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ORIGINAL RESEARCH

The relationship between asymmetric variations in plantar pressure distribution and cardiovascular performance

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Abstract

The aim of this study is to examine the relationship between asymmetric differences in plantar pressure distribution and cardiovascular performance. The study was designed using a descriptive model. A total of 24 female athletes, with an average age of 19.08±1.6 years, participated in the study. In the study, BTS P-walk baropodometry device was used for plantar pressure measurements. In the plantar pressure analysis, maximum plantar pressure was assessed with the toes (T), metatarsal region (MR) arch region (AR) and heel region (HR) parameters, foot surface area with the forefoot (A) midfoot (B) and hindfoot (C) parameters, and rotational movements of the foot during gait with the foot progression angle parameter (FPA). Cardiovascular performance was assessed using the COSMED K5 wearable metabolic system, with VO2max as the primary parameter. The relationships between these parameters were analyzed using Pearson and Spearman correlation tests in SPSS 25 software at a significance level of $p<0.05$. The findings of the study revealed a significant negative correlation between the MR, A and FPA parameters and the VO2max parameter ($p<0.05$). The results of this study indicate that as asymmetric differences in dynamic plantar pressure distribution increase, the efficiency of oxygen utilization decreases.

Introduction

Symmetry is defined as the property of an object to exhibit complete conformity in shape, size, and form when divided along a specific axis, whereas deviation from this symmetry is referred to as bilateral asymmetry (Maloney, 2019). Asymmetric differences directly affect overall posture and movement ability by causing greater loading on the stronger side due to the principle of compensating for the weaker side (Asghari et al., 2022). Researchers emphasize that the negative effects of increased asymmetry, particularly in the lower extremities, on athletic performance and sports-related injuries should be considered not only in sedentary lifestyles but also in environments where high achievement and performance expectations are present (Heil et al., 2024).

Plantar pressure distribution is a biomechanical parameter used to evaluate the structure and alignment of the foot and its segments, as well as changes in the transmission of stress exerted on the body to the ground (Liu et al., 2024). Examined dynamically and statically on technology-supported platforms, plantar pressure distribution is considered a key determinant of balance, postural control, and gait (Patel & Balaganapathy, 2024). In asymptomatic individuals, plantar pressure is generally expected to be symmetric or slightly asymmetric. However, abnormal pressure distribution and asymmetry in plantar pressure are closely associated with foot pathologies and foot functionality (Menz & Morris, 2006; Wafai et al., 2025). Particularly in sports-related injuries, it has been identified as a risk factor, and it is recommended that preventive measures be taken against asymmetries to reduce injury risk (Fox et al., 2023).

Reports on the association of asymmetric factors with metabolic activities and cardiovascular performance appear to be conflicting (D'Hondt et al., 2024). Cardiovascular performance is an indicator that reflects endurance levels and oxygen utilization efficiency, depending on the body's oxygen transport

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capacity (Bassett & Howley, 2000). It is assessed by the maximum oxygen consumption (VO_{2max}) during exercise and is determined by the body's ability to increase blood flow to the muscles. The efficiency of cardiovascular performance is closely related to muscle strength and endurance (Coyle, 1999; Kaminsky et al., 2015). Since asymmetric differences in plantar pressure distribution may lead to greater force exertion on muscles they can increase the strain on the cardiovascular system (Grevendonk et al., 2021; Hoffman et al., 2015; Wafai et al., 2015). Therefore, evaluating the relationship between cardiovascular performance and asymmetric variations in plantar pressure distribution could be of critical importance in enhancing performance, preventing injuries, and guiding rehabilitation processes.

