Feasibility Study of a Pair of 2-DOF Step-climbing Units for a Manual Wheelchair User

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Keywords: Wheelchair, Step-climbing, Assist Unit, Person with Lower Limb Disability, Rehabilitation, Mechatronics.

Abstract: We have developed a pair of step-climbing units that can be installed in a standard manual wheelchair. We aim to enable manual wheelchair users to establish an independent life that they can lead without assistance. This mechanism is simpler because it uses the capabilities of the wheelchair user. Each unit comprises two actuators and has two degrees of freedom: telescopic motion and rotational motion. We mainly discuss a step-climbing motion using this system. Experimental results obtained when ascending the step of 15 cm height confirm the design's 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 (Ministry of Health, Labour and Welfare, 2015). Most people with disability of lower limbs use wheelchairs because of their high maneuverability, stability, and wide availability at low cost. Nevertheless, wheelchairs have their shortcomings: traveling on uneven ground, e.g. a step or a steep slope, is difficult; wheelchairs necessitate the use of a multipurpose toilet; and difficulty in accessing high places and mental stress result from the low eye position of the user. Particularly, a worker using a wheelchair has strong demands related to the first problem because steps at a home or store entrance might prevent a wheelchair user from entering.

Various mechanisms for lifting wheelchairs have been proposed to solve difficulties in coping with surmounting steps. Many mechanisms have been proposed for the lifting of front casters. Yokota et al. applied a similar mechanism to each front caster of the wheelchair and added an electromagnetic brake. The prototype wheelchair climbed a 50-mm step with an oblique approach (Yokota, et. al., 2012). Most wheelchair users, however, are able to lift the front casters stably. Moreover, they are able to maintain the balance of their position through training at a rehabilitation center.

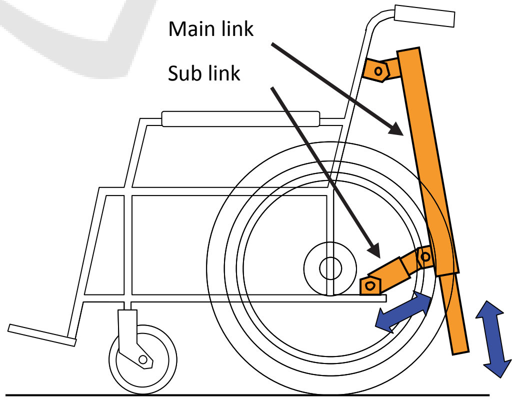


Figure 1: Conceptual design of the step-climbing unit.

J-MAX, which has two telescopic legs and which realizes smooth and continuous climbing motions, is an example for stairs (Nabtesco Corp., 2015). Although J-MAX is of great practical use, it requires a specially designed wheelchair and a caregiver who is trained to handle this system. Some stair-climbing wheelchairs, of which iBOT is a representative product, have been developed recently (Independence Technology LLC, 2015). Other wheelchairs have been developed with mechanisms using crawlers and links (Fang et al., 2012; Lawn et al., 2003, and TopChair, 2015). These wheelchairs have excellent properties for uneven ground. However, some room

Mori Y., Katsumura K. and Nagase K..
Feasibility Study of a Pair of 2-DOF Step-climbing Units for a Manual Wheelchair User.
DOI: 10.5220/0005510401960201
In *Proceedings of the 12th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2015), pages 196-201
ISBN: 978-989-758-123-6

remains for discussion to find the best wheelchair type for a wheelchair user who lives mainly in flat environments.

This paper presents a pair of step-climbing units for a manual wheelchair user based on actual demands. We aim to extend the range of action of wheelchair users who have no caregiver (Mori et al., 2011). The conceptual design and the hardware of the step-climbing unit are presented. We discuss the experimental results when surmounting a step.

