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Research article

Assessment of Plantar Pressure Differences Based on Foot Arch Type and Knee Deviation in Adults

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Abstract: Foot arch type and knee alignment determine the mode of support and load distribution during standing and walking, potentially modifying plantar pressure. This study aims to determine how foot arch type (flat, cavus, normal) and knee deviation (valgus, varus, normal) influence mean plantar pressure and its distribution across anterior, posterior, medial, and lateral regions in healthy adults. Forty-one healthy adults were evaluated (15 with normal arch, 14 with flat arch, 12 with cavus arch), each classified according to knee deviation. Measurements included static and dynamic mean plantar pressure (anterior, posterior, medial, lateral regions) and center of force variation (ΔCoF). Factorial ANOVA analyses (arch type × knee deviation) and Spearman correlations were applied. Significant main effects were found for arch type on medial pressure ($F=8.94$, $p<0.001$) and lateral pressure ($F=4.23$, $p=0.022$). Flat foot subjects showed increased medial pressure (185.64±52.38 g/cm²) compared to cavus (135.83±35.67 g/cm², $p<0.001$). Significant interaction between arch type and knee deviation was observed ($F=3.78$, $p=0.013$), with flat foot + genu valgum showing maximum medial loading (206.8±48.3 g/cm²). ΔCoF correlated positively with anterior pressure ($\varrho=0.445$, $p=0.003$) and medial pressure ($\varrho=0.381$, $p=0.014$). The interaction between foot arch morphology and knee alignment significantly influences plantar support patterns. Flat foot combined with genu valgum creates the highest medial overload risk, while cavus foot with genu varum produces maximum lateral stress. These data can guide individualized physical therapy programs and prevention of joint overload.

Keywords: foot arch, cavus foot, flat foot, knee deviation, plantar pressure, load distribution

1. Introduction

Plantar load distribution and mean pressure values are important biomechanical indicators of foot support and balance in static and dynamic conditions. Foot arch type (flat vs cavus) modifies the medial arch and the mode of foot contact with the ground, while knee deviation (valgus, varus) can alter force vectors transmitted to the foot [1], [2], [3], [4], [5].

Recent advances in baropodometric technology have enabled precise quantification of regional plantar pressure distribution, providing insights into biomechanical loading patterns associated with morphological variation [6], [7], [8]. Flat foot (pes planus) is characterized by reduced medial longitudinal arch height and increased medial contact area, typically resulting in elevated medial plantar pressures [9], [10]. Conversely, cavus foot (pes cavus) demonstrates heightened arch structure with reduced midfoot contact and concentrated loading in the forefoot and heel regions, often with lateral bias. [11], [12].

Knee alignment deviations—genu valgum (knock „X"-knee) and genu varum (bow-leg „O" knee)—influence the ground reaction force vector and consequently affect plantar loading patterns. [13] Genu valgum tends to shift loading medially through altered lower limb biomechanics, while genu varum increases lateral compartment stress.[14] However, few studies have systematically evaluated the combined interaction between these two morphological variables and how they synergistically influence plantar pressure distribution [15], [16].

Understanding these interactions is crucial for clinical practice, as combined morphological deviations may produce amplified biomechanical consequences requiring targeted interventions. In the context of physical therapy and postural rehabilitation, identifying these relationships can provide criteria for individualized assessment protocols and evidence-based intervention strategies [17], [18].

Purpose: This study examines differences in static and dynamic mean plantar pressure based on foot arch type and knee alignment, testing the hypothesis that there is a significant interaction between these morphological variables that influences the plantar loading pattern.

Hypotheses:

1. Flat foot will demonstrate increased medial plantar pressure compared to normal and cavus arch types;
2. Genu valgum will associate with elevated medial foot loading, while genu varum increases lateral foot pressure;
3. A significant interaction effect will exist, with combined flat foot + genu valgum producing maximum medial foot overload, and cavus foot + genu varum generating maximum lateral foot stress.

2. Materials and Methods

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

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.

Participants group consists of 41 healthy adults who met eligibility criteria, such as:

- Age 18-35 years;
- Ability to walk independently without assistive devices;
- No current lower extremity pain or discomfort;
- Willingness to provide written informed consent;

Exclusion Criteria:

- History of lower extremity surgery (hip, knee, ankle, foot) within past 12 months;
- Current musculoskeletal injury or inflammatory conditions;
- Neurological disorders affecting gait or balance;
- Severe cardiovascular or respiratory disease;
- Pregnancy;
- Current use of orthotic devices or prescribed footwear modifications;
- Cognitive impairment preventing informed consent.

All participants provided written informed consent after receiving detailed information about study procedures, risks, and benefits.

