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The Effect of Plantar Fasciitis on Vertical Foot-Ground Reaction Force

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Despite the implication that mechanical overload is fundamental to the development of plantar fasciitis, gait analysis has revealed inconsistent findings regarding its effect on lower limb loading. The aim of the current study was to evaluate the regional vertical ground reaction force in patients with and without plantar fasciitis. A pressure platform was used to determine the vertical ground reaction force beneath the feet of 16 patients with, and an equivalent number of patients without, unilateral plantar fasciitis while completing 10 gait trials at a self-selected walking speed. The magnitude and timing of ground reaction force for the entire foot and for the regions of the rearfoot, midfoot, forefoot, and digits were measured for each limb. The findings indicate that patients with plantar fasciitis make gait adjustments that result in reduced force beneath the rearfoot and forefoot of the symptomatic foot. In addition, increased digital loading was observed in patients with plantar fasciitis suggesting that digital function plays an important, and previously unidentified, protective role.

Plantar heel pain is the most common disorder of the foot.[13] Although numerous local and systemic conditions have been implicated,[14] plantar fasciitis is the most frequently reported cause of inferior heel pain.[28] Commonly referred to as heel spur syndrome or subcalcaneal pain, plantar fasciitis is characterized by pain localized to the insertion of the plantar fascia that is exacerbated by weightbearing especially after periods of rest.[8,31]

Despite its widespread prevalence, relatively little is known about the pathogenesis of plantar fasciitis.[29] Chronic inflammation secondary to mechanically induced microtrauma, however, seems to be the most widely cited mechanism.[21] Given that mechanical overload and excessive strain within the fascia are thought to be fundamental to the development of plantar fasciitis,[20] it is remarkable that few studies have shown an alteration in the mechanical loading of the affected limb during gait.

Liddle et al[23] observed no differences between symptomatic and asymptomatic limbs with respect to the magnitude and timing of the vertical heel strike transient or first vertical

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force maximum in patients walking at their preferred speed. They proposed that factors other than ground reaction force contributed to the development of heel pain. Katoh et al,[15–17] in contrast, showed a substantial change in the ground reaction force profile of patients with plantar fasciitis. In particular, they reported a relative flattening of the typically double-humped appearance of the vertical ground reaction force profile in shod patients walking at their preferred speed. They intimated that patients adopted a less energetic gait pattern in an attempt to reduce the regional loading of the heel. This conclusion was echoed by Daly et al.[10]

In support, Wearing et al[33] observed lowered rearfoot impulses in patients with heel pain, when impulses were derived from the location of the center of pressure. Most studies, however, have suggested that regional loading of the heel is unaffected by plantar fasciitis.[2,15,17,19] Moreover, although Katoh et al[16,17] and Bedi and Love[2] agreed that hindfoot impulses were unaffected by plantar fasciitis, they disagreed about the changes in the regional loading of the midfoot and forefoot. Katoh et al observed that midfoot impulses were substantially higher in patients with plantar fasciitis, whereas forefoot impulses were significantly lower. Bedi and Love, in contrast, found the exact opposite, with plantar fasciitis inducing heightened forefoot impulses at the expense of lowered midfoot impulses.

Consequently, there is little consensus regarding the effect of plantar fasciitis on the loading pattern of the involved limb during gait. The aim of the current study was to investigate the gait kinetics of patients with and without plantar fasciitis. It was hypothesized that plantar fasciitis would result in altered loading of the involved limb and foot.

MATERIALS AND METHODS

Patients

The study recruited 16 patients (two males and 14 females) from the podiatry clinic at the authors' institution with a history of unilateral plantar fasciitis. Criteria for inclusion into the patient cohort included localized tenderness isolated to the plantar fascia near its insertion into the medial calcaneal tuberosity with exacerbation of symptoms after periods of nonweightbearing.[13,23] Passive dorsiflexion and plantar flexion of the digits were used to isolate the fascial origin in all cases. Patients with an onset of heel pain less than 6 weeks were not included in the study. Other exclusion criteria included diffuse or bilateral heel pain, a history of gout or inflammatory joint disease, and a history of foot surgery or trauma.

An equivalent number of asymptomatic volunteers individually matched for age, gender, and body weight, were recruited from university staff and their families to form the control group. Volunteers with musculoskeletal disorders of the lower limb, gross deformity of the feet, or clinical signs of an antalgic gait pattern were excluded from entering the control group. In accordance with university ethics guidelines, written consent was obtained from all patients after a verbal and written explanation of the project.

