A Prototype of a Stair-Climbing System for a Wheelchair

Ekachai Chaichanasiri* and Teerapol Puangumpan

Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Nakornpathom, Thailand 73170

*Corresponding Author: teecc@mahidol.ac.th, Telephone 662 8892138 ext. 6409, Fax. 662 8892138 ext. 6429

Abstract

In general, lower limb disabled people do their daily activities on wheelchairs. The disabled people encounter difficulties when they have to ascend or descend the stairs. For example, enter or exit buildings that have no ramps, go up or down in buildings that have no elevators or cross pedestrian bridges. For these situations, many assistants are required to carry a lower limb disabled person and a wheelchair. This leads to a risk of injury for both the disabled person and the assistants. Therefore, this research presented a prototype of a stair-climbing system for a wheelchair. This research was aimed to enhance the quality of life for the lower limb disabled people by enabling the wheelchair to climb the stairs with only one assistant to control the wheelchair. The designed stair-climbing system consisted of two 5-spokes wheels and the slot plates. The 5-spokes wheels were used for climbing the stairs. The slot plates were used for sliding the rear wheels of the wheelchair. The 5-spokes wheels were installed at the rear of the wheelchair and were driven by power from an electric motor. When climbing the stair, the rear wheels were slid to the front of the wheelchair. To move on the floor, the rear wheels were slid back to the rear of the wheelchair. From test results, the wheelchair with the stair-climbing system could ascend and descend the stairs with the maximum riser height of 200 mm. The maximum payload was 80 kg. The stair-climbing system could reduce the number of the assistants to only one person and the wheelchair could still move on the floor as a general wheelchair.

Key words: Wheelchair, Stair-climbing system, Lower limb, Disability, Mechanical design

1. Introduction

In general, lower limb disabled people do their daily activities on wheelchairs. Although there are many facilities for the disabled people, the facilities still not cover in every place. Many times, the disabled people encounter difficulties when they have to ascend or descend the stairs. For example, enter or exit buildings that have no ramps, go up or down in buildings that have no elevators or cross pedestrian bridges. For these situations, many assistants are required to carry a lower limb disabled person and a wheelchair. However, this leads to a risk of injury for both the disabled person and the assistants. As a result, there are a number of researches about a stair-climbing wheelchair to help the disabled people. For example, Watkins [1] designed a customized stair-climbing wheelchair which used a sensor to detect a stair and a caterpillar track to climb the stair. Lawn et al [2] developed a dual section caterpillar track stair-climbing wheelchair. It could climb the twisting and irregular stairs. Wellman et al [3] designed a wheelchair equipped with two legs. The leg was used to walk like a human to climb the stair. Lawn and Ishimatsu [4] developed a stair-climbing wheelchair mechanism with high single step capability. The mechanism consisted of front and rear wheel clusters attached to powered linkages. Johnson & Johnson company [5] produced the powered wheelchair iBOT which equipped with many sensors and could climb the stair using four wheels. Although these systems could help the disabled people when climbing the stairs. Nevertheless, these systems were very complex and difficult to maintain.

Therefore, this research was aimed to provide an alternative and enhance the quality of life for the lower limb disabled people by enabling the wheelchair to climb the stairs using a simple system with only one assistant to control the wheelchair. A prototype of a stair-climbing system for a wheelchair was created and tested in this study.

2. Materials and Methods

In this research, the prototype of a stair-climbing system was designed to attach to general unfoldable wheelchairs. This concept had an advantage since it was more convenient than creating a customized wheelchair. In addition, it could be applied to other sizes of wheelchairs. Figure 1 shows a wheelchair used in this study before attached with a stair-climbing system. A spoke wheel was selected for climbing the stair because it was lighter and easier to maintain than a caterpillar track. The spoke wheel was designed to climb the stair that had the maximum riser height of 200 mm and minimum tread depth of 220 mm as shown in Fig. 2. These values were based on the Bangkok regulation on the building construction control B.E. 2544. The spoke wheel was designed to install at the rear of the wheelchair below the seat. Therefore, the diameter of the spoke wheel used in this research was 400 mm due to available space between the wheelchair seat and the floor. In order to select the appropriate number of spokes, the wheels from 3-spokes to 6-spokes with the diameter of 400 mm were studied as shown in Figs. 3-5.

