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# Designing a Low-Cost Force Plate for Postural Assessment

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## Abstract

The purpose of this study was to develop a pair of single-pedestal types with a low-cost and user-friendly force plate for assessing ground reaction force (GRF), center of pressure (COP), and plantar pressure distribution (PPD). These parameters are crucial for assessing human movement and maintaining body balance. The load cells were tested with standard weights of 5, 10, 15, and 20 kg. Using linear regression, the analysis showed a strong linear relationship between the load cell output and the standard weight, with an R-squared value of 0.99. Furthermore, the error margin was determined to be less than +/- 5%. In the initial equipment assessment, a healthy female was evaluated the posture under both eye-open and eye-closed conditions through three sets of measurements. The results showed about a two-fold change in the COP parameter, possibly due to swaying when the eyes were closed. Additionally, the PPD parameter revealed varying foot weight distribution levels, even though the GRF values were almost the same. The equipment's graphic user interface (GUI) provides real-time graphical representations for GRF, COP, and PPD, aiding in training effectiveness for enhancing postural assessment under professional guidance. In future studies, we plan to use the developed equipment to observe its effectiveness by measuring a larger and more diverse population.

***Keywords***: *force plate; ground reaction force (GRF); center of pressure (COP); plantar pressure distribution (PPD)*

## 1. Introduction

Maintaining balance and body posture while standing is crucial for various daily activities and sports. In sports science, there is a focus on analyzing movement patterns in athletes to minimize the risk of injuries. The use of a force plate, which measures ground reaction forces, is one tool employed to analyze walking patterns in individuals with cerebral palsy, elderly individuals, stroke patients, and athletes. The force plate allows for the analysis of kinetic and kinematic aspects, ground reaction forces, and the center of pressure of each foot during various movements such as standing, walking, running, and jumping (Silva et al., 2017). The data obtained from force plate measurements can provide insights into balance performance, which is essential in research related to fall prevention in the elderly, neurological rehabilitation, improving athletic performance, and reducing the risk of injuries in sports (Beckham et al., 2014). Maintaining stability during walking can continue to promote personality (Ohlendorf et al., 2019). To carry out everyday tasks and prevent and limit the risk of accidents that result in harm for people of all ages, but potentially more so for the elderly, balance and posture when standing and walking are vital (Sung, & Park, 2021). Muscle

endurance, flexibility, and strength all influence not only one's level of physical fitness but also one's gait and posture. The orientation of the torso along the spinal column, with the neck and head angled slightly forward. The legs are appropriately spaced apart and both feet are fully supported (Ohlendorf et al., 2020).
The assessment of human movements and postural balance involves measuring three-dimensional components, including anteroposterior direction (AP), mediolateral direction (ML), and ground reaction forces (GRF) at the center of pressure (COP). Parameters derived from COP trajectories on a laboratory-grade force plate are considered the gold standard for balance performance (Huurnink et al., 2013). However, these force plates (FPs) are expensive and not easily portable, limiting their use outside of laboratories. Due to the high cost, there is a need for low-cost alternatives for biomechanical analysis. Several force plates were developed for biomechanical analysis, each with distinct features. Rana (2009) created a foot pressure indicator using sensors on shoe insoles, demonstrating its potential in diabetic ulcer research. Alvarenga (2011) designed a low-cost force plate for balance assessment, emphasizing a ring-shaped load cell and precision testing. Kumar et al., (2011) developed a force plate with two springs to measure vertical and horizontal forces, aiding in walking analysis. Tamburini (2015) designed a simple force plate using strain gauges for gait analysis in children and neurological patients. Wardoyo et al., (2016) introduced a cost-effective, lightweight force plate with rubber sheet technology for biomechanical testing. Silva et al., (2017) presented a force plate with a significantly lower manufacturing cost, suitable for analyzing various biomechanical values and postural control. Recently, the equipment might help reduce the chance of falling and enhance balanced posture, allowing people to learn how to properly balance their weight when standing and walking and develop positive personalities (Rakpongsiri et al., 2023). Many studies emphasize the importance of assessing balance through force plate measurements, as it plays a significant role in understanding human movement patterns. The force plate can be instrumental in providing information for coaches and sports scientists to design effective training programs and evaluate the physical development of athletes (Janz et al., 2003). Plantar pressure distribution (PPD), measured by force plates, is crucial in predicting foot-related problems. It is observed that force plates can effectively assess balance and analyze various aspects related to foot posture. However, the installation of force plates is limited to specific facilities due to their high cost, complexity, and difficulty in transportation. Therefore, there is a need for the development of low-cost and portable force plates for wider usage. In this research, a low-cost force plate was designed with the objective of assessing balance and analyzing postural parameters. We hypothesize that the developed low-cost force plate will demonstrate sufficient reliability and accuracy, facilitating its effective utilization in evaluating balance and examining postural parameters such as ground reaction force, center of pressure, and plantar pressure distribution.

