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ORIGINAL ARTICLE – OPEN ACCESS

The Effects of Tibialis Posterior Muscle Fatigue and Walking Speed on Dynamic Plantar Pressure Characteristics in Healthy Individuals: A Single Group Pre-Post Test

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ABSTRACT

Objective: This study aims to investigate the effects of tibialis posterior muscle (TP) fatigue on dynamic plantar pressure (DPP) characteristics during different walking speeds.

Materials and Methods: Thirty healthy volunteers walked at normal and fast paces in three trials. The Footscan®3D system was used to obtain the distribution of dynamic plantar pressure before and after the TP fatigue protocol. The study measured the peak pressure (PP) of the hallux, toes 2–5, metatarsals (Meta 1-5), midfoot (MF), medial heel (MH) and lateral heel (LH), as well as the percentage of contact area (CA%) of the forefoot (FF), MF and hindfoot (HF), foot progression angle (FPA) and the minimum and maximum values of the subtalar angle.

Results: The results showed significant differences in the PP of Meta 4, MH and MF at a normal pace after the tibialis posterior muscle fatigue protocol. At a fast pace, significant differences were found in the PP of the MF and CA% of FF and MF. Before the fatigue protocol, there were significantly different values in the peak pressure of the hallux, toes 2–5 and MH between the two walking speeds. After the fatigue protocol, there were significantly different values in the peak pressure of toes 2–5, MH and LH between the two walking speeds. The study also found a significant difference in FPA between the two walking speeds ($p<0.05$).

Conclusion: The study provides evidence that TP fatigue may lead to injuries during long-term walking or sports activities. These results highlight the importance of endurance training and minimizing its negative effects on foot biomechanics by reducing fatigue.

Keywords: Pedobarography, plantar pressure distribution, walking speed, tibialis posterior, muscle fatigue

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INTRODUCTION

An important characteristic that sets humans apart from other creatures is the ability to maintain balance while standing upright. The human foot has a rigid structure that provides bodyweight support and acts as an elastic mechanism to recycle energy during the propulsion phase of gait, as well as a flexible structure to adapt to different terrains during the stance phase of gait (1). The medial longitudinal arch (MLA) is an essential component of the foot that is responsible for stabilization during walking and posture. The tibialis posterior (TP) muscle is a dynamic stabilizer of the MLA and also plays a role in the MLA's static adaptation. Therefore, disorders of the MLA and TP can have a negative impact on foot function (2).

Muscle fatigue or weakness has been identified as a primary contributing factor to atypical foot function (3), resulting in decreased shock attenuation capacity (4). When the TP's shock-absorbing ability is compromised due to localized muscle fatigue, abnormal loading occurs in the MLA, leading to altered foot kinematics (5).

Biomechanical research focuses on foot kinematics and emphasizes the role of the TP in controlling foot mechanics during gait (6, 7). While these studies provide valuable information for understanding foot kinematics, ground reaction forces and the relationship between the foot and ground during gait, they may not provide sufficient information to understand plantar pressure distribution (PPD).

The development of new analysis technologies has made it possible to measure PPD in research and clinical practice. This allows researchers and clinicians to differentiate between normal and pathologic gait, predict risk factors for lower extremity injuries and progression, determine treatment management and more. Additionally, a limited number of studies on PPD during walking have focused on specific pathologies, treatments or orthotic management (8–10).

The results of a cadaveric study demonstrated that the PT muscle has a role in shifting the center of pressure anteriorly between the contact and terminal stance phase (11). Similarly, an increased PPD on the medial forefoot was also reported in another study that compared patients with posterior tibial tendon dysfunction and healthy controls (12).

On the other hand, a recent study reported that higher speed increased the peak pressures of both the forefoot and heel in young healthy adults (13). Another study indicated that walking at slower speeds reduces plantar pressure and prevents peak pressure from being concentrated over a small area (14). It is essential to establish a foundation for understanding the effects of both fatigue and speed on PPD. Therefore, data from healthy individuals would be particularly valuable. Based on these results, exercise and rehabilitation programs can be adapted for different patient groups.

