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Shoe-Type Postural Stabilization Training System with Vibration Stimulation

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***Abstract*—In this study, we propose a shoe-based training system for preventing falls in elderly populations and evaluate the performance of its core component, namely the sensor-actuator insole, which is a low-cost, portable device that incorporates vibration motors and pressure sensors. To investigate the perceptual characteristics of vibration stimuli applied to a plantar surface, we examine combinations of various insole materials, which vary in thickness and hardness, and applied voltages to the vibration motors. The proposed system enables balance training by inducing center of pressure (COP) displacement through targeted vibration stimuli. To estimate the COP from pressure sensor outputs, individual calibration equations are derived using multiple regression analysis based on data collected from a force plate. In the verification experiment, for subjects instructed to lean in the direction of the presented vibration stimuli, COP coordinates estimated from the sensor-actuator insole are compared to those measured by the force plate. The results show that the mean COP estimation error using the regression model is 4.2 mm (standard deviation = 2.5 mm), indicating generally good accuracy using simple, low-cost sensors. A negative correlation (r = –0.58) is found between foot length and estimation error, suggesting that subject-specific characteristics may influence measurement precision. With further refinements, such as adjustments for individual differences, the proposed system has potential as a practical tool for supporting fall prevention in elderly populations.**

***Index Terms*—Fall prevention, Postural control, Vibration stimulation, Sensor-actuator insole**

I. Introduction

According to the White Paper on the Aging Society published by the Cabinet Office of Japan, the number of elderly individuals requiring nursing care or support continues to increase steadily amid the rapid progression of population aging. One of the primary causes of such care needs is falls and fractures, which are particularly prevalent among those aged 65 and older [1].

A single fall can significantly impair physical function, making fall prevention a critical issue directly related to improving the quality of life of older adults and reducing the associated care costs. Contributing factors to fall risk in elderly populations include age-related declines in muscle strength, balance ability, and cognitive function [2]-[4].

Moreover, decreased plantar sensation leads to a lack of essential information required for postural control during standing and walking, thereby significantly compromising stability [5]-[7]. Pressure and contact sensations from the soles of the feet are crucial for accurately perceiving and appropriately regulating the body's center of gravity. In recent years, sensory stimulation applied to the plantar surface has gained attention for enhancing balance and postural control [8]-[10].

Center of pressure (COP) analysis has long been used for evaluating standing balance ability [11]. The COP represents the projection of the center of gravity onto the sole of the foot during upright standing. It shifts as the body tilts and can be measured using devices (e.g., force plates) that detect ground reaction forces.

In 2005, an initial version of a fall-prevention training system (hereafter referred to as the original system) was developed by a member of our research group. This system combined vibration stimulation to the plantar surface with balance assessment using a force plate. While force plates provide highly accurate COP data and are reliable for research applications, their high cost and spatial requirements limit their practicality for home-based use or simple rehabilitation settings. Therefore, the need for a more convenient and affordable system was recognized.

In response, the present study proposes a shoe-type fall-prevention training system that incorporates a sensor-actuator insole (SAI), which integrates pressure sensors and vibration motors. This paper focuses on the experimental evaluation of the effectiveness of the SAI as the core component of the proposed system.

II. Fall-Prevention Training System

A. Original system

Older adults exhibit age-related declines in muscle strength, balance ability, and motor control. Stable standing posture is maintained by keeping the COP within the base of support, which refers to the contact area between the feet and the ground. However, in practice, postural stability is often lost before the COP reaches the edge of the base of support. The range within which the COP can move without loss of balance is referred to as the limits of stability. As these limits tend to be narrower in older adults than in younger individuals, the risk of falling increases with age.

To address this issue, we previously developed a fall-prevention training system (original system) for improving postural control in older adults. This system consists of a vibration sheet embedded with multiple electric vibration motors, placed on top of a force plate. The user first stands on the vibration sheet. A specific motor, such as one located near the toes, is then activated to deliver vibration

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stimuli to the plantar surface of the foot. Upon sensing the vibration, the user leans in the direction of the active motor. Once the COP reaches the target location, the vibration stops and the user is instructed to return to the initial standing position.

Through this method, vibration stimuli are used to guide COP displacement. Several beneficial effects are expected from this task. It is known that even under relatively stable conditions, older adults often rely on hip strategies for postural control. This task encourages movements centered around the ankle joint, thereby promoting improvement in ankle strategy usage. Moreover, by gradually shifting the COP target toward the periphery of the base of support, the limits of stability can be expanded.

