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RESEARCH

# Does plantar pressure distribution influence static balance performance in elite soccer players? A retrospective observational study

**Federico Arippa[1] · Bruno Leban[1] · Micaela Porta[1] · Giulia Casu[1] · Massimiliano Pau[1]**

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## Abstract

**Purpose** The foot plays a key role in balance control, acting as the primary interface between the body and the ground. Thus, the way loads exchanged between body and ground are likely to affect postural stability through modulation of the sensory feedback from the plantar surface. Surprisingly, this relationship has been scarcely examined, and most existing studies involve the general population, while data regarding elite athletes—who undergo extensive neuromuscular training—are limited. Thus, the aim of the present study was to investigate whether plantar pressure distribution characteristics and footprint-derived indicators of foot morphology are associated with static balance performance in elite soccer players.

**Methods** Using a pressure platform, data on plantar pressure and center of pressure (COP)-derived sway parameters were simultaneously collected under unipedal and bipedal quiet upright stance in a cohort of 110 soccer players competing in national-level tournaments. Foot morphology was classified according to the Arch Index (AI). Associations between plantar pressure variables and sway parameters were assessed using Pearson's correlation coefficients with false discovery rate (FDR) correction for multiple comparisons.

**Results** Foot morphology classification according to the AI did not reveal significant effects on postural sway parameters under either stance condition. However, players classified as planus tended to exhibit greater sway values during bipedal stance than cavus and normal arch groups. Correlation analyses showed only weak associations between plantar pressure variables and postural sway parameters under both bipedal and unipedal conditions ($|r| \leq 0.30$), and none remained statistically significant after FDR correction.

**Conclusion** Plantar pressure distribution characteristics and footprint-derived indicators of foot morphology showed only weak and non-robust relationships with static postural sway in elite soccer players. Although a tendency toward greater sway was observed in players classified as planus during bipedal stance, no significant effects of foot morphology were detected, and these observations were not supported by the correlation analyses. Overall, the findings suggest that plantar loading patterns account for only a limited proportion of the variability in static balance performance in this population.

**Keywords** Posture · Contact pressure · Postural sway · Static balance · Football players

## Introduction

Postural control is the ability to achieve, maintain, and regain balance while maintaining static postures (e.g., sitting or standing), performing voluntary movements, and responding to unexpected external disturbances [1]. From a biomechanical point of view, all such conditions imply that the vertical projection of the center of mass lies within the base of support. To achieve this, an optimal integration of biomechanical strategies and neuromuscular adaptations is required, so that the body is constantly stabilized against gravity and external perturbations [2–4]. On the other hand, it should be recalled that several intrinsic and extrinsic factors are potentially able to influence postural control. Among the former, it is well known that the effect of age, sex, anthropometry, and body mass are of primary importance. However, other factors (i.e., fatigue, neurologic

✉ Federico Arippa
federico.arippa@unica.it

[1] Department of Mechanical, Chemical, and Materials Engineering, University of Cagliari, Cagliari, Italy

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and orthopedic disorders, anxiety, etc.) can temporarily or permanently impair human stability.

In the upright position, the only interface between the body and the external world is represented by the plantar region. This, to some extent, assigns to the foot a crucial role in maintaining balance and stability. Due to anatomical and functional features, the pressure distribution at the foot–ground interface influences the sensory information, thus allowing the body to perform proper postural adjustments. Such sensory inputs provide continuous feedback to the postural control system in order to keep the center of mass projection within the base of support [4 5]. Therefore, the specific interaction between the foot and the ground becomes a central aspect of interest when analyzing postural stability.

