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Development of a Standing Style Transfer System ABLE with Novel Crutches for a Person with Disabled Lower Limbs*

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Abstract
A standing style transfer system, ABLE, is designed to assist a person with disabled lower limbs to travel in a standing position, to stand up from and sit down in a chair, and to go up and down steps. The ABLE system comprises three modules: a pair of telescopic Lofstrand crutches, a powered lower extremity orthosis, and a pair of mobile platforms. In this paper, the telescopic Lofstrand crutch is mainly discussed. This crutch has no actuator, and its length is switched between two levels; it assists the person when standing up and sitting down in the short length state, while it maintains the body stability in a standing position when traveling in the long length state. The experimental results related to the traveling in the standing position and standing up motion confirm the design's effectiveness.

Key words: Disabled Lower Limbs, Wearable, Standing Position, Moving Robot, Welfare Assistance, Lofstrand Crutch, Telescopic Motion

1. Introduction

Persons with disabled lower limbs are increasing globally. In Japan, their number was about 627,000 in 2006 (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 stability. Notwithstanding, they engender several problems. Wheelchairs require much space during travel and facility use. It is difficult to go up and down steps. 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 standing position.

Some standing style power-assisted systems have been developed: HAL (2), W.W.H-KH (3), RoboKnee (4), and so forth (5)-(7). Few systems, however, are designed for a severely disabled person. Although Sankai’s research group has been trying to apply HAL to assist people with spinal-cord injuries, the user still cannot operate it freely. Independence Technology L.L.C. developed the “iBOT®”, an electric wheelchair that gets up and balances using only two wheels, such as an inverted pendulum (8). However, it requires much space and medical problems from sitting remain unresolved. Moreover, iBOT® is unsuitable for all stairs in

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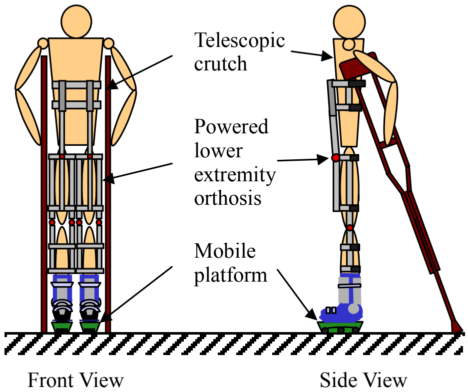


Fig. 1 Conceptual design of ABLE.

terms of the safety load, installation of a handrail, and the stair width. Previous studies have examined telescopic crutches and auxiliary tools for binding the legs. 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 [(9)]. This equipment is, however, intended for rehabilitation and its only available motion is to go straight.

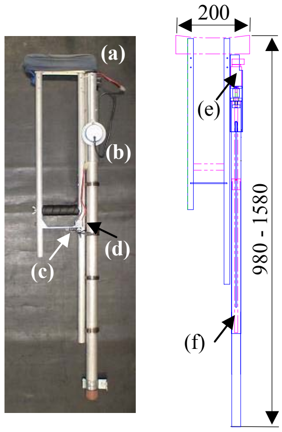
ABLE is mainly for the persons who have spinal cord injuries and cannot move hip joints and under: the level of spinal cord injury is L1 [(10)-(13)]. ABLE comprises three modules: a pair of telescopic crutches, a powered lower extremity orthosis, and a pair of mobile platforms, and it realizes three basic operations that are indispensable for our daily life: traveling in a standing position, even on uneven ground; standing up motion from a chair; and ascending stairs. In this study we propose a telescopic Lofstrand crutch as a substitute for the previous telescopic crutch for the purpose of usability. The crutch has no actuators, and its length is switched between a short stage and a long state. We show the experimental results of traveling and standing up motions with the telescopic Lofstrand crutches.

2. Design of ABLE

Figure 1 shows the illustration of ABLE that comprises three modules: a pair of telescopic crutches, a powered lower extremity orthosis, and a pair of mobile platforms. Telescopic 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 eases the movement through narrow spaces, whereas stability is emphasized in a wide space. The powered lower extremity orthosis has an actuator on each hip and knee joint and actively fixes, bends, and stretches each joint. Mobile platforms enable the user to travel [(12), (13)].

