Development of a Wheelchair with a Lifting Function

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Abstract: A wheelchair with a lifting function is designed to assist a caregiver when transferring a wheelchair user not only indoors but also outdoors. The target user is typically a severely disabled person with disabled upper and lower limbs, and therefore needs the physical support when using a toilet or transferring from a bed to a wheelchair and so forth. Both the wheelchair and the lift are driven by their respective motors. The user can approach above the toilet stool or the bed from the rear because the large driving wheels are located in front of the body and the seat can be folded. This wheelchair is allowed to travel on public roads because of the mechanism of folding the frame for lifting. This paper presents the concept design and the experimental results of a full-sized prototype wheelchair with the lifting function, which confirms the design effectiveness.

1 INTRODUCTION

Persons with disabilities attributable to the lower limbs are becoming increasingly numerous worldwide. In Japan, they number about 3,480,000 (severely disabled persons were about 760,000) in 2006. Most of them use wheelchairs in daily life. Representative nursing care in daily life entails basing, evacuating, and feeding. Transfer when basing, evacuating, and other processes causes back pain to caregivers. Matsumoto et al. reported that 77% of caregivers and 64% of nurses have back pain (Matsumoto and Kusunose, 1999). Consequently, various devices and robots have been developed. Molift Inc. developed the “Quick Raiser 2”, which lifts a user with a linear actuator and supports the standing-up and seating motions (Molift, 2012). Sankai proposed some exoskeleton-type power-assisted systems using electric motors and air actuators (Satoh et al., 2009). Bostelman et al. developed a robot system that a user himself wears and enables him to use a toilet, a bed, and so forth (Bostelman and Albus, 2007). A caregiver robot “RI-MAN” developed at RIKEN is aimed at realizing autonomous motion transfer (Onishi et al., 2007). Some of those tools and robots are, however, expensive and are limited for use in indoor environments.

We take notice of a transfer tool that can be used even when going away. Similar to some commercial transfer products, “Komawari-san” is a simple tool based on lever principles (HEARTS-EIKO, 2012). These tools, however, are too large and heavy to carry over long distances. “RODEM” is a new type of electric wheelchair on which the user can ride from the backside and which can run outdoors, but the target is limited to mild patients (VEDA, 2012).

This paper presents a wheelchair with a lifting function that is intended mainly for use by an electric wheelchair user with disabled upper and lower limbs. This equipment has good maneuverability. Moreover, it can move over a step because of the front driving wheels. It realizes easy and safe transfer from/to a bed and a toilet stool by virtue of the opposite wheel allocation of a usual wheelchair. Furthermore, the mechanism of folding the frame for lifting allows this wheelchair to travel on public roads. We demonstrate its design effectiveness through several indoor and outdoor experiments.

2 CONCEPTUAL DESIGN

We assume a single caregiver for the use of this wheelchair. It helps alleviate the burden of the caregiver when a disabled person moves between the wheelchair and toilet/bed easily and safely.

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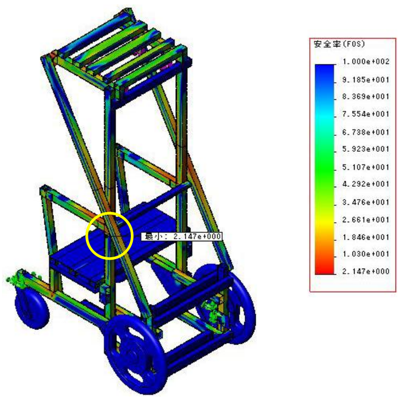


Figure 1: Analysis of the strength when lifting.

(1) The wheelchair has a lifting function. The lifting mechanism comprises a lifting frame, a sling seat, and a winch such as a conventional. The winch is driven by an electric motor that a caregiver operates using an up/down switch. This winch is not back-drivable because a worm gear and a worm wheel are used in it. Therefore, this design is safe: the previous state remains even if the power source is cut off. A toileting sling is used for this equipment. Therefore the user can wear it in a seated position and take off underclothes in the lifting position easily.

(2) Large driving wheels are located in front of the body, and the seat can be folded. Therefore, the user can approach above a toilet stool and a bed from the rear. As a result, this equipment can lift a user easily and safely. Furthermore, this location: front driving wheels are rigid and rear wheels are casters, has good maneuverability resembling that of a forklift truck.

The user can travel outdoors, even on public roads, because a driving unit for an electric wheelchair is used for this equipment and it has a mechanism of folding the frame for lifting.

