上海健康醫學院
SHANGHAI UNIVERSITY OF MEDICINE & HEALTH SCIENCES

Bachelor Thesis

Research on static balance ability of young men under closed and open eye conditions based on plantar pressure

College	College of Medical Instrument
Major	Clinical Engineering
Name	FERREIRA JOAQUIM ZE
No.	LB20040201062
Tutor	Jinfeng Cao
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ABSTRACT

Balance is a crucial factor for enabling safe engagement in daily activities, ensuring secure locomotion and preventing falls, which pose significant public health concerns. Visual feedback plays a vital role in balance regulation, yet the absence of visual cues can compromise balance. Understanding how visual input affects static balance, especially in young men, is essential for injury prevention and rehabilitation. Recent technological advancements, particularly in plantar pressure analysis, offer new insights into balance mechanisms. However, research on this topic in China is limited. This study aims to investigate the static balance ability of young men under closed and open eye conditions using plantar pressure analysis.

This research involved the recruitment of 15 healthy young male participants. Employing the F-scan insole-based plantar pressure analysis system, this experiment manipulated visual factors. Subsequently, participants engaged in unipedal and bipedal static standing experiments across varying step heights and on flat ground. Each experiment was captured for a duration of 10 seconds, followed by the extraction of plantar biomechanical parameters after processing.

The experimental results show that significant differences exist in plantar pressure center parameters between eyes-closed and eyes-open conditions during unipedal standing, and these differences increase with step height elevation. The differences in toe load between feet and conditions are highly statistically significant, and significant differences are also observed in midfoot and rearfoot loads. Most plantar pressure center parameters vary between feet and conditions during bipedal stance, with statistically significant overall load differences between eyes-open and eyes-closed conditions. Adjustments in the center of pressure (COP) and load distribution between forefoot and rearfoot regulate balance under different visual conditions and step heights. This study provides a simple method for evaluating human posture control and balance, aiming to reduce falls and offer tailored balance assessment protocols and training programs for diverse demographics.

KEY WORDS: Plantar pressure, Static balance, Plantar pressure center parameters, Plantar pressure distribution parameters

Content

Chapter 1 Theoretical background

1.1 Introduction

Maintaining balance is a fundamental aspect of human motor control essential for performing daily activities, athletic endeavors, and preventing falls[1] . The ability to sustain equilibrium relies on a complex interplay of sensory inputs, neuromuscular coordination, and feedback mechanisms. Among the sensory inputs crucial for balance regulation, visual information plays a pivotal role, providing valuable cues about body position and movement relative to the environment. However, the reliance on visual feedback for balance control raises intriguing questions about how individuals adapt when visual information is compromised[2]. Destabilization in balance can lead to fall, which is a significant public health concern worldwide. Injuries resulting from falls, especially falls from height (FFH), pose substantial risks, with the World Health Organization (WHO) identifying falls as the second leading cause of unintentional injuries resulting in deaths. Each year, approximately 37.3 millions of falls occur globally, resulting in severe injuries requiring medical attention, loss of potential years of life due to premature death, and considerable economic burden, particularly among older adults[3]. This underscores the importance of understanding balance mechanisms and addressing factors that may compromise balance, such as the absence of visual feedback, to mitigate the risk of falls and their associated consequences across various age groups.

Balance is defined as the ability to achieve, maintain and restore body posture. The human body's balance ability is generally divided into static balance ability and dynamic balance ability. Static balance ability refers to the ability of individuals to control the center of gravity of the body when in a relatively static state. The static balance ability training needs more time to keep the same posture. It’s more difficult to maintain sustained training. This stability is facilitated by input from various sensory systems, including somatosensory, vestibular, and visual. Through the integration of these sensory inputs, individuals continuously adjust their body's position and motion to uphold posture. Understanding how visual cues affect static balance, particularly in young men, is vital for optimizing training protocols, injury prevention strategies and rehabilitation[4].

In recent years, technological advancements in biomechanical assessment have facilitated novel approaches to studying balance mechanisms. Plantar pressure analysis, in particular, has emerged as a promising tool for quantifying balance performance by capturing the distribution of forces exerted on the foot during static tasks. By measuring parameters such as center of pressure (COP) sway, sway velocity, and sway area, plantar pressure analysis offers a detailed understanding of the subtle adjustments individuals make to maintain stability[5].

Recent research overseas has focused more on using plantar pressure analysis to measure balance, but there's limited research in China[2]. Studies have shown that visual input improves posture control for better balance. Foot movement control influences stance and posture. Previous studies have not yet reached a clear conclusion on the mechanism through which a single foot controls the balance function, and what is the connection between visual input and foot adjustment control. However, this study aims to investigate the static balance ability of young men under closed and open eye conditions using plantar pressure analysis. By employing sophisticated pressure-sensing technologies, researchers will quantify the distribution of force exerted on the foot during static balance tasks. Through this approach, the study seeks to elucidate how visual deprivation influences balance strategies and whether young men exhibit distinct patterns of adaptation compared to other demographic groups. Moreover, the findings may have broader implications for improving balance assessment protocols and informing the design of training programs across various age groups and demographics.

1.2 Concept of balance

1.2.1 Research on human stability and balance

Research both domestically and internationally has explored many innovative and meaningful aspects of human stability and balance in different movement states. In general, the current research on human balance ability roughly includes the following parts: balance disorder rehabilitation training, human fall prediction, balance experimental research based on electromyographic signals, dynamic cameras, and plantar pressure, and balance ability research before and after diagnosis and treatment of various diseases[6]. Research on human balance ability based on different physiological states and different sports. People have widely paid attention to the application of various experimental methods and testing equipment in the assessment and detection of balance ability, and they provide scientific basis for diagnosing movement disorders and evaluating the rehabilitation effects of balance disorders[7][8].

People with damage to the musculoskeletal system and nervous system, such as patients with plantar fasciitis or hip fracture, show a decrease in balance ability and decreased balance reduces functional movement and increases the rate of falls, a major risk factor for injury and death. Therefore, restoring and enhancing balance ability is essential for patients with musculoskeletal and nervous system injuries, the elderly, and people who require improvement of functional movements due to other problems[9][10].

Research on human stability and balance explores the plantar sole's stability mechanism and factors affecting balance in various conditions. Kinematic parameters like plantar pressure center trajectory, velocity, and displacement, along with kinetic parameters such as ground reaction force and average pressure, are utilized. Additionally, some scholars have used these parameters to establish new indices for evaluating human stability and balance ability, which is also one of the future research directions.

Nowadays, some parameters related to plantar pressure are used to test and evaluate balance ability. For instance, Lin Qiang and colleagues evaluated the postural balance of normal young individuals in open and closed eye states using the FreeMed plantar pressure analysis system. They used kinematic parameters and parameters such as plantar pressure distribution to assess the influence of visual factors on static balance function[2].

However, there are still few studies in china and abroad that only use plantar pressure to objectively and quantitatively evaluate human body stability and balance function. Therefore, this study also aims to measure a large amount of plantar biomechanical data of the human body in static state, hoping to objectively and quantitatively explore and analyze the balance function and stability of the human body.

1.2.2 Postural body balance

Body posture involves the concept of balance, neuro-muscular coordination, and adaptation, representing a specific body movement. Automatic postural responses are context-dependent, meaning they are adjusted to meet the needs of interaction between the postural organization systems (balance, neuro-muscular, and adaptation) and the environment. Many observations suggest that posture control is not simply based on a set of reflex responses, nor is it a pre-programmed response triggered by imbalance. Instead, posture control is an adaptable feature of the motor system, based on the interaction between afferent stimulus and efferent response[11].

Postural body balance relies on various sensory inputs, including auditory and vestibular pathways governed by the vestibulocochlear nerve, which manage balance and hearing, crucial elements in addressing postural issues[12]. The central nervous system plays a pivotal role in processing and integrating this sensory information. Visual input significantly influences balance control, as evidenced by studies demonstrating its efficacy in enhancing posture control[13][14]. Furthermore, visual positioning and movement control contribute to regulating the position of the body's center of gravity. Understanding the intricate relationship between visual input and balance control involves analyzing foot movement control, which remains an area requiring further exploration[4][15].

As shown in Figure 1, the visual system provides information on the surrounding environment; the vestibular system, consisting of the two inner-ear balance organs and several nervous structures (nerves and central nuclei), encodes angular and linear accelerations of the head to support the clear vision and balance control via rapid eye movements (vestibulo-ocular reflexes) and postural reflexes (vestibulo-spinal reflexes); the somatosensory system senses self-movement and body position through specialized sensory receptors located in the muscles (muscle spindles), joints (Ruffini endings, Pacinian corpuscles, and Golgi-like receptors) tendons (Golgi tendon organs), and skin (Merkel cells, Ruffini endings, Meissner corpuscles, and Pacinian corpuscles). Multisensory signals from visual, vestibular and somatosensory receptors are integrated in the central nervous system to provide an internal postural model and in turn, descending motor commands to muscles. Reactive postural strategies and anticipatory postural adjustments allow balance control under environmental circumstances (e.g., external postural perturbations) and motor initiative (e, g., voluntary movement), respectively.

