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Mechanical properties of extrinsic foot muscles, Achilles tendon, and plantar fascia in patients with a history of diabetic foot ulcers

Fatmagül Varol[1*], Ali Ilez[2] and Yavuz Aslan[3]

Abstract

Background Diabetic foot ulcers (DFU) are a major complication of diabetes, often leading to impaired mobility and increased risk of recurrence due to persistent biomechanical alterations. Understanding the mechanical properties of foot muscles, tendons, and fascia may provide insight into ulcer development, prevention and rehabilitation strategies. This study aimed to assess the biomechanical properties of the extrinsic foot muscles, Achilles tendon (AT), and plantar fascia (PF) in individuals with a history of DFU using myotonometry.

Methods A total of 38 diabetic feet with a history of DFU (Wagner Grade 0–1) and 40 healthy controls (HC) were evaluated. The MyotonPRO device was used to measure muscle tone (Natural Oscillation Frequency, F), stiffness, and elasticity in the tibialis anterior (TA), gastrocnemius medialis (GM), gastrocnemius lateralis (GL), AT, and PF. Measurements were performed in standardized positions, with statistical comparisons made between groups using independent t-tests.

Results TA and GM showed significantly increased muscle tone and stiffness in the DFU group compared to HC ($p < 0.05$), whereas GL did not exhibit significant differences. Similarly, PF and AT stiffness were higher in the DFU group ($p < 0.05$), suggesting alterations in tissue load distribution. No significant differences in elasticity were observed between groups.

Conclusions This study highlights persistent mechanical alterations in the TA, GM, AT, and PF in individuals with a history of DFU, despite ulcer healing. The increased stiffness and tone in these structures may contribute to abnormal foot loading patterns, potentially increasing the risk of ulcer recurrence. The findings emphasize the importance of early biomechanical assessment and targeted rehabilitation strategies, such as neuromuscular training, load redistribution, Achilles tendon stretching and custom orthotic interventions to mitigate mechanical dysfunction in diabetic foot patients.

Clinical trial number Not applicable.

Keywords Diabetic foot ulcer, Tone, Stiffness, Extrinsic foot muscles, MyotonPRO

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Introduction

Diabetes mellitus (DM) has emerged as a significant global health concern. One of the most common and severe complications of DM is diabetic foot (DF), which encompasses various pathologies affecting the foot due to diabetes-related chronic complications [1]. DF is a multifactorial condition resulting from peripheral neuropathy, peripheral vascular disease, foot deformities, muscle weakness, atrophy, trauma, and impaired infection resistance. Diabetic foot ulceration (DFU) is the most common lower-extremity complication in patients with DM that is associated with infection, amputation, and death, and is affecting increasing numbers of patients with diabetes mellitus [2]. The lifetime risk of developing a DFU is estimated to be between 19% and 34%, and this figure continues to rise as individuals with diabetes live longer and experience more complex disease progression. The morbidity associated with initial ulceration is considerable, with recurrence rates reaching 65% within 3–5 years, a lifetime incidence of lower-extremity amputation of approximately 20%, and a 5-year mortality rate ranging between 50% and 70% [3].

Diabetic foot-induced structural and soft tissue changes, including reduced joint mobility, compromised protection against mechanical stress, altered foot posture, and muscle atrophy, may impair tissue mechanics and contribute to ulcer formation [4]. People with diabetes have a rigid foot which absorbs shock poorly. This is due to a thickening of the plantar fascia and Achilles tendon [5]. These alterations not only affect passive tissue properties but also disrupt the functional integrity of active components, including the extrinsic foot muscles and their associated tendinous and fascial structures [6]. The extrinsic foot muscles, originating in the lower leg and inserting into the foot after crossing the ankle joint, play a crucial role in foot function and are often affected in diabetes due to neuromuscular dysfunction [7]. The Achilles tendon transmits forces from the muscles to the foot bones, contributing to plantar fascia tension, which plays a critical role in arch stabilization and shock absorption [8]. In individuals with type 2 DM, increased advanced glycation end products (AGEs), abnormal collagen crosslinking due to non-enzymatic glycosylation, collagen thickening, microvascular impairment, breakdown of elastic fibers, and alterations in glycosaminoglycans contribute to reduced fascial tissue mobility and disrupt force transmission [9]. Impairments in the mechanical properties of these structures may increase the risk of diabetic foot ulcer recurrence due to their critical role in foot biomechanics [10]. Consequently, mechanical assessments have become increasingly integrated into DF management as they help identify abnormal load distributions that elevate the risk of ulceration. Therefore, preventive strategies play a crucial role in diabetes care by mitigating the impact of DFU and its sequelae. The optimal management of DFU involves regular foot evaluation and early intervention and risk factor modification.

Several assessment tools are available for the early detection of diabetic foot complications. The 10-g Semmes-Weinstein monofilament test and vibration perception threshold (VPT) testing are widely used due to their simplicity and low cost; however, they primarily assess sensory deficits and do not provide information on mechanical tissue alterations [11]. Advanced imaging techniques such as ultrasound elastography and magnetic resonance imaging (MRI) offer valuable insights into soft tissue structure, but their routine use is limited by cost, accessibility, and the requirement for specialized expertise [12, 13]. Recently, portable devices like the MyotonPRO® have been introduced to evaluate the mechanical properties of soft tissues. The integration of mechanical property measurements into diabetic foot assessments may enhance early detection and preventive strategies.