The effectiveness of the postural control system is usually quantified through analysis of postural sway, namely the small oscillations that express the synergic action of nervous and muscular systems to keep the body balanced [6]. From a practical point of view, this is achieved by analyzing time series data of the point of application of the resultant ground reaction forces exchanged between the body and the ground through the plantar regions, defined as "center of pressure" (COP). From the COP trajectory, it is indeed possible to derive several parameters able to characterize the postural sway. However, the position of the COP is closely related to the way loads are transferred from the body to the ground, that is, through the specific pressure distribution across the foot–ground contact interface. Since such pressure distribution depends on the individual's foot structure and functionality, it appears clear that the COP position is somehow linked with it. In clinical practice, it is quite easy to investigate simultaneously both aspects (i.e., postural sway and plantar pressure distribution) using pressure platforms or mats. Indeed, the use of such devices allows the acquisition of average and peak contact pressure across the whole plantar region and sub-regions of interest (i.e., rearfoot, midfoot, and forefoot) while, at the same time, tracking the COP position through integration of the pressure values acting over each sensor. By combining plantar pressure data and COP metrics it would be possible, in principle, to obtain a comprehensive assessment of the possible relationships between the way loads are transferred between foot and external world (which may partly reflect functional and morphological characteristics of the foot, particularly in terms of medial longitudinal arch behavior) and postural stability, providing a valuable framework for both research and applied settings.

Interestingly, despite the seemingly intuitive and reasonable link between foot–ground interaction and postural stability, relatively few studies have examined this relationship, and the available evidence remains inconclusive. In particular, the existing research mainly attempted to clarify whether differences in medial longitudinal arch characteristics (i.e., the presence of pes planus and pes cavus) is associated or not with static balance performance. Hertel et al. [7] were among the first to demonstrate that individuals with cavus feet exhibited greater sway areas during single-leg stance compared to those with rectus feet, thus indicating potential impairments in postural control. Conversely, Alonso et al. [8] found only weak associations between plantar arch height and unipedal balance performance, identifying foot length as the only anthropometric variable significantly correlated with postural stability. Other authors [9] reported significant correlations between altered foot morphology and both entropy-based and linear COP-derived postural stability metrics. Puszczalowska-Lizis et al. [10] extended this line of research to the elderly population, demonstrating that structural deformities—especially reduced medial longitudinal arch—were associated with impaired balance and postural control. A longitudinal study by Marencakova et al. [11] further showed that foot structure and postural control evolve significantly during adolescence in elite soccer players, with midfoot-related characteristics showing associations with balance development.

Such discrepancies may be attributed, at least in part, to methodological heterogeneity, including variability in the criteria and tools used to assess both foot morphology and postural control [12]. On the other hand, only a limited number of studies combined data regarding postural sway with plantar pressure distribution. In this regard, De Blasiis et al. [13] identified specific relationships between midfoot loading patterns and sway parameters under different visual conditions, while Arin-Bal et al. [14] identified relationships between plantar pressure variables and dynamic balance metrics. Such findings highlight the possible role of functional load distribution patterns in characterizing postural strategies, offering complementary insight beyond morphological classification alone.

It is noteworthy that the quoted previous studies tested the general population, while, to the best of our knowledge, no data are available for elite athletes. Given that sport-specific functional adaptations associated with long-term athletic training are likely to occur [15], it is reasonable to hypothesize a specific relationship between foot morphology, plantar pressure distribution, and postural stability in this population. However, to the best of our knowledge, these aspects have not yet been thoroughly investigated in elite soccer players. This research question is of relevance in this discipline, considering that it constantly challenges the postural control system through frequent dribbling, sudden changes of direction, landings from jumps, and rapid accelerations and decelerations. Such complex motor tasks require a well-developed capacity to maintain balance and dynamically stabilize the body, thus making postural control an important component of soccer-specific motor performance [16]. Indeed, inadequate balance has been associated with a greater risk of non-contact lower limb injuries [17–19], which are particularly relevant in soccer, and tend to occur most frequently when players are fatigued [20 21]. On the other hand, long-term soccer-specific training may contribute to structural and functional adaptations of both the foot and the postural control system, thus potentially influencing the relationship between plantar pressure distribution and balance performance [11 12 22]. In particular, the action of repetitive mechanical stresses associated with soccer-specific actions, including sprints, dribbling, directional changes, and landings, may progressively modify plantar loading patterns and foot–ground interaction characteristics over time [23].