In addition, previous studies have shown that vibration stimulation applied to the plantar surface can improve two-point discrimination, suggesting that the system may enhance plantar sensory function [12]. Since the stimuli are applied only to the soles of the feet, the user's vision and hearing remain unimpeded, allowing for flexible use in multimodal training settings. Using this system, we confirmed that vibration stimulation during static standing balance training can effectively expand the limits of stability in older adults [13].

B. Proposed system

1) Background of development

Although the effectiveness of the original system was demonstrated through verification experiments, its reliance on a force plate—costing approximately JPY 3 million (about USD 20,000)—poses a major barrier to widespread adoption. Other limitations include its unsuitability for dynamic conditions such as walking.

To address these issues, we aimed to simplify the components responsible for COP measurement and vibration presentation. This approach was expected to reduce the overall system cost, miniaturize the hardware, and improve system versatility. With future application during walking in mind, we designed a shoe-type system that incorporates a SAI with built-in COP measurement and vibration output capabilities. As this study represents an early development phase, we focus here on static standing and report the design and performance evaluation of the SAI.

2) Overview of SAI

Fig. 1 shows the appearance of the SAI for the right foot. Using a sheet-type inkless foot printer (Obara Kogyo Inc., Tokyo, Japan), footprints were collected from 11 healthy subjects (eight males, three females) in their 20s. The general shape of the SAI was defined to encompass all collected footprints.

A schematic diagram of the cross section of the SAI is presented in Fig. 2. A urethane rubber sheet with excellent mechanical strength was placed in the area that contacts the sole of the foot. Three vibration motors (diameter: 12 mm; thickness: 3.5 mm) were mounted on the underside of the sheet. An ethylene-vinyl acetate (EVA) sheet—commonly used in shoe insoles—with a thickness of 5 mm (upper layer), identical in shape to the urethane rubber sheet and containing holes to avoid interference with the vibration motors, was attached to the underside of the urethane rubber sheet.

Fig. 1 Photograph of SAI for right foot

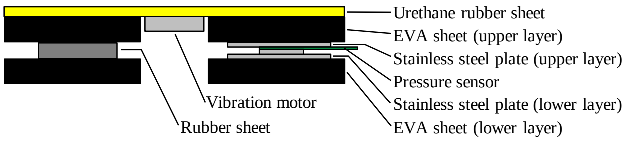


Fig. 2 Schematic diagram of SAI cross section

For load measurement, 0.2-mm-thick pressure sensors (FlexiForce, NITTA Co., Osaka, Japan) were used. When these sensors are subjected to pressure, their electrical resistance decreases, allowing for uniaxial load measurement when the sensors are incorporated into a simple amplification circuit. Each sensor costs approximately JPY 4,000 (about USD 27) and is capable of measuring loads up to 440 N. However, the sensing area of the sensor is a small circular region with a diameter of approximately 9 mm. To enlarge the sensing area, a stainless steel disk (diameter: 9 mm; thickness: 1 mm) was attached to the sensor surface. Additionally, two stainless steel plates—an upper plate (thickness: 0.5 mm) and a lower plate (thickness: 0.1 mm)—were laminated around the disk. This entire structure was then sandwiched between the aforementioned upper EVA sheet and a lower EVA sheet. The two EVA layers were partially connected via a rubber sheet with a thickness of 0.5 mm.

The internal structure of the SAI is shown in Fig. 3. Two to three pressure sensors were attached to a single stainless steel plate. The layout of the pressure sensors and vibration motors is shown in Fig. 4. Based on the footprint data used to define the insole shape, sensors were positioned in three regions: the forefoot, midfoot, and heel. Although the insole contains stainless steel plates, sufficient flexibility was maintained in the plantar surface for comfortable use.

III. Experiment

A. Selection of applied voltage and urethane rubber properties

For the SAI, the thickness and hardness of the urethane rubber sheet and the voltage applied to the vibration motor are critical factors that influence the intensity of the vibration stimulus perceived at the sole of the foot. Therefore, an experiment was conducted with various values of these parameters to determine the optimal stimulus conditions.

