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Review Article

ABLE: A Standing Style Transfer System for Persons with Lower Limb Disability

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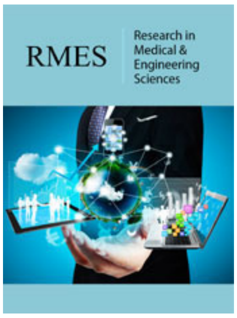
ISSN: 2576-8816



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Submission: June 26, 2019

Published: July 02, 2019

Volume 7 - Issue 5

How to cite this article: Yoshikazu M, Ken M, Masato Y. ABLE: A Standing Style Transfer System for Persons with Lower Limb Disability. Res Med Eng Sci. 7(5). RMES.000675.2019.
DOI: 10.31031/RMES.2019.07.000675

Abstract

A novel standing style transfer system, ABLE, has been developed to assist a person with disabled lower limbs during daily life. The ABLE-I and ABLE-II systems comprise three modules: a pair of telescopic crutches, a powered orthosis for the lower extremities, and a pair of mobile platforms. The crutches, which protect body stability in a standing posture, are useful when rising from a chair. All joints have actuators in this lower extremity orthosis. Together, these module components actively hold joints, bend joints, and extend joints. The platforms, which have crawlers to traverse uneven surfaces, facilitate turning on a rotation board mechanism. The third version, the ABLE-III, is designed to improve safety. The powered lower extremity orthosis is replaced with a two-link arm between legs of the person. No telescopic crutches are necessary because of the large mobile platform. Experimentally obtained results of basic operations related to movement while in a standing posture, sitting and standing with a chair, and descending and ascending a step confirm the design's effectiveness.

Keywords: Aids for the disabled; Rehabilitation; Standing Posture; Wearable

Introduction

Persons with disabilities of the lower limbs are becoming increasingly numerous worldwide. In Japan, the number of disabled persons in 2011 was estimated at about 3,922,000 [1]. Most of them use wheelchairs daily. Wheelchairs are used as "second legs" by numerous users. They are neither difficult to use nor expensive. Electric wheelchairs are widely used recently. They have excellent control features and running time. However, even with those benefits, wheelchairs do present several shortcomings. During movement and use at various locations and institutions, wheelchairs need a sufficient area for operation. Ascending stairs presents numerous obstacles. Actually, wheelchair users need a separate infrastructure. Moreover, conditions such as excretion failure, arthropathy, and hematogenous disorder of legs can result from prolonged sitting. All such physical difficulties must be resolved, in addition to mental stress deriving from the low eye position. One can surmise that a device that can move an ambulatory-disabled person stably in a standing posture can surmount most of these obstacles. Considerable advancement has been achieved in robotic and mechatronic technologies. Many researchers are developing applications in the rehabilitation field [2-15]. Some power-assisted devices of exoskeleton design have been developed [9-15], such as the HAL (Hybrid Assistive Limb) device [13]. This apparatus, which is designed for persons with leg muscle atrophy, can be coordinated using the surface potential of the leg. Unfortunately, people with disabled lower limbs find that using surface potential with the system not a simple matter. The automatic control mode provided with this device does not allow a user free operation. HAL is used lately mainly for medical purposes. It has been clinically tested and approved for CE marking in Europe [15]. WPAL (Wearable Power-Assist Locomotor) comprises powered lower limbs driven by an electric motor at each hip and knee and a cart with control switches [12]. The purpose of this robot is rehabilitation. ReWalk (Argo Medical Technologies Ltd.) has been commercialized to assist the independent walking patients with spinal cord injury. The ReWalk user maintains the body balance with crutches. All have been developed for use by patients for daily life activities in society.

