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Original Article

Dynamic balance and lower limb muscle activation in relation to plantar pressure distribution in patients with type 2 diabetes mellitus

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Abstract:
Background: Type 2 diabetes mellitus often causes neuromuscular dysfunction, decreased dynamic balance, and changes in plantar pressure distribution in the feet. These conditions contribute to an increased risk of diabetic foot ulcers. Dynamic balance function and lower limb muscle contraction are thought to influence plantar pressure distribution; however, the relationship between these neuromuscular parameters and peak plantar pressure remains unclear, with inconsistent results in previous studies. Methods: This study used a cross-sectional design involving 30 patients with type 2 diabetes mellitus who underwent examination at Dr. Soetomo General Hospital in Surabaya. Dynamic balance function was measured using the Y Balance Test and expressed as Composite Reach Length (CRL). Lower limb muscle activity was measured using sEMG, while peak plantar pressure was measured in five areas (M1–M5) on both limbs. The relationships among CRL, sEMG, and peak plantar pressure were analyzed using Spearman's correlation test at a significance level of $p \leq 0.05$. Results: In general, there is no relationship between Composite Reach Length and peak plantar pressure in either the right or left leg. In addition, no relationship was found between lower limb muscle activity measured by sEMG and peak plantar pressure. Although one statistically significant correlation was found in a specific plantar segment, the relationship was not consistent across other segments. Conclusion: This study concludes that, in patients with type 2 diabetes mellitus, peak plantar pressure is not related to dynamic balance function or lower limb muscle contraction when measured separately. These findings indicate that plantar pressure distribution in diabetic patients is multifactorial, requiring a comprehensive evaluation and rehabilitation approach to help prevent diabetic foot complications.
Key Words*:* Type 2 diabetes mellitus; diabetic peripheral neuropathy; dynamic balance; surface electromyography; peak plantar pressure; Y Balance Test.

Introduction

Diabetes mellitus is no longer regarded solely as a metabolic disorder but as a chronic systemic disease with substantial neurological, musculoskeletal, and biomechanical consequences. Persistent hyperglycemia promotes oxidative stress, inflammation, microvascular dysfunction, and advanced glycation, which progressively impair peripheral nerves and lower-limb function (Goycheva et al., 2023; Sibony et al., 2024). The growing prevalence of type 2 diabetes mellitus (T2DM), particularly in Southeast Asia, is therefore accompanied by an increasing burden of mobility limitations, falls, and diabetic foot complications (IDF, 2021; Oktora & Butar, 2022). These complications reduce functional independence and quality of life while increasing the need for long-term rehabilitation and healthcare services.

Diabetic peripheral neuropathy (DPN) is one of the most clinically important complications of T2DM. Chronic metabolic and microvascular injury affects sensory, motor, and autonomic nerve fibers, resulting in reduced plantar sensation, impaired proprioception, delayed neuromuscular responses, and progressive weakness of the distal lower-limb muscles (Alonso-Enríquez et al., 2023; Callaghan et al., 2012; Tavares et al., 2024; Tesfaye & Selvarajah, 2012). Because plantar sensory input is essential for maintaining postural control and adapting foot placement, its deterioration may compromise balance during standing and walking. Motor involvement may further impair the ability of the lower-limb muscles to stabilize the ankle and regulate body-weight transfer throughout the stance phase. Together, these impairments contribute to gait alterations and abnormal mechanical loading of the foot.

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Peak plantar pressure (PPP) is an important biomechanical indicator of localized mechanical stress. Increased or prolonged pressure, particularly when combined with loss of protective sensation, may contribute to repetitive tissue injury and diabetic foot ulceration. Patients with DPN commonly exhibit altered plantar loading patterns, including increased pressure and contact duration in the midfoot and forefoot regions (Fernando et al., 2013; Jorgetto et al., 2022). These abnormalities are influenced by several interacting factors, such as foot structure, joint mobility, muscle function, walking speed, body mass, disease duration, and previous foot complications (Bacarin et al., 2009; Lockhart et al., 2024; Yavuz, 2014). Consequently, plantar pressure distribution cannot be assumed to reflect a single neuromuscular impairment.

In-shoe pressure-measurement systems, including the Pedar-X system, enable the dynamic evaluation of regional plantar loading during walking. Such measurements may support the identification of areas exposed to excessive mechanical stress. However, instrumented plantar pressure analysis requires specialized equipment, trained personnel, and adequate testing facilities. These requirements may limit its routine use, particularly in clinical settings with limited resources. Identifying accessible functional measures that are meaningfully associated with plantar pressure could therefore support preliminary risk assessment and guide decisions regarding more comprehensive biomechanical evaluation.