The vibration plates used to deliver the stimuli were fabricated as follows. A vibration motor was mounted at the

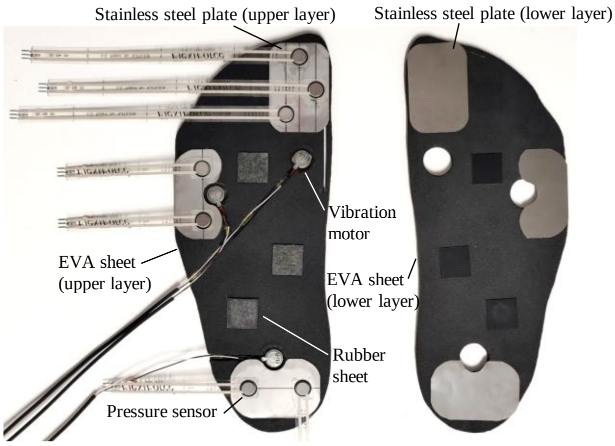


Fig.3 Internal Structure of the SAI for the right foot

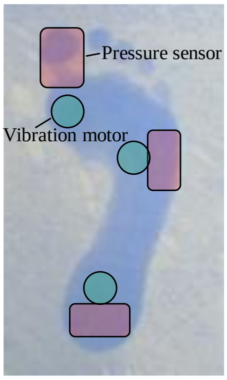


Fig. 4 Layout of pressure sensors and vibration motors on footprint (right foot)

center of the underside of a square urethane rubber sheet (100 mm × 100 mm). An EVA sheet (thickness: 5 mm), of the same shape as the urethane rubber sheet but with a 15 mm diameter hole in the center to avoid interfering with the motor, was attached beneath it.

The urethane rubber sheet in contact with the plantar surface was prepared with two thickness values, namely 1 and 2 mm, and two hardness values, namely 30 (soft) and 50 (hard). These combinations resulted in four types of vibration plates (A–D). Additionally, two values of the applied voltage to the vibration motor (4.5 and 6.5 V) were used, producing a total of eight stimulus conditions. The specific stimulus conditions are listed in Table I.

Although mechanical variability can exist among individual vibration motors, the same model (diameter: 12 mm; thickness: 3.5 mm) was used throughout the experiment and uniform voltage control and handling procedures were applied for all conditions. Therefore, any influence of inter-device variability was considered negligible for the purpose of comparing the relative clarity of each stimulus condition.

Each vibration plate was placed under the heel of a standing subject and the vibration stimulus was presented. Each subject evaluated all 28 unique stimulus pairs using a paired comparison method. For each pair, two trials were conducted, with the order of presentation reversed for the second trial, resulting in 56 trials per subject (28 pairs × 2 orders). To account for potential order effects, trials with different presentation orders were evaluated independently. The order of the stimuli was randomized for each subject. The flow of a single trial was as follows:

1. First vibration plate installed (9 seconds)
2. Vibration stimulus presented (2 seconds)
3. Plate replaced with second vibration plate (9 seconds)
4. Second stimulus presented (2 seconds)
5. Subject indicated which stimulus felt clearer on a five-point scale (5 seconds)

Subjects experienced the two vibration conditions in sequence and then selected one of five response options to indicate which stimulus felt more distinct. Subjects responded using verbal descriptors, which were converted into numerical scores for analysis, as shown in Table II.

To eliminate the influence of auditory cues from the vibration motors, all subjects wore sound-isolating headphones during the experiment. All instructions, response options, and prompts were thus presented as text on a screen positioned directly in front of the subject's line of sight.

Before beginning the main trials, each subject completed two practice trials using the same procedure to become familiar with the stimuli and the response format. To reduce subject fatigue, a 5-minute break was provided after the first 28 of the 56 trials.

Eleven healthy young adults in their twenties (eight males, three females) participated in the experiment. None of the subjects had a history of neurological or orthopedic

Table I Stimulation conditions based on sheet configuration and applied voltage

Condition	Thickness	Hardness	Applied Voltage
A1	1 mm	30	4.5 V
A2	2 mm	50	6.0 V
B1	1 mm	30	4.5 V
B2	2 mm	50	6.0 V
C1	1 mm	30	4.5 V
C2	2 mm	50	6.0 V
D1	1 mm	30	4.5 V
D2	2 mm	50	6.0 V

Table II Scoring criteria for subjective clarity based on presentation order

Response options	Assigned score
The first stimulus felt much clearer	+2
The first stimulus felt slightly clearer	+1
No noticeable difference between the two	0
The second stimulus felt slightly clearer	-1
The second stimulus felt much clearer	-2

conditions affecting the feet. All subjects were fully informed about the purpose and procedures of the experiment and provided written consent prior to participation.