Considering the effects of plantar pressure distribution on the kinetic chain and body biomechanics during movement, the idea that asymmetry and imbalances in pressure distribution may be related to cardiovascular performance forms the basis of this study. Previous research has reported associations between dynamic plantar pressure distribution, athletic performance, and sports injuries in athletes (Azevedo et al., 2017; Chow et al., 2021; Mocanu et al., 2021). However, due to variations in devices and methods, there is a lack of clarity regarding reference ranges for plantar pressure distribution, particularly concerning asymmetry. Additionally, no comprehensive study has been found that specifically examines the relationship between asymmetric differences and cardiovascular performance. For these reasons, the purpose of this study is to investigate the relationship between asymmetric differences in plantar pressure distribution and cardiovascular performance.

Methods

This study was designed using a descriptive model. Ethical approval for the study was granted by Giresun University of Social, Science, and Engineering Ethics Committee (06.01.2025 - 01/01). The study was conducted in accordance with the principles of the Helsinki Declaration.

Participants

The study included 24 female athletes with an average age of 19.08 ± 1.6 years, representing various sports disciplines: football (n=6), volleyball (n=5), handball (n=4), taekwondo (n=5), and boxing (n=4). The purpose of including only female athletes in the study is to minimize gender-related variability and to enhance the reliability of the results. The sample size was determined using G*Power software (version 3.1.9.2), based on reference study results examining the relationship between plantar pressure values of the left rearfoot and balance (Anjos et al., 2010). According to a two-tailed analysis with $\alpha = 0.05$, power = 0.95, and correlation pH1 = 0.5728, the required minimum number of participants for this study was found to be 24.

Inclusion and exclusion criteria for the study: Individuals who have been licensed athletes in a sport that actively uses the lower extremity for at least the last five years, with certification each year, who have been training at least three days a week for the last year excluding the season cycles, and who have not experienced any severe foot and ankle injuries requiring intervention in the last year, were included in the study. Individuals who are in their menstrual period, those with a body mass index above the normal weight category, and those who do not meet the inclusion criteria were excluded from the study.

Table 1
Demographic information of the participants.

Variables	Mean ± SD
Age (year)	19 ± 1.66
Height (cm)	166.12 ± 5.97
Body Weight (kg)	58.83 ± 7.25
Body Mass Index (kg/m^2)	21.28 ± 2.06

Procedure

Participants meeting the inclusion criteria underwent height, weight, and body mass index (BMI) measurements before being subjected to a standardized warm-up procedure. Following the warm-up, their plantar pressure distribution and cardiovascular performance were assessed. To minimize bias and external influences on the results, all participants performed the tests barefoot. Additionally, they were instructed to refrain from engaging in any physical activity within the last 24 hours and to avoid consuming any food or beverages at least two hours prior to the measurements. The data were analysed by an independent researcher who was not involved in conducting the study. All measurements were carried out at the Performance Testing and Measurement Laboratory of the Faculty of Sport Sciences at Giresun University.

Body weight, height measurement, and body mass index (BMI) calculation

Participants' body weight was measured in kg using a scale with a precision of 0.1 kg, while their height was recorded in cm using a digital height stadiometer integrated into the same scale (SECA, Germany). BMI was calculated by dividing body weight (kg) by the square of height (m^2).

Warm-up protocol

All participants underwent a standardized 15-minutes warm-up protocol, consisting of 5 minutes of running, 5 minutes of short sprints, and 5 minutes of stretching and flexibility exercises.

Cardiovascular performance measurement

Cardiovascular performance was assessed using the participants' VO_{2max} capacities (Ozaki et al., 2010). In the measurements, the COSMED K5 (Rome, Italy) wearable metabolic system, which is recognized for its validity and reliability, and an ergospirometric treadmill (Sprintex Natural Movement treadmill, USA) were used (Zacca et al., 2023). Participants were equipped with a Hans Rudolph face mask to control gas exchange, ensuring all respiration was conducted through the mask. Before each test, the flow turbine, oxygen, and carbon dioxide analysers were calibrated according to the manufacturer's instructions for the COSMED K5 system. The metabolic system unit was secured to a comfortable harness and worn on the shoulders. The exercise protocol was synchronized with both the metabolic system and treadmill settings. VO_{2max} values were measured before and after exercise, and all data were recorded. The collected data were transmitted via Bluetooth to a laptop and analysed using COSMED software. Oxygen consumption was expressed in millilitres per kilogram per minute (ml/kg/min).

