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The Relationship Between Foot Angle, Center of Force Variation, and Mean Plantar Pressure During Gait

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Abstract: Understanding the biomechanical relationships between kinematic parameters (foot angle) and kinetic variables (plantar pressure, center of force displacement) is essential for clinical assessment and therapeutic intervention in locomotor dysfunction. The study aims to investigate correlational relationships between foot angle, center of force variation (ΔCoF), and mean plantar pressure during dynamic gait in adults, considering foot arch type, knee alignment, and spinal alignment influences. Cross-sectional study of 41 healthy adults (18 males, 23 females; mean age: 22.17±3.89 years). Assessments included anthropometric measurements, postural evaluation (foot arch type, knee alignment, spinal alignment), and dynamic baropodometric analysis. Spearman correlations and multiple regression identified relationships between foot angle, ΔCoF, and regional plantar pressures. Significant positive correlations were found between foot angle and ΔCoF (left: $\rho=0.389$, $p=0.012$; right: $\rho=0.401$, $p=0.009$), and between ΔCoF and mean plantar pressure (left anterior: $\rho=0.445$, $p=0.003$). Flat foot subjects showed significantly higher medial pressure ($p<0.001$) and ΔCoF ($p=0.015$) compared to cavus foot. Genu valgum correlated with increased medial loading ($\rho=0.428$, $p=0.005$). Multiple regression revealed foot angle and ΔCoF as significant predictors of mean plantar pressure ($R^2=0.487$, $p<0.001$). Foot angle and center of force variation are significantly correlated with plantar pressure distribution during gait. These cinemato-biomechanical parameters interact with morphological factors (arch type, knee alignment) to determine loading patterns, providing clinical indicators for gait dysfunction assessment and intervention planning.

Keywords: foot angle, center of force variation, plantar pressure, gait dynamics, biomechanics, baropodometry

1. Introduction

Plantar pressure distribution and center of force (CoF) displacement are critical biomechanical indicators of foot function during gait. Foot angle—the angular deviation of the foot's longitudinal axis relative to the line of progression—influences loading patterns and propulsion efficiency [1], [2], [3]. Alterations in foot angle modify ground reaction force moment arms, thereby affecting joint loading throughout the lower extremity chain [4], [5], [6].

The center of force variation (ΔCoF) reflects medio-lateral and antero-posterior excursion of the pressure center during stance phase, indicating dynamic stability [7], [8]. Increased ΔCoF values suggest postural instability, reduced neuromuscular control, or compensatory mechanisms related to structural deformities [7], [8], [9].

Foot arch morphology (flat, normal, cavus) and knee alignment (valgus, varus, normal) create a biomechanical framework determining plantar loading patterns [10], [11], [12]. Flat foot associates with increased medial contact and altered CoF trajectories, [13], [14] while cavus foot demonstrates reduced contact area with elevated peak pressures [15], [16], [17]. Knee alignment deviations further modulate these patterns:

genu valgum increases medial loading, while genu varum elevates lateral pressures [18], [19].

Despite extensive research on individual parameters, limited studies systematically examine correlational relationships between foot angle, ΔCoF, and plantar pressure while considering confounding morphological influences. This study aims to investigate these kinematic-biomechanical relationships and test the hypothesis that foot angle and ΔCoF significantly correlate with and predict plantar loading patterns during dynamic gait.

2. Materials and Methods

2.1. Study Design and Participants

This cross-sectional observational study was conducted at Integrative Medicine Clinic „ Health with Ozone", Galati, Romania, Department of Physiotherapy and Posturology, between March and April 2025.

Based on correlation analysis power calculation (effect size ϱ=0.30, α=0.05, power=0.80), minimum sample size was 41 participants.

We recruited 41 healthy adults (18 males, 23 females) meeting inclusion criteria: age 18-35 years, independent ambulation, no current lower extremity pain. Exclusion criteria included: lower extremity surgery within 12 months, neurological disorders affecting gait, severe cardiovascular conditions, pregnancy, orthotic device use, or cognitive impairment. All participants provided written informed consent.

2.2. Data collection procedures

Anthropometric measurements: body weight (digital scale, ±0.1kg precision), height (stadiometer, ±0.1cm), and BMI calculation (weight/height^2).

Postural Assessment: foot arch classification: using foot posture index (FPI-6, where Normal (PLAT) denotes a physiologic foot arch, whereas Flat (PLAT) indicates a lowered arch) [20]:

- Cavus (CAV): FPI ≤ -4;
- Normal (PLAT): FPI -3 to +5;
- Flat (PLAT): FPI ≥ +6.