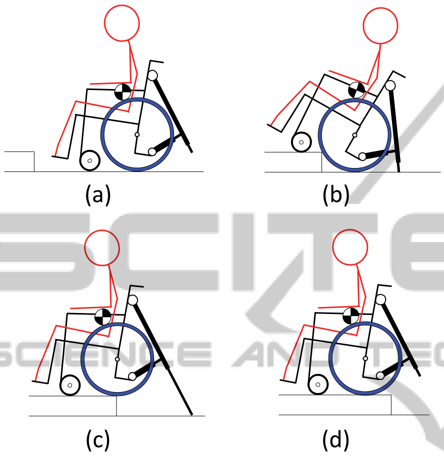


Figure 2: Procedure for climbing a step.

2 CONCEPTUAL DESIGN

An assistive device for steps greatly expands the sphere of activity of wheelchair users and supports their independent life. Our research concept is described below.

(1) Target users of this system are manual wheelchair users. Users climb a step (15 cm maximum height) with no helper.

(2) The units of this system can be attached to a conventional wheelchair as a retrofit.

(3) The mechanism is simple because it makes use of the wheelchair user capabilities.

(4) The mechanism prevents a user from falling backward by supporting the wheelchair from the rear.

First, regarding concept (1), some steps exist all over the environments even if barrier-free designs have been promoted. They present barriers to a wheelchair user's activity. Assistance for the wheelchair imposes a burden on a caregiver. The wheelchair user might sometimes feel it to be a mental burden. Therefore, step-climbing ability without a caregiver present is important, especially for active wheelchair users. We choose the maximum height of the target step as 15 cm. In terms of (2), many wheelchair users use each customized wheelchair fit to personal physical traits. This merit is also effective to prevent pressure ulcers of the buttocks. Concept (3) is effective for practical use. The ability to lift the front casters contributes to the light weight, the compact size, easy maintenance, and so forth. Concept (4) is related to the safety. Some supporting mechanism from the rear is indispensable when climbing the step.

We have proposed a pair of step-climbing units for a manual wheelchair user that satisfy the above conditions as shown in Figure 1. Each unit comprises two actuators and has two degrees of freedom: a prismatic joint and a rotational joint. Those units are installed on the back frames of the wheelchair. They do not prevent the wheelchair from being folded. It is therefore easy to carry the wheelchair with units by a car. The unit arrangement realizes effective step-climbing.

The procedure used for surmounting a step is depicted in Figure 2. The user approaches the step as shown in (a) and lifts the front casters, as shown in (b). From step (b) to step (c), the wheelchair is gradually going up to the top of the step as the links are stretching. Finally, in step (d), the user goes forward on the step and resets the links to the initial positions. The user executes the motion in the reverse direction when descending the step.

3 TRAJECTORY GENERATION WHEN ASCENDING A STEP

Figure 3 depicts the model applied when a wheelchair climbs up a step. Tilt angle ${}^{u}\theta_{w}$ is calculated from the following equation.

$$ {}^{u}\theta_{w} = -\psi - \Phi \quad (1) $$

In that equation, the following variables are used.

Σ_u : coordinate systems relative to the contact point between the rear wheel and the floor (the lowest position of the rear wheel when climbing a step)

Σ_m , Σ_w : coordinate systems relative to the wheel center of the front caster and the rear wheel, respectively

R_1 , R_2 : respective radii of the rear wheel and the front caster

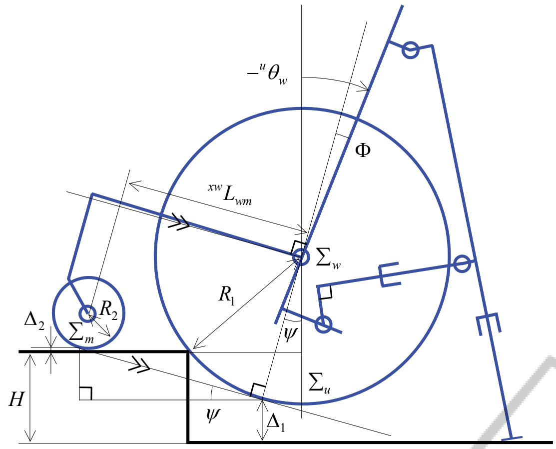


Figure 3: Model for generating trajectory.

