CASE REPORT

Real-time measurement of frozen gait in patient with parkinsonism using a sensor-controlled walker

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Abstract : Patients with Parkinson's disease develop gait disturbances. Although the use of walkers is very effective for maintaining locomotive ability, patients who have symptoms such as frozen gait (*FG*) and festinating gait may fall even with a walker equipped with a brake as they cannot use the brake well in an emergency and fail to follow the accelerating walker. None of the studies on walking aids to date have addressed real-time detection of *FG* or the use of this information for the control of the walking aid, monitoring of the state of improvement in the ambulatory function, or evaluation of the effect of the use of a walker. In this study, we evaluated whether the state called *FG*, a characteristic symptom of Parkinson's disease, can be detected by the use of a sensor-controlled walker with heel-to-toe pressure sensors. The following two measurements were carried out in one male healthy and a one male patient with stage 3 Parkinson's disease by the Hoehn-Yahr scale showing mild muscle rigidity, hypokinesia, and *FG*. In the healthy subject, the heel-to-toe pressure showed smooth heel-to-toe shifts during the standing phase. In the patient with Parkinson's disease, the heel-to-toe response time was about 2.4 times longer than in the healthy subject at the beginning of walking, and *FG* could be recorded as the difficulty in lifting the foot by the toes. Also, when *FG* was observed during walking, the pressure waves recorded by the same sensors showed two peaks occurring at a short interval, indicating double landings. J. Med. Invest. 51 : 108-116, February, 2004

Keywords : *sensor-controlled walker, heel-to-toe pressure sensors, parkinsonism, frozen gait*

INTRODUCTION

The number of patients with Parkinson's disease is estimated to be about 10 million in the world, and it is expected to exceed 40 million by the year 2020 with the increase in the elderly population (1). Patients with Parkinson's disease invariably develop gait disorders, which pose major difficulties in daily living. There is

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the report that 41% of patients in stage 2 and 64% of those in stage 3 by the Hoehn-Yahr scale have suffered from falls (2). Such patients who are likely to fall and those who have sustained fracture of the neck of the femur due to falling hesitate to walk for fear of falling again. This leads weakening or atrophy of limb muscles or joint contracture, which often lead to a bed-ridden state.

Walker may be the most effective environmental approaches to preventing falls (3), and also very effective for the prevention of a bed-ridden state, but patients who have symptoms such as frozen gait and festinating gait may fall even with a walker equipped with a brake as they cannot use the brake well in an emergency and cannot follow the accelerating walker (4, 5). Therefore, analysis of the relationship between gait disorders and the walker function and the development of a walking aid that prevents falling are needed.

None of the studies on walking aids to date (6, 7) have addressed real-time detection of frozen gait or the use of this information for the control of the walking aid, monitoring of the state of improvement in the ambulatory function, or evaluation of the effect of the use of a walker.

We devised a walking aid with a control function for the prevention of falling of the patient. This walking aid is controlled on the basis of information concerning " frozen gait ", which is a cause of falling, collected real-time.

In this study, we directed our attention particularly to characteristic symptoms of Parkinson's disease such as (a) the difficulty in making the first step at the beginning of walking and halting there after a few small stamps, (b) a state in which the feet appear fixed on the floor, and (c) the inability to step forward and consequent falling during walking when the patient suddenly has to walk through a narrow path. We evaluated whether the above conditions, which are called " frozen gait ", can be detected or not by the use of our tentative model of walking aid with heel-to-toe pressure sensors.

