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Plantar Parameters and Fall Risk in Community-Dwelling Older Adults with Sarcopenia

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Abstract

Background

Sarcopenia is a geriatric syndrome marked by progressive reductions in skeletal muscle mass, strength, and function, and it is an independent risk factor for falls among community-dwelling older adults. Biomechanical alterations of the foot may contribute to declines in lower-limb function and the increased incidence of falls in individuals with sarcopenia. However, the characteristics of plantar force distribution in sarcopenic patients and their relationship with balance function remain unclear. Investigating this issue using the latest diagnostic criteria is clinically important.

Objective

To provide evidence for early identification of community-dwelling older adults at high risk for falls, this study examined differences in plantar force, plantar pressure, foot axis angle, and eversion angle between older adults with and without sarcopenia, and analyzed the relationships with balance function.

Methods

This cross-sectional study enrolled 99 community-dwelling older adults, with 66 in the sarcopenia group and 33 in the non-sarcopenia group. It measured plantar parameters-plantar force, plantar pressure, foot axis angle, and eversion angle-and evaluated balance function using the Tinetti Performance Oriented Mobility Assessment (POMA). The study compared intergroup differences in plantar parameters, examined correlations between these parameters and POMA scores, and identified independent factors influencing POMA scores through stepwise and hierarchical multiple linear regression analyses.

Results

Compared with the non-sarcopenia group, the sarcopenia group showed significantly lower plantar force at the left toes 2–5, left 2nd-3rd metatarsal heads, left lateral heel, right 2nd-3rd metatarsal heads, and right medial arch (all $p < 0.05$), and significantly larger left and right foot axis and eversion angles (all $p < 0.001$). No significant differences were observed in any plantar pressure parameter between the sarcopenia and non-sarcopenia group. Within the sarcopenia group, after correction, left foot axis angle ($r = 0.257$, $p = 0.037$) and force at the left lateral heel ($r = 0.251$, $p = 0.042$) were positively correlated with POMA scores. Stepwise regression identified age ($\beta = -0.535$, $p < 0.001$) and left foot axis angle ($\beta = 0.217$, $p = 0.036$) as independent factors associated with POMA scores, with an adjusted R^2 of 0.336. Hierarchical regression further confirmed that left foot axis angle explained an additional 4.7% of the variance in POMA scores beyond age ($\Delta R^2 = 0.047$, $\Delta F = 4.573$, $p = 0.036$).

Conclusions

Community-dwelling older adults with sarcopenia show abnormal changes in plantar force distribution and foot alignment (axis angle and eversion angle). After adjusting for confounding factors, the left foot axis angle was independently associated with balance decline, suggesting it could serve as an additional biomechanical marker for fall risk. Furthermore, these abnormalities may work together in the pathophysiological processes that lead to balance impairment.

1 Introduction

Sarcopenia was originally described by Rosenberg as an age-related loss of skeletal muscle mass [1]. In its 2025 consensus update, the Asian Working Group for Sarcopenia (AWGS) defined sarcopenia as a geriatric syndrome characterized by progressive declines in skeletal muscle mass, muscle strength, and physical performance [2, 3]. With the rapid aging of populations worldwide, sarcopenia has become a major public health concern among community-dwelling older adults. A meta-analysis including 45 studies and 37,571 participants reported an overall prevalence of 20.7% among Chinese older adults, increasing to 45.4% in individuals aged 80 years and older [4]. Sarcopenia is associated with impaired mobility, reduced balance performance, and increased risks of falls, disability, hospitalization, and mortality [5]. Among these adverse outcomes, falls are particularly concerning because they frequently lead to fractures, traumatic brain injuries, loss of independence, and substantial healthcare costs [6, 7].

The foot serves as the primary interface between the body and the ground. Plantar biomechanical parameters include regional force distribution, plantar pressure, and foot alignment angles. These parameters determine the base of support and the center of pressure (COP) trajectory during quiet standing[8]. Pathological changes in them can impair postural stability and increase fall risk.Gait performance is a well-established predictor of both fall risk and all-cause mortality in older adults [9]. Previous studies have demonstrated that individuals with sarcopenia commonly exhibit spatiotemporal gait abnormalities, including reduced gait speed, shorter stride length, prolonged double-support time, and increased step width [10, 11]. Although these measures provide valuable information regarding overall walking performance, they offer limited insight into the biomechanical mechanisms underlying gait impairment. In particular, conventional spatiotemporal parameters cannot adequately characterize force transmission during foot–ground interactions or dynamic alterations in foot alignment during walking [12].

Plantar biomechanical parameters may help bridge this knowledge gap. Plantar force and plantar pressure directly quantify the mechanical characteristics of foot–ground contact [13, 14], whereas foot axis angle and eversion angle reflect dynamic foot alignment and stability during gait [15]. Emerging evidence suggests that these parameters may represent important biomechanical manifestations of sarcopenia-related gait dysfunction. In a large cross-sectional study involving 9,347 community-dwelling older adults, Yamagiwa et al. [16] reported significantly lower forefoot plantar pressure in participants

with sarcopenia. Similarly, a study of older women demonstrated a significant positive association between SARC-CalF scores and medial plantar loading [17]. However, existing studies have generally relied on relatively broad plantar region classifications, potentially obscuring localized biomechanical alterations associated with sarcopenia. Furthermore, most investigations have focused primarily on sarcopenia diagnosis or isolated fall-related risk factors, while the relationship between detailed plantar biomechanical characteristics and balance-related fall risk remains insufficiently understood.

Importantly, evidence regarding plantar biomechanics under the updated AWGS 2025 diagnostic framework remains scarce. To our knowledge, no study has comprehensively evaluated multidimensional plantar biomechanical parameters in community-dwelling older adults with sarcopenia while simultaneously examining their associations with balance performance assessed using the Tinetti Performance-Oriented Mobility Assessment (POMA). In addition, the relationship between sarcopenia severity, as reflected by SARC-CalF scores, and plantar biomechanical characteristics has not been fully explored.

Therefore, this study employed a refined plantar segmentation strategy that independently evaluated multiple anatomical subregions, including the toes, metatarsal heads, medial and lateral arches, and medial and lateral heel regions. This approach was designed to identify localized biomechanical alterations that may not be detectable using conventional regional classifications. Furthermore, we investigated the associations between plantar biomechanical parameters and POMA scores to explore their potential relevance to balance function and fall risk. By providing a more detailed characterization of foot biomechanics in community-dwelling older adults with sarcopenia, this study aims to contribute to the development of more precise screening, risk stratification, and intervention strategies, consistent with the AWGS 2025 emphasis on promoting muscle health across the life course.

2 Methods

2.1 Study Design

This was a cross-sectional study designed to compare the differences in plantar force, plantar pressure, foot axis angle, and eversion angle between community-dwelling older adults with and without sarcopenia, and to analyze the relationships between these plantar parameters and balance function, with the aim of providing evidence for early identification of community-dwelling older populations at high risk for falls.

All participants were informed of the study content and provided written informed consent before enrolment. The study protocol was approved by the Ethics Committee of the First Affiliated Hospital of Henan University of Chinese Medicine (approval No. 2024HL-296-01) and registered in the International Traditional Medicine Clinical Trial Registry (registration No. ITMCTR2024000131).This study was conducted in accordance with the principles of the Declaration of Helsinki.