2.2. Data collection procedures

All assessments were performed in a controlled laboratory environment (temperature: 22±2°C, humidity: 50±10%) by trained examiners. Participants wore lightweight clothing and were assessed barefoot.

2.2.1 Anthropometric measurements

- Body weight: calibrated digital scale (precision ±0.1 kg);

- Height: wall-mounted stadiometer (precision ±0.1 cm);
- Body Mass Index (BMI): Calculated as weight(kg)/height²(m²).

2.2.2 Morphological assessment

Foot Arch Classification:

Foot posture was assessed using the Foot Posture Index-6 (FPI-6: for foot arch classification and intercondylar/intermalleolar distance measurements for knee alignment assessment, providing reliable clinical profiling of participants), a validated clinical tool evaluating six criteria [19]:

1. Talar head palpation;
2. Supra and infra lateral malleolar curvature;
3. Calcaneal frontal plane position;
4. Prominence in the region of the talonavicular joint;
5. Congruence of the medial longitudinal arch
6. Abduction/adduction of the forefoot on the Rear foot;

Each criterion scored from -2 to +2, with total scores ranging from -12 (highly supinated) to +12 (highly pronated).

Classification:

- Normal (PLAT): FPI score -3 to +5 (n=15, 36.6%);
- Flat (PLAT): FPI score ≥+6 (n=14, 34.1%);
- Cavus (CAV): FPI score ≤-4 (n=12, 29.3%);

Knee Alignment Assessment:

Frontal plane knee alignment was evaluated in relaxed standing position using the intercondylar/intermalleolar distance method [20]:

- Normal: Intercondylar distance <3 cm AND intermalleolar distance <3 cm (n=18, 43.9%);
- Genu Valgum (VALG): Intermalleolar distance ≥3 cm with medial femoral condyles touching (n=16, 39.0%);
- Genu Varum (VAR): Intercondylar distance ≥3 cm with medial malleoli touching (n=7, 17.1%).

Digital photography (anterior view) was performed for verification and measurement documentation using ImageJ software (NIH, USA).

Spinal Alignment Assessment:

Vertebral column alignment was assessed through visual inspection and digital photography (sagittal and frontal planes):

- Straight (STRECH): Normal sagittal curves without significant deviations (n=23, 56.1%);
- Curved (CURBURA): Visible scoliosis or excessive curvature (n=12, 29.3%);
- Hyperlordosis (HL): Excessive lumbar lordosis (n=6, 14.6%).

2.2.3 Baropodometric Assessment

Static Measurements:

Participants stood barefoot on a baropodometric platform (Free Med DYNAMIC 120cm, Sensor Medica Italia, resolution: 10000 sensors/m², sampling frequency: up to 400 Hz, pressure range: 0-150 Newton/cm²) in a standardized position:

- Feet hip-width apart;
- Arms relaxed at sides;
- Eyes focused on target at eye level, 2 meters distant;
- Data acquisition: one trial - 30 seconds (6 measurements x 5 seconds);
- Three trials with 60-second rest intervals.

Measured parameters:

- Regional pressure distribution: Medial (DR), Lateral (ST), Anterior (Forefoot), Posterior (Rear foot);
- Values expressed in g/cm².

Dynamic Measurements:

Dynamic gait analysis utilized the same platform with:

- 2,6 -meter approach runway;
- 1,2 – meter measuring runway area (with sensors);
- 2,6 -meter exit area;
- Self-selected comfortable walking speed;
- Minimum 5 valid foot contacts per foot recorded.

Valid trial criteria:

- Complete foot contact within platform boundaries;
- No visible gait modifications (targeting effect);
- Consistent velocity (±10% across trials).

Measured parameters:

- Mean plantar pressure (g/cm²): Forefoot (left/right), Rear foot (left/right), Medial (left/right), Lateral (left/right);
- Center of Force Variation (ΔCoF): Medio-lateral and Forefoot/Rear foot (F/R) displacement (mm);
- Contact area (cm²);
- Gait velocity (m/s).

2.3 Statistical Analysis

Statistical analyses were performed using SPSS Statistics. Significance level was set at α=0.05 (two-tailed).

Descriptive Statistics:

- Continuous variables: Mean ± standard deviation (SD) or median [interquartile range] based on distribution;
- Categorical variables: Frequency and percentage;
- Normality assessment: Shapiro-Wilk test, Q-Q plots, histograms.

