■ FOOT AND ANKLE

Effect of shockwave therapy on plantar fasciopathy

A BIOMECHANICAL PROSPECTIVE

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It has been suggested that extracorporeal shockwave therapy is a safe and effective treatment for pain relief from recalcitrant plantar fasciopathy (PF). However, the changes in gait and associated biomechanical parameters have not been well characterised. We recruited 12 female patients with recalcitrant PF who had a mean age of 59 years (50 to 70) and mean body mass index of 25 kg/m^2 (22 to 30). The patients reported a mean duration of symptoms of 9.3 months (6 to 15). Shockwave therapy consisting of 1500 impulses (energy flux density 0.26 mJ/mm^2) was applied for three sessions, each three weeks apart. A pain visual analogue scale (VAS) rating, plantar pressure assessment and motion analysis were carried out before and nine weeks after first shock wave therapy. It was demonstrated that patients increased their walking velocity and cadence as well indicating a decrease in pain after shockwave therapy. In the symptomatic foot, the peak contact pressure over the forefoot increased and the contact area over the digits decreased. The total foot impulse also decreased as did stance duration. The duration the centre of pressure remained in the hindfoot increased in the symptomatic foot after shockwave therapy. The differences in centre of pressure trajectory at baseline decreased at final follow-up. In conclusion, shockwave therapy not only decreased the pain VAS rating but also improved the gait parameters of the symptomatic foot in PF patients.

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Plantar fasciopathy (PF) is a musculoskeletal disorder affecting insertion of the plantar fascia over the heel characterised by heel pain after a period of rest.[1] Although the exact mechanism of PF is not well understood, some predisposing factors have been suggested including poor foot contact strategy, excessive foot pronation, and tight calf musculature or tendo Achillis.[2-5] Biomechanical gait analyses and foot pressure assessment of patients with PF have provided objective methods for evaluating the related movement characteristics.[4-8] Foot pressure and time-force curves of the vertical ground reaction forces have been employed in evaluating gait and the effectiveness of treatment programmes.[5] Patients with PF usually modify their gait by decreasing the force under the symptomatic forefoot to avoid stretching the plantar fascia. A reduced hindfoot impulse along with a decreased period of loading of the hindfoot has also been observed.[6] In addition, female runners with a history of PF have shown an increase in ankle dorsiflexion.[4]

Extracorporeal shockwave therapy (ESWT) involving high energy acoustic waves has been suggested as a safe and effective measure to relieve the pain associated with PF.[9-13] In a randomised, placebo-controlled, double-blind clinical trial, Kudo et al[10] demonstrated a better reduction in pain on visual analogue scale (VAS) ratings and increases in Roles and Maudsley score[14] in the ESWT groups at 12 weeks.[10] Similar results were reported in studies with longer follow-ups ranging from 12 to 73 months.[9,11] However, there has been little investigation from the biomechanical perspective to shed light on the efficacy of treatment.

The aim of the current study is to investigate the effect of shockwave therapy on patients suffering from recalcitrant PF in terms of kinematics and kinetics. We proposed that EWST would result in an increase in pressure under the forefoot of the symptomatic foot in patients who suffered from recalcitrant PF.

Patients and Methods

From January 2010 to January 2011, 12 consecutive female patients suffering from recalcitrant unilateral PF were enrolled in this study. Their mean age was 59 years (50 to 70) and their mean body mass index was 25 kg/m^2 (22 to 30). The patients reported a mean duration of symptoms of 9.3 months (6 to 15). The

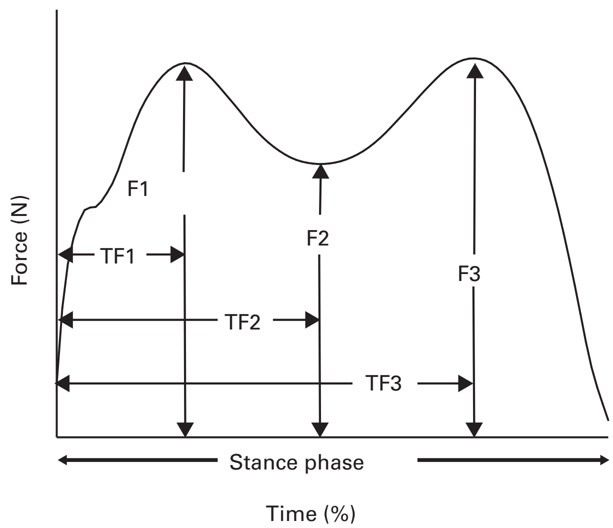

Fig. 1

The force-time curve of the stance phase in a representative example of a normal foot. Vertical ground reaction force parameters measured for the stance phase are shown. F1, F2 and F3 represent the first force maximum, topic minimum, and second force maximum, respectively. The corresponding times TF1, TF2, and TF3 were normalised and expressed as a percentage of the stance phase duration.

