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The relationship between clinical outcomes and gait biomechanics in individuals with plantar fasciitis

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ABSTRACT

Introduction: Plantar fasciitis (PF) is a common musculoskeletal disorder characterized by heel pain that disrupts gait and daily function. This study examined relationships between clinical outcomes and gait biomechanics, determined whether these relationships differ between recent- and chronic-onset cases, and identified key clinical predictors of gait speed.

Methods: A cross-sectional study was conducted with 42 individuals with PF. Clinical outcomes included worst pain, normalized gastrocnemius and soleus muscle length, normalized lower limb muscle strength, and normalized dynamic balance. Gait biomechanics during barefoot walking were captured using a motion analysis system and force plates, focusing on spatiotemporal parameters and ground reaction forces (GRFs). Correlation coefficients were used to assess relationships across the overall cohort, as well as in recent- and chronic-onset PF, while multiple linear regression identified clinical predictors of gait speed.

Results: Clinical outcomes related differently to sptiotemporal parameters and GRFs depending on symptom duration, with the recent-onset PF showing widespread correlations and chronic-onset PF showing more selective links with ankle strength and dynamic balance. Regression analysis identified gastrocnemius muscle length and anterior reach distance on the Y-Balance Test (YBT) as significant predictors of gait speed, explaining 28.0% of the variance ($p = 0.002$).

Conclusion: Symptom duration influences gait biomechanics in PF, with recent onset showing broad adaptations and chronic onset exhibiting more specific strength- and balance-related changes. Gastrocnemius muscle length and dynamic balance in the anterior direction were identified as significant contributors to gait performance. Targeting these factors, with consideration of symptom duration, may improve gait in individuals with PF.

Keywords: Association, Dynamic balance, Gait, Muscle strength, Muscle tightness, Plantar fasciitis

What is already known about this topic?

- *Clinical factors, including pain, muscle length, muscle strength, and balance, contribute to altered gait biomechanics in individuals with plantar fasciitis.*

What does the study add?

- *This study reveals that relationships between clinical outcomes and gait differ based on symptom duration. Gastrocnemius muscle length and anterior reach balance emerge as important predictors of gait speed and potential targets for rehabilitation.*

Introduction

Plantar fasciitis (PF) is a common musculoskeletal condition characterized by chronic heel pain that significantly interferes with daily activities, particularly those involving weight-bearing. It typically affects individuals between the ages of 40 and 60 years and accounts for approximately 15% of all foot-related injuries in the general population. PF occurs in both athletic and non-athletic individuals, with no notable gender difference in its prevalence (1,2). The cause of PF remains unclear, which may contribute to the limited success of treatment, as many individuals continue to experience symptoms even after receiving non-operative treatment (3). The persistence of symptoms of PF may be related to the chronic degenerative nature of the condition, involving repetitive overuse that leads to microtrauma and impaired biomechanics in the lower limbs (4).

Several clinical alterations are commonly observed in individuals with PF, including pain, muscle weakness, and reduced muscle flexibility, which significantly affect foot function and gait mechanics (5-7). Weakness in key foot muscles, including the ankle dorsiflexors, evertors, toe flexors, and intrinsic foot muscles, is correlated with impaired propulsion and foot control during walking, while reduced muscle length of the ankle plantarflexors leads to limited dorsiflexion, altered stance mechanics, and increased tensile

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stress on the plantar fascia (6-8). These clinical impairments result in reduced arch stability and compromised shock absorption, further exacerbating mechanical stress on the plantar fascia (9). Additionally, pain severity and discomfort influence weight-bearing strategies and compensatory gait patterns, and deficits in balance compromise postural control and balance (10). Collectively, assessments of pain, muscle strength, muscle length, and balance provide relevant, quantifiable information on lower-limb function and are expected to be correlated with spatiotemporal and kinetic alterations observed in PF gait.

Gait biomechanics in individuals with PF often show notable alterations, particularly in spatiotemporal variables and ground reaction forces (GRFs) during the stance phase. Several studies have reported reduced gait speed, cadence, and step length, alongside prolonged step time and stance duration in individuals with PF compared to healthy controls (10,11). These changes are thought to result from compensatory strategies adopted to minimize heel pain during walking. Regarding kinetic alterations, findings on GRFs in individuals with chronic PF have been inconsistent. A previous study demonstrated a reduction in the 2nd peak of vertical GRF (V-GRF), occurring during the push-off phase, suggesting impaired propulsion (12). In contrast, another study found no significant differences in V-GRF or loading rates between the symptomatic and contralateral asymptomatic feet (13). Furthermore, altered loading patterns have been observed, with reduced force under the rearfoot and forefoot and a compensatory increase in loading beneath the toes on the symptomatic side (14).

Although previous studies have reported alterations in clinical impairments and gait biomechanics among individuals with PF, most have focused on isolated gait parameters and their correlations with selected clinical outcomes. This limited scope limits a comprehensive understanding of the underlying pathophysiology of PF. A deeper investigation into how clinical impairments, such as pain, muscle strength, muscle length, and balance, interact with gait biomechanics, including spatiotemporal parameters and GRFs, may help elucidate mechanisms contributing to PF and inform more targeted treatment strategies. Moreover, variability in gait biomechanics may reflect distinct clinical mechanisms related to symptom duration. Prior research has shown that individuals with chronic PF exhibit reduced dorsiflexor and toe flexor strength compared to those with recent-onset symptoms, yet report better self-perceived foot function, suggesting adaptive strategies to manage symptoms. These findings highlight the importance of considering symptom duration, as it may influence both clinical presentation and gait behavior (15). However, no previous studies have explicitly examined the relationship between clinical outcomes and gait biomechanics while accounting for the onset of PF. Addressing this gap is essential to identifying subgroup-specific adaptations and optimizing clinical management.