This paper presents a conceptual design of standing style transfer system "ABLE" for those with disabled lower limbs [16-19]. Mainly ABLE is intended for use by persons who have spinal cord injuries and who cannot move hip joints those with L1 of lower spinal cord injury. A pair of telescopic crutches, a powered lower extremity orthosis, and a pair of mobile platforms are the three main component systems of the ABLE-I and ABLE-II systems. Together, those components realize three fundamentally indispensable operations of daily life: moving in a standing posture, even when traversing uneven surfaces; standing from a chair; and stair-ascension. Three ABLE systems are proposed in this paper. The second section presents the conceptual design, the design of each module, and experimentally obtained results of the ABLE-I. The third section describes ABLE-II, which was improved by the use of crutches and mobile platforms. We propose ABLE-III in the fourth section. The mobile platform and upper link mechanisms are discussed. The experimentally obtained results of the scale model are presented. Concluding remarks follow in the last section (Figure 1).

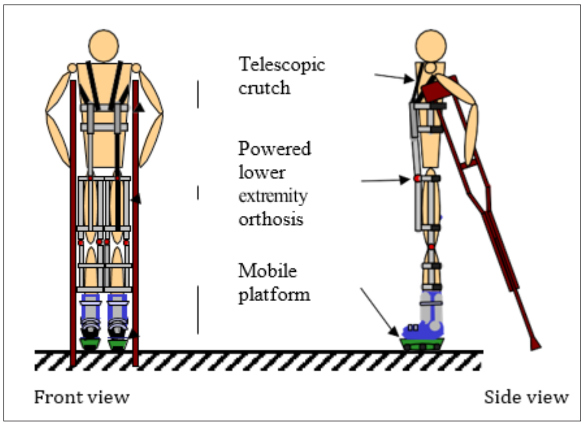

Figure 1: ABLE-I design.

ABLE-I Development

Figure 1 presents an illustration of the standing style transfer system ABLE-I, comprising three modules: a pair of telescopic crutches, a powered lower extremity orthosis, and a pair of mobile platforms [16,17]. After a user puts on the powered lower extremity orthosis to secure the user posture, the user can ride on the mobile platforms in a standing posture. During the movement, the user touches the ground immediately with the telescopic crutches because they can realize motion while preserving body stability. These crutches also facilitate standing sitting motions or when negotiating a step. Some benefits over those provided by wheelchairs are that ABLE-I enables a user to enter narrow spaces, but it has particular stability in wide spaces because it can alter the crutch contact points freely according to different circumstances.

Figure 2a depicts a shoulder crutch prototype that can supply power and maintain body balance. The weight is 2.9 kg; its dimensions are 200(W)×65 (L) × (980-1580) (H)mm. The ABLE-I interface are two touch switches under the grip. They can limit crutch length adjustment, changing them according to different tasks. A PC can also use a pre-calculated target trajectory or a reference value of the inclinometer to change the crutch length according to the circumstances without the need for any special command. Figure 2b portrays a prototype of the powered lower extremity orthosis. This module, which is used for actively fixing, bending, and stretching each leg joint, has actuators at the hip and knee joints. Ankle joints can move only slightly because the user puts on a pair of ski boots. Their weight is 10.0kg. Its dimensions are 471(W) × 246(L)× (690-875) (H)mm. No joint is back drivable because worm gears are used in each gearbox. Therefore, although the transmission efficiency is not high, this design is safe: even if the power source is cut off, the previous state remains. The hip joint gearbox is set in front of the leg to prevent disturbances caused by crutch swinging. The knee joint gearbox is oriented on the same axis of a human. Actually, a user wearing ABLE-I can use both ABLE-I and the wheelchair in parallel. The mobile platforms, worn as shown in Figure 2c, carry a user over flat surfaces and over uneven surfaces. This 4.1kg system can even be used outside because it has crawlers. Its dimensions are 265(W) × 153 (L) × 87(H)mm.