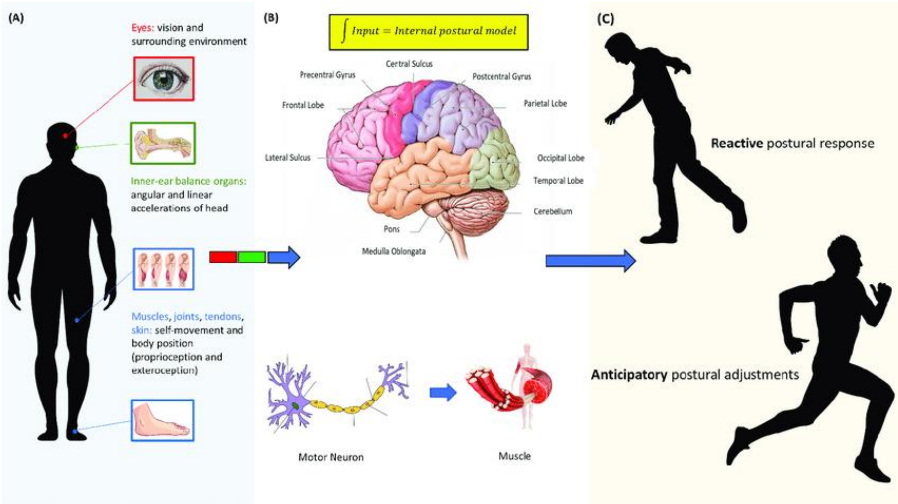

Figure 1. (A) The visual system; (B) Multisensory signals from visual, vestibular and somatosensory receptors; (C) Reactive postural strategies and anticipatory postural adjustments (Alessandro Zampogna, Eduardo Palermo, June 2020)[15].

1.3 Human Plantar pressure

1.3.1 Plantar pressure Measurement technology

Biomechanical analysis of plantar pressure is essential in evaluating gait and posture, offering insights into foot structure, function, and posture control. The human foot, often likened to the "second heart" plays a vital role in supporting the body's mass and maintaining posture. In the upright position, 25% of the body weight is distributed to each calcaneus and 25% to the heads of the five metatarsals of each foot; in the proportion of about one part to the first metatarsal and 2.5 parts to the metatarsals II to V. Most of the tension in the longitudinal arch is supported by the plantar ligaments. Only about 15 to 20% of the tension is supported by the posterior tibial and fibular muscles. When the body is on the tip of a foot, the tension in the arch is increased fourfold[16].

Originating from clinical diagnosis, research on plantar pressure has expanded to include static and dynamic assessments, influencing fields like sports biomechanics and footwear design[17][18]. Understanding plantar pressure is pivotal for foot health and performance optimization. Recent advancements include the utilization of data mining and mathematical modeling techniques to develop predictive and dynamic models of plantar pressure[19][20][21]. However, there's a need for more research focusing on experimental setups to enhance the accuracy and reliability of plantar pressure analysis techniques.

Human plantar pressure measurement has evolved through four stages: the footprint method, plantar pressure scanning, force plates/platforms, and pressure shoes/insoles. Initially, the footprint method, dating back to 1930, utilized ink marks to assess pressure distribution. Advancements introduced sophisticated techniques like plantar pressure scanning. Force plates/platforms enabled precise measurement of ground reaction force but lacked in assessing the "foot-shoe interface" force. Pressure shoes/insoles addressed this limitation, offering real-time monitoring[22][23].

Presently, plantar pressure detection devices categorize measurements into static and dynamic aspects, capturing data with time effects during basic posture or dynamic movements like gait analysis. Gait analysis is crucial for assessing normal and pathological movement, with a focus on foot function due to its role in support and adaptation. The gait cycle is divided into the stance phase (60%), where the foot bears the body's weight, and the swing phase (40%), where the foot moves forward to start the next stance, as shown in Figure 2. Various parameters, including force and pressure, maximum force (pressure), average force (pressure), contact area, force-time integral, pressure-time integral, single (double) foot standing time, changes in the plantar pressure center, and continuous plantar pressure trajectory, are evaluated. Notably, maximum pressure, average pressure, and pressure-time integral stand out as widely used parameters crucial for comprehensive plantar pressure analysis[22][24][25].

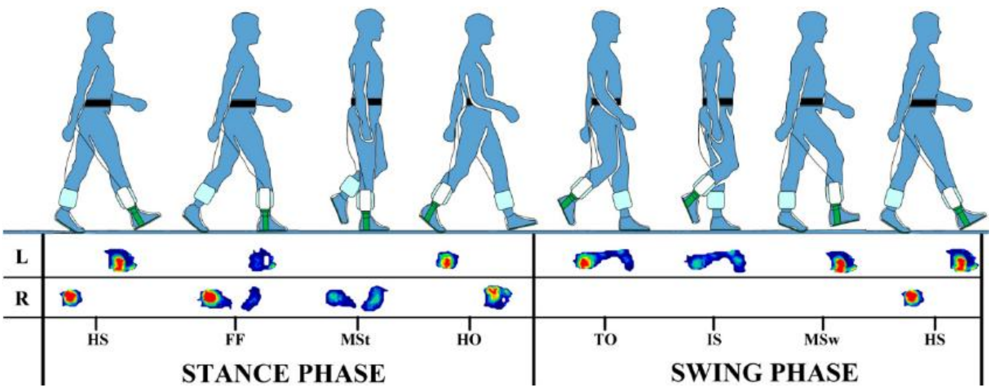

Figure 2. An example of in-shoe plantar pressure measurement during the major phases and events of a full gait cycle (right heel strike to right heel strike). HS = heel strike, FF = foot flat,
MSt = midstance, HO = heel off, TO = toe off, IS = initial swing, MSw = midswing. (Linah Wafai, Aladin Zayegh, Sensors 2015, 15)[25].

1.3.2 Plantar pressure Acquisition system

Plantar pressure acquisition systems have evolved with two main approaches: force plates/platforms and pressure insoles. Force plates/platforms systems are among the earliest devices used for measuring and evaluating plantar pressure. These systems offer precise measurement of interaction forces during static and simple dynamic movements, but they lack detailed pressure distribution analysis and real-time monitoring[26].

The commonly used plantar pressure devices include force plates and pressure insoles. Force plates mainly include the Footscan plantar pressure testing system from Belgium, the Bertec 3D force plate from the United States, and the 3D force platform from AMTI.

Pressure insole systems, such as Pedar-X and F-scan Lite VersaTek, utilize tactile sensors for real-time monitoring and feedback during the entire gait support phase. However, they may interfere with posture control and have limitations in coverage and sensor performance over time. These systems are extensively used in various fields including gait analysis, sports biomechanics research, and rehabilitation assessment, offering insights into pressure distribution and dynamics in different foot areas.

With the emergence of plantar pressure detection devices, laboratory testing methods have become mainstream. These methods offer strong objectivity, reducing the subjectivity of participants, and provide highly quantitative data, facilitating further research analysis and evaluation. Laboratory testing methods mainly include static and dynamic tests. Static tests involve collecting changes in the center of pressure while standing on a pressure plate in a static state, while dynamic tests require participants to perform balance tests under specific tasks, such as focusing on targets on a screen or walking along a route. These testing methods enable more precise evaluation of patients' balance function, providing detailed data analysis to assist clinicians in making more accurate diagnoses and rehabilitation plans. With the continuous development of technology and increased attention to the rehabilitation industry, instrument testing methods will be more widely applied and further innovated in evaluating human balance function.

1.4 Innovation points and significance

The innovation of this article mainly lies in the following aspects:

- Evaluation using plantar biomechanical parameters: The article innovatively evaluates using only a plantar pressure testing system, without involving electromyographic signals or spatiotemporal parameters, making the evaluation process simple and convenient.
- Introduction of new plantar pressure center parameters: The article proposes some plantar pressure center parameters and plantar pressure distribution parameters closely related to body posture control and balance by algorithmically processing the collected raw data from experiments, making the evaluation more comprehensive and accurate.
- Exploration of rare experimental conditions: The static experiment involved in this article is relatively rare both domestically and internationally. Additionally, in this experiments the height of the steps and visual input are important factors influencing balance ability. When subjects stand on steps of a certain height, they may develop a fear of falling, thereby altering their posture control and affecting balance ability. Therefore, this article suggests using data related to plantar pressure center and plantar pressure distribution to describe the changes in single and double foot standing under different step heights and visual input conditions. This contributes to understanding the biomechanical characteristics of the human body in these specific situations, providing reference basis for body posture adjustment and balance.

Chapter 2 Experimental preparation and parameter establishment

2.1 Experimental preparation

2.1.1 Participants

Criteria for inclusion:

- Participants must be between the ages of 18 and 35.
- Participants must exhibit good physical health and standard motor function.
- Participants should have no medical history that could lead to balance issues, including but not limited to cerebrovascular disease, multiple sclerosis, bilateral lower limb fractures, lower limb pain, limb length inequality, arthritis, etc.
- Participants must not be currently taking medications that could impact their balance.
- Participation requires the voluntary completion and signing of an informed consent document.