## 2. Objectives

The primary objective of this study was to contribute to the development of a low-cost and reliable force plate, emphasizing its potential applications in assessing balance and analyzing postural parameters, i.e., ground reaction force, center of pressure, and plantar pressure distribution.

## 3. Materials and methods

The study received approval from the Human Research Ethics Committee of Thammasat University (Science), Thailand, and was conducted in accordance with the compliance to the declaration of Helsinki, the Belmont report, CIOMS guidelines and the international practice (ICH-GCP) (project no.060/2565).

### 3.1 Hardware and software design

The base is constructed using aluminum sheets (250 x 500 x 6 mm) to ensure structural rigidity and direct force application capability. 40 strain gauges were attached to measure weight distribution during foot placement. Single-axis load cell sensors were installed to measure reaction weight and the center of pressure. Load cells were positioned at all four corners of the aluminum sheet (Figure 1).

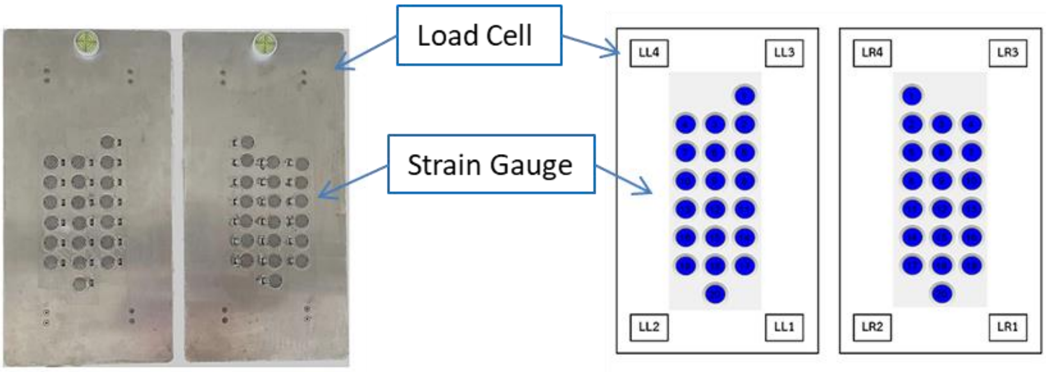


**Figure 1** Hardware design of low-cost force platform with the 8 load cells and 40 strain gauges

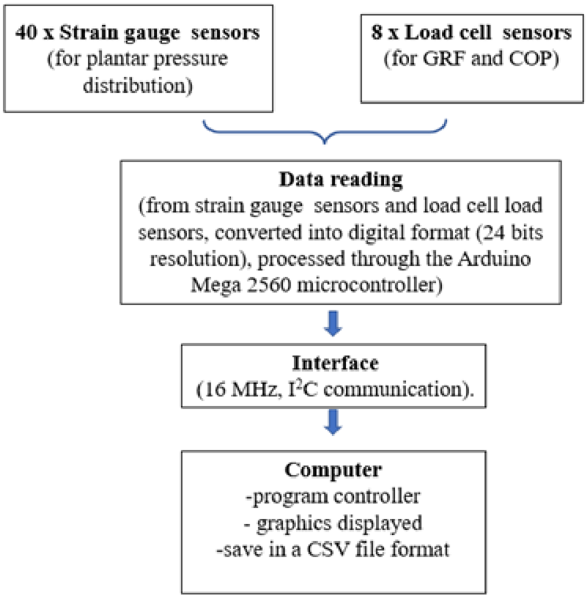


**Figure 2** Low-cost force plate software design diagrams

The data obtained from 40 strain gauge sensors and 8 load cell sensors underwent conversion into digital format with 24-bit resolution. Processed through the Arduino Mega 2560 microcontroller, leveraging its maximum sampling frequency, the data was communicated via I2C at a frequency of 16 MHz, enabling simultaneous readings from multiple sensors and ensuring interference prevention. The control of the system and the graphical interface were managed by a computer, with software developed using Visual Basic programming. Recorded data can be conveniently saved in CSV file format for further analysis (Figure 2).