patients rated their pain on a visual analogue scale (VAS, with 0 denoting no pain and 10 maximum pain) as a mean of 6.3 (5 to 8) at presentation. The inclusion criteria were localised tenderness near the insertion site of the plantar fascia over the medial calcaneal tuberosity with exacerbation of symptoms after a period of non-weight bearing, and those symptoms having been present for more than six months. The exclusion criteria were bilateral plantar fasciopathy, comorbidity interfering foot sensation such as diabetes mellitus and peripheral arterial occlusive disease, and previous surgery involving spine, hip, knee or ankle. The current study was approved by Chang Gung Memorial Hospital Institutional Review Board and all participants provided informed consent. All patients underwent foot pressure assessment and gait analysis before the first shockwave therapy and nine weeks after the end of treatment. ESWT was the only treatment permitted, with non-steroid anti-inflammatory drugs, insoles and orthoses withdrawn.

ESWT was administered in three sessions, each three weeks apart.[9] A total of 1500 shock waves were delivered per session with a Dornier Epos Ultra system (Dornier MedTech GmbH, Wessling, Germany) at an energy flux density of 0.26 mJ/mm^2 and a rate of 1 Hz without any local anaesthetic. Before the intervention, the point of maximum tenderness over the calcaneal medial tubercle was located. This was examined by applying thumb pressure over hindfoot of patients, from medial to lateral and from distal to proximal. The maximal tenderness was usually located at medial calcaneal tubercle. Under the guidance of sonography (approximately < one minute of assessment), the ESWT was applied to the insertional site of plantar fascia, where an osseous spur usually occurred (in cases where present).

Plantar forces and pressures were recorded during level barefoot walking using the Tekscan Walkway system (Tekscan Inc., Boston, Massachusetts). This system of multistep barefoot analysis used a 5 mm thick floor mat (map: 7101 QL: 542 × 1976 mm), comprising 33 792 resistive sensors (four sensors per cm^2), and sampling data at a frequency of 100 Hz. Patients began walking from a point 2 m in front of the mat and took four steps to walk over the mat. Plantar force and pressure were recorded during five passages across the mat for each patient, immediately before treatment and at final follow-up.[15] An array of gait parameters, such as step and gait time, distance, velocity, cadence and gait cycle were calculated using the output from Tekscan Walkway Research Software v.7 (Tekscan Inc.). This enabled detailed information about the independent function of four different segments of the foot (hindfoot, midfoot, forefoot and digits) to be studied.[5,6] The contact duration (ms), maximum force (% body weight), peak contact pressure (kPa), contact area (cm^2) and impulse (% body weight × seconds) were determined for the four regions, respectively. In addition, the impulse for the whole foot was calculated for the entire plantar surface area. An arch index was calculated as described by Cavanagh and Rodgers.[16] Briefly, arch index was calculated as the ratio of the area of the middle third of the footprint over the entire footprint area (excluding the toes).

The gait analysis was conducted at the Sports Medicine Center, Chia Yi, Taiwan). An optoelectronic eight-camera Vicon motion analysis system (T20; Oxford Metrics Ltd., Oxford, United Kingdom) was used to capture three-dimensional (3D) kinematic data at 100 Hz during five walking trials. The bilateral gait evaluation was performed using the modified Helen Hayes marker set,[17] with the markers attached to the skin with adhesive surgical tape.

Patients were instructed to walk barefoot at their preferred walking speed. Two force plates (OR6, AMTI, Watertown, Massachusetts) embedded in the floor were synchronised with the motion capture system to record ground reaction force (GRF) during walking at a sampling rate of 1000 Hz. While kinematics and kinetics of the segments are calculated, the whole body is modelled as a 15-segment-linkage system consisting of the head, trunk, pelvis, and bilateral upper arms, forearms, hands, thighs, shanks and feet. Reflective markers attached on the segments were used to establish co-ordinate systems representing each segment. Data were processed utilising the Nexus motion analysis system (Vicon; Oxford Metrics Ltd), which was integrated with data recording software. Joint angles, vertical GRF, and gait parameters were obtained for further comparison. Three commonly used vertical GRF parameters (F1, F2 and F3) were derived from the total force-time curve and normalised to body weight. Their relative times (TF1, TF2 and TF3) also were calculated and expressed as a proportion of the stance phase duration (Fig. 1).[5] The