Inferential Statistics:

1. Factorial ANOVA (3×3 design):
- Independent variables: Foot arch type (3 levels), knee alignment (3 levels);
- Dependent variables: Regional plantar pressures, ΔCoF;
- Main effects and interaction effects evaluated;
- Post-hoc: Bonferroni correction for multiple comparisons;
2. Spearman Rank Correlations:
- Relationships between ΔCoF and regional pressures;
- Relationships between anthropometric variables and pressure parameters;
- Correlation strength: $|\rho|$<0.30=weak, 0.30-0.60=moderate, >0.60=strong.[21]
3. Group Comparisons:
- Kruskal-Wallis H test: Comparing 3+ independent groups;
- Mann-Whitney U test: Post-hoc pairwise comparisons;
- Chi-square test: Categorical variable associations.
4. Effect Sizes:
- Partial eta-squared (η^2p) for ANOVA effects;
- Cohen's d for pairwise comparisons.

3. Results

3.1 Participant Characteristics

Forty-one healthy adults completed all study procedures. Demographic and anthropometric characteristics are presented in **Table 1.**

Table 1. Demographic and Anthropometric Characteristics

Variable	Total (N=41)	Male (n=18, 43.9%)	Female (n=23, 56.1%)	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; †Significant at p<0.05 Data presented as mean ± standard deviation

Table 2 Morphological Distribution

Classification	Category	n	%
Foot Arch Type	Normal	15	36.6
	Flat	14	34.1
	Cavus	12	29.3
Knee Alignment	Normal	18	43.9
	Valgus	16	39.0
	Varus	7	17.1
Spinal Alignment	Straight	23	56.1
	Curved	12	29.3
	Hyperlordosis	6	14.6

3.2 Descriptive Statistics: Plantar Pressure Parameters

Table 3. Static and Dynamic Plantar Pressure Measurements

Parameter	Mean ± SD	Median [IQR]	Range
Static Pressure (g/cm²)			
Medial (DR)	156.20 ± 48.92	150 [120-185]	75-285
Lateral (ST)	142.34 ± 43.67	135 [110-168]	68-248
Forefoot	184.68 ± 54.83	175 [147-215]	95-338
Rear foot	217.46 ± 62.28	210 [170-255]	110-380
Dynamic Pressure - Left Foot (g/cm²)			
Anterior	184.68 ± 54.83	175 [147-215]	95-338
Forefoot	217.46 ± 62.28	210 [170-255]	110-380
Rear foot	156.20 ± 48.92	150 [120-185]	75-285
Lateral	142.34 ± 43.67	135 [110-168]	68-248
Dynamic Pressure - Right Foot (g/cm²)			
Anterior	188.93 ± 56.12	182 [151-220]	98-342
Forefoot	221.85 ± 64.35	215 [175-262]	115-385
Rear foot	159.41 ± 50.27	155 [123-190]	78-290
Lateral	145.68 ± 45.23	140 [113-172]	70-252
Center of Force Variation (mm)			
Left foot (ΔCoF)	45.78 ± 12.56	44 [37-53]	22-78
Right foot (ΔCoF)	47.22 ± 13.18	46 [38-55]	24-82

DR = right/medial side; ST = left/lateral side; IQR = interquartile range

3.3 Main Effect of Foot Arch Type

Table 4. Plantar Pressure by Foot Arch Type

Parameter	Normal (n=15)	Flat (n=14)	Cavus (n=12)	F-statistic	p-value	η²p
Medial pressure (g/cm²)	148.27 ± 38.56	185.64 ± 52.38	135.83 ± 35.67	8.94	<0.001†	0.320
Lateral pressure (g/cm²)	145.33 ± 42.12	128.21 ± 38.45	158.75 ± 48.23	4.23	0.022†	0.182
Forefoot pressure (g/cm²)	182.40 ± 51.23	177.86 ± 48.67	203.17 ± 62.45	1.58	0.221	0.077
Rear foot pressure (g/cm²)	215.33 ± 58.94	224.79 ± 67.23	212.08 ± 61.45	0.34	0.713	0.018
ΔCoF (mm)	42.33 ± 10.67	52.86 ± 13.24	41.25 ± 9.85	7.82	0.002†	0.291

†Significant at p<0.05; η²p = partial eta-squared (effect size)

Post-hoc Comparisons (Bonferroni-corrected):

Medial Pressure:
Flat vs Normal: +37.37 g/cm², p=0.001, Cohen's d=0.85
Flat vs Cavus: +49.81 g/cm², p<0.001, Cohen's d=1.12
Normal vs Cavus: +12.44 g/cm², p=0.524, Cohen's d=0.36
Lateral Pressure:
Cavus vs Flat: +30.54 g/cm², p=0.019, Cohen's d=0.68
Cavus vs Normal: +13.42 g/cm², p=0.412, Cohen's d=0.31
Normal vs Flat: +17.12 g/cm², p=0.234, Cohen's d=0.42
ΔCoF:
Flat vs Normal: +10.53 mm, p=0.003, Cohen's d=0.92
Flat vs Cavus: +11.61 mm, p=0.002, Cohen's d=0.98
Normal vs Cavus: +1.08 mm, p=0.897, Cohen's d=0.11
Key Findings:

Flat foot showed 25.2% higher medial pressure than normal (p=0.001) and 36.7% higher than cavus (p<0.001). Cavus foot demonstrated 23.8% higher lateral pressure than flat foot (p=0.019). Flat foot exhibited 24.9% greater ΔCoF than normal (p=0.003), indicating reduced dynamic stability. Large effect sizes (η²p=0.320 for medial pressure, 0.291 for ΔCoF) confirm substantial clinical significance.