Myotonometry quantifies mechanical parameters such as tone, stiffness, and elasticity by applying brief mechanical impulses, and has previously been used to assess plantar fascia alterations in individuals with diabetes [10, 14]. Its non-invasive nature, quick assessment time, and ease of use make it a practical tool for both clinical and research purposes. Unlike imaging-based techniques, myotonometry provides direct mechanical data without the need for sophisticated equipment or operator specialization. Building on this background, the present study aims to assess the mechanical properties of the extrinsic foot muscles, Achilles tendon, and plantar fascia in individuals with a history of diabetic foot ulcers using myotonometry. By examining tone, stiffness, and elasticity, we aim to provide new insights into persistent biomechanical alterations following ulcer healing and to support the development of targeted preventive strategies.

Materials and methods

Study design and participants

This study included individuals with diabetic foot who presented to a tertiary care department specializing in diabetic foot management. This study was conducted in accordance with the Declaration of Helsinki (https://www.wma.net/policies-post/wma-declaration-of-helsinki). Ethical approval was obtained from the Hamidiye Scientific Research Ethics Committee of Health Sciences University in Turkey (Approval No: 23/507). The approval was granted during the committee meeting on September 1, 2023 (Meeting No: 2023/16, Decision No: 16/15). All participants provided written informed consent prior to their inclusion in the study. A total of 38 diabetic feet from individuals with a history of DFU and 40 healthy feet from control participants were analyzed. A minimum of 30 participants per group (total 60 participants) was

determined to achieve a statistical power of 80% ($\beta = 0.20$) with a significance level of $\alpha = 0.05$. A p-value < 0.05 was considered statistically significant.

Participants were required to be between 30 and 60 years old, have a diagnosis of DM for more than five years, and have a glycated hemoglobin A1c (HbA1c) level of ≥ 6.5%. All participants had fully healed DFUs at the time of data collection, and special care was taken to exclude any cases with active or open ulcers. Wagner classifications were determined by the same specialized clinician to ensure consistency in diagnosis [15]. Patients with Wagner Grade 2 or higher ulcers were excluded to maintain homogeneity in the biomechanical evaluation. Ulcers at Grade 2 and above involve deeper tissue structures such as tendons, joint capsules, or bone, which can significantly alter local biomechanics and introduce variability unrelated to the soft tissue properties under investigation. Including such cases could confound the interpretation of muscle and fascia mechanical characteristics, which were the primary focus of this study.

For the healthy control group, participants were required to be within the same age range (30–60 years old) and have no history of DM or any other metabolic disease. In the diabetic group, 27 participants were included. Among them, 11 participants had both feet assessed due to a history of ulceration in both limbs, while 16 participants contributed one foot each, resulting in a total of 38 diabetic feet evaluated. In the healthy group, 20 participants were recruited, and both feet of each participant were assessed, leading to a total of 40 healthy feet included in the analysis. They were also required to have no previous or current foot-related musculoskeletal disorders, no history of foot or ankle surgery, no significant joint motion restrictions, and no neurological conditions affecting gait or lower limb function.

Exclusion criteria for all participants included individuals with type 1 or gestational diabetes, diabetic peripheral neuropathy, severe peripheral vascular disease (e.g., critical limb ischemia), recent physical therapy interventions affecting foot biomechanics within the past 48 h, active plantar fasciitis, and neurological disorders that impact gait and motor function (e.g., Parkinson's disease or a history of stroke). Additionally, participants with previous foot or ankle surgery leading to structural deformities, significant ankle joint motion restrictions unrelated to diabetes, and musculoskeletal conditions that alter foot loading patterns (e.g., rheumatoid arthritis or advanced osteoarthritis) were excluded. Individuals with HbA1c levels between 6.0% and 6.5% were excluded from the healthy population, as these values indicate prediabetes [13]. This criterion was applied to ensure a homogeneous study group and to minimize potential confounding factors in biomechanical assessments.

Assessments and measurements

Demographic data, including age, height, body weight, and medications used, were recorded for all participants. Blood samples were collected by the endocrinologist responsible for follow-up, and fasting blood glucose and HbA1c levels were analyzed.

The MyotonPRO® (MyotonAS, Tallinn, Estonia) device was used to measure muscle tone (Natural Oscillation Frequency, F), stiffness (S), and elasticity (Logarithmic decrement, D) in the tibialis anterior (TA), gastrocnemius medialis (GM), gastrocnemius lateralis (GL), AT, and PF. The device applies a brief mechanical impulse (15 ms) to the skin surface, generating damped oscillations in the underlying tissues. The MyotonPRO® device has been previously validated for assessing soft tissue mechanical properties with high reliability [16, 17]. These oscillations are recorded via an integrated triaxial accelerometer, which enables precise measurements of tissue stiffness, tone, and elasticity. The collected data is processed using computational algorithms to quantify the viscoelastic properties of the assessed structures.

