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Development of Straight Style Transfer Equipment for Lower Limbs Disabled

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***Abstract*– We developed straight style transfer equipment for a person with disabled legs. It realizes travel in a standing position even on uneven ground, standing-up motion from a chair, and ascending stairs. This equipment comprises three modules: a pair of elastic crutches, a powered lower extremity orthosis, and a pair of mobile platforms. We show the conceptual design of the equipment and the motion of each module. Cooperative operations using three modules are discussed through simulations. We verified travel in a standing position, including rotation, through experiments using prototypes of elastic crutches and mobile platforms.**

Index Terms*– *component, person with disabled legs, elastic crutch, powered lower extremity orthosis, mobile platform.

I. INTRODUCTION

Persons with disabled lower limbs are increasing globally. In Japan, their number was about 600,000 in 2001 [1]. Most of them use wheelchairs in daily life. Wheelchairs are now utilized widely as "second legs" because they are inexpensive and have simple mechanisms. Electric wheelchairs have come into wider use recently because of improvement of their controllability and running time. Notwithstanding, they engender several problems. Wheelchairs require much space during travel and facility use. It is difficult to ascend stairs. Therefore, a separate infrastructure for wheelchair users is inevitable. Moreover, medical failures must be addressed such as hematogenous disorder of legs caused by maintaining a sitting position, excretion failure, and arthropathy. Mental stress also occurs because of the low position of the eyes. However, most of these problems can be solved by the use of some equipment that transfers an ambulatory-disabled person with a straight posture.

Some exoskeletonic power-assisted devices have been developed [2]–[4], such as the "HAL" device [3],[4]. This system is intended for persons with leg muscle atrophy; the system is controlled using the surface potential of the leg. Therefore, it is difficult for people to use the system if they have disabled lower limbs without that surface potential. This system also has an automatic control mode, but the person cannot operate it freely in that mode. Independence Technology LLC developed the "IBOT", an electric wheelchair that gets up and balances using only two wheels, such as an inverted pendulum. It also realizes a motion of ascending stairs. However, its movement requires much space. Moreover, medical problems caused by maintaining a sitting position remain unsolved.

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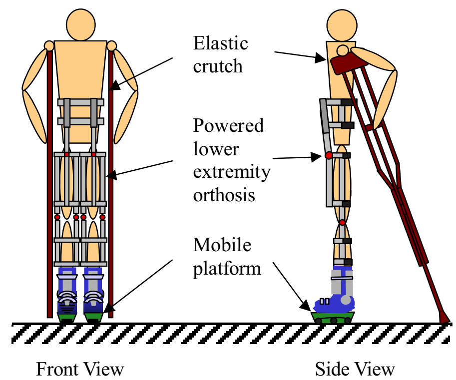


Figure 1. Straight style transfer equipment for lower limbs disabled.

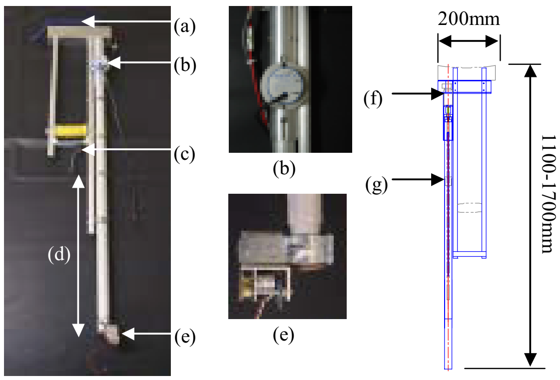
Previous studies have examined elastic crutches and auxiliary tools for binding the legs, but there was no transfer equipment addressed along with them. At the National Rehabilitation Center for Persons with Disabilities, ambulation equipment has been developed which combines a pair of constant-length crutches with an auxiliary leg tool whereby the base of the leg performs a vertical motion [5],[6]. However, it is intended for rehabilitation and its only available motion is forward.