Equipment

An EMED-SF (Novel GmbH, Munich, Germany) capacitance, mat transducer system, mounted at the midpoint of an 8-m walkway, was used to collect regional force and temporal data. The platform surface was 23 cm × 44 cm and had a sensor matrix of 2736 force transducers with a density of 4 sensors/cm^2 and a sampling frequency of 50 Hz.

Body weight was measured directly using a set of clinical scales (Soehnle, Montlingen, Switzerland) with a resolution of 0.2 kg, and standing height was recorded with a stadiometer to the nearest 5 mm.

Patients were required to rate their level of heel pain by positioning a marker on a 100-mm visual analog pain scale (Pain Relief Foundation, Liverpool, England) anchored with the terms no pain and worst pain ever. The relative position of the marker was measured to the nearest 5-mm interval.

Procedure

Pressure platform data were collected for both feet using a midgait protocol. A 10-minute familiarization period preceded each gait condition during which the starting position for each patient was adjusted such that their foot would arrive at the pressure platform on the fifth step without notable alterations to their gait pattern. In accordance with findings of Zijlstra et al,[34] cadence and walking speed were not constrained, rather patients adopted a self-selected walking speed. Consistency between walking trials was ensured by monitoring the stance phase duration. Barefoot data were recorded once the stance phase duration for 10 consecutive trials varied by less than 30 ms.[26] Trials were repeated if the subject's foot was not entirely contained within the boundaries of the pressure platform, or if the investigators observed atypical foot placement. Ten trials were recorded for each limb.

Data Analysis

Novel-Ortho Automasks software (Novel GmbH, Munich, Germany) was used to divide the footprint in four sites representing the rearfoot, midfoot, forefoot, and digits (Fig 1). Force and accompanying temporal data were extracted for the total foot and for each foot segment using the Novel Win Multimask Evaluation software (Novel GmbH, Munich, Germany). Six hundred and forty trials (32 patients × two limbs × 10 trials) were processed.

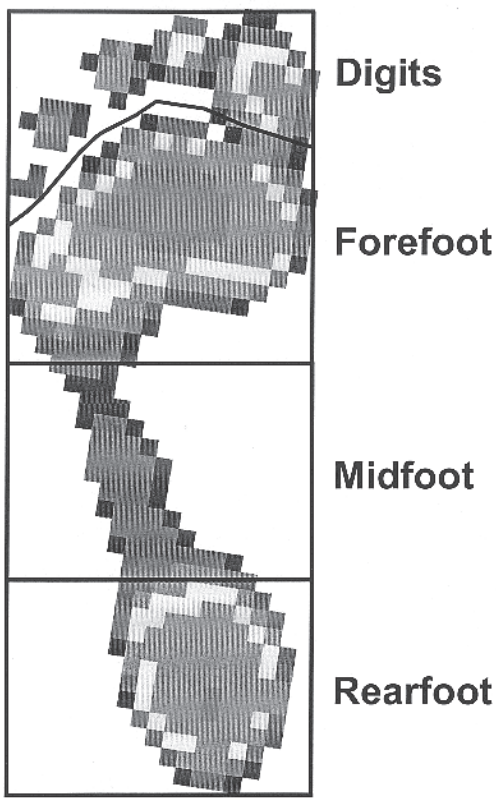

Fig 1. Division of the surface of the foot into four sites using the NovelOrtho Automask software is shown. The rearfoot and midfoot partitions were set at 28% and 55% of foot length, respectively. The digital partition was calculated automatically by the system software on the basis of pressure gradients.

Total Foot Variables

To facilitate comparisons with previous gait studies, three commonly used vertical ground reaction force parameters (F1, F2, F3) were derived from the total force-time curve and normalized to body weight. Their relative times (TF1, TF2, TF3) also were calculated and expressed as a percentage of the stance phase duration (Fig 2).

Regional Foot Variables

Likewise, the regional maximum force, normalized for body weight, and the instant of maximum force, expressed as a percentage of the stance phase duration, were calculated in each of the four defined foot segments. The onset and duration of load in each segment were determined and expressed as a percentage of the stance phase duration.