The graphic user interface (GUI) of the software has been shown the calculation results of the measurement parameters follow the procedure of the principles and data transformation.

- Receive data from the signal receiver (load cell amplifier), representing the foot pressure, for further processing.
- Calculate the GRF values to convert from voltage to newtons (N) using equations (1), (Gurgel et al., 2006).

$$\begin{aligned} VMx &= A + B - C - D \\ VMy &= A - B - C + D \\ VMz &= A + B + C + D \end{aligned} \qquad (1)$$

where: A = F1, B = F2, C = F3, D = F4; Fz is the sum of F1, F2, F3, F4

- Calculate the COP using equations (2,3), (Dias et al., 2011)

$$COPap = x/2[(F1 + F4) – (F2 + F3)/Fz] \quad (2)$$
$$COPml = y/2[(F3 + F4) – (F1 + F2)/Fz] \quad (3)$$

where: A = F1, B = F2, C = F3, D = F4; Fz is the sum of F1, F2, F3, F4

GRF and COP are important concepts in biomechanics, particularly in the study of human movement and gait analysis. These terms are often used in the context of force and pressure distribution during activities such as walking or running. GRF is the force exerted by the ground on a body in contact with it. When a person stands, walks, or runs, GRF represents the force exerted by the ground on the foot or feet during these activities. GRF is essential in understanding human movement, biomechanics, and sports performance. GRF is typically measured using force plates or force platforms. These devices are embedded in the floor and can measure the three components of force: vertical (upward force against gravity), anterior-posterior (AP), and medial-lateral (ML) exerted by the foot or feet on the surface. The data collected from force plates provides information about the magnitude and direction of the forces acting on the body. Some potential errors in GRF measurement include misalignment or displacement of the force plate, calibration errors, and variability in the participant's foot placement. The PPD parameter utilizes a color-coded distribution from the 40 x strain gauge sensors to illustrate variations in force levels across different areas, providing pressure distribution patterns (Rana, 2009). In this scheme, blue, green, yellow, orange, and red represent 0, 25, 50, 75, and 100 percent, respectively (Figure 3).

### 3.2 Load-Cell-Left (LL) and Load-Cell-Right (LR) testing procedure

The load cell weight measurement testing was conducted for all load cell positions (Figure 4) following the steps outlined below.

1. Place the 5 kg. standard weight on the load cell sensor position at LL1 point.
2. Read the load cell sensor output in kg. unit, and record the data.
3. Repeat step (1) and (2) two times.
4. Repeat step (1) – (3) with 10, 15 and 20 kg.
5. Repeat step (1) – (4) on the load cell sensor position at LL2, LL3, LL4, LR1, LR2, LR3, and LR4 points.