Therefore, this study aimed to investigate the relationships between clinical outcomes and gait biomechanics in individuals with PF. Specifically, we examined whether these relationships differ between individuals with recent- and chronic-onset PF and identified which clinical variables predict gait speed, a global variable commonly used to assess gait performance (16). We hypothesized that clinical impairments would be significantly correlated with gait biomechanics and that these correlations, including predictors of gait speed, would differ based on symptom duration.

Methods

Study design, setting, and recruitment

A cross-sectional design was used in this study to investigate the relationship between clinical outcomes and gait biomechanics in individuals with PF. Data collection was conducted at the motion analysis laboratory, Faculty of Physical Therapy, Mahidol University. Participants were recruited via social media and informational posters displayed at the center.

Ethical statement

The study was conducted in accordance with the Declaration of Helsinki and complied with all relevant regulations and institutional policies. Ethical approval was granted by the Mahidol University Central Institutional Review Board (COA No. MU-CIRB 2023/033.1603. All participants were fully informed about the study and provided written informed consent prior to participation.

Participants

Individuals aged 18-65 years were recruited using a convenience sampling method. Screening was conducted by a licensed physical therapist using detailed history-taking and physical examination. Diagnostic criteria for PF included tenderness at the proximal insertion of the plantar fascia and plantar medial heel pain, particularly noticeable during the first steps after a period of rest or non-weight-bearing.

Participants were eligible if they (1) experienced medial heel pain for at least one month, (2) reported a worst pain score between 3 and 7 on the Visual Analog Scale (VAS), indicating mild to moderate pain, and (3) had a negative tarsal tunnel test. Participants were excluded if they had (1) a history of systemic diseases such as rheumatoid arthritis, ankylosing spondylitis, or Reiter's syndrome; (2) symptoms of paresthesia, tingling, or numbness in the foot; (3) clinical signs of ankle inflammation; or (4) a leg length discrepancy of 1 cm or more.

Demographic and clinical information were collected from eligible participants, including age, weight, height, body mass index, gender, dominant side (determined by asking participants to simulate kicking a ball and drawing a figure-eight), symptomatic side, symptom onset, and type of PF (unilateral or bilateral). Physical activity and psychological status were assessed using the Thai version of the Global Physical Activity Questionnaire (GPAQ-TH) (17) and the Thai version of the Pain Catastrophizing Scale (PCS) (18). Additionally, foot arch type was assessed using the Foot Posture Index (19). In addition, participants were categorized based on symptom duration into two onset groups: recent onset (1-6 months) and chronic onset (≥6 months) (20). The relationships between clinical outcomes and gait biomechanics were first examined in the overall sample and then analyzed separately by onset group to explore potential differences correlated with symptom duration.

Data collection protocol

Clinical outcomes

The clinical outcomes assessed in this study included pain severity, muscle length, muscle strength, and balance performance. Pain severity (the worst pain) was assessed using the VAS, a 10-centimeter horizontal line representing a continuum from 0 cm (no pain) to 10 cm (worst imaginable pain). Participants were instructed to mark the point that best represented the intensity of their worst pain, with higher scores indicating greater pain severity.

Muscle length of the gastrocnemius and soleus was indirectly assessed using a digital inclinometer during the weight-bearing lunge test, following a previous protocol (21). Participants were instructed to position themselves in a forward lunge position facing a wall. The great toe and midline of the heel of both feet were aligned parallel to a floor-marked tape and positioned perpendicular to the wall. With their hands placed against the wall for support, participants positioned the test leg behind the non-test leg. They were then asked to lean forward as far as possible until reaching the end range of motion (ROM), defined as the point of maximal ankle dorsiflexion in the test leg. During the test, a digital inclinometer was placed over the tibial tuberosity on the symptomatic side. The ankle dorsiflexion angle was measured as the absolute angle between the tibial line and a horizontal reference line in degrees.

Ankle dorsiflexion ROM was measured under two conditions: with the knee fully extended to assess gastrocnemius muscle length, and with approximately 30 degrees of knee flexion to assess soleus muscle length. Greater inclinometer values indicated reduced dorsiflexion ROM, reflecting reduced muscle length of the respective muscles. These values were then normalized to leg length in cm. Excellent intra- and inter-rater reliability has been reported for this method in a previous study (ICC: 0.97-0.98) (21).

Muscle strength was assessed using a handheld dynamometer for six muscle groups of the lower limb: ankle plantarflexors, ankle dorsiflexors, ankle invertors, ankle evertors, great toe flexors, and lesser toe flexors. For the assessment of ankle plantarflexors, ankle dorsiflexors, ankle invertors, and ankle evertors, participants were positioned in a supine lying position with the ankle in a neutral position and the hips and knees fully extended. The dynamometer was placed over the symptomatic side at standardized locations: the plantar surface over the metatarsal heads for ankle plantarflexors, the dorsum of the foot for ankle dorsiflexors, the 1st metatarsal head for invertors, and the fifth metatarsal head for evertors. For the great toe and lesser toe flexors, participants were seated with hips and knees flexed to 90 degrees and the heels resting on a flat box surface. The dynamometer was placed over the plantar surface of the symptomatic hallux and the interphalangeal joints of the lesser toes, respectively. Muscle strength was assessed using an isometric test in kg, in which participants were instructed to exert maximal force against a dynamometer without producing joint movement. Higher dynamometer readings indicated greater muscle strength. Each muscle group was tested three times, and the mean of the two highest values was used for analysis. The muscle strength values were normalized by the participant's body weight in kg. To ensure testing accuracy and consistency, the investigator underwent specific training in the standardized use of the handheld dynamometer. Good to excellent intra- and inter-rater reliability has been reported for this method in a previous study (ICC: 0.78-0.94) (22).