This paper presents a conceptual design of straight style transfer equipment for those with disabled lower limbs. It realizes: travel with a standing position, even on uneven ground; a standing up motion from a chair; and ascending stairs [7]. Its effectiveness is examined through experiments using the prototype.

II. CONCEPTUAL DESIGN

What kinds of tools are required for a person with disabled legs to travel stably with a straight posture? We propose the three modules shown in Fig. 1: a pair of elastic crutches, a powered lower extremity orthosis, and a pair of mobile platforms.

Elastic crutches are useful to maintain body stability without taking an unnatural posture. It is possible to freely change the contact points to the ground according to different situations. Thereby, it is easy to pass through a narrow space, whereas

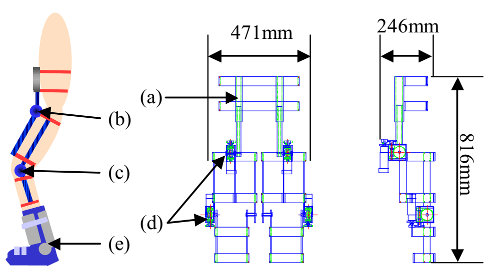


(a) Cushion
(b) Inclinometer
(c) Up/Down switch
(d) Elastic function
(e) Measurement wheel
(f) Motor
(g) Ball screw

Figure 2. Elastic crutch.

Table 1. Specifications of an elastic crutch.

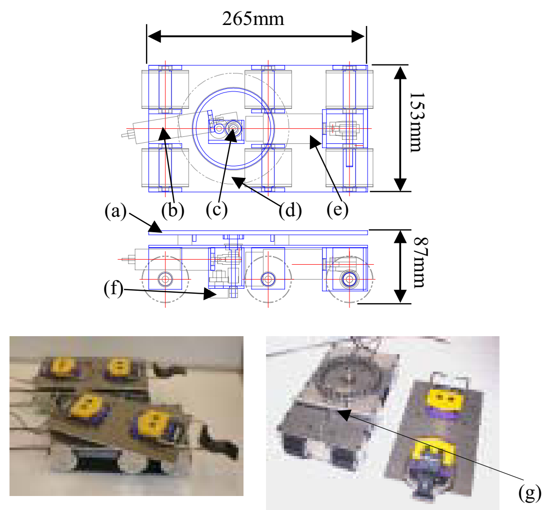
Weight	2.91[kg]
Length	1100-1700[mm]
Motor output	70[W]
Maximum force	75.3[kgf]
Maximum speed	621[mm/s]
Lead of the ball screw	6[mm]



(a) Sliding mechanism
(b) Hip joint
(c) Knee joint
(d) Motor
(e) Ski boot

Figure 3. Powered lower extremity orthosis.

stability is emphasized in a wide space. An ability to surmount steps is required considering the actual environment. Crutches are also used for supplying power when ascending stairs. The powered lower extremity orthosis has an actuator on each joint. Mobile platforms enable the person to travel. Their size is nearly identical to that of shoes. Combining and coordinating these modules allows the following operations that are basic for daily life: travel in a standing position, even on uneven ground; a standing-up motion from a chair; and ascending stairs.



(a) Rotation board
(b) Steering motor
(c) Center of rotation of a rotation board
(d) Thrust bearing
(e) Driving motor
(f) Potentiometer
(g) Load cell

Figure 4. Mobile platform.

Table 2. Specifications of a mobile platform.

Weight	4.05[kg]
Size	265 x 87 x 153[mm]
Maximum speed	5.65[km/h]
Driving output	70[W]
Steering output	20[W]
Maximum angular velocity of the rotation board	143[deg/s]
Operational range of the rotation board	$-45 \le \theta\,[\text{deg}] \le 45$

III. Design of Each Module

A. Elastic Crutch

The length of the elastic crutch is adjustable by touch switches attached to the grip through a microcomputer (V55 board, 16 MHz; Japan System Design Co., Ltd.). The touch switch serves not only to limit adjustment of the crutch length; it is also changeable according to the desired task. The main roles of this module are to maintain body balance and to supply power. Fig. 2 shows the elastic crutch with an inclinometer and a measurement wheel. Table 1 shows elastic crutch specifications.