Assessments were completed by a qualified physiotherapist who underwent a minimum of five hours of hands-on practice with the device, consistent with previous studies reporting this duration as sufficient for familiarization with MyotonPRO® measurements under standardized conditions [18]. All assessments were conducted at a constant room temperature (21–23 °C) across sessions, following previously established protocols and manufacturer recommendations [18–20]. For each muscle, a line was drawn between two anatomical landmarks, and the central part of the muscle belly was identified using palpation and muscle contraction. These points were then marked with a skin-friendly pen to maintain accuracy across measurements (Fig. 1).

The tibialis anterior was assessed in a supine position, with the heels extending beyond the foot of the stretcher [20], while the GM and GL were evaluated in a prone position, with the feet extending beyond the edge of the stretcher (Fig. 1). Participants remained in these positions for at least one minute before testing to ensure full muscle relaxation, and measurements were obtained in a fully relaxed state [18].

For the PF, assessments were conducted in a prone position, maintaining a neutral hip joint (0°), extended knee, and supported ankle joint in a neutral (0°) position, controlled using a goniometer. Measurements were taken from the proximal beginning of the PF, at the anatomical reference point where the distal anterior corner of the calcaneus meets the inner corner of the medial longitudinal arch, aligning with the borderline between the first and second metatarsal bones [10, 21]. Similarly, the AT was evaluated in a prone position, ensuring the same standardized lower limb positioning. Measurements

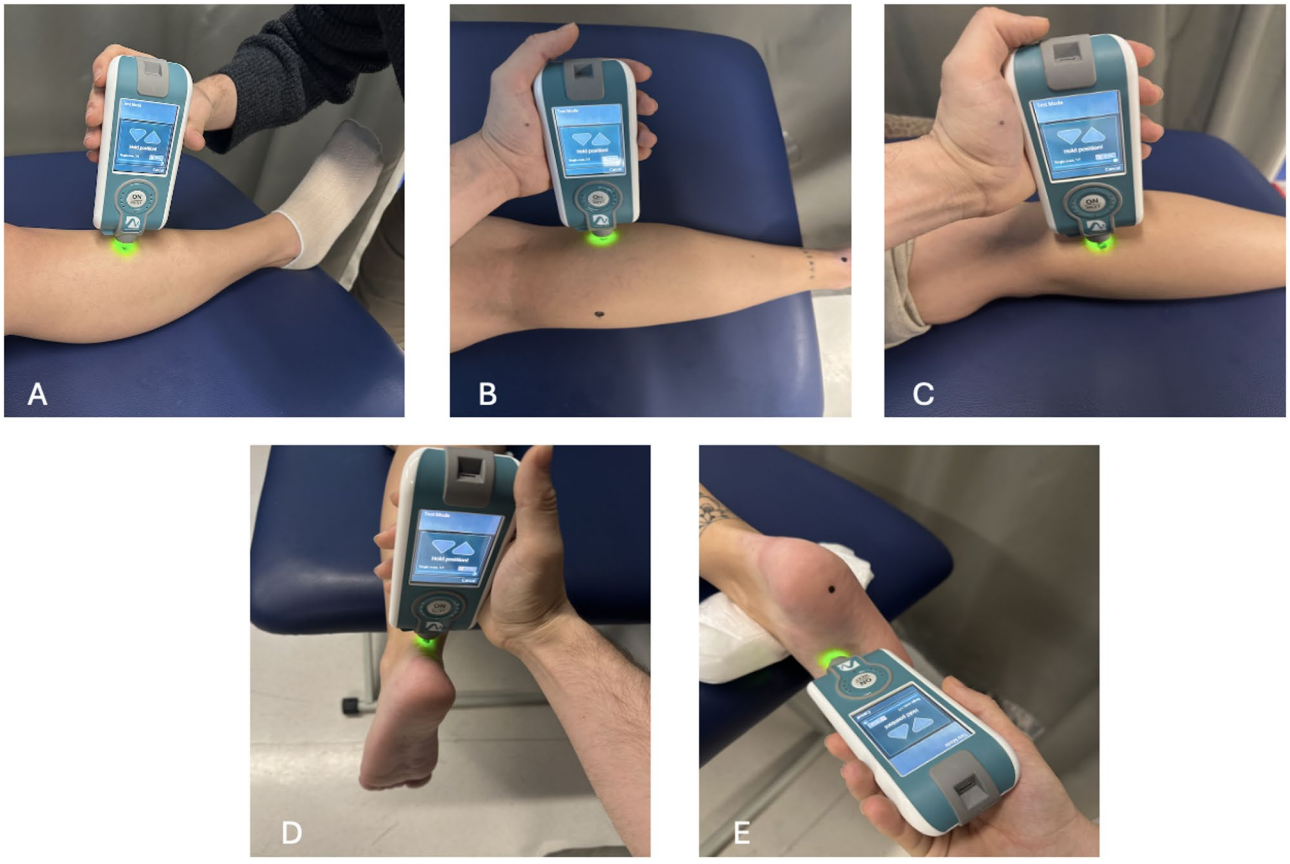

Fig. 1 Myotonometric assessment of lower limb muscles and soft tissues. (**A**) Measurement over the tibialis anterior at the muscle belly in a supine position. (**B**) Assessment of the gastrocnemius lateralis at the muscle belly in a prone position. (**C**) Measurement over the gastrocnemius medialis at the muscle belly in a prone position. (**D**) Evaluation of the Achilles tendon at 4 cm above the calcaneal insertion in a neutral position. (**E**) Assessment of the plantar fascia at its proximal insertion near the calcaneus. Standardized measurement positions were maintained across all participants

were taken 4 cm above the calcaneal tuberosity an anatomical landmark commonly used for AT assessments [22]. Given the biomechanical continuity between the AT and PF, both structures were assessed under the same conditions to provide a comprehensive evaluation of tissue stiffness and load distribution in diabetic foot (Fig. 1).