Dynamic balance performance was assessed using the Y-Balance Test (YBT). Prior to testing, the investigator demonstrated the procedure to ensure participants fully understood the task. Participants were instructed to perform a single-leg stance in the center of a Y-shaped layout with the symptomatic or more painful leg while using the contralateral (asymptomatic or less painful) leg to reach in three directions: anterior (ANT), posteromedial (PM), and posterolateral (PL). Three trials were conducted for each direction, and the maximum reach distance was recorded (23). These values were then normalized to leg length. The composite score was calculated by summing the three reach distances in all three directions, dividing by three times the limb length, and multiplying by 100, following the formula: [(ANT + PM + PL)/(3 × limb length)] × 100 (24).

Gait biomechanics

Gait biomechanics were assessed using a three-dimensional motion analysis system (Vicon™ Oxford, UK) comprising 10 high-speed cameras (Vantage series) and two force plates, dimensions 464 × 508 × 83 mm (AMTI-OR67, Advanced Mechanical Technologies Inc., USA), embedded in the middle of an 8-meter walkway. Participants walked barefoot along the walkway at their self-selected, natural speed for five consecutive trials. To promote consistency and reduce the potential for discomfort or injury, 2-3 familiarization trials were conducted before formal data collection began. Kinematic data were collected at 100 Hz, and kinetic data at 1,000 Hz. The lower-limb Plug-in-Gait with Oxford Foot Model using 42 spherical reflective markers was applied, and foot marker trajectories were used to identify gait events and extracted for the spatiotemporal gait parameters in the Nexus software (version 2.16).

For participants with bilateral PF, the more symptomatic limb was selected for data analysis. Data were filtered using the fourth-order Butterworth low-pass method with cut-off frequencies of 6 Hz for kinematic data and 15 Hz for kinetic data. To account for the influence of gait speed on kinetic variables, the three trials with the most comparable self-selected walking speeds out of five testing trials were selected, and the average values from these trials were used to reduce speed-related variability.

Gait biomechanical outcomes included spatiotemporal variables comprising cadence (steps/min), gait speed (m/s), step length (m), step time (s), step width (m), single support time (SST) (s), and double support time (DST) (s). The normalized GRFs were analyzed during the stance phase of gait across three axes: vertical (V-GRF), anterior-posterior (AP-GRF), and medial-lateral (ML-GRF), following a previously established methodology (25) and as illustrated in Figure 1. The V-GRF included three key points: F1 (1st peak during early stance), F2 (midstance valley), and F3 (2nd peak during propulsion). The AP-GRF comprised F4 (braking peak) and F5 (propulsive peak), while the ML-GRF included F6 (1st medial peak) and F7 (2nd medial peak).

Statistical analysis

All statistical analyses were performed using the IBM SPSS Statistics (version 26.0, IBM Corp., Chicago, IL, USA), with the level of statistical significance set at $p < 0.05$. Descriptive statistics were used to summarize participant demographic characteristics. Normality assumptions were assessed using the Shapiro–Wilk test in combination with visual inspection of Q–Q plots. Most variables were normally distributed with no substantial deviations observed; however, visual inspection of the Q-Q plots showed clear deviations from normality for variables F1-F5 (Supplementary Material 1). Accordingly, parametric or non-parametric analyses were applied as appropriate.

Pearson's or Spearman's correlation coefficient (r) was used to examine the linear relationships between clinical outcomes and gait biomechanics. The strength and direction of the correlation were interpreted based on Cohen's guideline (26), where r values of 0.10-0.29 indicate a small (weak) correlation, 0.30-0.49 represent a moderate correlation, and values equal to or greater than 0.50 reflect a strong (large) correlation. Positive r values indicate that both variables increase together, whereas negative r values indicate an inverse relationship. Multiple linear regression was used to identify clinical predictors of gait speed. Predictor variables were selected based on theoretical relevance and the results of bivariate correlations. Multicollinearity was assessed using the variance inflation factor (VIF) values to ensure the robustness of the regression model.

Sample size calculation

The sample size for this study was determined using evidence from two previous studies that investigated the correlation between gait parameters and pain. One study reported a significant positive correlation between gait speed and pain (r = 0.57) (10), while another found a significant relationship between midfoot force, which is defined as the magnitude of force acting on the midfoot during the stance phase of gait and pain (r = 0.76) (27). These values were used as the effect size inputs for sample size estimation. The calculations were performed using G*Power software (version 3.1.9.6), employing Correlation: Bivariate normal model. An alpha level of 0.05 and statistical power of 0.80 were applied. Based on the reported effect sizes, the required minimum sample sizes were 22 participants for detecting the gait speed and pain relationship and 11 participants for the midfoot force and pain relationship.

Given that the present study examined these relationships both across the overall cohort and within subgroups (recent-onset and chronic PF), ensuring sample adequacy was essential. The final sample comprised 42 participants (19 recent-onset, 23 chronic), exceeding the minimum sample size suggested by prior studies and deemed sufficient to detect the anticipated correlations at both cohort and subgroup levels.