For safety and ethics, young healthy males were chosen to establish baseline parameters. 15 students from Shanghai Institute of Technology participated. They were aged (20.9±1.16) years, with average height (174.4±6.14) cm, and weight (75.02±10.78) kg. All had dominant right feet, determined through a ball-kicking experiment, Shoe sizes ranged from 39 to 42. Prior to experiments, they passed the Berg Balance Scale test (52.63±1.49). All volunteered and provided consent. Experiments occurred from January 2024 to March 2023 at Shanghai University of Medicine & Health Sciences.

Table 1. Participant Characteristics

Gender	Number of Participants	Age	Height	Body Mass	Berg Balance Scale Score
Male	15	20.9±1.16	174.4±6.14	75.02±10.78	52.63±1.49

Experimental Equipment

The experimental setup includes the F-scan Lite VersaTek System for analyzing plantar pressure, manufactured by the American company Tekscan. This system comprises measurement hardware and analysis software, as shown in Figure 3 and Figure 4. The customizable insole is 0.15 mm thick and equipped with 4 resistive sensors per square centimeter, totaling 955 sensors or measurement points. These sensors, model 3000E, have a measurement range of 7-862 kPa. Encased in polyester sheets, the sensors form a reusable complete insole.

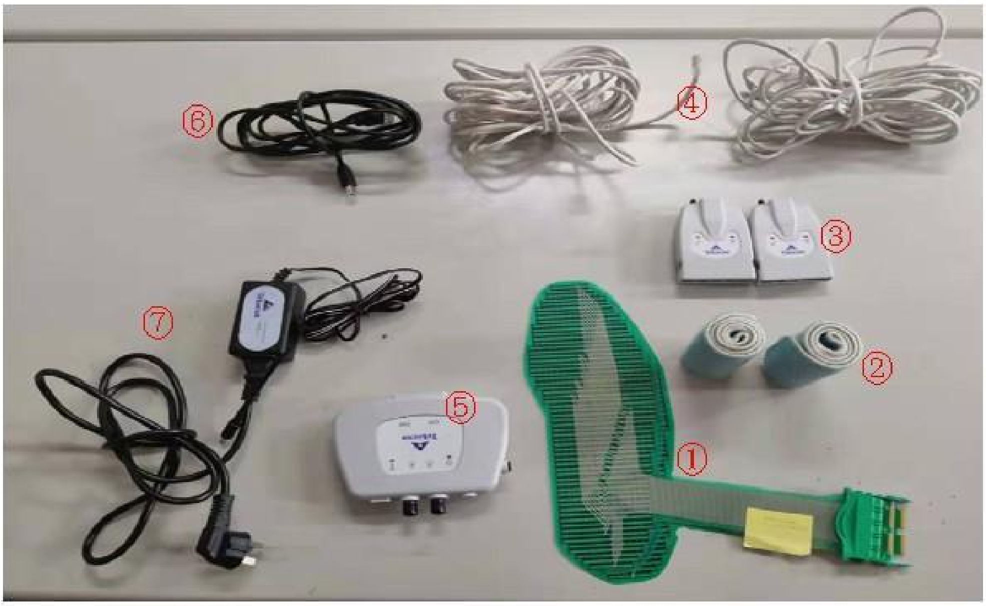

Figure 3. F-scan Foot Pressure Analysis System (Hardware)

1-Customizable foot pressure insole; 2-Ankle strap; 3-VC-1 VersaTek converter; 4-CAT5E cable connector; 5-VersaTek dual-port hub; 6-USB data connection cable; 7-Medical 27-watt power supply

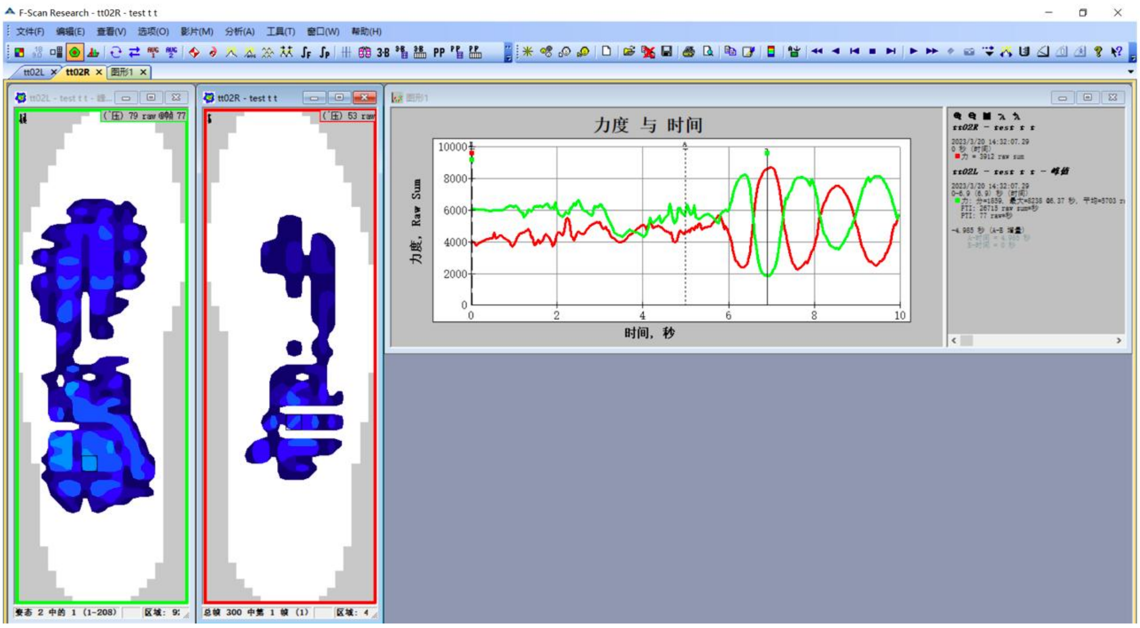

Figure 4. F-scan Foot Pressure Analysis System (Software)

The computer environment and software version used for data processing in this study:

11th Gen Intel(R) Core (TM) i7-11850H @ 2.50GHz, IBM SPSS Statistics 26 (IBM, Chicago, IL, USA), Excel 2016 (Microsoft, Chagrin Falls, OHIO, USA), GraphPad Prism 9 (Microsoft, Chagrin Falls, OHIO, USA), Pycharm Community Edition 2022.2(JetBrains s.r.o., Prague, Czech Republic).

2.2 Acquisition of Plantar Pressure Data

2.2.1 Method for Obtaining and Collecting Foot Pressure Data

In anticipation of potential inaccuracies from shoes linings, participants will remove their shoes for all upcoming experiments. A standard cotton sock will serve as a buffer, with pressure insoles securely affixed to the subject's toes, arches, and heels using standard double-sided tape. This precaution will maintain consistent alignment between the insole and the foot throughout both preparatory activities and the experiment, ensuring the stability of measured data positioning.

Obtaining Method:

1. Before conducting the experiment, calibrate the F-scan testing equipment twice using the subject's body weight to ensure a good experimental environment, normal functioning of the equipment, and the subject's normal condition.
2. Create a new profile on the F-scan software with all necessary personal information of participant.
3. Affix the testing insoles with ordinary double-sided tape to the toes, arches, and heels of the subject's feet. Have the subject stand and walk for 5 minutes to ensure that the insoles are securely attached to the subject's feet and will not fall off during the experiment. Ensure that the subject stands and walks naturally and steadily, looking straight ahead.
4. After a 3-minute rest period, have the subject perform the experimental actions according to the experimental method.
5. Monitor foot pressure data continuously using the monitoring system, record and save experimental data directly, and repeat the experiment twice for accuracy.
6. Rename and save all subject experimental data. Observe and export foot pressure center and distribution data files from the computer displaying pressure distribution graphs.

2.3 Establishment and Implementation of Evaluation Parameters

2.3.1 Establishment of Foot Pressure Center Related Parameters

Kinematic parameters are used to describe the spatial movement of the human body, detailing displacements, velocities, and accelerations of anatomical key points during walking. They also include key angles, angular velocities, and angular accelerations, particularly focusing on the hip, knee, and ankle joints of the lower limbs. Additionally, they describe variations in the body's center of gravity, which is closely linked to the foot pressure center.

Therefore, the foot pressure center related parameters in this experiment include COP-ML (Medial-lateral) adjustment speed (mm/s), COP-AP (Anterior-posterior) adjustment speed (mm/s), COP adjustment speed (mm/s), 95% confidence ellipse area (mm2), ML range (mm), AP range (mm), maximum swing (mm), minimum swing (mm), average X (mm), and average Y (mm). The foot pressure center (Center of Pressure, COP) is located through the X-axis (average X) and Y-axis (average Y) data. These data are obtained through custom Python programs based on relevant formulas.