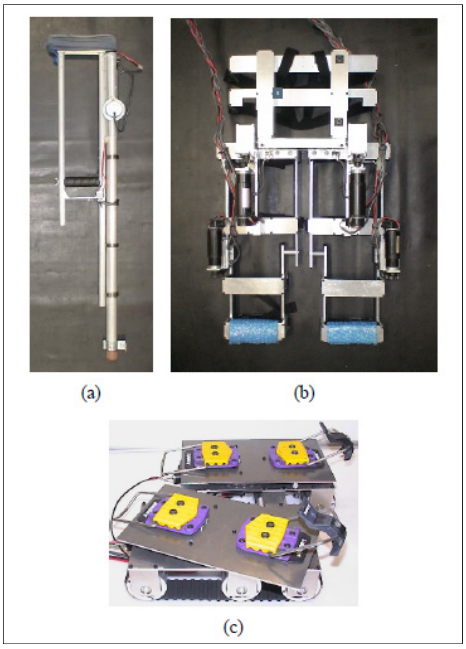

Figure 2: ABLE-I modules

Telescopic shoulder crutch

Powered lower extremity orthosis, and

Mobile platforms.

Experiments

Movement in a standing posture: Traveling and rotating when in a standing posture require balance provided by the telescopic crutches. Crutches are controlled automatically by an installed inclinometer. Figure 3 presents straight- line movement in a in a standing posture. A user uses two touch switches of the right crutch to control the mobile platform velocity. The right and left crutches were, respectively, placed forward and backward of the body. Particularly when starting and stopping, moving in a standing posture presents a fall risk. We are certain that the predictability of motion, i.e., devoting attention to the crutch that supports the body weight, dampens the anxiety of falling and leads to stable travel. A verification of rotation movement in a standing posture is shown in Figure 4.

Figure 3: Traveling in a standing posture.

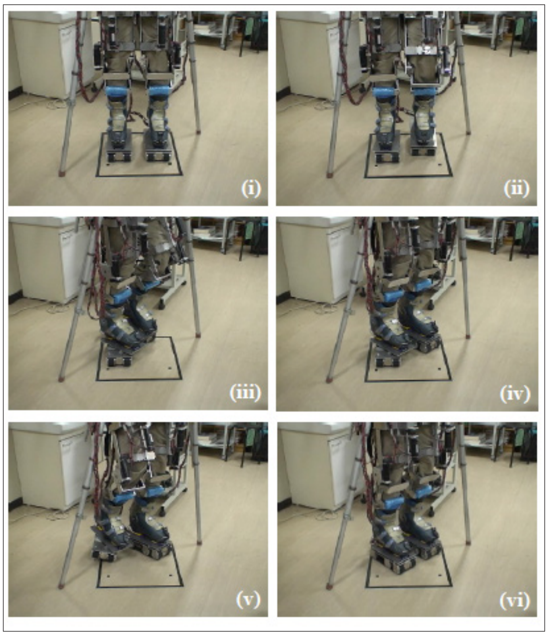

Figure 4: Rotating in a standing posture.

Standing and sitting with a chair: When standing or sitting with a chair, telescopic crutches can be used to provide power assistance. The ground position of each crutch determines the shared load ratio of the crutch and the orthosis. They support the body weight when placed under the armpits, especially near a sitting position. The crutches control each length in synchronous with the powered lower extremity orthosis. Figure 5 shows sequential photographs of a sitting and standing experiment.

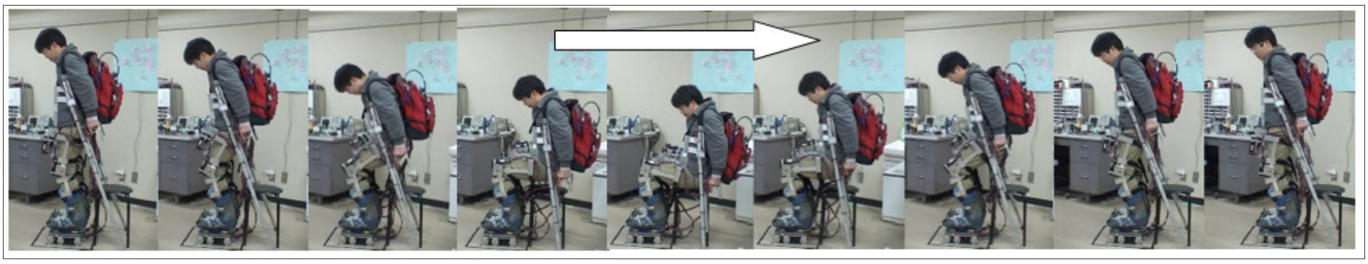

Figure 5: Sitting and standing with a chair.