To enhance measurement reliability, five consecutive recordings were obtained at 0.8-second intervals. Proper probe positioning was ensured to minimize gravitational effects on the tissues. As the properties of muscle and fascia may vary depending on postural factors and underlying bone structure, the MyotonPRO® was kept perpendicular to the skin 90^0 to allow effective oscillation transmission and consistent data acquisition [19, 21, 23].

Statistical analysis

The statistical analysis was performed using IBM SPSS v.27, and normality was assessed using both the Shapiro-Wilk and Kolmogorov-Smirnov tests. Data were presented as mean ± standard deviation (SD) for continuous variables and frequencies (n, %) for categorical variables. Depending on normality, the independent samples t-test was applied for normally distributed variables, while the Mann-Whitney U test was used for non-normally distributed data. Effect size was calculated using Cohen's d, where d = 0.2 was considered a small effect, d = 0.5 a medium effect, and d = 0.8 or above a large effect. Sample size estimation was based on a priori power analysis using G Power software [24].

Results

The demographic and clinical characteristics of both groups are summarized in Table 1. There were no statistically significant differences between the groups in terms of age, sex, height, weight, and body mass index (BMI) ($p > 0.05$), ensuring comparability between the study populations. The biomechanical properties of the TA, GM, GL, AT, and PF were assessed using MyotonPRO®, and the findings are presented in Table 2.

The results demonstrated a significant increase in the resting tone (F) of the tibialis anterior (TA) ($p = 0.003$, Cohen's d = 0.78) and gastrocnemius medialis (GM) ($p = 0.03$, Cohen's d = 0.69) in the diabetic foot (DF) group compared to the healthy control (HC) group (Fig. 2;

Table 1 Demographic and clinical characteristics of the study groups

Descriptive Istatistic	Diabetic Foot *n* = 38	Healthy Foot *n* = 40	*p*
Gender (M)	17 (64%)	10 (50%)	0.551
Age	58 ± 28.15	55 ± 25.19	0.302
Height	169.92 ± 8.37	170.0 ± 8.6	0.962
Weight	81 ± 41.48	77.5 ± 29.3	0.124
Body Mass Index	28.74 ± 5.51	26.47 ± 2.66	0.179
HbA1C	7.76 ± 2.26		
Wagner Grade			
Wagner 0	24 (63.2%)		
Wagner 1	14 (36.8%)		
Type of Medication Used			
Pill	6 (22.2%)		
Insulin	5 (18.5%)		
Mix	16 (59.3%)		
Duration of Diabetes (Year)	14.34 ± 7.71		

Results are presented as mean ± SD or n (%). The χ^2 test was used for categorical variables, and the independent samples t-test or Mann-Whitney U test was applied for continuous variables. $p < 0.05$ was considered statistically significant

Table 2). No significant differences were observed in the resting tone of the gastrocnemius lateralis (GL) ($p = 0.141$, Cohen's d = 0.34) between the groups.

In terms of stiffness, the TA, AT, PF, and GM exhibited significantly higher stiffness in the DF group than in the HC group (TA: $p = 0.04$, Cohen's d = 0.70; AT: $p = 0.02$, Cohen's d = 0.50; PF: $p = 0.04$, Cohen's d = 0.70; GM: $p = 0.01$, Cohen's d = 0.54) (Fig. 3; Table 2). Meanwhile, the stiffness values of gastrocnemius lateralis (GL) did not show significant differences ($p = 0.53$, Cohen's d = 0.38).

Regarding elasticity (as represented by the logarithmic decrement), the PF did not show a statistically significant difference between the DF and HC groups ($p = 0.05$, Cohen's d = − 0.49). Although not statistically significant, this finding may have clinical implications. Similarly, no significant differences were found in the elasticity values (logarithmic decrement) of the Achilles tendon (AT: $p = 0.24$) or the gastrocnemius muscles (GM: $p = 0.10$, GL: $p = 0.57$) (Table 2).

Discussion

In this study, we investigated the mechanical properties of TA, GM, GL, AT, and PF in individuals with diabetic foot and compared them to healthy controls. Our findings revealed increased stiffness in PF and AT, along with elevated tone and stiffness in TA and GM. Although GL did not show a statistically significant difference in all parameters, slight changes observed may indicate compensatory adaptations. These findings indicate that individuals with diabetic foot exhibit increased tone in the gastrocnemius medialis, as well as greater stiffness and reduced elasticity in the plantar fascia and Achilles tendon, based on myotonometric measurements. Each parameter was analyzed independently to describe the viscoelastic characteristics of the soft tissues. To the best of our knowledge, this is the first study to assess myotonometric parameters in diabetic foot patients with a history of ulcers that have completely healed. These findings suggest that biomechanical alterations may persist even after ulcer resolution, potentially contributing to ongoing foot dysfunction and an increased risk of recurrence. Further research involving larger cohorts is needed to validate these results. Therefore, the development of innovative strategies for the prevention of diabetic foot ulcers remains essential.