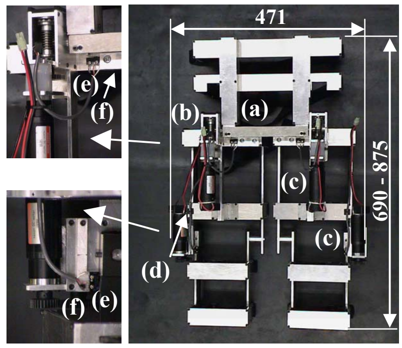
Figure 2 depicts the telescopic shoulder crutch. It has a DC motor (70W) connected directly to a ball screw, and the crutch length is measured using an encoder connected to the motor. The weight is 2.9kg: its dimensions are 200 (W) × 65 (L) × (980-1580)(H) mm, and the maximum force is 75.3 kgf (transmission efficiency = 90%) and the maximum speed (with no load) is 621 mm/s. Two touch switches attached under the grip are used as the ABLE interface. These switches serve not only to limit adjustment of the crutch length; they are also changeable according to the desired task. The crutch length is also controlled automatically by PC using the reference value of an inclinometer attached to the crutch.

Figure 3 portrays the powered lower extremity orthosis. Ankle joints can move only slightly because the user puts on a pair of ski boots (27.5–29 cm, Freecarve; The Burton Corporation). The weight is 10.0 kg and the dimensions are 471 (W) × 246 (L) × (690–875)



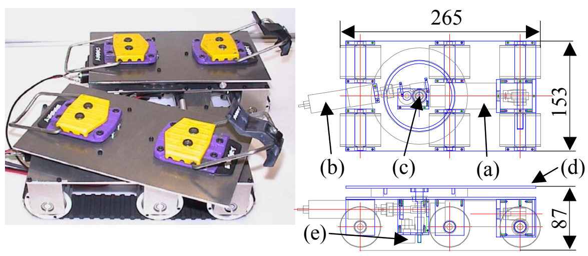
(a) Cushion
(b) Inclinometer
(c) Touch switches
(d) Emergency stop switch
(e) Motor
(f) Ball screw

Fig. 2 Telescopic shoulder crutch.



(a) Sliding mechanism
(b) Hip joint
(c) Motors
(d) Knee joint
(e) Touch switches
(f) Stoppers

Fig. 3 Powered lower extremity orthosis.



(a) Driving motor
(b) Steering motor
(c) Center of rotation
(d) Rotation board
(e) Potentiometer

Fig. 4 Mobile platform.

(H) mm. The same DC motors (70 W) and gearboxes (1/411) are used for each hip and knee joint. The maximum torque is 12.9 kgf m (transmission efficiency = 39.2%), and ranges of motion of the hip and knee joints are, respectively, from 0 to -145 deg and from -135 to 0 deg. The maximum angular velocity (with no load) is 90.7 deg/s. 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. Comparing this mechanism with back-drivable mechanisms, each joint consumes little energy if the user does not change his/her posture. Each joint has a stopper and a touch switch. They work together to retain the movable scope of the human joint.

The user puts on a pair of mobile platforms, as shown in Fig. 4. They carry the user not only on flat floors, but on uneven ground or even outdoors because of the crawlers for the transfer mechanism. The weight is 4.1 kg and the dimensions are 265 (W) × 153 (L) × 87 (H) mm. The platform has two DC motors: one DC motor (70 W) and a gearbox (1/10) are used for driving; another DC motor (20 W) and a gearbox (1/376) are used for steering. The maximum speed with no load is 7.5 km/s, and the ranges of rotation are from -45 to 45 deg. The maximum angular velocity (with no load) is 143 deg/s.

3. Design of Telescopic Lofstrand Crutch

3.1 Mechanism of the telescopic Lofstrand crutch

The weak points of the shoulder telescopic crutch are the heavy weight and the necessity of controlling the actuator using an encoder and an inclinometer that interferes quick motions, particularly in the standing position. In this paper we propose a novel type of

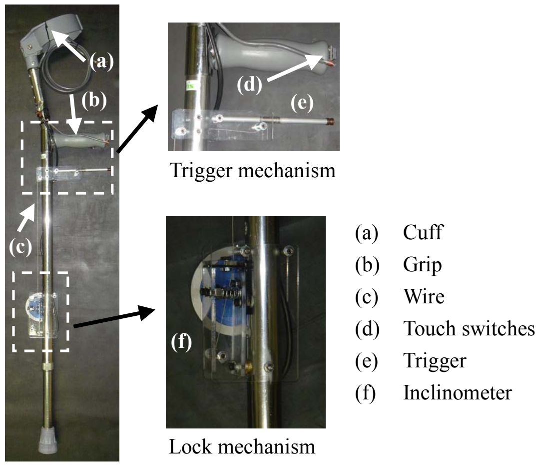


Fig. 5 Telescopic Lofstrand crutch.