B. Powered Lower Extremity Orthosis

The powered lower extremity orthosis is for actively fixing, bending, and stretching each leg joint. This module has actuators at the hip joints and knee joints. As a person puts on a pair of ski boots, ankle joints are able to bend passively. This

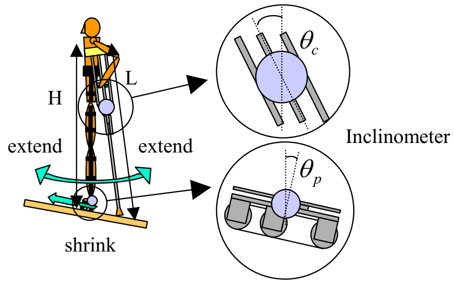


Figure 5. Action with straight motion in a standing state.

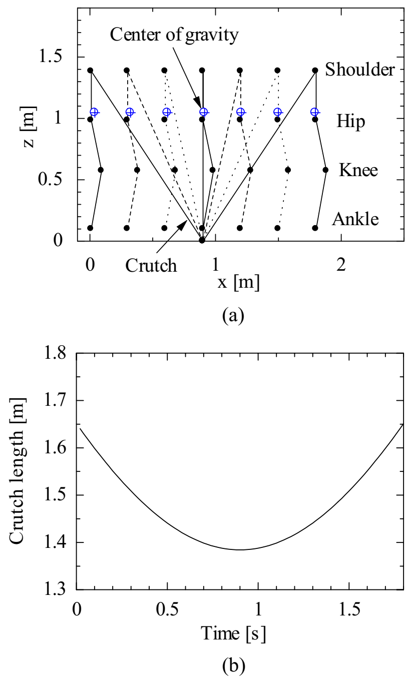


Figure 6. Simulation for straight motion in a standing state.

module is being made now. Fig. 3 shows the conceptual scheme of the powered lower extremity orthosis.

C. Mobile Platform

Mobile platforms carry the user not only on flat floors, but also on uneven ground, or even outdoors, because they use crawlers for the transfer mechanism.

These platforms also enable a user to turn. Two mechanisms turn the platform: one is the power wheeled steering mechanism and the other is a rotation board mechanism. However, the former is simple, requiring much torque when loading a heavy weight because the distance of the two crawler belts is narrow. We confirmed that case through experiments. We adopted the latter mechanism. Fig. 4 shows the mobile platforms. One load cell is installed between the base part and the rotation board. Table 2 shows the mobile platform specifications. The platform is fixed to the ski boot with a binding.

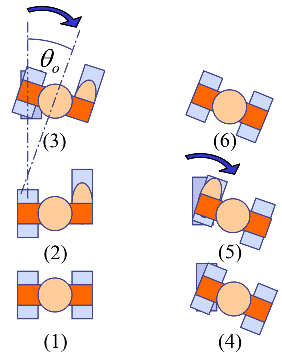


Figure 7. Sequence when rotating in a standing state.

IV. COOPERATIVE OPERATION

This section presents discussion of concrete motions of each module for three representative actions.

A. Traveling in Erect Posture

This action has two phases: straight motion and rotation. At least one side of crutches is on the ground in each phase to prevent turnover.