Assuming that the recorded COP trajectory contains N data points sampled at a constant frequency F, T represents the total duration of the signal in seconds, i.e.:

$$T = \frac{N}{Fs}$$

Formula (2.1)

For each $AP[n]$ and $ML[n]$, and $AP\ [n+1]$ and $ML\ [n+1]$ representing the coordinates of the COP position on the AP (Anterior-posterior) axis from posterior to anterior and on the ML (Medial-lateral) axis from left to right at the moments n/Fs and $(n+1)/F$s, respectively, for each $1 \le n \le N$.

$$COP - AP\ adjustment\ path = \sum_{n=1}^{N-1} (AP[n+1] - AP[n])$$

Formula (2.2)

$$COP - ML\ adjustment\ path = \sum_{n=1}^{N-1} (ML[n+1] - ML[n])$$

Formula (2.3)

According to the Euclidean distance formula, the total adjustment path of the COP is as follows:

$$COP -\ adjustment\ path = \sum_{n=1}^{N-1} \sqrt{(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2}$$

Formula (2.4)

After normalization of the duration, the average velocity of the COP in the AP and ML directions, as well as the total adjustment velocity, can be calculated to represent the average velocity of the COP.

$$COP - AP\ adjustment\ velocity = \frac{1}{T}\sum_{n=1}^{N-1} (AP[n+1] - AP[n])$$

Formula (2.5)

$$COP - ML\ adjustment\ velocity = \frac{1}{T}\sum_{n=1}^{N-1} (ML[n+1] - ML[n])$$

Formula (2.6)

$$COP - adjustment\ velocit = \frac{1}{T}\sum_{n=1}^{N-1} \sqrt{(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2}$$

Formula (2.7)

In the above equation, T represents the time period selected for analysis. Additionally, it is necessary to calculate the average distance, which represents the average distance between the COP and the mean COP (i.e., the center point of the COP).

$$Mean\ Distance = \frac{1}{N}\sum_{n=1}^{N}(AP[n]^2 + ML[n]^2)^{1/2}$$

Formula (2.8)

Meanwhile, the RMS distance represents the root mean square distance between the COP and the mean COP (i.e., the center point of the COP).

$$RMS\ \ Distance = \left(\frac{1}{N}\sum_{n=1}^{N}(P[n]^2 + ML[n]^2)\right)^{1/2}$$

Formula (2.9)

The area of the 95% confidence circle is the area of the circle with a radius equal to the one-sided 95% confidence limit of the distance from the COP to the mean COP (i.e., the center point of the COP):

$$95\%\ confidence\ circule\ area = \pi\left(MDIST + 1.645[RDIST^2 - MDIST^2]^{1/2}\right)^2$$

Formula (2.10)

The COP trajectory range, or amplitude, is widely studied for fall risk prediction, with conflicting results[27]. Quijoux et al.'s review highlighted distinct range differences in both medial-lateral (ML) and anterior-posterior (AP) directions between fallers and non-fallers among elderly participants, prompting the provision of range definitions[28].

$$AP\ range = \max_{1\le n\le m\le N}(AP[n] - AP[m])$$

Formula (2.11)

$$ML\ range = \max_{1\le n\le m\le N}(ML[n] - ML[m])$$

Formula (2.12)

The maximum and minimum swings of COP are defined as the maximum and minimum values of the path within each pair of time points at n/Fs and $(n + 1)/F$s moments within a time frame T.

$$Maximum\ swing = \max_{1\le n\le N-1}\sqrt{(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2}$$

Formula (2.13)

$$Minimum\ swing = \min_{1\le n\le N-1}\sqrt{(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2}$$

Formula (2.14)

Finally, the average position is considered to be the arithmetic mean position coordinates of the COP trajectory before centering. Therefore, for the average positions of ML and AP, there are:

$$\text{Mean X} = \frac{1}{N}\sum_{n=1}^{N-1} ML[n]$$

Formula (2.15)

$$\text{Mean Y} = \frac{1}{N}\sum_{n=1}^{N-1} AP[n]$$

Formula (2.16)

2.3.2 Establishment of Foot Pressure Distribution Parameters

Dynamics parameters, including foot-ground contact force, are vital in this experiment. Ground reaction force (GRF) in the vertical direction reflects the pressure exerted on the ground by the body, pointing from the pressure center to the body's center of mass. During normal walking, the force-time curve of vertical GRF displays a symmetrical bimodal pattern. All experiments analyze foot pressure distribution data using pressure-sensing insoles. This includes vertical ground reaction force, overall foot load, and specific loads during single-limb stance. The foot is divided into regions to clarify individual foot structures' roles. In this study, regions are delineated at 30%, 30%, and 40% of the Y-axis of the insole, as shown in Figure 5.

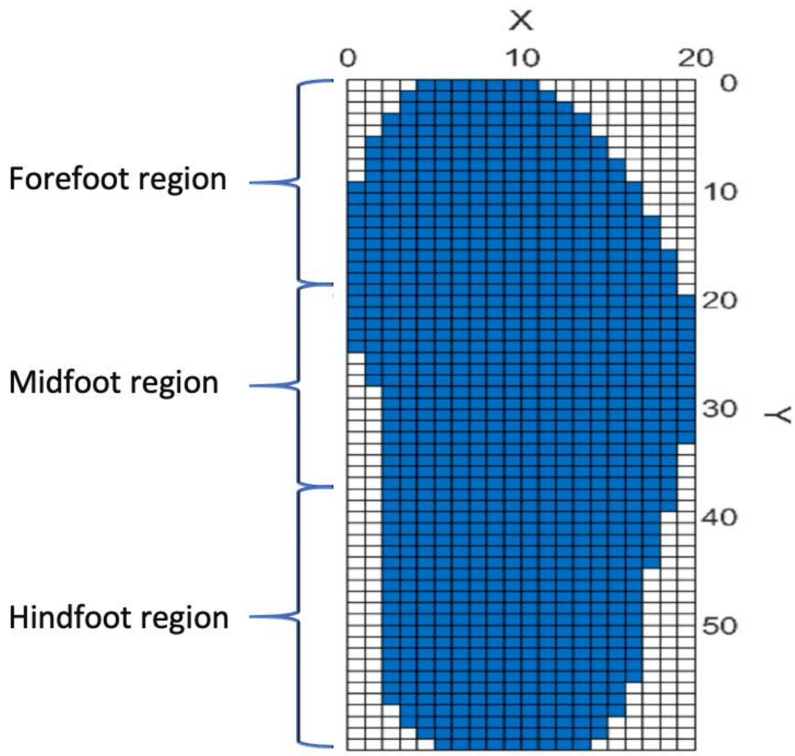

Figure 5. Schematic Diagram of Plantar Area Division

Chapter 3 Experiment and Analysis Methods

3.1 Experimental design

3.1.1 Experimental Procedure

To ensure minimal external interference, the experiment took place in a quiet room. The plantar pressure analysis device was positioned approximately 1.5m away from a blank wall, featuring an adjustable black "+" mark measuring about 10cm×10cm. This mark could be tailored to the subject's eye level. Subjects swayed their pelvis in four directions—anterior-posterior and medial-lateral—to distribute plantar pressure evenly. The experiment was conducted on flat ground (0cm step) and three uniformly hard, flat steps with adjustable heights of 5cm, 15cm, and 25cm, simulating standard curb and building regulation stair heights. The variations in step height aimed to mimic individuals of varying heights, with subjects performing tasks with both eyes open and closed to simulate different visual inputs. Subjects were informed of the step heights during the experiment, and actual standing feet were used for data collection.

Subjects were instructed to stand at three different heights, flat-ground, and steps measuring 5cm, 15cm, and 25cm, to complete experiments with both eyes open and closed. Two sets of distinct experiments were conducted, as depicted in Figure 7.

Experimental Group 1:

Bilateral stance with eyes open

Bilateral stance with eyes closed

Experimental Group 2:

Right foot stance with eyes open

Left foot stance with eyes open

Right foot stance with eyes closed

Left foot stance with eyes closed.

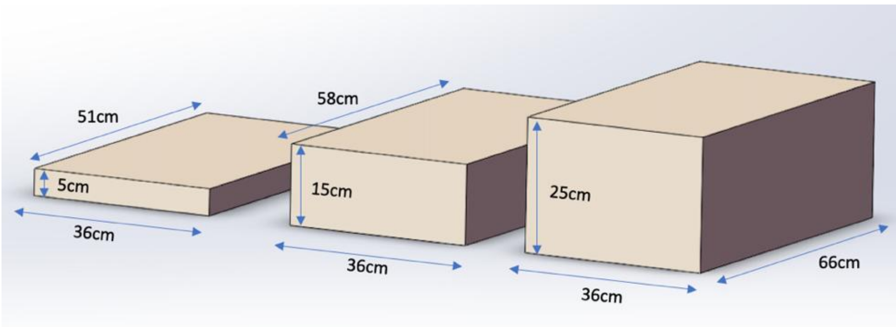

Figure 6. Three different heights of steps: 5cm, 15cm, and 25cm.