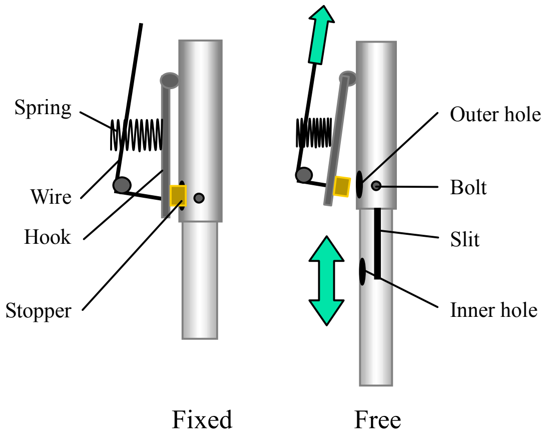


Fig. 6 Mechanism of the telescopic crutch.

telescopic crutch as follows:

1. We use a pair of Lofstrand crutches in order to adjust the distance from the body to the floor by using elbow joints. Therefore minor adjustment of the crutch length is not necessary.
2. The length of the crutch is possible to switch in two states: short and long. The short length is better when standing up from a chair because the user feels a pain due to unnatural posture if the length of the crutch is long. On the other hand, the length has to be long when traveling in the standing position so that the tip of the crutch can reach the ground.
3. The mechanism of the adjustment of the states is realized with no actuators; therefore, the crutch is light and has high manipulability.

Figure 5 shows the telescopic Lofstrand crutch, and its telescopic mechanism is shown in Fig. 6. If the user pulls the trigger, the wire connected to the trigger lifts the hook and the user is able to switch the length of the crutch. The crutch becomes short if the user pushes it against the ground, while it becomes long by the force of gravity if the user pulls the trigger with the tip of the crutch downward. The weight of a telescopic Lofstrand crutch is 0.86 kg (without the inclinometer). Two touch switches attached under the grip are used for sending a start signal to the PC as well as those of the former type. An inclinometer attached to the crutch is used for measuring the angle of the crutch and is needless for controlling the crutch length.

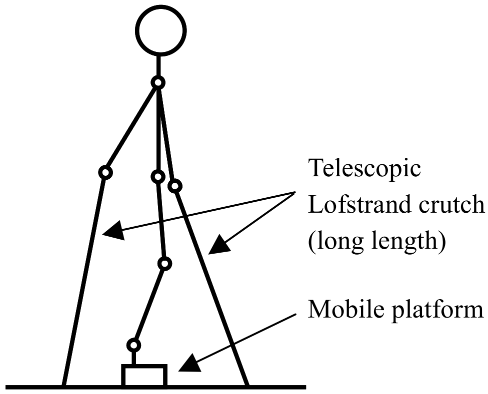
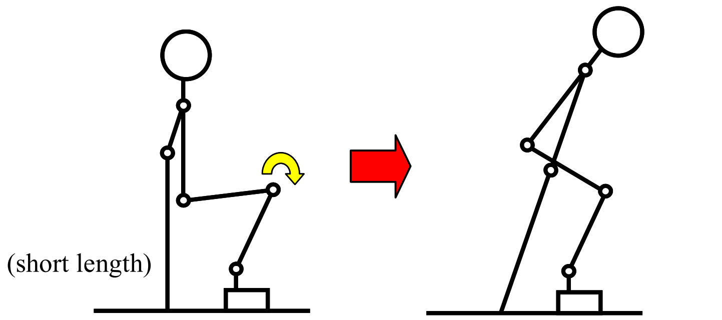


Fig. 7 Traveling in a standing position.



(a) sitting position. (b) half-sitting position.

Fig. 8 Standing up motion.

3.2 Cooperative operation of modules

Figure 7 shows a standing position when traveling. The hip and knee joints of the powered lower extremity orthosis are fixed. The crutch is in the long state. The user places the right and the left crutches forward and backward to the body respectively so as to prevent the body from falling.

The standing up motion is realized by coordinating the telescopic Lofstrand crutches and the powered lower extremity orthosis. There are three phases in this operation.