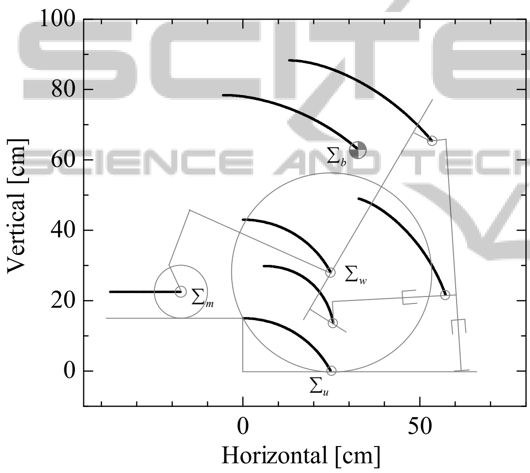


Figure 4: Trajectory when climbing a step.

$^{xw}L_{wm}$: constant distance between the wheel center of the front caster and the rear wheel

H : step height

ψ : tilt angle of the wheelchair against the floor

Φ : tilt angle of the backrest of the wheelchair (constant)

In (1), ψ is derived as

$$\psi = -\tan^{-1}\frac{-R_1 + R_2}{^{xw}L_{wm}} + \sin^{-1}\frac{H - R_1 + R_2 - {^yU}}{\sqrt{^{xw}L_{wm}^{\ 2} + (-R_1 + R_2)^2}} \quad (2)$$

where ^yU is the y -coordinate of the coordinate system Σ_u . From the following equations:

$$\sin\psi = \frac{(H - \Delta_1) + \Delta_2}{^{xw}L_{wm}} \quad (3)$$

$$\Delta_1 = R_1(1 - \cos\psi) + {^yU} \quad (4)$$

$$\Delta_2 = R_2(1 - \cos\psi) \quad (5)$$

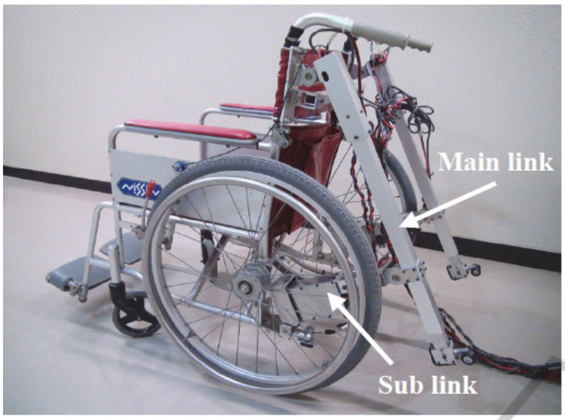
Figure 4 presents results obtained for climbing up a 15-cm-high step from the position at which the rear wheel contacts the floor to the position it reaches to the top of the step, where Σ_b is the coordinate system relative to the CoG including the total weight of the system (wheelchair = 16.8 kg, step-climbing units = 5.8 kg, user = 55.0 kg). The described circular arcs from each origin of the coordinate systems show the appropriateness of the kinematics and trajectory generation. The projected point of the CoG to the floor exists in the supporting polygon between the rear wheel and the contact point of the main link to the floor from the initial period to the latter period of the step-climbing motion. It exists between the front caster and the rear wheel from the latter period through the finish period.

4 HARDWARE

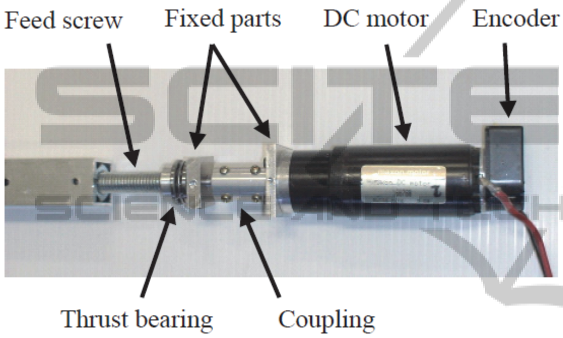
Figure 5 presents the appearance and inside mechanisms of the step-climbing units. The main link size is 12.0 (L) × 5.0 (W) × 65.5 (H, minimum length) cm. That of the sub links is 30.2 (L, minimum length) × 8.3 (W) × 10.0 (H) cm. The weight of the pair of units is about 2.9 kg. A standard manual wheelchair (16.8 kg; Nissin Medical Industries) is used for these experiments.