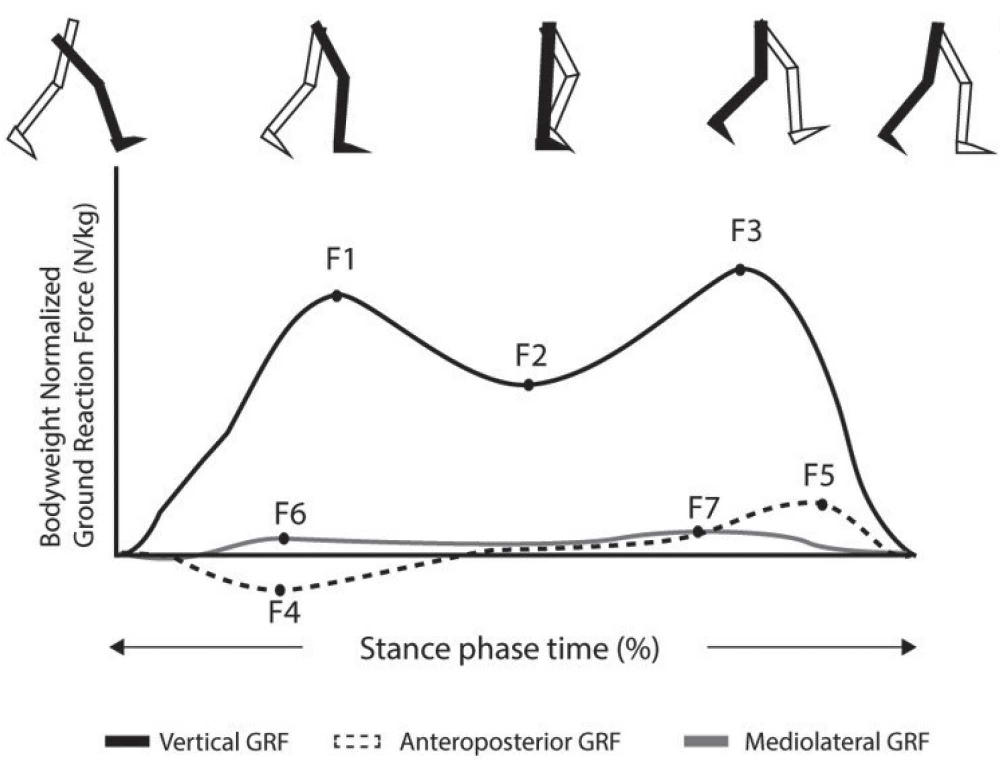

FIGURE 1 - Ground reaction force (GRF)-time variables during gait.

Results

Demographic data

Table 1 presents demographic characteristics of 42 participants with PF, including 19 with recent-onset and 23 with chronic-onset symptoms. The overall mean age was 48.26 ± 11.46 years. Participants had a mean body weight of 62.32 ± 10.16 kg, a mean height of 158.69 ± 5.37 cm, and a mean body mass index (BMI) of 24.75 ± 3.92 kg/m². Most participants were female (95.24%) and right-leg dominant (93.33%). The majority had bilateral PF, with greater involvement of the dominant side (42.86%), followed by greater involvement of the non-dominant side (19.05%), and isolated dominant or non-dominant side symptoms (each 19.05%). Regarding symptom duration, the majority reported symptoms persisting for over 12 months (47.62%), followed by 1-3 months (30.95%), 3-6 months (14.29%), and 6-9 months (7.14%). Physical activity levels were predominantly low (50%), followed by moderate (42.86%) and high (7.14%). The mean PCS score was 14.21 ± 11.73, indicating a low to moderate level of catastrophizing. Foot arch types were predominantly normal (52.38%), followed by low arches (42.86%) and high arches (4.76%). Between-group comparisons showed no significant differences in most demographic variables between the recent- and chronic-onset PF groups ($p > 0.05$). Age was the only variable that differed significantly between groups ($p = 0.047$), with a lower mean age observed in the chronic-onset group.

Clinical and gait biomechanics outcomes between recent- and chronic-onset subgroups

Table 2 presents comparisons of clinical and gait biomechanical outcomes between individuals with recent- and chronic-onset PF. There were no significant differences across most clinical outcomes: muscle length, muscle strength, dynamic balance, and gait biomechanics ($p > 0.05$). The only significant between-group difference was observed in normalized gastrocnemius muscle length, which was lower in the chronic PF group ($p = 0.041$).

Relationships between clinical outcomes and gait biomechanics in individuals with PF

Table 3 summarizes the ranges of correlation coefficients between clinical and gait biomechanic outcomes for the whole PF group and for the recent- and chronic-onset subgroups. The complete correlation matrices for each variable pair within the overall sample and each subgroup are presented separately in Supplementary Material 2.

In the whole group, the strongest and most consistent relationships were observed for gastro-soleus muscle length, ankle-foot muscle strength, and dynamic balance measures with gait biomechanics rather than pain. Gastrocnemius muscle length demonstrated significant correlations with several spatiotemporal parameters, including cadence ($r = -0.402$), walking speed ($r = -0.447$), and DST ($r = 0.497$), as well as with V- and ML-GRFs (F3: $r = -0.321$, F4: $r = 0.326$, and F5: $r = -0.336$). Soleus muscle length demonstrated significant but weaker correlations with walking speed ($r = -0.360$) and step length ($r = -0.339$). Several muscle strengths, especially ankle invertors, evertors, dorsiflexors, plantarflexors, and lesser toe flexor, were significantly correlated with SST and different GRF variables. The YBT, particularly anterior and posterolateral reach and the composite score, showed significant correlations with walking speed, step time, and AP- and ML-GRFs. In contrast, pain exhibited limited correlations with gait biomechanics, with a significant correlation observed only with the 2nd peak V-GRF (F3).

In the recent-onset PF subgroup, significant relationships were mainly observed between muscle-related variables and gait biomechanics. Gastrocnemius muscle length was correlated with walking speed ($r = -0.515$), DST ($r = 0.550$), and V-GRFs ($r = -0.607$ for F1 and $r = -0.480$ for F3), while soleus muscle length was correlated with step length ($r = -0.626$). Ankle muscle strength, particularly of the invertors, evertors, and dorsiflexors, showed significant correlations with SST ($r = 0.486$, $r = 0.469$, and $r = 0.481$, respectively). Great toe flexor strength was correlated with step time ($r = -0.480$). Anterior reach performance on the YBT was correlated with the 1st peak ML-GRF (F6) ($r = 0.474$).