Dynamic balance is a potential functional indicator because it depends on the integration of sensory information, neuromuscular control, lower-limb strength, and coordinated weight transfer. The Y Balance Test (YBT) provides a practical method for assessing dynamic postural control through reach performance in the anterior, posteromedial, and posterolateral directions. Its composite reach length (CRL), normalized to limb length, has demonstrated acceptable reliability and validity for evaluating dynamic balance (P. Plisky et al., 2021). In people with T2DM, reduced plantar sensation and proprioceptive input may limit the ability to maintain single-limb stability while reaching, potentially resulting in a lower CRL. Because both the YBT and walking require controlled displacement of the center of mass over the supporting foot, impaired dynamic balance may also be associated with less efficient plantar load transfer.

Lower-limb muscle activation may represent another mechanism linking functional impairment to regional plantar loading. The tibialis posterior contributes to inversion, medial arch support, and control of foot pronation, whereas the peroneus longus assists with eversion, lateral ankle stability, and stabilization of the first ray during propulsion. Altered activation of these muscles could theoretically modify foot position and redistribute pressure across the plantar surface. Previous studies have demonstrated reduced lower-limb strength and altered muscle activation in individuals with T2DM, particularly in the presence of peripheral neuropathy (Ahmad et al., 2020; Nakashima et al., 2025; Pang et al., 2025; Watari et al., 2014). Nevertheless, surface electromyography (sEMG) reflects electrical muscle activation rather than the complete mechanical output of the muscle. Its relationship with regional plantar pressure may therefore be indirect and influenced by sensory loss, muscle coordination, foot structure, and gait strategy (Amitrano et al., 2026; Gunaratne & Tamura, 2025).

Although dynamic balance, muscle activity, and plantar pressure have each been investigated in people with diabetes, they have generally been evaluated separately. Consequently, it remains unclear whether functional balance performance or activation of selected ankle-stabilizing muscles is associated with plantar pressure across specific foot regions. Existing evidence also does not establish whether any relationship is generalized across the plantar surface or limited to particular regions and limbs. This distinction is clinically relevant because a global functional test may not adequately reflect localized mechanical loading during gait.

The present study addressed this gap by examining the correlations between CRL, lower-limb muscle activation, and PPP in patients with T2DM. Dynamic balance was assessed using the YBT, while activation of the tibialis posterior and peroneus longus was measured using sEMG, and regional PPP was recorded using the Pedar-X in-shoe pressure system. The study aimed to determine whether CRL and lower-limb muscle activation were associated with PPP across five plantar regions in the right and left limbs. By integrating functional, neuromuscular, and biomechanical assessments, this study was expected to clarify whether relatively accessible functional measurements could complement, although not replace, instrumented plantar pressure assessment when evaluating the risk of diabetic foot complications.

Material & methods

Study Design and Setting

This study employed an observational analytical design with a cross-sectional approach. The study was conducted at the Rehabilitation Medicine Department of Dr. Soetomo General Hospital, Surabaya, Indonesia, from February 2025 until completion.

Participants

The study population consisted of patients with type 2 diabetes mellitus attending the Endocrinology and Rehabilitation outpatient clinics. Participants were recruited using consecutive sampling until the required sample size was achieved. The minimum sample size was calculated using a correlation estimation formula based on an expected correlation coefficient of 0.5, $\alpha = 0.05$, and a power of 80%, resulting in a minimum of 30 participants.

Inclusion criteria were: (1) diagnosis of type 2 diabetes mellitus according to the PERKENI 2021 criteria; (2) age 18–59 years; (3) hemodynamic stability; (4) normal cognitive function (MoCA-Ina); (5) body mass index between 18.5 and 24.9 kg/m²; and (6) ability to walk independently. Exclusion criteria included active foot ulcers, Charcot foot, lower-limb deformities, neuromusculoskeletal disorders affecting gait, uncontrolled glycemic conditions, cardiovascular instability, visual impairment, and lower-limb muscle weakness. Participants who withdrew consent were classified as dropouts.

Variables and Measurements

The independent variables were dynamic balance, assessed using composite reach length (CRL) from the Y Balance Test (YBT), and lower-limb muscle contraction, measured using surface electromyography (sEMG) of the tibialis posterior and peroneus longus muscles. The dependent variable was peak plantar pressure, measured using the Pedar-X in-shoe pressure system.

