Proceedings of the 12th International Conference on Biomedical Engineering and Systems (ICBES 2025)
Paris, France– August 17 - 19, 2025
Paper No. ICBES 111
DOI: 10.11159/icbes25.111

Detection of Optimum Tilt Angle in Outward Inclination of Ground Plane for Walking Support

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Abstract **-** Extending healthy life expectancy has become a social issue, and walking is an effective form of exercise for improving health. However, walking safely and efficiently is becoming increasingly difficult with age. This study focuses on the outward tilting of the ground surface to improve stability during the one-leg support period. Specifically, we propose a method to detect the optimal outward tilting angle that facilitates balance based on the foot-pressure distribution during one-leg standing. We conduct experiments in which the foot-pressure distribution during 35 s of one-legged standing is measured thrice in 19 elderly subjects on a tilt table whose tilt angle is variable from 0° to 7° in 1° increments. The experimental results indicate the following: (1) The variation in the center of foot pressure for 18 subjects is smaller when the foot is tilted outward instead of flat. (2) The variation in the center of foot pressure during one-leg standing at the optimal tilt angle obtained using the proposed method reduced significantly as compared with the case of a flat surface.

Keywords**:** Foot-Pressure Distribution, Center of Foot Pressure, Sample Entropy, Elderly, One-legged Support

1. Introduction

Population aging is progressing worldwide, and extending healthy life expectancy has become a social issue [1]. Walking, which can be performed easily, is an effective form of exercise for promoting health [3,4]. However, with aging, the stride length decreases and the step width increases [5], thus rendering prolonged walking challenging. Stabilizing one-legged support is believed to increase the stride length and decrease the step width. Additionally, plantar motion during ground contact contributes significantly to walking, and foot pronation and supination are required for efficient walking. Patients who do not achieve proper pronation and supination typically experience foot pain [6].

In this study, we propose the external tilting of the ground plane to improve stability during the one-leg support period.

2. Proposal to Incline Ground Contact Surface Outward

Tilting the ground plane outward offers two advantages: one is the suppression of ankle joint twisting during one-leg support, and the other is the induction of foot pronation and supination. When supporting one foot, the supporting leg is tilted outward such that the center of gravity is directly above the foot to maintain balance, which causes the ankle joint to twist. The outward inclination of the ground plane is believed to alleviate the twisting of the ankle joint, stabilize one-leg support, and improve the stride length and step width.

Additionally, the outward inclination of the ground surface can induce the proper pronation and supination of the foot. Proper gait requires the following three types of foot motion: First, shock is absorbed by pronation of the plantar foot when the heel establishes contact with the ground. Next, the entire plantar surface of the foot is grounded in supination to facilitate weight transfer and one-legged support. Finally, it is accelerated by kicking up the grounded forefoot during foot pronation. Outward tilting of the ground plane can correct a gait that tilts the sole inward excessively when grounding with the heel. The outward tilt of the ground plane can correct excessive sole tilting when grounding with the heel. Foot supination, which is to be performed immediately after that, can be performed naturally by supporting the foot with one leg while stepping onto an externally inclined ground surface. The final pronation, i.e., by kicking up the forefoot, can be easily performed via the foot reaction.

3. Method of Determining Optimum Inclination Angle of Grounding Surface

3.1. Basic Idea

The optimal inclination angle of the ground plane should be determined for each individual to account for differences in foot shape and ankle and knee joint angles. Because the one-leg support period is the most unstable in the gait of the elderly, stable support during this period can contribute to improved stride length and step width. Regarding the induction of two pronation and one supination of the foot, the second pronation, which results in stable one-leg support, is important. Hence, the optimal tilt angle for the external tilting of the ground surface was determined by evaluating the task of maintaining balance during one-legged standing.

3.2. Method for Determining Optimal Inclination Angle from Foot-Pressure Distribution

The center of foot pressure (COP) distribution is typically used to evaluate balance retention in the standing position [7,8]. The method for determining the optimal tilt angle from the foot-pressure distribution measured over three trials of 35 s of one-legged standing is described below.

Step1: Calculate the cumulative moving distance of the COP for 30 s, excluding the first 5 s.

Step2: Select the maximum value of the cumulative COP moving distance for the three trials as the COP variation evaluation value, Pvar. The maximum value is adopted considering the fact that cases exist where the COP cumulative moving distance is accidentally small even at inclination angles that challenge balance maintenance, and that trials with small COP cumulative moving distances can be reproduced at inclination angles that facilitate balance maintenance.