Fig. 1 Wheelchair before attached with a stair-climbing system

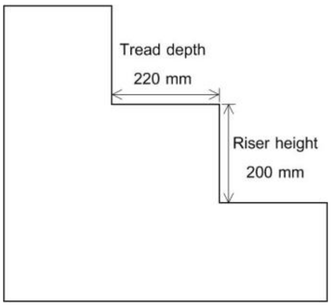

Fig. 2 Stair riser height and tread depth used for designing a spoke wheel

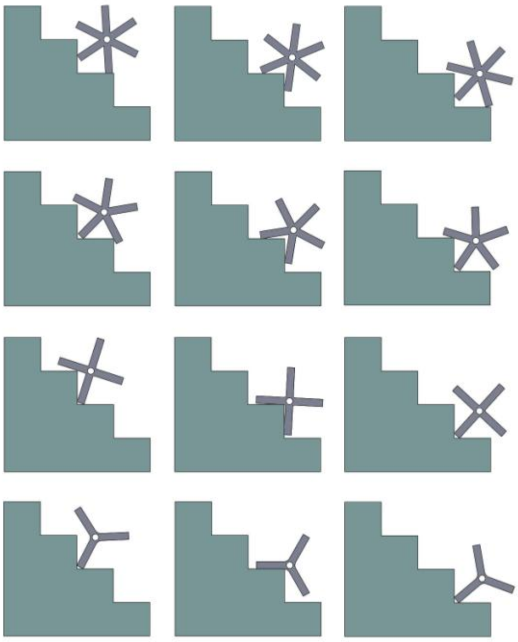

Fig. 3 Motion of spoke wheels

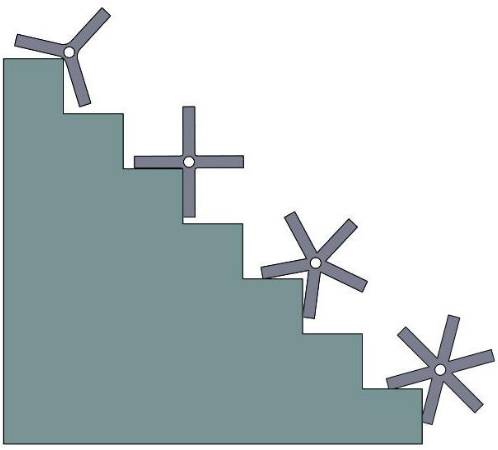

Fig. 4 Comparison for number of wheel spokes

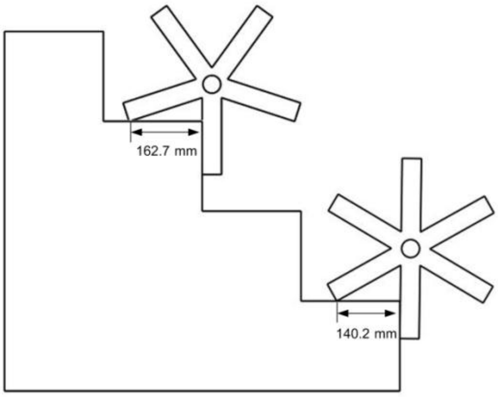

Fig. 5 Comparison of contact depth

From Fig. 3, the smoothness for the stair-climbing increased when number of spokes increased. However, more number of spokes will increase the weight of the wheel. In Fig. 4, the 3-spokes and 4-spokes wheels had the possibility to strike the stair while the 5-spokes and 6-spokes had no possibility. Thus the 3-spokes and 4-spokes wheels were not appropriate for the stair-climbing system. From Fig. 5, it could be observed that the 5-spokes wheel was more stable than the 6-spokes wheel because the 5-spokes wheel had a contact depth longer than the 6-spokes wheel. Therefore, it could be concluded that the 5-spokes wheel was the most appropriate for the stair-climbing system.

