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Evaluating the link between static foot alignment and dynamic plantar loading in type 2 diabetes: a cross-sectional study

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Abstract

Introduction: In type 2 diabetes mellitus (T2DM), elevated cumulative plantar loading contributes to ulcer risk, especially in patients with neuropathy. Static foot posture may influence plantar load distribution, but evidence remains limited. **Objective:** This study aimed to examine the association between FPI-6 and PTI during walking in adults with T2DM attending outpatient services at RSUD Dr. Soetomo, Surabaya. **Methods**: A cross-sectional study was conducted in May–July 2025 at RSUD Dr. Soetomo, enrolling 33 adults with T2DM (no dropouts). Foot posture was assessed using the FPI-6, and plantar pressure-time integral (PTI) was recorded with an in-shoe pressure system (Pedar-X) during walking; participants completed 20 steps while cadence was maintained with a metronome. Normality testing used the Shapiro–Wilk test; correlation used Pearson when assumptions were met. **Results:** Most participants had neutral foot posture (right 82.4%; left 70.6%). The mean PTI was highest in the forefoot, followed by the hindfoot. Correlation between total FPI and PTI was not significant for hindfoot or forefoot (all p > 0.05). **Conclusion:** Static foot posture (FPI-6) was not associated with dynamic cumulative plantar loading (PTI) in this T2DM cohort. These findings support the use of a combined risk assessment strategy (neuropathy, deformity, joint motion, and dynamic plantar pressure) rather than relying on static posture alone.

Keywords: Diabetes Mellitus type 2. Rehabilitation. Foot Posture Index. Pressure Time Integral.

Introduction

Type 2 diabetes mellitus (T2DM) is common worldwide and continues to rise, with major downstream morbidity from microvascular and macrovascular complications **[1,2]**. Among these, diabetic foot disease is clinically consequential because ulceration often precedes infection, hospitalization, and lower-limb amputation, and recurrence remains frequent even after healing **[3,4]**. Pathophysiologically, chronic hyperglycemia drives oxidative stress and inflammatory pathways that damage peripheral nerves and microvasculature, creating a substrate for tissue breakdown under mechanical stress **[5,6]**.

Mechanical loading is a central modifiable factor in ulcer pathogenesis. Classic work and subsequent syntheses have linked neuropathy and elevated plantar pressure to ulcer risk, and newer reviews emphasize that gait alterations in neuropathy can further change plantar loading patterns **[7,8]**. Contemporary prevention guidance therefore recommends systematic foot risk assessment and early offloading strategies in people with diabetes at increased risk **[9,10]**.

Plantar loading can be characterized beyond peak pressures. Pressure–time integral (PTI) quantifies cumulative pressure exposure over the stance phase and has been proposed as a clinically meaningful determinant of neuropathic ulceration, although it remains underused compared with peak pressure metrics **[11,12]**. PTI is also sensitive to changes in contact time and rollover strategy, which may be particularly relevant in neuropathic gait **[8]**.

In routine practice, static foot posture is often assessed because it is rapid and inexpensive. The Foot Posture Index (FPI-6) provides a standardized clinical method to classify standing foot posture across a spectrum from supinated (cavus) to pronated (planus). However, static alignment does not necessarily translate to dynamic loading during gait, and evidence linking FPI to plantar pressure measures in people with T2DM is still emerging **[13,14]**. This study aimed to examine the association between FPI-6 and PTI during walking in adults with T2DM attending outpatient services at RSUD Dr. Soetomo, Surabaya.

Methods

It was conducted a cross-sectional study at Dr. Soetomo General Academic Hospital Center, Surabaya, Indonesia, between May and July 2025. Adults with T2DM were recruited consecutively from outpatient endocrine and rehabilitation services. The diagnosis of T2DM was made in accordance with national and international criteria, consistent with PERKENI guidance and ADA classification frameworks. Consecutive sampling was conducted to reduce selection bias in a clinic-based population. Participants provided written informed consent, and the study was approved by the institutional health research ethics committee. Eligibility was designed to ensure that participants could safely complete the gait assessment and that the measurements reflected typical ambulatory loading. Individuals with active ulceration, Charcot neuroarthropathy, acute inflammatory foot conditions, substantial gait-limiting comorbidities, or unstable cardiopulmonary status were excluded, consistent with standard precautions for functional testing and gait measurement

Foot Posture Index (FPI-6)

Standing foot posture was assessed using the six-item Foot Posture Index (FPI-6) following the published user guide and validation work. The FPI-6 has demonstrated reliability in clinical settings and provides a graded score across multiple anatomical observations, allowing categorization of the foot as supinated, neutral, or pronated. Normative values and population variability have been described, supporting interpretation in adult cohorts.