In the chronic-onset PF subgroup, gait biomechanics were broadly correlated with ankle muscle strength and dynamic balance. Ankle muscle strength, including the invertors, evertors, dorsiflexors, and plantarflexors, showed moderate correlations with gait biomechanics. Specifically, invertor strength was related to V- and ML-GRFs (F3−5), evertor strength correlated with SST ($r = 0.512$) and F5 ($r = 0.428$), dorsiflexor strength correlated with step time ($r = -0.472$), DST ($r = -0.466$), and F3 ($r = 0.512$), while plantarflexor strength correlated with walking speed ($r = 0.453$) and GRFs (F3, F5, and F6). The YBT was moderately correlated with various gait biomechanics. It was found that anterior reach correlated with walking speed ($r = 0.449$) and F6 ($r = 0.504$), posteromedial reach correlated with SST ($r = -0.468$), posterolateral reach correlated with F6 ($r = 0.760$), and composite score correlated with F6 ($r = 0.636$).

Potential predictive factors between clinical outcomes and gait speed in individuals with PF

Gait speed, a key indicator of walking ability and overall functional status, was identified as the clinical outcome most strongly correlated with various clinical measures (see Table 2). Consequently, gait speed was selected as the dependent variable for predictive modeling against selected clinical outcomes.

Table 4 presents the results of a multiple linear regression analysis exploring potential predictors of gait speed in individuals with PF. Five independent variables included normalized gastrocnemius and soleus muscle lengths, the anterior and posterolateral directions of the YBT, and the composite YBT were initially included based on significant preliminary correlations.

A stepwise multiple regression was performed to determine which variables best predicted gait speed. The final model identified two significant predictors of gait speed: normalized gastrocnemius muscle length ($\beta = -0.422$, $p = 0.004$) and the normalized anterior reach direction of the YBT ($\beta = 0.274$, $p = 0.044$). The regression model was statistically significant, $F(2, 39) = 7.601$, $p = 0.002$, accounting for 28.0% of the variance in gait speed ($R^2 = 0.280$, Adjusted $R^2 = 0.244$).

TABLE 1 - Demographic characteristics of the participants

Variables	Total (n = 42) Mean ± SD or n, %	Recent (n = 19) Mean ± SD or n, %	Chronic (n = 23) Mean ± SD or n, %	*p*-value
Age[a] (years)	48.26 ± 11.46	52.11 ± 10.23	45.09 ± 11.66	**0.047**
Weight[a] (kg)	62.32 ± 10.16	60.08 ± 9.07	64.17 ± 10.83	0.198
Height[a] (cm)	158.69 ± 5.37	157.74 ± 5.56	159.48 ± 5.20	0.302
Body mass index[a] (kg/m^2)	24.75 ± 3.92	24.14 ± 3.36	25.26 ± 4.34	0.364
Gender[b]				
Male	2, 4.76	0, 0	2, 8.70	0.188
Female	40, 95.24	19, 100.00	21, 91.30	
Dominant side[b]				
Right	42, 93.33	18, 94.74	21, 91.30	0.667
Left	3, 6.67	1, 5.26	2, 8.70	
Symptomatic side[b]				
Dominant	8, 19.05	6, 31.58	2, 8.70	0.083
Non-dominant	8, 19.05	3, 15.79	5, 21.74	
Dominant > Non-dominant	18, 42.86	9, 47.37	9, 39.13	
Non-dominant > Dominant	8, 19.05	1, 5.26	7, 30.43	
Onset of the last recent PF[b]				
1-3 months	13, 30.95	13, 68.42	0, 0	**<0.001**
3-6 months	6, 14.29	6, 31.58	0, 0	
6-9 months	3, 7.14	0, 0	3, 13.04	
9-12 months	0, 0	0, 0	0, 0	
>12 months	20, 47.62	0, 0	20, 86.96	
Type of PF[b]				
Unilateral	16, 38.10	9, 47.37	7, 30.43	0.261
Bilateral	29, 61.90	10, 52.63	16, 69.57	
Physical activity level[b]				
High	3, 7.14	1, 5.26	2, 8.70	0.894
Moderate	18, 42.86	8, 42.11	10, 43.48	
Low	21, 50.00	10, 52.63	11, 47.83	
Pain catastrophizing scale[a] (scores)	14.21 ± 11.73	12.32 ± 10.97	15.78 ± 12.34	0.347
Arch of foot type[b]				
Normal	22, 52.38	8, 42.11	14, 60.87	0.474
Low	18, 42.86	10, 52.63	8, 34.78	
High	2, 4.76	1, 5.26	1, 4.35	

PF: Plantar Fasciitis; [a]Indicate tested by independent T-test; [b]Indicate tested by Chi-square test; Significant difference at $p < 0.05$; Bold represents significant difference between recent and chronic group.
Percentage (%) values represent the proportion of participants within each group of analysis [overall (n = 42), recent-onset (n = 19), and chronic-onset (n = 23)].

Discussion

The objective of the study was to explore the correlation between clinical outcomes and gait biomechanics, determine whether these relationships differ between recent- and chronic-onset cases, and identify key clinical predictors of gait speed.