Recent studies emphasize the importance of early assessment methods in identifying the risk of foot ulceration in diabetic patients [25–28]. To reduce the burden of diabetes-related foot disease, standardized assessment protocols that incorporate preventive strategies are essential. Trebbi et al. believed to be crucial to analyze the behavior of soft tissues under shearing loads configurations, as these are considered the most dangerous for triggering diabetic foot ulcers. Furthermore, there is a necessity to enhance the capabilities of current finite element models so that they can accurately estimate their capacity to simulate realistic strains [29]. Evaluating tissue mechanical properties using a simple and non-invasive technique, such as myotonometry, may serve as a practical tool for the early detection of diabetes-associated foot complications. In this study, we utilized the MyotonPRO® device to assess mechanical properties of fascia, tendons, and muscles. The MyotonPRO® is an emerging tool in clinical biomechanics, offering a radiation-free and cost-effective alternative to ultrasound elastography (USG) and magnetic resonance imaging (MRI), particularly for frequent tissue evaluations [17]. Unlike ultrasound imaging, which provides high-resolution visualization of muscle structure, the MyotonPRO® offers complementary quantitative data on mechanical properties such as

Table 2 Biomechanical properties of extrinsic foot muscles, Achilles tendon, and plantar fascia in diabetic foot and healthy foot

	F-Natural Oscillation Frequency				S-Dynamic Stiffness				D-Logarithmic Decrement			
	Diabetic Foot *n* = 38	Healthy Foot *n* = 40	*p*	d	Diabetic Foot *n* = 38	Healthy Foot *n* = 40	*p*	d	Diabetic Foot *n* = 38	Healthy Foot *n* = 40	*p*	d
Tibialis Anterior	19.84 ± 3.96	17.09 ± 3.02	**0.003**	0.78	396.2 ± 119.5	336.2 ± 75.12	**0.01**	0.6	1.02 ± 0.2	1.04 ± 0.2	0.47	0.1
Gastrocnemius Medialis	16.99 ± 2.95	15.12 ± 2.46	**0.03**	0.69	307.05 ± 75.02	271.5 ± 45.61	**0.01**	0.54	1.21 ± 0.23	1.19 ± 0.28	0.75	0.08
Gastrocnemius Lateralis	17.88 ± 3.57	16.77 ± 2.94	0.141	0.34	334.65 ± 81.58	306.6 ± 66.65	0.53	0.38	1.15 ± 0.25	1.21 ± 0.29	0.57	0.22
Achilles Tendon	31.56 ± 5.54	29.51 ± 3.06	0.08	0.46	817.36 ± 151.61	757.5 ± 68.56	**0.02**	0.50	0.80 ± 0.2	0.84 ± 0.1	0.1	0.24
Plantar Fascia	25.99 ± 3.17	25.66 ± 2.87	0.3	0.1	575.55 ± 82.95	525.2 ± 58.11	**0.04**	0.7	1.26 ± 0.17	1.33 ± 0.11	0.05	0.49

Mean ± SD values for natural oscillation frequency (F), dynamic stiffness (S), and logarithmic decrement (D) are presented for the diabetic foot and healthy foot. Statistically significant differences ($p < 0.05$) are in bold. Cohen's d effect sizes are provided

tone, stiffness, and elasticity [23]. While structural imaging is valuable for anatomical assessment, myotonometry captures functional tissue characteristics that may reflect early biomechanical changes. Its accessibility, non-invasive nature, and ability to provide real-time mechanical feedback support its integration into diabetic foot evaluation. Rather than suggesting methodological superiority or assuming that ease of use implies greater diagnostic accuracy, we consider myotonometry a complementary approach that adds value to existing diagnostic tools by addressing mechanical aspects of soft tissue function.