During straight motion, all angles of the powered lower extremity orthosis are fixed and the mobile platform produces a propelling force to move the user. In this action, the elastic crutches repeat telescopic motions so that the person may touch the ground with the crutches immediately when losing balance. It is desirable that the motions are automated. Automation of telescopic motions is realized by installation of inclinometers to the elastic crutches and the mobile platforms. Fig. 5 shows the action when going straight in a standing state. Target crutch length L is calculated from Eq. (1), where the distance from the armpit to the ground is H, the tilt angle of the crutch is θ_c, and the tilt angle of the mobile platform is θ_p. The simulation when going straight on the flat surface in a constant velocity is shown in Fig. 6(a). The crutch length changes as in Fig. 6(b).

$$L = \frac{H}{\cos\theta_c + \tan\theta_p \sin\theta_c}. \quad (1)$$

When rotating, the powered lower extremity orthosis lifts the legs, the rotation board of the mobile platform rotates the base of the platform, and the crutches support the body, as shown in Fig. 7. In that figure, panels (1) to (6) show the process of rotating from the top view. The process starts from the state condition of support of both legs (1). The right leg is lifted from the ground by the powered lower extremity orthosis in (2) and the rotation board of the left side is made to rotate for optional angles θ_o by the switch attached to the grip of the crutch in (3). The right leg is grounded again in (4). Next, the left leg is lifted and the rotation board of the left side is made to rotate for $-\theta_o$ in (5). Finally, the left leg is grounded in (6).

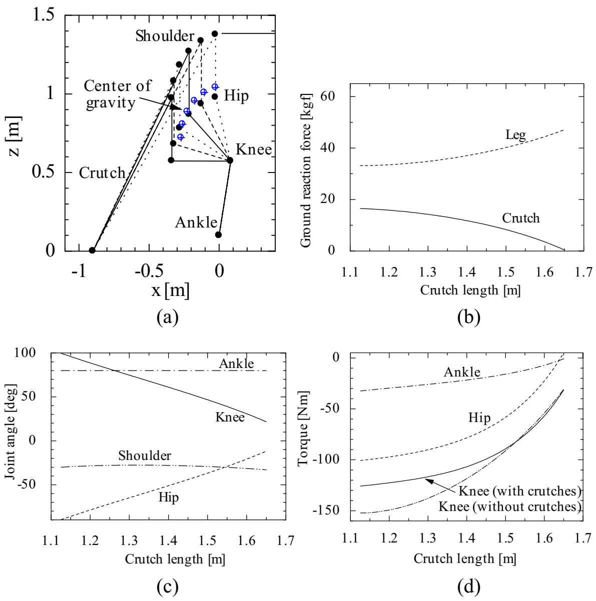


Figure 8. Simulation of standing up from a seating position.

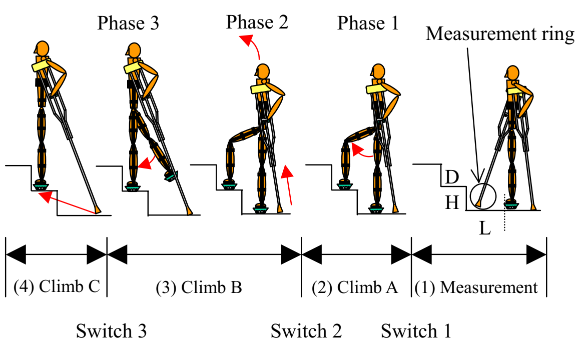


Figure 9. Ascending stairs in a standing state.

B. *Standing up and sitting down*

The elastic crutches play an important role in standing up and sitting down. They support the body weight. The powered lower extremity orthosis controls the angle of each joint in synchronization with the crutches. The mobile platforms maintain their positions. Fig. 8 shows a simulation of standing up from a seated position: Fig. 8(a) shows the state; Fig. 8(b) shows the relationship between the crutch length and the ground reaction force; and Fig. 8(c) shows the transition of each joint angle. In this action, large torque is required at the knees. Fig. 8(d) shows a simulation of comparison of knee torques with and without the crutches. These figures show that the required torque is clearly less when using the crutches, especially at the beginning.