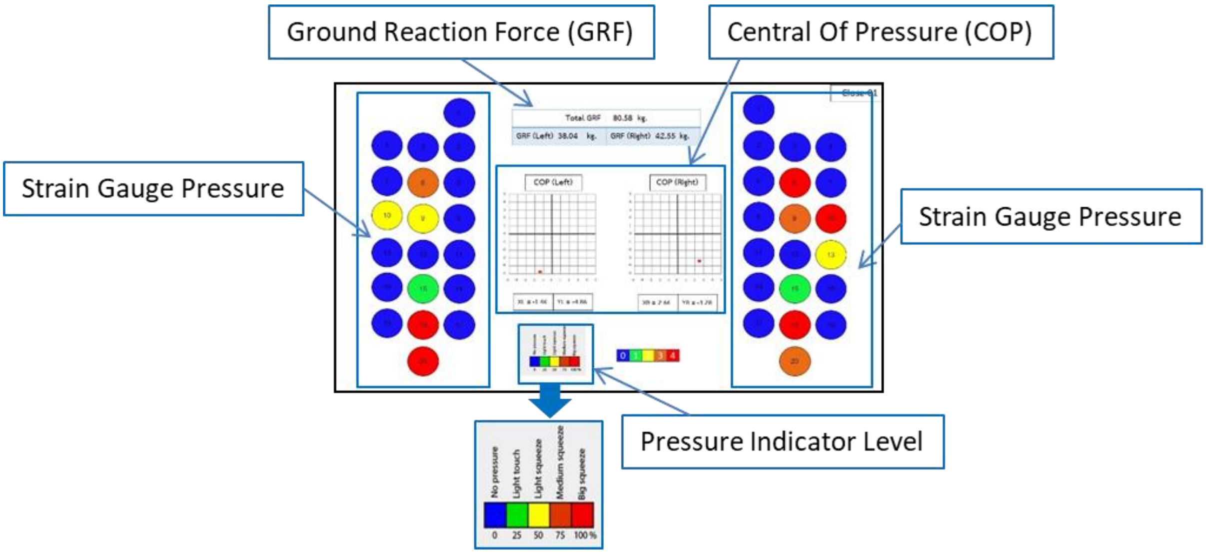


**Figure 3** Low-cost force plate graphic user interface (GUI)

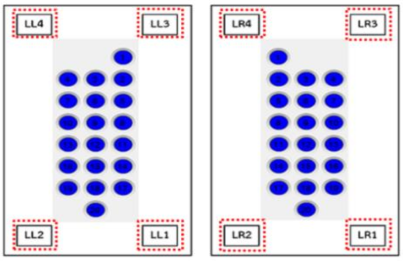


**Figure 4** Load cell testing points on the force plate

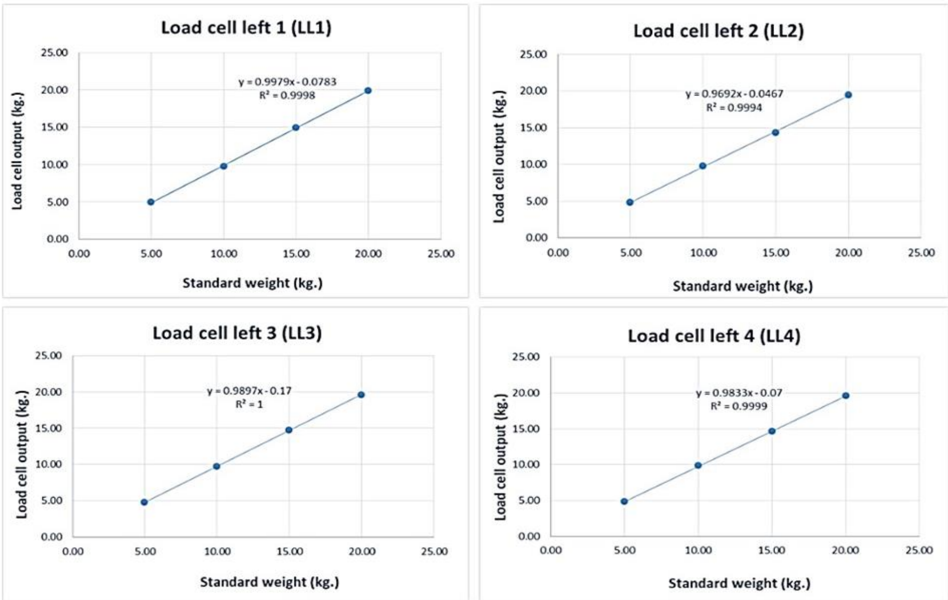


**Figure 5** Load cell weight measurement testing result on LL1, LL2, LL3, and LL4 load cell positions

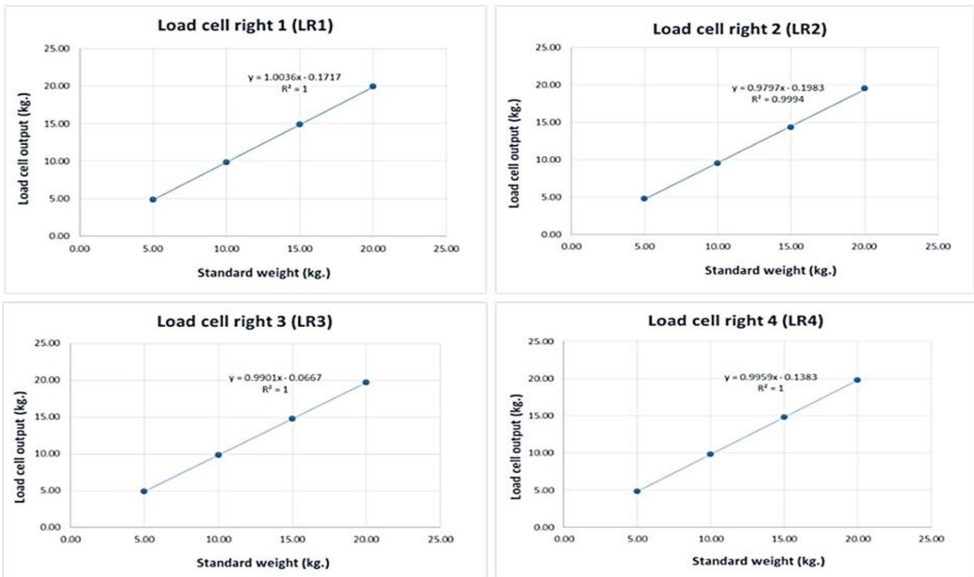


**Figure 6** Load cell weight measurement testing result on LR1, LR2, LR3, and LR4 load cell positions

### 3.3 Assessment of human posture

In the initial equipment assessment for human posture, a healthy 20-year-old female volunteer with no history of neurological, posture-related disorders, musculoskeletal disorders, or leg injuries within the past 6 months. The evaluations were conducted under both eye-open and eye-closed conditions following the steps outlined below:

1. Stand straight without wearing shoes, keep arms close to the body, and avoid any movement for 30 seconds.
2. Record the parameters for GRF, COP, and PPD.
3. Take a 1-minute break.
4. Repeat steps (1) – (3) two more times.

## 4. Results

### 4.1 Load cell (LL and LR) testing

The load cell weight measurement testing was conducted for all load cell positions (LL1, LL2, LL3, LL4, LR1, LR2, LR3, and LR4) by using the 5, 10, 15 and 20 kg standard weights. The linear regression statistical, the analysis showed a strong linear relationship between the load cell output and the standard weight, with an R-squared value of about 0.99 (Figure 5-6). Furthermore, the error margin was determined to be less than +/- 5% (Table 1).