B. Evaluation of directional guidance accuracy and COP measurement accuracy using vibration stimuli

For force plates, load sensors such as strain gauges are installed at the four corners of a rigid metal plate, enabling the entire body weight of the user to be detected. The coordinates of the COP can then be calculated using the following equation based on the positions and outputs of these sensors [14].

$$COP_x = \frac{f_{z1} \cdot x_1 + f_{z2} \cdot x_2 + f_{z3} \cdot x_3 + f_{z4} \cdot x_4}{f_{z1} + f_{z2} + f_{z3} + f_{z4}}$$

$$COP_y = \frac{f_{z1} \cdot y_1 + f_{z2} \cdot y_2 + f_{z3} \cdot y_3 + f_{z4} \cdot y_4}{f_{z1} + f_{z2} + f_{z3} + f_{z4}}$$

where *COPx* and *COPy* are the *x* and *y* coordinates of the COP (mm), respectively, x_1–x_4 and y_1–y_4 are the *x* and *y* coordinates of sensors 1–4 (mm), respectively, and f_{z1}–f_{z4} are the measured values from sensors 1–4 (N), respectively. The typical accuracy of previously used force plates is approximately ±2.5 mm [15].

In contrast, the SAI employs pressure sensors mounted on a flexible sheet. Due to the deformation of the sheet, certain areas may contact the floor directly without transmitting force through the sensors. As a result, the COP cannot be calculated using the above equations for force plates. In this study, we adopted a calibration-based approach, in which COP positions were estimated using individual-specific calibration data obtained in advance with a force plate.

Although this method still requires a force plate, it differs from the original system in terms of application. While the original system required each home user to have their own force plate, with the proposed system, the force plate would be installed at a rehabilitation facility. Users would borrow only the SAIs for home use. In this case, only a single force plate is needed at the facility for calibration, reducing the overall cost.

The COP accuracy evaluation experiment was conducted as follows. As shown in Fig. 5, the SAI was fixed on a force plate (9260AA3, Kistler Japan G.K., Kanagawa, Japan). Each subject stood on the insole and was instructed to shift their body forward, backward, left, and right by pivoting around the ankle joint. Calibration data were collected accordingly (Fig. 6).

The output voltages from the left and right pressure sensors served as explanatory variables, while the *x* and *y* coordinates of the COP, calculated from the force plate, were used as dependent variables. Multiple regression analyses were conducted to derive equations for each axis. Subsequently, COP positions were estimated by inputting the SAI sensor outputs into these equations.

To verify the effectiveness of this method, both calibration and evaluation data were collected using the force plate. The COP position obtained from the force plate during evaluation trials was regarded as the ground truth and compared to the COP values estimated using the regression equations generated from the calibration data.

For calibration data collection, subjects stood on the SAI placed on the force plate. They were instructed to cross their arms in front of their chest and fix their gaze forward. Over approximately 10 seconds, they performed a cross test, slowly leaning forward, backward, left, and right, and continued this movement for about 2 minutes and 30 seconds. During this task, subjects maintained straight hips and moved primarily at the ankle joints, ensuring that their feet remained in contact with the insole at all times.

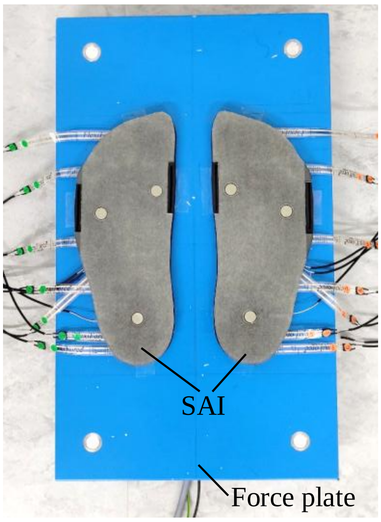


Fig.5 Photograph of the experimental system

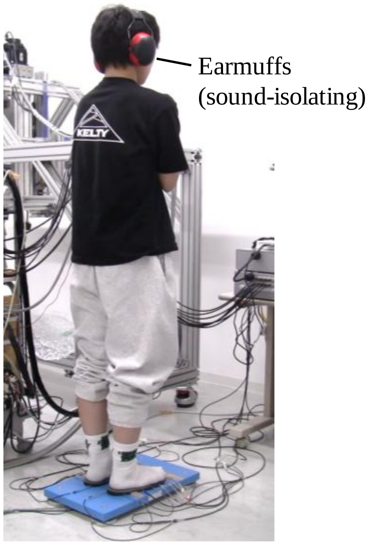


Fig. 6 Experimental setup for COP measurement and directional guidance using SAI

The subjects were the same 11 individuals as those in the material selection experiment. Because the pressure sensor signals contained substantial noise, data sampled at 400 Hz were averaged in blocks of 10, resulting in an effective sampling rate of 40 Hz. Multiple regression equations were calculated using Microsoft Excel.