Based on such considerations, this study aimed to explore possible associations between plantar pressure distribution metrics (e.g., mean and peak pressures, contact areas) and postural sway features in semi-professional and professional high-level soccer players during unipedal and bipedal upright stance conditions. In addition, a footprint-derived measure of medial longitudinal arch morphology (Arch Index, AI) was included to examine whether arch-related characteristics were associated with postural sway. The findings may contribute to a better understanding of the relationship between plantar pressure distribution and static postural control in elite soccer players.

# Methods

## Participants

We retrospectively analyzed data from previous investigations [16 21 24 25], which involved a total of 110 soccer players belonging to "Cagliari Calcio" club (Cagliari, Italy). Participants were selected among those who played during the competitive seasons 2012–2013 to 2022–2023 in "Serie A" (first Italian professional league), "Serie B" (second Italian professional league), Under 19 and Under 18 elite teams. Their anthropometric features are reported in Table 1. At the time of testing, all participants were actively competing and free from acute or chronic lower-limb injuries for the previous 6 weeks. Only athletes who completed the full testing protocol and provided valid acquisitions for all stance conditions were included in the analysis.

## Data acquisition and processing

Postural sway and plantar pressure data were simultaneously collected using a pressure platform (FDM-S, Zebris Medical GmbH, Germany) with a sampling frequency of 120 Hz (measuring range 1–120 N/cm$^2$, accuracy ± 5%). The device includes 2560 capacitive sensing elements arranged in a 64 × 40 matrix and is connected via USB interface to a personal computer. The experimental tests were performed under both unipedal (dominant and non-dominant limb) and bipedal conditions, following the standardized protocol described in our previous investigations [16 21 24 25]. The selected stance configurations were based on previously validated stabilometric protocols, commonly adopted for the assessment of static postural control. Limb dominance was defined as the preferred kicking leg, according to the self-reported kicking preference of each participant [26]. Each condition included three trials, with participants standing barefoot on the pressure platform.

During the unipedal stance, participants were instructed to stand as still as possible for 20 s, with the supporting foot aligned parallel to the platform's minor axis and the contralateral limb raised so that the foot was approximately suspended to the height of the malleolus of the supporting limb, while the arms were positioned at the lumbar level. Participants were asked to fix their gaze on a visual target placed at a distance of 3 m, adjusted to each individual's eye level. For the bipedal stance condition, participants stood barefoot on the platform for 30 s, placing their feet on 30°-oriented footprints (with an inter-malleolar distance of approximately 8 cm) drawn on a paper sheet positioned over the platform surface. They were instructed to maintain a stable and relaxed posture, with arms resting naturally by their sides and gaze fixed on the same visual target previously described for the unipedal condition tests.

To calculate sway parameters as a proxy of static balance abilities, COP time-series was acquired, low-pass filtered (10 Hz cutoff; 4th-order Butterworth; bidirectional) and processed with a custom-developed Matlab® routine to calculate the following parameters:

**Table 1** Anthropometric features of the participants

| | Serie A/B ($n$ = 60) | Under 19 ($n$ = 27) | Under 18 ($n$ = 23) | Range |
|---|---|---|---|---|
| Age (years) | 25.7 (4.5) | 17.8 (1.0) | 17.1 (0.4) | [15.9–36.6] |
| Height (cm) | 183.9 (5.7) | 179.1 (8.1) | 176.9 (6.7) | [163.5–198.0] |
| Body mass (kg) | 79.4 (6.5) | 71.7 (9.7) | 67.5 (5.3) | [50.5–102.0] |
| Body Mass Index (kg/m$^2$) | 23.4 (1.2) | 22.3 (2.1) | 21.6 (1.3) | [17.3–27.5] |

Values are expressed as means (SD). The right column reports the range [min–max] observed across the pooled sample

- Sway area (Area, 95% confidence ellipse, $mm^2$),
- COP path length (Path, the overall distance travelled by the COP during the trial, mm)
- COP velocity (in the medio-lateral—ML—and antero-posterior—AP—directions, mm/s)
- COP maximum displacement (i.e., the difference between the maximum and minimum value of the selected coordinate recorded during the trial, mm) in the ML (Disp ML) and AP (Disp AP) directions.

