Region-Specific Association Between Heel Pad Thickness and Peak Plantar Pressure in Diabetic Peripheral Neuropathy

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ABSTRACT:

Objective: The aims of this research was to assess the correlation between peak plantar pressure and heel pad thickness in individuals with diabetic peripheral neuropathy. **Material and Methods:** A cross-sectional analytical observational research including 21 individuals with peripheral neuropathy and type 2 diabetes mellitus was carried out. The maximal plantar pressure in four distinct locations of the foot—the hindfoot, the midfoot, the forefoot, and the hallux were measured using a Pedar-X device. To find out how thick the heel pad was, ultrasonography was used. We used correlation analysis to find out how the variables were related to one another. **Results:** The average peak plantar pressure was within the normal range in every area, with the hindfoot showing the highest values. Similarly, the thickness of the heel pads was within the typical range and did not change noticeably between the right and left feet. With the exception of the right hindfoot, where a robust positive correlation between heel pad thickness and peak plantar pressure was seen ($r = 0.650$, $p = 0.002$), no significant associations were found in other plantar sites. **Conclusion:** Heel pad thickness is not a universal predictor of peak plantar pressure in patients with diabetic peripheral neuropathy. The relationship appears to be region-specific and influenced by multiple factors. Dynamic plantar pressure assessment may provide more clinically relevant information for identifying ulcer risk. These findings support a multifactorial approach in evaluating and preventing diabetic foot complications.

Keywords: diabetic peripheral neuropathy, heel pad thickness, peak plantar pressure, plantar biomechanics, diabetic foot

1. Introduction

Diabetic mellitus is defined by persistently elevated blood sugar levels due to inadequate insulin production or action [1]. Over the last several decades, diabetes has become much more common, and it continues to be a major concern for healthcare systems worldwide. The number of people diagnosed with diabetes is continuing to rise, according to the International Diabetes Federation. This is particularly true in countries with low or medium incomes. There was a substantial increase in the disease burden in Indonesia, as the prevalence of diabetes rose from 6.9% in 2013 to 8.5% in 2018, according to national health surveys [2]. Diabetes is becoming one of the most common diagnoses in outpatient services in big cities like Surabaya, underscoring the growing clinical need for long-term problem care and prevention.

Diabetic foot is one of the most dangerous and expensive disorders among the many consequences of diabetes. Significant morbidity, functional impairment, and increased mortality are linked to diabetic foot. Peripheral neuropathy, vascular dysfunction, and compromised wound healing mechanisms are all part of the complex pathophysiology of diabetic foot [3]. Lower-extremity amputation is more likely when peripheral artery disease worsens tissue ischemia and slows wound healing [4]. Not only do 84% of non-traumatic lower limb amputations worldwide occur before diabetic foot ulcers, but they also have a significant financial and therapeutic effect [5]. Diabetics are 15–25% more likely to have foot ulcers throughout their lifetimes, and recurrence rates may approach 50–70% in the five years after ulcer healing[6].

Diabetic foot issues are mostly caused by biomechanical factors in addition to metabolic and vascular abnormalities. One of the most reliable signs of foot ulceration in patients with diabetic neuropathy is high plantar pressure. Due to changed walking patterns, muscular weakness, and anatomical abnormalities in the foot, people with diabetes often have greater plantar pressure than healthy people [7]. According to earlier research, up to 94% of diabetic foot ulcers develop in regions that are subjected to high plantar pressure. [8]. In addition, patients who subsequently develop ulcers often demonstrate significantly higher baseline peak plantar pressure compared with those who remain ulcer-free, particularly in the presence of neuropathy, foot deformities, or previous amputations [9].

Given this strong biomechanical component, evaluation of plantar pressure distribution has become an important approach for identifying high-risk areas on the foot. Advances in pressure measurement technology have enabled more accurate and dynamic assessment of plantar loading during gait. In-shoe pressure measurement systems such as PEDAR-X allow detailed analysis of plantar pressure distribution under real-life walking conditions and have been widely used in clinical research to guide preventive strategies, footwear modifications, and rehabilitation interventions [10,11].