Muscle tone refers to the mechanical stiffness that exists when skeletal muscles are in a steady-state condition without voluntary contraction [16, 22, 30]. Stiffness is defined as the resistance of muscle tissue to contractile and external deforming forces [18, 31]. Clinically, tissue stiffness is crucial as it directly influences mechanical load distribution and movement quality. It is influenced by both neural and non-neural components. The neural aspects of muscle tone include active muscle tension and stretch reflex contractions, while the non-neural (intrinsic) components are associated with passive stiffness and the inherent mechanical properties of the tissues [30]. Natural Oscillation Frequency (F) was used to assess muscle tone, reflecting the intrinsic tension of the tissue at rest. We observed elevated F-values in the affected limbs of patients with a history of diabetic foot ulcers, indicating increased baseline muscle tone. This may reflect underlying neuromuscular dysregulation or chronic structural adaptation in response to prior ulceration. Such alterations could impair load distribution and contribute to ulcer recurrence, emphasizing the clinical relevance of tissue tone in diabetic foot management [21, 32]. Furthermore, increased muscle tone and stiffness were specifically identified in the TA and GM muscles. Kim et al. have suggested that increased TA tone may contribute to tendon stiffness and shortening, potentially leading to excessive plantar loading and increased ulceration risk [33]. Similarly, our findings indicate that not only was TA tone elevated, but its stiffness was also significantly increased, suggesting a more rigid and mechanically altered muscle state in diabetic foot patients. Moreover, previous researches indicate that diabetic foot can lead to altered motor unit recruitment and reduced TA activation [34, 35]. The compensatory increase in TA tone observed in our study may be a response to motor unit loss, where fewer but more actively recruited fibers sustain baseline muscle activity. This motor unit remodeling could explain the persistence of increased tone even after ulcer healing. Additionally, structural changes such as increased collagen cross-linking and extracellular matrix remodeling in diabetes may further contribute to the observed increase in stiffness [36, 37]. Chronic elevation in TA tone and stiffness could lead to abnormal gait

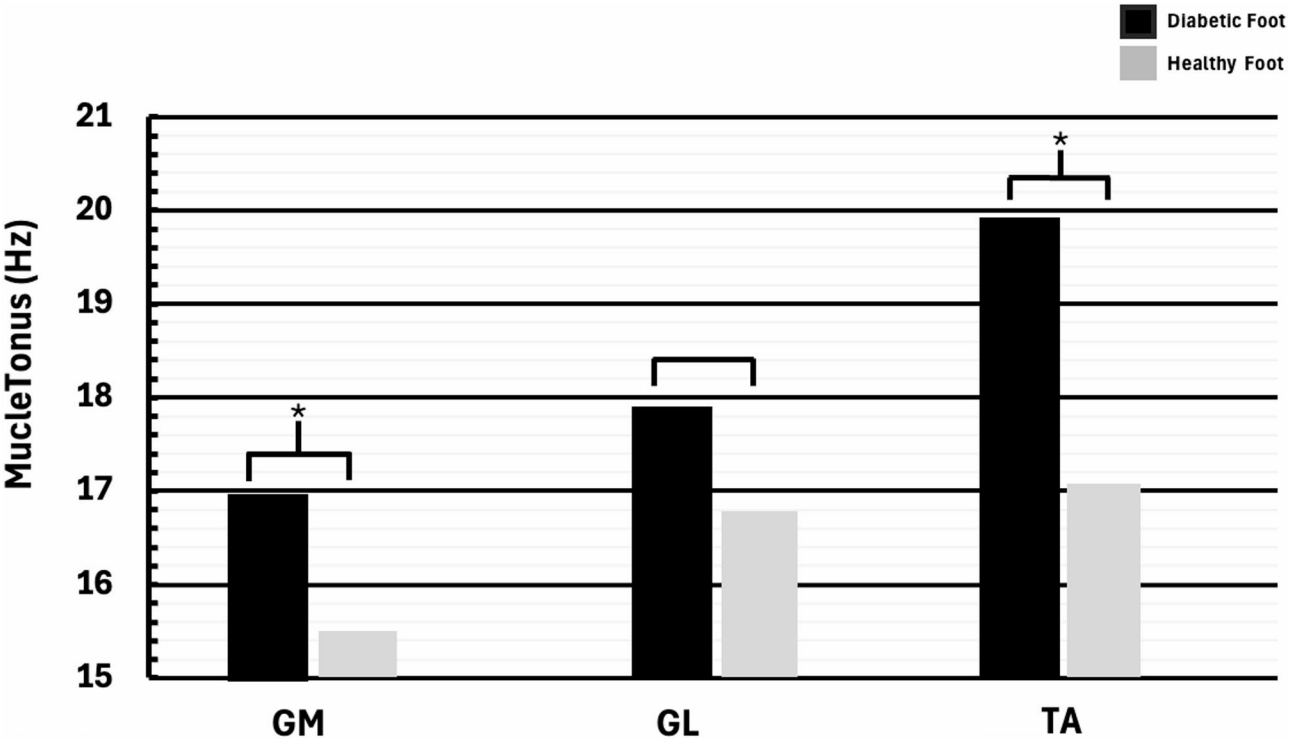

Fig. 2 Muscle Tone (Hz) in Diabetic Foot and Healthy Control Groups. Muscle tone (Hz) of the, gastrocnemius medialis (GM), gastrocnemius lateralis (GL) and tibialis anterior (TA) in the diabetic foot (DF) and healthy control (HC) groups. Statistically significant differences ($p < 0.05$) are marked with (*)