3 ANALYSES OF STRENGTH AND STABILITY

The strength of the equipment is analyzed using finite element method with COSMOSWorks, which is add-in software of 3D-CAD software SolidWorks. The conditions of the analysis are the following: The user weight is 150 kg. Vertical loads are taken to the lifting frame or the seat frame. Aluminum alloy (A6063, yield stress = 145 N/mm^2) is referred. The following results were obtained through these analyses:

(1) The maximum stress is 54.8 N/mm^2 at the lifting frame when lifting. This value is under the yield stress of the aluminum alloy (145 N/mm^2).

(2) The maximum displacement is 4.00 mm at the lifting frame when lifting.

(3) The safety ratio is 2.15 FOS when lifting. The results are portrayed in Figure 1. Here, the minimum value is shown in a circle.

Next, the equipment stability during transfer is discussed. We discuss two cases because the user is lifted vertically in a stationary state; then the user moves to a target point in horizontal direction. We analyze the former and latter cases respectively using the stability margin and Zero moment point (ZMP).

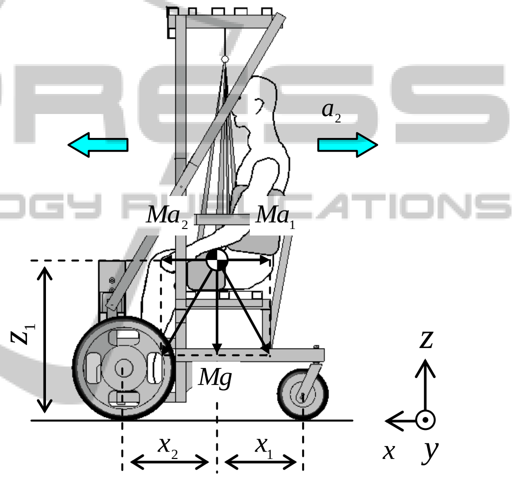
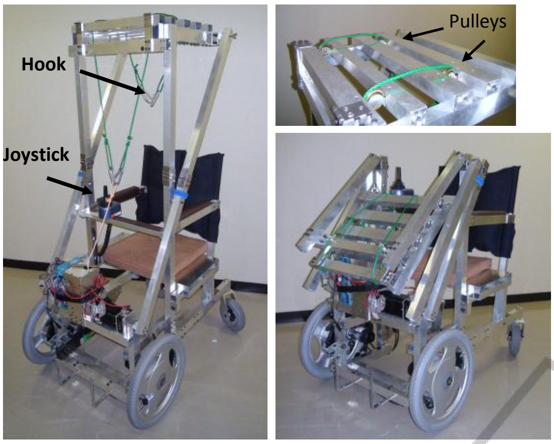


Figure 2: Model for analysis of falling.

Figure 2 shows the model during expansion. Here, x_1 and x_2 respectively signify the distances between the projected point of the center of gravity (COG) and the positions of the rear casters and the front wheels. y_1 signifies the distance between COG and the line that connects the front wheel and the rear caster. Also, z_1 denotes the height of COG from the floor.

The calculated position of COG of the equipment when carrying a subject (166 cm height, 65 kg weight), considering the weights of the equipment and the subject, is nearly at the top of his thigh (z_1 = 651.8 mm), and x_1, x_2 and y_1 are 352.6 mm, 357.4 mm and 292.1 mm, respectively. Those values respectively equal the backward, forward and sideward stability margins. Here, the direction of the rear casters is assumed to be in the front of each rotation axis because the equipment goes backward to a toilet stool and a bed (see Figure 2).



(a) when expanding (b) when folding

Figure 3: A full-sized prototype of a wheelchair with a lifting function.

Next, we discuss stability during travel. The safety acceleration against falling a_i (i =1, 2, 3) is calculated as

$$Mg \cdot x_i = Ma_i \cdot z_1 \quad (i = 1, 2) \text{ and} \tag{1}$$

$$Mg \cdot y_1 = Ma_3 \cdot z_1, \tag{2}$$

where M represents the total mass of the user and the equipment, and g signifies acceleration of gravity. The position of the rear caster to the rotation axis changes according to the traveling direction, x_1 =472.6 mm, x_2 =357.4 mm and y_1 =295.9 mm when traveling forward, whereas x_1 =352.6 mm, x_2 =357.4 mm, and y_1 =292.1 mm when traveling backward. Therefore, the safety accelerations against falling are calculated: a_1 =7.11 m/s^2 and a_3 =4.46 m/s^2 when traveling forward, whereas a_2 =5.31 m/s^2 and a_3 =4.41 m/s^2 when traveling backward.

4 EXPERIMENTS

We address two basic operations: traveling and transfer experiments. The subject was a man (166 cm, 65 kg) with no leg motion impairment.