Step 3: Sort Pvar at various tilt angles in the descending order. If the difference between the lowest and second lowest values exceeds the threshold value Th, then select the tilt angle with the minimum value as the optimal tilt angle. If it is less than Th, then select the optimal tilt angle from the three smallest angles using the following method: For each tilt angle, calculate the sample entropy Pse, which represents the complexity of the COP time variability [9]. Subsequently, select the angle closest to the tilt angle with the largest Pse.

4. EXPERIMENT

4.1. Methods

Nineteen male subjects aged 65–74 years participated in the experiment. Using a stand constructed using strong wood with a tilt angle of 1°, the subjects stood on their right leg for 35 s, and measurements were performed thrice. The subjects were instructed to (1) face the supporting foot in the frontal direction with a foot angle of 0°, (2) observe a landmark 2 m away such that their eyes were at the eye level, (3) lower their arms naturally next to their waist, and (4) elevate the left foot of the swing leg approximately 10 cm above the ground surface with the knee bent.

The Pedar-x SYSTEM by Novel was used to measure the foot-pressure distribution. This insole-type foot pressure sensor can measure 99 load points at 50 Hz, thus yielding a high-resolution foot-pressure distribution. The measurement results are shown in Figure 1.

4.2. Results

4.2.1 COP Variation

An example of the foot-pressure distribution for the right and supporting feet in the one-legged standing position is shown in Figure 2. This figure shows that the foot-pressure distribution varied significantly during 35 s to maintain balance. For subjects A and B, Figures 3 and 4 show the variation in the evaluated COP variation, Pvar, which is the maximum value of three trials for each inclination angle, COP cumulative moving distance, and sample entropy Pse with the inclination angle. Subject A in Figure 3 represents the case in which the optimal tilt angle is 3° because Pvar at a tilt angle of 3° is smaller than that at other angles. For reference, Pse was shown to be the maximum at a tilt angle of 3°. For subject B in Figure 4, Pvar was smaller at 6° and 7°; therefore, Pse was used to determine the optimum angle of inclination. Thus, the optimal oblique angle was determined when the cumulative COP moving distance in 30 s in the one-legged standing posture was small.

4.2.2 Results of Optimal Inclination Angle

Figure 5 shows the calculation results for the optimal tilt angle using the proposed method. Among the 19 subjects, 18 were shown to incline better externally at 1° or more, and approximately 70% of the subjects inclined at 4° or more, thus indicating that inclining externally at an angle above a certain level is effective. The mean values and standard deviations of Pvar for the 18 subjects with an optimal tilt angle of 1° or greater are shown in Figure 6 for the plane with a tilt angle of 0° and for the optimal tilt angle. The COP variability reduced significantly at the optimal tilt angle relative to 0° ($p < 0.01$, t-test). Furthermore, as shown in Figure 7, the COP variability decreased more at larger optimum tilt angles.

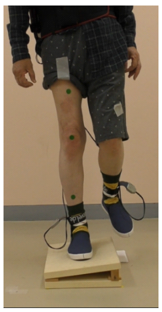

Fig.1 One-legged support.

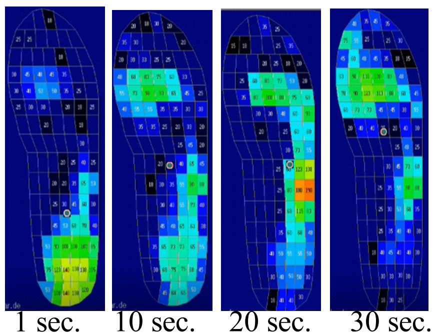

Fig.2 Foot pressure distribution.

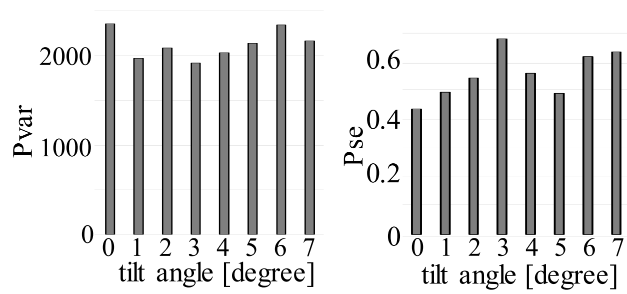

Fig.3 Pvar and Pse of subject A.