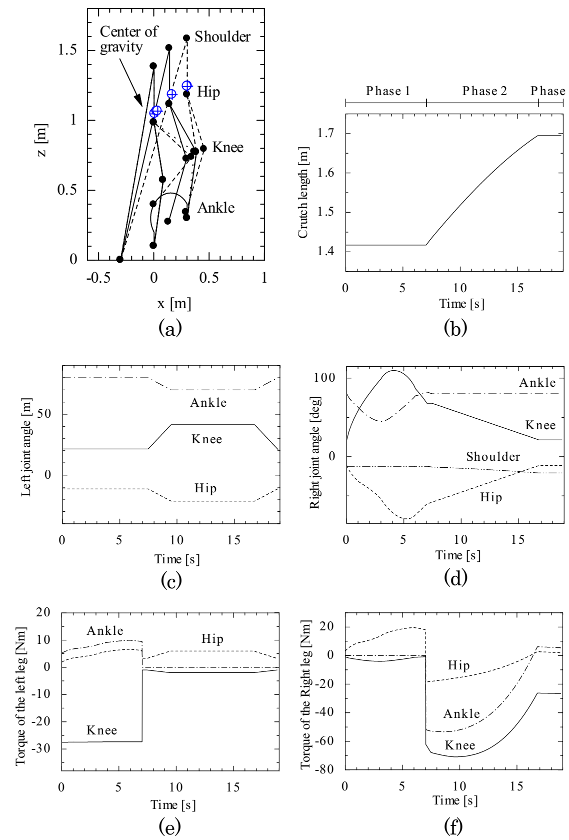


Figure 10. Simulation of ascending stairs.

C. *Ascending and Descending Stairs*

Ascending and descending stairs are applications of standing up from a seat. The mobile platforms do not move without approaching the stairs. Fig. 9 shows the sequence. In (1), a measurement wheel attached at the tip of the crutch measured the parameters of stairs, the distance to the stairs L, the height H, and the depth D. The trajectory to ascend stairs is calculated based on those parameters. Then the person approaches the stairs. In (2), the right leg is moved along the trajectory to the first step of the stairs controlled by the powered lower extremity orthosis (Phase 1). In (3), the elastic crutches lift the body on the first step (Phase 2); then the orthosis moves the left leg avoiding bumping the leg against the stair (Phase 3). In (4), the crutches are shrunk to the legs after the center of gravity of the body shifts on the mobile platform. The operation is simply repeated after the second step: the patterns of ascending stairs are (1) $\rightarrow$ (2) $\rightarrow$ (3) $\rightarrow$ (4), (2) $\rightarrow$ (3) $\rightarrow$ (4), (2) $\rightarrow$ (3) $\rightarrow$ (4), $\cdots$. At each transition point, the touch switch attached to the grip of the crutch is pressed to confirm the motion.

Fig. 10 shows a simulation of ascending stairs where the height of the stair H =20 cm and the depth D =30 cm: Fig. 10(a) shows the state; Fig. 10(b) shows the time response of the crutch length; Figs. 10(c) and 10(d) show the time response of

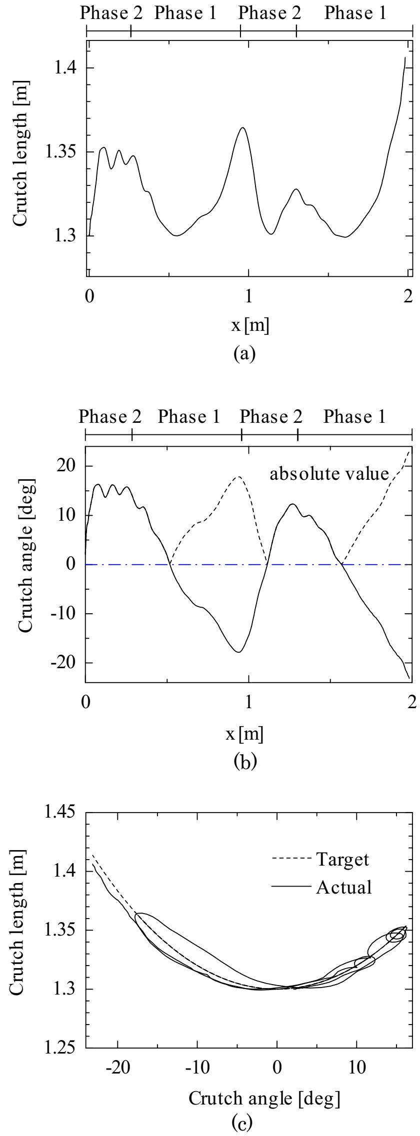


Figure 11. Experimental results for straight motion in a standing state.