CRL was calculated as the average of three successful reach attempts in the anterior, posteromedial, and posterolateral directions, normalized to limb length. Muscle contraction was assessed as maximum voluntary isometric contraction (MVIC), recorded in millivolts (mV). Peak plantar pressure was recorded in kilopascals (kPa) during walking trials.

Potential confounders included age, sex, body mass index, physical activity, lifestyle factors, genetic history, and gait patterns.

Data Collection Procedure

All participants provided written informed consent prior to data collection. Baseline characteristics were obtained through anamnesis and physical examination. Participants performed a standardized warm-up before testing.

Dynamic balance was assessed using the Y Balance Test, following a standardized protocol with six practice trials and three recorded trials per direction. Muscle activity was recorded using sEMG during testing, with electrodes placed over the target muscles after skin preparation to reduce impedance.

Peak plantar pressure was measured using the Pedar-X system. Participants walked at a self-selected speed along a straight pathway while wearing standardized footwear with in-shoe sensors. Data were recorded after a consistent walking pattern was achieved.

Statistical Analysis

Data were analyzed using SPSS version 26.0. Descriptive statistics were used to summarize participant characteristics. Normality was assessed using the Shapiro–Wilk test. The relationships among composite reach length, lower-limb muscle contraction, and peak plantar pressure were analyzed using Spearman's correlation test, with statistical significance set at $p < 0.05$.

Ethical Considerations

This study was approved by the Health Research Ethics Committee of Dr. Soetomo General Hospital (No. 1247/KEPK/II/2025). All participants provided written informed consent prior to participation.

Results

The results provide an overview of participant characteristics, followed by an analysis of the relationships between dynamic balance, neuromuscular function, and plantar pressure distribution.

Table 1 presents the baseline characteristics of the study participants.

Variable	Category	n (%)	Mean ± SD	p-value
Dominant Limb	Right	30 (100%)	–	–
	Left	0 (0%)	–	–
Sex	Male	12 (40%)	–	–
	Female	18 (60%)	–	–
Age (years)	–	–	52.23 ± 5.34	0.089
Body Weight (kg)	–	–	62.80 ± 11.21	–
Height (cm)	–	–	162.00 ± 8.90	–
Body Mass Index (kg/m²)	–	–	23.83 ± 2.31	0.090
Duration of T2DM (years)	–	–	7.85 ± 6.20	0.050
Peripheral Neuropathy (PNP)	PNP	26 (86.6%)	–	–
	Non-PNP	4 (13.3%)	–	–

Table 1 summarizes the baseline characteristics of the study participants. A total of 30 patients with type 2 diabetes mellitus were included, with a predominance of female participants (60%), and all individuals presented with right-limb dominance. The cohort's mean age was 52.23 ± 5.34 years, indicating a middle-aged population with a relatively homogeneous age distribution. Anthropometric measurements indicated a mean body mass index of 23.83 ± 2.31 kg/m², suggesting a predominantly normal to borderline overweight profile according to the Asia-Pacific classification. The average duration of diabetes was 7.85 ± 6.2 years, reflecting prolonged disease exposure, which is clinically relevant given its association with chronic complications. Notably, the majority of participants (86.6%) were classified as having peripheral neuropathy, indicating a high-risk population for functional impairment and plantar pressure abnormalities. Overall, the relatively homogeneous demographic and clinical profile supports the internal consistency of the sample for subsequent correlation analysis.