METHODS

1. Composition of the devices and safety mechanisms

1) Walking aid

Figure 1 shows the appearance of the sensor-controlled walker. This device is a Hitachi Automatic Walking Aid (JHS-1, Hitachi Chemical Co., Ltd.) with motors attached to both rear wheels. Position sensors were also mounted on the walking aid. Light-emitting diodes

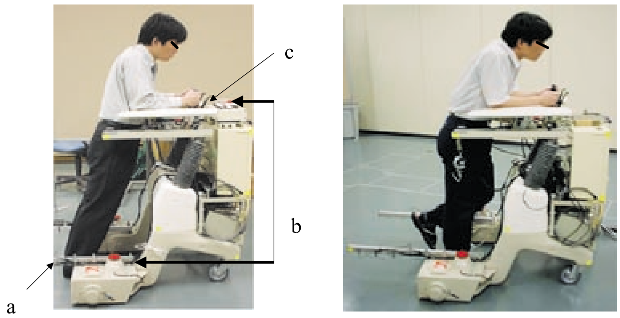


Figure 1. Sensor-controlled walker
a : Position sensors were also mounted on the walking aid. Light-emitting diodes were attached to the left lower part, and light sensors in the right lower part, of the walking aid at even intervals and opposing each other pair-wise, and the positions of the feet were detected as the feet block the light between the light-emitters and the sensors.
b : As safety mechanisms, two emergency stop buttons each were placed on the bilateral driving mechanisms and the handles.
C : Pressure sensors were attached to the bases of the handled, which the subject held while walking, so that the force of pushing by the subject could be detected.

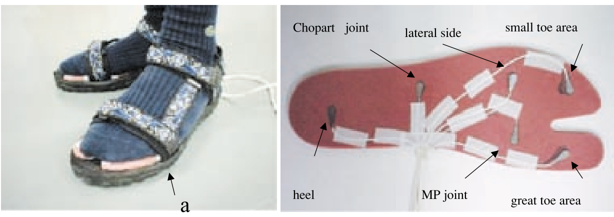
were attached to the left lower part, and light sensors in the right lower part, of the walking aid at even intervals and opposing each other pair-wise, and the positions of the feet were detected as the feet block the light between the light- emitters and the sensors. In addition, pressure sensors were attached to the bases of the handled, which the subject held while walking, so that the force of pushing by the subject could be detected. The wheels of the walker were driven by AC servomotors with built-in encoders. As safety mechanisms, two emergency stop buttons each were placed on the bilateral driving mechanisms and the handles. The above position sensors and the force sensors along with the heel-to-toe pressure sensors described below were connected to a personal computer (DOS/V) that controlled the walking aid, and data synchronized with the movements of the walking aid were collected real-time. *C language* was used for programming the software for the control of the walking aid and data collection.

2) Control methods and safety measures

Patients with Parkinson's disease are likely to fall as their feet lag behind the movement of the walker due to festinating gait or frozen gait. The force that pushes the walking aid forward increases when festinating gait occurs, and as the walker is accelerated by this force, the patient becomes unable to move the feet at the speed of the walker, increasing the risk of falling. Therefore, the following control paradigms and safety measures were adopted. When the subject pushes the two handles of the walking aid, the forward movement is sensed by the force sensors, and the walking aid is driven at a fixed speed. As safety measures, the emergency stop buttons mentioned above were placed in easy reach of the subject. Moreover, when the light on the sixth sensor was blocked by the patient's feet as they lag behind the walker, the risk of falling was judged to be high, and the walker was stopped automatically.

3) Heel-to-toe pressure sensors

Small pressure sensors (PS-10 KAM183, Kyowa Dengyo) were arranged at 6 sites of sponge insoles, which were attached to the sandals. The sandals were adjusted by the use of Velcro straps according to the size and shape of the feet of each subject. The sensors were placed at the heel, MP joint, Chopart joint, lateral side, great toe area, and small toe area according to the shift of heel-to-toe pressure reported by Turu *et al.* (8) and Nagata *et al.* (9)(Figure 2). Changes in the heel-to-toe pressure at these sensors during walking were recorded in both feet.