(1) In Phase 1, the user shifts from the sitting position to the half-sitting position, as shown in Figs. 8 (a), (b) respectively, by moving the upper part of the body forward. Only the knee joint angles increase and the hip joint angles keep constant in order to shift the center of gravity (COG) of the human on the mobile platforms as soon as possible. The crutch length is short during this phase.

(2) In Phase 2, the user extends the crutches in the half-sitting position. If the user can keep the balance in this position, he/she extends both of the crutches at the same time. However, the user is able to realize the stable motion by extending them one by one.

(3) In Phase 3, the user stands up gradually maintaining the balance of the body. The user shifts from the half-sitting position to the standing position in Fig. 7.

4. System model

Figure 9 shows a human model wearing ABLE. The nomenclature is the following:

Σ_f, Σ_i ($i = 0, 1, \cdots, 6$): Coordinate systems relative to the floor, the foot, the ankle joint, the knee joint, the hip joint, the shoulder joint, the upper limb, and the forearm including the crutch, respectively,

Σ_{Gi} : Coordinate system relative to the center of mass of the link i ($i = 0, 1, \cdots, 5$),

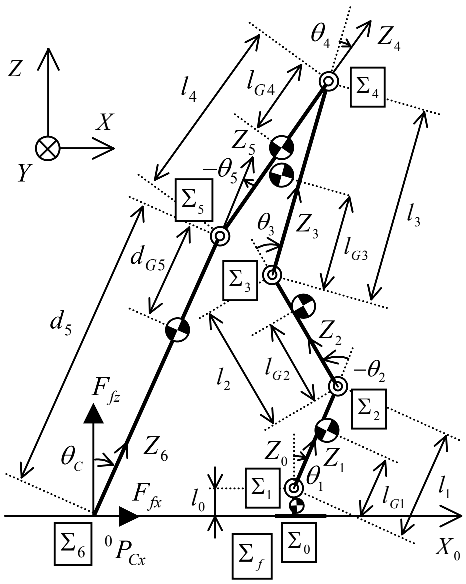


Fig. 9 Model of a human wearing ABLE.

l_* : link length (constant) , and l_*^x, l_*^z are the components of the link length l_* in Σ_*,
d_* : link offset (variable) in Σ_*,
θ_i , θ_{Gi} : joint angles in Σ_i and Σ_{Gi} ($i = 1, 2, \cdots, 5$), respectively,
θ_c : slant angle of the crutch measured from Z_f, which is the z-axis in Σ_f ,
F_{fx}, F_{fz} : floor reaction forces of the crutch tip of X_f and Z_f , respectively.

We assumed that the foot contacts the floor at the point directly below the ankle joint, and the shoulder torque equals zero. By applying the Newton-Euler equations on the condition of a quasi-static model, the floor reaction forces F_{fx}, F_{fz} and joint torque τ_i ($i = 1, 2, \cdots, 5$) , which are summed up both sides of the body, are derived as

$$\begin{aligned} {}^0P_{GAx} = {} & m_0 l_{G0}^x + (m_1 l_{G1}^z + m_{2345} l_1) S_1 + m_1 l_{G1}^x C_1 + (m_2 l_{G2}^z + m_{345} l_2) S_{12} + m_2 l_{G2}^x C_{12} \\ & + (m_3 l_{G3}^z + m_{45} l_3) S_{123} + m_3 l_{G3}^x C_{123} - (m_4 l_{G4} + m_5 l_4) S_{1234} - m_5 d_{G5} S_{12345}, \end{aligned} \tag{1}$$

$$F_{fx} = \frac{F_{fz}(d_5 S_{12345} + l_4 S_{1234}) - d_{G5} m_5 g S_{12345} - l_4 m_5 g S_{1234} - l_{G4} m_4 g S_{1234}}{d_5 C_{12345} + l_4 C_{1234}}, \tag{2}$$

$$F_{fz} = \frac{m_{012345}({}^0P_{GAx} - {}^0P_{Px}) g}{{}^0P_{Cx} - {}^0P_{Px}}, \tag{3}$$

$$\tau_1 = \tau_2 - l_{G1} m_1 g S_{G1} - l_1 (F_{fx} C_1 - F_{fz} S_1 + m_{2345} g S_1), \tag{4}$$