Exercise protocol

The Bruce protocol was applied to determine the participants' VO_{2max} capacities. The Bruce protocol was performed on a treadmill. The protocol has specific phases where the speed and incline increase as time progresses until the participant feels the need to terminate the test. Termination of the test by the participant indicates failure of the participant. However, participants met at least three criteria that indicated a successful test before reaching the termination point. These criteria are: VO_2 respiratory exchange ratio (RER)> 1.10, a plateau in VO_{2max}, and 95% of age-estimated maximum heart rate (HR) (HRmax = 220- age) (von Schaumburg et al., 2022).

Dynamic plantar pressure measurement

Dynamic plantar pressure was assessed using the P-Walk baropodometry system (BTS, S.p.A., Italy), which has a 2.4-meter-long platform. Before the evaluation, the device was calibrated individually for each participant. Prior to the test, participants were instructed to walk on the system for 2 minutes to familiarize themselves with the platform. However, they were not informed about the exact start time of the test. The test was initiated at the first minute of walking while the participant was still outside the platform. Once the participant completed their walk and exited the platform, the system automatically ended the test. In the plantar pressure analysis, maximum plantar pressure (kPa) (Figure 2) was assessed with the toes (T), metatarsal region (MR) arch region (AR) and heel region (HR) parameters, foot surface area (%) (Figure 2) with the forefoot (A) midfoot (B) and hindfoot (C) parameters, and rotational movements of the foot during gait with the foot progression angle (°) (Figure 3) parameter (FPA) (McNab et al., 2022).

Figure 1. VO_{2max} and plantar pressure measurement.

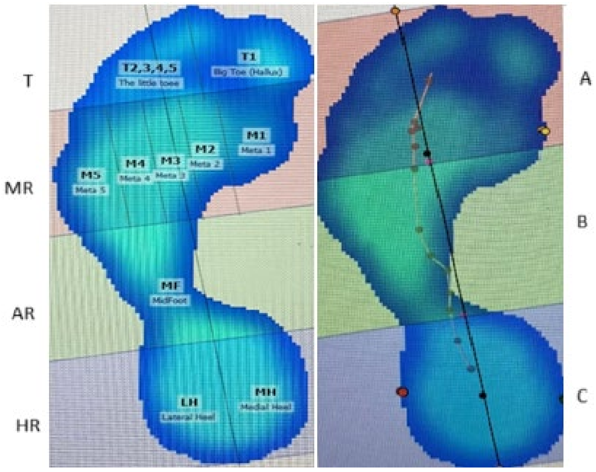

Figure 2. Maximum plantar pressure (T, MR, AR, HR) and foot surface area (A, B, C) parameters.