For the evaluation phase, subjects maintained the same posture and procedure as those during calibration. Although the subjects were young and healthy, with no evident decline in muscle strength, balance, or plantar sensitivity, a directional guidance task using vibration stimuli was conducted to confirm the functionality of the system.

First, subjects tilted their bodies in each of the four directions to determine their maximum COP displacement in each direction. These values were then used as the target goals for COP movement. For forward movement, vibration motors in the forefoot and midfoot on both sides were activated. For backward movement, the heel motors were activated. For left or right movement, the three motors on the corresponding side were activated to deliver vibration stimuli to the plantar surface (Fig. 7).

Upon sensing the vibration, subjects tilted their bodies in the perceived direction. When the COP reached the target position—as measured by the force plate—the vibration was manually stopped by the experimenter. The subject then returned to a neutral upright posture and maintained it until the next stimulus.

A total of 20 stimuli were presented in random order, five for each of the four directions (forward, backward, left, right). To prevent subjects from inferring direction based on motor sound, they wore sound-isolating headphones throughout the experiment. In addition, subjects wore socks to mimic the reduced plantar sensitivity often observed in elderly individuals. After all stimuli had been presented, COP values were calculated offline using the previously obtained regression equations.

IV. Experimental Results and Discussion

A. *Selection of applied voltage and urethane rubber sheet properties*

To evaluate the subjective clarity of vibration stimuli applied to the sole of the foot, a scoring method based on the paired comparison technique (Ura's paired comparison) was employed [16]. The 11 subjects were presented with all possible pairs of the eight stimulus conditions (A1 to D2), with the order of presentation counterbalanced. For each pair, subjects rated the condition they perceived as clearer on a five-point scale.

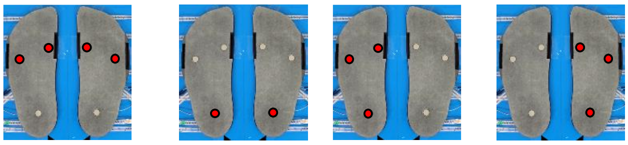
For each condition, 14 scores (7 other conditions × 2 presentation orders) were collected per subject. The mean preference score was then calculated by summing these scores. This score served as a relative index of perceived clarity: a higher value indicates that the condition was judged clearer more frequently and with greater intensity compared to the other conditions (Fig. 8).

The analysis revealed that condition C2 (thickness: 2 mm; hardness: 30; voltage: 6.0 V) had the highest mean preference score of +1.19, making it the most subjectively preferred stimulus condition. This was followed by B2 (1 mm; 50; 6.0 V) with a score of +0.98. Both C2 and B2 used a high voltage (6.0 V), corresponding to stronger physical vibration intensity.

Other conditions, such as C1 (+0.35) and A2 (+0.26), received moderate ratings, while A1 (−0.47), D2 (−0.75), and D1 (−1.35) were rated as having relatively lower clarity.

Both C2 (soft, thick sheet with high voltage) and B2 (hard, thin sheet with high voltage) achieved high clarity scores, suggesting that both material properties and motor output significantly affect the transmission of vibration stimuli to the plantar surface.

Condition C2 likely provided high adherence to the foot due to its flexibility (hardness 30) and 2-mm thickness.



(a) (b) (c) (d)

Fig. 7 Activated vibration motors (red circles) for directional guidance: (a) forward, (b) backward, (c) leftward, and (d) rightward leaning

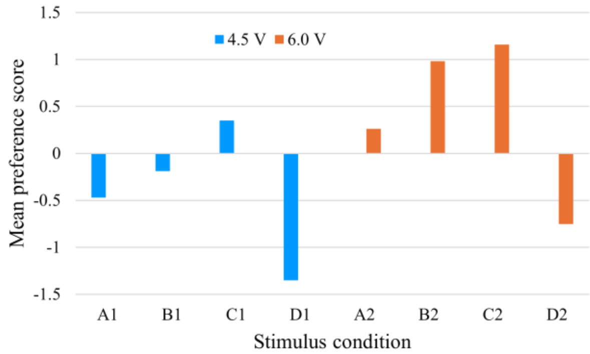


Fig. 8 Mean preference score for various stimulus conditions

Combined with high-voltage stimulation (6.0 V), this configuration may have efficiently stimulated both superficial and deep cutaneous receptors, resulting in a more enveloping sensation that contributed to the perceived clarity.