To our knowledge, although there have been studies investigating the effects of localized muscle fatigue of the TP on foot kinematics and the effects of different walking speeds on PPD, no study has assessed the effects of localized muscle fatigue of the TP and walking speed on PPD simultaneously. Therefore, this study aims to advance the understanding of the effects of TP muscle fatigue on dynamic plantar pressure characteristics during different walking speeds. This study hypothesizes that localized muscle fatigue of the TP will mimic insufficiency and lead to an increased walking speed, resulting in PPD values reaching their highest values.

MATERIALS and METHODS

This prospective study using a single group pre- and post-test design has been approved by the Hacettepe University Non-Interventional Clinical Research Ethics Board (LUT 12/46-16). All participants read and signed an informed consent form.

Based on peak PPD measurements of the hallux (mean (SD)=250.2 (56) kPa at a normal pace of 1.25 m/s; mean (SD)=315.5 (77) kPa at a faster pace of 2.00 m/s from Segal et al. (15) via G-Power version 3.1.9.6, with a significance level of α=0.05 and a statistical power of 80%, we determined that a sample size of 30 participants was needed for the study to provide sufficient authority. The snowball sampling system was applied and the first few participants were from the close circle of researchers.

The inclusion criteria for participants were as follows: right foot dominance, no congenital or traumatic deformity or prior history of surgery to either lower extremity, no history of foot pain or traumatic injury to the ankle or foot 12 months prior to the start of data collection. High body mass index (BMI) and low arch are known predictors for elevated PPD; therefore, only participants categorized as having a normal BMI (18.5–24.9 kg/m^2) according to the World Health Organization (WHO) were recruited. Additionally, participants were required to have a normal foot type according to the foot posture index (FPI). Only participants with a score of 0 to +5 (normal foot) were recruited (16). Participants were excluded if they had any orthopedic or neurological disorder, needed to use an assistive device or orthoses or were competing in sporting activities.

Before collecting data, a manual muscle test was performed by the same examiner. The strength of the foot dorsiflexors, plantar flexors, invertors and evertors on both sides were assessed in standard muscle test positions. Since all participants were healthy, all muscle test results were recorded with 5 (out of 5) points.

Dynamic PPD was obtained using the Footscan® 3D system (RSscan International, Olen, Belgium). The pressure platform contained 16384 resistive sensors arranged in 200x40 cm active sensor areas with dimensions of 180x40 cm and with a data acquisition frequency of 100 Hz. The active sensor area was leveled with the ground and hidden to ensure the actual gait pattern. The Footscan® 3D system was calibrated according to the manufacturer's manual. The intra-session reliability of the Footscan® 3D system was reported to be good (for PP intraclass correlation coefficients (ICCs)=0.81 and coefficient variation (CV)=17.1%; for CA% ICCs=0.89 and CV=6.7%) and inter-session reliability was also reported as good (for PP; ICCs=0.84 and CV=11.5%, for CA%; ICCs=0.89 and CV=4.5%) (17).

