Study on Walking Training System using High-Performance Shoes constructed with Rubber Elements

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Abstract. The number of accidental falls has been increasing among the elderly as society has aged. The main factor is a deteriorating center of balance due to declining physical performance. Another major factor is that the elderly tend to have bowlegged walking and their center of gravity position of the body tend to swing from side to side during walking. To find ways to counteract falls among the elderly, we developed walking training system to treat the gap in the center of balance. We also designed High-Performance Shoes that showed the status of a person’s balance while walking. We also produced walk assistance from the insole in which insole stiffness corresponded to human sole distribution could be changed to correct the person’s walking status. We constructed our High-Performances Shoes to detect pressure distribution during walking. Comparing normal sole distribution patterns and corrected ones, we confirmed that our assistance system helped change the user’s posture, thereby reducing falls among the elderly.

1. Introduction

The number of elderly in the Japanese population has been increasing as shown in Figure. 1, and is expected to reach about 40% by 2060. This means that those aged 65 and over in Japan will be roughly every one in 2.5 persons [1]. With this are increases in the need for elder-to-elder nursing and shortage in and an increased burden on care takers. These developments have resulted in efforts to promote independence among the elderly - something that has brought walking to the attention of those promoting good health and independence among the elderly. The increasing number of accidental falls among the elderly while walking [2]. Among the main factors in falls are a deteriorating center of gravity of balance due to declining physical performance and weakening in the muscular strength of the lower limbs. Figure. 2 shows the center of gravity of the human body during walking in younger persons defined have as those aged 0 ~ 30 and elder persons, defined have as those aged 70 ~ 100. Solid lines show the center of gravity of the human body and broken lines show the center of gravity of the foot sole. The motion of both sets of lines shake more in the elderly than in the young. The sense of balance in the elderly tends to decrease, so it is difficult to notice the bias in their own center of gravity. Because muscular strength in the elderly also tends to decrease, it is difficult for them to return to a regular state from fall down motion. Training is frequently needed for them to rebuild their declining muscular strength and sense of balance to minimize falls.

Against this background, a variety of home-care and support equipment has been developed to effectively help prevent accidental falls [4]-[8], including that for assisting lower limb use or worn on the lower limb. This equipment may be too large, however, to use daily or may make users so
uncomfortable that they dislike using it continually. In short, the availability and operability of equipment for helping the elderly walk safely, easily and without stress may be significantly lacking. In this study, we focused on shoes to be worn daily in walking aimed at both assisting walking and preventing falls. We propose training in walking that is continues and daily that detects and corrects the center of balance during walking. To add detection of staggering, we used a sponge-core soft-rubber actuator (SCSRA) consisting of open-cell foam sponge coated in silicon rubber. This actuator changes stiffness with inner pressure. Equipping insoles, with it means that it can be uses for both detecting the pressure distribution of the foot sole while prompting correct walking by changing the stiffness of the insole. We also developed a means of walking status presentation that confirms walking status on a display in real time.

In this paper, we begin by presenting the specifications of the High-Performance Shoe we designed and walking training using these. We then discuss results and considerations of evaluation experiments involving younger persons. Last, we evaluated smoothed pressure distribution data on the sole acquired during normal and bowlegged walking in 10 healthy persons.

2. High-performance shoes

2.1. Sponge-Core Soft-Rubber Actuator (SCSRA)
We introduced the SCSRA for the insole. Figure. 3 shows the structure of SCSRA. Sponge is coated and sealed in silicon rubber and a tube is attached for add or remove air. Thus, it can change the stiffness along with the inner pressure. Inner pressure is also changed by external pressure. So, the SCSRA is used both to detect pressure and assist in walking. Additionally, the actuator is more suitable for use on the human skin than others composed plastics or metals, because it’s made up of these soft materials. Endurance test results confirmed that SCSRA endures up to 84.2kPa when it kept hermetically-sealed, so that it has enough pressure resistance for use as an insole [9].