Knee Alignment: Inter-malleolar/inter-condylar distance method [21]:

- Genu Valgum (VALG): Inter-malleolar distance ≥3cm with knees touching;
- Normal: Both distances <3cm;
- Genu Varum (VAR): Inter-condylar distance ≥3cm with malleoli touching.

Spinal Alignment: visual and photographic assessment (sagittal/frontal planes) classified as: straight, curved/scoliosis, or hyperlordosis.

Dynamic baropodometry: participants stood barefoot on a baropodometric platform (Free Med DYNAMIC 120cm, Sensor Medica Italia, resolution: 10000 sensors/m^2, sampling frequency: up to 400 Hz, pressure range: 0-150 Newton/cm^2) [22]. Participants walked barefoot at self-selected speed across 2,6-meter approach runway. Five valid trials per foot were recorded. Measured parameters:

- Mean plantar pressure (g/cm^2): forefoot, rear foot, medial, lateral regions;
- Foot angle (degrees): angular deviation from line of progression;
- ΔCoF (mm): medio-lateral and forefoot – rear foot displacement range;
- Gait velocity (m/s).

2.3 Statistical Analysis

Statistical analyses used IBM SPSS Statistics version 26.0. Descriptive statistics: mean±SD for continuous variables, frequency (percentage) for categorical variables. Normality assessed via Shapiro-Wilk test.

Inferential statistics:

- Spearman rank correlations (ϱ) for relationships between foot angle, ΔCoF, and plantar pressure parameters;

- Kruskal-Wallis H test comparing continuous variables across arch types and knee alignment groups;
- Mann-Whitney U test for post-hoc pairwise comparisons (Bonferroni correction);
- Multiple linear regression (stepwise method) with mean plantar pressure as dependent variable; independent variables: foot angle, ΔCoF, BMI, age, arch type, knee alignment;
- Chi-square test for categorical variable associations.

Significance level: $p<0.05$ (two-tailed). Correlation strength interpretation: $|\rho|<0.30$=weak, 0.30-0.60=moderate, >0.60=strong [23]

3. Results

3.1 Participant Characteristics

Forty-one participants completed the study. Demographic and anthropometric characteristics are presented in **Table 1.**

Table 1. Participant characteristics

Variable	Total (N=41)	Male (n=18)	Female (n=23)	p-value
Age (years)	22.17±3.89	22.56±4.23	21.87±3.67	0.583
Height (cm)	169.85±9.54	177.22±6.89	164.17±7.12	<0.001*
Weight (kg)	67.76±14.82	77.89±13.45	59.96±10.67	<0.001*
BMI (kg/m²)	23.32±3.86	24.72±3.54	22.24±3.84	0.042*

*Mann-Whitney U test; *p<0.05

Morphological Distribution:

- Foot arch: Normal (n=15, 36.6%), Flat (n=14, 34.1%), Cavus (n=12, 29.3%)
- Knee alignment: Normal (n=18, 43.9%), Valgus (n=16, 39.0%), Varus (n=7, 17.1%)
- Spinal alignment: Straight (n=23, 56.1%), Curved (n=12, 29.3%), Hyper-lordosis (n=6, 14.6%)

3.2 Descriptive Statistics of Biomechanical Parameters

Table 2. Dynamic Plantar Pressure and Kinematic Parameters

Parameter	Mean±SD	Median [IQR]	Range
Left Foot			
Forefoot pressure (g/cm²)	184.68±54.83	175 [147-215]	95-338
Rear foot pressure (g/cm²)	217.46±62.28	210 [170-255]	110-380
Medial pressure (g/cm²)	156.20±48.92	150 [120-185]	75-285
Lateral pressure (g/cm²)	142.34±43.67	135 [110-168]	68-248
Foot angle (°)	12.85±4.23	13 [10-16]	5-23
ΔCoF (mm)	45.78±12.56	44 [37-53]	22-78
Right Foot			
Forefoot pressure (g/cm²)	188.93±56.12	182 [151-220]	98-342
Rear foot pressure (g/cm²)	221.85±64.35	215 [175-262]	115-385
Medial pressure (g/cm²)	159.41±50.27	155 [123-190]	78-290
Lateral pressure (g/cm²)	145.68±45.23	140 [113-172]	70-252
Foot angle (°)	13.12±4.47	13 [11-16]	6-24
ΔCoF (mm)	47.22±13.18	46 [38-55]	24-82

3.3 Correlational Analysis

3.3.1 Foot Angle and ΔCoF Relationship

Table 3. Correlation Between Foot Angle and ΔCoF

Side	Spearman ρ	p-value	95% CI	Interpretation
Left foot	0.389	0.012*	0.091-0.623	Moderate positive
Right foot	0.401	0.009*	0.107-0.633	Moderate positive

*Significant at p<0.05

Significant positive correlations indicate that increased external foot rotation associates with greater CoF excursion, suggesting compromised dynamic stability with altered foot progression angle.