Baseline demographic and clinical characteristics were largely comparable between the recent- and chronic-onset

TABLE 2 - Comparison of the clinical and gait biomechanic outcomes between recent- and chronic-onset of PF subgroups

Variables	Recent-onset PF (Mean ± SD)	Chronic PF (Mean ± SD)	*p*-value*
Clinical outcomes			
Worst pain (scores)	5.57 ± 1.91	5.67 ± 2.16	0.869
Normalized muscle length (degrees/cm)			
Gastrocnemius	0.72 ± 0.11	0.65 ± 0.11	**0.041**
Soleus	0.52 ± 0.07	0.51 ± 0.10	0.770
Normalized muscle strength			
Ankle invertors	0.12 ± 0.03	0.13 ± 0.04	0.518
Ankle evertors	0.13 ± 0.03	0.12 ± 0.04	0.375
Ankle dorsiflexors	0.15 ± 0.04	0.15 ± 0.06	0.989
Ankle plantarflexors	0.28 ± 0.06	0.28 ± 0.07	0.816
Great toe flexors	0.09 ± 0.03	0.09 ± 0.04	0.585
Lesser toe flexors	0.08 ± 0.02	0.08 ± 0.03	0.802
Normalized Y-Balance Test			
Anterior	0.84 ± 0.13	0.82 ± 0.13	0.568
Posteromedial	0.88 ± 0.25	0.85 ± 0.22	0.640
Posterolateral	0.79 ± 0.21	0.84 ± 0.24	0.549
Composite	83.85 ± 17.15	83.45 ± 16.82	0.940
Gait biomechanics			
Cadence (step/min)	103.36 ± 8.96	107.10 ± 7.03	0.137
Speed (m/s)	0.99 ± 0.14	1.01 ± 0.11	0.670
Step length (m)	0.57 ± 0.05	0.56 ± 0.04	0.446
Step time (s)	0.59 ± 0.08	0.56 ± 0.04	0.140
Step width (m.)	0.17 ± 0.03	0.15 ± 0.03	0.108
Single support time (s)	0.41 ± 0.03	0.41 ± 0.02	0.844
Double support time (s)	0.31 ± 0.09	0.28 ± 0.04	0.171
F1 (N/kg)	104.64 ± 4.72	99.74 ± 22.43	0.357
F2 (N/kg)	85.15 ± 4.66	79.82 ± 17.92	0.215
F3 (N/kg)	108.66 ± 6.35	105.28 ± 23.55	0.548
F4 (N/kg)	-14.33 ± 3.17	-13.22 ± 5.28	0.427
F5 (N/kg)	18.50 ± 3.47	18.07 ± 5.14	0.762
F6 (N/kg)	6.06 ± 1.74	6.09 ± 1.93	0.948
F7 (N/kg)	5.52 ± 1.62	5.59 ± 1.87	0.900

Note: Data expressed as mean ± standard deviation. F1: 1st peak V-GRF; F2: midstance valley V-GRF; F3: 2nd peak V-GRF; F4: braking force; F5: propulsive force; F6: 1st peak ML-GRF; F7: 2nd peak ML-GRF. *Indicates significant difference at $p<0.05$, tested by the independent sample t-test; Bold represents significant difference

PF groups, except for age and gastrocnemius muscle length, reducing the likelihood of substantial confounding effects. This supports the interpretation that differences in correlation patterns were more closely related to symptom duration and natural adaptive mechanisms. As most participants had bilateral PF, only the more symptomatic limb was analyzed to enhance clinical relevance and reduce within-subject variability (7,12,28). Nevertheless, unilateral and bilateral PF may influence gait strategies differently, with bilateral PF associated with greater impairments in balance, muscle strength, and gait symmetry (29), potentially leading to more pronounced gait adaptations that should be considered when interpreting the results.

TABLE 3 - Summary of correlation coefficients (*r*) between clinical outcomes and gait biomechanics in PF (whole group, recent-onset, and chronic-onset subgroups)

Clinical outcomes		Gait Biomechanics					
		Whole group (n = 42)		Recent onset (n = 19)		Chronic onset (n = 23)	
		Spatiotemporal	Force	Spatiotemporal	Force	Spatiotemporal	Force
Pain	Worst	−0.263-0.210	**−0.254-0.384**	−0.332-0.265	−0.293-0.264	−0.361-0.395	**−0.340-0.522**
Normalized muscle length	Gastroc	**−0.447-0.497**	**−0.336-0.326**	**−0.515-0.550**	**−0.607-0.274**	−0.387-0.387	−0.360-0.361
	Soleus	**−0.360-0.265**	**−0.280-0.329**	**−0.626-0.205**	−0.447-0.225	−0.352-0.351	**−0.354-0.525**
Normalized muscle strength	Invertors	**−0.530-0.410**	**−0.295-0.356**	**−0.185-0.486**	−0.187-0.237	−0.335-0.371	**−0.525-0.548**
	Evertors	**−0.190-0.459**	−0.269-0.304	**−0.349-0.469**	−0.168-0.243	**−0.269-0.512**	**−0.391-0.428**
	DF	**−0.287-0.324**	**−0.282-0.311**	**−0.218-0.481**	−0.231-0.249	**−0.472-0.349**	**−0.372-0.512**
	PF	−0.279-0.270	**−0.304-0.382**	−0.200-0.284	−0.285-0.211	**−0.391-0.453**	**−0.360-0.593**
	GTF	**−0.309-0.147**	−0.174-0.244	**−0.480-0.303**	−0.106-0.177	−0.141-0.116	−0.239-0.341
	LTF	**−0.251-0.342**	**−0.259-0.313**	−0.376-0.401	−0.183-0.212	−0.190-0.328	−0.321-0.385
Normalized YBT	ANT	**−0.339-0.322**	**−0.249-0.487**	**−0.409-0.230**	**−0.240-0.474**	−0.361-0.449	**−0.299-0.504**
	PM	−0.157-0.201	−0.282-0.273	−0.204-0.340	−0.398-0.223	**−0.468-0.208**	−0.214-0.322
	PL	**−0.227-0.342**	**−0.343-0.531**	−0.352-0.340	−0.430-0.257	**−0.407-0.351**	**−0.297-0.760**
	Composite	**−0.202-0.332**	**−0.338-0.492**	−0.215-0.371	−0.367-0.304	**−0.372-0.362**	**−0.266-0.636**