The stair-climbing system must be able to support the weights of the disabled person, the wheelchair and the stair-climbing system itself. The maximum weight of the disabled person was 80 kg. The weight of the wheelchair was 28.4 kg and the weight of the stair-climbing system was approximated as 40 kg. Two 5-spokes wheels installed on both sides of the wheelchair were used for climbing the stair. The 5-spokes wheel was made of SS400 steel plate with the thickness of 4 mm. The strength of the 5-spokes wheel was analyzed by finite element (FE) method. The FE analysis was performed using Solidworks Simulation program. The material properties of the SS400 steel were shown in Table. 1. The material was assumed to be isotropic linear elastic. Four-noded tetrahedral elements were used to construct the FE model. A mesh convergence study was performed to determine the mesh refinement level necessary. The FE model consisted of 86,599 elements and 151,099 nodes (Fig. 6). The displacements of nodes at the hub of the 5-spokes wheel were fixed. The worst-case scenario was simulated which was the case that only one spoke of each wheel was in contact with the stair. The safety factor of 2 was used for the applied force. The two 5-spokes wheels were assumed to share the load equally. Therefore, the force of 1,455.8 N was applied at the tip of the spoke. The von

Table. 1 Material properties of SS400 steel [6]

Young's Modulus	206,900 MPa
Poisson's ratio	0.3
Yield stress	338 MPa

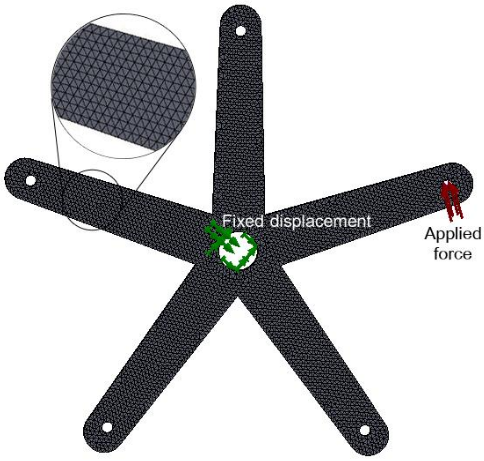

Fig. 6 FE model of the 5-spokes wheel

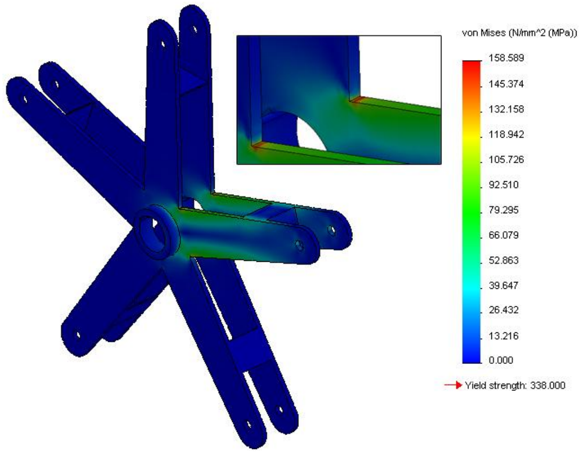

Fig. 7 Stress distribution of the 5-spokes wheel

Mises stress distribution was analyzed to examine the strength of the 5-spokes wheel. Figure 7 shows the von Mises stress distribution of the 5-spokes wheel. It could be observed that high stress occurred at the root of the spoke. The maximum stress was 158.589 MPa that was less than the yield stress of the SS400 steel. Therefore, the designed 5-spokes wheel had sufficient strength for climbing the stair.

The 5-spokes wheels were installed at the rear of the wheelchair. During climbing the stair, the rear of the wheelchair faced the stair. Both rear wheels of the wheelchair will interfere with the stair steps. Therefore, each rear wheel was designed to be slid to the front the wheelchair through a slot plate as shown in Fig. 8. The shape of the slot was the mirrored "N" to lock the rear wheel when it was at the front or rear of the wheelchair. To climb the stair, the rear wheel was slid to the front of the wheelchair as shown in Fig. 9. Note that the 5-spokes wheels and a left rear wheel were omitted from this figure for clarity.

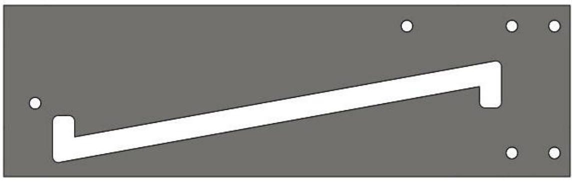

Fig. 8 Slot plate

Fig. 9 Sliding of a right rear wheel of a wheelchair

A driving unit was installed behind the backrest. The two 5-spokes wheels were driven by power from a DC motor. The rechargeable batteries were attached near the front wheels below the wheelchair seat to provide a balance when moving on the floor. Safety was the most important in using the stair-climbing wheelchair. Therefore, the wheelchair was equipped with a safety belt, a cover, an emergency switch and brakes as shown in Fig. 10. The safety belt was installed at the backrest of the wheelchair. The cover was used to protect the driving unit from jamming. The emergency switch was attached at the side of the cover. The brakes were installed on both sides of the wheelchair. A retractable handle was attached behind the backrest to provide a grip for an assistant when climbing the stair. In order to ascend or descend the stair, the assistant had to turn on the system by the on/off switch and then release the emergency switch. The assistant could select either to ascend or descend the stair by a directional switch that situated behind the backrest.