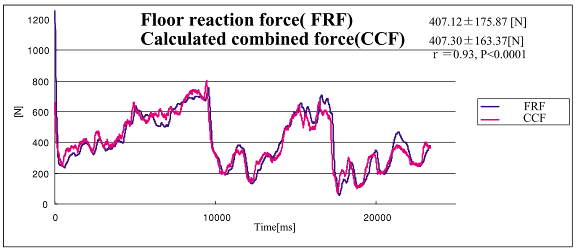
Planter pressure sensors [a]   Sensors position [b]

Figure 2. Planter pressure sensors and position of the sensors
a : The sandals were adjusted by the use of Velcro straps according to the size and shape of the feet of each subject.
b : Small pressure sensors were arranged at 6 sites of sponge insoles, which were attached to the sandals. The sensors were placed at the heel, MP joint, Chopart joint, lateral side, great toe area, and small toe area.

4) Representation of the combined heel-to-toe pressure

The area of measurement by each sensor must be estimated to convert the pressure [kgf/cm^2] measured with the heel-to-toe pressure sensors into force [N]. In this study, multiple regression analysis was carried out, and this area was determined from the regression constant and partial regression coefficient. In the analysis, the pressure data from the heel-to-toe pressure sensors were used as the independent variable, and the vertical vector of the reactive force from the floor [EFP-S-2 KNSA12, Kyowa Dengyo] as the dependent variable.

Since the MP joints are related to the driving force (10-12), the data used for calculation of the combined force were restricted to those from the sensors at the heel, Chopart joint, MP joint, and lateral side. Figure 3 shows the combined force calculated from the 4 planter pressure sensors and the vertical component of floor reaction force with the multiple regression equa-



Calculated combined force =W

W_L : Left foot W_R : Right foot

$$W = \sum_i A_1 X_1$$

W_L=0.269X_1+1.027X_2+0.394X_3+0.243X_4-0.1853
W_R=0.274X_1+1.059X_2+0.475X_3+0.129X_4-0.1929

A: the area of validity
X: forces from each sensors

X_1 :heel X_2 :Chopart joint
X_3 :MP joint X_4 :lateral side

Figure 3. Combined force calculated from heel-to-toe pressure sensors and vertical component of floor reaction force (right foot)

tion. Pearson's correlation coefficient was determined to examine the precision of the multiple regression coefficient, and significant precision was confirmed (r=0.93, p<0.0001).

2. Experimental procedures and subjects

1) Experiment using a healthy subject

The subject was a 21-year- old healthy male who was 163 cm tall and weighed 55 kg. The sampling time was 10 ms, and the heel-to-toe pressure sensors were calibrated during stationary standing of the subject.

The following two measurements were carried out in this experiment.

(1) The subject was asked to walk naturally without any direction (free walking), and changes in the heel-to-toe pressure during walking were recorded.

(2) While the subject put his forearms on the elbow rests of the walking aid, their height was adjusted to a level comfortable for the subject to walk. The subject walked at a fixed speed of 0.13 m/s with the walking aid (aided walking), and changes in the heel-to-toe pressure were recorded.

2) Experiment using a patient with Parkinson's disease

(1) The patient was a 76-year- old male with Parkinson's disease with a height of 165 cm and a weight of 53 kg. He showed mild muscle rigidity, hypokinesia, and frozen gait, and was rated at stage 3 according to the Hoehn-Yahr severity scale.

(2) The gait of the patient during free walking and aided walking was analyzed using the heel-to-toe pressure sensors. In this study, a physician and a physiotherapist evaluated the gait of the patient, and the speed of aided walking was set at 0.20 m/s in consideration of the mean maximum speed (13) of individuals comparable in age with the patient. To prevent the patient from falling, two physiotherapists accompanied the

patient during the experiment and monitored his movements. Informed consent was obtained from the patient and his family before the study.

RESULTS

1. Heel-to-toe pressure of the healthy subject

1) Free walking

The upper panel of Figure 4 shows changes in the vertical component of the pressure waves of the right foot recorded through the heel-to-toe pressure sensors. The pressure [kgf/cm^2] is shown along the vertical axis, and the time [ms] is shown along the horizontal axis. In each graph, the standing phase (ST) and swinging phase (SW) are marked with vertical lines. During the standing phase, the heel-to-toe pressure shifted serially from the heel→MP joint area→toe area, and the pressure was confirmed to be zero in the swinging phase. The time of heel-to-toe shift of the pressure immediately before the beginning of walking was 1,555 ms.