Range shows minimum–maximum correlation coefficients (*r*) across gait biomechanics [spatiotemporal (cadence, speed, step length, step time, step width, single support time, and double support time) and ground reaction forces (F1-F7)]. Bold values indicate that at least one pair of variables shows a statistically significant correlation. Correlation tests were performed using the Pearson or Spearman coefficients at $p<0.05$; Gastroc: gastrocnemius; DF: dorsiflexor; PF: plantarflexor; GTF: great toe flexor; LTF: lesser toe flexor; YBT: Y-Balance Test; ANT: anterior reach; PM: posteromedial reach; PL: posterolateral reach; Composite: composite score.

TABLE 4 - Multiple regression analysis to predict gait speed in individuals with PF (n = 42)

Predictors	B	SE	Beta (ß)	t	p-value
Constant[a]	1.070	0.152	–	7.024	< 0.001*
Normalized gastroc muscle length	−0.436	0.141	−0.422	−3.097	0.004*
Normalized anterior direction of the YBT	0.274	0.132	0.285	2.086	0.044*

*Significance level at $p < 0.05$; B: unstandardized coefficient; SE: standard error; ß: standardized coefficient; gastroc: gastrocnemius, YBT: Y-Balance Test; [a] = R^2 of the regression model (0.280).

Relationships between clinical outcomes and gait biomechanics

Whole group of PF

Overall, gait biomechanics in individuals with PF appear to be more strongly influenced by different neuromusculoskeletal impairments than by pain severity alone. Reduced gastro-soleus muscle length likely limits ankle dorsiflexion during stance, constraining forward progression and delaying the transition to propulsion (30). This gastro-soleus restriction likely contributes to altered spatiotemporal variables, such as lower cadence, slower walking speed, and shorter step length, prolonged DST, and altered GRF patterns, reflecting a less efficient and cautious gait strategy (31). The correlations of ankle-foot muscle strength with SST highlight the importance of ankle control in maintaining stability during single-limb support. Adequate strength in these muscles may help regulate stance duration and load distribution in individuals with PF. Similarly, better dynamic balance, particularly in the posterolateral direction and as reflected by the composite score, was correlated with reduced braking force, increased propulsive force, and greater medial force, suggesting that balance capacity supports efficient gait control (32).

In contrast, pain severity demonstrated only modest and limited correlation with the midstance valley of vGRF (F2). Greater midfoot loading may occur as a strategy to avoid heel pain and disrupt the V-GRF profile (33). This finding was consistent with prior evidence showing weak correlations between pain severity and gait parameters in PF, suggesting that pain alone does not adequately explain gait biomechanical alterations (34). Collectively, these findings suggest that gastro-soleus flexibility, ankle-foot muscle strength, and dynamic balance should be considered key components when assessing and managing gait impairments in individuals with PF.

Recent-onset PF

In individuals with recent-onset PF, gait biomechanics appear to be strongly influenced by muscle-related impairments, particularly gastro-soleus muscle length. Reduced gastrocnemius muscle length was associated with slower walking speed and prolonged DST. This limits propulsive force generation during push-off and increases energy expenditure, which may contribute to a less efficient walking strategy (30,35). Similarly, reduced soleus muscle length was correlated with shorter step length, which may reflect a limited role of the muscle in controlling tibia movement and generating dorsiflexion during mid-stance (36). Reduced soleus muscle flexibility limits forward tibia movement and dorsiflexion, leading individuals to use shorter strides as a compensatory strategy to maintain stability, support forward movement, and minimize plantar stress. The strong correlations between gastrocnemius muscle length and V-GRFs (F1 and F3) indicate that reduced gastrocnemius muscle length correlated with reduced force generation during load acceptance and push-off phases. These biomechanical adaptations likely serve to enhance stability and mitigate plantar strain, highlighting the importance of gastrocnemius flexibility in proper force distribution during gait (25,31).

The observed correlations also suggest that ankle-foot muscle strength and dynamic balance contribute to temporal control and frontal-plane stability during gait in recent-onset PF. Ankle invertor, evertor, and dorsiflexor strength correlated with prolonged SST, reflecting a greater capacity to maintain stable single limb support and control foot position during stance. This finding highlights the role of ankle stabilizers in postural control and balance, consistent with previous studies demonstrating that stronger ankle muscles contribute to improved stability and reduced postural sway (37,38). Correlation between great toe flexor strength and step time further suggests that intrinsic and extrinsic toe flexors facilitate more efficient rollover and timely progression through stance, supporting forward propulsion even in the early onset of PF. In addition, the correlation between anterior reach performance on the YBT and ML-GRF indicates that dynamic balance capacity is linked to the ability to regulate frontal-plane forces during walking.

Chronic-onset PF

In the chronic-onset PF subgroup, gait biomechanics were more closely related to ankle muscle strength and dynamic balance than to pain severity or muscle length. Ankle muscle strength, particularly plantarflexor strength, demonstrated the most relevant correlations with gait biomechanics, including faster walking speed and increased different GRFs, notably the 2nd peak vGRF (F3) and propulsive force (F5), and the 1st peak ML-GRF (F6). These findings highlight the plantarflexor's role in push-off, forward progression, and force modulation, emphasizing that adequate plantarflexor strength is essential for efficient sagittal-plane gait. The observed relationships also suggest that evertor and dorsiflexor strength contribute primarily to the temporal regulation of gait. Ankle evertor strength was correlated with longer SST, suggesting that stronger evertors enhance mediolateral stability during single-leg stance and facilitate greater limb advancement of the contralateral side. Dorsiflexor strength was correlated with shorter step time and DST, highlighting its role in promoting timely foot lift-off and balance, contributing to a more efficient and stable gait.