Fig.10 Wheelchair equipped with the stair-climbing system

3. Results and Discussion

The stair-climbing system was tested with the building stairs and pedestrian bridge stair. The sizes of the stairs were shown in Table. 2. The payload tested was from 50 to 90 kg. The stair-climbing system was tested two times per stair. From the results, when the payload was not over 80 kg, the stair-climbing system could climb all tested stairs. The test results of building stair A and the pedestrian bridge stair were shown in Tables. 3 and 4, respectively. From the tables, when the payload was over 80 kg, the motor did not have enough torque to drive the 5-spokes wheels for ascending the stairs. However, it still could descend the

Table. 2 Dimension of tested stairs

Stairs	Riser height (mm)	Tread depth (mm)
Building stair A	140	400
Building stair B	180	320
Building stair C	200	300

Building stair D	160	360
Pedestrian bridge stair	170	260

Table. 3 Test results of the building stair A

Weight (kg)	First test		Second test	
	Ascend	Descend	Ascend	Descend
50	Pass	Pass	Pass	Pass
55	Pass	Pass	Pass	Pass
60	Pass	Pass	Pass	Pass
65	Pass	Pass	Pass	Pass
70	Pass	Pass	Pass	Pass
75	Pass	Pass	Pass	Pass
80	Pass	Pass	Pass	Pass
85	Fail	Pass	Fail	Pass
90	Fail	Pass	Fail	Pass

Table. 4 Test results of the pedestrian bridge stair

Weight (kg)	First test		Second test	
	Ascend	Descend	Ascend	Descend
50	Pass	Pass	Pass	Pass
55	Pass	Pass	Pass	Pass
60	Pass	Pass	Pass	Pass
65	Pass	Pass	Pass	Pass
70	Pass	Pass	Pass	Pass
75	Pass	Pass	Pass	Pass
80	Pass	Pass	Pass	Pass
85	Fail	Pass	Fail	Pass
90	Fail	Pass	Fail	Pass

(a) (b)

Fig. 11 Testing of the stair-climbing system: (a) Building stair A, (b) Pedestrian bridge stair

stairs. Only one assistant was used to control the wheelchair as shown in Fig. 11. Before climbing the stairs, the assistant slid the rear wheels from their original positions at the rear to the front of the wheelchair one by one while the person was sitting on the wheelchair. A moving of the stair-climbing system on the floor was also tested. The tests were conducted with and without an assistant as shown in Fig. 12. The test results were shown in Table. 5. From the table, when the payload was over 85 kg, the rear wheels could not be rotated. This was due to the alignment of the rear wheels changed.

(a) (b)

Fig. 12 Testing of the stair-climbing system when moving on the floor: (a) With an assistant, (b) Without an assistant

Table. 5 Test results of the stair-climbing system when moving on the floor

Weight (kg)	First test		Second test	
	With an assistant	Without an assistant	With an assistant	Without an assistant
50	Pass	Pass	Pass	Pass
55	Pass	Pass	Pass	Pass

60	Pass	Pass	Pass	Pass
65	Pass	Pass	Pass	Pass
70	Pass	Pass	Pass	Pass
75	Pass	Pass	Pass	Pass
80	Pass	Pass	Pass	Pass
85	Pass	Pass	Pass	Pass
90	Fail	Fail	Fail	Fail

4. Conclusion

In this research, the prototype of a stair-climbing system for a wheelchair was designed based on simplicity and easy maintenance. The 5-spokes wheels were used for the stair-climbing system. From the results, the system could ascend and descend the stairs with the maximum riser height of 200 mm. Only one assistant was required to control the wheelchair. It could also move on the floor as a general wheelchair. The maximum payload was 80 kg. The sliding of the rear wheels of the wheelchair will be improved to enable the assistant to slide both rear wheels simultaneously. This will reduce the time required for sliding the rear wheels.

5. Acknowledgement

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