In addition, the force-time integral, outlined by Katoh et al[15–17] and shown in Figure 3, was estimated by integrating the total force-time curve with

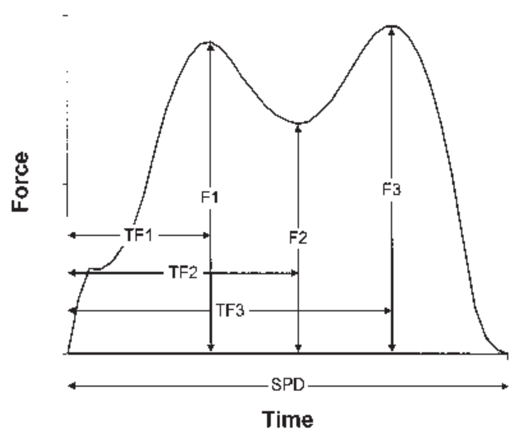

Fig 2. Vertical ground reaction force parameters measured for the entire foot are shown. Force parameters F1, F2, and F3 represent the first force maximum, topic minimum, and second force maximum, respectively. For comparative purposes, forces were expressed as a percentage of body weight. Similarly, the corresponding times TF1, TF2 and TF3, were normalized and expressed as a percentage of the stance phase duration.

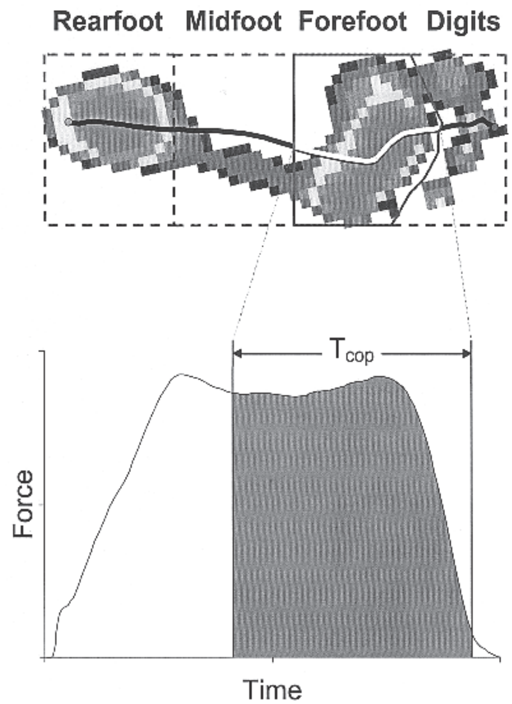

Fig 3. The method used to calculate the force-time integral for the forefoot is shown. The FTI_{cop} method, indicated by the shaded area ■, is the area under the total force-time curve while the center of pressure is in the forefoot, T_{cop}. The impulse was expressed as a percentage of the total foot impulse.

respect to the time that the center of pressure remained in each foot segment (FTI_{cop}). The FTI_{cop} for each site subsequently was expressed as a percentage of the total foot impulse. Similarly, the time that the center of pressure remained in each site (T_{cop}) was expressed as a percentage of the stance phase.

Statistical Analysis

Underlying assumptions of normality were evaluated using Kolmogorov-Smirnov tests with Lilliefor's correction.[24] Outcome variables were determined to be normally distributed, therefore, means and standard deviations were used as summary statistics for all data. Because the study used a matched group research design, differences between patient and control groups with respect to age, body height, body weight, and body mass index were evaluated using paired t tests. For all other variables, differences between limbs for each site of the foot were assessed using a generalized linear modeling framework to fit repeated measures models for which a univariate interpretation was used to assess significance. In each case, group (patient and control) and limb (symptomatic and asymptomatic) were treated as within subject factors. Assumptions of sphericity of the variance-covariance matrix were assessed using Mauchly's test of sphericity.[25] Where significant departures from sphericity occurred, the most conservative adjustment with Greenhouse-Geisser Epsilon was used.[30] An alpha level of 0.05 was used for all two-tailed tests of significance.

RESULTS

There were no significant differences between patient and control groups with respect to any of the anthropometric variables (Table 1). Patients with plantar fasciitis reported a median symptom duration of 9 months (range, 3–48 months) and rated their pain between 10 and 80 mm on the 100 mm visual analog scale, with a median pain rating of 30 mm.