In furtherance of abnormal plantar pressure, structural alterations in plantar soft tissues may also contribute to increased mechanical stress in individuals with diabetes. Walking-related repetitive stress may cause the heel fat pad to degenerate, changing the tissue's thickness and suppleness [12]. Important for distributing mechanical stresses and protecting the underlying calcaneus from excessive stress during the stance phase of locomotion, the heel fat pad is a shock-absorbing tissue [13]. Degeneration or structural alteration of this tissue may compromise its cushioning capacity, potentially increase local plantar pressure and predispose the foot to tissue breakdown.

Heel pad thickness (HPT) has been proposed as an indicator of structural changes in plantar soft tissues among patients with diabetes and ultrasonographic assessment offers a non-invasive and accessible method for evaluating heel fat pad morphology[3]. Although alterations in plantar soft tissue thickness may influence pressure distribution and ulcer development, the biomechanical relationship between heel pad structure and plantar pressure remains poorly understood. Most prior studies have focused on forefoot pressure, with relatively little attention given to the heel region[14,15]. Despite occurring less frequently, heel ulcers are often associated with delayed healing, higher treatment costs, and poorer clinical outcomes[16,17], making this an important area of investigation. Studies specifically examining the relationship between HPT and plantar pressure in diabetic peripheral neuropathy remain scarce, particularly in Southeast Asian populations, where in-shoe plantar pressure assessment is not yet routinely adopted in clinical practice. This study therefore aimed to investigate the relationship between HPT and heel peak pressure in patients with type 2 diabetes mellitus and peripheral neuropathy, with the broader goal of supporting early screening strategies for diabetic foot complications.

2. Methodology

Study Design and Setting

This research used a cross-sectional methodology and an analytical observational design. Between October 2024 until the end of data collection, the research was carried out at the Dr. Soetomo General Hospital's Department of Physical Medicine and Rehabilitation in Surabaya, Indonesia.

Population and Sampling

Patients with T2DM who visited the Endocrinology Clinic or the Rehabilitation Medicine Clinic at Dr. Soetomo Hospital comprised the research population. Consecutive sampling was used to enroll participants until the necessary sample size was reached. Based on earlier research by Bus et al. [18], the correlation coefficient formula was used to determine the minimal sample size, assuming $\alpha = 0.05$, $\beta = 0.20$, and an anticipated correlation coefficient (r) of 0.59. Twenty-one people in all fulfilled the study's qualifying requirements.

Inclusion and Exclusion Criteria

Participants were included if they: (1) Had a diagnosis of type 2 diabetes mellitus according to PERKENI 2021 criteria; (2) Had peripheral neuropathy confirmed by the MNSI; (3) Were aged 18–59 years; (4) Had stable hemodynamic status; (5) Had normal cognitive function (MoCA-Ina); (6) Had normal BMI (18.5–24.9 kg/m^2); (7) Were able to walk independently without assistive devices; (8) Provided written informed consent. Individuals were disqualified if they had: (1) An active foot ulcer or Charcot foot; (2) Neuromusculoskeletal disorders affecting gait; (3) Uncontrolled hypertension or unstable vital signs; (4) Hypoglycemia (blood glucose <70 mg/dL) or severe hyperglycemia (≥250 mg/dL); (5) Cardiorespiratory conditions limiting physical performance. Participants who withdrew consent or died during the study were considered dropouts.

Statistical Analysis

All data were analyzed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test was employed to assess the normality of data distribution. Pearson's correlation coefficient was applied to normally distributed variables, while Spearman's rank correlation coefficient was used for non-normally distributed variables, to examine the association between heel pad thickness and heel peak pressure. Statistical significance was set at $p < 0.05$.