2.2 Participants

A total of 99 community-dwelling older adults meeting the definition of community residence were recruited from Wenhua Street Community, Huayuan Community, and Hongqi Community in Xinxiang City, Henan Province, China.

Inclusion criteria for the sarcopenia group

(1) age ≥ 60 years, either sex; (2) meeting the Chinese expert consensus on prevention and intervention for elderly with sarcopenia(2023) diagnostic criteria for sarcopenia[18]; (3) able to walk independently for at least 10 meters (with a single-point cane allowed); (4) in a stable phase of chronic diseases (e.g., well-controlled hypertension or diabetes, no acute exacerbation of chronic bronchitis, etc.), and willing to participate and sign the informed consent form.

Inclusion criteria for the non-sarcopenia group

(1) age ≥ 60 years, either sex; (2) may have disease states unrelated to gait, such as respiratory or gastrointestinal disorders; (3) in a stable phase of chronic diseases, willing to participate and sign the informed consent form.

Exclusion criteria for both groups

(1) diagnosed with Parkinson's disease, obvious hemiplegic gait after stroke, or other diseases causing gait abnormalities; (2) cognitive impairment preventing understanding and cooperation with tests; (3) use of oral or intravenous systemic glucocorticoids within the past 3 months, or uncontrolled thyroid disease or adrenal dysfunction; (4) severe dehydration, edema, or fluid/electrolyte imbalance; (5) concurrent severe primary diseases such as cardiovascular or cerebrovascular conditions, deemed by the investigator as unsuitable for participation; (6) presence of metal implants or cardiac pacemakers that preclude body composition measurement, or severe joint deformities preventing completion of plantar pressure and gait tests; (7) history of lower limb fracture or joint replacement within the past 6 months.

2.3 Sarcopenia Assessment

Participants were assessed according to the Chinese expert consensus on prevention and intervention for elderly with sarcopenia(2023) diagnostic criteria.

Muscle mass measurement

Appendicular skeletal muscle mass (ASM) was measured using multi-frequency bioelectrical impedance analysis (BIA) and adjusted by height squared (ASM/height²). ASM was measured using the YUNKANGBO body composition analyzer (CP10A).

The cut-off values for low muscle mass were

for individuals aged ≥ 60 years, < 7.0 kg/m² for males and < 5.7 kg/m² for females.

Muscle strength measurement

Handgrip strength was measured using an electronic handgrip dynamometer (EH101, CAMRY). Participants were instructed to stand upright with the elbow fully extended and the proximal interphalangeal joints of the dominant hand flexed at 90°, performing maximal voluntary isometric contraction. The test was repeated three times, and the maximum value among the three trials was recorded.

The cut-off values for low muscle strength were

for individuals aged ≥ 60 years, < 28.0 kg for males and < 18.0 kg for females.

The 6-meter gait speed test

The 6-meter gait speed test was conducted on a flat, straight corridor with a marked 6-meter course, with at least 2-meter acceleration and deceleration zones at each end. Participants walked at their usual comfortable pace starting from the beginning of the acceleration zone; the timer started the stopwatch when the participant's foot crossed the start line of the 6-meter course and stopped it when crossing the end line, accurately recording the time required to traverse the 6-meter distance. The test was repeated at least 2–3 times, and the average time was used to calculate gait speed (6 meters divided by average time), with < 1.0 m/s adopted as the diagnostic cut-off value for declined physical function.

Case finding and screening process

Initial screening was performed using the SARC-CalF scale (score ≥ 11) in individuals with high-risk factors such as heart failure, chronic obstructive pulmonary disease, diabetes, chronic kidney disease, recurrent falls, or involuntary weight loss. Those screening positive underwent handgrip strength testing and 6-meter gait speed test; if handgrip strength and 6-meter gait speed test were reduced and muscle mass was confirmed by BIA to be below the aforementioned cut-offs, a diagnosis of sarcopenia was established (Fig. 1).

2.4 Acquisition of Plantar-Related Parameters

Plantar parameters were collected using the Freestep plantar pressure measurement system (SENSOR MEDICA S.A.S., Italy). The system converts analogue signals to digital signals via a USB module, and the accompanying analysis software directly outputs and visualizes the distribution and changes in plantar force. All measurements were performed by trained professionals under constant environmental conditions. Participants removed shoes and socks, stood upright with eyes open, feet together, and arms hanging naturally at the sides. After the plantar pressure curve stabilized, static standing data were continuously recorded for 30 seconds. All participants received standardized instructions before testing to ensure consistency.

The Freestep system divides the plantar surface into nine anatomical regions: the hallux, toes 2–5, first metatarsal head, second–third metatarsal heads, fourth–fifth metatarsal heads, medial arch, lateral arch, medial heel, and lateral heel. Based on these regions and the whole foot, the system simultaneously collects and calculates the following main parameters:

(1) Plantar force: records instantaneous force values for each region and the entire foot, and calculates mean force and peak force, reflecting the magnitude and concentration of plantar loading during static standing.

(2) Plantar pressure: calculates the vertical force per unit contact area (i.e., pressure) for each region, thereby eliminating the confounding effect of contact area differences on force assessment.

(3) Foot axis angle: the angle between the long axis of each foot and the midline sagittal plane or direction of progression, quantifying foot orientation and symmetry.

(4) Foot eversion angle: the angle between the hindfoot axis and the forefoot axis projected on the coronal plane, used to evaluate arch deformation and the tendency toward varus/valgus.

To ensure data accuracy and reproducibility, all tests were performed by the same biomechanical specialist who had received standardized training from the manufacturer, using the same equipment under constant environmental parameters. Standardized instructions and fixed testing procedures effectively minimized human-factor interference with the results.

2.5 Functional Assessments

Sarcopenia self-assessment: Sarcopenia risk was assessed using the SARC-CalF scale. This scale comprises six items: muscle strength, assistance in walking, rising from a chair, stair climbing, falls, and calf circumference, with a total score of 20. Higher scores indicate greater sarcopenia risk; a total score ≥ 11 was considered screening positive.

Balance and gait function: Balance and gait function were evaluated using the Tinetti Performance Oriented Mobility Assessment (POMA). The POMA consists of two subscales: balance and gait. The balance subscale includes 8 items (e.g., sitting balance, rising from a chair, standing balance, nudge test, standing with eyes closed, turning), scored from 0 to 2, with a maximum score of 16. The gait subscale includes 7 items (e.g., initiation, step length, step width, gait symmetry, gait continuity, path deviation) scored from 0 to 2, with a maximum score of 12. The total score is 28 points. Higher scores indicate better balance and gait function: < 19 indicates high fall risk, 19–24 moderate fall risk, and > 24 low fall risk.

2.6 Statistical Analysis

Data were analyzed using SPSS 27.0 and GraphPad Prism 10.1.2. Continuous variables were tested for normality with the Shapiro-Wilk test. Normally distributed data were expressed as mean ± standard deviation ($\bar{x} \pm s$), and between-group comparisons were performed with the independent samples t-test.

Non-normally distributed data were expressed as median (interquartile range) [M (Q1, Q3)], and between-group comparisons used the Mann-Whitney U test. Categorical data were expressed as frequencies (percentages), and between-group comparisons used the χ^2 test or Fisher's exact test.