Outcome measure: pressure–time integral (PTI)

Dynamic plantar loading was measured using an in-shoe plantar pressure system (Pedar-X). In-shoe measurement is widely used in diabetic foot biomechanics because it captures pressure distribution under footwear conditions relevant to daily walking. PTI was defined as the time integral of plantar pressure during stance, representing cumulative load exposure. Device repeatability for Pedar-X has been reported, supporting its use in clinical research. Because plantar pressure metrics can show within-subject variability, standardized walking procedures and consistent footwear conditions were used to improve measurement stability

Procedure

Participants wore standardized socks and suitable walking shoes. After familiarisation walking, plantar pressure data were recorded during straight-line walking over a defined number of steps, and PTI was extracted for predefined plantar regions. Approaches to testing footwear and in-shoe pressure protocols in the context of diabetic foot have been described previously. Data distribution was assessed and correlation analysis was used to test the primary association between FPI-6 and PTI. R-Studio RStudio 2025.05. version was used for statistical analysis.

Before conducting research on patients about Evaluating the Link Between Static Foot Alignment and Dynamic Plantar Loading in Type 2 Diabetes, first make a declaration of informed consent as approval to participate in this research.

Ethical Approval

This research was conducted after ethical of proposal was approved by the ethics committee of Dr. Soetomo General Academic Hospital Center with the ethical clearance number 1247/KEPK/II/2025.

Results

Participants

Thirty-three adults with T2DM were include. The study sample was assessed between May and July 2025. Mean age was 52.47 years (SD 5.48; range 40-57), with 21 (63.6%) women. Mean BMI was 23.79 kg/m² (± 2.22; range 18.2–24.7), and mean diabetes duration was 7.62 years (SD 6.05; range 1-23). The use of habitual footwear was most commonly sports shoes (33.3%) and barefoot walking (30.3%). Peripheral neuropathy status was recorded in 28 participants, with 5 recorded as non-PNP (Table 1).

Table 1. Baseline characteristics of Subject

Characteristic	
Age, years	52.47 ± 5.48 (range 40–57)
Sex, n (%)	Male 12 (36.4%); Female 21 (63.6%)
Weight, kg	62.58 ± 10.96
Height, cm	161.67 ± 8.90
BMI, kg/m²	23.79 ± 2.22 (range 18.2–24.7)
Duration of T2DM, years	7.62 ± 6.05 (range 1–23)
Neuropathy category, n (%)	PNP 28 (84.8%); non-PNP 5 (15.2%)
Habitual footwear, n (%)	Sports shoes 11 (33.3%); other shoes 6 (18.2%); sandals 6 (18.2%); barefoot 10 (30.3%)

Source: Own authorship.

Foot Posture Index

Mean FPI-6 score was 1.45 (±2.53) for the right foot and 0.42 (± 2.01) for the left foot. Most participants had neutral foot posture: 28 (82.4%) in the right foot and 24 (70.6%) in the left foot. Supinated posture was observed in 5 (14.7%) right feet and 10 (29.4%) left feet; pronation was uncommon (1 right foot; none in the left) (Table 2).

Table 2. Foot Posture Index and Pressure Time Integral.

Measure	Right foot	Left foot
FPI-6 total score (mean ± SD)	1.45 ± 2.53	0.42 ± 2.01
FPI-6 category, n (%)		
Supinated	5 (14.7%)	10 (29.4%)
Neutral	28 (82.4%)	24 (70.6%)
Pronated	1 (2.9%)	0
PTI (combined right + left), mean ± SD (kPa·s)		
Hindfoot (M01)	55.34 ± 13.08	
Midfoot (M02)	56.80 ± 12.44	
Forefoot (M03)	73.06 ± 16.05	
Hallux (M04)	42.57 ± 8.24	
Toes (M05)	25.99 ± 10.28	

Source: Own authorship.

Pressure Time Integral

PTI distributions across plantar regions met normality criteria (Shapiro–Wilk p values >0.05 across regions). The forefoot showed the highest mean PTI (73.06 kPa·s, SD 16.05), followed by the hindfoot (55.34 kPa·s, SD 13.08). Mean PTI values for other regions were: midfoot 56.80 kPa·s (SD 12.44), hallux 42.57 kPa·s (SD 8.24), and toes 25.99 kPa·s (SD 10.28).

Association between FPI-6 and PTI

Pearson correlation analysis found no statistically significant association between total FPI-6 score and PTI in the hindfoot or forefoot regions for either foot (all $p>0.05$). Correlation coefficients ranged from −0.261 to 0.116, indicating no strong linear relationship in this sample (Table 3).

Table 3. Correlation analysis between FPI and PTI.

PTI region (mean ± SD, kPa·s)	Correlation with Right FPI (r)	p value	Correlation with Left FPI (r)	p value
Hindfoot (55.34 ± 13.08)	0.116	0.520	−0.035	0.845
Forefoot (73.06 ± 16.05)	−0.075	0.680	−0.261	0.142

Source: Own authorship.