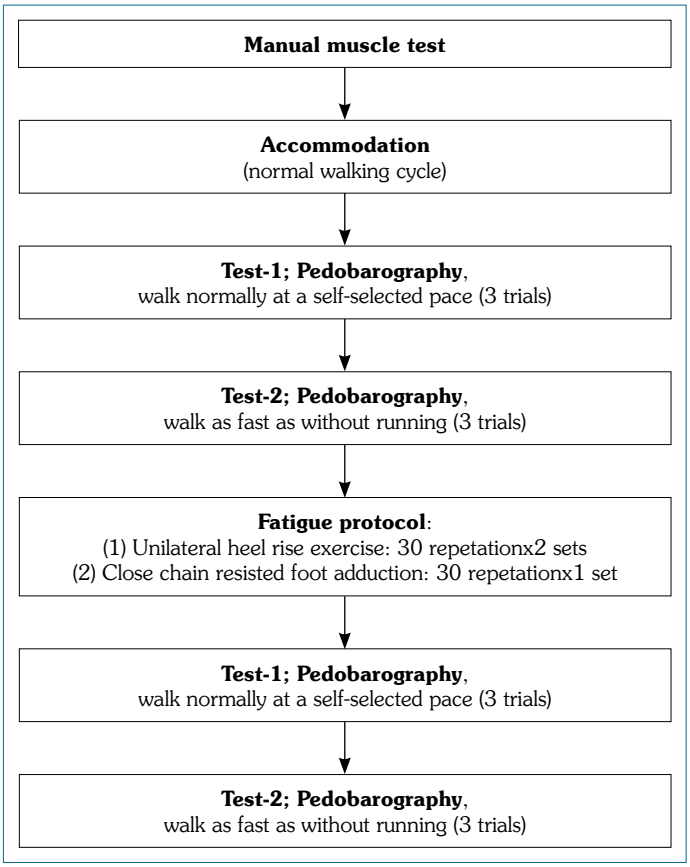

Figure 1. Timeline diagramming the experimental protocol

All participants were instructed to walk barefoot normally at a self-selected pace (normal) and to walk as fast as possible without running (fast). In each protocol, three representative and reliable trials were performed for each walking speed, respectively. In cases where participants paused on the platform, their gait was disturbed or they did not continue walking past the platform, the trial was discarded and repeated. Prior to data collection, the normal walking cycle was completed at least three times over the pressure platform to ensure acclimatization. The test protocol was performed before and after the muscle fatigue protocol assessed during the study (Fig. 1).

Following the muscle fatigue protocol, participants' self-assessed fatigue was evaluated, using the Borg CR-10 scale, which ranges from 0 (nothing at all) to 10 (maximal). Muscle fatigue was defined as a score of 4 or higher on the Borg scale in the current study.

To fatigue the TP, two exercises were performed, which were selected based on MRI research indicating selective activation of the TP (18).

The unilateral heel-raise exercise involved performing as a maximal unilateral heel-raise with the knee in full extension while standing. Participants were allowed to touch an adjacent wall with their right index fingers to provide balance. They performed two consecutive sets of 30 repetitions using only their right extremities.

The close-chain resisted foot adduction exercise was performed in a sitting position with approximately 80 degrees of knee flexion and a forearm-length distance between both knees. The ipsilateral hand of the participant stabilized the contralateral knee. A silver elastic exercise band was looped and fixed around the midfoot and metatarsals, with the other edge of the exercise band fixed by the examiner and stretched to full tension. Participants were encouraged to complete full foot adduction, starting from the full abduction position while maintaining the elastic band's 45-degree angle of inclination with the floor. The foot remained flat on the floor during the entire exercise. Participants completed one set of 30 repetitions using only their right extremities.

The Scientific Footscan Software (RSscan International) was used to divide the PP profiles into ten anatomical regions, including the hallux, toes 2–5, metatarsals (Meta 1, 2, 3, 4, 5), midfoot (MF), medial heel (MH) and lateral heel (LH). Peak pressure (N/cm^2) was analyzed separately for all regions. The following variables were also analyzed: percentage of contact area (CA%) of the forefoot (FF), MF and hindfoot (HF), foot progression angle (FPA) and minimum and maximum values of the subtalar angle (STA). To maintain data independence, the right foot of each participant was chosen for analysis and the first and third trials of all tests were excluded from statistical analyses to avoid acclimatization, boredom or tiredness. The entire assessment and fatigue protocol took approximately one hour per participant and all participants were evaluated within 15 days.

The IBM Statistical Package for Social Sciences (Version 21 for Mac) was used for statistical analysis. The normality of the variables was assessed using Shapiro-Wilk's test. Since the data were normally distributed, the paired samples Student's t test was used to analyze the mean (X), standard deviation (SD), 95% confidence intervals (95% CI), mean difference and Cohen's d-effect size (ES). The significance level was set at 0.05. The effect size was classified as small if d=0.20, medium if d=0.50 and large if d=0.80.