2) Aided walking

The lower panel of Figure 4 shows changes in the

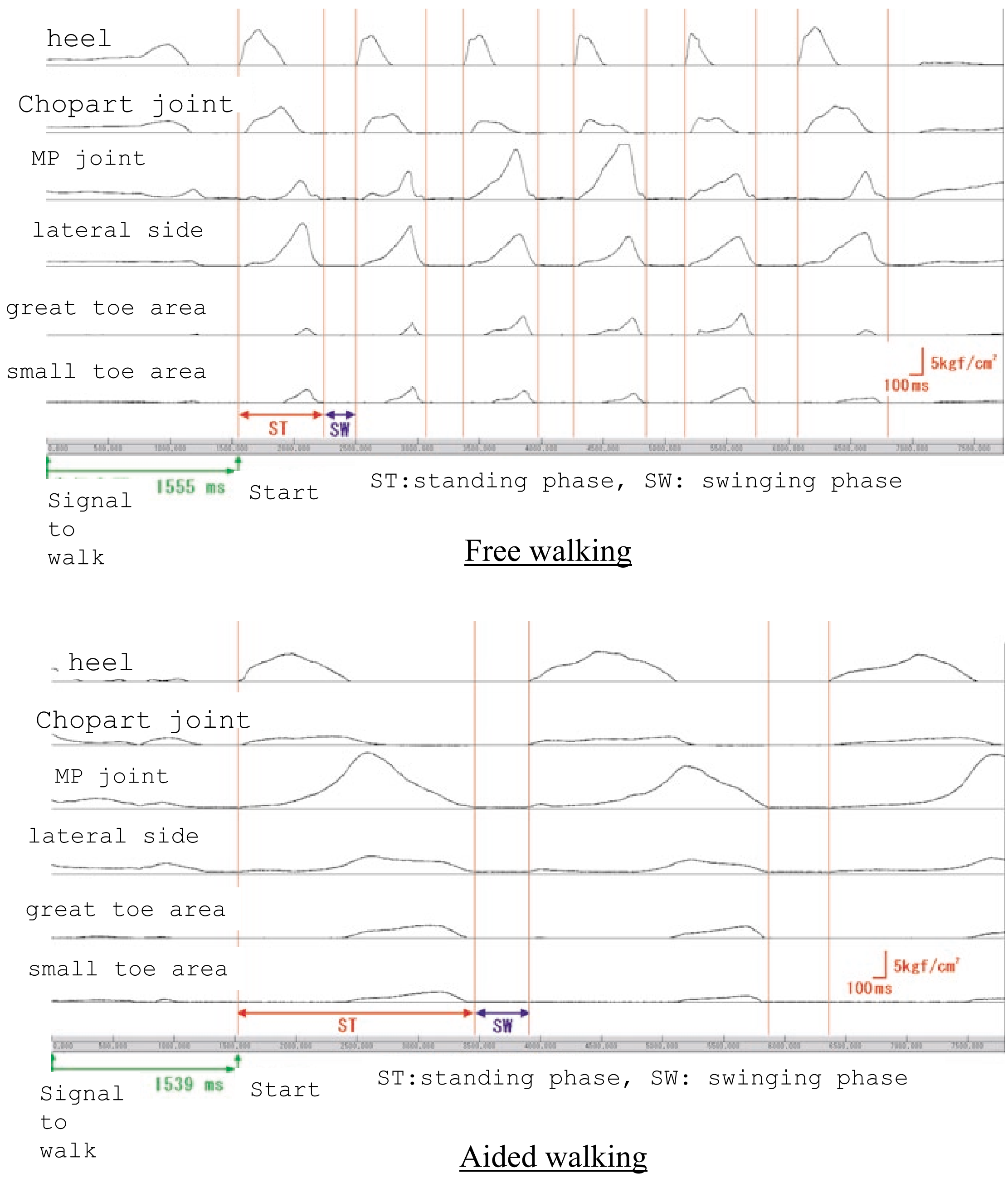


Figure 4. Pressures of the healthy subject (right foot)