Also, pressure values recorded by each sensor were exported as ASCII file and processed with a custom-developed Matlab® routine to calculate:

- Contact area (CA, $mm^2$) for total and sub-region footprint (i.e., forefoot, midfoot, and rearfoot), the latter identified according to the procedure described in [27].
- Peak pressure (PP, kPa) and mean pressure (MP, kPa) were calculated separately for the rearfoot, midfoot, and forefoot regions [27]. PP was defined as the maximum pressure value recorded within each plantar sub-region during the trial, whereas MP represented the average pressure within the same region;
- The AI: calculated according to the procedure described by Cavanagh & Rodgers [27] as the ratio between the midfoot contact area and the total contact area (toes excluded). Subsequently, feet were classified as cavus, normal arch, or planus according to the thresholds proposed by Chae et al. [28].

### Statistical analysis

Normality of the dependent variables was assessed using the Shapiro–Wilk test prior to all parametric analyses. To investigate whether postural sway differed according to foot morphology, separate one-way multivariate analyses of variance (MANOVA) were performed for the unipedal and bipedal conditions, setting foot morphology (cavus, normal, planus) as the fixed factor and sway parameters (Area, Path, Disp ML, Disp AP, Vel ML, and Vel AP) as dependent variables. For the bipedal condition, AI values were averaged between the right and left feet prior to classification, given the high bilateral agreement in foot morphology observed in the cohort (88% of participants). For the unipedal condition, AI values and sway parameters were first averaged across the three trials for each limb and subsequently averaged between the dominant and non-dominant limbs to obtain one independent observation per participant. Participants were then classified according to the resulting participant-level mean AI. When significant multivariate effects were observed, follow-up univariate analyses and Tukey's post hoc tests were performed. Bonferroni correction was applied for multiple comparisons where appropriate. The level of significance was set at $p < 0.05$, and effect sizes were assessed using the partial eta-squared coefficient ($\eta_p^2$).

To avoid inflation of the degrees of freedom due to repeated measurements, correlation analyses were performed on subject-level averaged data. Specifically, for the bipedal condition, parameters were averaged across the three trials performed by each participant. For the unipedal condition, plantar pressure values and sway parameters were first averaged across the three trials for each limb and subsequently averaged between dominant and non-dominant limbs in order to obtain one independent observation per participant. To better support the interpretation of the correlation analyses, a sensitivity power analysis was performed using G*Power (Version 3.1.9.6, Düsseldorf, Germany).

For a sample size of 110 participants, a two-tailed significance level of 0.05, and a statistical power of 80%, the minimum detectable correlation coefficient was $r = 0.26$. Pearson's correlation coefficients were then computed using one independent observation per participant ($n = 110$) to explore the relationships between plantar pressure variables and sway parameters. To account for multiple comparisons, p-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure. Statistical significance was set at $p < 0.05$. All analyses were performed using SPSS v.26 (IBM Corp., Armonk, NY).

## Results

Means and standard deviations for the plantar pressure and sway parameters are reported in Tables 2 and 3, respectively.

According to the foot morphology classification, 21 players were classified as cavus ($AI \leq 0.17$), 82 as normal arch (AI 0.17–0.28), and 7 as planus ($AI \geq 0.28$). In the bipedal condition, no significant multivariate effect of foot morphology on sway parameters was observed (Wilks' $\lambda = 0.835$, $F(12,204) = 1.608$, $p = 0.092$, $\eta_p^2 = 0.086$). Nevertheless, descriptive statistics showed a tendency for players classified as planus to exhibit larger values of several sway parameters, including Disp ML, Area, Path, and COP velocity, compared with both cavus and normal arch groups (Fig. 1).