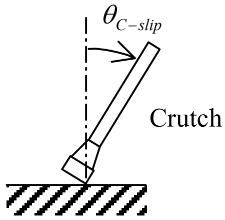
$$\tau_2 = \tau_3 - l_{G2} m_2 g S_{G12} - l_2 (F_{fx} C_{12} - F_{fz} S_{12} + m_{345} g S_{12}), \tag{5}$$

$$\tau_3 = \tau_4 - l_{G3} m_3 g S_{G123} - l_3 (F_{fx} C_{123} - F_{fz} S_{123} + m_{45} g S_{123}), \tag{6}$$

$$\tau_4 = \tau_5 + l_{G4} m_4 g S_{1234} + l_4 (F_{fx} C_{1234} - F_{fz} S_{1234} + m_5 g S_{1234}), \tag{7}$$

$$\tau_5 = d_{G5} m_5 g S_{12345} + d_5 (F_{fx} C_{12345} - F_{fz} S_{12345}), \tag{8}$$

where m_i :mass of the link ($i = 0, 1, \cdots, 5$), S, C : sin and cos respectively, ${}^0P_{Px}, {}^0P_{Cx}$: the x-coordinates of the contact points in Σ_0 for the mobile platform and the crutch



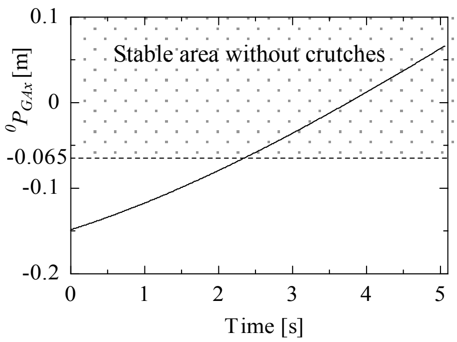
(a) Friction angle.

(b) Rubber crutch cap.

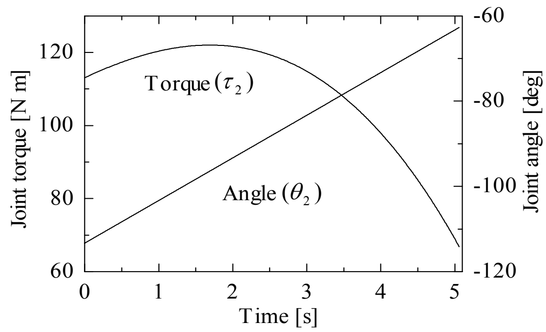
Fig. 10 Measurement of the friction angle of the crutch.

Table 1 Friction angles of three kinds of surfaces.

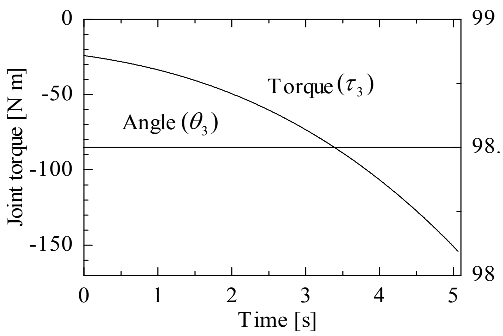
Surface	Direction	Friction angle θ_{C-slip} [deg]
Plastic floor	Forward	-28.7
	Backward	22.0
Carpet	Forward	-56.0
	Backward	50.9
Asphalt	Forward	-53.5
	Backward	52.1



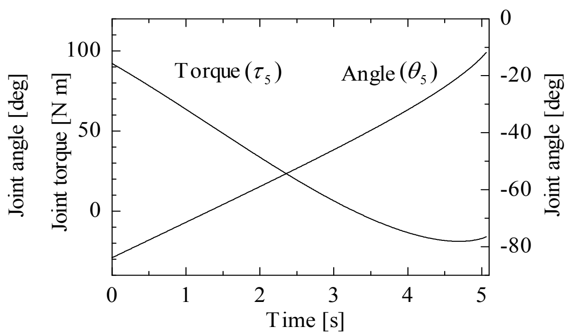
(a) x-coordinate of the COG.



(b) Knee.



(c) Hip.



(d) Elbow.

Fig. 11 Calculated results from the sitting position to the half-sitting position when standing up motion.

respectively, $^0P_{GAx}$: the x-coordinate of the COG of the human model wearing ABLE, and g : acceleration of gravity. The sequent suffixes of m, S, C and θ represent the sum of each component. For example, m_{12} equals the sum of m_1 and m_2.