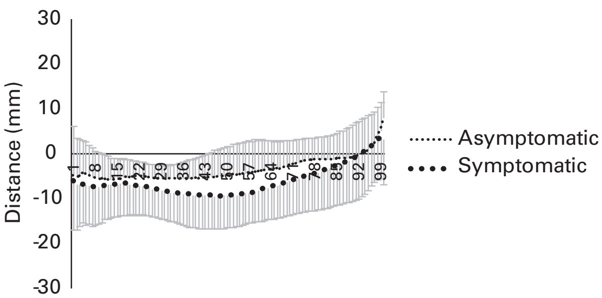

Fig. 2a

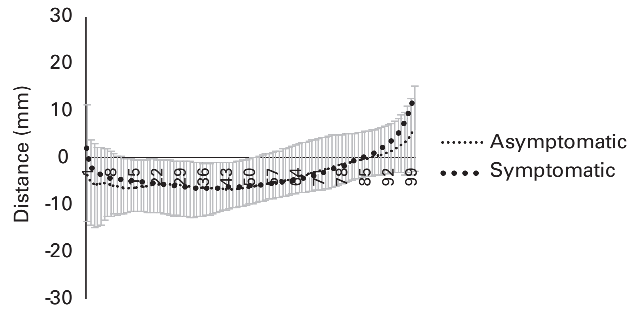

Fig. 2b

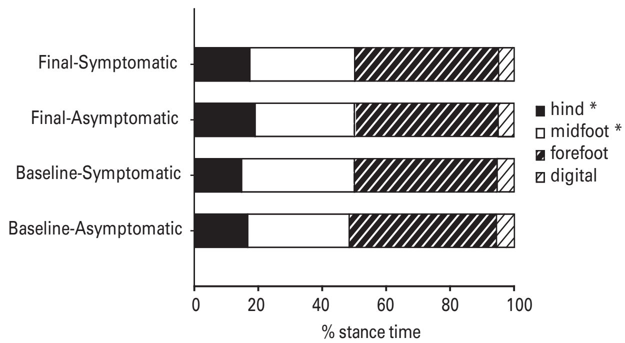

Fig. 2c

Figures 2a and 2b – graphs showing the distance between centre of pressure (COP) and foot axis a) at baseline and b) at final follow-up for both the symptomatic and asymptomatic feet, with % stance phase on the x-axis. Figure 2c – chart showing the COP time occurring in each region of the foot on the asymptomatic foot and symptomatic foot at baseline and final follow-up expressed as a percentage of the stance phase (* hind of asymptomatic side: p = 0.037; hind of symptomatic side: p = 0.038; midfoot of asymptomatic side: p = 0.016; midfoot of asymptomatic side: p = 0.033, significant difference between baseline and final follow-up by two-way analysis of variance).

trajectory of the centre of pressure (COP) was also recorded as suggested by De Cock et al[18] (Fig. 2). The x-axis represents the foot axis, from heel to the second toe, and the y-axis denotes the distance from the COP to the foot axis. A negative value stood for the lateral side of the foot and a positive value stood for the medial aspect of the foot[19] (Fig. 2). Time elapsed as the COP progressed from the hindfoot, midfoot and forefoot to the digits and was calculated and expressed as percentage of the stance phase.[5]

Statistical analysis. A two-way analysis of variance (ANOVA) with repeated measures was performed to compare the differences between the symptomatic foot and asymptomatic foot at initial measurement and final follow-up after shockwave therapy, followed by one-way ANOVA to determine the statistical significance for the gait-associated parameters. A paired *t*-test was employed to compare the cadence and walking velocity between the pre-treatment recording and final follow-up. The statistical software SPSS (IBM SPSS Statistics for Windows Version 21.0; IBM Corp., Armonk, New York) was used for the analysis. Statistical significance was assumed at a p-value < 0.05. All values were shown as mean and standard deviation (SD).

Results

The mean VAS for pain significantly decreased (p = 0.018, paired *t*-test) from 6.3 (5 to 8) at presentation to 3.7 (3 to 5) at final follow-up after shockwave therapy, with every patient reporting improvement in pain.