3.3.2 ΔCoF and Plantar Pressure Relationships

Table 4. Correlations Between ΔCoF and Regional Plantar Pressure

Pressure Region	Left Foot ρ	p-value	Right Foot ρ	p-value
Forefoot	0.445	0.003*	0.428	0.005*
Rear foot	0.312	0.046*	0.298	0.057
Medial	0.381	0.014*	0.367	0.018*
Lateral	0.246	0.118	0.234	0.139

*Significant at p<0.05

Increased ΔCoF significantly correlates with elevated anterior and medial plantar pressures, indicating that greater postural instability associates with increased loading in these regions.

3.3.3 Foot Angle and Plantar Pressure Relationships

Table 5. Correlations Between Foot Angle and Regional Plantar Pressure

Pressure Region	Left Foot ρ	p-value	Right Foot ρ	p-value
Forefoot	0.289	0.065	0.301	0.054
Rear foot	-0.198	0.213	-0.185	0.245
Medial	0.412	0.007*	0.428	0.005*
Lateral	-0.334	0.032*	-0.356	0.022*

*Significant at p<0.05

External foot angle positively correlates with medial pressure and negatively with lateral pressure, suggesting rotation-induced medial load shift.

3.4 Influence of Foot Arch Type

Table 6. Biomechanical Parameters by Foot Arch Type

Parameter	Normal (n=15)	Flat (n=14)	Cavus (n=12)	p-value	Post-hoc
Foot angle (°)	11.87±3.45	15.21±4.12	11.08±3.89	0.008*	Flat>Normal, Cavus
ΔCoF (mm)	42.33±10.67	52.86±13.24	41.25±9.85	0.015*	Flat>Normal, Cavus
Medial pressure (g/cm²)	148.27±38.56	185.64±52.38	135.83±35.67	<0.001*	Flat>Normal>Cavus
Lateral pressure (g/cm²)	145.33±42.12	128.21±38.45	158.75±48.23	0.042*	Cavus>Normal>Flat
Forefoot pressure (g/cm²)	182.40±51.23	177.86±48.67	203.17±62.45	0.289	NS

*Kruskal-Wallis H test; Post-hoc: Mann-Whitney U with Bonferroni correction (p<0.017)

Key Findings:
Flat foot: significantly greater foot angle (+27% vs normal), elevated ΔCoF (+25%), medial pressure predominance (+25%);
Cavus foot: highest lateral pressure (+19% vs flat), lowest medial loading (-27% vs flat) ΔCoF significantly elevated in flat foot indicates reduced dynamic stabilityGenu valgum associated with 24.9% higher medial pressure than normal alignment (p=0.008). Genu valgum showed 28.4% higher medial pressure than genu varum (p=0.018). Trend toward increased lateral pressure in genu varum (+23.4% vs valgus, p=0.056). Moderate effect size ($\eta^2 p$=0.230) indicates clinically meaningful influence.

3.5 Influence of Knee Alignment

Table 7. Biomechanical Parameters by Knee Alignment

Parameter	Normal (n=18)	Valgus (n=16)	Varus (n=7)	p-value
Foot angle (°)	11.94±3.78	14.19±4.23	12.57±4.61	0.156
ΔCoF (mm)	43.22±11.23	49.94±13.45	46.71±11.89	0.178
Medial pressure (g/cm²)	142.78±42.34	178.31±51.67	138.86±38.92	0.012*
Lateral pressure (g/cm²)	146.89±44.56	131.56±39.23	162.43±49.87	0.089

*Kruskal-Wallis H test; *p<0.05

Genu valgum associates with significantly increased medial pressure (+25% vs normal, p=0.008), while genu varum shows elevated lateral loading trend (+17% vs valgus, p=0.067).

3.6 Multiple Regression Analysis

Stepwise multiple regression identified significant predictors of mean plantar pressure (**Table 8**).