Within the sarcopenia group, Spearman's rank correlation was used to analyze the correlation between plantar parameters and POMA scores. Correlation coefficients were corrected using the Benjamini-Hochberg method, with $p < 0.05$ considered statistically significant. Stepwise multiple linear regression analysis was performed with POMA score as the dependent variable and age and plantar parameters as independent variables (entry criterion $\alpha = 0.05$, removal criterion $\alpha = 0.10$). Collinearity diagnostics were performed before regression; a variance inflation factor (VIF) > 10 indicated severe collinearity. Hierarchical regression was used to verify the predictive value of plantar parameters for POMA scores. Two-sided tests were used, and $p < 0.05$ was considered statistically significant.

In exploratory analyses, Spearman's rank correlation was used to analyze the correlations of the SARC-CalF score with plantar parameters and POMA scores. Correlation coefficients were corrected with the Benjamini-Hochberg method, and $p < 0.05$ was considered statistically significant.

3 Results

3.1 Characteristics of Plantar Parameters in Patients with Sarcopenia

This study included 99 older adults. Of these, 33 participants (33.3%) were in the non-sarcopenia group, and 66 (66.7%) were in the sarcopenia group. The overall mean age was 70.55 ± 6.55 years. The mean age was 69.61 ± 4.90 years for the non-sarcopenia group and 71.02 ± 7.22 years for the sarcopenia group.The two groups did not differ significantly in sex distribution, age, weight, or BMI (all p > 0.05). However, the sarcopenia group had a significantly lower median height (156.50 cm vs. 160.00 cm, p = 0.045) (Additional file 1: Table S1).

For plantar force distribution (Additional file 2: Table S1, Fig. 2), the sarcopenia group showed significantly lower force at the left toes 2–5, left 2nd-3rd metatarsal heads, left lateral heel, right 2nd-3rd metatarsal heads, and right medial arch compared with the non-sarcopenia group (all $p < 0.05$). In contrast, force at the left 4th-5th metatarsal heads and right lateral arch was significantly higher in the sarcopenia group ($p < 0.05$). The differences at the left 2nd-3rd metatarsal heads and right lateral arch yielded p values below 0.001. The two groups showed no significant differences in any maximum or mean plantar pressure parameter (Additional file 2: Table S2, Fig. 3, all $p > 0.05$). For foot eversion and axis angles (Additional file 2: Table S3, Fig. 4), the sarcopenia group had significantly larger left foot eversion angle, left foot axis angle, right foot eversion angle, and right foot axis angle than the non-sarcopenia group (median eversion angles: 13°-13° vs. 7°-7.5°; median axis angles: 9°-11° vs. 5°-7.5°; all $p < 0.001$).

Data are shown as box plots (median, IQR, whiskers: 1.5×IQR) with individual values overlaid as black dots. The x-axis regions: HAL (hallux), TO25 (toes 2–5), MT1/23/45 (1st/2nd-3rd/4th-5th metatarsal heads), MA (medial arch), LA (lateral arch), MH (medial heel), and LH (lateral heel). Groups are shown side-by-side for each region (non-sarcopenia, n = 33; sarcopenia, n = 66).

Data are shown as box plots (median, IQR, whiskers: 1.5×IQR) with individual values overlaid as black dots. The x-axis parameters: L_MAX_P (left foot maximum pressure), L_MEAN_P (left foot mean pressure), R_MAX_P (right foot maximum pressure), and R_MEAN_P (right foot mean pressure). Groups are shown side-by-side for each parameter (non-sarcopenia, n = 33; sarcopenia, n = 66).

Data are shown as box plots (median, IQR, whiskers: 1.5×IQR) with individual values overlaid as black dots. The x-axis parameters: L_EV_ANG (left foot eversion angle), L_AX_ANG (left foot axis angle), R_EV_ANG (right foot eversion angle), and R_AX_ANG (right foot axis angle). Groups are shown side-by-side for each parameter (non-sarcopenia, n = 33; sarcopenia, n = 66).

3.2 Analysis of Plantar Parameters Associated with Fall Risk Stratification in the Sarcopenia Group

Based on POMA scores, we divided the sarcopenia group into low-risk (n = 0), moderate-risk (n = 25), and high-risk (n = 41) subgroups. We compared baseline characteristics and plantar parameters across these strata.

In the subgroup analysis of sarcopenia patients stratified by fall risk based on POMA scores, the high-risk group (n = 41) had a significantly higher median age than the moderate-risk group (n = 25) (74.0 vs. 63.0 years, $p < 0.001$). Other baseline characteristics did not differ between the two risk subgroups (Table 2 1). The two subgroups showed no significant differences in plantar force in 16 regions, maximum or mean plantar pressure, or most foot angle parameters (Additional file 3: Table S1-S2). The only exception was that the left foot axis angle was significantly larger in the moderate-risk group than in the high-risk group (14.0° vs. 12.0°, $p = 0.049$) (Table 2 2).

Table 2
1 Baseline characteristics by fall risk strata

Variable	Moderate-risk group(n = 25)	High-risk group(n = 41)	H statistic	*p* value
Age(years)	63.00(60.50,71.00)	74.00(70.00,77.50)	18.029	< 0.001
Height(cm)	160.00(153.50,165.00)	156.00(152.50,160.00)	2.566	0.109
Weight(kg)	56.00(49.70,61.55)	54.20(49.40,58.65)	1.233	0.267
BMI(kg/m^2)	21.26(20.32,23.44)	22.04(20.24,23.26)	0.027	0.869
Note:The Kruskal-Wallis H test was used. Continuous data are presented as median (P25,P75). Fall risk strata: low-risk group(n = 0),moderate-risk group(n = 25),and high-risk group(n = 41)				

Table 2
2 Foot axis and eversion angle parameters by fall risk strata

Variable	Moderate-risk group(n = 25)	High-risk group(n = 41)	H statistic	*p* value
Left foot eversion angle	14.00(10.50,16.50)	12.00(8.50,16.00)	1.360	0.244
Left foot axis angle	14.00(11.50,17.00)	12.00(11.00,15.00)	3.880	0.049
Right foot eversion angle	10.00(8.00,13.50)	9.00(7.00,13.00)	0.356	0.551
Right foot axis angle	11.00(8.50,15.50)	12.00(9.00,15.00)	0.057	0.811
Note:The Kruskal-Wallis H test was used. Continuous data are presented as median(P25,P75)				

3.3 Correlation between plantar parameters and balance function in the sarcopenia group

Within the sarcopenia group (n = 66), Spearman rank correlation analyses with Benjamini-Hochberg correction showed that left foot axis angle (r = 0.257, p = 0.037) and force at the left lateral heel (r = 0.251, p = 0.042) were positively correlated with POMA scores. All other parameters showed no statistically significant correlations (Additional file 4: Table S1-S3, Fig. 5).

The color gradient represents the magnitude and direction of the correlation, with red indicating positive and blue indicating negative correlations (or the reverse, depending on your actual color scheme). The x-axis and y-axis list the plantar parameters (plantar force parameters, plantar pressure parameters, and angle parameters) as shown. All displayed correlations were not statistically significant after Benjamini-Hochberg correction ($p > 0.05$), except for left foot axis angle and left lateral heel force which are reported separately in the text. Spearman rank correlation coefficients were used.