The main link has one DC motor (RE-40, 70 W; maxon motor) with a planet gear (reduction ratio = 1/5.8), an optical encoder (500 PPR), and a feed screw (length = 46 cm, diameter = 10 mm, lead = 1.8 mm). The main link total length is 65.5 cm at its shortest. Its extension length is 39.5 cm. A coupling connects the feed screw with the motor. The fixed part on the left of the coupling supports the force from the feed screw to prevent an overload against the motor. A thrust bearing between the feed screw and the fixed part enables the feed screw to rotate smoothly under a heavy load. The feed screw used in this study has larger friction than a ball screw. Therefore, although the former is unfavorable in terms of transmission efficiency, it is safer: even if the power source is cut off, the previous state is retained.

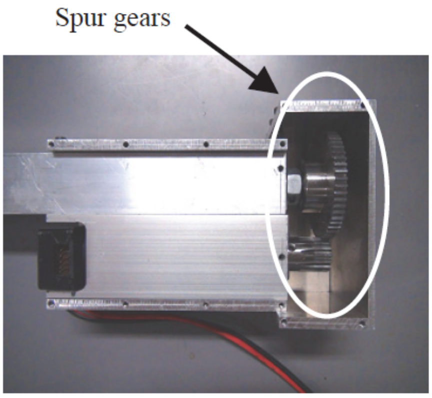
The sub link is located on each side of the wheelchair using its tipping lever. The basic internal structure is the same as that of the main link. However, the motor is located parallel to the feed screw using spur gears (reduction ratio = 1/3.375) to design the link length as short.



(a) Wheelchair with step-climbing units.



(b) Main link



(c) Sub link

Figure 5: Step-climbing units.

5 EXPERIMENTS

We next address the experimental results obtained when climbing up and down a step. The subject was a man with no leg motion impairment. His height was 158 cm. His weight was 55 kg. We measured the wheelchair tilt angle using an inclinometer (NA4-70, measuring range ± 70°, resolution <0.01°; Seika Mikrosystemtechnik GmbH). Each link was controlled based on PD control theory; the sampling time was 5 ms. The step was made of concrete blocks and a wooden board. Its height was 15 cm. Experiments were conducted in an indoor environment on a linoleum floor surface.

Figure 6 shows photographs taken when the device was ascending a step. The sequence of this motion is the following. The Greek characters of each item given below correspond to those of the panel in Figure 6.

(i) The user measured a step height and inputted the data into the PC. Then the user approached the step as shown in the snapshot.

(ii) The user lifted the front casters to the top of the step independently, and went forward until the back wheels touched the step. Then the main and sub links were adjusted respectively to the initial positions for this motion.

(iii) The main and sub links pushed the wheelchair upward gradually.

(iv) The wheelchair was lifted on the top of the step without any help from the user.

(v) The user went forward until the links did not support the weight.

(vi) The links were then reset to the initial positions.