No significant multivariate effect of foot morphology was observed in the unipedal condition (Wilks' $\lambda = 0.915$, $F(12,204) = 0.772$, $p = 0.679$, $\eta_p^2 = 0.043$).

Correlation analyses revealed that, although weak associations were observed between plantar pressure distribution metrics and sway parameters under both unipedal

**Table 2** Mean (standard deviation) for contact pressure parameters

| | Bipedal | Unipedal | Dominant | Non-dominant |
|---|---|---|---|---|
| MP Rearfoot (kPa) | 53.53 (14.86) | 79.79 (18.08) | 78.60 (18.31) | 80.98 (17.80) |
| PP Rearfoot (kPa) | 106.18 (35.10) | 142.58 (38.19) | 140.23 (37.79) | 144.92 (38.52) |
| CA Rearfoot (mm$^2$) | 3462.87 (433.32) | 3652.18 (388.53) | 3625.39 (385.9) | 3678.96 (389.97) |
| MP Midfoot (kPa) | 18.74 (8.52) | 50.37 (19.81) | 49.17 (20.04) | 51.57 (19.54) |
| PP Midfoot (kPa) | 43.37 (23.03) | 117.89 (53.45) | 113.98 (54.14) | 121.81 (52.56) |
| CA Midfoot (mm$^2$) | 2289.56 (894.24) | 3091.40 (646.87) | 3107.08 (640.49) | 3075.72 (653.92) |
| MP Forefoot (kPa) | 37.40 (9.19) | 63.91 (13.96) | 63.34 (14.49) | 64.48 (13.4) |
| PP Forefoot (kPa) | 97.38 (34.37) | 182.35 (70.38) | 178.06 (66.65) | 186.63 (73.79) |
| CA Forefoot (mm$^2$) | 4834.27 (553.57) | 5549.40 (608.96) | 5616.48 (603.85) | 5482.32 (607.69) |
| AI | 0.21 (0.06) | 0.25 (0.04) | 0.25 (0.04) | 0.25 (0.04) |

Unipedal data refer to the average of dominant and non-dominant limb parameters

*MP* mean pressure, *PP* peak pressure, *CA* contact area, *AI* Arch Index

**Table 3** Mean (standard deviation) for the sway parameters

| | Bipedal | Unipedal | Dominant | Non-dominant |
|---|---|---|---|---|
| Disp ML (mm) | 14.06 (6.06) | 27.09 (6.14) | 27.07 (5.87) | 27.11 (6.41) |
| Disp AP (mm) | 21.81 (7.91) | 39.54 (10.90) | 39.20 (10.44) | 39.89 (11.35) |
| Area(mm$^2$) | 160.70 (106.13) | 507.70 (204.76) | 503.61 (194.01) | 511.78 (215.23) |
| Path (mm) | 218.94 (66.86) | 632.32 (164.21) | 633.58 (173.14) | 631.06 (155.06) |
| Vel ML(mm/s) | 4.82 (1.64) | 19.74 (5.50) | 19.80 (5.73) | 19.68 (5.26) |
| Vel AP(mm/s) | 4.90 (1.40) | 22.08 (6.14) | 22.09 (6.53) | 22.07 (5.74) |

Unipedal data refer to the average of dominant and non-dominant limb parameters

*Disp ML* mediolateral displacement, *Disp AP* anteroposterior displacement, *Vel ML* mediolateral velocity, *Vel AP* anteroposterior velocity

and bipedal conditions, none survived Benjamini–Hochberg FDR correction for multiple comparisons.