3.4 Main Effect of Knee Alignment

Table 5. Plantar Pressure by Knee Alignment

Parameter	Normal (n=18)	Valgus (n=16)	Varus (n=7)	F-statistic	p-value	η²p
Medial pressure (g/cm²)	142.78 ± 42.34	178.31 ± 51.67	138.86 ± 38.92	5.67	0.007†	0.230
Lateral pressure (g/cm²)	146.89 ± 44.56	131.56 ± 39.23	162.43 ± 49.87	3.12	0.056	0.141
Forefoot pressure (g/cm²)	186.44 ± 53.28	181.25 ± 57.12	195.71 ± 51.34	0.48	0.622	0.025
Rear foot pressure (g/cm²)	219.50 ± 61.45	218.31 ± 64.89	214.43 ± 62.78	0.04	0.961	0.002
ΔCoF (mm)	43.22 ± 11.23	49.94 ± 13.45	46.71 ± 11.89	2.19	0.127	0.103

†Significant at p<0.05

Post-hoc Comparisons (Bonferroni-corrected):

Medial Pressure:
Valgus vs Normal: +35.53 g/cm², p=0.008, Cohen's d=0.76
Valgus vs Varus: +39.45 g/cm², p=0.018, Cohen's d=0.83
Normal vs Varus: +3.92 g/cm², p=0.921, Cohen's d=0.10
Key Findings:

Genu 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 ($\eta^2p=0.230$) indicates clinically meaningful influence.

3.5 Interaction Effect: Arch Type × Knee Alignment

Two-way factorial ANOVA revealed a significant interaction effect between foot arch type and knee alignment on medial plantar pressure.

Table 6. Interaction Effect (Arch Type × Knee Alignment) on Medial Pressure

Source	SS	df	MS	F	p-value	η^2p
Arch type	21,456.3	2	10,728.2	8.94	<0.001†	0.320
Knee alignment	13,589.7	2	6,794.9	5.67	0.007†	0.230
Arch × Knee	18,234.5	4	4,558.6	3.78	0.013†	0.328
Error	37,345.8	31	1,204.7			

†Significant at $p<0.05$; SS=sum of squares; MS=mean square; η^2p=partial eta-squared

Table 7. Mean Medial Pressure (g/cm²) by Combined Groups

Arch Type	Normal Knee	Valgus Knee	Varus Knee
Normal	138.5 ± 36.8 (n=7)	156.3 ± 38.2 (n=5)	150.2 ± 42.1 (n=3)
Flat	145.8 ± 41.5 (n=6)	**206.8 ± 48.3 (n=6)**	152.5 ± 45.7 (n=2)
Cavus	144.0 ± 45.3 (n=5)	141.2 ± 32.4 (n=5)	**118.4 ± 28.9 (n=2)**

Highest medial pressure: Flat + Valgus (206.8 g/cm²) Lowest medial pressure: Cavus + Varus (118.4 g/cm²) Difference: +88.4 g/cm² (+74.7%), $p<0.001$

Table 8. Mean Lateral Pressure (g/cm²) by Combined Groups

Arch Type	Normal Knee	Valgus Knee	Varus Knee
Normal	147.2 ± 43.5 (n=7)	138.7 ± 39.8 (n=5)	150.6 ± 46.2 (n=3)
Flat	142.5 ± 38.9 (n=6)	116.3 ± 32.1 (n=6)	135.8 ± 41.3 (n=2)
Cavus	151.0 ± 47.8 (n=5)	142.5 ± 44.2 (n=5)	**178.5 ± 52.1 (n=2)**

Highest lateral pressure: Cavus + Varus (178.5 g/cm²) Lowest lateral pressure: Flat + Valgus (116.3 g/cm²) Difference: +62.2 g/cm² (+53.5%), $p=0.002$

Interpretation: The significant interaction ($p=0.013$, $\eta^2p=0.328$) demonstrates that the effect of foot arch type on plantar pressure depends on knee alignment status:

- Synergistic amplification: Flat foot + genu valgum produces additive medial overload (206.8 g/cm²), exceeding either factor alone.
- Opposite-direction synergy: Cavus foot + genu varum creates maximum lateral stress (178.5 g/cm²) with minimum medial loading (118.4 g/cm²).
- Compensatory patterns: Opposing morphologies (flat+varus or cavus+valgus) show more balanced pressure distribution, suggesting partial mutual compensation.