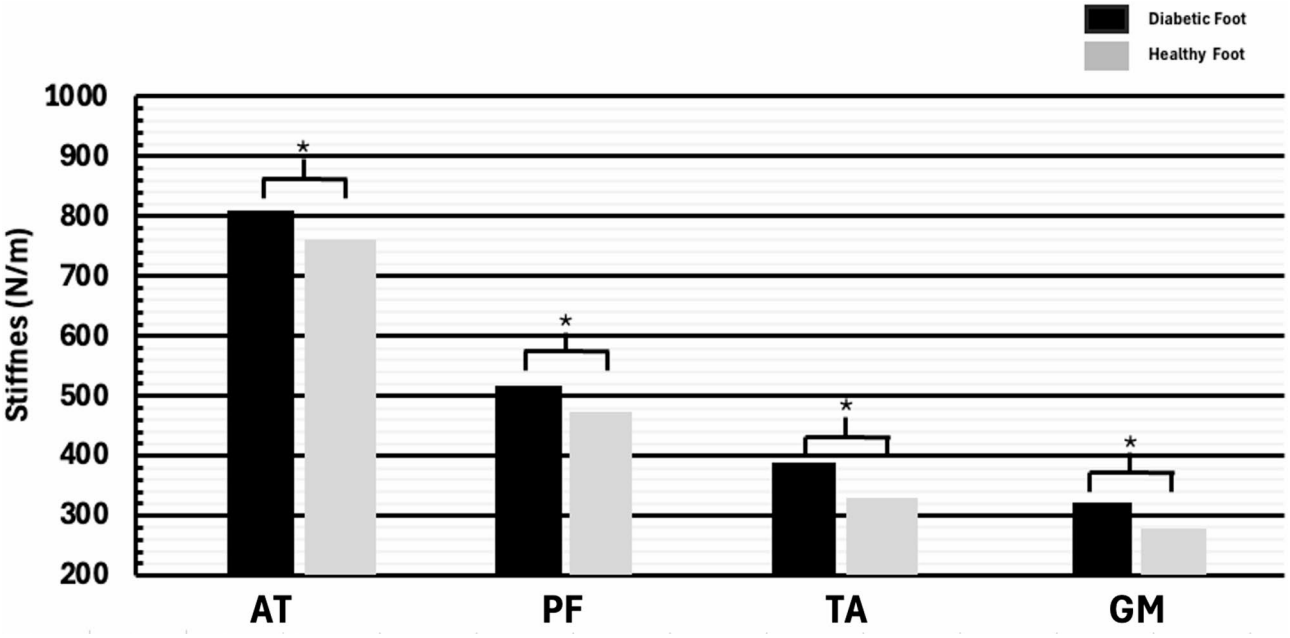

Fig. 3 Stiffness (N/m) of Achilles Tendon, Plantar Fascia, and Tibialis Anterior in Diabetic and Healthy Feet. Stiffness (N/m) of the Achilles tendon (AT), plantar fascia (PF), tibialis anterior (TA), gastrocnemius medialis (GM), and gastrocnemius lateralis (GL) in the diabetic foot (DF) and healthy control (HC) groups. Statistically significant differences ($p < 0.05$) are marked with (*)

mechanics, altered foot posture, and increased plantar pressure in specific regions, thereby contributing to ulcer recurrence. Given this, addressing excessive TA tone and stiffness through targeted rehabilitation strategies, including stretching, neuromuscular re-education, and load redistribution interventions, may be beneficial in reducing the risk of ulcer recurrence in diabetic patients.

In our study, we observed a significant increase in muscle tone and stiffness in the GM, whereas no significant changes were detected in the GL. While there was a slight increase in GL tone and stiffness, this change was not statistically significant, suggesting that mechanical adaptations in diabetic foot primarily affect the GM rather than the GL. This asymmetry may stem from the distinct functional roles of these muscles, their fiber composition, and mechanical adaptations to altered gait mechanics. The GM plays a dominant role in plantar flexion and weight-bearing, making it more susceptible to mechanical stress and compensatory hyperactivity [38]. In contrast, GL primarily contributes to postural stabilization, which may explain why it remained less affected [39]. Furthermore, GM exhibits a higher degree of proprioceptive input, which could make it more vulnerable to neuromuscular compensations and altered activation timing in diabetic foot [40]. The selective increase in GM stiffness may lead to abnormal foot loading, plantar pressure imbalances, and an increased risk of ulcer recurrence. Although GL did not show a statistically significant change, the slight increase observed could indicate a compensatory response that warrants further investigation. These mechanical alterations may disrupt plantar loading and contribute to an increased risk of ulcer recurrence. Targeted interventions such as fascia, tendon and muscle stretching exercises, neuromuscular retraining and load redistribution strategies may help mitigate these biomechanical alterations.