Total Foot Variables

Table 2 shows the mean and standard deviation of the commonly used vertical ground reaction force parameters. The average within subject standard deviation, a measure of the precision of force measurements, was approx-

TABLE 1. Anthropometric Data for Patients and Matched Control Subjects

Variable	Units	Plantar Fasciitis	Control Group
Age	Years	52.9 (11.4)	53.5 (12.3)
Body weight	kg	79.7 (13.7)	79.0 (13.5)
Body height	m	1.67 (0.07)	1.68 (0.08)
Body mass index	$kg\ m^{-2}$	28.7 (4.3)	28.1 (4.4)

No significant differences were observed between groups ($p > 0.05$); Standard deviations are shown in brackets

TABLE 2. Total Force-Time Curve Parameters

		Plantar Fasciitis		Control Group	
Variable	**Units**	*Asymptomatic Limb*	*Symptomatic Limb*	*Asymptomatic Match*	*Symptomatic Match*
F1	%	110 (4)	108 (5)	111 (3)	111 (4)
TF1	%	30 (2)	31 (3)	29 (2)	29 (2)
F2	%	94 (5)	93 (6)	95 (5)	95 (5)
TF2	%	50 (4)	50 (3)	46 (5)	47* (3)
F3	%	116 (6)	113 (6)	115 (2)	115† (3)
TF3	%	73 (3)	73 (3)	73 (2)	73 (2)
Stance Duration	ms	865 (123)	851 (103)	853 (105)	848 (95)

*indicates a significant difference between groups ($p < 0.05$); †indicates a significant group-limb interaction ($p < 0.05$); standard deviations are shown in parentheses

imately 2% body weight during the 10 gait trials. Statistical analysis revealed no statistically significant differences in the stance phase duration between limbs. Similarly, there were no significant differences between any of the limbs with respect to the magnitude of the first force maximum, F1, or topic minimum, F2. However, there was a significant group-limb interaction in the magnitude of the second force maximum, F3 ($F_{1,15} = 5.81$; $p = 0.03$), with a lowered peak force occurring in the symptomatic limb of patients.

The timing to the second force maximum (TF3), however, was unaffected by plantar fasciitis. In contrast, there was a significant main effect in the timing of the topic force minimum, TF2, between groups ($F_{1,15} = 9.47$; $p = 0.01$), with the onset of TF2 delayed in patients. A similar, although not statistically significant, main effect ($F_{1,15} = 3.78$; $p = 0.07$) and interaction also was observed for the timing of the initial force maximum, TF1 ($F_{1,15} = 3.90$; $p = 0.07$) between groups.

Regional Foot Variables

The mean and standard deviation of the regional maximum force, expressed as a percentage of body weight are presented in Table 3. Patients had a significantly lower force beneath the rearfoot of the symptomatic limb compared with the asymptomatic and control limbs ($F_{3,45} = 5.03$; $p = 0.04$). Similarly, the force beneath the forefoot in patients was lower than the control subjects ($F_{1,15} = 5.45$; $p = 0.03$). Digital forces, in contrast, were significantly higher in the patients with plantar fasciitis compared with control subjects ($F_{1,15} = 7.66$; $p = 0.01$).

Figure 4 shows the instant of maximum force in each of the foot segments expressed as a percentage of the stance phase duration. No statistically significant differences were observed among limbs at the rearfoot, midfoot, forefoot, or digits.

Similarly, there were no significant differences in the contact duration of the heel, or midfoot when expressed as a percentage of stance (Fig 5). Although the group main effect for the contact duration of the forefoot approached significance ($F_{1,15} = 4.18$; $p = 0.06$), digital contact times were of significantly greater duration in patients than in controls ($F_{1,15} = 7.47$; $p = 0.02$).

Figure 6 summarizes onset of load, expressed as a percentage of stance, at each region

TABLE 3. Maximum Force for Regional Foot Sites

		Plantar Fasciitis		Control Group	
Site	**Units**	*Asymptomatic Limb*	*Symptomatic Limb*	*Asymptomatic Match*	*Symptomatic Match*
Rearfoot	%	78 (8)	70 (9)	79 (7)	78*† (8)
Midfoot	%	16 (10)	15 (10)	19 (6)	19 (8)
Forefoot	%	104 (8)	102 (9)	109 (4)	107* (6)
Digits	%	34 (9)	33 (9)	25 (6)	26* (9)

*Indicates a significant difference between groups ($p < 0.05$); †Indicates a significant group-limb interaction ($p < 0.05$); Standard deviations are shown in brackets

of the foot in control subjects and patients. No significant differences were observed in the initiation of load at the midfoot between groups. However, patients were found to have earlier loading of the forefoot ($F_{1,15} = 6.30$; $p = 0.02$) and digits ($F_{1,15} = 7.54$; $p = 0.02$).