3.6 Correlational Analysis: ΔCoF and Plantar Pressure

Table 9. Spearman Correlations Between ΔCoF and Regional Pressures

Pressure Region	Left Foot ρ	p-value	Right Foot ρ	p-value	Interpretation
Forefoot	0.445	0.003†	0.428	0.005†	Moderate positive
Rear foot	0.312	0.046†	0.298	0.057	Weak positive
Medial	0.381	0.014†	0.367	0.018†	Moderate positive
Lateral	0.246	0.118	0.234	0.139	Weak/NS

†Significant at $p<0.05$; NS=not significant

Key Findings:

Anterior pressure: Moderate positive correlation with ΔCoF (ϱ=0.445, p=0.003). Interpretation: 10mm increase in ΔCoF associates with ~24g/cm² increase in anterior pressure. Medial pressure: Moderate positive correlation (ϱ=0.381, p=0.014). Interpretation: Greater CoF excursion accompanies increased medial loading. Posterior pressure: Weak positive correlation (ϱ=0.312, p=0.046). Lateral pressure: No significant correlation (p>0.05).

Clinical Significance: Increased ΔCoF (indicating reduced dynamic stability) preferentially associates with anterior and medial pressure elevation, suggesting these regions experience greater stress during postural instability.

3.7 Additional Correlations

Table 10. Correlations Between Anthropometric Variables and Pressure Parameters

Variable Pair	Spearman ϱ	p-value	Interpretation
BMI ↔ Medial pressure	0.389	0.012†	Moderate positive
BMI ↔ Forefoot pressure	0.356	0.022†	Moderate positive
BMI ↔ ΔCoF	0.298	0.057	Weak/NS
Weight ↔ Medial pressure	0.412	0.007†	Moderate positive
Age ↔ ΔCoF	0.156	0.332	Weak/NS

†Significant at p<0.05

Key Finding: Higher BMI significantly correlates with increased medial and anterior plantar pressures, consistent with obesity's role in loading pattern alterations.[22]

3.8 Summary of Statistical Results

Table 11. Hypothesis Testing:

Hypothesis	Result	Evidence
H1: Flat foot shows increased medial pressure	**SUPPORTED**	Flat: 185.64 vs Normal: 148.27 vs Cavus: 135.83 g/cm², F=8.94, p<0.001
H2: Knee alignment influences pressure distribution	**SUPPORTED**	Valgus: 178.31 vs Normal: 142.78 vs Varus: 138.86 g/cm² (medial), F=5.67, p=0.007
H3: Significant arch × knee interaction exists	**SUPPORTED**	F(4,31)=3.78, p=0.013, η^2p=0.328
H3a: Flat+valgus produces maximum medial loading	**SUPPORTED**	206.8 g/cm² (highest observed combination)
H3b: Cavus+varus generates maximum lateral stress	**SUPPORTED**	178.5 g/cm² lateral, 118.4 g/cm² medial (extreme lateral bias)

4. Discussion

4.1 Principal Findings

This study demonstrates that foot arch morphology and knee alignment independently and interactively influence plantar pressure distribution patterns in healthy adults. The significant interaction effect (F=3.78, p=0.013, η^2p=0.328) provides empirical evidence that these morphological variables operate synergistically rather than additively, creating combined biomechanical profiles with distinct clinical implications.

4.2 Foot Arch Type Effects

Flat foot subjects exhibited 36.7% higher medial pressure than cavus foot (p<0.001) and 24.9% greater ΔCoF (p=0.003), confirming biomechanical consequences of arch collapse. These findings align with previous research demonstrating that flat increases medial contact area and alters load distribution.

The elevated ΔCoF in flat foot (52.86±13.24 mm vs 41.25±9.85 mm in cavus) indicates compromised dynamic stability,[22] suggesting that arch insufficiency impairs neuromuscular control during gait. This instability-loading relationship creates a high-risk profile for:

Medial tibial stress syndrome: Repetitive medial overload;

Plantar fasciitis: Excessive arch strain;

Posterior tibial tendon dysfunction: Chronic pronation stress;

Medial knee osteoarthritis progression: Transmitted valgus moments.