(a) When starting to travel.

(b) When stopping traveling.

Fig. 12 Traveling in a standing position.

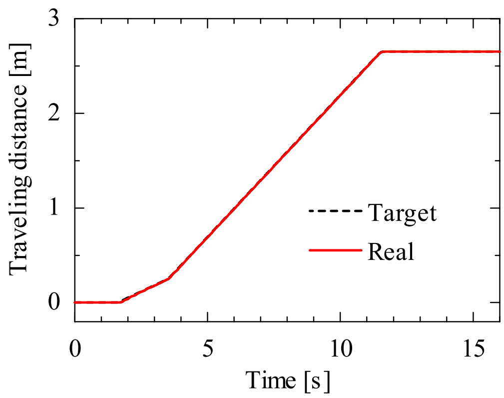


Fig. 13 Experimental results of traveling in a standing position.

First, we discuss the length of the crutch. The long length is related to the standing position (see Fig. 7). If the crutch length is too long, the crutch slips when traveling. Figure 10 (a) shows the situation of measuring the friction angle of the crutch, and Fig. 10 (b) shows the rubber cap attached to the tip of the crutch. Table 1 shows the friction angles of three kinds of surfaces. Each of them is the average of ten measurements for the forward and backward direction, respectively. Each difference between the forward and backward friction angles dues to the grip position of the crutch. We designed the length from the grip to the bottom at 94.3 cm when it is in the long state. In this case, the forward and backward angles of the crutches θ_C are -15.8 deg and 6.8 deg, respectively. Here, θ_1 =20 deg, θ_2 =-25.9 deg, θ_3 =5.9 deg. The forward θ_4 and ${}^0P_{Cx}$ equal 0 deg and 0.44 m respectively, and the backward ones equal 30 deg and –0.20 m respectively (see Fig. 9). Both angles of the crutches (-15.8 deg and 6.8 deg) are within the friction angles of three kinds of surfaces, respectively; therefore, the crutch is designed safely in the long length.

The short length is decided based on the sitting position (see Fig. 8). Too long crutches prevent the user from applying the force to stand up in the sitting position. The user, however, cannot shift the COG on the mobile platforms using the too short crutches in the half-sitting position. We designed the length from the grip to the bottom at 71.5 cm when it is in the short state.

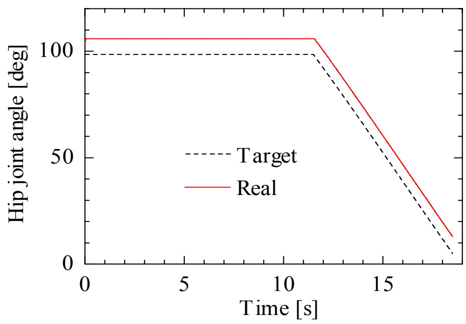
Figure 11 shows the calculated results of the x-coordinate of COG and the joint torques and angles from the sitting position to the half-sitting position when standing up motion, considering the backpack weight (12.2 kg). In the dotted area in Fig. 11 (a), the user is stable without crutches because the COG of the human is within the support polygon formed by the mobile platforms. The x-coordinate of COG of the human wearing ABLE ${}^0P_{GAx}$ is increasing monotonously and is within the stable area after 2.4 s. The knee torque in Fig. 11 (b) is decreasing as a whole. In Fig. 11 (c), the hip motor does not have to produce

(a) Phase 1.

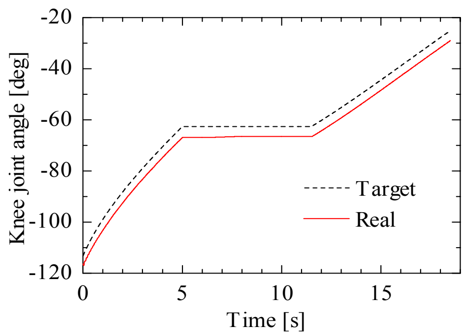
(b) Phase 2.

(c) Phase 3.

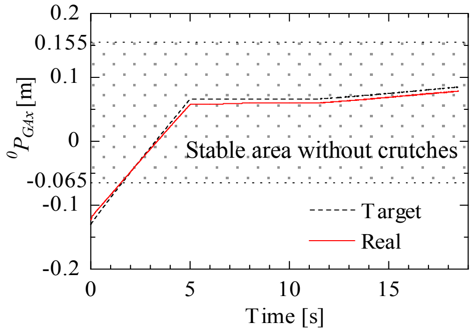
Fig. 14 Snap shots of an experiment of standing up motion from a chair.