vertical component of pressure waves of the right foot in aided walking. Since the walking speed was slow at 0.13m/s, one cycle of walking was longer than in free walking, and the ascending phase was gentler. The time of heel-to-toe shift of the pressure immediately before the beginning of walking was 1,539 ms. Although the duration of one cycle of walking and the angle of ascend of the pressure wave differed compared with free walking, changes in the pressure during the standing phase were confirmed to be similar to those in free walking.

2. Heel-to-toe pressure of a patient with Parkinson's disease

1) Free walking

The upper panel of Figure 5 shows changes in the

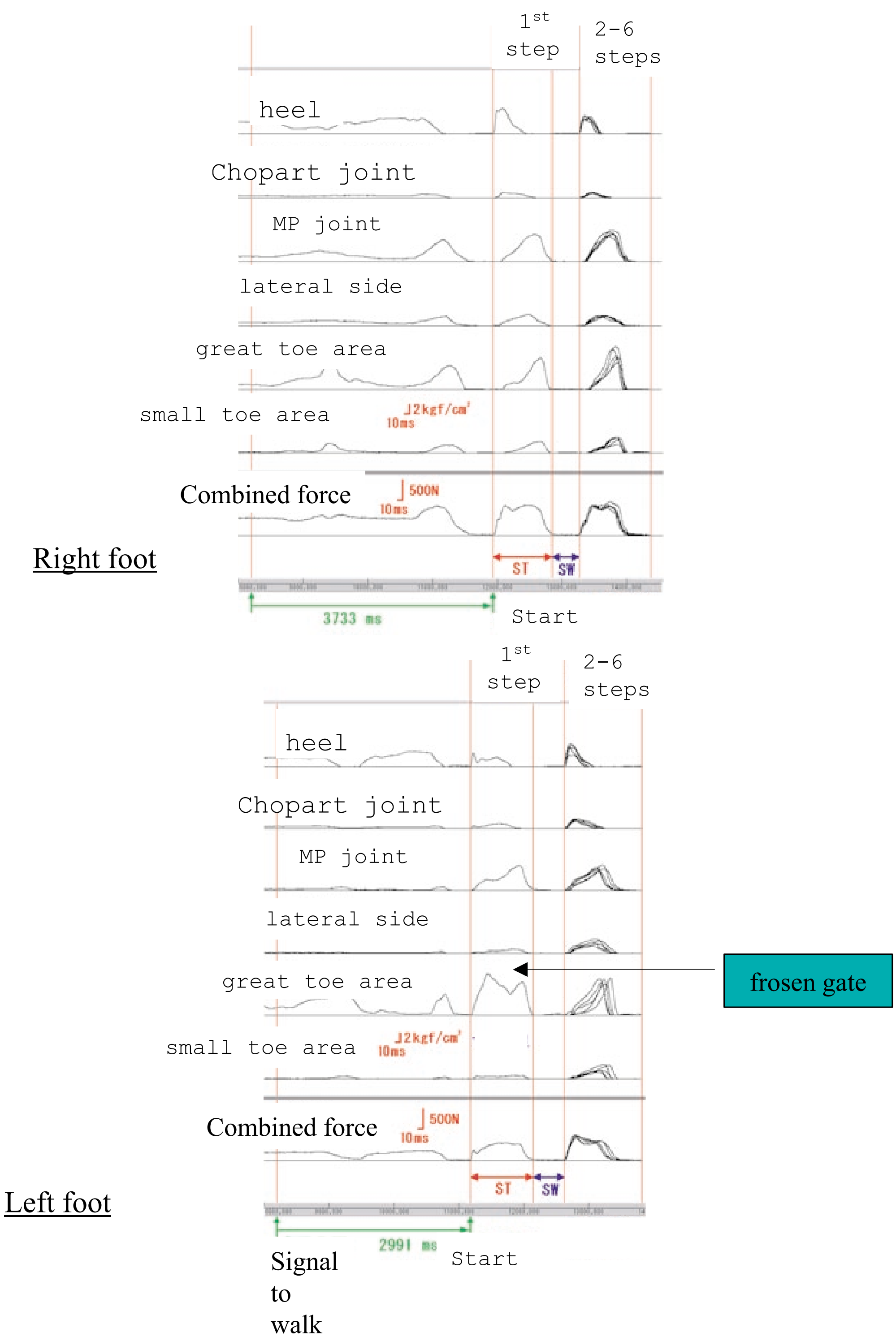


Figure 5. **Pressures changes of the patient with Parkinson's syndrome in free walking**

heel-to-toe pressure of the patient with Parkinson's disease in free walking. The time of heel-to-toe shift of pressure immediately before the beginning of walking was 3,773 ms. Changes in the heel-to-toe pressure during the standing phase immediately after the beginning of walking were confirmed to be similar to those in free walking of the healthy subject. The figure also shows the combined force of the 4 heel-to-toe pressure sensors. The vertical component of combined force showed two peaks (P_1 and P_2) similarly to the reaction force from the floor. Next, the lower panel of Figure 5 shows changes in left foot pressures of the patient. In the first step, a two-peak wave was observed in the great toe area, but the combined force did not show P_1 or P_2 in this step. The time of heel-to-toe shift of the pressure at the beginning of walking was 2,991 ms.

2) Aided walking

The upper panel of Figure 6 shows changes in the pressure of the right foot in aided walking. The time of heel-to-toe shift of the pressure at the beginning