Conversely, cavus foot demonstrated 23.8% higher lateral pressure than flat foot (p=0.019) with the lowest ΔCoF (41.25 mm), reflecting rigid arch structure. While seemingly more "stable" (lower CoF excursion), this represents rigid rather than controlled stability with concentrated loading on reduced contact areas. The cavus foot profile increases risks for: lateral ankle instability: supination tendency; fifth metatarsal stress fractures: concentrated lateral forefoot loading; plantar fascia strain: limited shock absorption capacity; metatarsalgia: elevated forefoot peak pressures.

These findings extend previous work by quantifying the magnitude of pressure differences and demonstrating the stability-loading trade-off between foot arch types.[10–12]

4.3 Knee Alignment Effects

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.[13–16]

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.[17],[18]

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 Synergistic Interaction Effects

The most clinically significant finding is the significant interaction between arch type and knee alignment (p=0.013, η^2p=0.328), demonstrating that combined morphological deviations produce non-additive biomechanical consequences.

High-Risk Combinations

Flat Foot + Genu Valgum (Maximum Medial Overload): medial pressure: 206.8±48.3 g/cm² (highest observed), represents 49.3% increase over normal arch + normal knee (138.5 g/cm²), synergistic mechanism: arch collapse + valgus knee alignment both promote medial loading, creating additive stress concentration.

Clinical Implications: this combination creates the highest risk profile for: rapid medial knee OA progression: chronic medial compartment overload accelerates cartilage degeneration [15], [16], posterior tibial tendon insufficiency: sustained pronation stress exceeds tendon capacity[24], medial longitudinal arch pain: excessive and prolonged loading causes structural fatigue, patellofemoral pain syndrome: valgus-associated tracking abnormalities.

Cavus foot + genu varum (maximum lateral stress): lateral pressure: 178.5±52.1 g/cm² (highest lateral loading), medial pressure: 118.4±28.9 g/cm² (lowest medial loading), medial: lateral ratio: 0.66 (extreme lateral bias), represents 53.5% higher lateral pressure than flat+valgus (116.3 g/cm²).

Clinical Implications: This profile increases risks for: lateral ankle sprains: chronic supination stress and reduced proprioceptive control [19], [20] lateral knee OA: concentrated lateral compartment loading, fifth metatarsal fractures: repetitive lateral column stress, peroneal tendinopathy: compensatory muscle overuse.

Compensatory Combinations. Interestingly, opposing morphologies (flat foot + genu varum or cavus foot + genu valgum) demonstrated more balanced pressure distributions: Flat + Varus: 152.5 g/cm² medial, 135.8 g/cm² lateral (ratio: 1.12), Cavus + Valgus: 141.2 g/cm² medial, 142.5 g/cm² lateral (ratio: 0.99). This suggests partial biomechanical compensation where opposite-direction deformities may neutralize each other's effects. However, this "balance" may mask underlying structural issues requiring intervention, and the compensatory mechanisms may still create abnormal joint stresses despite normalized pressure distribution.

4.5 Center of Force Variation Relationships

The moderate positive correlations between ΔCoF and anterior pressure (ϱ=0.445, p=0.003) and medial pressure (ϱ=0.381, p=0.014) provide mechanistic insights into the stability-loading relationship.

Interpretation: Greater CoF excursion (indicating reduced postural control) associates with increased loading in structurally critical regions—the forefoot (essential for propulsion) and medial arch (primary weight-bearing structure). This pattern suggests that when dynamic stability is compromised, the neuromuscular system compensates by: increasing muscle co-contraction to stiffen joints [21], redistributing loads to more stable anatomical regions [22], prolonging contact time to enhance balance at cost of efficiency[30]. The absence of significant ΔCoF-lateral pressure correlation ($p>0.05$) may reflect that lateral structures (fifth metatarsal, lateral arch) serve more specialized roles in directional control rather than primary stability maintenance.

4.6 Clinical Application Framework

Based on these findings, we propose a risk stratification and intervention targeting framework:

Risk Stratification:

TIER 1 – Critical Risk (Immediate Intervention Required):

- Flat foot + Genu valgum + Elevated BMI (≥25 kg/m²)
  - o Expected medial pressure: >200 g/cm²
  - o OA progression risk, PTTD risk, chronic pain trajectory
- Cavus foot + Genu varum + High ΔCoF (>55 mm)
  - o Expected lateral pressure: >170 g/cm²
  - o Ankle instability risk, stress fracture risk, proprioceptive deficits

TIER 2 – Moderate Risk (Preventive Intervention Recommended):

- Single morphological deviation (arch OR knee alignment abnormal)
- Opposing deformities with balanced distribution but abnormal mechanics
- ΔCoF elevation (45-55 mm) without morphological deviations

TIER 3 – Low Risk (Monitoring Only):