2.2. Insole
Using SCSRA as insole material, we developed High-Performance Shoes that both measure the pressure distribution of the foot sole enable the center of gravity to be corrected in walking. Figure. 4
shows the weight transfer during the stance phase of the walking cycle. This determines the arrangement of the insole. According to this figure, it is pertinent that the measurement of the heel, little toe, thenar and big toe [10]. Based on these, we arranged the corresponding SCSRA for pressure detection (P.D. SCSRAs) is arranged to heel (SCSRA1), little toe (SCSRA2), thenar (SCSRA3) and big toe (SCSRA4), and SCSRAs for walking correction (W.C. SCSRAs) as shown in Figure. 5. Tables 1 and 2 show P.D. SCSRAs and W.C. SCSRAs specifications for individual parts. Inner sponges for P.D. SCSRAs are formed by sponge manufacture, so all these specifications are the same. On the other hand, Inner for W.C. SCSRAs were formed manually, so they are slightly different.

![Figure 4 Weight transfer during the stance phase of the walking cycle](image)

![Figure 5 SCSRA arrangement](image)

Table 1 P.D. SCSRAs specifications

| Volume [cm³] | Weight [g] | Volume of Sponge [cm³] |
|--------------|------------|------------------------|
| 25.1         | 12         | 9.62                   |

Table 2 W.C. SCSRAs part specifications

| Shoe | Number of SCSRAs | Volume [cm³] | Weight [g] | Volume of Sponge [cm³] |
|------|------------------|--------------|------------|------------------------|
| Right|                  |              |            |                        |
| 1    | 70.1             | 107          | 20.8       |
| 2    | 64.9             | 98           | 18.7       |
| 3    | 59.9             | 94           | 18.3       |
| 4    | 38.1             | 73           | 15.4       |
| Left |                  |              |            |                        |
| 1    | 70.4             | 108          | 20.9       |
| 2    | 64.6             | 96           | 18.5       |
| 3    | 59.7             | 93           | 18.2       |
| 4    | 38.3             | 74           | 15.5       |

2.3. Structure of High-Performance Shoes

Our High-Performance Shoes, shown in Figure. 6, consist of an insole which is described in section 2.2, an electrical circuit that measures pressure distribution, processes data and assists walking correction [11][12]. These are separated into the shoes, which weigh 720g, and a shin pad, which weighs 180g. P.D. SCSRAs have small pressure sensors for measuring inner pressure. W.C. SCSRAs have small three-port two-position air solenoid valves for controlling of inner pressure. The electrical control circuit has an AVR microcomputer and a XBee, which is a wireless communication module, along with micro air pump for changing inner pressure mounted on the shin pad. Figure. 7 shows the electrical circuit. The details of using components are listed in Table 3.
2.4. Walking Training System
A total system of proposed walking training for realizing steady walking is shown in Figure.8 (1). The system is constructed with a foot orthosis that is driven by rubber muscle actuators, an active walker which is driven by electric motors, output devices (Tablet, Computer, etc) and high performance shoes. Further, Figure.8 (2) shows a high performance shoes system. With respect to the high performance shoes, the figure shows an example of our walking training. In the training, walking status of the foot part is shown on an Android tablet, a head-mounted Android-powered transmission display (HMD) (EPSON MOVERIO BT-100) and a PC [13]. The flow of the system is described in the following. First, a patient puts on both the proposed shoes and HMD, and walks around in them. During this situation, pressure distribution on the insole is measured by pressure sensors on the P.D. SCSRA. The measured data is carried out A/D converter in electrical circuits, then sent to displays through wireless communication modules and on displays. A physical therapist confirms the patient’s walking status on an Android tablet and change the arbitrary W.C. SCSRA stiffness using the Android tablet. This gives the patient information that where one should apply force by the sense of the foot sole, and thereby learn correct walking. Note that muscles used little in ordinary activities can be strengthened through this training.

2.5. Walking Assist System
The objective of our walk-assistance system is to enable users to realize self-sustained walking training that stimulates the sole to walk correctly by changing insole stiffness automatically when a constant pressure value is exceeded. Figure. 9 shows the proposed configuration of walking assist
system. In system operation, the pressure value from the P.D. SCSRA is sent to the electrical circuit. If it exceeds 10KPa, the solenoid valve on the W.C. SCSRA corresponding to the P.D. SCSRA is turned on. Then, the impounded air from the micro pump is introduced into the W.C. SCSRA through a tube, making it stiffness. When pressure is less than the threshold, the valve is turned off and inner air is exposed to the atmosphere to make it soft. Table4 shows the stiffness shift.