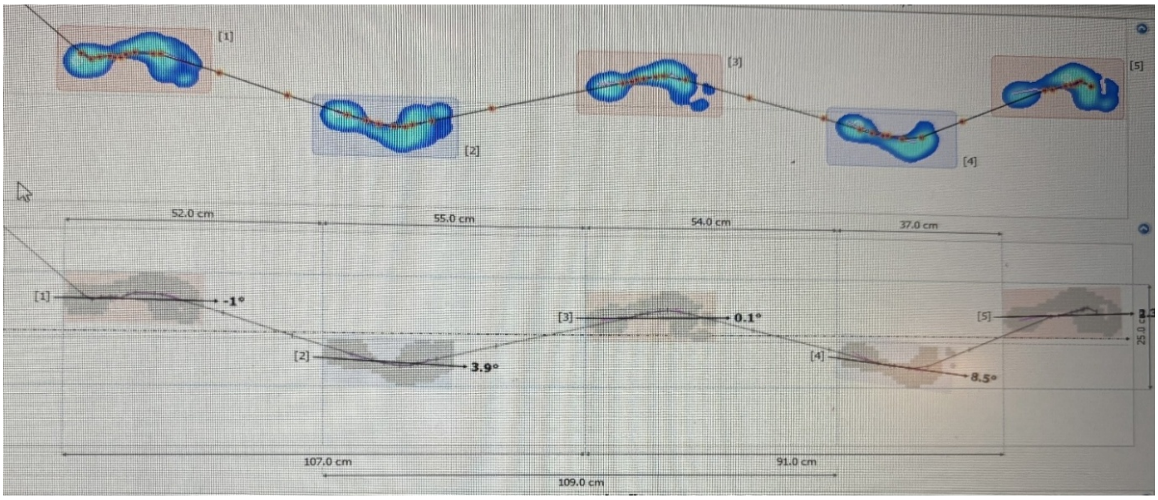

Figure 3. Foot progression angle (FPA) parameter.

Data Analyses

To determine asymmetry in plantar pressure distribution, the differences in pressure distribution between the right and left feet were calculated, and absolute values were considered in the analysis. Data analysis was performed using SPSS 25.0 software. Initially, the Shapiro-Wilk normality test was applied to assess the distribution of the data: 1) for parameters that showed normal distribution (VO_{2max} and FPA), relationships were analysed using the Pearson correlation test, 2) for parameters that did not follow normal distribution (T, MR, AR, HR, A, B and C), relationships were evaluated using the Spearman correlation test. Results were analysed at a significance level of $p<0.05$. The correlation coefficients were interpreted as follows: 0.00-0.25 little or no correlation, 0.26-0.49 low correlation, 0.50-0.69 moderate correlation, 0.70-0.89: high correlation, and 0.90-1.00: very high correlation (Carter & Lubinsky, 2016).

Results

The results of the normality analysis of the variables are presented in Table 2, and the asymmetric differences in the distribution of measured plantar pressure and VO_{2max} are presented in Table 3.

Table 2

Shapiro-Wilk normality test results.

Variables	*p*-values
VO_{2max}	0.135
T (kPa)	0.001*
MR (kPa)	0.002*
AR (kPa)	0.048*
HR (kPa)	0.000*
A (%)	0.000*
B (%)	0.000*
C (%)	0.000*
FPA (°)	0.058

*VO_{2max}: Maximum oxygen consumption capacity, T: Toes, MR: Metatarsal region, AR: Arch region, HR: Heel region, A: Forefoot, B: Midfoot, C: Hindfoot, FPA: Foot progression angle, *Statistical significance at p<0.05.*

Table 3
Descriptive statistics of VO_{2max} and plantar pressure asymmetry.

Variables	Mean ± SD
VO_{2max}	50.42 ± 4.66
T (kPa)	80.45 ± 91.36
MR (kPa)	27.70 ± 27.48
AR (kPa)	16.54 ± 13.92
HR (kPa)	14.83 ± 18.09
FPA (°)	4.03 ± 3.00
A (%)	2.83 ± 3.62
B (%)	4.37 ± 5.28
C (%)	2.53 ± 3.29

VO_{2max}: Maximum oxygen consumption capacity; T: Toes, MR: Metatarsal region; AR: Arch region; HR: Heel region; A: Forefoot; B: Midfoot; C: Hindfoot; FPA: Foot progression angle.

When examining the relationship between asymmetry in plantar pressure distribution and VO_{2max}, a significant negative correlation was found between VO_{2max} and the MR, A and FPA parameters ($p<0.05$). However, no significant differences were observed for the other parameters ($p>0.05$; Table 4).

Table 4
The relationship between plantar pressure distribution asymmetry and VO_{2max}.