### 4.2 Assessment of human posture

In the initial equipment assessment, human posture was evaluated under both eye-open and eye-closed conditions through three sets of measurements of GRF, COP, and PPD parameters. The mean values and standard deviations of the GRF parameter indicate that the weight distribution between the left and right feet remained similar under both eye-open (left foot = 23.17 ± 0.24, right foot = 22.34 ± 0.22) and eye-closed conditions (left foot = 23.15 ± 0.16, right foot = 22.36 ± 0.16), as shown in Table 2. The COP parameter for the ML direction on both the left and right feet, with mean values and standard deviations presented as follows: for eye-open conditions, 12.40 ± 0.10 mm and 14.50 ± 0.50 mm, respectively, compared to eye-closed conditions, 27.50 ± 0.80 mm and 33.30 ± 0.70 mm, respectively (Table 3). The results indicate approximately a two-fold change in the COP parameter, possibly due to swaying when the eyes were closed. For the PPD parameter, a comparison between the eye-open and eye-closed conditions revealed a notable increase in high-pressure zones within the heel area for both the left and right feet (Figure 7).

## 5. Discussions

This study aims to develop a pair of low-cost and user-friendly single-pedestal force plates for assessing GRF, COP, and PPD parameters. The hardware and software design consists of aluminum sheets (250 x 500 x 6 mm), 40 strain gauge sensors, 8 single-axis load cell sensors, an Arduino Mega 2560 microcontroller, and Visual Basic programming for hardware control and GUI.

In the equipment testing, weight measurements were taken for all load cell positions (LL1, LL2, LL3, LL4, LR1, LR2, LR3, and LR4) using standard weights of 5, 10, 15, and 20 kg. Through linear regression analysis, a strong linear relationship between the load cell output and the standard weight was observed, with an R-squared value of approximately 0.99. Additionally, the error margin was found to be less than +/- 5%. This equipment has the potential for further research in human postural assessment across various biomechanical and physiological studies.