In contrast, condition B2 used a harder material (hardness 50) but was only 1 mm thick. The shorter transmission path may have reduced energy loss, and in combination with high-voltage stimulation, the stimulus may have been perceived as sharper or more immediate. Thus, B2 may have achieved high clarity through a mechanism distinct from that of C2.

Comparisons between conditions with the same material composition but different voltages (e.g., C1 vs. C2, B1 vs. B2) confirmed that vibration output (applied voltage) plays a critical role in perceived clarity.

Although A2 (+0.26) used a less favorable material configuration than that of C2 or B2, its high voltage likely compensated for this, resulting in moderate clarity. Conversely, C1 (+0.35), despite its low voltage (4.5 V), still achieved a mid-range clarity score, suggesting that flexibility and thickness can partially offset reduced motor output. This implies that high voltage is not the sole determinant of clarity; appropriate material selection can enable effective stimulation even under energy-saving conditions.

In contrast, conditions such as D1 (−1.35) and D2 (−0.75), which combined hard and thick materials, received the lowest clarity scores. Even with high voltage, these configurations likely failed to transmit vibration effectively due to energy loss from extended propagation distance and higher mechanical impedance, which reduced the transmission efficiency to the plantar surface.

In summary, delivering clear plantar vibration stimuli requires a careful balance between material flexibility, sheet thickness, and motor output. Notably, C2 and B2 demonstrate that distinct strategies can both achieve high clarity, offering valuable design insights for future device development. Based on these findings, a urethane rubber sheet with a thickness of 2 mm and a hardness of 30 and a motor voltage of 6.0 V were selected as the optimal configuration for the SAI.

B. Evaluation of directional guidance accuracy and COP measurement accuracy using vibration stimuli

With regard to the accuracy of directional guidance using vibration stimuli, it was initially expected that healthy young adults would make no directional errors. However, across all subjects, one instance of misdirection was recorded. Specifically, although the stimulus was intended to induce backward leaning, the subject initially failed to detect the vibration at the left heel, leaned to the right, and then subsequently leaned backward. The heel region is known to have relatively poor two-point discrimination sensitivity among plantar regions. This sensitivity is further diminished in older adults compared to younger individuals [17]. This suggests that when targeting older populations, it may be necessary to increase the intensity of vibration stimuli. In future iterations, we plan to implement adjustable settings to accommodate individual sensory characteristics.

Next, the accuracy of COP measurement was evaluated by analyzing the interval from the onset of the vibration stimulus to the point where the COP reached the intended target. Fig. 9 shows the average of the maximum errors in each directional trial per subject, calculated as the difference between the true COP position measured by the force plate and the estimated position derived from the multiple regression model. The data indicate a slight trend toward lower maximum errors in backward leaning trials. This may be because, during quiet standing, the COP tends to be located slightly posterior within the base of support, requiring less displacement during backward leaning, thereby reducing error potential.

Fig. 10 presents the mean COP estimation error per subject. Although the accuracy is not as high as that of a force plate, the overall average error was 4.2 mm (standard deviation: 2.5 mm), which is considered reasonably acceptable. Variability in error across subjects led us to investigate its relationship with individual foot length—a unique anthropometric factor for each subject. Fig. 11 illustrates the foot lengths of all subjects. The results show a tendency for a shorter foot length to correlate with a larger COP estimation error. The Pearson correlation coefficient between foot length and average error was –0.58, indicating a moderate negative correlation. This suggests that individuals with shorter feet tended to exhibit greater estimation error.

A likely reason for this trend is that individuals with shorter feet may have had difficulty pressing the center of the stainless steel plate, located beneath the sensor and aligned with the hallux (big toe). As a result, pressure may have been applied at an oblique angle, leading to instability in readings from the uniaxial pressure sensors, which are optimized for vertical force measurement only.