Ethical Consideration

This study was conducted in accordance with the Declaration of Helsinki. Ethical approval was granted by the Ethics Committee of Dr. Soetomo General Academic Hospital, Surabaya, Indonesia (Approval No. 1247/KEPK/II/2025). All participants provided written informed consent prior to enrollment, after receiving a thorough explanation of the study's objectives, procedures, and potential risks.

3. Results

The research comprised 21 individuals with type 2 DM who met the inclusion criteria (Table 1); no participants were excluded during the research period. To measure the heel's peak plantar pressure while walking, researchers used the PEDAR-X in-shoe pressure device. To assess the thickness of the heel pad, they used ultrasonography. The PEDAR-X in-shoe pressure measuring device was used to quantify peak plantar pressure while walking in four plantar regions: the hindfoot, midfoot, forefoot, and hallux. Table 2 shows the average peak plantar pressure values for the right and left foot in each plantar area.

Table 1. Baseline characteristics of the study participants (n = 21)

Characteristics	n (%) / Mean ± SD
Sex	
Male	13 (61.9)
Female	8 (38.1)
Age (years)	53.16 ± 4.57
BMI (kg/m²)	23.81 ± 2.61
Normal	6 (28.6)
Overweight	15 (71.4)
Insulin therapy	
Yes	9 (42.9)
No	12 (57.1)
Duration of type 2 diabetes	
< 10 years	8 (38.1)
≥ 10 years	13 (61.9)
Type of footwear	
Sports shoes	7 (33.3)
Barefoot	7 (33.3)
Sandals	4 (19.1)
Shoes	3 (14.3)
Dominant foot	
Right	21 (100)
Left	0 (0)

There were no statistically significant variations between the left and right foot's peak plantar pressure across plantar areas. The mean HPT values for the left and right foot are presented in Table 3. The thickness of the mean heel pad differed somewhat but not significantly between the right and left feet. The results show that the distribution of heel pad thickness was very constant between the right and left feet in persons with T2DM and peripheral neuropathy.

Table 2. Comparison of peak plantar pressure between right and left foot

Plantar Region	**Right Foot (Mean ± SD, kPa)**	**Left Foot (Mean ± SD, kPa)**	**p-value***
Hindfoot (Mask 1)	178.32 ± 41.45	186.57 ± 50.37	0.634
Midfoot (Mask 2)	137.35 ± 40.74	136.26 ± 42.18	0.739
Forefoot (Mask 3)	136.69 ± 40.33	136.26 ± 42.18	0.892
Hallux (Mask 4)	175.23 ± 62.23	159.93 ± 60.71	0.403

*Note: p-value 0,05

Table 3. Heel pad thickness in study participants

Foot	Mean ± SD (mm)	95% Confidence Interval	p-value*
Right	15.38 ± 2.35	14.31 – 16.45	0.782
Left	15.28 ± 1.98	14.38 – 16.18	

*Note: p-value 0,05

Relationship Between Heel Pad Thickness and Peak Plantar Pressure

Table 4 depicts a correlation analysis of peak plantar pressure and heel pad thickness in different plantar locations. Heel pad thickness and peak plantar pressure in the right hindfoot region (Mask 1) had a statistically significant positive relationship ($r = 0.656$, $p = 0.001$). This data suggests that a thicker heel pad was associated with higher peak plantar pressure in this location. The other plantar areas, however, showed no discernible associations. The connection was modest and not statistically significant in the left hindfoot area (Mask 1) ($r = 0.214$, $p = 0.352$). Similarly, no significant associations were observed in the midfoot (Mask 2), forefoot (Mask 3), or hallux (Mask 4) regions for either the right or left foot ($p > 0.05$).