**Table 1** Mean and Error Calculation for Load Cell Weight Measurements

| Standard | Load-cell-left (LL) output (kg) | | | | | | | | Load-cell-right (LR) output (kg) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weight (kg) | LL1 | Error (%) | LL2 | Error (%) | LL3 | Error (%) | LL4 | Error (%) | LR1 | Error (%) | LR2 | Error (%) | LR3 | Error (%) | LR4 | Error (%) |
| **5.00** | 4.97 | 0.60 | 4.80 | 4.00 | 4.78 | 4.47 | 4.81 | 3.87 | 4.86 | 2.80 | 4.80 | 4.00 | 4.88 | 2.47 | 4.84 | 3.13 |
| **10.00** | 9.78 | 2.23 | 9.75 | 2.47 | 9.70 | 2.97 | 9.84 | 1.63 | 9.85 | 1.50 | 9.54 | 4.57 | 9.84 | 1.63 | 9.82 | 1.83 |
| **15.00** | 14.96 | 0.27 | 14.27 | 4.84 | 14.73 | 1.80 | 14.65 | 2.31 | 14.87 | 0.87 | 14.31 | 4.62 | 14.80 | 1.31 | 14.80 | 1.33 |
| **20.00** | 19.87 | 0.63 | 19.45 | 2.77 | 19.60 | 2.02 | 19.59 | 2.05 | 19.91 | 0.43 | 19.54 | 2.30 | 19.72 | 1.38 | 19.78 | 1.10 |
| **5.00** | 4.97 | 0.60 | 4.80 | 4.00 | 4.78 | 4.47 | 4.81 | 3.87 | 4.86 | 2.80 | 4.80 | 4.00 | 4.88 | 2.47 | 4.84 | 3.13 |

**Table 2** The GRF parameter in eye-open and eye-closed conditions (Mean ± SD)

| | GRF | | |
|---|---|---|---|
| | **Total (kg)** | **Left (kg)** | **Right (kg)** |
| **Eye-open** | 45.52 ± 0.05 | 23.17 ± 0.24 | 22.34±0.22 |
| **Eye-closed** | 45.51 ± 0.04 | 23.15±0.16 | 22.36±0.16 |

**Table 3** The COP parameter in eye-open and eye-closed conditions (Mean ± SD)

| | COP | |
|---|---|---|
| | **Left (mm)** | **Right (mm)** |
| **Eye-open** | 12.40 ± 0.10 | 14.50 ± 0.50 |
| **Eye-closed** | 27.50 ± 0.80 | 33.30 ± 0.70 |

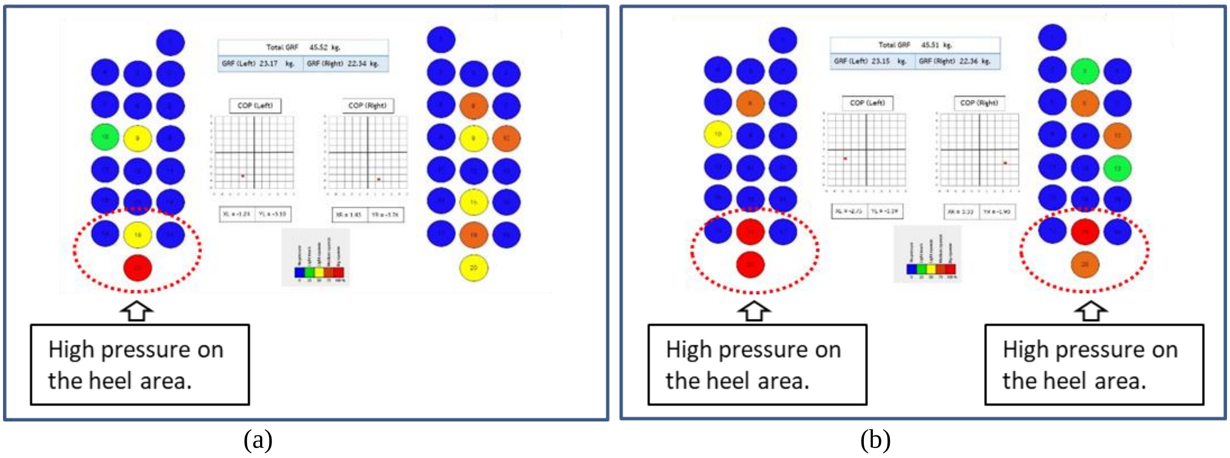


**Figure 7** The PPD parameter while standing under eye-open condition (a) and eye-closed condition (b)

For the initial equipment assessment on the human posture was evaluated under both eye-open and eye-closed conditions through three sets of measurements of GRF, COP, and PPD parameters. The mean values and standard deviations of the GRF parameter reveal a consistent weight distribution between the left and right feet, evident in both eye-open (left foot = 23.17 ± 0.24, right foot = 22.34 ± 0.22) and eye-closed conditions (left foot = 23.15 ± 0.16, right foot = 22.36 ± 0.16). However, while analyzing ground reaction forces (GRF), a critical aspect of postural control crucial for understanding various issues like neurological disorders, muscle weakness, or Parkinson's disease (Minamisawa et al., 2012, Minamisawa et al., 2020), we found no differences in our results. This might be because we studied young, healthy volunteers without any neurological or musculoskeletal issues.