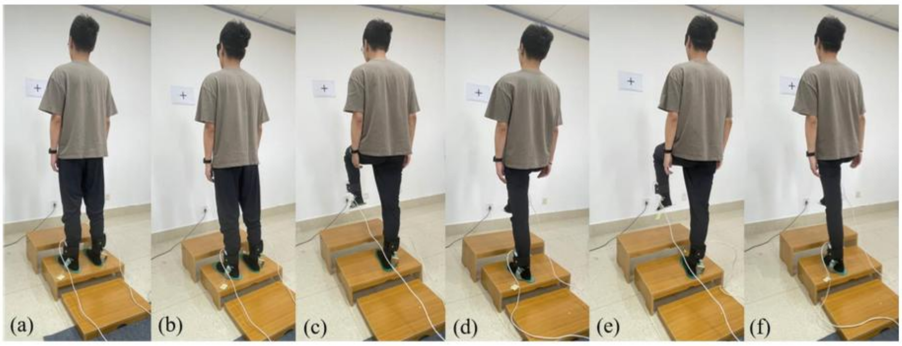

Figure 7. Experimental process example at a step height of 15cm.
(a) Bilateral stance with eyes open;
(b) Bilateral stance with eyes closed;
(c) Single-foot stance (right foot on the ground) with eyes open;
(d) Single-foot stance (left foot on the ground) with eyes open;
(e) Single-foot stance (right foot on the ground) with eyes closed;
(f) Single-foot stance (left foot on the ground) with eyes closed.

Subjects were asked to avoid vigorous exercise two days before and on the day of the test to minimize its impact on the experiment. Subjects were instructed to rest for five minutes before the test to adapt to the environment and alleviate stress, thus avoiding psychological factors affecting the experimental results.

The specific experimental procedures are as follows:

1. Monitoring with eyes open: Instruct each subject to stand upright on flat ground or on elevated steps, and focus on a black "+" mark 1.5m ahead. Collect plantar pressure data from the subjects with their eyes open for a total of 10 seconds.
2. Monitoring with eyes closed: Instruct each subject to maintain a standing position with eyes closed on flat ground or on elevated steps, and collect plantar pressure data from the subjects for a total of 10 seconds.
3. Bilateral stance: Instruct the subjects to stand upright with both feet on the ground.
4. Unilateral stance: Instruct the subjects to stand on one foot, first on the right foot and then on the left foot, with the foot on the opposite side raised upwards throughout the entire unilateral standing process, not touching the ground, and not generating plantar pressure data.
5. To minimize the influence of auditory stimulation or stress on the results, subjects were not informed that data were being recorded. Throughout the entire experimental process, another tester stood behind the subject ready to provide protection to prevent the subject from falling.

3.1.2 Data Processing

Processing plantar pressure data involves several steps. Firstly, a video recording of the entire testing process capturing "foot-ground contact" is obtained for each subject and each trial. From these videos, two CSV files are exported: one containing the center of pressure data for each frame, and the other containing plantar pressure distribution data. Customized Python programs are then utilized to calculate parameters related to the center of pressure and plantar pressure distribution, as described in sections 2.3.1 and 2.3.2 of the current data. Finally, the results of both sets of data are compiled into separate Excel files.

3.1.3 Statistical Analysis

Data analysis was conducted using SPSS Statistics 26 and Excel 2016, with scatter plot visualization performed using GraphPad Prism 9. Results are presented as mean ± standard deviation (M±SD).

For single-foot and double-foot parameters of plantar pressure center, and single-foot plantar pressure distribution parameters: A three-factor analysis of variance (ANOVA) with a 2×2×4 (vision × dominant side × step height) within-subject design was initially conducted to assess the effects of vision, dominant side, step height, and their interactions. If significant differences ($P<0.05$) were observed, repeated measures two-way ANOVA was employed to explore main effects and interactions. Post-hoc multiple comparisons were conducted using Bonferroni correction.

For single-foot plantar pressure distribution parameters: Paired t-tests were used for normally distributed data, while Wilcoxon signed-rank tests were employed for skewed distribution. The significance level (α) was set at 0.05, with $P<0.05$ considered statistically significant and $P<0.001$ considered extremely significant.

3.2 Experimental Results

3.2.1 Plantar Pressure Center Parameters

Plantar Pressure Center Parameters during Single-Foot Stance

A three-factor analysis of variance was conducted on plantar pressure center parameters, considering visual input, dominant side, and step height. The results revealed that the dominant side factor during single-foot stance did not exhibit statistically significant differences in the plantar pressure center parameters. Subsequently, a repeated measures two-way analysis of variance was performed to explore the effects of visual input and step height, as detailed in Table 2. No significant differences were observed in any interaction.

As shown in Table 2, significant statistical differences ($P < 0.001$) were observed in various plantar pressure center parameters between open-eye and closed-eye conditions, including COP-ML adjustment velocity (mm/s), COP-AP adjustment velocity (mm/s), COP adjustment velocity (mm/s), 95% confidence ellipse area (mm^2), ML range (mm), AP range (mm), maximum sway (mm), minimum sway (mm), and average Y (mm) for the left foot. Significant differences ($P = 0.003$) were also observed in the average Y (mm) for the right foot, and (P = 0.007) in the average X (mm) for the left foot. All these parameters significantly increased under closed-eye conditions compared to open-eye conditions. Regarding the four step heights, significant differences (P = 0.029) were observed in the COP adjustment velocity (mm/s) for the left foot, and highly significant differences (P < 0.001) were observed in the COP-ML adjustment velocity (mm/s) for the left foot. All these plantar pressure center parameters increased with increasing step height.

Table 2. illustrates the COP parameters during single-foot stance with different visual input factors at various step heights.

Project	0cm step		5cm step		15cm step		25cm step	
	Eyes open	Eyes closed	Eyes open	Eyes closed	Eyes open	Eyes closed	Eyes open	Eyes closed
				Right foot				
COP-ML Adjustment Velocity(mm/s)	18.50 ± 4.81	45.91 ±16.16	19.62 ±6.05	48.39 ±14.78	22.18 ±4.51	49.41 ±15.09	21.45 ±5.77	49.95 ±14.15***
COP-AP Adjustment Velocity(mm/s)	21.45 ±8.39	55.48 ±23.61	23.66 ±8.35	75.40 ±71.09	27.19 ±9.05	66.98 ±36.85	30.31 ±20.16	75.26 ±59.83***
COP Adjustment Velocity(mm/s)	31.44 ±9.06	80.62 ±28.46	33.97 ±9.31	100.78 ±67.98	38.74 ±8.90	92.75 ±38.36	41.05 ±19.82	101.30 ±56.75***
95%Confidence Ellipse Area(mm2)	833.11 ±681.07	2618.88 ±1659.87	1123.13 ±1015.96	3485.55 ±3961.47	1372.77 ±1173.38	3173.98 ±2560.72	1336.88 ±1291.91	3290.28 ±3164.00***
ML range (mm)	21.47 ±5.32	39.27 ±9.25	22.01 ±6.34	40.05 ±6.23	25.99 ±7.12	40.38 ±8.79	23.41 ±6.30	40.49 ±9.16***
AP range (mm)	34.68 ±14.77	70.97 ±33.88	40.38 ±20.07	76.58 ±37.52	43.29 ±17.62	76.98 ±33.62	49.1 ±28.54	74.95 ±34.64***
Maximum sway (mm)	3.35 ±1.57	11.41 ±10.11	3.90 ±1.89	17.89 ±27.83	4.10 ±1.19	15.00 ±15.97	5.83 ±6.13	14.03 ±12.73***
Minimum sway (mm)	0.02 ±0.01	0.04 ±0.02	0.02 ±0.01	0.04 ±0.03	0.02 ±0.01	0.04 ±0.03	0.02 ±0.02	0.04 ±0.03***