Table 1. Normality Test

Variable	Direction / Muscle / Region	Limb	Mean ± SD	p-value	Distribution
CRL (cm)	Anterior	Right	53.76 ± 9.89	0.600	Normal
		Left	53.67 ± 8.52	0.944	Normal
	Posterolateral	Right	61.80 ± 10.04	0.095	Normal
		Left	60.43 ± 9.51	0.510	Normal
	Posteromedial	Right	62.20 ± 11.54	0.605	Normal
		Left	62.54 ± 10.36	0.954	Normal
	CRL (%)	Right	72.97 ± 10.64	0.670	Normal
		Left	72.52 ± 8.22	0.835	Normal
Surface EMG	Anterior - Invertor (Tibialis posterior)	Right	0.96 ± 0.36	0.079	Normal
		Left	0.83 ± 0.34	0.023	Non-normal
	Anterior - Evertor (Peroneus longus)	Right	1.13 ± 0.35	0.001	Non-normal
		Left	0.69 ± 0.34	0.005	Non-normal
	Posterolateral - Invertor (Tibialis posterior)	Right	0.84 ± 0.40	0.096	Normal
		Left	0.74 ± 0.32	0.169	Normal
	Posterolateral - Evertor (Peroneus longus)	Right	0.90 ± 0.29	0.137	Normal
		Left	0.58 ± 0.26	0.020	Non-normal
	Posteromedial- Invertor (Tibialis posterior)	Right	0.93 ± 0.42	0.104	Normal
		Left	0.85 ± 0.43	0.099	Normal
	Posteromedial - Evertor (Peroneus longus)	Right	0.89 ± 0.30	0.456	Normal
		Left	0.58 ± 0.26	0.006	Non-normal
Peak Plantar Pressure	M1 (Heel)	Right	188.40 ± 46.21	0.242	Normal
		Left	198.44 ± 50.32	0.099	Normal
	M2 (Midfoot)	Right	162.82 ± 53.72	0.054	Normal
		Left	152.92 ± 48.88	**0.042**	Non-normal
	M3 (Forefoot)	Right	230.67 ± 51.98	0.086	Normal
		Left	232.88 ± 52.31	0.086	Normal
	M4 (Big Toes)	Right	194.07 ± 63.49	0.345	Normal
		Left	185.83 ± 68.29	0.171	Normal
	M5 (Toes)	Right	116.34 ± 41.45	0.742	Normal
		Left	103.16 ± 38.84	**0.038**	Non-normal

Normality testing using the Shapiro–Wilk test demonstrated that all composite reach length (CRL) variables were normally distributed across both limbs ($p > 0.05$). In contrast, several surface EMG parameters showed non-normal distributions, particularly in the evertor muscle groups and selected left-limb measurements ($p < 0.05$). For peak plantar pressure, most regions were normally distributed; however, non-normality was observed in the left midfoot (M2) and toe region (M5). These findings indicate a mixed distribution across variables, with neuromuscular parameters showing greater variability than functional balance measures. Given the presence of non-normal data, non-parametric statistical analysis using Spearman's correlation was deemed appropriate for subsequent analyses.

Following the descriptive and normality analyses, correlation testing was conducted to examine the relationships between dynamic balance, lower-limb muscle contraction, and peak plantar pressure. Given the presence of several variables with non-normal distributions, a non-parametric analysis using Spearman's correlation was applied. This analysis aimed to explore whether functional parameters, particularly composite reach length as a measure of dynamic balance, were associated with plantar pressure distribution across different foot regions in patients with type 2 diabetes mellitus.

Table 3. Correlation between Composite Reach Length and Peak Plantar Pressure

Variable	PPP M1		PPP M2		PPP M3		PPP M4		PPP M5	
	rho	p	rho	p	rho	p	rho	p	rho	p
CRL Right	-0.224	0.234	**-0.392**	**0.032***	-0.209	0.267	-0.045	0.813	-0.101	0.594
CRL Left	-0.048	0.801	**-0.368**	**0.046***	-0.212	0.262	0.186	0.326	0.114	0.550

As shown in Table 3, composite reach length demonstrated a predominantly negative correlation with peak plantar pressure across most plantar regions. A statistically significant moderate negative correlation was observed in the midfoot region (PPP M2) in both the right (rho = −0.392, p = 0.032) and left limbs (rho = −0.368, p = 0.046). These findings indicate that better dynamic balance performance is associated with lower plantar pressure in the midfoot region. No significant correlations were identified in other plantar regions ($p > 0.05$), suggesting that the relationship between dynamic balance and plantar loading may be region-specific rather than generalized across the entire foot.

Table 4. Correlation between Surface Electromyography (sEMG) and Peak Plantar Pressure in the Right Limb

Direction (Muscle)	**PPP M1**		**PPP M2**		**PPP M3**		**PPP M4**		**PPP M5**	
	rho	**p**	**rho**	**p**	**rho**	**p**	**rho**	**p**	**rho**	**p**
Anterior – Evertor (Peroneus longus)	0.148	0.435	0.01	0.959	-0.189	0.318	-0.462	0.010*	-0.053	0.783
Anterior – Invertor (Tibialis posterior)	0.063	0.742	0.272	0.146	-0.043	0.823	-0.123	0.517	-0.207	0.273
Posterolateral – Evertor (Peroneus longus)	-0.128	0.501	-0.083	0.664	-0.064	0.738	-0.265	0.158	-0.078	0.681
Posterolateral – Invertor (Tibialis posterior)	-0.318	0.086	0.073	0.702	-0.223	0.237	-0.246	0.19	-0.19	0.315
Posteromedial – Evertor (Peroneus longus)	0.131	0.491	-0.112	0.557	-0.094	0.62	-0.079	0.678	-0.16	0.398
Posteromedial – Invertor (Tibialis posterior)	0.032	0.865	0.162	0.393	-0.093	0.623	-0.174	0.357	-0.058	0.759