RESULTS

A total of 30 healthy adult volunteers, including 15 females and 15 males, participated in this study, with a mean age of 24.88 (SD=4.39, range 18–35) years, mean height of 171 cm (SD=8.9), mean weight of 68.7 (SD=14.5) kg and mean BMI of 23.33 kg/m^2 (SD=3.95).

Table 1 presents the pairwise comparisons of the PP from ten anatomical regions, CA% of the FF, MF, HF, FPA and the minimum and maximum values of STA. Following the TP fatigue protocol, significant differences were found in the PP for the Meta4, MH and MF at a normal pace ($p<0.05$). These findings suggest TP fatigue resulted in increased loads in the MH and MF regions but the effect of fatigue on these anatomical regions remained small compared to the pre-fatigue condition ($d<0.50$) (Table 1).

The PP from the MF and the CA% of the FF and MF showed significant differences at a fast pace ($p<0.05$). While the PP from the MF and the CA% of the MF increased, the CA% of the FF trend decreased. However, the effect of fatigue on the PP from the MF and the CA% of the MF and FF remained small compared to the pre-fatigue condition ($d<0.50$) (Table 1).

Significant differences were observed in the values recorded between the two walking speeds before the fatigue protocol in terms of PP from the hallux, toes 2–5 and the MH ($p<0.05$). A medium amount of PP from the hallux and MH ($d\geq0.50$) and a large amount of PP from toes 2–5 were calculated ($d\geq0.80$) (Table 1).

After the fatigue protocol, significant differences were recorded between the two walking speeds in terms of PP from the toes 2–5, MH and LH ($p<0.05$). A medium amount of PP from toes 2–5 ($d\geq0.5$) and a small amount of PP from the MH and LH were calculated ($d<0.50$) (Table 1).

For both trials (before and after fatigue protocol), significant differences were observed in the values recorded between the two walking speeds in terms of FPA. A large amount of FPA was calculated for both trails ($d\geq0.80$) (Table 1).

DISCUSSION

The aim of this study was to advance the understanding of the effects of TP muscle fatigue on dynamic PP characteristics during different walking paces. The findings indicate that an increase in walking speed increases a trend towards pronation, which is consistent with previous studies (13, 19). Overall, the results of this study demonstrate that the PP of the MF and MH increased following TP fatigue. Moreover, the contact area of the MF increased in line with increased pronation when the walking speed increased, while the CA of the FF decreased following fatigue and at a fast walking pace. The findings from this study also suggest that an increased walking speed increases the PP of the toes and MH, regardless of fatigue.

Human feet begin developing at birth and are shaped by a combination of genetic and environmental factors, including gender. PPD values can be influenced by a range of factors, including anatomical structure, lower extremity dominancy, range of motion, BMI, muscle strength and foot deformities (20).

The primary function of the TP muscle is to dynamically the medial longitudinal arch (MLA) and elevate it. Additionally, it indirectly supports the calcaneus and the hindfoot (HF) due to its relationship with various ligaments and the pulley effect on the posterior of the medial malleolus (21). The dysfunction of the TP is often caused by prolonged and excessive pronation of the HF, leading to flat foot deformity in adults. The development of flat foot deformity is thought to result from two mechanisms: the loss of the TP's direct support for the MLA and the loss of its function as a HF invertor during the stance phase of gait, which normally locks the HF in a rigid position for push-off. These mechanisms ultimately lead to a relatively unstable valgus position of the foot (21).

Table 1. Pairwise comparisons of the plantar pressure for ten anatomical regions (the CA% of the FF, MF, HF, foot progression angle, the minimum and maximum values of STA) between pre- and post-fatigue protocol and walking at a normal and fast pace