3.4 Multiple linear regression analysis of factors affecting balance function

We performed multiple linear stepwise regression analysis with POMA score as the dependent variable and age and plantar parameters as independent variables. Before regression, we conducted collinearity diagnostics. These diagnostics revealed severe collinearity for left foot mean pressure (VIF = 19.678) and right foot mean pressure (VIF = 19.413), so these variables did not enter the equation. We then used stepwise regression to examine the influence of each indicator on the POMA score. The results showed (Table 5 1) that age and left foot axis angle entered the final regression equation. The overall model was statistically significant (F = 17.411, $p < 0.001$), with R^2 = 0.356 and adjusted R^2 = 0.336, explaining 33.6% of the variance in POMA scores.

Table 5
1 Stepwise multiple linear regression of factors affecting POMA

Variable	*B*	SE	*β*	t	*p* value	95%CI
Constant	33.818	4.014	-	8.425	< 0.001	25.797 ~ 41.839
Age	-0.267	0.051	-0.535	-5.263	< 0.001	-0.369~-0.166
Left foot axis angle	0.227	0.106	0.217	2.138	0.036	0.015 ~ 0.439

Hierarchical regression analysis (Additional file 5: Table S1, Fig. 6) used POMA as the dependent variable. Age was entered as a control variable in the first step, and left foot axis angle was entered as the core variable in the second step. The first model was significant ($F = 28.649$, $p < 0.001$). Age explained 30.9% of the variance in POMA. After adding the left foot axis angle in the second step, the overall model remained significant ($F = 17.411$, $p < 0.001$). R^2 increased significantly by 4.7% ($\Delta F = 4.573$, $p = 0.036$). In the final model, age had a significant negative effect on POMA (β=−0.535, $p < 0.001$), and left foot axis angle had a significant positive effect ($\beta = 0.217$, $p = 0.036$). The VIFs for both variables were below 1.02, indicating no multicollinearity.

The plot displays standardized regression coefficients (β) with 95% confidence intervals (error bars) for variables entered in two sequential models. Model 1 (control model) included age as the sole predictor. Model 2 (final model) added left foot axis angle to age. In Model 2, age (β = -0.535, $p < 0.001$) and left foot axis angle ($\beta = 0.217$, $p = 0.036$) were both significant predictors. The addition of left foot axis angle in Model 2 resulted in a significant increase in R^2 of 4.7% ($\Delta F = 4.573$, $p = 0.036$). The overall Model 2 explained 33.6% of the variance in POMA scores (adjusted $R^2 = 0.336$, $F = 17.411$, $p < 0.001$). VIFs for all predictors were below 1.02, indicating no multicollinearity.

3.5 Exploratory analysis: Correlation between SARC-CalF score, plantar parameters, and POMA

To explore whether sarcopenia severity affects fall risk through altered foot biomechanics, we analyzed the relationships between the SARC-CalF score, POMA, and plantar parameters. The details are shown in Additional file 6: Tables S1-S3 and Figure S1.The SARC-CalF score was significantly negatively correlated with POMA score ($r = -0.360$, $p = 0.003$), force at the right 2nd-3rd metatarsal heads ($r = -0.405$, $p < 0.001$), and left foot axis angle ($r = -0.410$, $p < 0.001$).

4 Discussion

Through a refined analysis of plantar biomechanical parameters in community-dwelling older adults with sarcopenia, this study yielded two principal findings. First, participants with sarcopenia demonstrated a distinct plantar force redistribution pattern characterized by diminished anteromedial loading and enhanced posterolateral support, whereas mean and peak plantar pressure did not differ significantly between groups. Second, foot axis and eversion angles were significantly greater in the sarcopenia

group, and the left foot axis angle was independently and positively associated with balance performance among participants with sarcopenia. Collectively, these findings suggest that alterations in foot alignment may represent an adaptive biomechanical response to sarcopenia-related functional decline. In particular, changes in foot axis angle may reflect an intermediate phenotype linking muscular deterioration to impaired balance control, although longitudinal studies are required to clarify its temporal evolution and clinical significance.

The present study identified region-specific reductions in plantar force among older adults with sarcopenia, which is consistent with the findings reported by Yamagiwa et al. [16] in a large community-based cohort. However, whereas previous studies primarily examined broad plantar regions such as the forefoot and hindfoot, the anatomically refined regional segmentation employed in the present study enabled more precise localization of force alterations within the forefoot. Specifically, peak force beneath the bilateral second and third metatarsal heads was significantly reduced in the sarcopenia group during terminal stance. This finding may be attributable to sarcopenia-related declines in the function of the gastrocnemius, soleus, and intrinsic foot muscles, resulting in reduced ankle plantarflexion moment generation and diminished toe-flexor strength [19, 20]. From a biomechanical perspective, these changes are likely indicative of impaired propulsive capacity during late stance.

Conversely, increased force beneath the right lateral arch and the left fourth and fifth metatarsal head regions suggests a tendency toward lateralized load transfer during gait [21, 22]. This redistribution pattern, characterized by diminished anteromedial loading and enhanced posterolateral support, may reflect a compensatory strategy adopted to maintain gait stability in the presence of reduced plantarflexor function. One possible explanation is that insufficient ankle-generated propulsion necessitates alterations in foot alignment and loading patterns, thereby shifting weight-bearing demands toward the relatively rigid lateral midfoot structures. Such adaptations may facilitate progression through the stance phase and partially preserve mediolateral stability, albeit potentially at the expense of propulsive efficiency.

The lack of significant between-group differences in mean and peak plantar pressure should not be interpreted merely as a negative finding; rather, it may provide important insights into the mechanisms underlying gait instability in individuals with sarcopenia. Although plantar force and plantar pressure are closely related biomechanical variables, they represent distinct mechanical constructs, with pressure being determined by the magnitude of force distributed over a given contact area. Consequently, if sarcopenia is accompanied by compensatory increases in plantar contact area and alterations in load distribution patterns, potential differences in plantar pressure may be attenuated or obscured despite measurable changes in plantar force [23]. From a methodological perspective, these findings underscore the importance of simultaneously assessing both plantar force and plantar pressure, as reliance on either parameter alone may fail to capture the full biomechanical complexity of foot–ground interactions during gait.

More importantly, from the perspective of the dynamics of the center of pressure (COP), the pattern of "anteromedial reduction and postlateral enhancement" observed in this study would clearly be demonstrated as a reduction in the speed of pre-COP progression and an increase in the lateral deviation of COP during the final phase [24, 25]. These abnormal COP dynamics represent the basic biomechanical mechanism underlying the degradation of propulsion and lateral stability. Increased axis and eversion angles in older adults living in the community with sarcopenia can be interpreted as compensatory strategies in response to the restricted effective COP displacement and the reduction of stability limits, temporarily improving static stability by expanding the support base. However, the simultaneous decline of plant sensory afferent function and the delay in motor activation of the peri-ankle muscle in sarcopenia impair the rapid forward-feedback regulation mechanisms necessary to counteract minor COP disturbances, thus creating a sustained dependency on passive structural compensation [26, 27]. This functional evolution of active neuromuscular regulation to dependency on passive biomechanical structures can represent one of the potential neuro-biomechanical mechanisms that underpin the high risk of fall in sarcopenic patients, even without significant differences in average and maximum plant pressure.