Variables		VO_{2max}
T (kPa)	r/rho	-0.351
	p	0.093
MR (kPa)	r/rho	-0.467*
	p	0.021
AR (kPa)	r/rho	-0.300
	p	0.154
HR (kPa)	r/rho	-0.321
	p	0.126
A (%)	r/rho	-0.522**
	p	0.009
B (%)	r/rho	-0.386
	p	0.063
C (%)	r/rho	-0.084
	p	0.696
FPA (°)	r/rho	-0.466*
	p	0.022

*VO_{2max}: Maximum oxygen consumption capacity, T: Toes, MR: Metatarsal region, AR: Arch region, HR: Heel region, A: Forefoot, B: Midfoot, C: Hindfoot, FPA: Foot progression angle, * p<0.05, ** p<0.01.*

Discussion

In this study, the relationship between asymmetric differences in plantar pressure distribution and cardiovascular performance was examined. In previous studies, no comprehensive research has been found on the relationship between bilateral asymmetry in plantar pressure distribution and cardiovascular performance elements. From this perspective, the limitation in the literature reveals the originality of the present study. The results of the study showed a significant negative relationship between the plantar pressure parameters MR, A, and FPA and VO_{2max} consumption.

It is emphasized that VO_{2max} consumption is an important parameter in evaluating cardiovascular performance (Bassett & Howley, 2000; Day et al., 2003). The metabolic system used in the study provides valid and reliable results regarding VO_{2max} consumption (Bassett & Howley, 2000). The increase in VO_{2max} consumption is interpreted as being directly proportional to the improvement in cardiovascular performance (Wang & Zhou, 2021). The primary finding of the study is that as the maximum pressure distribution in the forefoot and the asymmetries in the forefoot surface area increase, VO_{2max} consumption decreases (Table 4). The foot is the final region of the movement chain, where all the stress applied to the body in both static and dynamic conditions is transferred to the ground (Liu et al., 2024). Therefore, the proper absorption and transmission of the encountered load to the ground are directly influenced by the anatomical structure of the foot and the coordinated movement of its segments (Sivachandiran & Kumar, 2016). From this perspective, these findings align with reports emphasizing that the morphological and kinesiological analysis of the foot and its segments can be among the determinants of athletic performance (Chow et al., 2021; Mocanu et al., 2021).

Although the results of the study provide supporting insights into the importance of plantar pressure distribution in athletic performance, the research hypothesis is based on asymmetry in plantar pressure distribution. Asymmetry in plantar pressure distribution refers to the pressure differences between the right and left foot (Gawronska & Lorkowski, 2021). Previous reports indicate a consensus among researchers that asymmetrical structures disrupt movement patterns and, consequently, optimal biomechanical efficiency (Hart et al., 2014; Kanchan et al., 2008). It has been emphasized that impairments in biomechanical efficiency are directly linked to cardiovascular performance and aerobic endurance (Fox et al., 2023; Bishop et al., 2022). Studies have shown that individuals with lower extremity asymmetry exert greater vertical forces on their knee joints during physical activity (Melo et al., 2020; Thijs et al., 2007). This may lead to changes in muscle properties such as muscle tone, stiffness, and elasticity, leading to the development of stiffer tendon structures in the knee extensors (Kubo et al., 2000). Increased tendon stiffness has been reported to induce an exaggerated joint muscle-tendon stretch reflex, ultimately resulting in higher energy demands (Beck et al., 2018; Jin & Hahn, 2018). It has been reported that asymmetric differences increase the demand on soft tissues, and this increased demand disrupts oxygen consumption efficiency, leading to an increased cardiac load and higher energy expenditure (Salvador et al., 2016). The results of this study suggest that the relationship between plantar pressure distribution asymmetry and VO_2 consumption may be due to the biomechanical changes caused by asymmetric differences during movement. These changes require the body to increase muscle activation to maintain balance, which in turn reduces the efficiency of energy and oxygen utilization.