In (i), the subject measured the step height with a measuring tape while seated on the wheelchair. In (ii), it is true that the motion of lifting the front casters requires some skill, but most wheelchair users have already obtained such skills because they are necessary for daily life. The subject, who is not a wheelchair user, understood this motion after several trials because the main links of this system prevented him from falling backward. Each tip of the main links slipped backward about 3 cm. The back wheels stopped before about 6 cm from the target position in the motions from (iii) to (iv). However, the subject was able to reach the top of the step easily in (v). Figure 7 shows the time response of the main and sub links on the right side when climbing up the step. The left side data were similar because the motion was bilateral symmetry. The Greek characters in Figure 7 correspond to those in Figure 6. The time for control started from (ii) with the following intervals: (ii) 0–6.0 s, (iii) 6.0–7.9 s, (iv) 7.9–24.9, (v) 24.9–28.6 s, and (vi) 28.6–44.6 s. The user pressed a push-button to send the signal to the PC. It was pressed three times in (ii), (iii) and (v). Figure 7(a) presents the time response of the length of the main link. This result shows that the main link can follow the target with the maximum error of 8.0 mm (t=12.0 s). The sub link also follows the target with the maximum error of

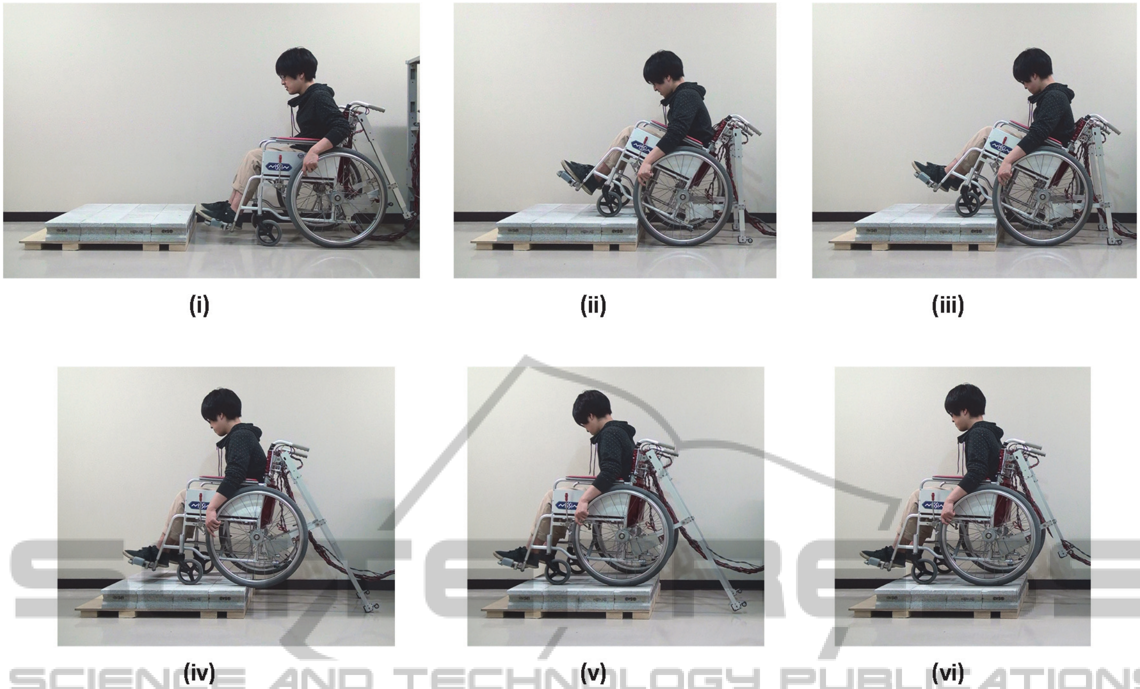
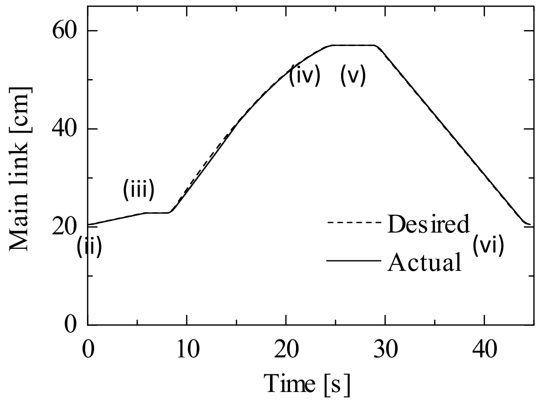


Figure 6: Photographs showing step ascent.