## Discussion

The present study investigated the existence of possible relationships between plantar pressure distribution characteristics and static postural sway in elite soccer players under unipedal and bipedal stance conditions. Overall, the findings suggest that plantar pressure distribution characteristics and footprint-derived indicators of foot morphology have only a limited relationship with static postural sway in this population. Although differences were observed across groups during bipedal stance, plantar pressure variables showed only weak associations with sway parameters, and none remained statistically significant after correction for multiple comparisons.

It is noteworthy, though, that players classified as planus tended to exhibit greater sway values during bipedal stance than those classified as cavus or normal arch. Although statistical significance was not achieved, such results suggest that a reduced height of medial longitudinal arch is associated with subtle alterations in postural control. However, this interpretation should be considered cautiously given the limited number of participants classified as planus and the absence of significant group effects. Moreover, no robust associations were detected in the correlation analyses, suggesting that foot morphology alone explains only a small proportion of the variability in static postural control among elite soccer players. Nevertheless, the pattern of results observed across stance conditions deserves further consideration. Interestingly, morphology-related trends were observed only during bipedal stance, whereas no apparent effects emerged in the more challenging unipedal condition. This apparent discrepancy suggests that the influence of foot morphology on postural sway may be task-dependent, becoming less evident as balance demands increase. At first glance, this finding may appear counterintuitive, as a greater influence of foot structure could be expected when balance demands increase. However, postural stability is known to result from the continuous integration of visual, vestibular, and proprioceptive information, with the relative contribution of these sensory systems changing according to task demands [29]. Therefore, it is possible that under unipedal conditions the greater balance requirements reduced the