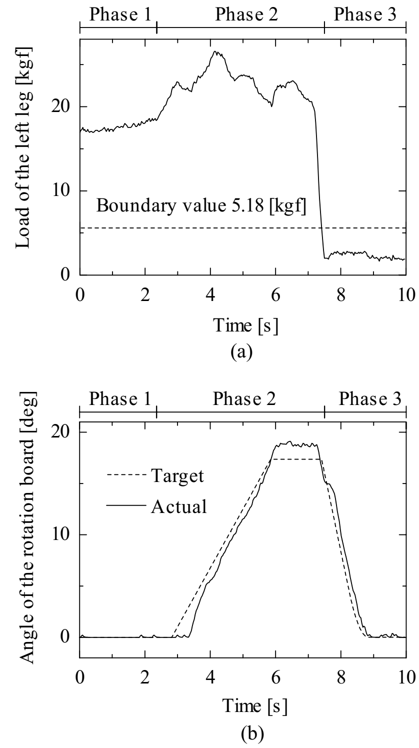


Figure 12. Experimental results when rotating in a standing state.

the joint angles; and Figs. 10(e) and 10(f) show the time response of the leg torque.

V. EXPERIMENTS

This section addresses travel with a standing position. Inclinometers were attached only to the crutches because the experimental environment surface was flat.

A. Straight Motion

Mobile platforms moved straight at a constant velocity; the elastic crutches were used for maintaining balance. Lengths of crutches were automatically adjusted based on Eq.(1). However, the inclinometer outputs were disturbed at the moment when the crutch touched on the ground. Data were filtered by a low-pass filter that had the first Butterworth characteristics. Results are shown in Fig. 11. In Phase 1, the crutch was on the ground and its angle was changed according to the traveling distance of the mobile platforms x. In Phase 2, the crutch was swung to change the contact point on the ground. Fig. 11(a) and Fig. 11(b) show the relationship between the position of the body and the crutch length and angle respectively. Fig. 11(c) shows correspondence of the crutch angle and length, and it shows the tracking performance of the crutch. Crutches were controlled based on PD control theory.

B. Rotating

The rotation sequence is shown in Fig. 7. It is difficult to go straight if substantial rotational error remains after the rotating action. A returning operation to the neutral rotational angle would preferably be controlled automatically, not manually, at (5) of Fig. 7. The load cell installed between the base part and the rotation board senses the load weight. It informs the timing when the rotation board should be rotated. Fig. 12 shows time responses of the load and the angle of the rotation board of the left side. The boundary value was 5.18 kgf. The rotation board was controlled based on PD control theory. Fig. 12(a) can be separated into three phases: (1) of Fig. 7 is included in Phase 1; from (2) to (4) of Fig. 7 are in Phase 2; (5) of Fig. 7 is in Phase 3.

Fig. 12(b) shows the time response of the angle of the rotational board. The final error of the rotation board was about 0.19 deg.

VI. SUMMARY

This study proposed straight style transfer equipment that helps users with disabled lower limbs to enjoy their life without special infrastructure. This equipment comprises a pair of elastic crutches, a powered lower extremity orthosis, and a pair of mobile platforms. We showed the conceptual design of this equipment and the motion of each module. We discussed how to realize three basic actions in daily life: traveling in a standing position, a standing up motion from a chair, and ascending stairs. Experiments showed that traveling and rotating with a standing position were possible by cooperative operation of modules semi-automatically.

In future work, we plan to repeat improvement of this equipment for practical use: traveling in the field; embarking, riding, and debarking from a train; and so forth.

ACKNOWLEDGMENT

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