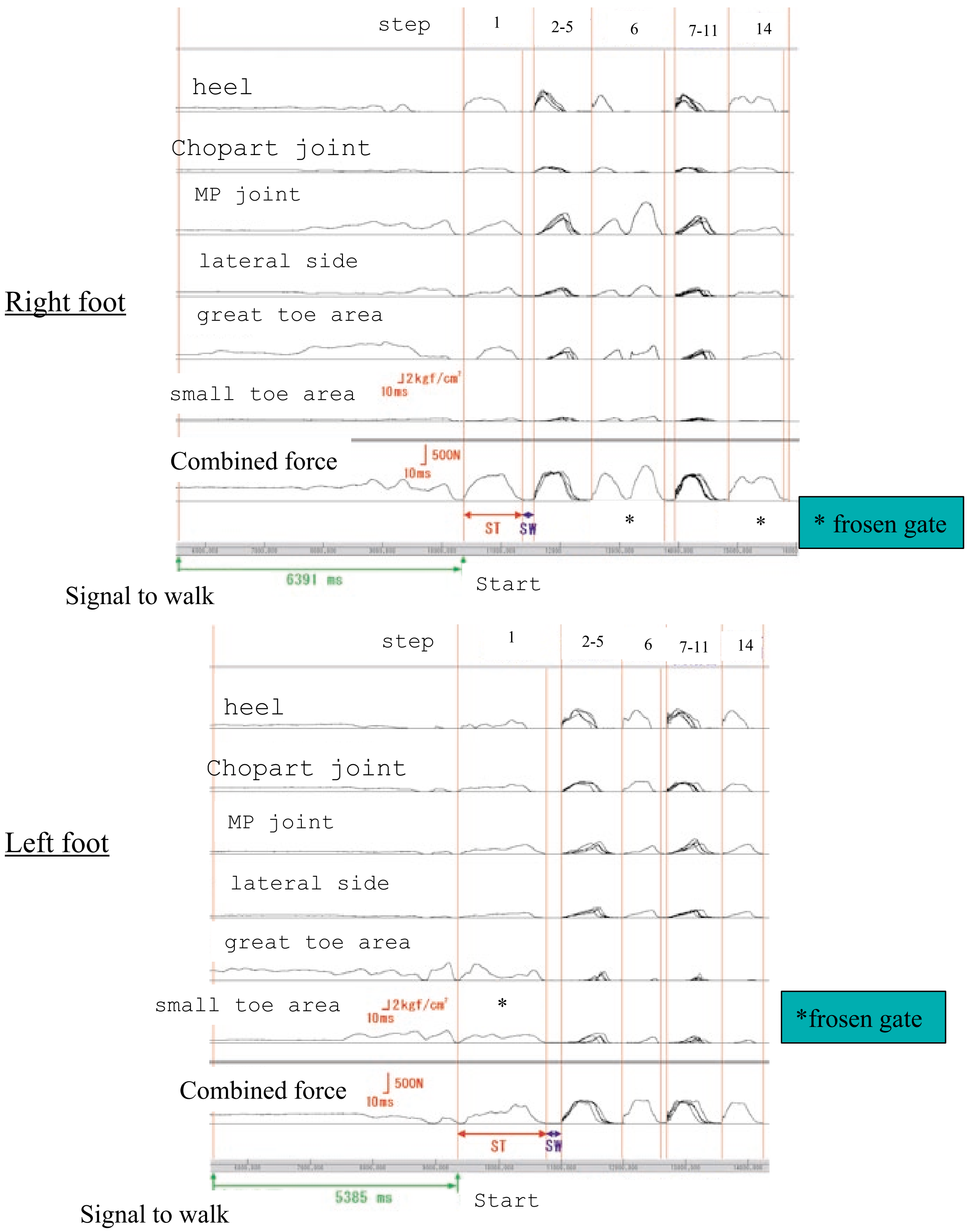


Figure 6. **Pressures changes of the patient with Parkinson's syndrome in aided walking**

of walking was 6,391 ms. In the 6th walking cycle, two peaks of pressure were observed in the sensors at the MP joint, lateral side, great toe, and small toe after the reaction of the heel sensor and before the next landing of the heel. Furthermore, in the 14th cycle, the heel landed twice at a very short interval, after which the pressure shifted toward the toe area. In this step, the wave of the combined force showed a characteristic pattern.

The lower panel of Figure 6 shows changes in the pressure of the left foot. The time of heel-to-toe shift of the pressure at the beginning of walking was 5,383 ms. Irregular changes in the heel-to-toe pressure characterized by a long standing phase and small pressure increases were observed in the first step of the left foot. However, once the patient started walking, the heel-to-toe pressure showed a heel-to-toe shift, indicating a smooth gait.

DISCUSSION

Permanently installed type floor reaction meters and gait analyzers commercially available today such as Gait Scan are large systems, and they are difficult to use conveniently or evaluate in routine clinical activities. Also, they can be used for analysis of only a short distance of walking and are not appropriate for analyzing walking function in continued walking. The walking aid and the heel-to-toe pressure sensors that we designed for this study were mobile apparatuses capable of real-time measurement of the pressure via the 6 sensors placed on the bilateral plantar and transmission of the pressure data to a computer regardless of the distance of walking.

The number and positions of the sensors used vary with the intended precision of measurement, calculation speed, and cost. A greater number of sensors are desirable for the precision and the quantity of data but a smaller number of sensors are advantageous for the calculation speed and cost. We are presently studying the optimal number and the positions of sensors in the heel-to-toe pressure sensors.

The performance of the heel-to-toe pressure sensors is evaluated with regard to the detection of phases of walking and the control of the walking aid using a computer. As shown in Figure 4, the heel-to-toe pressure was shown normally to shift regularly from the heel to the toe area during the standing phase in the healthy subject. There were differences in the response time, shape of the pressure wave, and the angle of its ascent between free walking and aided walking depending on conditions of walking such as the walking speed and walking posture.