Table 8. Multiple Regression Model for Mean Plantar Pressure

Predictor	B	SE	β	t	p-value	VIF
Constant	82.45	18.67	-	4.42	<0.001	-
Foot angle (°)	4.23	1.34	0.342	3.16	0.003*	1.23
ΔCoF (mm)	1.89	0.56	0.381	3.38	0.002*	1.19
BMI (kg/m²)	2.67	0.98	0.287	2.73	0.009*	1.12
Arch type (Flat)	28.34	10.23	0.298	2.77	0.008*	1.34
Knee alignment (Valgus)	21.56	9.87	0.234	2.18	0.035*	1.28

*All predictors significant at p<0.05

Model: R^2=0.487, Adjusted R^2=0.413, F(5,35)=6.63, p<0.001

Interpretation: The model explains 48.7% of variance in mean plantar pressure. Foot angle (β=0.342) and ΔCoF (β=0.381) emerge as strongest predictors alongside BMI, flat foot morphology, and genu valgum alignment.

3.7 Interaction Effects

Two-way ANOVA revealed significant interaction between foot arch type and knee alignment on medial plantar pressure (F(4,31)=3.78, p=0.013, partial η^2=0.328).

Key Pattern: Flat foot + genu valgum combination produced highest medial pressures (mean=206.8±48.3 g/cm²), while cavus foot + genu varum showed maximum lateral loading (mean=178.5±52.1 g/cm²). Opposing combinations (flat+varus, cavus+valgus) demonstrated more balanced distribution, suggesting partial compensation.

4. Discussion

4.1 Principal Findings

This study demonstrates significant biomechanical relationships between foot angle, ΔCoF, and plantar pressure distribution during gait. The moderate positive correlations (ϱ=0.389-0.445) between these kinematic-biomechanical parameters confirm our primary hypotheses and extend understanding of lower extremity kinetic-kinematic coupling.

4.2 Foot Angle-ΔCoF Relationship

The significant correlation between foot angle and ΔCoF (ϱ=0.389-0.401, p<0.05) indicates that external foot rotation associates with increased medio-lateral CoF displacement, compromising dynamic stability. When the foot progresses externally rotated, the base of support geometry alters, modifying moment arms of ground reaction forces [24], [24], [25]. This relationship may reflect: structural compensation - flat foot collapse requiring lateral base widening [26], [27], [28], [29], proximal malalignment - hip external rotation or knee valgus transmitted distally [30], [31], neuromuscular deficit - insufficient foot core musculature necessitating broader support [32], [33]. Clinically, excessive foot angle serves as an accessible indicator of postural instability, with implications for fall risk assessment and intervention targeting. [34], [35].

4.3 ΔCoF-Pressure Relationships

The positive correlations between ΔCoF and anterior/medial pressures (ϱ=0.381-0.445, p<0.05) suggest that postural instability manifests as regional loading increases. Greater CoF excursion indicates less precise center of mass control, potentially requiring compensatory strategies [36], [37], [38]:

Muscle co-contraction: Simultaneous antagonist activation stiffens joints;

Loading redistribution: Shift to structurally stable regions (medial arch, forefoot);

Contact time prolongation: Extended stance for enhanced stability.

These findings support multimodal interventions addressing both pressure reduction AND stability enhancement through proprioceptive training, foot strengthening, and balance exercises [39], [40], [41]. Genu valgum significantly increased medial plantar pressure by 24.9% compared to normal alignment (p=0.008) and 28.4% compared to genu varum (p=0.018). This medial shift reflects biomechanical chain transmission from proximal to distal segments: the valgus knee position creates a medially directed ground reaction force vector that promotes foot pronation and medial arch loading [10], [11], [13].

While genu varum showed a trend toward increased lateral pressure (+23.4% vs valgus, p=0.056), this did not reach statistical significance, possibly due to limited sample size in the varus subgroup (n=7). However, the directional pattern supports the biomechanical rationale that varus alignment shifts loading laterally through supination mechanisms [14].

These findings confirm that knee alignment should be routinely assessed in plantar pressure evaluations, as it substantially modulates foot loading patterns independent of arch morphology.

4.4 Foot Arch Morphology Effects

Flat foot subjects demonstrated significantly elevated foot angle (+27%), ΔCoF (+25%), and medial pressure (+25%) compared to normal/cavus groups. This profile creates high-risk biomechanics for [42], [43], [44]:

Medial tibial stress syndrome: repetitive medial overload;

Plantar fasciitis: excessive arch elongation;

Posterior tibial tendon dysfunction: chronic pronation stress;

Medial knee osteoarthritis: transmitted valgus moments.

Conversely, cavus foot exhibited reduced ΔCoF (rigid stability) but concentrated lateral loading, increasing risks for lateral ankle instability and fifth metatarsal stress fractures [45], [46], [47]. While seemingly more stable (lower ΔCoF), this represents rigid rather than controlled stability with impaired shock absorption [47], [48].