Table 4

| (1) Total System
| (2) High-Performance Shoes System

Figure 8 Walking Training System using High-Performance Shoes
3. Walking measurement experiment

3.1. Experimental Method
We conducted walking measurement experiments to confirm the effectiveness of our proposed High-Performance Shoes. Pressure distribution was measured using two walking patterns -- normal and bowlegged -- at a constant speed 2km/h for 10 seconds on a treadmill when the assist system is turned on or off. Bowlegged walking was tested with the subject instructed and trained to consciously walk bowlegged. Previous research reported that the minimum walking speed of a physically unimpaired elderly person who has previous fallen is about 2.0km/h, so we used this in our experiments [14]. One foot contacted land surface for 1.01 second at least when an elderly person walked at 36.2 m/min (about 2.0 km/h) in steps of 60cm, which is an average for the elderly people. This proved that a maximum fulfill time of 0.780 seconds, as shown in Table 4, is enough for a response. We averaged results each walking cycle. We separated walking during one cycle into 7 patterns as shown in Figure. 4. We used these as results for instantaneous pressure and average pressure. We evaluated the effectiveness of our High-Performance Shoes from these results. Figure. 10 shows sole measurement and Table 5 lists the information on subjects of experiments.

| Shoe | No. of SCSRA | Inlet Velocity [cm/s] | Fulfill Time [s] |
|------|--------------|-----------------------|-----------------|
| Right | 1            | 26.5                  | 0.785           |
|       | 2            | 26.4                  | 0.708           |
|       | 3            | 26.4                  | 0.693           |
|       | 4            | 26.5                  | 0.581           |
| Left  | 1            | 26.5                  | 0.789           |
|       | 2            | 26.4                  | 0.701           |
|       | 3            | 26.4                  | 0.689           |
|       | 4            | 26.5                  | 0.585           |
### Table 5. Subjects details

| Subject No. | Age | Sex  | Height [cm] | Weight [kg] | Foot size [cm] | Dominant leg |
|-------------|-----|------|-------------|-------------|----------------|--------------|
| (1)         | 20  | Male | 173.4       | 63.4        | 27.0           | Right        |
| (2)         | 20  | Male | 182.3       | 58.4        | 27.5           | Right        |
| (3)         | 20  | Male | 167.5       | 65.3        | 26.5           | Right        |
| (4)         | 21  | Male | 172.3       | 64.2        | 27.0           | Right        |
| (5)         | 21  | Male | 168.9       | 58.5        | 26.5           | Right        |
| (6)         | 22  | Male | 163.9       | 53.4        | 26.0           | Right        |
| (7)         | 19  | Male | 178.4       | 75.2        | 27.5           | Right        |
| (8)         | 20  | Male | 172.1       | 60.5        | 27.0           | Right        |
| (9)         | 20  | Male | 156.4       | 65.4        | 25.5           | Right        |
| (10)        | 19  | Female | 154.2     | 55.2        | 25.0           | Right        |

#### 3.2. Measurement Results of Instantaneous Pressure

Figure. 11 – Figure. 14 show instantaneous pressure transition at SCSRA1, the heel; SCSRA2, the little toe; SCSRA3, the thenar; and SCSRA4, the big toe. These results occur when the assist system is turned on or off with two walking patterns (normal or bowlegged). The vertical axis shows the obtained pressure and the horizontal axis is the walking phase (A) – (G) corresponded to Figure. 4. Pressure was greatest in the treading phase ((i) (F) and (ii) (B) in Figure. 11) in transition patterns of the heel in both normal and bowlegged walking. The pressure value decreased when the assist system was turned on during both of these two patterns. The transition of pressure was gentler when subjects have bowlegged walking on the left foot. The most pressure occurred when the other foot in the swing phase crossed ahead of the foot supporting the subject’s weight ((i) (G) and (ii) (D) in Figure. 12) in the transition patterns of the little toe in both normal and bowlegged walking. Pressure decreased when the system was turned on more decreasing than turned off with both these walking patterns in the walking phase (G) on the left foot. The same characteristics thus occurred at both (G) and (A) in normal walking.