Average X (mm)	58.15 ±3.49	58.82 ±5.54	57.64 ±5.24	56.23 ±5.51	57.19 ±5.09	56.07 ±5.50	56.31 ±6.09	56.46 ±5.53***
Average Y (mm)	141.38 ±13.75	147.73 ±15.88	137.12 ±19.11	145.92 ±14.44	139.52 ±18.48	144.14 ±19.83	138.09 ±18.65	145.04 ±18.19***
				Left foot				
COP-ML Adjustment Velocity(mm/s)	18.21 ± 4.92	44.08 ±11.69	19.44 ±4.73	45.35 ±13.05	22.85 ±6.44	50.20 ±9.57	23.82 ±7.28	50.55 ±13.43***###
COP-AP Adjustment Velocity(mm/s)	23.28 ±11.83	65.27 ±34.71	23.03 ±11.32	66.26 ±36.29	29.99 ±27.94	74.58 ±45.44	38.60 ±53.15	86.61 ±88.64***
COP Adjustment Velocity(mm/s)	32.65 ±12.64	87.44 ±39.98	33.20 ±12.36	88.99 ±37.36	41.98 ±28.65	100.14 ±43.62	50.93 ±52.87	111.87 ±85.55***#
95%Confidence Ellipse Area(mm2)	895.99 ± 930.23	3295.92 ± 2989.8	845.97 ± 736.13	3006.7 ± 2210.12	1155.6 ± 1857.87	3857.9 ± 3653.01	1748.49 ± 3375.01	3682.59 ±4622.27***
ML range (mm)	21.20 ±5.86	38.97 ±9.28	22.34 ±5.52	39.74 ±8.96	23.48 ±6.31	41.53 ±5.53	23.53 ±6.93	39.48 ±7.32***
AP range (mm)	35.30 ±20.11	72.77 ±36.78	36.50 ±18.16	70.72 ±35.98	39.64 ±29.73	79.50 ±37.72	45.42 ±39.91	72.81 ±43.66***
Maximum sway (mm)	0.01 ±0.01	0.04 ±0.02	0.01 ±0.01	0.04 ±0.02	0.02 ±0.01	0.04 ±0.02	0.02 ±0.01	0.04 ±0.03***
Minimum sway (mm)	0.02 ±0.01	0.04 ±0.02	0.02 ±0.01	0.04 ±0.02	0.02 ±0.01	0.04 ±0.02	0.02 ±0.01	0.04 ±0.03***
Average X (mm)	45.30 ±4.34	46.42 ±5.91	47.24 ±4.00	48.22 ±4.85	45.86 ±4.65	49.34 ±6.50	46.45 ±5.63	48.24 ±5.79*
Average Y (mm)	138.60 ±16.52	145.45 ±14.05	142.18 ±16.50	147.73 ±15.69	141.27 ±15.44	147.56 ±10.87	138.39 ±14.29	148.13 ±13.66***

Note: * indicates statistically significant differences ($P < 0.05$) between open-eye and closed-eye conditions for different visual factors; *** indicates extremely significant differences (P < 0.001) between open-eye and closed-eye conditions for different visual factors. # indicates statistically significant differences (P < 0.05) among step heights of 0cm, 5cm, 15cm, and 25cm; ### indicates extremely significant differences (P < 0.001) among step heights of 0cm, 5cm, 15cm, and 25cm.

Comparison of Scatter Plots of Plantar Pressure Center during Single-Foot Stance

Scatter plots of Center of Pressure (COP) data for left and right foot single-foot stance were generated based on average X and average Y coordinates. The scatter plot distribution of **COP in Figure 8(a) and Figure 8(b) allowed for determination of COP position. The results indicated** that under closed-eye conditions, COP was more distributed towards the mid-front of the foot compared to open-eye conditions.

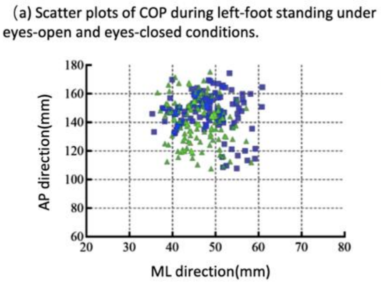

Figure 8 (a) left foot stance

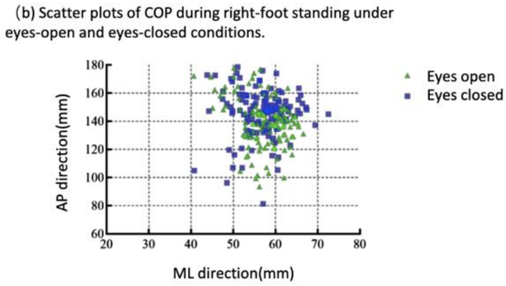

Figure 8 (b) right foot stance.

Figure 8 Scatter plots of COP under open-eye and closed-eye conditions.

Plantar Pressure Center Parameters during Bilateral Stance

A three-factor analysis of variance was conducted on the plantar pressure center parameters considering visual input, dominant side, and step height. The results indicated no statistically significant differences in plantar pressure center parameters during bilateral stance with respect to visual input. Therefore, a repeated measures two-way analysis of variance was conducted again to investigate the effects of dominant side and step height. As shown in Table 3, no significant differences were observed in any interaction.

As shown in Table 3, comparisons between left and right foot conditions revealed extremely significant statistical differences (P < 0.001) in COP-ML adjustment velocity (mm/s) and average X (mm) under open-eye conditions. Significant statistical differences were observed in COP-AP adjustment velocity (mm/s) (P = 0.022), COP adjustment velocity (mm/s) (P = 0.016), and ML range (mm) (P = 0.030). Under closed-eye conditions, extremely significant statistical differences (P < 0.001) were found in COP-ML adjustment velocity (mm/s) and average X (mm). Significant statistical differences were observed in COP-AP adjustment velocity (mm/s) (P = 0.004), COP adjustment velocity (mm/s) (P = 0.002), maximum sway (mm) (P = 0.025), and minimum sway (mm) (P = 0.005). All these plantar pressure center parameters for the right foot were significantly larger compared to the left foot.

When comparing step heights of 0cm, 5cm, 15cm, and 25cm under open-eye conditions, statistically significant differences were observed in COP-ML adjustment velocity (mm/s) (P = 0.008), COP-AP adjustment velocity (mm/s) (P = 0.030), COP adjustment velocity (mm/s) (P = 0.025), AP range (mm) (P = 0.032), and average Y (mm) (P = 0.011). The difference in average X (mm) was extremely statistically significant (P < 0.001). Under closed-eye conditions, significant differences were observed in COP-ML adjustment velocity (mm/s) (P = 0.019), COP-AP adjustment velocity (mm/s) (P = 0.033), COP adjustment velocity (mm/s) (P = 0.031), maximum sway (mm) (P = 0.051), and average X (mm) (P = 0.004) with respect to step height. All these plantar pressure center parameters increased with increasing step height.

Table 3. COP Parameters during Bilateral Stance of Right and Left Feet at Different Step Heights

Project	0cm step		5cm step		15cm step		25cm step	
	Eyes open	Eyes closed	Eyes open	Eyes closed	Eyes open	Eyes closed	Eyes closed	Eyes open
				Right foot				
COP-ML Adjustment Velocity(mm/s)	2.46 ±1.60	2.44 ±1.95	3.27 ±1.70	2.49 ±1.68	3.53 ±1.62	2.64 ±1.87	4.48 ±2.59	2.71 ±1.42#$$$
COP-AP Adjustment Velocity(mm/s)	11.70 ±8.81	11.78 ±7.33	15.5 ±8.83	12.32 ±8.25	15.52 ±5.64	12.35 ±8.11	17.59 ±7.91	14.53 ±7.51#$
COP Adjustment Velocity(mm/s)	12.33 ±9.12	12.39 ±7.77	16.28 ±9.16	12.95 ±8.62	16.42 ±5.94	13.02 ±8.49	18.82 ±8.58	15.17 ±7.77#$
95%Confidence Ellipse Area(mm2)	588.39 ±1236.85	484.19 ±618.75	595.90 ±1338.71	839.06 ±2180.87	468.86 ±448.64	569.45 ±789.45	855.24 ±1312.69	1128.8 ±1710.36
ML range (mm)	2.53 ±1.57	2.21 ±2.30	2.82 ±1.63	2.38 ±2.65	2.61 ±1.51	1.99 ±1.18	3.51 ±1.91	2.78 ±1.90$
AP range (mm)	25.44 ±19.19	24.84 ±16.85	26.30 ±20.56	28.20 ±24.52	26.06 ±11.30	27.04 ±16.61	33.25 ±21.31	36.58 ±23.71#

Maximum sway (mm)	2.04 ±19.19	1.81 ±16.85	2.96 ±20.56	1.95 ±24.52	2.58 ±11.30	1.91 ±16.61	2.70 ±21.31	2.64 ±23.71#
Minimum sway (mm)	0.002 ±0.004	0.004 ±0.007	0.003 ±0.004	0.002 ±0.004	0.004 ±0.005	0.002 ±0.004	0.005 ±0.006	0.003 ±0.004
Average X (mm)	51.23 ±3.90	49.16 ±3.53	53.62 ±5.16	51.55 ±3.68	55.25 ±4.67	52.52 ±4.50	54.97 ±5.54	53.12 ±5.21###$$$
Average Y (mm)	131.07 ±18.93	129.53 ±27.27	112.89 ±22.15	120.36 ±23.18	115.71 ±19.76	123.89 ±27.55	120.89 ±24.16	120.34 ±24.02#
					Left foot			
COP-ML Adjustment Velocity(mm/s)	2.57 ±1.26	2.25 ±1.47	3.36 ±1.44	2.24 ±1.21	3.38 ±1.25	2.35 ±1.71	3.95 ±1.59	2.50 ±1.31#$$$
COP-AP Adjustment Velocity(mm/s)	12.85 ±6.25	12.83 ±7.52	16.45 ±6.67	12.62 ±6.79	17.42 ±7.64	14.45 ±8.11	18.39 ±7.65	14.41 ±6.94#$
COP Adjustment Velocity(mm/s)	13.49 ±6.48	13.35 ±7.79	17.22 ±6.92	13.15 ±7.00	18.20 ±7.86	14.94 ±8.45	19.36 ±7.91	15.00 ±7.17#$
95%Confidence Ellipse Area(mm2)	935.93 ±1491.39	1074.51 ±2002.06	839.21 ±1105.53	852.03 ±1255.97	1164.21 ±1837.69	1316.18 ±2732.26	1713.86 ±4227.93	1456.77 ±3816.6
ML range (mm)	2.62 ±1.49	2.11 ±1.80	2.77 ±1.54	2.10 ±1.25	2.83 ±1.76	2.80 ±4.18	3.52 ±2.21	2.77 ±2.38
AP range (mm)	31.28 ±18.88	31.50 ±22.57	33.43 ±20.69	31.69 ±18.96	37.51 ±29.96	37.43 ±30.43	37.59 ±30.05	34.99 ±26.96***
Maximum sway (mm)	2.06 ±1.55	1.94 ±1.43	2.50 ±1.33	1.86 ±1.38	3.05 ±1.76	2.52 ±1.85	3.00 ±2.55	2.23 ±1.81#$
Minimum sway (mm)	0.003 ±0.00	0.002 ±0.004	0.003 ±0.00	0.001 ±0.003	0.003 ±0.00	0.001 ±0.003	0.004 ±0.005	0.003 ±0.005$