The plantar fascia (PF) is a key structure affected by diabetes, playing a crucial role in foot biomechanics [41, 42]. Our study demonstrated that PF stiffness was significantly higher in individuals with T2DM compared to healthy controls. Additionally, increased stiffness in the AT was also observed in individuals with T2DM. The anatomical and functional continuity between these structures suggests that diabetes-related connective tissue alterations may affect the mechanical properties of multiple components within the foot. The concurrent increase in stiffness observed in both structures may reflect systemic alterations in tendon and fascia biomechanics due to diabetes-related changes in collagen structure and glycation processes. Previous research has indicated that the PF and AT function as a mechanically linked system, where increased AT tension can lead to compensatory changes in PF stiffness [43–45]. These findings are consistent with Banerjee et al. who also reported increased PF stiffness in T2DM patients, with further deterioration over time [14]. Similarly, Çakıcı et al. found that higher PF stiffness was associated with impaired gait mechanics and increased fall risk in individuals with diabetes [10]. Todros et al. demonstrated through experimental tests that the nonlinear stress–strain and time-dependent behavior of the plantar fascia in individuals with diabetes indicates increased stiffness compared to healthy subjects, as well as a more pronounced stress-relaxation response [46]. These findings suggest that diabetes-related alterations in PF biomechanics may play a role in promoting instability and abnormal plantar load distribution. While previous studies have investigated plantar fascia stiffness in individuals with diabetic foot, to the best of our knowledge, this is the first study to examine the mechanical and viscoelastic properties of the AT and extrinsic foot muscles in this population. Given their biomechanical continuity, the AT and PF were assessed under the same conditions. This ensured a more comprehensive evaluation of tissue stiffness and load distribution in diabetic foot. These findings highlight potential implications for gait mechanics and foot function, as altered stiffness in these structures may contribute to changes in plantar pressure distribution and an increased risk of foot complications and ulceration. Future studies incorporating dynamic plantar pressure assessments and gait analysis could provide further insights into the functional implications of these stiffness alterations.

This study has several limitations. First, ankle joint biomechanics were not assessed, which could have provided additional insights into foot–ankle interactions in individuals with diabetic foot. Second, myotonometric measurements were performed at rest, capturing passive mechanical properties rather than dynamic muscle function. Future research should incorporate functional assessments, such as gait analysis or electromyography, to better understand tissue behavior during movement. Third, the exact time elapsed since ulcer healing was not recorded, which limits the interpretation of how long biomechanical alterations may persist after resolution. Moreover, while viscoelasticity was addressed using parameters such as logarithmic decrement, other indicators like stress-relaxation time (R) and creep (C) were not included. The MyotonPRO® device was used in accordance with standard protocols, but its proprietary algorithm limits access to internal computations, which may affect cross-device comparability. Lastly, the cross-sectional design precludes causal inferences. Future longitudinal studies are needed to determine whether the observed biomechanical alterations contribute to ulcer recurrence. Despite these limitations, the findings underscore the importance of biomechanical assessment

in the comprehensive management of diabetic foot complications.

In conclusion, increased plantar fascia (PF) stiffness, along with elevated Achilles tendon (AT) stiffness and higher gastrocnemius medialis (GM) tone, was observed in individuals with diabetes and a history of previous foot ulcers. These findings indicate that mechanical alterations in foot structures persist even after ulcer healing, potentially leading to long-term biomechanical dysfunction and an increased risk of recurrence. Naemi et al. reported that active diabetic foot ulcers significantly alter plantar soft tissue mechanical properties, including reduced stiffness and impaired elasticity [47]. In contrast, the present study focused on individuals with fully healed ulcers. Therefore, the biomechanical characteristics observed here may reflect chronic adaptations following ulcer resolution, rather than acute tissue degradation associated with active ulceration.As soft tissue stiffness progresses, altered plantar pressure distribution may further exacerbate foot complications, reinforcing the importance of early detection and intervention. Considering the early involvement of intrinsic foot muscles in diabetes, progressive soft tissue stiffening may be a key factor contributing to ulcer recurrence. Addressing these mechanical changes through targeted rehabilitation strategies could help mitigate the risk of future complications. Stretching programs may enhance soft tissue flexibility, neuromuscular training could improve muscle function and coordination, and orthotic interventions may assist in redistributing plantar pressure to optimize foot mechanics. Incorporating routine biomechanical assessments into diabetic foot care may allow for the early identification of at-risk individuals and facilitate timely, personalized preventive strategies. Determination of tissue mechanical properties with a simple method such as a myotonometer may be useful in the early diagnosis of diabetes-associated foot ulceration. Integrating the assessment of key tissue mechanical parameters—such as muscle tone, stiffness, and elasticity—into routine diabetic foot evaluations may enhance preventive strategies and improve long-term clinical outcomes. By identifying and addressing underlying mechanical dysfunctions, these measures have the potential to reduce ulcer recurrence, improve mobility, and enhance the quality of life in individuals with diabetes. Incorporating such parameters into standard screening protocols could also help reduce the healthcare burden associated with ulcer treatment and lower-extremity amputations.

Abbreviations

DFU Diabetic foot ulcer
DM Diabetes mellitus
DF Diabetic foot
AT Achilles tendon
PF Plantar fascia
TA Tibialis anterior
GM Gastrocnemius medialis
GL Gastrocnemius lateralis

Author contributions

F.V. provided the overall design ideas and specific implementation steps for the completion of the manuscript, analyzed subject data, collected data. A.I. was a major contributor in writing the manuscript, analyzed subject data, collected data, and prepared Figs. 1, 2 and 3. Y.A. contributed to data analysis, data collection, and determined Wagner classifications. All authors reviewed and approved the final manuscript.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki (https://www.wma.net/policies-post/wma-declaration-of-helsinki). Ethical approval was obtained from the Hamidiye Scientific Research Ethics Committee of Health Sciences University in Turkey (Approval No: 23/507). The approval was granted during the committee meeting on September 1, 2023 (Meeting No: 2023/16, Decision No: 16/15). All participants provided written informed consent prior to their inclusion in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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