Both the angle of the axis of the foot and the angle of the eversion were significantly greater in the sarcopenia group than in the group of the non-sarcopenia, indicating significant changes in the dynamic foot position and orientation during walking. The increased angle of the foot axis reflects greater foot abduction, while the increased angle of eversion indicates a more pronounced valgus of the hind foot. Both changes affect the mechanical efficiency of the foot as a rigid lever during launching and shift the COP trajectory laterally, thus compromising dynamic shoulder control. More importantly, the angle of the left axis of the feet was not only independently associated with POMA results, but also explained 4.7% of the variation beyond age in hierarchical regression. This finding suggests that sarcopenia can lead to a decrease in balance by inducing abnormal foot alignment, which ultimately increases the risk of falling. Therefore, plant biomechanical changes provide a plausible and quantifiable intermediate mechanism linking sarcopenia to fall risk. The positive correlation between the angle of the left axis of the foot and the POMA scores - where the sarcopenia group overall showed larger angles than the non-sarcopenia group, but within the group larger angles were associated with better balance - may reveal stage-specific differences in walking control among sarcopenia patients.

Among people who have been diagnosed with sarcopenia, moderately larger foot axis angles can represent a balanced and effective physiotherapy strategy that partially compensates for the weakness of hip and knee muscles in walking stability by expanding the lateral base of support. On the contrary, too small angles may indicate a rigid and compensated foot movement model, a sign of further deterioration in neuromuscular control that undermines balance. This interpretation is consistent with the risk relationship of U-shaped or reverse U-shaped observed for certain movement parameters in weak populations [28, 29]. In addition, the left lateral heel strength was positively correlated with POMA scores, suggesting that loading characteristics in the heel region could also contribute to the maintenance of balance. The lateral heel is the main weight-bearing area during the first contact phase

of the walking cycle; the relative strength preservation in this area can reflect a more stable initial contact model, providing a stable mechanical base for the next position phase. However, the left lateral heel force did not enter the final regression model, indicating that the relationship with the balance function may be partially explained by age or other variables with limited independent predictive values.

In particular, age was the strongest predictor of POMA scores in this study. Degeneration related to age in the sensorimotor system is a well-established driver of balance loss. In this context, the fact that the angle of the left foot axis explains 4.7% of the variance above age, although modest, shows that the foot alignment can provide valuable additional information to balance assessments dominated by age, especially in the discrimination risk of fall among people of similar age.

The exploratory analyses provided additional support for the proposed mechanisms. Higher SARC-CalF scores were associated with lower POMA scores, reduced loading beneath the second and third metatarsal heads, and a smaller foot axis angle. Given that altered forefoot loading and restricted foot kinematics have been linked to impaired gait function and increased fall risk, these findings suggest that sarcopenia may compromise gait stability through changes in plantar biomechanics as well as declines in overall muscle function[30].

The combination of reduced metatarsal loading and a smaller foot axis angle may indicate a cautious, mechanically constrained gait strategy. Such adaptations are commonly observed in older adults with impaired neuromuscular control and may represent compensatory attempts to preserve stability[31]. However, while potentially beneficial in the short term, they may also reduce movement adaptability and increase vulnerability to balance perturbations.These observations further suggest that plantar biomechanical alterations may partially mediate the relationship between sarcopenia severity and balance impairment. Future longitudinal studies are needed to determine whether changes in plantar loading and foot alignment constitute mechanistic pathways linking sarcopenia to gait instability and fall risk.

Synthesizing the evidence above, the angle of the foot axis may show nonlinear changes during the course of sarcopenia. Internal evidence supporting this hypothesis includes: the greater foot angle in the sarcopenia group than in the non-sarcopenia group, suggesting changes in the adaptive foot orientation under sarcopenia conditions; the positive correlation between the foot angle and the balance function in sarcopenia patients, suggesting that such changes in the orientation may help maintain walking stability; and the lower foot angle in the high risk subgroup than in the moderate risk subgroup, suggesting that this increasing trend can reverse as the risk increases. Based on these observations, the angle of the axis of the feet can increase in early sarcopenia as an adaptive biomechanical adjustment to compensate for muscle dysfunction and maintain walking stability. As the disease progresses to an advanced stage, neuromuscular reserves diminish, this compensatory mechanism becomes unsustainable, the angle of the foot axis decreases, and the balance function deteriorates accordingly. This hypothesis of dynamic evolution requires long-term validation, but current findings indicate that the

foot angle may be quantifiable biomechanical indicators to monitor changes in balanced function in sarcopenic patients.

Several limitations of this study should be recognized. Firstly, cross-sectional design excludes causal inferences about the relationship between the foot angle angle and the equilibrium function and cannot directly validate the temporal sequence of the "compensation-decompensation" hypothesis. Secondly, relatively limited sample sizes, especially in subgroup analysis, may reduce the statistical ability to detect subtle differences. Thirdly, potential confounders such as the degree of joint degeneration that may affect plant mechanics and foot posture have not been thoroughly adjusted. Fourthly, plant force measurements are subject to seasonal variations and a single measurement session cannot fully represent the true status during unlimited community ambulation.

Future research should adopt longitudinal design, including three-dimensional motion and electromyography, to track the dynamic changes of the foot axis angle directly during sarcopenia and to validate its increasing validity in fall prediction, thereby clarifying the temporal relationships between changes in plant parameters, muscle loss and fall events. In larger sample sizes, mediation analysis could formally verify whether plant pressure parameters mediate the relationship between the severity of sarcopenia and balance dysfunction. Furthermore, it is recommended to construct a more comprehensive biomechanical model of the deterioration of the walking speed associated with sarcopenia using multiregional plant power ratios combined with kinetic data.

Abbreviations

Abbreviation	Full English name
L_ / R_	Left / Right
HAL	Hallux
TO25	Toes 2–5
MT1/MT23/MT45	1st/2nd-3rd/4th-5th metatarsal head
MA	Medial arch
LA	Lateral arch
MH	Medial heel
LH	Lateral heel
MAX_P	Maximum pressure
MEAN_P	Mean pressure
EV_ANG	Eversion angle
AX_ANG	Axis angle

Declarations

Consent to participate

The participants provided their written informed consent to participate in this study.

Ethical approval

All participants were informed about the study and provided written informed consent prior to enrollment. The study protocol was approved by the Ethics Committee of the First Affiliated Hospital of Henan University of Chinese Medicine (Approval No. 2024HL-296-01) and registered at the International Traditional Medicine Clinical Trial Registry (Registration No. ITMCTR2024000131).This study was conducted in accordance with the principles of the Declaration of Helsinki.

Consent for publication

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financialinterests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Tianchong Huang: Writing - review & editing, Writing - original draft. Ting Dai: Writing - review & editing, Writing - original draft. Yan Chen: Writing - review & editing, Writing - original draft. Jun Chen: Visualization. Jing Gao: Supervision. Xiaodong Feng: Supervision.