Step ascension and descension: This motion is executed by application of standing and sitting with a chair. The powered lower extremity orthosis and the crutches are the components that a user must rely upon for such motions. The user measures the step height before ascending and descending a step. The user lengthens it by operating touch switches on the right crutch and makes the crutch tip touch the ground. The encoder calculates the stair height from beginning and end points. Figure 6 portrays images of an experiment to assess stair ascent and descent. Similarly, to rotation in a standing posture, this motion was done intermittently (Figure 6).

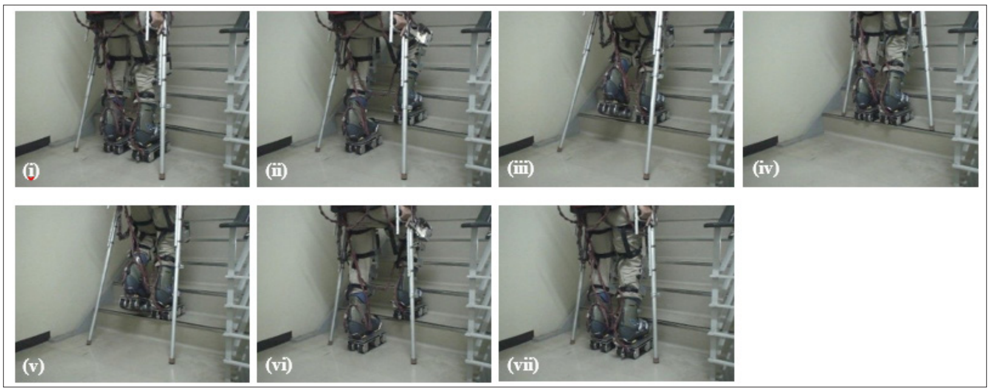

Figure 6: Ascending and descending a stair.

Step descent was more difficult than ascent, probably because of a user's fear of falling. Nevertheless, the motion for step descension is not frightening if the user executes the motion in the back direction of step ascension. This motion is both stable and safe.

ABLE-II Development

The crutch and the mobile platform were improved. The crutches' weight is an important shortcoming of the shoulder telescopic crutch. Moreover, the necessity of controlling the actuator using an encoder and an inclinometer interferes with quick motions, particularly in a standing posture. The mobile platform was improved to reduce rotation errors when changing direction, and for increasing stability during movement in a standing posture [18,19]. Traveling in a standing posture can be done with good stability if a user does so with the legs spread forward and backward. This device includes addition of active ankle joints to the mobile platform and connection of them to the powered lower extremity orthosis. Figure 7 depicts this new system. A novel type of telescopic crutch has several important attributes in addition to being light and having high manipulability. First of all, it has two Lofstrand crutches for distance adjustment from the body to the floor using elbow joints. No minor crutch length adjustment is necessary. Secondly, short and long states can be selected for crutch length. Shorter is better when standing up because a user can feel pain because of the difficult posture that might occur with a long crutch. Nevertheless, longer crutches are needed for traveling in the standing posture: the crutch tip must touch the ground. Thirdly, the state adjustment mechanism has no actuators. Figure 8 portrays a telescopic Lofstrand crutch. If the user pulls the trigger, then the wire connected to the trigger lifts the hook. The user can then switch the crutch length. The telescopic Lofstrand crutch weighs 0.86kg without the inclinometer [20]. The rotation board of the mobile platform can change the direction. The rotational errors of this motion cause the legs to open or the mobile platforms to bump when moving while in a standing posture. Worm gears used for the rotational mechanism lead to this error. The ultrasonic motor, which we used, can serve as a brake when not generating electricity, but it generates large torque at low speed. Figure 9 presents the novel mobile platforms.

