wheelchair use test for going up and down the stairs is at a very satisfactory level.

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