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Author Contribution

Tianchong Huang: Writing - review & editing, Writing - original draft. Ting Dai: Writing - review & editing, Writing - original draft. Yan Chen: Writing - review & editing, Writing - original draft. Jun Chen:

Visualization. Jing Gao: Supervision. Xiaodong Feng: Supervision.

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Data Availability

All raw data generated and analyzed by our research team during this study are available from the corresponding author upon reasonable request. Requests for data should be sent to the email address: fxd0502@163.com.

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Figures

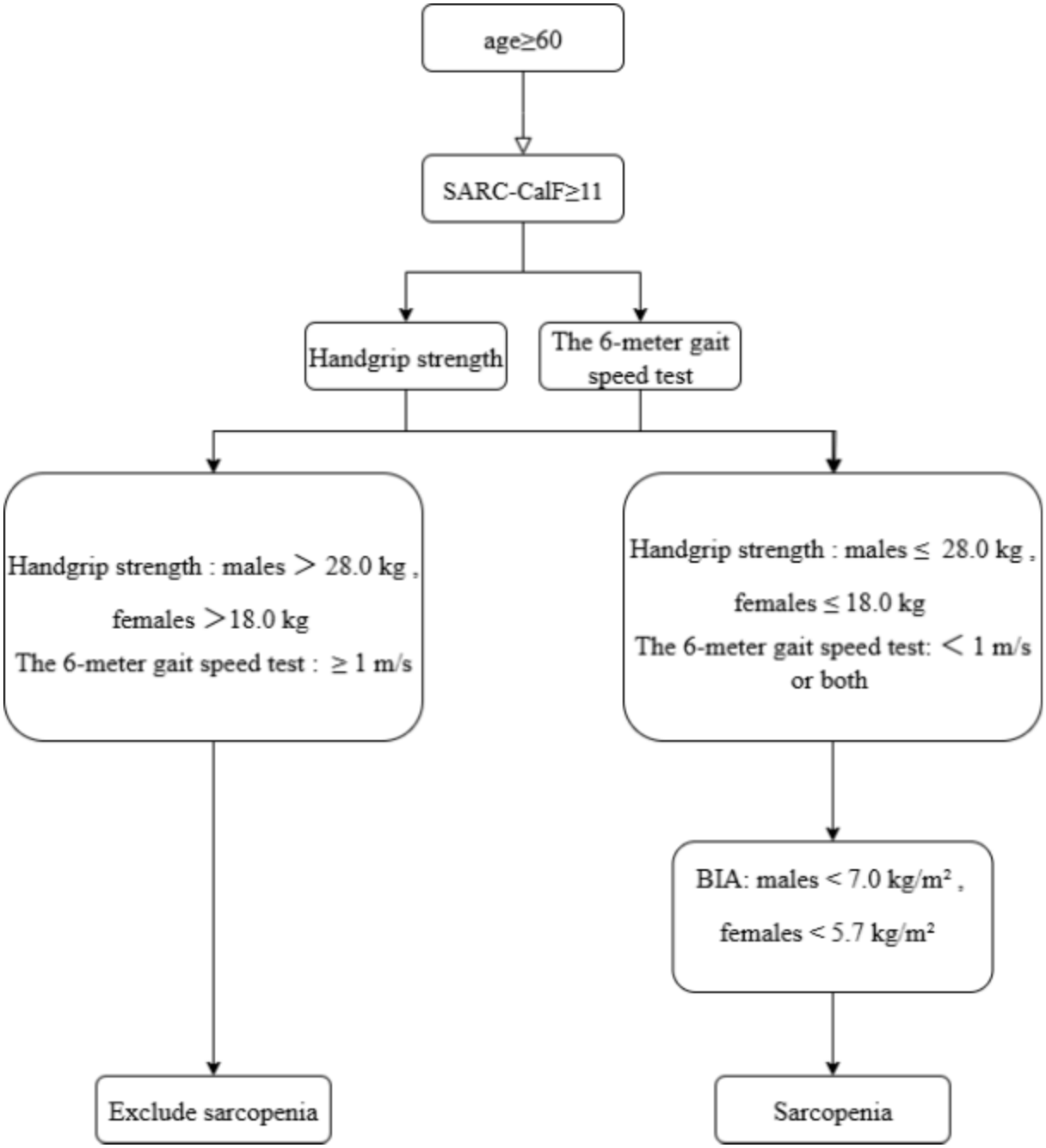


Figure 1

Sarcopenia Screening Flowchart . SARC-CalF: SARC-F combined with calf circumference; BIA: bioelectrical impedance analysis.