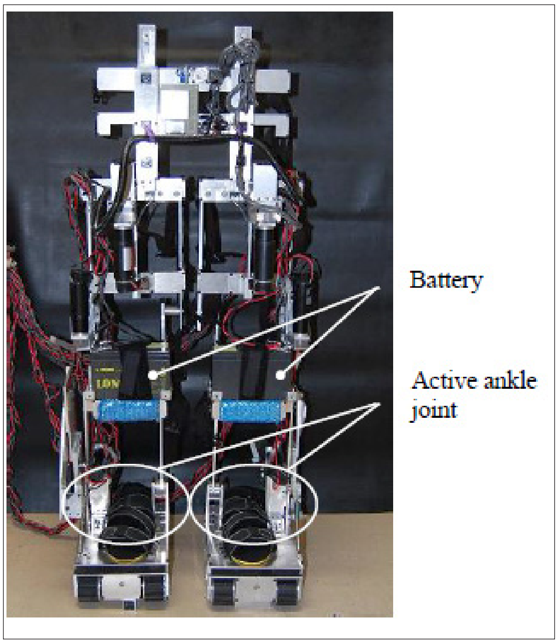

Figure 7: ABLE-II system.

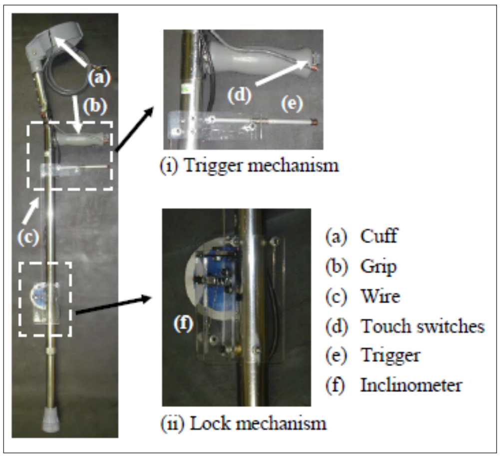

Figure 8: Telescopic Lofstrand crutch.

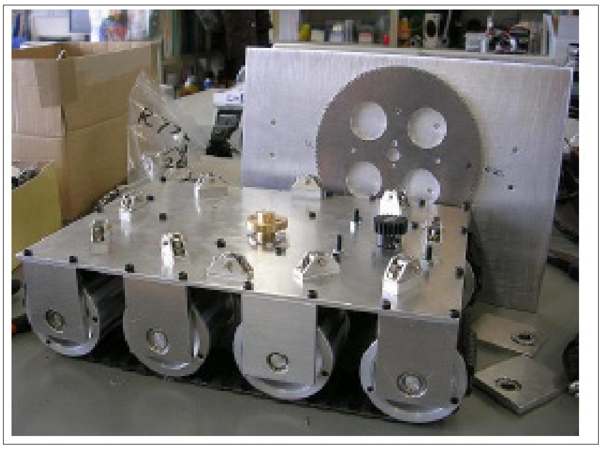

Figure 9: Mobile platform

Experiments

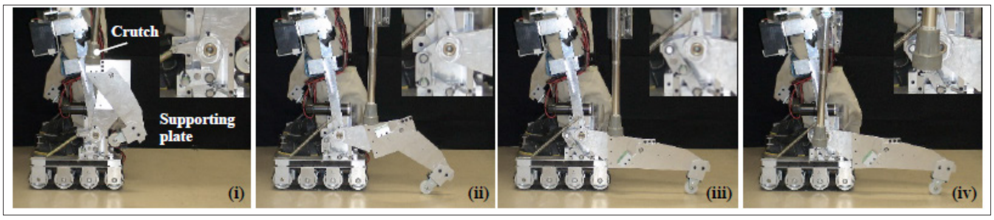

Figure 10: Standing support plate expansion.

The rubber cap at the crutch tip mitigates slippage when using crutches, which rarely occurs. Nevertheless, rubber wear, floor conditions, and some outdoor conditions can cause slippage. A "supporting plate" added to the mobile platform can maintain a margin of stability, even in cases crutches are not used. Additional actuators lead to important difficulties that entail malfunction, costs, and space. The device uses a link mechanism for supporting plate rotation. Figure 10 portrays photographs taken during supporting plate expansion. Figure 11 depicts an experiment to assess standing from a chair when using supporting plates. That experiment also assessed a man in his 60s with an L3 spinal cord injury.