As shown in Table 4, the correlation analysis between lower-limb muscle contraction and peak plantar pressure in the right limb showed predominantly weak, non-significant associations across most plantar regions ($p > 0.05$). However, a statistically significant moderate negative correlation was observed between anterior evertor muscle activity (peroneus longus) and plantar pressure in the M4 region (rho = −0.462, p = 0.010). This finding suggests that greater activation of the peroneus longus muscle is associated with lower plantar pressure in the M4 region. In contrast, no significant correlations were found for the tibialis posterior muscle across any plantar region or direction, indicating no significant association between invertor muscle activity and plantar pressure distribution in this cohort. Overall, these results suggest a selective and muscle-specific relationship between neuromuscular activity and plantar loading patterns.

Table 5. Correlation between Surface Electromyography (sEMG) and Peak Plantar Pressure in the Left Limb

Direction (Muscle)	**PPP M1**		**PPP M2**		**PPP M3**		**PPP M4**		**PPP M5**	
	rho	**p**	**rho**	**p**	**rho**	**p**	**rho**	**p**	**rho**	**p**
Anterior – Evertor (Peroneus longus)	0.148	0.440	-0.360	0.05	-0.190	0.320	0.277	0.140	0.172	0.363
Anterior – Invertor (Tibialis posterior)	-0.020	0.93	-0.230	0.23	-0.090	0.650	0.252	0.180	0.240	0.201
Posterolateral – Evertor (Peroneus longus)	0.000	1.00	-0.100	0.600	-0.290	0.120	-0.200	0.300	-0.040	0.853
Posterolateral – Invertor (Tibialis posterior)	-0.060	0.760	0.149	0.430	0.064	0.740	-0.070	0.700	-0.080	0.672
Posteromedial – Evertor (Peroneus longus)	0.208	0.270	-0.250	0.190	-0.210	0.280	-0.010	0.980	-0.130	0.501
Posteromedial – Invertor (Tibialis posterior)	0.020	0.920	-0.250	0.180	0.038	0.840	0.166	0.380	0.240	0.202

As shown in Table 5, no statistically significant correlations were observed between lower-limb muscle contraction and peak plantar pressure across the plantar regions of the left limb ($p > 0.05$). However, a moderate negative correlation was observed between anterior evertor muscle activity (*peroneus longus*) and plantar pressure in the M2 region (rho = −0.357, p = 0.053), although this did not reach statistical significance. This pattern suggests a potential relationship between evertor muscle activation and midfoot load distribution. Overall, both invertor and evertor muscle groups demonstrated weak and inconsistent associations with plantar pressure, indicating that the relationship between neuromuscular activity and plantar loading may be limited or more variable in the left limb. The absence of significant findings in the left limb, in contrast to the right, may reflect asymmetrical neuromuscular control or compensatory loading patterns in patients with type 2 diabetes mellitus.

Discussion

This study employed an analytical observational design involving 30 patients with type 2 diabetes mellitus to examine the relationships between composite reach length, lower-limb muscle contraction, and peak plantar pressure. The study population had a mean age of 52.23 ± 5.34 years, a predominance of female participants (60%), and a mean body mass index of 23.83 ± 2.31 kg/m², indicating a predominantly normal-to-overweight profile. The mean duration of diabetes was 7.85 ± 6.2 years, with the majority of participants (86.6%) presenting with peripheral neuropathy, reflecting a high-risk cohort for neuromuscular and biomechanical impairment.

The age distribution of participants is consistent with global epidemiological trends, in which the prevalence of type 2 diabetes increases significantly after age 45 (IDF, 2021). In addition, both advancing age and longer disease duration are well-established risk factors for diabetic peripheral neuropathy, mediated by chronic hyperglycemia, microvascular dysfunction, and impaired nerve regeneration (Boulton et al., 2005; Tesfaye & Selvarajah, 2012). These mechanisms contribute to reduced nerve conduction velocity and diminished proprioceptive function, which may subsequently affect postural control and lower-limb function.