Table 4 shows the means and standard deviations for the FTI_{cop} in each site of the foot, expressed as a percentage of the total foot-ground vertical impulse. A significantly lower impulse was observed beneath the rearfoot of the symptomatic limb in patients compared with all other limbs ($F_{1,15} = 7.66$; $p = 0.01$). There were no statistically significant differences among limbs in the FTI_{cop} for the midfoot, forefoot, or digits.

Similarly, as shown in Figure 7, the center of pressure spent significantly less time in the rearfoot of the symptomatic limb than in either the asymptomatic or control limbs ($F_{1,15} = 7.96$;

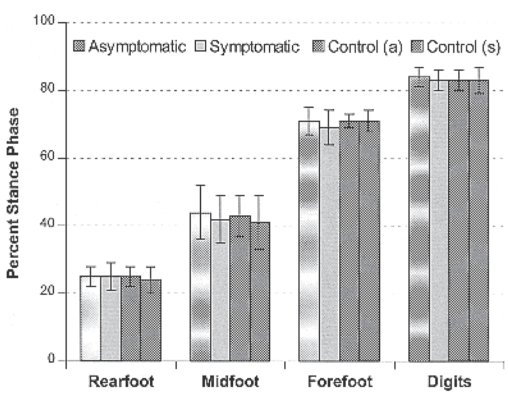

Fig 4. The instant of maximum force, expressed as a percentage of the stance phase duration, at each site of the foot in symptomatic, asymptomatic, and control limbs is shown. No statistically significant differences were observed among limbs for the rearfoot, midfoot, forefoot, or digits ($p > 0.05$).

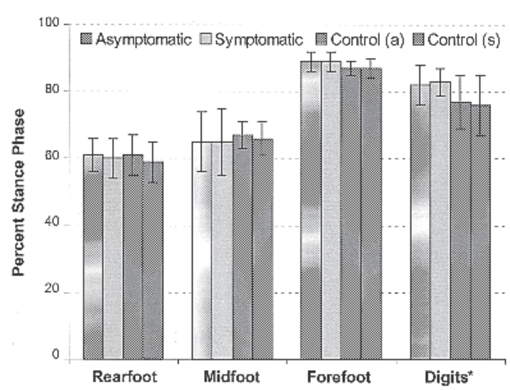

Fig 5. The contact duration, expressed as a percentage of the stance phase, at each site of the foot in symptomatic, asymptomatic, and control limbs is shown. * indicates a significant difference between patient and control groups ($p < 0.05$).

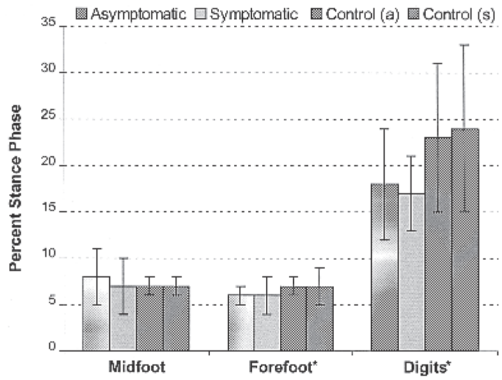

Fig 6. The onset of load in the midfoot, forefoot, and digits expressed as a percentage of the stance phase duration in symptomatic, asymptomatic, and control limbs is shown. * indicates a significant difference between patient and control groups ($p < 0.05$).

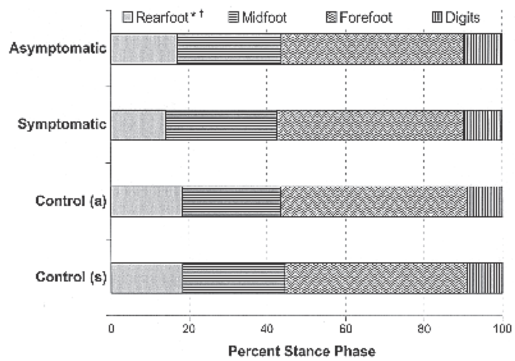

Fig 7. The time, expressed as a percentage of stance, that the center of pressure remained in each area of the foot in symptomatic, asymptomatic, and control limbs is shown. * indicates a significant difference between patient and control groups ($p < 0.05$). †indicates a significant group-limb interaction ($p < 0.05$).