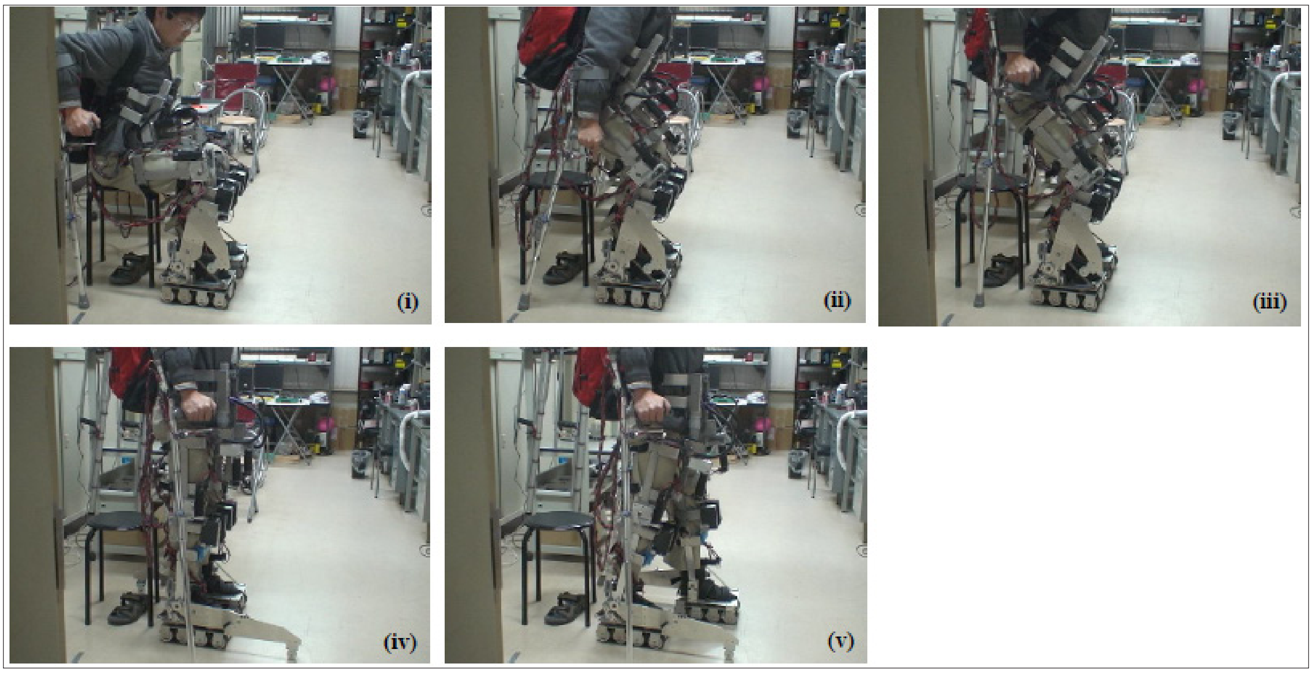

Figure 11: Standing up from a chair.

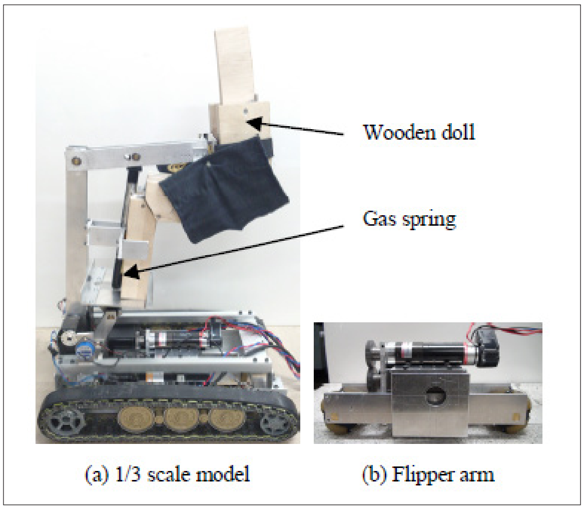

Figure 12: A scale model of the ABLE-III system.