The COP parameter, crucial for assessing postural stability, was analyzed in the medial-lateral (ML) direction for both the left and right foot. Mean values and standard deviations were recorded as follows: under eye-open conditions, 12.40 ± 0.10 mm for the left foot and 14.50 ± 0.50 mm for the right foot, while under eye-closed conditions, they measured 27.50 ± 0.80 mm for the left foot and 33.30 ± 0.70 mm for the right foot. This considerable increase in the COP parameter under eye-closed conditions suggests heightened postural sway, likely reflecting the reliance on proprioceptive and vestibular inputs in the absence of visual feedback, thus highlighting the intricate interplay between sensory systems in maintaining balance (Valle et al., 2016; Wood et al., 2022; Lo et al., 2022).

Regarding the PPD parameter, during the eye-open condition, there was a clear observation of heightened pressure localized to the heel area of the left foot. However, when transitioning to the eye-closed condition, a substantial increase in pressure was evident across both the left and right feet's heel areas. This observed shift in pressure distribution implies a notable alteration in weight bearing and balance strategies, likely reflecting adaptive mechanisms in response to the absence of visual input. Such findings underscore the intricate interplay between sensory modalities and postural control mechanisms, highlighting the dynamic nature of human locomotion and stability under varying perceptual conditions. Studying PPD helps us understand how weight is distributed on the foot and can indicate foot-related issues that affect overall body stability (Buldt et al., 2018; Rogerio, & Guedes, 2023).

With only one participant and a standing position plate design, the generalizability of the study's findings may be limited. In future studies, we will test the equipment across a broader population. In the next phase, it is also possible to develop the equipment to have enhanced flexibility in design for verifying important parameters.

Low-cost force plates were examined for various biomechanical assessments such as Bellicha et al., (2022) found comparable results for vertical jump performance, Clark et al., (2017) demonstrated effectiveness in gait assessment, and Chen et al., (2021) affirmed reliability in balance assessment. In comparison with our developed low-cost force plate, in terms of: (1) technology, (2) analysis and display, and (3) comfort. The low-cost force plate tool is unique, it can clearly display foot weight and weight distribution on both feet using easy-to-understand numerical and graphical representations. Data can be conveniently recorded in CSV format on a computer for tracking progress in weight training and correcting foot weight distribution. Additionally, this equipment is compact, easy to set up, and user-friendly (Table 4).

## 6. Conclusion

In conclusion, our study addresses the need for cost-effective and user-friendly tools for assessing posture and balance. We developed low-cost force plates capable of analyzing ground reaction forces (GRF), center of pressure (COP), and plantar pressure distribution (PPD). While our analysis of the open and closed-eye conditions for the standing position showed consistent weight distribution in GRF, increased postural sway in COP and adaptive weight distribution changes in PPD were found in the closed eye condition, likely due to the good health of participants. Our tool offers simplicity and efficiency compared to traditional plates, making it valuable for both research and clinical use. Future studies will expand testing across a broader population to evaluate its effectiveness in enhancing body balance, movement, and posture under professional guidance.

**Table 4** The comparison of Low-cost force plate with standard force plate

| | Low-Cost Force Plate | Standard Force Plate |
|---|---|---|
| **Technology** | A device for analyzing abnormalities in foot weight and foot weight distribution by visualizing the graphics in real time of measurement. | It consists of a flat plate with weight measurement units underneath; the measurement data are shown in numerical only. |
| **Analysis and display** | Displays the weight of the foot and the distribution of weight on both feet using numerical and graphics, which are clear and easy to understand. Values can be recorded in the computer's memory in a CSV file format to evaluate progress in weight training and correct foot weight distribution. | The test data collection is quite complicated and requires an expert to interpret the results. |
| **Comfortable** | The equipment is compact, easy to set up, and has a user-friendly design. | Installation is complicated; most of the equipment is large and heavy. |

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