$p = 0.01$). However, there were no significant differences among symptomatic, asymptomatic, and control limbs for the duration of the center of pressure in the midfoot, forefoot, or digits.

DISCUSSION

Although gait analysis has been cited as an objective technique for evaluating the progression of plantar fasciitis and the efficacy of treatment regimes,[2,16] the effect of plantar fasciitis on gait has been sparingly reported in the literature. Given that mechanical overload is thought to be fundamental to the genesis of the condition,[5] it is remarkable that only a few published studies have shown an alteration in the loading pattern of the involved limb.[2,15–17] The findings of the current investigation showed that patients with plantar fasciitis make subtle gait adjustments that change the loading of the

TABLE 4. The Force-Time Integral Based on the Location of the Center of Pressure (FTI_{cop}) for Regional Foot Sites

		Plantar Fasciitis		Control Group	
Site	**Units**	*Asymptomatic Limb*	*Symptomatic Limb*	*Asymptomatic Match*	*Symptomatic Match*
Rearfoot	%	11	9	12	14*†
		(4)	(4)	(5)	(5)
Midfoot	%	32	33	32	33
		(5)	(7)	(5)	(5)
Forefoot	%	56	57	55	53
		(6)	(7)	(7)	(6)
Digits	%	1	1	1	1#
		(1)	(1)	(1)	(0)

*Indicates a significant difference between groups ($p < 0.05$); †Indicates a significant group-limb interaction ($p < 0.05$); #Zero value reported because of rounding effect; Standard deviations are shown in brackets involved limb and alter regional loading in the affected foot.

The Effect of Plantar Fasciitis on Total Foot Variables

Consistent with the findings of Liddle et al,[23] the gait adjustments induced by plantar fasciitis were not sufficient to affect the magnitude of the first vertical force maximum or topic minimum (F1 and F2) and, in the current study, reduced the second force maximum (F3) by only 3% bodyweight. Although statistically significant, this difference is minor considering the average within-subject standard deviation, a measure of variability in the force parameters during the 10 trials, was approximately 2% bodyweight.

In contrast to the current study, Katoh et al,[15,16] reported flattening of the normally double-humped, vertical force-time curve in patients with plantar fasciitis. Daly et al[10] described a similar finding in patients who had recovered from surgical resection of the plantar fascia for intractable heel pain. However, the differences between the force maxima and minimum observed in patient and control groups in the current study were less than those reported by Katoh et al[15,16] and Daly et al.[10] It would seem, therefore, that in the current investigation, control subjects and patients already had relative flattening of the vertical force-time curve. As shown by Nilsson and Thorstensson,[27] the magnitude of the vertical ground reaction force is dependent on the walking speed adopted by patients, and the observed flattening of the vertical force-time curve suggests that all subjects adopted a relatively slow walking velocity. Based on the work of Andriacchi et al,[1] the average stance phase duration observed in the current study is equivalent to a walking speed of approximately 0.8 to 1.0 m/s, which is less than the 1.2 m/s to 1.4 m/s reported for normal gait in similarly aged individuals.[3] Modifying walking speed provides an effective global mechanism for altering the magnitude of load experienced by a limb during gait and may be a deliberate strategy adopted by people with plantar fasciitis for reducing inertial forces acting on the painful foot.

There was also a trend for a delay in the timing of the first force maximum and topic minimum in the patient group. Although the altered timing is suggestive of a reduced walking speed in patients with heel pain, there was no significant difference in the average stance phase duration between patients and control subjects. Given the almost linear relationship known to exist between stance duration and walking speed,[1] it is unlikely that the observed temporal shift reflects a slower walking speed in the patients. Speculatively, the modified timing of the force maximum and minimum may be an attempt to delay the transfer of load onto the symptomatic limb by increasing the period of initial double support or by reducing the instantaneous walking speed of subjects with plantar fasciitis.

The Effect of Plantar Fasciitis on Regional Foot Variables

Although the changes in the force-time curve for the entire foot were diminutive, the effect of plantar fasciitis was far more pronounced when the regional distribution of force was considered. In comparison with the control subjects, patients with plantar fasciitis had reduced forces beneath the heel and forefoot of the symptomatic foot (by approximately 8% and 6% bodyweight, respectively). Even though a similar trend was observed in the asymptomatic foot, suggesting a global gait adaptation, a significant asymmetry between rearfoot forces was evident in the patients, suggesting that they also used a localized strategy involving only the symptomatic limb. The reduced loading of the rearfoot is consistent with the reported location of pain, indicating that patients with plantar fasciitis actively reduced direct vertical loading of the painful heel.