The predominance of female participants aligns with national data and may reflect differences in risk factor profiles, including obesity, psychosocial stress, and hormonal influences (Kautzky-Willer et al., 2023). Furthermore, the observed overweight status supports existing evidence linking increased body mass index with an increased risk of type 2 diabetes, with obesity significantly elevating disease susceptibility (Stanaway et al., 2018).

Importantly, the relatively long duration of diabetes in this cohort is clinically relevant, as prolonged exposure to hyperglycemia is associated with the development of vascular and neural complications through oxidative stress, inflammation, and advanced glycation processes (Goycheva et al., 2023; Sibony et al., 2024). This is further reflected in the high prevalence of peripheral neuropathy observed in this study, consistent with previous findings that neuropathic complications commonly emerge after several years of disease progression, particularly in poorly controlled diabetes (Callaghan et al., 2012; Kebede et al., 2021).

The mean composite reach length (CRL) was 72.97 ± 10.64% in the right limb and 72.52 ± 8.22% in the left limb, indicating relatively symmetrical dynamic balance performance. Both variables were normally distributed ($p > 0.05$), indicating that the data met the assumption of normality. However, CRL values in this study were lower than those reported in healthy populations (89–94%) (P. Plisky et al., 2021), reflecting impaired dynamic balance in patients with type 2 diabetes mellitus. This finding is consistent with previous studies demonstrating that diabetic peripheral neuropathy leads to reduced dynamic balance due to impaired sensorimotor integration and proprioceptive deficits (Courtemanche et al., 1996; Tesfaye & Selvarajah, 2012). Loss of plantar sensation diminishes afferent input from foot mechanoreceptors, which are essential for postural control, resulting in delayed postural responses and decreased stability during weight shifting (Boulton et al., 2005; Fernando et al., 2013). The use of the Y Balance Test (YBT) in this study provides a reliable and valid assessment of dynamic balance, with high reliability and discriminative validity across various populations (P. Plisky et al., 2021; P. J. Plisky et al., 2009). Therefore, CRL serves as a robust indicator of neuromuscular control and postural stability in this cohort (Alissa et al., 2024). In addition, age and disease duration likely contributed to reduced CRL values through chronic hyperglycemia-induced nerve damage and impaired neuromuscular adaptation (Boulton et al., 2005; Iliescu et al., 2025; Tesfaye & Selvarajah, 2012). The absence of side-to-side differences further supports the bilateral nature of diabetic peripheral neuropathy, which typically affects both lower limbs symmetrically.

Surface EMG (sEMG) amplitudes varied across muscles and limbs, with slightly higher values observed in the right limb than in the left. In the right limb, mean amplitudes ranged from 0.84–0.96 mV for the invertor muscles and 0.89–1.13 mV for the evertor muscles, whereas in the left limb, the corresponding values ranged from 0.74–0.85 mV and 0.58–0.69 mV, respectively. This pattern suggests heterogeneity in distal neuromuscular activation among patients with type 2 diabetes mellitus, the majority of whom presented with peripheral neuropathy. Although normative reference values for sEMG amplitudes of the tibialis posterior and peroneus longus have not been well established, sEMG amplitude is generally considered to reflect motor unit recruitment and synchronization during muscle contraction. In patients with diabetic peripheral neuropathy, chronic hyperglycemia-induced nerve damage, microvascular dysfunction, and impaired neural conduction may contribute to reduced neuromuscular efficiency and altered muscle activation patterns (Akhtar, 2024; Boulton et al., 2005; Lecce et al., 2026; Tesfaye & Selvarajah, 2012). These findings are consistent with previous studies reporting reduced or altered EMG activity in patients with diabetic neuropathy, particularly in distal muscles involved in gait and postural control (Fernando et al., 2013; Watari et al., 2014). Furthermore, reduced muscle strength and neuromuscular impairment have been reported even in the early stages of diabetes, suggesting that neural dysfunction may play a more prominent role than structural muscle changes (Henderson et al., 2020). The variability and relatively lower sEMG amplitudes observed in this study may therefore reflect impaired neuromuscular activation associated with diabetic neuropathy. The potential asymmetry between limbs may indicate individual differences in neuromuscular responses rather than a consistent compensatory mechanism.