	5		5		5			
Average X (mm)	52.51 ±4.29	49.70 ±4.51	54.05 ±6.19	51.81 ±4.59	55.05 ±4.59	51.80 ±4.17	55.67 ±5.30	52.85 ±4.80#$$$
Average Y (mm)	121.62 ±19.72	126.42 ±25.38	118.80 ±22.22	125.23 ±26.46	118.79 ±21.66	120.14 ±24.71	119.20 ±19.80	120.92 ±21.54

Note: # indicates statistically significant differences (P < 0.05) among step heights of 0cm, 5cm, 15cm, and 25cm; ### indicates extremely significant differences (P < 0.001) among step heights of 0cm, 5cm, 15cm, and 25cm.$ indicates statistically significant differences (P < 0.05) between right and left feet; $$$ indicates extremely significant differences (P < 0.001) between right and left feet.

Comparison of Scatter Plots of Plantar Pressure Center during Bilateral Stance

Scatter plots of COP data for bilateral stance of the left and right feet were plotted based on average X and average Y. According to the scatter plot distribution of COP in Figure 9(a) and Figure 9(b), the position of COP was further determined. The results showed that there were no significant differences in the distribution of COP under closed-eye conditions compared to open-eye conditions.

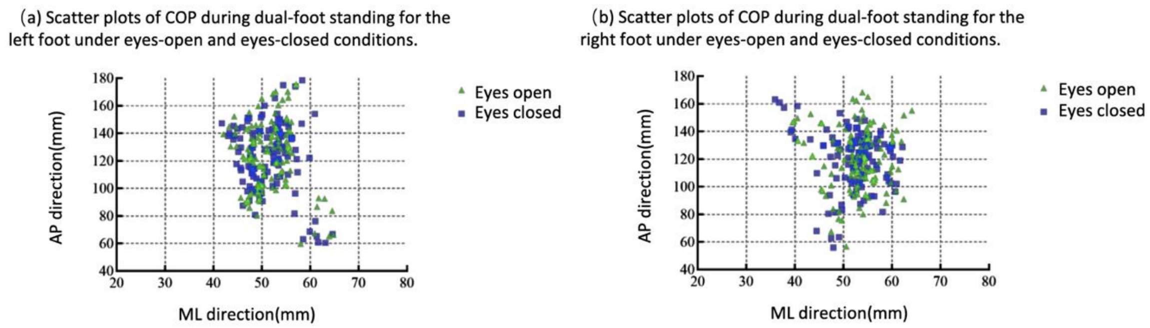

Figure 9 (a) left foot stance

Figure 9 (b) right foot stance

Figure 9. Scatter plots of COP under open-eye and closed-eye conditions.

3.2.2 Plantar Pressure Distribution Parameters

Plantar Pressure Distribution Parameters during Single-Foot Stance

Initially, a three-factor analysis of variance was conducted to assess the effects of visual input, dominant side, and step height on plantar pressure distribution parameters. Results indicated that different step heights did not significantly affect plantar pressure distribution parameters, while dominant side and visual input factors exhibited significant differences. Subsequently, a repeated measures two-way analysis of variance was performed to analyze these differences, with no significant interaction effects observed.

Table 4 illustrates that differences in toe load between left and right feet under different visual input conditions were extremely statistically significant (P < 0.001). Additionally, the toe load of the right foot exceeded that of the left foot, with greater load observed under closed-eye conditions compared to open-eye conditions. A statistical difference in midfoot load between open-eye and closed-eye conditions (P = 0.024) was noted, along with extremely significant differences between midfoot loads of left and right feet (P < 0.001). Load increased under closed-eye conditions compared to open-eye conditions, with the right foot bearing greater load than the left foot. Hindfoot load differences exhibited extremely significant statistical differences under both open-eye and closed-eye conditions (P < 0.001), with statistical significance between left and right feet (P = 0.002). Hindfoot load under closed-eye conditions was significantly smaller than under open-eye conditions, while hindfoot load of the right foot exceeded that of the left foot.

Table 4. Plantar Pressure Distribution Parameters during Left and Right Foot Stance under Different Visual Input Factors

		Right foot		**Left foot**
Project	Eyes open	Eyes closed	Eyes open	Eyes closed
	(M±SD, %)	(M±SD, %)	(M±SD, %)	(M±SD, %)
Toe load	5.80±4.05	8.73±5.49	3.52±3.43	6.10±4.61***$$$
Midfoot load	48.29±10.69	50.32±9.92	53.57±11.83	56.07±11.15*$$$
Hindfoot load	45.92±10.74	40.95±10.65	42.91±11.11	37.83±9.62***$

Note: * indicates statistically significant differences (P < 0.05) between open-eye and closed-eye conditions for different visual input factors; *** indicates extremely significant differences (P < 0.001) between open-eye and closed-eye conditions for different visual input factors. $ indicates statistically significant differences (P < 0.05) between right and left feet; $$$ indicates extremely significant differences (P < 0.001) between right and left feet.

Comparison of Plantar Pressure Distribution Parameters between Left and Right Feet during Bilateral Stance under Open-Eye and Closed-Eye Conditions

Initially, a three-factor analysis of variance was conducted to compare the effects of visual input, dominant side, and step height on the plantar pressure distribution parameters. The results indicated that the main effect of different step heights on plantar pressure distribution parameters was not statistically significant, while the main effects of the remaining dominant side and visual input were statistically significant. Subsequently, paired t-tests were conducted.

As shown in Table 5, the overall load differences between the left and right feet under open-eye and closed-eye conditions were statistically significant (P = 0.003). After closing the eyes, the overall load of the right foot increased while the overall load of the left foot decreased. There were no statistically significant differences in forefoot and hindfoot loads between the left and right feet under both open-eye and closed-eye conditions.

Table 5. Plantar Pressure Distribution Parameters between Different Feet under Different Visual Input Factors during Stance

Project	Position	Eyes open	Eyes closed	T value	P value
		(M±SD, %)	(M±SD, %)		
Overall load	Right foot	49.29±7.11	53.10±6.71	3.09	0.003
	Left foot	50.71±7.11	46.90±6.71	-3.09	0.003
Forefoot load	Right foot	36.49±16.51	36.66±13.82	0.08	0.935
	Left foot	42.86±15.94	42.82±16.55	0.02	0.983
Hindfoot load	Right foot	63.51±16.51	63.34±13.82	0.08	0.935
	Left foot	57.14±15.94	57.19±16.55	-0.02	0.983

Comparison of Bilateral Plantar Pressure Distribution Parameters under Different Visual Input Factors during Bilateral Stance

As shown in Table 6, under open-eye conditions, the difference in overall load between the left and right feet was not statistically significant (P = 0.445). However, under closed-eye conditions, the difference in overall load between the left and right feet was extremely statistically significant (P < 0.001). After closing the eyes, the overall load of the right foot was greater than that of the left foot. Significant statistical differences (P < 0.001) were observed in both forefoot and hindfoot loads between the right and left feet under both open-eye and closed-eye conditions. The forefoot load of the right foot was less than that of the left foot, while conversely, the hindfoot load of the right foot was greater than that of the left foot.

Table 6. Plantar Pressure Distribution Parameters of Left and Right Feet under Different Visual Input Factors

Project	state	Right foot	Left foot	T value	P value
		(M±SD, %)	(M±SD, %)		
Overall load	Eyes open	49.29±7.11	50.71±7.11	-0.77	0.445
	Eyes closed	53.10±6.71	46.90±6.71	-3.57	<0.001
Forefoot load	Eyes open	36.49±16.51	42.86±15.94	-4.26	<0.001
	Eyes closed	36.66±13.82	42.82±16.55	-4.63	<0.001

Hindfoot load	Eyes open	63.51±16.51	57.14±15.94	4.26	<0.001
	Eyes closed	63.34±13.82	57.19±16.55	4.63	<0.001

Comparison of Forefoot and Hindfoot Plantar Pressure Distribution Parameters between Open-Eye and Closed-Eye Conditions during Bilateral Stance

As shown in Table 7, significant statistical differences ($P < 0.001$) were observed in the forefoot and hindfoot loads of the right foot under both open-eye and closed-eye conditions. For the left foot, significant statistical differences ($P < 0.001$) were observed in the forefoot and hindfoot loads under open-eye conditions, while under closed-eye conditions, the differences were statistically significant ($P = 0.001$). The hindfoot load was significantly greater than the forefoot load in both cases.