The lowered force observed beneath the rearfoot in plantar fasciitis also was associated with a reduced rearfoot impulse (FTI_{cop}). As shown in Figure 7, the decreased rearfoot impulse resulted primarily from a reduction in the time that the center of pressure remained in the rearfoot. Although rapid movement of the center of pressure away from the heel would be consistent with an antalgic gait response, a similar finding was reported in predominantly asymptomatic individuals who had recovered from surgical resection of the plantar fascia.[10] It is unclear, therefore, if the displacement of the center of pressure is a true antalgic gait response, especially because the type and magnitude of gait disturbance induced by plantar fasciitis seems dependent on the subject's perceived level of pain.[22] As indicated by the visual analog scale, the pain perceived by patients in the current study was commensurate with a moderate level of pain.[7] Previous studies evaluating plantar fasciitis, however, have not commonly incorporated measures of foot pain, making comparisons with the current study difficult.[2,15–17] Consequently, it is unknown if anterior displacement of the center of pressure and the subsequent change in the impulse pattern reflects an antalgic gait adaptation, a learned movement pattern, or an inherent gait characteristic.

Daly et al[10] proposed that the forward displacement of the center of pressure indicated that patients progressed through the stance phase more rapidly. Given that the center of pressure remained in the rearfoot for only 14% of the stance phase, its position in the foot could only be influenced by the earlier contact and loading of the forefoot because digital loading was not initiated until after this period. The earlier forefoot contact could be achieved by placing the foot on the ground in a relatively plantigrade position which, in turn, would result in a reduced step length of the involved side. Chandler and Kibler,[5] in a review of the topic, suggested that runners with plantar fasciitis made similar stride adjustments and moved from a heel-first to a metatarsal-first landing position. Moreover, a reduction in step length, coupled with a relatively plantigrade placement of the foot, also would explain the asymmetric force reductions seen for the rearfoot and forefoot of the symptomatic limb of patients with plantar fasciitis.

Although a simultaneous decrease in the force beneath the rearfoot and forefoot would reduce the tension of the plantar fascia, the peak force in the forefoot actually occurred at 70% of the stance phase, a time when the heel was no longer in contact with the ground. Consequently, the reduced forefoot load is more likely to represent decreased muscular activity in the triceps surae muscle complex, thereby reducing fascial tension and producing a less propulsive gait pattern.[4,32] In support, calf muscle weakness and limited ankle dorsiflexion have been postulated to contribute to the development of plantar fasciitis.[20] Alternatively, the decreased forefoot force may indicate an active shift of load onto the digits.[12]

In the current study, patients with plantar fasciitis were observed to have earlier contact and heightened force beneath the toes suggesting greater muscular activity in the digital flexors. Several authors have reported increased electromyographic activity in extrinsic and intrinsic foot muscles in patients with foot pain.[11,18] Activation of the intrinsic or extrinsic digital flexors in the symptomatic limb could, in principle, splint or brace the medial longitudinal arch, thereby reducing stress in the plantar fascia. In contrast, increased muscular activity in the asymptomatic limb may work to reduce loading of the symptomatic heel by controlling the transfer of weight during the initial period of double support. Alternatively, the increased digital force seen in the patients with plantar fasciitis may reflect a structural or functional reduction in the range of motion of the toes. Creighton and Olson,[9] in a clinical study, reported a decrease in the passive and active ranges of motion of the hallux in nonweightbearing patients with plantar fasciitis. Functional limitations, particularly of the hallux, also have been reported anecdotally in painful rheumatic conditions of the forefoot.[6] Additional research incorporating kinematic analysis of the foot is required to ascertain if the increased digital load is associated with reduced digital movement or increased muscular activity.

Previously, gait analysis revealed inconsistent findings regarding the effect of plantar fasciitis on lower limb loading. The current study found that patients with plantar fasciitis made global gait adjustments that influenced the loading pattern of both limbs, and limb-specific adjustments that resulted in reduced force beneath the heel and forefoot of the symptomatic limb. In addition, the current investigation is the first to show increased digital loading in patients with plantar fasciitis which is indicative of a protective role in the disease process.

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