In bowlegged walking on the right foot, pressure also decreased when the system was turned on more decreasing than the value in normal walking. In both Figure. 13 and Figure. 12, pressure was also the most when the foot in the swing phase crossed ahead of the foot which supporting the subject’s weight ((i) (G) and (ii) (D) in Figure. 13) in the transition patterns of the thenar in both normal and bowlegged walking. In these two walking patterns, the pressure of bowlegged walking was greater than that value of normal walking on the right foot. The pressure value when the assist system was turned on exceeded that when it is turned off in normal walking. According to Figure. 14, the most pressure occurred at the moment the foot was kicked backward ((i) (A) and (ii) (E) in Figure. 14)
in the transition patterns of the big toe in both normal and bowlegged walking. Pressure was greater in walking bowlegged in the walking phase (G) on the right foot. On the other hands, on the left foot, the pressure value in bowlegged walking when the assist system was turned off increased more than when it was turned on.

(i) Left P.D.SCSRA1
(ii) Right P.D.SCSRA1
Figure.11 Transition of instantaneous pressure at the heel (I)

(i) Left P.D. SCSRA2
(ii) Right P.D.SCSRA2
Figure.12 Transition of instantaneous pressure at the little toe (I)

(i) Left R.D.SCSRA3
(ii) Right P.D.SCSRA3
Figure.13 Transition of instantaneous pressure at the thenar (I)
3.3. Measurement Results of Average Pressure
As seen in Section 3.2, obtained data was conducted using our proposed method in section 3.1. Figure.15 – Figure.18 show transitions of average pressure at SCSRA1, the heel; SCSRA2, the little toe; SCSRA3, the thenar; and SCSRA4, the big toe. In other words, results when the assist system was turned on or off during normal and bowlegged walking were the same as in Section 3.2. The vertical axis shows obtained pressure and the horizontal axis corresponds to the walking phase (A) – (G) in Figure. 4. According to Figure. 15, pressure transition is conspicuous in the two walking patterns in the stance phase ((i) (D) – (G), (ii) (B) – (E) in Figure.15). Accordingly, the pressure value decreases when the assist system is turned on. Note that the average transition at the left heel in bowlegged walking is conspicuous. According to Figure.16, pressure transition is conspicuous in the two walking patterns in the kicking backward phase ((i) (E) – (A) and (ii) (B) – (E) in Figure.16). The pressure value at the little toe during bowlegged walking notably decreased more than that in normal walking. According to Figure. 17, pressure transition is conspicuous in the two walking patterns in kicking backward phase ((i) (E) – (A), (ii) (B) – (E) in Figure.17). The pressure value in bowlegged walking is greater than the value in normal walking. Accordingly, the pressure value when the assist system is turned on is also greater than when it is turned off in normal walking. According to Figure. 18, pressure transition is also conspicuous in the two walking patterns in the kicking backward phase ((i) (E) – (A), (ii) (B) – (E) in Figure. 18).

The pressure value when the assist system was turned on increased more than when the system was turned off in right bowlegged walking. These results indicate that the heel tends to be supported by a change in stiffness in heel W.C.SCSRA when one foot is kicked backward, so the pressure at the big toe was increased easily by shifting the pressure to forward easily. This indicates that the assist system has a correction effect on the inside centroid of the sole, with results from the decrease in the pressure value at the little toe tending to increase the value at the thenar. We thus concluded that preventing staggering to the outer side during walking training is provided by using our proposed assist system.

4. Conclusion
We have discussed the background, development and results for the High-Performance Shoes we developed in this study. These shoes detect and help correct the pressure distribution on the sole of the foot, helping to correct walking balance and to minimize falls in elderly through walking training. Results of experiments for evaluating the effectiveness of these shoes showed that kicking up support and correction of human body center.

Although our shoes had a certain effectiveness in support in walking by younger person’s. However, these shoes have some problems to conduct walking experiments by elderly people such as weight of
shoes, ease to wear and so on. Therefore, we have been improving in order to reduce size and weight and become easy to wear. After these improvements, we plan to conduct walking experiments involving pseudo elderly persons. Furthermore, we also plan to conduct walking experiments and sensory evaluation involving the elderly at welfare and rehabilitation facilities.

Figure 15 Transition of average pressure at the heel (II)
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