The YBT was correlated with ML-GRF, particularly the posterolateral direction and composite score with the 1st peak ML-GRF (F6), suggesting that dynamic balance is closely linked to frontal-plane force control during walking. The correlation between the anterior direction of YBT and walking speed further indicates that better balance facilitates more efficient and confident gait. Overall, these findings highlight dynamic balance as a key contributor to gait stability in chronic PF and support incorporating balance-focused interventions in rehabilitation.

In summary, symptom duration appears to meaningfully shape the relationships between clinical impairments and gait biomechanics in PF. In recent-onset PF, gait behavior is likely influenced predominantly by acute pain and tissue irritability, leading to broader protective gait adaptations involving gastro-soleus muscle length, ankle-foot muscle strength, and dynamic balance. These early-stage adaptations may reflect attempts to reduce plantar loading and avoid heel pain rather than established motor control strategies. In contrast, in chronic PF, repetitive pain exposure may promote neuromuscular and motor adaptations, resulting in more selective correlations between ankle muscle strength, dynamic balance, and gait biomechanics. This pattern suggests a duration-dependent transition from pain-driven gait alterations in the early stage to more stable, adaptation-based gait strategies in chronic PF, consistent with models of neuroplastic adaptation in chronic musculoskeletal conditions (15,39).

Predictors of gait speed in PF

The regression analysis identified two significant predictors of gait speed in individuals with PF: normalized gastrocnemius muscle length and the anterior reach distance on the YBT. These findings underscore key biomechanical and neuromuscular factors influencing functional mobility within this population. Among these predictors, normalized gastrocnemius muscle length emerged as the strongest factor, suggesting that greater muscle length facilitates greater ankle mobility and smoother forward progression during gait.

These results were consistent with previous research linking balance to walking ability in individuals with PF (10), suggesting that impairments in balance and flexibility may restrict gait performance through compensatory strategies driven by pain or plantar fascia dysfunction. Limited ankle dorsiflexion due to reduced gastrocnemius muscle length may induce altered gait patterns, including reduced stride length, premature heel rise, and compensatory movements at proximal joints (25,40). Such adaptations often result in decreased gait speed as a protective mechanism aimed at reducing pain or mechanical stress on the plantar fascia (6-8,12). This highlights the clinical importance of gastrocnemius flexibility as a modifiable factor that can be addressed through stretching or other therapeutic interventions to improve gait mechanics in individuals with PF. A greater anterior reach distance indicates enhanced postural control during forward weight shifting, an essential component of safe and effective walking (41).

Together, these two predictors accounted for 28.0% of the variance in gait speed, indicating that gastrocnemius muscle length and dynamic balance are significant contributors, while other factors pain severity, lower-limb muscle strength, age, gender, joint mobility, body composition, sensory input, comorbidities, physical activity levels, neuromuscular control, foot biomechanics, and socioeconomic factors likely influence the remaining variance. Additionally, coexisting musculoskeletal conditions and variations in foot morphology may also affect gait but were not assessed in the current analysis. Based on these findings, rehabilitation programs focusing on improving gastrocnemius flexibility and dynamic balance may help enhance gait efficiency in this population.

Clinical relevance

Understanding the relationship between clinical impairments and gait biomechanics at different stages of the condition gives valuable insight for customizing rehabilitation treatments. At the initial stage, prioritizing the restoration of gastro-soleus flexibility, ankle–foot muscle strength, and dynamic balance may help maintain functional gait patterns and prevent compensatory adaptations that typically develop as the condition progresses. In the chronic stage, interventions should place greater emphasis on ankle muscle strengthening and targeted dynamic balance training to optimize force generation, mediolateral control, and walking efficiency. Integrating these clinically relevant findings into both assessment and intervention planning may improve outcomes and reduce long-term functional deterioration.

Limitations and future directions

This study used a cross-sectional design, which limits the ability to determine cause-and-effect relationships. Although muscle strength was assessed using a handheld dynamometer, which is practical in a clinic, a more advanced neuromuscular tool, such as electromyography, could have offered deeper insight into muscle activation patterns in individuals with PF. The sample size within each subgroup was relatively small, which may affect the generalizability of the findings. Future longitudinal studies are recommended to explore whether improving muscle flexibility and balance can lead to better gait performance and functional outcomes in individuals with PF. The present study involved multiple correlation analyses across several clinical and gait parameters, which may increase the risk of Type I errors. As this study was exploratory, multiple correlation analyses were performed without adjustment for multiple testing. Therefore, significant relationships should be interpreted as preliminary and hypothesis-generating, and further studies using appropriate error control procedures are required to confirm these findings.

Conclusions

Pain, muscle length, muscle strength, and dynamic balance show significant correlations with gait biomechanics in individuals with PF, but the pattern of these relationships differs with symptom duration. Recent-onset PF is characterized by broader correlations between gastro-soleus muscle length, ankle-foot muscle strength, and dynamic balance with multiple spatiotemporal and GRF variables, and chronic-onset PF shows selective relationships, particularly involving the ankle muscle strength and dynamic balance with temporal gait parameters and GRFs. Among the measured variables, anterior reach distance and gastrocnemius muscle length emerged as the strongest predictors of gait speed. These findings highlight the importance of targeting dynamic balance and gastrocnemius muscle flexibility with explicit consideration of symptom duration when designing rehabilitation programs to optimize gait performance in this population.

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