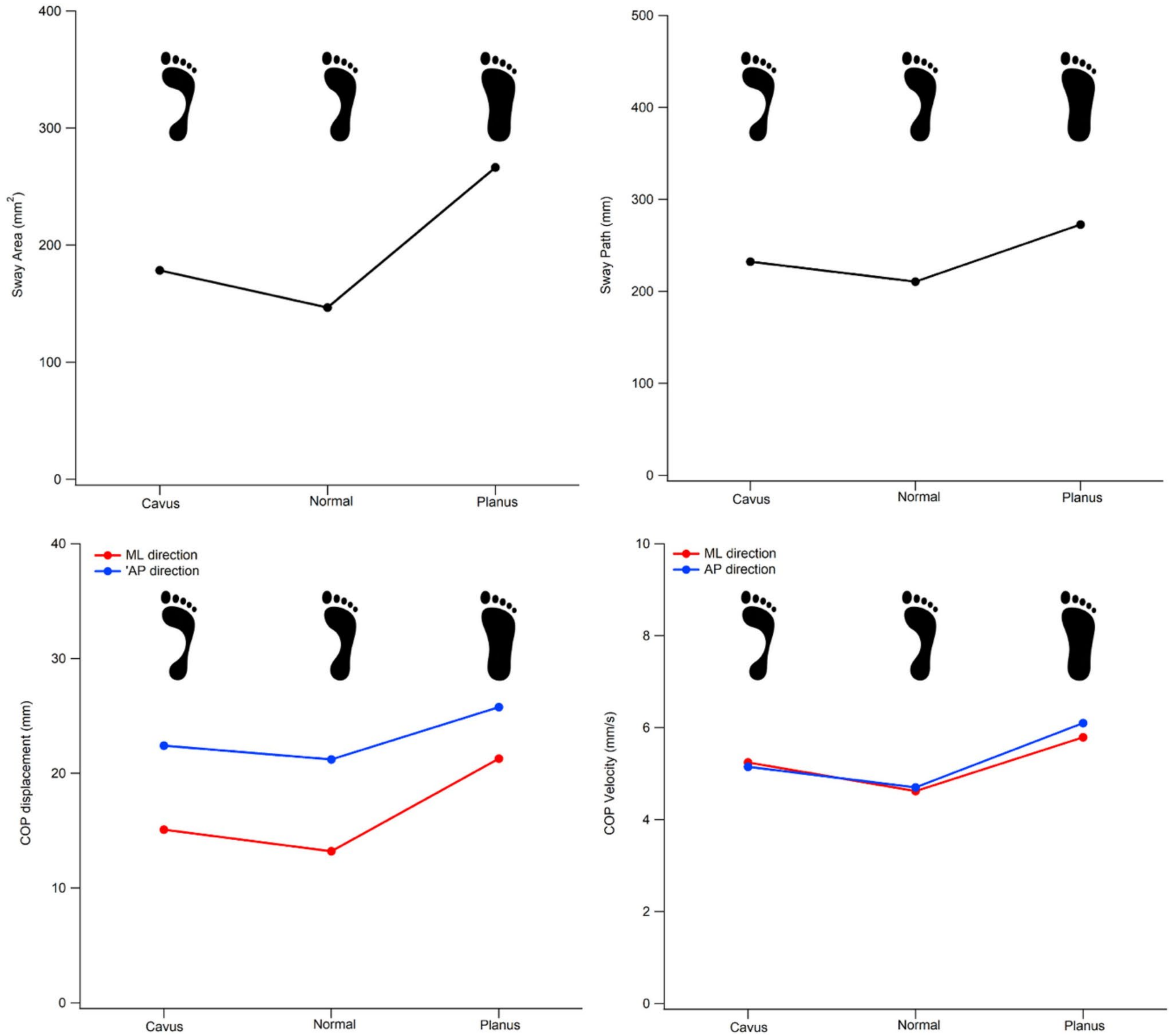


**Fig. 1** Mean values of postural sway parameters during bipedal stance according to foot morphology. Upper panels: Area and Path. Lower panels: COP displacement and COP velocity. *ML* mediolateral, *AP* anteroposterior

relative contribution of foot morphology and increased the importance of high-level sensorimotor control mechanisms. This effect may be particularly relevant in elite soccer players, as long-term soccer-specific training has been associated with adaptations in postural control and sensorimotor function [11 15], potentially leading athletes to adopt highly effective stabilizing strategies that compensate for structural differences in foot morphology. Such adaptations may explain, to some extent, why morphology-related trends were observed during bipedal stance but not under the more demanding unipedal condition. However, these interpretations remain speculative, as the present study did not include direct assessments of neuromuscular activity, proprioceptive function, or central nervous system mechanisms.

The relationship between foot–ground interaction and postural control has been previously explored mainly in non-athletic populations, where altered foot morphology and plantar loading patterns have often been associated with impaired balance performance [12 27 30] or modified sway behavior [13 14]. However, the available evidence remains heterogeneous, likely due to differences in participant characteristics, stance conditions, plantar subregion definitions, and sway assessment methodologies. Compared with these previous reports, the associations observed in the present cohort were generally weaker, as none of the relationships between plantar pressure variables and postural sway remained statistically significant after correction for multiple comparisons. Nevertheless, the differences observed among foot morphology groups during bipedal stance suggest that foot structure may still exert a measurable influence on postural behavior, at least when individuals are categorized according to broad morphological characteristics. This apparent discrepancy may indicate that although broad foot morphology categories are associated with differences in postural behavior at the group level, plantar pressure variables and continuous footprint-derived measures explain only a limited proportion of the inter-individual variability in postural sway. The attenuated associations observed in the present cohort may also reflect the specific functional adaptations developed by elite soccer players, who are routinely exposed to tasks requiring rapid stabilization, single-leg stance, directional changes, accelerations, decelerations, and landing maneuvers, all of which challenge the postural control system and promote highly refined neuromuscular strategies [15 16 22 31].

A greater number of nominally significant correlations were observed during unipedal stance than during the bipedal condition; however, all associations were weak in magnitude ($|r| \leq 0.30$), and none remained statistically significant after correction for multiple comparisons (please refer to Supplementary Tables S1 and S2 for details). Given that the study was adequately powered to detect moderate correlations ($r \geq 0.26$), these findings suggest that any relationship between plantar pressure distribution and static postural sway is likely to be weak and of limited practical relevance. The largest correlation coefficients were observed for selected midfoot and forefoot pressure variables and measures of Path and Disp ML, although these associations remained weak. In contrast, the AI showed negligible relationships with sway parameters under both stance conditions. Taken together, these findings suggest that plantar pressure distribution characteristics, including footprint-derived indicators of medial longitudinal arch morphology, are only weakly associated with static postural control in elite soccer players.