	Pre X (SD) (95% CI)	p†	Post X (SD) (95% CI)	p‡	M. Dif. (95% CI)	ES (Cohen's d)	p¶
Hallux PP (N/cm²)		**0.004**§		0.061			
Normal	12.21 (3.28) (10.98–13.43)		11.92 (4.49) (10.24–13.54)		-2.90 (-2.32–1.74)	0.073	0.724
Fast	14.22 (3.21) (13.02–15.41)		13.54 (4.24) (11.95–15.12)		-0.68 (-2.62–1.26)	0.180	0.345
M.Dif. (95% CI)	-2.01 (-3.69– -0.33)		-1.62 (-3.88–0.64)				
ES (Cohen's d)	0.619		0.370				
Toes 2-5 PP (N/cm²)		<**0.001**§		**0.002**§			
Normal	7.07 (4.62) (5.34–8.79)		6.73 (4.91) (4.89–8.56)		-0.34 (-2.80–2.12)	0.071	0.687
Fast	11.70 (4.97) (9.84–13.55)		10.68 (5.35) (8.68–12.67)		-1.02 (-3.68–1.64)	0.197	0.254
M.Dif. (95% CI)	-4.63 (-7.11– -2.15)		-3.95 (-6.60– -1.30)				
ES (Cohen's d)	0.964		0.769				
Meta1 PP (N/cm²)		0.145		0.080			
Normal	11.17 (4.60) (9.45–12.88)		12.09 (3.44) (10.80–13.37)		0.92 (-1.17–3.01)	0.226	0.170
Fast	12.16 (3.39) (10.89–13.42)		13.09 (3.51) (11.77–14.40)		0.93 (-0.85–2.71)	0.269	0.203
M.Dif. (95% CI)	-0.99 (-3.08–1.10)		-1.00 (-2.80–0.80)				
ES (Cohen's d)	0.245		0.287				
Meta2 PP (N/cm²)		0.408		0.567			
Normal	10.70 (2.18) (9.88–11.51)		10.88 (2.02) (10.12–11.63)		0.18 (-0.90–1.26)	0.385	0.536
Fast	10.31 (2.75) (9.28–11.33)		10.67 (2.61) (9.69–11.64)		0.36 (-1.02–1.74)	0.134	0.429
M.Dif. (95% CI)	0.39 (-0.89–1.67)		0.21 (-1.00–1.42)				
ES (Cohen's d)	0.157		0.089				
Meta3 PP (N/cm²)		0.742		0.890			
Normal	8.65 (1.86) (7.95–9.34)		9.00 (1.57) (8.41–9.58)		0.35 (-0.5–1.23)	0.203	0.234
Fast	8.49 (2.31) (7.62–9.35)		8.95 (2.26) (8.10–9.79)		0.46 (-0.72–1.64)	0.201	0.277
M.Dif. (95% CI)	0.16 (-0.9–1.24)		0.05 (-0.96–1.06)				
ES (Cohen's d)	0.076		0.256				
Meta4 PP (N/cm²)		0.879		0.339			
Normal	8.73 (1.95) (8.00–9.45)		9.39 (1.78) (8.72–10.05)		-0.66 (-0.30–1.62)	0.353	**0.050**§
Fast	8.65 (2.40) (7.75–9.54)		9.07 (2.45) (8.15–9.98)		0.42 (-0.83–1.67)	0.173	0.336
M.Dif. (95% CI)	0.08 (-1.05–1.21)		0.32 (-0.77–1.41)				
ES (Cohen's d)	0.036		0.151				
Meta5 PP (N/cm²)		0.570		0.333			
Normal	8.30 (2.56) (7.34–9.25)		7.89 (3.09) (6.73–9.04)		-0.41 (-1.87–1.05)	0.144	0.424
Fast	8.60 (3.28) (7.37–9.82)		7.38 (3.44) (6.09–8.66)		-1.22 (-2.95–0.51)	0.362	0.057
M.Dif. (95% CI)	-0.30 (-1.82– -1.22)		0.51 (-1.18–2.20)				
ES (Cohen's d)	0.101		0.155				

Table 1 (cont). Pairwise comparisons of the plantar pressure for ten anatomical regions (the CA% of the FF, MF, HF, foot progression angle, the minimum and maximum values of STA) between pre- and post-fatigue protocol and walking at a normal and fast pace