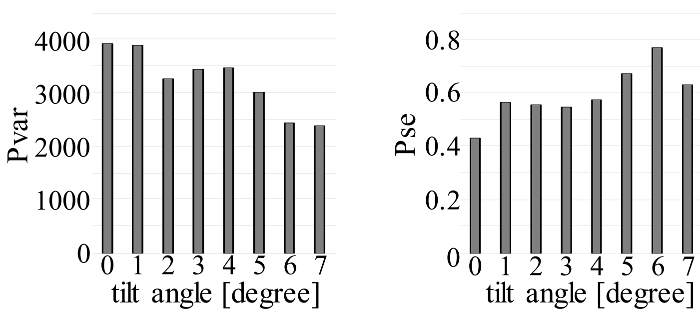

Fig.4 Pvar and Pse of subject B.

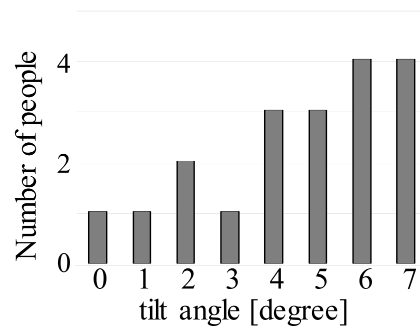

Fig.5 Number of people at optimum tilt angle.

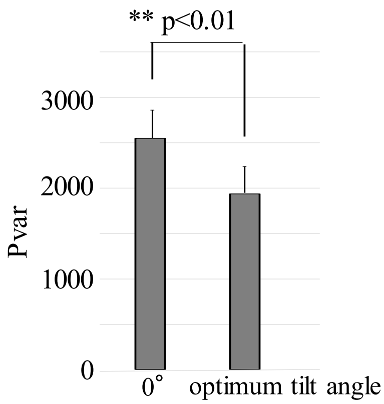

Fig.6 Comparison of Pvar.

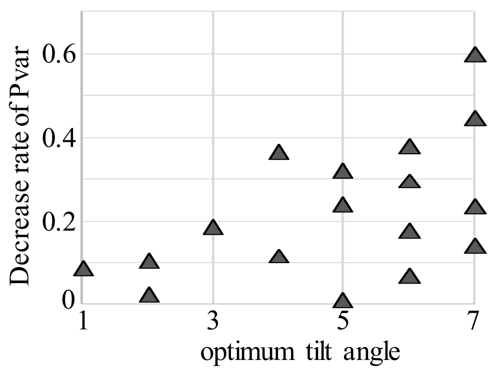

Fig.7 Relationship between optimum tilt angle and decrease rate of Pvar.

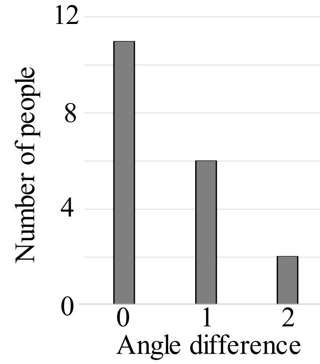

Fig.8 Angular difference between the angle at which Pse is maximum and the optimum.

4.3. Discussion

Figure 8 shows the results of comparing the tilt angle that maximized Pse for each subject with the optimal tilt angle obtained using the proposed method. The horizontal axis of the figure represents the difference between the compared angles. Approximately 60% of the subjects indicated at an angle difference of 0°, whereas approximately 90% indicated an angle difference within 1°, thus confirming that the optimum tilt angle is typically selected when Pse is at its maximum. At the optimal tilt angle, ankle twisting was eliminated, and the subjects were able to maintain a complex balance, thus resulting in a larger Pse and, consequently, less COP variability.

5. Conclusion

In this study, we proposed a method to identify the optimal external tilt angle that facilitates balance retention from the foot-pressure distribution during one-legged standing. We verified that 18 among 19 elderly subjects showed less fluctuations in the center of foot pressure when they were inclined more externally than when they stood on a flat plane. Additionally, the optimal inclination angle obtained using the proposed method significantly reduced the fluctuation in the center of foot pressure compared with the case of standing on a flat plane. We measured the foot-pressure distribution during 35 s of one-legged standing thrice in 19 elderly subjects on a tilt table whose tilt angle was variable from 0° to 7° in 1° increments. The experimental results verified the following: (1) The variation in the center of foot pressure for the 18 subjects was smaller when the foot was tilted outward instead of flat. (2) The variability in the center of foot pressure during one-leg standing reduced significantly under the optimal tilt angle obtained using the proposed method as compared with the case of a flat surface.

In the future, we plan to verify whether walking motion improves when an insole externally tilted at the optimal tilt angle is attached to a shoe. This study was supported by the JSPS Grant-in-Aid for Scientific Research (23K11354).

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