Discussion

Our study showed that static foot posture, as quantified by the FPI-6, was not associated with cumulative plantar loading, measured by PTI, at the hindfoot or forefoot during walking. This result is clinically relevant because diabetic foot risk assessment often includes static observations, yet ulceration risk reflects dynamic tissue stresses during gait and their interaction with neuropathy and tissue vulnerability **[10]**.

Several mechanisms may explain the absence of association. First, static posture in standing and dynamic loading during walking are related but non-equivalent constructs. PTI is influenced by both pressure magnitude and contact time, and neuropathic gait can alter rollover and stance duration in ways not captured by static alignment measures **[8,11]**. Furthermore, the plantar tissue environment in diabetes is affected by neuropathy and microvascular compromise, meaning similar postures can yield different loading patterns and tissue tolerance profiles across individuals **[5,6]**. Lastly, measurement variability is inherent to plantar pressure assessment; even with standardization, residual within-person variation can attenuate posture–loading correlations in moderate sample sizes **[15]**.

Our findings fit with a broader literature suggesting that relationships between foot posture or morphology and plantar pressure are complex and context-dependent. Studies have reported associations between posture and plantar pressures in mixed diabetes and non-diabetes samples, but effect sizes and regional patterns vary by neuropathy status, footwear condition, and the pressure metric used **[13,16]**. Recent work in community-dwelling adults with T2DM examining FPI–pressure relationships similarly suggest posture may explain only part of plantar loading variability, with dynamic and neuropathy-related factors often predominating **[8,14]**. Footwear can also substantially modify plantar pressure profiles, while real-world adherence to protective footwear is variable, complicating posture-based inference **[17,18]**.

Clinically, the implication is not that posture assessment is unhelpful, but that it should not be used as a surrogate for dynamic plantar loading. Prevention frameworks emphasise multifactorial risk assessment incorporating neuropathy evaluation, deformity, skin status, and previous ulceration, supported by offloading strategies where appropriate **[9,10]**. Where available, dynamic plantar pressure assessment can add actionable information to guide targeted offloading and footwear prescription, particularly in neuropathic feet or in those with recurrent callus formation **[12,19]**.

This study has limitations. The cross-sectional design precludes causal inference or prediction of ulcer outcomes **[20]**. A clinic-based sample may limit generalisability, and restricted variability in posture categories can reduce power to detect associations. In addition, unmeasured or residual confounding related to walking speed, habitual footwear, and activity exposure could influence PTI independent of posture **[17,21]**. Future studies would benefit from longitudinal designs linking posture and PTI to incident ulceration, multivariable adjustment for gait speed and exposure, and stratification by neuropathy severity.

Strength and limitations

This study combined pragmatic clinical exposure to using the FPI-6 with an objective biomechanical outcome, the PTI, under a standardized walking procedure, while being monitored with the Pedar-X. The use of a validated posture tool and a reproducible plantar pressure platform supports the credibility of the measurements. Several limitations were noticed in this research. The cross-sectional design limits the understanding of directionality or clinical prediction. Moreover, a modest sample size together with a posture distribution concentrated around neutral reduces the power to detect posture-related gradients. Generalisability may also be limited by the single-center outpatient setting and restrictive eligibility criteria. Finally, residual confounding and measurement variability may have attenuated associations. The primary analysis was an unadjusted correlation despite plausible influences such as walking speed, habitual footwear, activity exposure, diabetes duration, and neuropathy severity; these factors may modify PTI independently of posture. Plantar pressure metrics, including PTI, also show within-person variability even with standardisation, which can dilute effect estimates in smaller cohorts.

Conclusion

Static foot posture (FPI-6) was not associated with dynamic cumulative plantar loading (PTI) in this T2DM cohort. These findings support using a combined risk assessment strategy (neuropathy, deformity, joint motion, and dynamic plantar pressure) rather than relying on static posture alone.

CRediT

Author contributions: Conceptualization: Amelinda Vashistiyana Traviata Prakarti (AVTP), I Putu Alit Pawana (IPA), Nurul Kusuma Wardani (NKW), Sony Wibisono Mudjanarko (SWM), Atika (ATK) Methodology: AVTP, IPA, NKW, SWM, ATK Validation: IPA, NKW, SWM, ATK. Data curation: AVTP, ATK. Formal analysis: AVTP, ATK. Supervision: IPA, NKW, SWM,. Writing – original draft: AVTP, IPA, NKW, SWM Writing – review & editing: AVTP, IPA, NKW, SWM, ATK.

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Not applicable.

Ethical Approval

This research was conducted after ethical of proposal was approved by the ethics committee of Dr. Soetomo General Academic Hospital Center with the ethical clearance number 1247/KEPK/II/2025.

Informed Consent

Not applicable. This study was observational and cross-sectional.

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Data Sharing Statement

The data used in this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

Similarity Check

It was applied by Ithenticate@.

Application of Artificial Intelligence (AI)

Not applicable.

Peer Review Process

It was performed.

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