Figure 3 shows the appearance of the hardware. The size in expanding is 100(L) $\times$ 68(W) $\times$ 162(H) cm, and that in folding is 100(L) $\times$ 68(W) $\times$ 105(H) cm, excluding the height of the cushion, and the weight is 47 kg. Road Traffic Law in Japan does not allow a wheelchair which size is over 120(L) $\times$ 70(W) $\times$ 109(H) cm to travel on public roads, however, the size in folding is within the limited size.

Figure 4: Snapshots of the traveling experiments when going up a step.

The winch gearbox of the lifting mechanism that comprises a DC motor (250 W, RE75; Maxon Corp.), a winding rod, spur gears, a worm gear and a worm wheel. The worm gear and the worm wheel make this winch back-drivable, so the user is safe even if the power source is cut off. The lifting cord connected to the winding rod is split into two parts and passes on the pulleys that are attached to the lifting frame. A hook is attached to each end of the lifting cord, and two hooks connect the lifting cord to the sling seat. Output torque of 44.2 Nm is necessary to lift a 100 kg load. The maximum torque of the winch (its reduction ratio = 1/257) is 95.6 Nm (transmission efficiencies of the spur gears and worm gears = 0.98% and 0.5%, respectively). The maximum lifting rate is designed to be 10 mm/s. We used a V55 CPU board (16 MHz; Japan System Design Corp.) and two batteries (WP2.6-12; Kung Long Batteries Industrial Co., Ltd.) for the lifting mechanism, which was controlled based on PD control theory. The sampling time was 20 ms.

This equipment has large driving wheels in the front that are the parts of a commercial electric driving unit for a wheelchair (Joy Unit, 8.2 km/1-charge, forward: 2.5 km/h and 4.5 km/h, backward: 2.0 km/h, approximately 17 kg including a battery, YAMAHA Corp.).

4.1 Traveling Experiments

First, we confirmed the motions of traveling forward and backward and for turning in indoor environments. The user operated the equipment using a joystick in the same way as that used for a commercial electric wheelchair. Consequently, we noted that the user was not required to lean the joystick when turning because the driving wheels were arranged in front of the body.

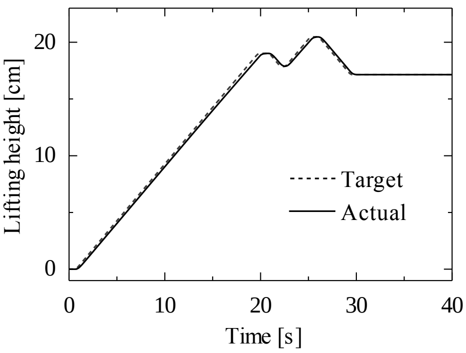


Figure 5: Time response of the lifting height when lifting.

Figure 6: Snapshots when transferring to a toilet.

Figure 4 shows results of the outdoor examination when ascending a 5 cm step. It was possible to go up/down the step because of the front driving wheels, although it is difficult for a conventional electric wheelchair to go up about 3 cm step. We also confirmed that the equipment had sufficient ability to travel on a field.

4.2 Transfer Experiment

We examined the lifting motions. The results are presented in Figure 5. The lifting velocity was calculated from the difference of the lifting height measured by an encoder installed in the winch. The motion is operated manually using an up/down switch. The lifting mechanism was controlled with trapezoidal speed profile, with target acceleration of 2.5 cm/s^2 and target maximum velocity of 1 cm/s. The directing maximum lifting velocity was about one-third of that of commercial lifts considering the clearance about 20 cm from the lifting frame to the head of the user. Accuracy of better than approximately 0.3 cm for the lifting height and approximately 0.04 cm/s for the lifting velocity at 25 s was obtained. The error of the lifting height was approximately 0.01 cm after 30 s. Those results show that this winch can follow the target trajectory. The trapezoidal speed controller realized smooth up/down motions, and the subject was lifted stably.

Figure 6 depicts the experimentally obtained result obtained for transfer to a toilet stool in a toilet for physically handicapped persons. The toilet stool height was 45.6 cm. The toilet stool width was about 20 cm, although the minimum width between the rear frames of the equipment is 37 cm. We confirmed that the subject was able to approach above the toilet stool from the rear.

5 CONCLUSIONS

We proposed a novel wheelchair with a lifting function for an electric wheelchair user with disabled upper and lower limbs. This equipment facilitates easy and safe transfer from/to a bed and a toilet stool by virtue of the opposite allocation of wheels from that for a usual wheelchair. Furthermore, the mechanism of frame folding for lifting allows this wheelchair to be used on public roads. Results show that this equipment had good maneuverability like a forklift truck. We also demonstrated that the equipment had sufficient ability of moving up/down a 5 cm step and of traveling on a field. It can be used in an actual toilet. In future works, we plan to improve this system for better practical use, mechanical strength, and design.

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