1.3 mm (t=0.7–5.6 s, around 23.2 s) (see Figure 7(b)). Figure 7(c) portrays the time response of the tilt angle of the wheelchair. The broken line represents the calculated values. We infer that the errors during (iii)–(iv) occurred by the slips of the main links. The large fluctuations during (iv)–(v) were generated when the wheelchair went forward and stopped at the top of the step. The tilt angle itself did not change in that manner.

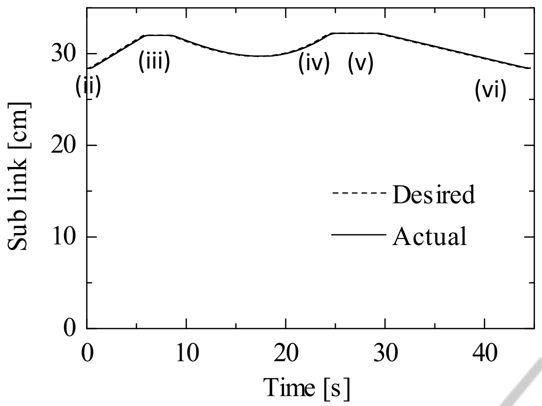
The subject followed the reverse procedure of the climbing-up motion. Descending a step was apparently more difficult than ascending it because of the fear of falling. However, we confirmed that the user was able to realize this motion stably with no help because the main link stopped the wheelchair from going backward.

We examined this system for use in outdoor environments. As results of the examination using the part of the main link removed from the system, less slippage occurred on the asphalt surfaces, which are the environments most likely for use, than on the indoor linoleum surface. Even if a small amount of sand was on the asphalt surface, the slippage condition was almost the same because of the roughness of the rubber surface of the main link tip. On gravel or soft soil it was difficult to realize ascending and descending motions because the main link slipped or sank down. Next we discuss whether the wheelchair can reach the top of the step or not. The subject can climb up a step even though there was about 1.2 cm height error. On flat ground, the maximum step height he was able to climb independently was about 5 cm. The user confirmed the situation and was able to retry the task calmly after changing the environment and the input value of the step height because the wheelchair does not fall backward in the cases that the rest height error exceeds the limit or that the back wheel detaches from the step.

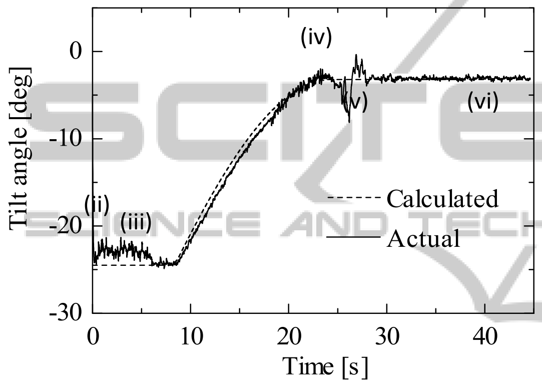


(a) Time response of the length of the main link.

Figure 7: Results of step-ascent experiment.



(b) Time response of the length of the sub link.



(c) Time response of the tilt angle of the wheel chair.

Figure 7: Results of step-ascent experiment (cont.).

6 CONCLUSIONS

We proposed a pair of step-climbing units for a manual wheelchair user. This unit comprises links of two types: a main link and a sub link. The former link works for pushing up the wheelchair. The latter link works for changing the angle of the main link. A pair of the units is installed on the back frames of the wheelchair. They prevent the user from falling backward. The trajectory generation when climbing up a step was presented. Using a pair of portable slopes, we demonstrated that this system can ascend and descend a 15-cm-step and that it can cope with several steps. This system supports only 15-cm height for a single step, but the maximum step height can exceed 20 cm by redesigning the main link in the same mechanism as the sub link. In addition, this system can reduce ground slippage by improvement of the mechanism, shape, and material of the tip of the main link.

In future works, we plan to improve this system for better practical use. We will attempt to use it in various actual environments.

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