Fig. 12 shows the mean squared error of COP estimation in the mediolateral and anteroposterior directions. For most subjects, estimation errors were larger in the anteroposterior direction than in the mediolateral direction. Foot length ranged from 213 mm (Subject F) to 267 mm (Subject D), a difference of 54 mm. In contrast, foot width ranged from 82 mm (Subject C) to 102 mm (Subject D), a difference of only 20 mm—less than half the foot length variation. This likely

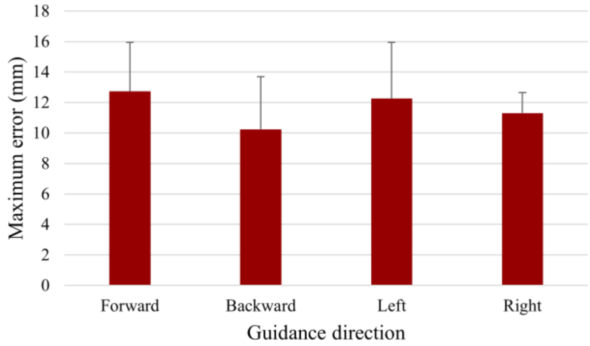


Fig. 9 Comparison of maximum COP error for various guidance directions

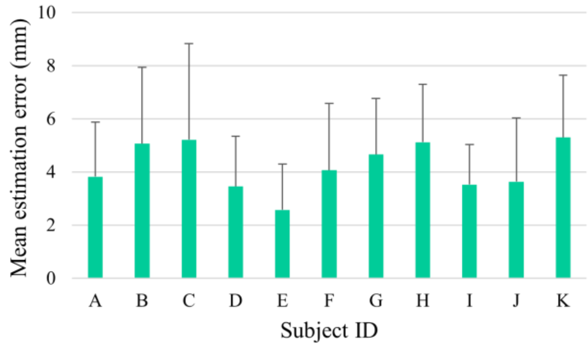


Fig. 10 Average distance between actual and estimated COP for various subjects

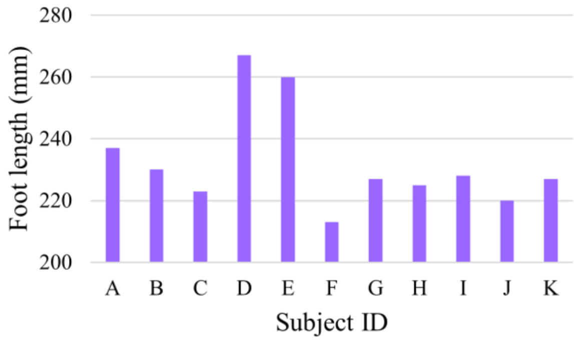


Fig. 11 Foot length for various subjects

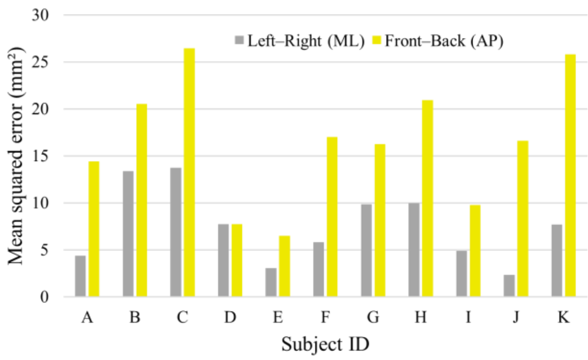


Fig. 12 Mean squared error of estimated COP in mediolateral and anteroposterior directions for various subjects

resulted in greater alignment deviations between the hallux and the center of the stainless steel plate in the anteroposterior axis, thereby increasing error in that direction. Based on these findings, custom-made SAIs would offer the best fit for accuracy. However, from a cost-effectiveness standpoint, full customization is impractical. As a viable alternative, we plan to explore the production of a limited number of standardized insole sizes to determine whether this approach can improve overall measurement accuracy.

V. Summary

In this study, we proposed a shoe-type fall-prevention training system and evaluated the performance of its key component—the SAI—in terms of the clarity of vibration stimulation and the accuracy of COP measurement. Experimental results revealed that the flexibility, thickness, and vibration output of the SAI significantly influenced the perceptibility of plantar stimulation.

Furthermore, the study demonstrated that even with low-cost pressure sensors, satisfactory COP estimation accuracy could be achieved by accounting for individual user characteristics. Moving forward, we aim to further improve the system’s practicality and versatility through personalized insole design, dynamic evaluations including during walking, and field testing with elderly individuals.

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