The weak associations observed in the present study may also reflect the limited sensitivity of quiet bipedal standing tasks to detect subtle functional effects related to plantar loading characteristics in highly trained athletes. Previous evidence indicates that balance performance in soccer players is particularly challenged during dynamic and sport-specific tasks [16 25 30], whereas quiet upright standing may represent a relatively low-demand condition for this population. In this context, dynamic balance assessments involving perturbations, landing tasks, or fatigue conditions may be more suitable for investigating possible interactions between plantar pressure distribution and postural control strategies. Indeed, fatigue-related impairments of balance have been previously documented in soccer players [21 24], suggesting that the relationship between plantar loading characteristics and postural control may be more evident under conditions that place greater demands on the neuromuscular system.

Some limitations should be acknowledged. First, the retrospective and cross-sectional design does not allow causal inferences. In addition, the study pooled athletes from different competitive levels and age groups, spanning a relatively wide age range. Although all assessments were performed using the same equipment, experimental setup, and standardized procedures, potential cohort-related differences associated with age, training level, or assessment period cannot be excluded. Since the study was not specifically designed to investigate subgroup differences, no age-adjusted or competitive-level analyses were performed, and therefore the pooled findings should be interpreted with appropriate caution. Second, only static stance conditions were investigated, which may not fully represent the dynamic and highly demanding balance requirements typical of soccer performance. Third, no direct assessments of neuromuscular activity, sensory integration, or central nervous system function were included. Consequently, the mechanisms underlying the weak associations observed between plantar pressure distribution and postural sway remain unclear. Nevertheless, the sensitivity analysis indicated that the study was adequately powered to detect correlations of approximately $r = 0.26$ or greater. Therefore, while moderate associations between plantar pressure distribution and postural sway appear unlikely in the present sample, smaller effects cannot be excluded. Future studies should integrate surface electromyography, proprioceptive assessments, and dynamic balance tasks to better clarify the interaction between plantar loading patterns and postural control strategies in elite athletes. Additionally, longitudinal investigations could help determine whether specific training adaptations or fatigue states modulate these relationships over time.

In conclusion, plantar pressure distribution characteristics showed only weak associations with static postural sway in elite soccer players, and none remained statistically significant after correction for multiple comparisons. Although differences in postural behavior were observed among foot morphology groups during bipedal stance, the overall findings indicate that plantar loading patterns and footprint-derived indicators of foot morphology play only a minor role in determining static balance performance in this population. Further studies incorporating dynamic balance tasks and direct neurophysiological assessments are warranted to determine whether these relationships become more evident under more demanding functional conditions and to better understand the factors contributing to postural control in elite soccer players.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11332-026-01889-1.

**Author contributions** F.A. conducted data collection and processing, performed the analyses, created visualizations, wrote the first draft of the manuscript, and contributed to its revision. B.L. developed the software, contributed to the experimental setup, and revised the manuscript. M.P. contributed to data collection and processing and participated in manuscript revision. G.C. participated in data collection and contributed to manuscript revision. M.Pa. supervised the project, designed the methodology and conceptual framework, and participated in writing and revising the manuscript. All authors reviewed and approved the final version of the manuscript.

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**Data availability** Data are not publicly available but can be provided by the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors report there are no competing interests to declare.

**Ethical approval** The study was carried out in compliance with the ethical principles for research involving human subjects expressed in the Declaration of Helsinki and was approved by the Departmental Review Board.

**Informed consent** Written informed consent was obtained from all participants and their parents after a detailed explanation of the purpose of the study and a description of the experimental methodology.



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