Table 4. Correlation of Heel Pad Thickness with Peak Plantar Pressure Across Plantar Regions

Mask	Left			Right		
	r	95% CI	p-value*	r	95% CI	p-value*
M1	0.214	(-0.240 – 0.591)	0.352	0.656	(0.312 – 0.847)	0.001**
M2	0.040	(-0.399 – 0.464)	0.864	0.273	(-0.180 – 0.630)	0.231
M3	0.040	(-0.399 – 0.464)	0.864	0.273	(-0.180 – 0.630)	0.231
M4	0.023	(-0.413 – 0.450)	0.922	0.090	(-0.355 – 0.502)	0.698

** Statistically significant at $p < 0.05$ (Partial Pearson's correlation)

Relationship Between Heel Pad Thickness and Peak Plantar Pressure

Table 5 shows the association analysis of peak plantar pressure and heel pad thickness across plantar locations. The right hindfoot area (Mask 1) showed a statistically significant positive connection between greater heel pad thickness and higher peak plantar pressure ($r = 0.650$, 95% CI: 0.291–0.848, $p = 0.002$). In contrast, no significant correlations were found in the other regions. In the left hindfoot region, the correlation was moderate but not statistically significant ($r = 0.310$, $p = 0.183$). Similarly, weak, non-significant correlations were observed in the midfoot (Mask 2), forefoot (Mask 3), and hallux (Mask 4) regions for both the left and right feet ($p > 0.05$).

Table 5. Correlation between heel pad thickness and peak plantar pressure according to duration of type 2 diabetes mellitus.

Mask	Left			Right		
	r	95% CI	p-value*	r	95% CI	p-value*
M1	0.310	(-0.153 – 0.662)	0.183	0.650	(0.291 – 0.848)	0.002**
M2	0.159	(-0.305 – 0.562)	0.503	0.285	(-0.180 – 0.646)	0.224
M3	0.159	(-0.305 – 0.562)	0.503	0.285	(-0.180 – 0.646)	0.224
M4	0.066	(-0.388 – 0.494)	0.781	0.187	(-0.279 – 0.581)	0.430

**Statistically significant at $p < 0.05$ (Partial Pearson's correlation)

Table 6 shows the difference in peak plantar pressure between those on insulin treatment and those without. Peak plantar pressure for both the left and right foot did not vary statistically significantly across all plantar locations ($p > 0.05$). With p-values that were close to statistical significance, the right foot's hindfoot (Mask 1), midfoot (Mask 2), and hallux (Mask 4) areas had marginal differences ($p = 0.07$, $p = 0.060$, and $p = 0.059$, respectively). These variations, however, fell short of statistical significance. Insulin and non-insulin groups did not vary significantly ($p > 0.05$) in peak plantar pressure across all left foot plantar regions. Figure 1 shows the correlation between heel pad thickness and mean heel peak pressure for various foot sides and plantar areas (M1–M4).

Table 6. Comparison of Peak Plantar Pressure According to Insulin Therapy

Mask	Right		Left	
	F-Score	P-value^a	F-Score	P-value^a
M1	3.669	0.070	0.437	0.517
M2	4.024	0.060	1.122	0.323
M3	0.995	0.332	1.122	0.303
M4	4.076	0.059	1.227	0.283

*Statistically significant at $p < 0,05$, uji ANCOVA

4. Discussion

The research participants' features align with the established epidemiology of type 2 diabetes. The participants' average age was 53, which is consistent with data from throughout the world indicating that those over 45 are more likely to get diabetes [2]. Insulin resistance and β-cell dysfunction are two age-related metabolic alterations that increase the risk of diabetes [19]. Furthermore, the majority of individuals were categorized as overweight, a recognized risk factor for T2DM and its consequences. [20].

This study's average duration of diabetes was around 8 years, indicating a group at higher risk for long-term problems. Progressive harm to the brain and blood vessels may result from long-term exposure to high blood sugar levels through oxidative stress, inflammatory pathways, and the formation of advanced glycation end products (AGEs). [21,22]. These pathways mostly influence changes in foot biomechanics and diabetic peripheral neuropathy.