4.5 Knee Alignment Influences

Genu valgum significantly increased medial plantar pressure (+25% vs normal), confirming biomechanical chain transmission from knee to foot [49], [50]. The synergistic interaction between flat foot and genu valgum (producing maximum medial overload) versus cavus foot and genu varum (maximum lateral stress) demonstrates that:

Isolated assessment is insufficient: combined evaluation provides superior risk stratification;

Aligned deformities amplify risk: same-direction biases (both medial or lateral) create additive stress;

Opposing deformities may compensate: partial neutralization possible with opposite-direction patterns.

This interaction has direct implications for intervention prioritization and orthotic prescription strategies [51], [52], [53].

4.6 Predictive Model

The multiple regression model (R^2=0.487) demonstrates that kinemato-biomechanical parameters (foot angle, ΔCoF) combined with morphological factors (arch type, knee alignment) and anthropometrics (BMI) predict nearly 50% of mean plantar pressure variance. This provides clinicians with evidence-based framework for:

Risk screening: estimating loading patterns from measurable clinical parameters;

Intervention targeting: addressing significant modifiable predictors;

Outcome monitoring: quantifying pressure changes from kinematic/morphological modifications.

The unexplained variance (~50%) reflects additional unmeasured factors including neuromuscular control patterns, gait velocity variations, footwear effects, and individual adaptations [54], [55], [56].

4.7 Clinical Recommendations

Assessment Protocol:

Level 1 (all patients): Foot arch type (FPI-6), knee alignment, static pressure;

Level 2 (high-risk): Dynamic baropodometry with ΔCoF and foot angle quantification;

Level 3 (complex cases): 3D motion capture, EMG analysis.

Risk Stratification:

High-risk: Flat+valgus+elevated BMI (medial overload); Cavus+varus (lateral stress); High ΔCoF+large foot angle (instability);

Moderate-risk: Single morphological deviation; opposing deformities;

Low-risk: Normal alignment; minimal deviations.

Intervention Guidelines:

For Flat Foot + Medial Loading:

- Arch-support orthoses with medial posting [57], [58];
- Intrinsic foot strengthening (short foot exercise) [59], [60];
- Hip abductor strengthening (if concurrent valgus) [61];
- Gait retraining to reduce foot angle [62].

For Cavus Foot + Lateral Loading:

- Cushioned orthoses with shock absorption [63];
- Ankle flexibility training;
- Peroneal strengthening and proprioceptive exercises [64];
- Lateral stability training.

For Elevated ΔCoF:
Progressive balance training [65];
Core stabilization exercises [66];
Neuromuscular reeducation;
Functional task practice.

4.8 Study Limitations

- Design: cross-sectional nature precludes causal inference; longitudinal intervention studies needed;
- Sample: healthy young adults; findings may not generalize to pathological, pediatric, or elderly populations;
- Measurement: baropodometric platform captures foot-ground contact only; internal joint loading unmeasured; single-session assessment without test-retest reliability;
- Statistical: multiple comparisons increase Type I error risk despite corrections; nonlinear relationships may exist but remain unmodeled.

4.9 Future Directions

- Intervention trials: RCTs evaluating orthoses, exercise, and gait retraining with biomechanical outcomes;
- Population expansion: Clinical cohorts (diabetes, arthritis), athletes, elderly;
- Advanced analysis: 3D kinematics, musculoskeletal modeling, machine learning prediction algorithms [67], [68];
- Wearable technology: in-shoe pressure monitoring for real-world gait assessment [69], [70].

5. Conclusions

This study demonstrates significant correlational relationships between foot angle, center of force variation, and plantar pressure distribution during dynamic gait.

Key conclusions:

Kinemato-biomechanical coupling: foot angle and ΔCoF significantly correlate (ϱ=0.389-0.401), with external rotation associating with compromised stability

Stability-loading relationship: increased ΔCoF correlates with elevated anterior and medial pressures (ϱ=0.381-0.445), indicating instability manifests as regional loading increases.

Morphological moderation: foot arch type and knee alignment significantly influence these relationships, with synergistic deformity patterns producing amplified biomechanical consequences

Multivariate prediction: foot angle, ΔCoF, BMI, arch type, and knee alignment collectively predict 48.7% of plantar pressure variance, providing clinically useful predictive framework

Clinical implications: comprehensive lower extremity assessment integrating dynamic baropodometry with morphological evaluation enables superior risk stratification and intervention targeting

Clinical bottom line: kinemato-biomechanical parameters are significantly correlated with plantar loading patterns and modulated by structural morphology. Multimodal interventions addressing the entire lower extremity kinetic chain are essential for optimal outcomes.

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