	Pre Mean (SD) (95% CI)	p†	Post Mean (SD) (95% CI)	p‡	M. Dif. (95% CI)	ES (Cohen's d)	p¶
Midfoot PP (N/cm²)		0.313		0.387			
Normal	18.86 (12.00) (14.37–23.34)		22.72 (12.12) (18.19–27.24)		3.86 (-2.37–10.09)	0.320	**0.003**§
Fast	20.17 (13.68) (15.06–25.07)		23.57 (13.31) (18.5–28.54)		3.40 (-3.57–10.37)	0.251	**0.004**§
M.Dif. (95% CI)	-1.31 (-7.95–5.33)		-0.85 (-7.43–5.73)				
ES (Cohen's d)	0.401		0.066				
Medial heel PP (N/cm²)		<**0.001**§		<**0.001**§			
Normal	17.63 (3.16) (16.45–18.80)		18.33 (2.84) (17.2–19.39)		0.70 (-0.85–2.25)	0.233	**0.043**§
Fast	19.11 (2.79) (18.0–20.15)		19.33 (3.03) (18.19–20.46)		0.22 (-1.28–1.72)	0.075	0.485
M.Dif. (95% CI)	-1.48 (-3.0– -0.06)		-1.00 (-2.52–0.52)				
ES (Cohen's d)	0.496		0.340				
Lateral heel PP (N/cm²)		0.178		**0.016**§			
Normal	16.08 (3.42) (14.80–17.35)		16.10 (2.50) (15.16–17.03)		0.20 (-1.52–1.56)	0.006	0.974
Fast	16.79 (2.38) (15.90–17.67)		16.76 (2.73) (15.74–17.77)		-0.30 (-1.35–1.29)	0.011	0.928
M.Dif. (95% CI)	-0.71 (-2.23–0.81)		-0.66 (-2.01–0.69)				
ES (Cohen's d)	0.240		0.252				
Forefoot CA%		0.119		0.387			
Normal	55.27 (7.96) (52.29–58.24)		54.60 (4.38) (52.96–56.23)		-0.67 (-3.99–2.65)	0.041	0.657
Fast	57.39 (5.31) (55.40–59.37)		55.51 (5.54) (53.44–57.57)		-1.88 (-.468–0.92)	0.075	**0.021**§
M.Dif. (95% CI)	-2.12 (-5.62–1.38)		-0.91 (-3.49–1.67)				
ES (Cohen's d)	0.313		0.431				
Midfoot CA%		0.114		0.243			
Normal	16.40 (10.18) (12.59–20.20)		18.16 (8.46) (15.00–21.31)		1.76 (-3.07–6.59)	0.428	0.297
Fast	14.29 (7.13) (11.62–16.95)		16.74 (6.96) (14.14–19.33)		2.45 (-1.19–6.09)	0.045	**0.003**§
M.Dif. (95% CI)	2.11 (-2.43–6.65)		1.42 (-2.58–5.42)				
ES (Cohen's d)	0.240		0.179				
Hindfoot CA%		0.829		0.963			
Normal	28.39 (3.04) (27.25–29.52)		27.78 (4.76) (26.00–29.55)		-0.61 (-2.67–1.45)	0.360	0.332
Fast	28.28 (4.02) (26.77–29.78)		27.75 (3.55) (26.42–29.07)		-0.53 (-2.49–1.43)	0.139	0.295
M.Dif. (95% CI)	-0.89 (-2.73–0.95)		0.03 (-2.14–2.20)				
ES (Cohen's d)	0.249		0.192				
Foot progression angle (FPA)		**0.005**§		**0.013**§			
Normal	13.43 (8.02) (10.43–16.42)		13.13 (6.44) (10.72–15.53)		-0.30 (-4.05–3.45)	0.152	0.793
Fast	19.11 (2.79) (18.0–20.15)		19.33 (3.03) (18.19–20.46)		0.22 (-1.28–1.72)	0.069	0.991
M.Dif. (95% CI)	3.13 (-0.60–6.86)		2.82 (-0.56–6.20)				
ES (Cohen's d)	0.945		1.231				