Table 7. Comparison of Forefoot and Hindfoot Plantar Pressure Distribution Parameters between Open-Eye and Closed-Eye Conditions

Position	state	Forefoot load	Hindfoot load	T value	P value
		(M±SD, %)	(M±SD, %)		
Right foot	Eyes open	36.49±16.51	63.61±16.51	-6.34	<0.001
	Eyes closed	36.66±13.82	63.34±13.82	-7.48	<0.001
Left foot	Eyes open	42.86±15.94	57.14±15.94	-3.47	<0.001
	Eyes closed	42.82±16.55	57.19±16.55	-3.36	<0.001

3.3 Discussion Analysis Balance

Control of body stability relies primarily on three factors: vision, vestibular sensation, and proprioception, which must coordinate with motor and cognitive systems. In healthy individuals, proprioceptive input from the lower limbs and visual input are vital for balance regulation during standing. When eyes are closed, the vestibular system compensates for lack of visual input by adjusting body parts to maintain balance based on head position and movement. Varying step heights simulate real-life scenarios, potentially increasing psychological burden and fear of falling in participants, which can negatively impact static balance ability. Studies suggest that balance performance significantly influences balance confidence, with decreased balance ability leading to heightened fear of falling. This fear can result in cautious behavior, affecting gait, muscle strength, and motor function, ultimately impairing daily activities and reducing quality of life. In this experiment, visual deprivation was simulated through open-eye and closed-eye conditions, while standing at different step heights simulated varied real-life situations. To eliminate unstable effects on proprioception and the vestibular system, foot contact area and body/head positions remained constant. The impact of visual factors and step height on static standing balance function was explored through plantar pressure center and distribution parameters.

3.3.1 Changes in Single-Leg Plantar Pressure Center Parameters

In the closed-eye condition compared to open-eye, significant swaying of participants' feet was observed during single-leg standing, reflected in changes in plantar pressure center parameters. These changes, related to center of pressure (COP) activity, indicate balance maintenance and adjustment. Previous research, like Muir's study, demonstrated decreased COP-related parameters in fallers. Healthy young men exhibited higher COP sway amplitudes in the closed-eye condition due to balance control after visual deprivation. Vision plays a crucial role in predicting and reacting to balance challenges. Furthermore, no differences in plantar pressure center parameters were found between dominant and non-dominant lower limbs in healthy young males, consistent with prior studies. The increase in COP-AP adjustment velocity and COP adjustment velocity of the left foot with height suggests heightened fear and anxiety among participants. Increased height exacerbates the challenge of balance control due to the inherent instability of single-leg standing. Enhancing single-leg standing exercises can benefit limb stability, as observed in Freeman's study, making them valuable for assessing balance disorders linked to musculoskeletal injuries. Adjustments in step height during single leg standing exercises are anticipated to enhance confidence and mitigate fear of falling.

3.3.2 Changes in Bilateral Plantar Pressure Center Parameters

During bilateral standing, significant adjustments are observed in the medial-lateral (ML) direction, particularly in the right foot. This aligns with findings indicating differences in sway characteristics between fallers and non-fallers, emphasizing the predictive value of ML sway for falls. Moreover, adjustments in the anterior-posterior (AP) direction are also noted in the right foot during bilateral standing, possibly influenced by lower limb dominance. The dominant lower limb plays a crucial role in bilateral standing balance, contributing more to stability. Healthy young men primarily use the dominant foot to adjust the body's center of gravity, maintaining balance and stability. Comparing standing heights of 0cm, 5cm, 15cm, and 25cm, COP adjustments increase significantly with height, regardless of visual condition. Psychological burden and fear of falling increase with higher steps, suggesting the importance of prioritizing the dominant side to maintain stability.

3.3.3 Changes in Unilateral Plantar Pressure Distribution Parameters

Visual deprivation during single-foot standing with closed eyes may lead to increased toe grip force among participants, resulting in higher toe load under closed-eye conditions. Difficulty in maintaining balance without visual input may necessitate higher midfoot load, contributing to differences in midfoot and rearfoot loads between open-eye and closed-eye conditions. This increase in toe and midfoot loads could explain the decrease in rearfoot load observed under closed-eye conditions. Research indicates that fallers tend to have greater loads on specific areas of the foot, such as the medial midfoot and forefoot. The toes, particularly the big toe, play a critical role in providing neural feedback for postural stability, enhancing stability during standing and movement by gripping the ground. Toe muscle strength is closely linked to walking and balancing posture, with toe pressure intensity during standing serving as an indicator of fall risk in older adults. Thus, toe pressure intensity during standing is an important muscle strength related to standing stability. The observed differences between the left and right feet may stem from lower limb dominance, with healthy young males favoring their dominant side, typically the right foot, for support and exertion. Consequently, pressure load on the toes and rearfoot of the right foot tends to be higher compared to the left foot, reflecting greater stability on the dominant side. Previous research has similarly noted significant disparities in postural control between the dominant and non-dominant sides during single-leg standing.

3.3.4 Changes in Bilateral Plantar Pressure Distribution Parameters

Under closed-eye conditions, significant changes in overall load distribution were observed between the left and right feet, with an increase in the right foot and a decrease in the left foot, indicating the influence of visual factors on the center of gravity position in bilateral standing. This suggests a lateralization effect of visual factors, particularly notable in the medial-lateral (ML) direction. However, there were no significant differences in forefoot and rearfoot loads between closed-eye and open-eye conditions, indicating subtle changes in plantar pressure distribution during bilateral standing for healthy young men. Unlike previous studies, which suggested greater body sway induced by visual factors in the anterior-posterior (AP) direction, this experiment found increased sway primarily in the ML direction under different visual inputs. This discrepancy may stem from variations in experimental methods, participant characteristics, or fatigue levels.Under closed-eye conditions, there's a notable increase in overall load on the right foot compared to the left, indicating adjustments in body balance. Participants adapt by increasing the load on the dominant side, primarily on the right foot, to maintain balance. Interestingly, under both open-eye and closed-eye conditions, the forefoot load is higher on the left foot, while the rearfoot load is higher on the right foot. These results contradict the assumption that healthy young men predominantly use the dominant foot's heel for support during prolonged standing.

3.4 Experimental Conclusion

In conclusion, visual input, step height, and dominant side significantly impact the static balance of healthy young men during both single-leg and bilateral standing. These factors influence COP adjustments in the AP and ML directions and alter the load distribution between the forefoot and rearfoot, regulating balance function. During bilateral standing, participants adjust the COP position and load distribution, primarily using the heel of the dominant foot for support. During single-leg standing, adjustments in the Center of Pressure (COP) axes and weight distribution between forefoot and rearfoot help regulate balance under varied visual conditions. Additionally, increasing standing height intensifies COP adjustments, affecting balance regulation in both stances. Plantar pressure analysis offers a quantitative method to objectively assess static balance, aiding in fall prevention and balance improvement.

Chapter 4 Research Outlook

4.1 Summary

This study investigated the balance and stability of healthy young men using insole-type plantar pressure devices. It collected biomechanical data of the foot sole during static standing and single transitional steps on stairs, varying visual factors, step heights, and foot conditions. The research aimed to understand human balance laws and plantar biomechanics to prevent falls and guide movement effectively. The study involved:

- Reviewing literature on balance and plantar pressure studies, understanding human gait analysis, and learning relevant programming and statistical analysis.
- Determining the research content and experimental design framework.
- Extracting quantitative evaluation parameters for human balance from literature and designing experiments accordingly.
- Conducting formal experiments measuring plantar pressure during static standing and single-step transitions on stairs.
- Processing and analyzing experimental data using Python and statistical methods to draw conclusions about human balance and stability under different conditions.

4.2 Shortcomings and Future Prospects of the Research Topic

This study, which focuses on static balance in healthy adult males, acknowledges potential differences in balance function between genders and age groups. Future research will expand to include females, children, and older individuals as participants to gain a comprehensive understanding of foot biomechanics during transitional steps. Additionally, exploring the effects of visual factors on dynamic transitioning through steps (dynamic stability), including walking speed on stability during step ascent and descent, is planned. Investigating the role of fatigue in balance control is also crucial, as it may explain lateralization observed during bilateral standing. Furthermore, the study aims to quantify balance assessment using foot pressure parameters and hopes to contribute to the diagnosis and rehabilitation of patients with balance impairments. Further research could also explore the impact of various environmental factors, such as different types of surfaces and obstacles, on dynamic stability during transitional steps. Additionally, investigating the long-term effects of balance training interventions on improving dynamic stability and reducing the risk of falls could provide valuable insights for clinical practice.

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