Peak plantar pressure values demonstrated regional variation, with the highest pressures consistently observed in the forefoot region (M3) of both limbs, whereas the lowest pressures were observed in the toe region (M5). This pattern indicates a concentration of load in the forefoot during the stance phase of gait, which has commonly been reported in patients with type 2 diabetes mellitus and peripheral neuropathy (Boulton et al., 2005; Tesfaye & Selvarajah, 2012). This altered plantar pressure distribution may be attributed to a combination of sensory deficits, impaired distal motor control, and structural adaptations of the foot. Reduced plantar sensation and intrinsic foot muscle dysfunction may shift the load anteriorly, increasing pressure in the forefoot region, as previously reported in patients with diabetic neuropathy and a history of foot complications (Bacarin et al., 2009). In addition, elevated shear forces and prolonged plantar contact time may further contribute to the accumulation of mechanical stress in this region, exacerbating abnormalities in plantar loading (Fernando et al., 2013; Yavuz, 2014).

These findings are supported by meta-analytic evidence indicating increased plantar pressure and prolonged contact duration in the midfoot–forefoot regions among patients with diabetic neuropathy (Fernando et al., 2013). Furthermore, factors such as higher body mass index and longer disease duration may amplify these effects by altering foot structure and load distribution (Jorgetto et al., 2022). The predominance of forefoot loading observed in this study reflects the biomechanical consequences of neuropathic changes, characterized by reduced protective sensation, impaired neuromuscular control, and increased mechanical stress during gait.

Correlation analysis showed that dynamic balance, as measured by composite reach length (CRL), was not consistently associated with peak plantar pressure (PPP) across the plantar regions. A significant, moderate negative correlation was observed only in the midfoot (M2) region of both limbs, whereas the other regions showed no meaningful associations. This finding suggests that the relationship between global balance performance and plantar loading is selective rather than uniform.

The absence of a consistent association may be explained by the different biomechanical constructs represented by CRL and PPP. CRL reflects global neuromuscular control during a controlled balance task, whereas PPP represents localized mechanical loading influenced by foot structure, gait dynamics, and shear forces during walking. In patients with diabetic peripheral neuropathy, sensory deficits and delayed motor responses may contribute to a dissociation between global postural control and local plantar loading (Boulton et al., 2005; Tesfaye & Selvarajah, 2012). The significant association observed in the midfoot region highlights its role as a transitional loading zone between heel strike and forefoot propulsion. Better dynamic balance may facilitate more efficient load transfer, resulting in lower midfoot pressure. This finding is supported by previous studies linking impaired sensorimotor integration to increased midfoot loading and prolonged contact time in patients with diabetic neuropathy (Fernando et al., 2013; Yavuz, 2014).

In contrast, plantar pressure in other regions appears to be predominantly influenced by local structural and mechanical factors rather than by balance performance. Forefoot loading, for example, is more strongly associated with intrinsic muscle dysfunction, foot deformity, and disease duration (Bacarin et al., 2009; Jorgetto et al., 2022), while gait mechanics and push-off dynamics influence heel and toe pressures. Additionally, the limb asymmetry observed in this study may reflect the influence of limb dominance, with the dominant limb showing more consistent patterns of neuromuscular adaptation (Bowling, 2015). These findings also emphasize the potential role of confounding factors such as BMI, disease duration, and gait variability, which may independently affect plantar pressure distribution.

Correlation analysis showed no consistent or significant association between lower-limb muscle activity (sEMG) and peak plantar pressure (PPP) across most plantar regions in either limb. This finding indicates that muscle contraction alone may not be a reliable predictor of plantar pressure distribution in patients with type 2 diabetes mellitus. The complex neuromuscular and biomechanical alterations associated with diabetic peripheral neuropathy may explain the lack of a consistent association. Although the invertor (tibialis posterior) and evertor (peroneus longus) muscles play key roles in foot stability and load modulation, neuropathic changes, such as impaired neural conduction, reduced motor unit recruitment, and disrupted proprioception, may limit the effectiveness of muscle activation in modulating dynamic plantar loading (Fernando et al., 2013; Tesfaye & Selvarajah, 2012). A significant association was observed only in the right limb, where anterior evertor activity showed a moderate negative correlation with plantar pressure in the hallux region (M4). This finding suggests a localized role of the peroneus longus in reducing pressure during the terminal stance and push-off phases (Bacarin et al., 2009; Fernando et al., 2013). However, as this relationship was not consistently observed across other regions or limbs, it likely represents a region-specific rather than global effect. Overall, these findings highlight that plantar pressure is influenced by multiple interacting factors, including foot structure, gait dynamics, and proximal joint compensation, rather than by isolated muscle contraction (Fernando et al., 2013; Jorgetto et al., 2022). Additionally, asymmetrical patterns between limbs may reflect limb dominance, with the dominant limb exhibiting more coordinated neuromuscular control (Bowling, 2015). These results emphasize the complexity of neuromuscular–biomechanical interactions in diabetic neuropathy and suggest that muscle activation alone is insufficient to explain plantar loading patterns.