Table 1 (cont). Pairwise comparisons of the plantar pressure for ten anatomical regions (the CA% of the FF, MF, HF, foot progression angle, the minimum and maximum values of STA) between pre- and post-fatigue protocol and walking at a normal and fast pace

	Pre Mean (SD) (95% CI)	p†	Post Mean (SD) (95% CI)	p‡	M. Dif. (95% CI)	ES (Cohen's d)	p¶
Subtalar angle (min.- degree)		0.416		0.598			
Normal	-3.80 (7.31) (-6.52–1.07)		-0.88 (6.27) (-3.22–1.46)		2.92 (-0.59–6.43)	0.188	0.109
Fast	-1.95 (6.27) (-4.29–0.39)		-2.31 (9.37) (-5.80–1.18)		-0.36 (-4.48–3.76)	0.347	0.860
M.Dif. (95% CI)	-1.82 (-5.34–1.70)		1.43 (-2.69–5.55)				
ES (Cohen's d)	0.267		0.183				
Subtalar angle (max.- degree)		0.416		0.445			
Normal	12.40 (10.21) (8.58–16.21)		15.94 (9.39) (12.4–19.44)		3.54 (-1.52–8.60)	0.104	0.150
Fast	12.48 (10.12) (8.70–16.25)		13.96 (11.15) (9.79–18.12)		1.48 (-4.02–6.98)	0.346	0.543
M.Dif. (95% CI)	-0.08 (-5.33–5.17)		1.98 (-3.35–7.31)				
ES (Cohen's d)	0.007		0.182				

Pre: Before fatigue; Post: After fatigue protocol performed; FF: Forefoot; MF: Midfoot; HF: Hindfoot; PP: Plantar pressure; STA: Subtalar angle; SD: Standard deviation; CI: Confidence of interval; M.Dif.: Mean difference; ES: Effect size; CA: Contact area; †: Pairwise comparison between normal and fast walking before fatigue protocol; ‡: Pairwise comparison between normal and fast walking after fatigue protocol; ¶: Pairwise comparison between before and after fatigue protocol at normal and fast walking speeds; §: P<0.05

In this study, healthy participants were recruited based on a lack of flat foot deformity or TP dysfunction. The purpose of the study was to investigate the modifications that occur with TP fatigue in healthy individuals, which can affect foot flexibility by altering the pronation of the subtalar and midtarsal joints during the stance phase and locking the foot for rigid lever function during the push-off phase. The MF, which is located at the junction of the FF and HF, compensates for changes in the HF until the FF adapts and develops a consistent gait pattern. Previous studies have also emphasized the importance of fatigue in ankle sprain injuries, as the fatigued TP may not provide sufficient support for maximum peak torques of the gastrocnemius muscle complex during the loading phase of the FF (22, 23).

In this study, we found a statistically significant but small increase in the plantar pressure (PP) of the medial forefoot (MF) and medial heel (MH) at both walking speeds. We believe that this increase may be due to the elevated angle and prolonged pronation resulting from fatigue. After the fatigue protocol, the tired tibialis posterior muscle mimics partial signs of insufficiency and cannot support the medial longitudinal arch (MLA), leading to an increased load on the MF.

A previous study suggested that increased pronation leads to a collapse in the MLA, resulting in an increase in the CA% in patients with flat feet (24). Another study reported that low-arched feet have increased CA% of the MF compared to feet without low arches. They also reported that low-arched feet have asymmetry in the PP on the lateral side of the MF, with negative implications (25).

Regarding the increased load of the MF, another noteworthy result from this study is the decrease in the CA% of the FF following fatigue and when walking at a fast pace. One possible explanation for this result is that the increased pronation of the HF leads to an increase in the PP and CA% of the MF, thereby reducing the load on the FF during the gait cycle. Segal et al. (15) speculated that the explanation for their findings of a decrease in the PP of the FF at faster walking speeds was the duration of contact time. They suggested that the foot moves quickly through the sub-stages of the stance phase, spending less time loading the FF. Therefore, reducing contact time may also decrease the CA% of the FF at faster walking speeds.