- Normal arch + Normal knee alignment
- ΔCoF <45 mm
- Balanced medial:lateral pressure ratios (0.90-1.10)

Intervention Guidelines

For Flat Foot + Genu Valgum:

- Orthotic management: Custom foot orthoses with medial arch support and posting to control pronation [23]
- Proximal strengthening: Hip abductor and external rotator exercises to reduce dynamic knee valgus [24]
- Intrinsic foot strengthening: Short foot exercise, toe curls to enhance active arch support [25]

- Gait retraining: Techniques to reduce excessive pronation and improve alignment [26]
- Weight management: If BMI elevated, targeted weight reduction to decrease loading magnitude

For Cavus Foot + Genu Varum:

- Cushioned orthoses: Shock-absorbing insoles without rigid arch support
- Flexibility training: Ankle dorsiflexion and plantar flexion mobility exercises
- Peroneal strengthening: Resistance band eversion exercises for lateral stability
- Proprioceptive training: Single-leg balance progressions, wobble board exercises
- Lateral wedge consideration: For severe varus, lateral wedge insoles may redistribute loading medially

For Elevated ΔCoF:

- Progressive balance training: Static → dynamic → perturbation-based exercises
- Core stabilization: Trunk and hip control to improve proximal stability
- Neuromuscular reeducation: Controlled single-leg stance with visual feedback
- Functional task practice: Sport-specific or ADL-specific stability challenges

4.7 Comparison with Previous Research

Our findings corroborate and extend the existing literature:

Confirming previous evidence: arch type effects on pressure distribution [9], knee alignment influence , CoF-pressure relationships.

Novel Contributions:

- Quantification of interaction magnitude: $\eta^2 p=0.328$ demonstrates large effect size for arch×knee interaction
- Identification of extreme risk profiles: Specific combinations (flat+valgus, cavus+varus) with quantified loading patterns
- Compensatory pattern documentation: Evidence for partial biomechanical neutralization with opposing deformities
- Stability-loading coupling: Correlation structure linking ΔCoF to regional pressure distribution

4.8 Study Strengths

- Comprehensive morphological assessment: Simultaneous evaluation of foot arch, knee alignment, and spinal posture
- Validated measurement tools: FPI-6 for arch classification, standardized baropodometry protocols
- Factorial design: Enables interaction effect detection beyond main effects
- Adequate statistical power: Sample size supports ANOVA and correlational analyses
- Clinically relevant outcomes: Direct translation to assessment and intervention protocols

4.9 Study Limitations

Design Limitations. Cross-sectional design: precludes causal inference and temporal sequence determination. While we observe associations between morphology and pressure patterns, we cannot determine: whether pressure patterns caused morphological adaptations (e.g., chronic loading leading to arch changes), whether morphology causes pressure alterations (structural determinism), whether both result from shared underlying factors (e.g., genetic predisposition, early development).

Future direction: longitudinal studies tracking morphological and pressure changes over time; intervention trials demonstrating causality through manipulation.

Sample Characteristics. Healthy young adult population: Mean age 22.17±3.89 years limits generalizability to: pediatric populations: developing skeletal structure may show different patterns, elderly populations: age-related tissue changes (fat pad atrophy, ligamentous laxity) alter biomechanics, clinical populations: diabetes, arthritis, neurological conditions produce distinct pathomechanics, convenience sampling: non-random recruitment may introduce selection bias toward physically active, health-conscious individuals.

Small subgroup sizes: Some combined categories had limited participants (e.g., cavus+varus: n=2), reducing statistical power for interaction detection and increasing type II error risk.

Future direction: Larger multi-site studies with stratified sampling; targeted recruitment of clinical populations; pediatric and elderly cohort studies.

Measurement considerations. Single-session assessment: day-to-day variability in biomechanical parameters not evaluated; test-retest reliability unknown for this specific protocol. Baropodometric platform limitations: captures only foot-ground interface; cannot measure internal joint forces or muscle activation patterns, single platform crossing may not represent habitual gait patterns, targeting effect possible despite runway approach.

Static vs dynamic discrepancy: static measurements may not fully predict dynamic loading patterns during functional activities. Future direction: multi-session reliability studies; integration with 3D motion capture and EMG for comprehensive biomechanical characterization; in-shoe pressure monitoring for real-world data.

Statistical considerations. Multiple comparisons: despite Bonferroni corrections, familywise error rate accumulates across multiple dependent variables; risk of type I error inflation.

Unequal group sizes: particularly for knee alignment categories (varus: n=7 vs valgus: n=16), may affect ANOVA robustness despite non-parametric alternatives.

Assumption violations: some pressure variables showed non-normal distributions, necessitating non-parametric approaches that may have reduced statistical power.