(a) Time response of the hip joint.



(b) Time response of the knee joint.



(c) Time response of the x-coordinate of the COG.

Fig. 15 Experimental results of standing up motion from a chair.

large torque because the hip joint angle is constant and its gearbox is not back-drivable. Figure 11 (d) shows that the user requires the large elbow torque at the beginning of the standing up motion; however the torque is decreasing. Here, the sign of the elbow torque changes around 3.3 s, and this corresponds to the sign of ${}^{0}P_{GAx}$. These results mean that the system needs less electric power as the user stands up.

5. Experiment

In this section we address two basic operations that are indispensable for daily life: traveling in a standing position; standing up motion. We used ART-Linux as an operating system in view of the stability (14). The PC was libretto U100 (CPU 1.1 GHz). The interface board was a Ritech Interface Board (IF-0145-1, ZUCO Co., Ltd.). The command was transmitted via wireless LAN. Each module was controlled based on PD control theory. The sampling time was 10 ms. The subject was a man with no leg motion impairment whose height was 166 cm and weight was 65 kg.

Figure 12 displays the appearance of traveling in a straight line in a standing position. The ankle, knee, and hip joints are fixed: θ_1=20 deg, θ_2=-25.9 deg, and θ_3=5.9 deg, which are the same values in Section 4. In this position, the x-coordinate of the COG of the human wearing ABLE ${}^{0}P_{GAx}$ calculated from the Eq. (1) is 0.08 m. The floor was flat. The user can control the traveling velocity with two buttons attached to the touch switches of the right crutch; the forward one is for accelerating and the backward one is for decelerating. Both mobile platforms were controlled based on the same trajectory. The target velocity was 0.3 m/s. Figure 13 shows the time response of the traveling distance. The accelerating time was about 2 s, whereas the stopping time was about 0.2 s in order to avoid collisions. The user touched the ground with the crutches alternately.

The snap shots of an experiment of standing up motion from a chair using a pair of the telescopic Lofstrand crutches are shown in Fig. 14. The chair height was 45 cm, and the crutch tip position was 50 cm behind the ankle. The experimental results are shown in Fig. 15. Figures 15 (a), (b) show the time response of the hip and knee angles, respectively. Only the knee joint angles increase from –113.3 deg to –62.7 deg and the hip joint angles keep constant from the sitting position to the half-sitting position. Although there are some tracking errors, the subject succeeded in standing up. The user required the large elbow torque in the beginning of standing up motion. This corresponds to the calculated results in Fig. 11 (d). Figure 15 (c) shows time response of the x-coordinate of the COG. Here, the weight of the arms and the crutches are ignored because of the difficulty of measuring the actual shoulder angle in 3D and the low ratio of weight (5.8 %). In the dotted area, the subject was stable without crutches, and he changed the crutch length in the half-sitting position between 5 s and 11.5 s, and then stood up gradually keeping the COG position.

In ABLE system, the stability when traveling in a standing position is the most important issue. Traveling in the standing position presents the danger of falling, especially when starting and stopping. 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. In addition we are considering a standing support plate attached to the mobile platform for contributing stability.

6. Conclusions

This study proposed a standing style transfer system ABLE that helps users with disabled lower limbs to enjoy mobility without special infrastructure. ABLE comprises a pair of telescopic crutches, a pair of mobile platforms, and a powered lower extremity orthosis.

We proposed the telescopic Lofstrand crutch as a substitute for the telescopic shoulder crutch. The merit of the telescopic Lofstrand crutch is its light weight because it has no motor. The length of the crutch is possible to switch mechanically in two states: a short state and a long state. The distance from the body to the floor is adjusted by using elbow joints. We demonstrated the effectiveness of this crutch through the experiments of the traveling in the standing position and the standing up motion from a chair.

The subject for this study, however, was a person with no leg motion impairment. Therefore, the results of this study merely present the possibility of the use of this system. As future works, we plan the improvement of this system for better practical use and will attempt to use ABLE in various actual environments, and plan to test ABLE for persons with disabled legs under secure circumstances. We also consider utilization of ABLE for rehabilitation or boosting motivation under the support of physical therapists at a rehabilitation center.

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