ABLE-III Development

Another type of system is proposed to support wheelchair users. A 1/3 scale model is shown in Figure 12a. The ABLE-III was developed based on a clawer-typed electric wheelchair. The clawer is suitable for traversing uneven surfaces. The clawer belts of a model tank were used. They were covered with rubber belts to prevent slippage on stairs.

The ABLE-III has a flipper arm on the center of the base frame (Figure 12b). The rear clawers are lifted when a flipper arm rotates clockwise, whereas the front clawers are lifted when it rotates counterclockwise. The respective maximums the rear and front lifting heights are 6cm and 1cm. The flipper arm lifts the front of the clawers when moving over flat surfaces. For that reason, it can move with less energy consumption. This flipper is also useful when ascending stairs.

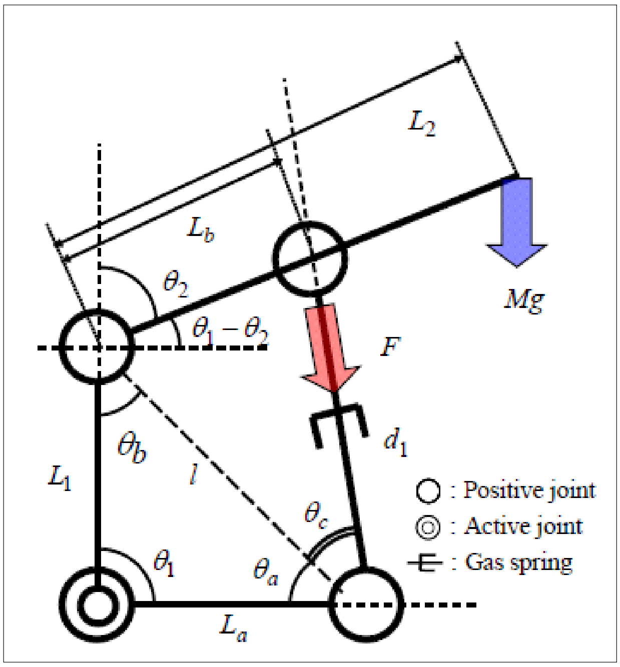

Figure 13: Model of the ABLE-III..

A closed two-link arm is installed between the user's legs. This system has no telescopic crutches. A gas spring supports the weight of the user. Therefore, weak torque is sufficient when the user takes a standing posture.

A model of the upper link is depicted in Figure 13.

d_1: link length (variable),

θ_1, θ_2, θ_a, θ_c: joint angle,

L_1, L_2, L_a, L_b: link length (constant),

M: user mass,

g: acceleration of gravity.

The gas spring reaction force is calculated as

$$F = \frac{MgL_2}{L_b \sin(\theta_a + \theta_c)} \quad (1)$$

Where

$$\theta_a = \cos^{-1}\left(\frac{L_a^2 + l^2 - L_1^2}{2L_a l}\right) \quad (2)$$

$$\theta_c = \cos^{-1}\left(\frac{l^2 + d_1^2 - L_b^2}{2ld_1}\right) \quad (3)$$

$$l = \sqrt{L_1^2 + L_a^2 - 2L_1 L_a \cos\theta_1} \quad (4)$$

The gas spring length is derived as

$$d_1 = \sqrt{L_b^2 + l^2 - 2L_b l \cos(\pi - \theta_2 - \theta_b)} \quad (5)$$

Experiments

Traversing a flat surface: The flipper arm effectiveness was examined. The scale model traveled over a flat linoleum surface. Figure 14 presents the experimentally obtained results. The current was reduced by approximately 30% when going straight; it was reduced by approximately 48% when rotating in the case of lifting the front.