The findings of the current study highlight asymmetry in the forefoot. Previous studies examining plantar pressure distribution have primarily focused on balance, postural control, and sports injuries (Azevedo et al., 2017; Chow et al., 2021; Mocanu et al., 2021; Wafai et al., 2015). Cobb et al., (2004) reported that increased forefoot varus could negatively impact postural stability, while Sarıalioğlu (2023) emphasized a positive relationship between a wider forefoot and balance performance. Additionally, a study by Bito et al. (2018) reported that asymmetry in the transverse arch is associated with foot injuries. Prior research indicates that forefoot morphology and forefoot pressure distribution influence balance functions. It is emphasized that maintaining and sustaining balance is associated with cardiovascular performance and that the effort to preserve impaired balance reduces the efficiency of oxygen utilization (Guner & Alsancak, 2023; Yalfani & Asgarpoor, 2024). The findings in the literature appear to support the results of the present study.

The second key finding of the study is that as FPA asymmetry increases, there is a significant relationship indicating a decrease in VO_{2max} consumption (Table 4). FPA represents the angle between the long axis of the foot and the walking direction, influenced by rotational movements of the foot during gait. An increase in FPA asymmetry signifies a growing angular difference between the right and left foot in gait kinetics, highlighting asymmetrical FPA as a gait disorder (Di Stasi et al., 2013; Rerucha et al., 2017). FPA significantly impacts walking and running biomechanics, as well as plantar pressure distribution (Lai et al., 2014; Nishizawa et al., 2022). Previous research has indicated that excessive rotation in FPA increases pressure on the soft tissues of the foot, knee, and hip, compromising lower extremity functionality (Buldt et al., 2018; Iijima et al., 2019). The functionality and coordination of body components are recognized as key factors in successfully performing required movements. The effort to eliminate the mismatch caused by asymmetry is known to lead to higher energy costs and inefficient oxygen utilization, accelerating the onset of fatigue (Konieczny et al., 2023). Additionally, reports indicate that asymmetry in FPA can cause balance issues, increasing the frequency of sports injuries (Bito et al., 2018; Guan et al., 2022). When the findings of the present study are evaluated in light of this information, the negative relationship between FPA and VO_{2max} can be attributed to the changes and disruptions in body kinematics caused by FPA asymmetry. The extra effort required to compensate for impaired kinematics may reduce the efficiency of oxygen consumption.

Limitations

The first limitation of this study is the sample size. Although power analysis indicated that a minimum of 24 participants was sufficient, larger groups could enhance reliability and contribute to the generalizability of the findings. The second limitation is the lack of repeated measurements, particularly in the assessment of cardiovascular performance. While plantar pressure distribution is a biomechanical characteristic, it is also influenced to some extent by anthropometric structure, meaning that similar results may be obtained in measurements conducted at different times. However, cardiovascular performance assessments are subject to a much greater range of internal and external factors, which may lead to significant variability in the results.

Conclusion

The results of this study indicate that as asymmetric differences in dynamic plantar pressure distribution increase, the efficiency of oxygen utilization decreases. While these findings are promising for future research in this field, the study's limitations highlight the need for more advanced investigations to draw definitive conclusions.

Practical Applications

While acknowledging the limitations of the study, several practical application suggestions can be made based on the research findings. According to these results;

- The early detection of individual asymmetries through plantar pressure analysis may be important for identifying personalized intervention strategies aimed at maintaining or improving VO_{2max} levels.
- These findings may suggest that plantar load balance should be considered an important target parameter in aerobic endurance development protocols.
- Training programs aimed at optimizing bilateral load distribution may contribute to the improvement of cardiovascular capacity.

Authors' Contribution

The research is single authored

Ethical Approval

The study was approved by the Giresun University of Social, Science, and Engineering Ethical Committee (dated 06.01.2025 and numbered 01/01) and it was carried out in accordance with the Code of Ethics of the World Medical Association also known as a declaration of Helsinki.

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Conflict of Interest

The authors hereby declare that there was no conflict of interest in conducting this research.

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