This study offers several strengths that contribute to the understanding of neuromuscular function, dynamic balance, and foot biomechanics in patients with type 2 diabetes mellitus. A key strength lies in its multimodal approach, integrating composite reach length (CRL), surface electromyography (sEMG), and peak plantar pressure (PPP) to provide a more comprehensive assessment of the interplay between functional performance and plantar loading. This integrative framework addresses a gap in the literature, as these parameters have typically been examined in isolation.

Furthermore, this study demonstrates novelty by specifically investigating the relationships among dynamic balance, lower-limb muscle activity (invertor and evertor), and plantar pressure within a single analytical framework. These findings provide preliminary insights into the complex interplay between neuromuscular control and biomechanical loading, with potential implications for the early detection and prevention of diabetic foot complications in clinical practice.

However, several limitations should be considered. The cross-sectional design precludes causal inference regarding the relationships among neuromuscular function, balance performance, and plantar pressure. In addition, sEMG measurements were conducted under static conditions, which may not fully capture muscle activation patterns during dynamic activities such as walking. Finally, potential confounding factors, including demographic characteristics, disease duration, treatment variability, physical activity, and gait patterns, may have influenced the observed relationships.

Conclusions

This study indicates that dynamic balance and lower-limb muscle activation are not consistently associated with peak plantar pressure across all plantar regions in patients with type 2 diabetes mellitus. Composite reach length demonstrated moderate negative correlations with midfoot peak plantar pressure in both limbs, indicating that better dynamic balance may be associated with lower loading in this transitional region of the foot. In addition, anterior peroneus longus activation was negatively correlated with peak plantar pressure in the M4 region of the right foot. However, comparable associations were not consistently observed across the remaining plantar regions, muscle-testing directions, or the contralateral limb. These findings should therefore be interpreted as region-specific signals rather than evidence of a generalized relationship between functional performance and plantar loading.

The results reinforce the concept that plantar pressure distribution in patients with T2DM is determined by multiple interacting factors. Dynamic balance and isolated muscle activation represent only part of this biomechanical system, which is also influenced by plantar sensory loss, foot structure, joint mobility, muscle coordination, body mass, walking speed, and gait strategy. Consequently, neither CRL nor static sEMG measurements should be used independently as a substitute for direct plantar pressure assessment. The absence of consistent correlations is clinically informative because it demonstrates that apparently adequate balance performance or muscle activation does not necessarily exclude localized plantar loading abnormalities.

From a clinical perspective, assessment of patients at risk of diabetic foot complications should remain multidimensional. Functional balance tests and muscle evaluation may provide useful information regarding postural control and neuromuscular impairment, but they should be interpreted alongside peripheral sensory examination, foot inspection, gait assessment, and, where available, instrumented plantar pressure measurement. This integrated approach may facilitate the identification of patients requiring more detailed biomechanical assessment, individualized footwear or offloading strategies, balance training, and gait-oriented rehabilitation.

The principal contribution of this study is the simultaneous evaluation of dynamic balance, selected ankle-stabilizing muscle activation, and regional plantar pressure in patients with T2DM. The findings refine the current understanding by demonstrating that the relationships among these measures are more localized and complex than a simple direct association. Nevertheless, given the cross-sectional design, small sample size, predominance of participants with peripheral neuropathy, static sEMG assessment, and multiple correlation tests, the statistically significant findings should be regarded as exploratory and require confirmation.

Future studies should involve larger and more clinically diverse samples, including comparative groups with and without peripheral neuropathy. Longitudinal and intervention-based designs are needed to determine whether improvements in balance, neuromuscular control, or gait mechanics lead to meaningful reductions in regional plantar pressure. Simultaneous sEMG, plantar pressure, and three-dimensional gait measurements during walking would also provide a more representative assessment of neuromuscular–biomechanical interactions. Such evidence may ultimately support the development of more precise rehabilitation and diabetic foot prevention strategies.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve the English language, grammar, clarity, and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Conflicts of Interest
The authors declare that they have no conflicts of interest related to this study.
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