Ascending stairs: The ABLE-III ascends stairs from the rear wheels. The procedure is the following:

a. The flipper-arm lifts the rear wheel.

b. Go straight until the rear wheel touches to the first stair.

c. The flipper-arm that touches on the first stair lifts the rear wheel to the second stair.

d. Ascending the stairs to the top of the stairs.

e. When it reaches the top, the flipper-arm touches the floor in order not to fall down.

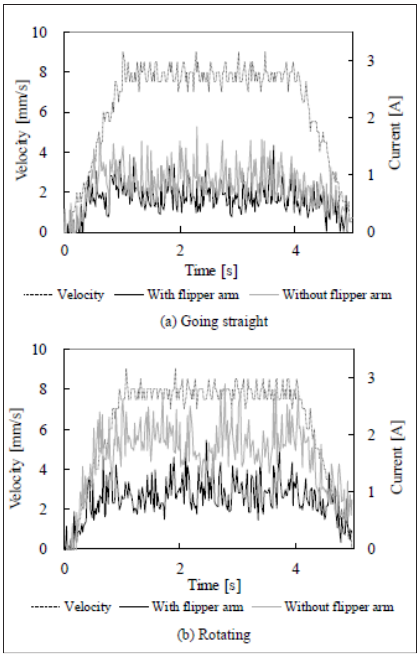

Figure 14: Current when traveling.

Figure 15 presents images taken as the scale model ascended stairs. The sequence of descending the stairs was the reverse of ascending them. A switch sent a signal to the micro-computer. Then the procedure advanced to the next step. We have also confirmed that the motions can be controlled automatically using three PSD sensor modules (range: 4-50cm, GP2Y0E03; Sharp Corp.): two are attached on the front for arranging the body direction to the stairs; the other is attached on the bottom of the body for sensing each stair.

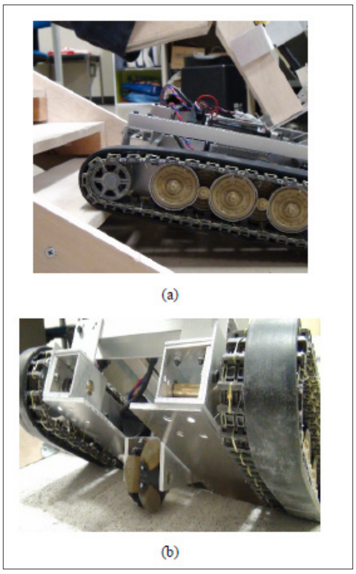

Figure 15: Ascending stairs

The flipper arm lifts the rear wheel

When ABLE-III reaches the top of the stairs, the flipper arm touches the floor to prevent falling.

Conclusion

This paper described a system, ABLE, that can accommodate standing of a user during movement. This novel transfer system is especially useful for anyone with lower limb disability. In fact, a user of this system, without special infrastructure, becomes able to execute necessary functions of daily living. Basic, indispensable operations for daily life were assessed through several experiments using this system, which has three modules. The experimentally assessed operations were step ascent and descent, traversing different surfaces in a standing posture, and sitting and standing with a chair. Earlier mobile platforms were modified to provide better stability and operability when traveling in a standing posture. For ABLE-II, the DC motor was replaced by an ultrasonic motor for steering. A supporting plate and an active ankle joint were also added to the mobile platform. We presented experimentally obtained results obtained using platforms when standing and traversing several surfaces in a standing posture. Crutches were also improved for better usability.

Then ABLE-III was developed to improve safety. Based on a clawer-typed electric wheelchair, ABLE-III incorporates a flipper arm that can lift the front of the clawers when traveling over flat surfaces. Therefore, it can traverse over a surface using less energy. This flipper also facilitates ascending stairs. Results of this study demonstrate that a person with disabilities of the lower limbs using ABLE-II can rise to a standing posture from a chair and then move. However, these findings merely present the relevant possibilities. Additional studies can improve this system for practical use and can assess ABLE in diverse situations. With the support of physical therapists at a rehabilitation center, we can investigate ABLE utilization for rehabilitation and boosting of motivation.

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