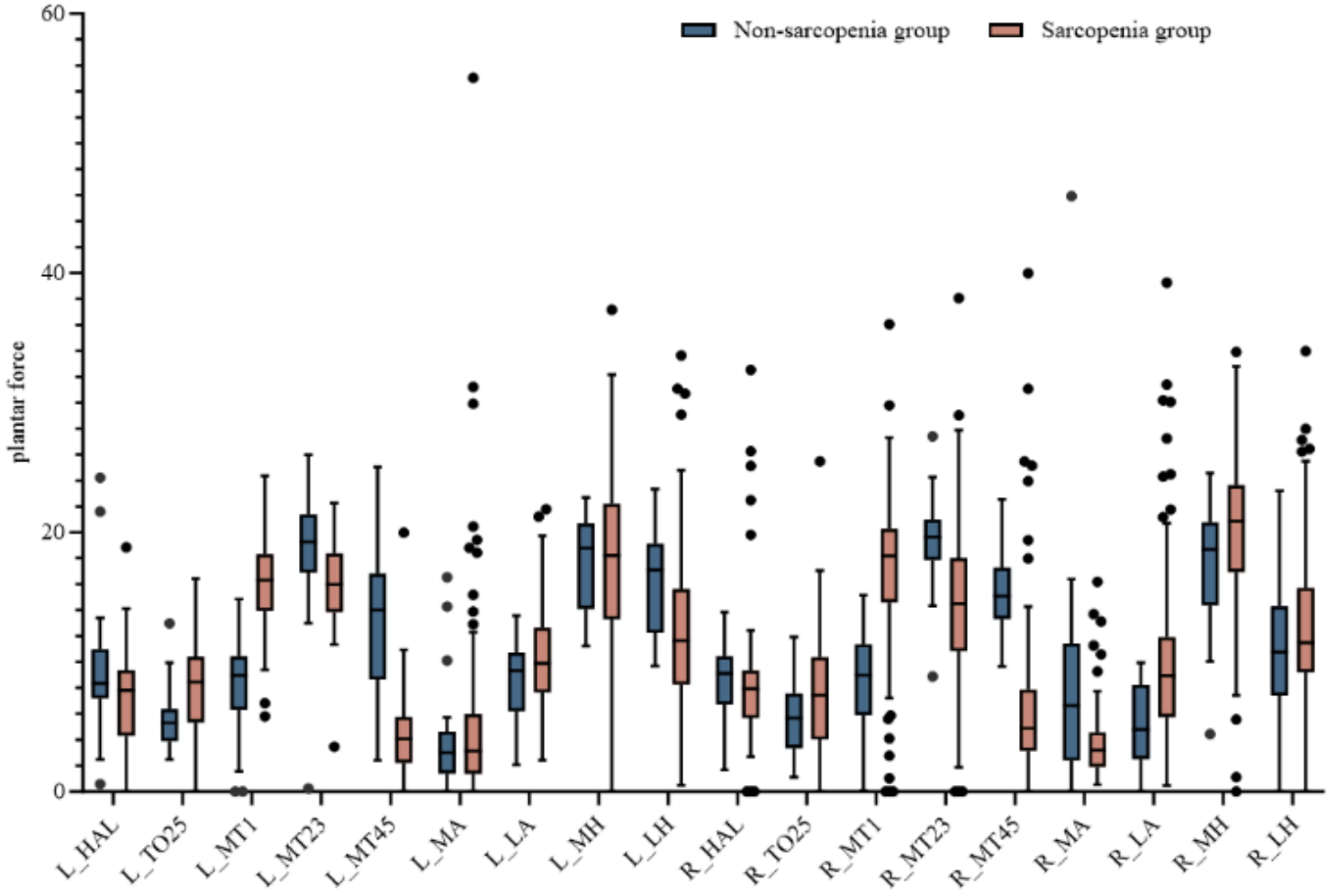


Figure 2

Distribution of plantar force (N) across left (L) and right (R) foot regions in the non-sarcopenia and sarcopenia groups.

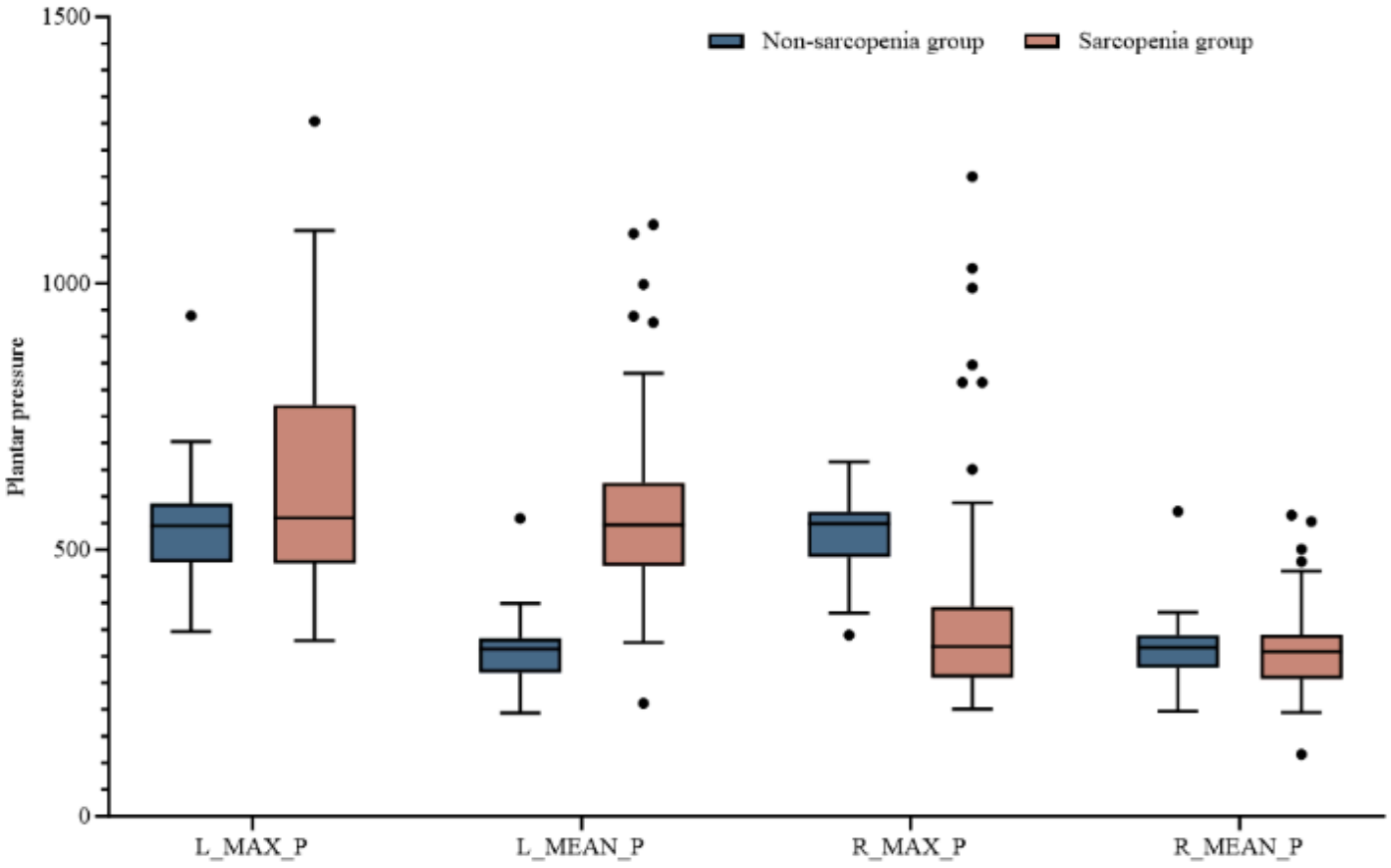


Figure 3

Distribution of maximum and mean plantar pressure (kPa) across left (L) and right (R) feet in the non-sarcopenia and sarcopenia groups.