Regarding treatment, a proportion of participants were receiving insulin therapy, which is typically associated with more advanced disease and declining pancreatic β-cell function [23]. Although insulin use may reflect disease severity, its direct relationship with plantar biomechanics remains complex and may be influenced by multiple confounding factors, including glycemic control and disease duration. Footwear patterns in this study also reflect local cultural practices. Although sports shoes were common, a considerable proportion of participants reported walking barefoot. This differs from international guidelines that recommend protective footwear to reduce plantar pressure and prevent ulcer formation [24]. Cultural and environmental factors in Indonesia may influence footwear habits, potentially contributing to variations in plantar loading and risk of foot complications. All participants in this study had right-foot dominance, consistent with general human motor patterns in whichhe dominant limb is more actively involved in dynamic activities such as walking [25]. This may partly explain the asymmetry observed in plantar pressure distribution, particularly in the right foot.

Peak Plantar Pressure

The mean peak plantar pressure readings in this investigation were within the typical range. Previous research has suggested using the PEDAR system with a goal peak plantar pressure of less than 200 kPa to minimize the prevalence of foot ulcers. [26]. This finding indicates that, overall, the participants did not exhibit excessive plantar loading despite having diabetic peripheral neuropathy.

Compared to the midfoot, forefoot, and hallux, the hindfoot area had the greatest peak plantar pressure. This pattern is in line with earlier research showing that the heel, metatarsal heads, and hallux, all of which are often ulcerated are high-pressure locations [27]. In addition, plantar pressure in the heel and hallux has been shown to increase with walking speed, reflecting the mechanical load during gait [28].

All plantar areas showed a largely symmetrical distribution of peak plantar pressure between the right and left feet. This result is consistent with earlier research showing that, without antecedent ulceration or structural abnormalities, plantar pressure patterns are often bilaterally constant in individuals with diabetic neuropathy [18].

Heel Pad Thickness

The average heel pad thickness in this research was 15.38 ± 2.35 mm for the right foot and 15.28 ± 1.98 mm for the left, falling within the typical range. According to earlier research, healthy people's heel pad thickness normally varies from 12 to 28 mm [29]. Nonetheless, research indicates that people with diabetes often have thicker heel pads than those without the disease [30,31].

Chronic hyperglycemia-induced tissue alterations may account for the observed increase in heel pad thickness in diabetic individuals. Advanced glycation end products (AGEs), which change collagen structure, decrease tissue elasticity, and encourage structural thickening of soft tissues, build up as a result of extended exposure to hyperglycemia. These modifications might weaken the heel fat pad's mechanical qualities, lessen its ability to absorb stress, and make it more vulnerable to tissue injury [30].

The thickness of the heel pads on the right and left feet did not vary significantly. This result is in line with other research showing symmetrical heel pad features in individuals with diabetes [31,32]. The absence of side-to-side differences suggests that variations in plantar pressure are unlikely to be solely explained by structural differences in heel pad thickness, indicating the contribution of additional biomechanical or functional factors.

Relationship Between Heel Pad Thickness and Peak Plantar Pressure

Heel pad thickness and peak plantar pressure in the right hindfoot were shown to be significantly positively correlated in this investigation. However, no significant correlations were detected in other plantar locations. This result is consistent with earlier research demonstrating that one of the most frequent locations for plantar ulcers in diabetic individuals is the heel [27].

From a biomechanical standpoint, this result is plausible. During the initial contact phase of walking, the heel is the first region to receive the body's load, making it a primary site for pressure concentration [33,34]. Under normal conditions, the heel fat pad functions as an effective shock absorber. However, in patients with diabetes, prolonged hyperglycemia leads to structural changes in the tissue, including the accumulation of AGEs. These changes reduce tissue elasticity and increase stiffness, which in turn diminishes the ability of the heel pad to absorb impact forces [35,36]. As a result, a thicker heel pad does not necessarily indicate better cushioning, but may instead reflect degenerative changes that contribute to higher plantar pressure. Neuropathy may further influence this relationship. Motor neuropathy can disrupt the balance of intrinsic foot muscles and alter gait patterns, leading to uneven load distribution and increased pressure in specific regions, particularly the hindfoot [6].