Unexplored nonlinear relationships: regression models assume linearity; potential threshold effects or quadratic relationships not investigated. Future direction: false discovery rate corrections for multiple testing; larger balanced samples; advanced modeling (generalized additive models, machine learning) for nonlinear pattern detection.

4.10 Future Research Directions

Based on current findings and identified limitations, we recommend: intervention efficacy trials. Randomized controlled trials evaluating: custom orthoses vs prefabricated insoles in flat+valgus subjects, hip strengthening programs for dynamic valgus control, intrinsic foot muscle training for arch support enhancement. Outcome measures: pre-post baropodometry, pain scales, functional performance, imaging.

Longitudinal cohort studies. Pediatric development: tracking arch-knee-pressure relationships from childhood through adolescence, aging trajectories: following adults through middle age to identify degenerative patterns, injury prediction, prospective studies linking baseline biomechanics to incident musculoskeletal injuries.

Clinical population studies. Diabetes cohorts: neuropathy effects on pressure-morphology relationships, osteoarthritis patients: pre-post arthroplasty biomechanical changes, neurological conditions: stroke, Parkinson's disease, cerebral palsy pressure patterns.

Advanced biomechanical analysis

3D motion capture integration, complete lower extremity kinematics during gait, musculoskeletal modeling, computational simulation of joint forces and muscle demands; finite element analysis: internal tissue stress distribution modeling; machine learning: predictive algorithms for injury risk stratification and intervention response.

Mechanism investigation. EMG analysis: intrinsic and extrinsic foot muscle activation patterns during loading; sensory testing: plantar mechanoreceptor function and pressure regulation.

Fatigue protocols: changes in biomechanics with prolonged walking;

Dual-task paradigms: cognitive loading effects on stability and pressure.

5. Conclusions

This study provides comprehensive evidence that foot arch morphology and knee alignment independently and synergistically influence plantar pressure distribution patterns in healthy adults. Key conclusions include:

5.1 Primary Findings

- **Significant main effect of arch type:** Flat foot increases medial pressure by 25-37% and ΔCoF by 25% compared to normal/cavus arch ($p<0.001$), indicating both structural and stability deficits.
- **Significant main effect of knee alignment:** Genu valgum elevates medial pressure by 25-28% compared to normal/varus alignment ($p=0.007$), confirming proximal-to-distal biomechanical transmission.
- **Significant interaction effect:** Arch type and knee alignment interact to influence pressure distribution ($F=3.78$, $p=0.013$, $\eta^2p=0.328$), with:
  - **Flat foot + Genu valgum** producing maximum medial overload (206.8 g/cm², +49% vs normal);
  - **Cavus foot + Genu varum** creating maximum lateral stress (178.5 g/cm², +54% vs flat+valgus lateral);
  - **Opposing morphologies** showing partial compensation with more balanced distributions.
- **Stability-loading relationship:** ΔCoF positively correlates with anterior ($\varrho=0.445$) and medial ($\varrho=0.381$) pressures, indicating that compromised dynamic stability manifests as regional loading increases.

5.2 Clinical Implications

For assessment:

- Comprehensive evaluation required: Isolated assessment of arch OR knee is insufficient; combined evaluation provides superior risk stratification
- Dynamic stability measurement: ΔCoF should be integrated into baropodometric assessments as stability indicator
- Risk profiling: Synergistic morphological combinations (flat+valgus, cavus+varus) warrant priority intervention

For intervention:

- Multimodal approaches: Address both structural (orthoses) and neuromuscular (exercise, gait training) components
- Proximal targeting: Hip strengthening for valgus control, core stabilization for overall stability
- Individualized prescription: Match intervention to specific arch-knee combination profile

- Distal-proximal integration: Foot interventions should consider knee mechanics; knee interventions should monitor foot loading

For prevention:

- Early screening: Combined arch-knee assessment in adolescents may identify future injury risks
- Athletic populations: Sport-specific loading patterns should inform injury prevention programs
- Weight management: BMI reduction beneficial for medial pressure control in flat+valgus profile

5.3 Practical Application

Clinical decision framework:

- Screen: FPI-6 + intercondylar/intermalleolar distance measurement
- Stratify: Identify high-risk combinations (flat+valgus, cavus+varus)
- Quantify: Baropodometric assessment with regional pressure and ΔCoF
- Intervene: Targeted multimodal program based on specific profile
- Monitor: Serial pressure measurements to evaluate intervention efficacy

Evidence-based recommendation: Combined foot arch and knee alignment assessment should be standard practice in biomechanical evaluations for musculoskeletal conditions, athletic screening, and fall risk assessment. The significant interaction effect demonstrates that these morphological variables operate synergistically, requiring integrated rather than isolated intervention approaches.

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