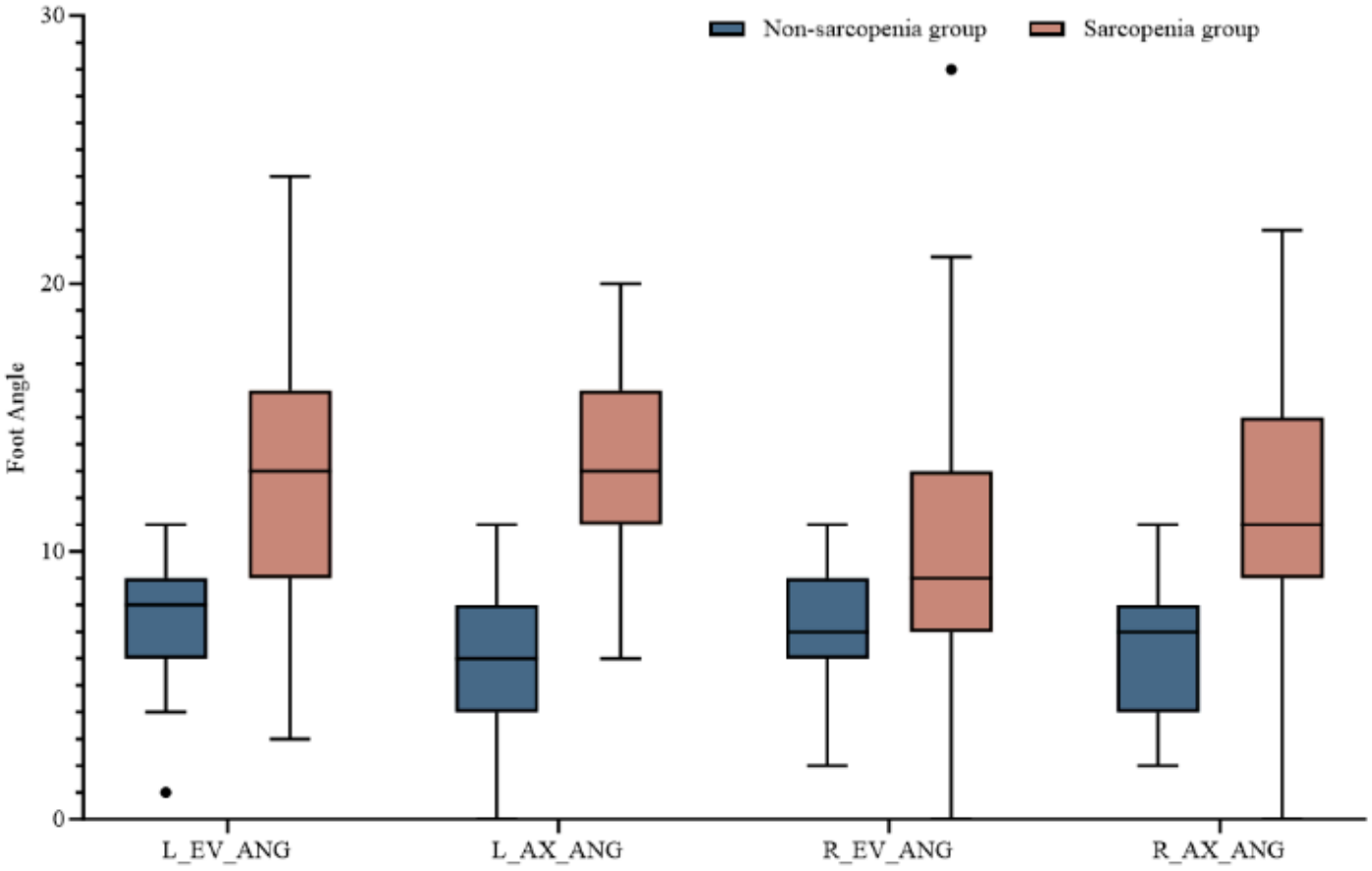


Figure 4

Distribution of foot eversion and axis angles (°) across left (L) and right (R) feet in the non-sarcopenia and sarcopenia groups.

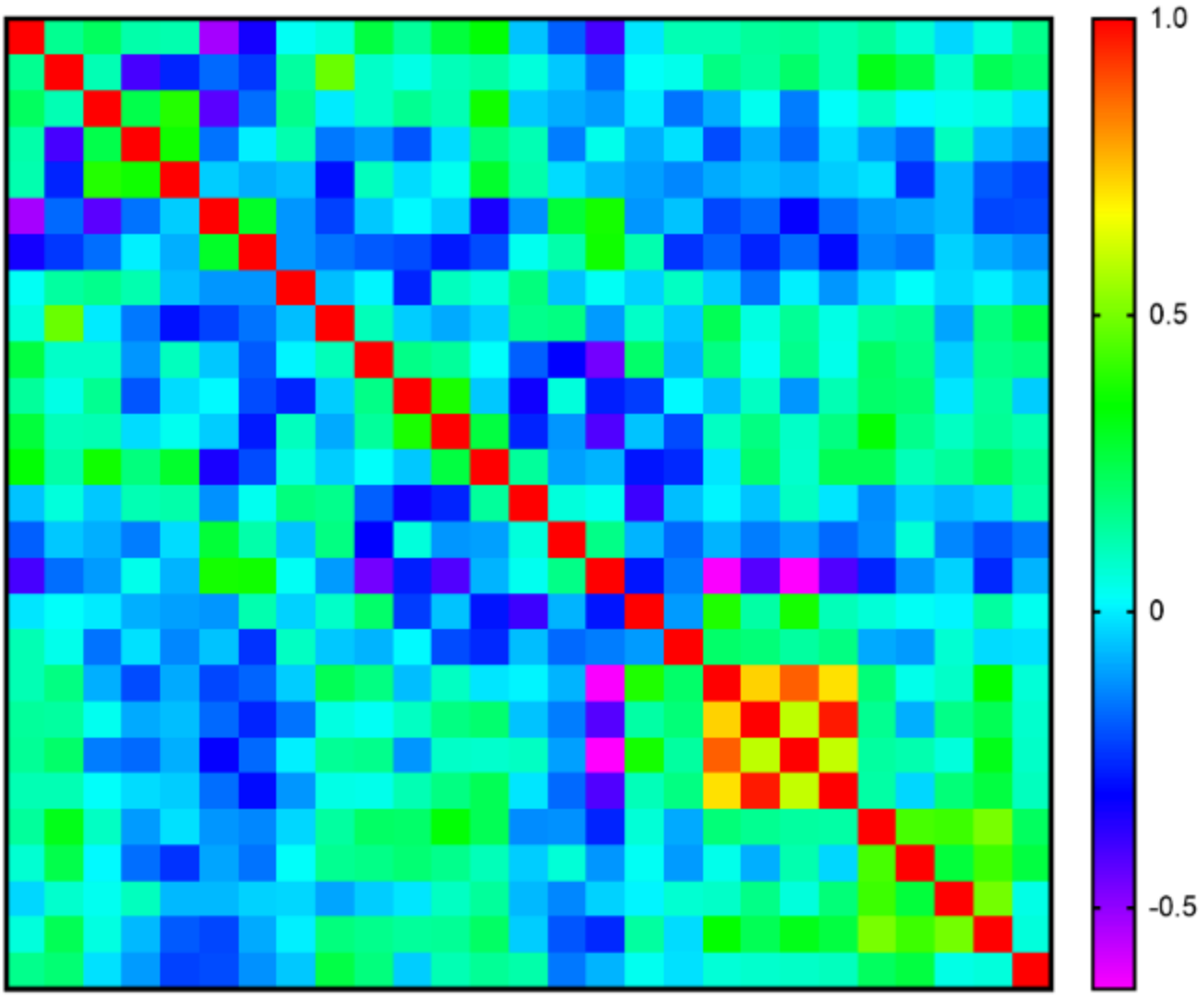


Figure 5

Heatmap of Spearman correlation coefficients (*r*) between plantar parameters and POMA scores in the sarcopenia group (n = 66).

Model/Variable	*B*	*p value*	95%CI
Model 1			
age	-0.278	<0.001	-0.382~-0.174
Model 2			
age	-0.267	<0.001	-0.369~-0.166
L_AX_ANG	0.227	0.036	0.015~0.439

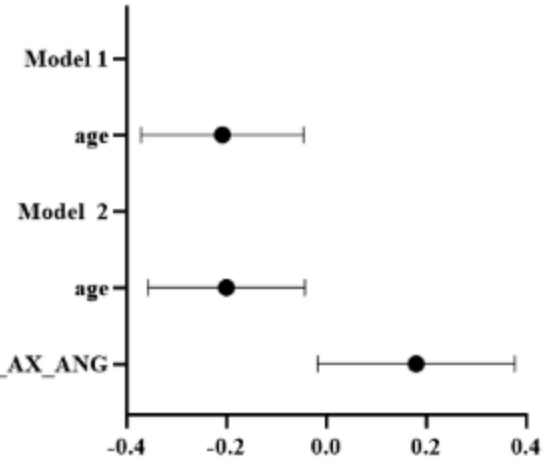


Figure 6

Forest plot of hierarchical regression analysis for factors associated with POMA scores in the sarcopenia group (n = 66).

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