Interestingly, this association was only observed in the right foot. All participants in this study had right-foot dominance, which may explain this asymmetry. The dominant foot is generally more involved in propulsion and tends to bear greater mechanical loads during walking, resulting in higher plantar pressure [25,37]. This might make the pressure distribution in the dominant limb more sensitive to structural alterations in the heel pad.

In contrast, no significant associations were found in the midfoot, forefoot, or hallux regions. These areas are influenced by more complex factors, such as foot structure, joint mobility, and muscle function, which may weaken the direct relationship between heel pad thickness and plantar pressure. This supports the idea that heel pad thickness alone is not a reliable predictor of plantar pressure. Instead, the mechanical properties of the tissue, such as stiffness and viscoelastic behavior, likely play a more important role [18,35].

After accounting for diabetes duration, the association in the right hindfoot remained significant. Previous research has shown that the length of time a patient has been sick is not the primary determinant of heel pad thickness, which is in agreement with our current discovery. [31,35]. Although longer disease duration is associated with a higher risk of complications due to chronic hyperglycemia [38,39], plantar pressure appears to be more directly influenced by local biomechanical factors.

Research Contribution

This study contributes both methodologically and clinically to understanding plantar biomechanics in diabetic peripheral neuropathy. Ultrasonography provides a practical, non-invasive, and accessible means of assessing heel pad thickness, while the Pedar-X in-shoe system enables dynamic, real-time plantar pressure measurement during walking, enhancing data reliability and ecological validity. Clinically, peak plantar pressure remains a key parameter for ulceration risk, particularly when exceeding 200 kPa, reinforcing the importance of regular pressure monitoring alongside appropriate footwear and patient education [23]. Importantly, heel pad thickness alone was not a reliable predictor of peak plantar pressure, underscoring the need for a multifaceted assessment approach that integrates structural, biomechanical, and clinical factors, including neuropathy severity and glycemic control, to more accurately identify patients at risk for diabetic foot complications.

Study Limitations

Several limitations should be acknowledged. Ultrasonography captures structural dimensions but does not fully reflect mechanical properties such as tissue elasticity and stiffness, which are more directly related to plantar pressure distribution [40]. MRI offers superior soft-tissue contrast and has demonstrated lower fat signal fraction in the subcalcaneal fat pad of patients with diabetic neuropathy, linked to reduced cushioning and elevated plantar pressure[19], though its clinical use remains limited by cost and accessibility[41]. Furthermore, the cross-sectional design precludes causal inference, while the small sample size limits statistical power and generalizability. Several confounding factors were not fully controlled, including gait speed, neuropathy severity, physical activity, and structural foot abnormalities, all of which may influence plantar pressure distribution. Although disease duration was included as a clinical variable, prior evidence suggests it does not consistently correlate with heel pad thickness changes[31].

5. Conclusion

Heel pad thickness alone does not fully account for variations in peak plantar pressure among patients with diabetic peripheral neuropathy. Although a significant association was found in the right hindfoot, no consistent pattern emerged across other plantar regions, suggesting that plantar pressure is shaped by multiple factors beyond structural anatomy, including gait patterns and neuromuscular changes related to neuropathy. These findings reinforce the value of dynamic plantar pressure assessment over static structural measurements alone in identifying patients at risk for foot ulceration. Targeted offloading interventions based on pressure mapping may therefore contribute to more effective prevention of diabetic foot complications. Further studies using advanced imaging and multivariate approaches are needed to better understand the factors driving plantar pressure distribution in this population.

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