Next, detection of frozen gait of the patient with Parkinson's disease is evaluated. The heel-to-toe response time immediately before the beginning of walking was about 2.4 times longer in the patient than in the healthy subject, suggesting the difficulty of the patient in foot lifting by the toes (Figures 4-6). This state is judged to be the difficulty in making the first step at the beginning of walking (2), or frozen gait. Frozen gait is an indication of the inability to smoothly shift the body weight at the beginning of walking. Healthy individuals are reported to show a slight posterior shift of the weight followed by an anterior shift of the weight at the beginning of walking. The lack of this pattern of secondary muscle activities associated with such shifts of the weight and a reduction in muscle activities are considered to be factors in the difficulty to start walking observed in Parkinson's disease. In aided walking, also, the time until the beginning of walking was 4.15 times longer, and changes in the heel-to-toe pressure were irregular, in the patient compared with the healthy subject (Figures 6). Since the subject's body weight is supported by the walking aid, the subject must make an active motion to start walking. This may have delayed the beginning of walking.

Once walking was started with the walking aid, the heel-to-toe pressure shifted from the heel to the toe area, suggesting a smooth gait. Therefore, the state of walking of the subject can be evaluated by monitoring the reaction pattern of pressure sensors during the standing and swinging phases using a computer.

Two peaks were observed in the pressure wave in the first step of free walking (left foot) in the patient (Figure 5). During aided walking, double peaks were observed in the sensors at the MP joint and the lateral part of the right foot after the response of the heel sensor in the 6 th cycle and in the heel sensor, indicating two landings at a short interval, in the 14th cycle (Figure 6). These responses represent the state of frozen gait observed in Parkinson's disease. Thus, the patient intended to lift the foot, but, being unable to do so, he landed the toe area. This indicates disturbance of the rhythm of walking. In normal walking, the heel-to-toe pressure increases in the early standing phase, reaches a peak in the middle of the standing phase, and decreases in the late standing phase. In the swinging phase, the heel-to-toe pressure drops to 0 kgf/cm^2. Walking cycles consisting of a standing phase and a swinging phase can be recognized in the data of increases and decreases in the heel-to-toe pressure transmitted real-time from the sensors if they consist of repetition of the patterns of the standing and swinging phases. If the subject shows frozen gait during walking, signals from a sensor show two peaks during a gait cycle. Therefore, the computer recognizes frozen gait on detection of double peaks of heel-to-toe pressure in a single gait cycle.

A long standing phase and a short swinging phase have been reported as characteristics of dysbasia of Parkinson's disease (14). A merit of incorporating heel-to-toe pressure sensors in a walking aid is that the data from the sensors are input into the computer real-time. The ratio of the normal durations of the standing phase and swinging phase is about 3:2 (15), so that evaluation of the state of dysbasia from the viewpoint of kinesiology becomes possible if a program for computerized monitoring of the ratio between the response times of the sensors between the two phases is prepared. Also, real-time monitoring of the stride according to the information of the speed of the walking aid and the heel-to-heel landing time will also become possible. Furthermore, if this walking aid, which can store the data of walking in the computer, is used for walking training of patients, the state of improvement can be assessed numerically. For example, the effect of medication may be evaluated objectively by comparing changes in the state of walking between before and after the administration.

Statistical analysis of data of many cases is necessary for the assessment of the performance of this instrument for evaluation of frozen gait consisting of a walking aid and heel-to-toe pressure sensors. We are planning an experiment of prevention of falling using an algorism derived from the data obtained from the sensors of this instrument. Further studies for finer control of the walking aid by effective utilization of real-time data of walking will also be needed.

CONCLUSIONS

We carried out experiments to detect frozen gait using our tentative model of walking aid with heel-to-toe pressure sensors in a healthy subject and a patient with Parkinson's disease and obtained the following results.

(1) The normal pattern of changes in the heel-to-toe pressure during walking could be recorded in the healthy subject.

(2) The heel-to-toe pressure pattern of frozen gait could be confirmed in the patient with Parkinson's disease.

(3) These data were shown to be useful for the control of the walking aid suited for the walking pattern of patients with Parkinson's disease.

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