The insignificant difference in the PP in other regions may be due to the failure of localized fatigue to induce specific biomechanical changes in the whole foot in the short term.

Based on current literature, it is known that different regions of the foot respond differently to various walking speeds. In the present study, a statistically significant and medium-to-large increase was observed in the PP of the hallux, toes 2–5 and metatarsal head, irrespective of fatigue.

One of the noteworthy results of this study is the identification of walking speed-dependent changes before the fatigue protocol was applied. The study found a statistically significant and medium-to-large increase in PP at the hallux, toes 2–5 and MH, regardless of fatigue. These findings are consistent with previous studies (15). For example, Drerup et al. (26) reported an approximately 20% increase in PP at the heel when walking at a faster speed (1.3 m/sec). Zhu et al. (27) examined in-shoe PP measurements at two controlled cadences of 70 steps/min and 120 steps/min and reported a pressure increase of 119% at the heel. Segal et al. (15) also found a linear increase in PP at the heel and hallux as gait speed increased, which they attributed to the association between PP and speed-vertical ground reaction forces.

Vaughan et al. (28) suggested that propulsive forces increase before foot-off. In this respect, they explained that the combination of increased force and the pressure with decreased CA% was the reason for the increased PP at the hallux.

Previous studies have had limited focus on the toes and to our knowledge, only one other study has reported plantar pressure distribution on toes 2–5 with different walking speeds. Similarly to our study, Warren et al. (29) also found a linear relationship between increasing gait speed and increasing PP at the toes. This may be due to the toes controlling pronation-related flexibility through ground adherence reactions. The findings from our study indicate that TP fatigue may alter HF biomechanics, causing more loading on the FF than normal, regardless of fatigue, when walking at faster speeds.

FPA is defined as the angle between the foot-long axis and the line of progression averaged from heel strike to toe-off during the stance phase of walking for each step (30). Our results are consistent with previous studies that show trends toward foot abduction in advanced stages of acquired flat-foot (21, 24). In other words, as HF pronation increases, FPA also increases. We hypothesize that the increase in FPA observed in this study may be due to the increase in foot pronation caused by the faster walking speed.

The results of this study should be interpreted with consideration to various factors that may impact the pressure measurements, such as the equipment used for measuring PPD, the frequency of sampling and the speed of movement. Moreover, participant-related factors such as age can also affect PPD. To mitigate this effect, the current study only recruited young adult participants with no history of foot or lower extremity injuries or pain. However, this may also limit the generalizability of the study's findings.

On the other hand, to minimize the effect of muscle strength on PPD, manual muscle tests were performed and only healthy participants with maximum strength were recruited. However, this may still be considered a potential source of bias and the second limitation of this study. Third, the range of walking speeds was limited and subjective, which may not be representative of all conditions. Fourth, since the participants were evaluated in a study setting environment, the results of our study may not be fully applicable to natural walking conditions.

To our knowledge, our study is one of the first to examine the minimum and maximum angular value measurements of the subtalar joint. Although we did not find any significant changes, this preliminary report suggests the need for further investigation. To address this issue in future studies, it is recommended to induce more severe fatigue and to recruit a larger sample size.

CONCLUSION

The effects of localized fatigue of the TP induced by selective exercises on PPD were examined using the pedobarographic method in this study. It can be concluded that increasing muscular endurance can be an effective solution to mitigate functional and biomechanical issues that may arise with muscle fatigue. Based on our findings, we believe that health professionals can better inform preventive and treatment recommendations by identifying differences between at-risk populations with insufficient TP function and normal populations.

Ethics Committee Approval: The Hacettepe University Non-Interventional Clinical Research Ethics Committee granted approval for this study (date: 08.11.2013, number: LUT 12/46-16).

Informed Consent: Written informed consent was obtained from patients who participated in this study.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – ART, NB; Design – ART, NB; Supervision – NB; Resource – NB; Materials – ART, PK; Data Collection and/or Processing – ART, PK; Analysis and/or Interpretation – PK; Literature Search – ART; Writing – PK; Critical Reviews – ART, NB.

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