A generally symmetrical gait pattern between the symptomatic and asymptomatic limbs was demonstrated. No discrepancy was detected in the stance or swing phase either at baseline or after shockwave therapy (Table I). The velocity and cadence increased significantly after shockwave therapy. Although there were no differences in maximum force of either foot between baseline and final follow-up, peak contact pressure increased from a mean of 429 kPa (SD 78) to a mean of 479 kPa (SD 71) in the forefoot of the symptomatic foot (p = 0.004, two-way ANOVA) (Fig. 3a). Meanwhile, the contact area in the digits decreased from a mean of 11.8 cm^2 (SD 2.2) to a mean of 10.8 cm^2 (SD 2.0) (p = 0.003, two-way ANOVA) (Fig. 3b). The arch index remained unchanged for both the symptomatic and asymptomatic foot between baseline and final follow-up. The range of movement of the ankle, knee and hip during gait at baseline was not significantly different from that at final follow-up (Table I). While there were no differences in the impulse in any particular foot segment there was a decrease in the total foot impulse at final follow-up when compared with those at baseline either for the symptomatic foot or asymptomatic foot (Fig. 3c). In contrast, no differences could be detected in contact duration either at baseline or final follow-up (Fig. 3d).

In the force-time curve analysis, F2 decreased from a mean of 85% (SD 7) of body weight to 78% (SD 6) in the symptomatic foot at final follow-up (p = 0.031, two-way ANOVA).

Table I. Comparison of gait parameters between pre-treatment and final follow-up (GC, gait cycle; BW, body weight)

	Baseline			Final follow-up			p-values (baseline *vs* follow-up)	
Mean parameter (SD)*	**Asymptomatic**	**Symptomatic**	**p-value**	**Asymptomatic**	**Symptomatic**	**p-value**	**Asymptomatic**	**Symptomatic**
Stance phase (%GC)	65 (1)	65 (1)	0.943	65 (1)	64 (2)	0.454	0.256	0.198
Swing phase (%GC)	35 (1)	35 (1)	0.943	35 (1)	36 (2)	0.454	0.256	0.198
Heel contact	43 (3)	43 (6)	0.886	41 (3)	40 (4)	0.665	0.219	0.114
Foot flat	34 (5)	36 (8)	0.675	30 (3)	32 (5)	0.608	0.052	0.131
Mid-stance	28 (2)	29 (6)	0.804	27 (3)	26 (4)	0.527	0.473	0.141
Propulsion	22 (3)	21 (5)	0.861	23 (3)	23 (4)	0.994	0.289	0.337
Velocity (cm/s)	81.8 (8.48)			95.5 (11.7)*			0.005	
Cadence (steps/min)	98.4 (10.1)			111 (12.2)*			0.001	
Step length (cm)	50.0 (2.15)			51.3 (1.18)			0.285	
Maximum force (%BW)	104 (8.22)	107 (12.2)	0.708	107 (9.97)	104 (8.22)	0.624	0.398	0.313
Arch index (%)	22.9 (1.67)	22.6 (1.96)	0.659	22.1 (1.77)	22.1 (1.96)	0.919	0.175	0.741
Contact area (cm^2)								
Hind foot	22.6 (1.92)	22.0 (1.64)	0.591	22.0 (1.07)	21.4 (1.33)	0.395	0.329	0.384
Mid-foot	18.4 (2.59)	18.2 (1.98)	0.873	17.9 (3.08)	18.0 (3.25)	0.965	0.326	0.785
Forefoot	39.3 (3.90)	40.4 (4.19)	0.667	39.4 (3.81)	39.6 (3.86)	0.927	0.890	0.208
Digital	12.6 (1.78)	11.8 (2.18)	0.467	11.5 (1.87)*	10.8 (2.00)*	0.539	0.029	0.003
Peak contact pressure (kPa)								
Hind foot	291 (48.4)	278 (47.5)	0.648	303 (51.7)	291 (21.4)	0.624	0.324	0.463
Mid-foot	104 (13.0)	111 (45.7)	0.725	95.8 (28.3)	109 (29.3)	0.440	0.316	0.915
Forefoot	427 (110)	429 (77.8)	0.349	451 (101)	479 (71.0)*	0.447	0.125	0.004
Digital	343 (100)	309 (36.9)	0.454	347 (86.7)	315 (68.1)	0.503	0.877	0.867
Range of movement (°)								
Ankle	24.4 (2.88)	26.6 (4.79)	0.376	26.4 (4.19)	27.1 (3.40)	0.786	0.273	0.779
Knee	57.2 (8.37)	50.0 (8.21)	0.165	54.8 (5.85)	57.1 (5.22)	0.491	0.241	0.059
Hip	38.3 (4.12)	39.3 (3.85)	0.747	42.2 (6.83)	41.1 (5.99)	0.663	0.292	0.272

* $p < 0.05$, significant difference between baseline and final follow-up by two-way analysis of variance

The corresponding decreases were also observed in the asymptomatic foot (Table II). A trend in decrease in TF2 was shown after shockwave therapy, although it was not statistically significant (p = 0.059, two-way ANOVA). The stance duration decreased from a mean of 710 ms (SD 88) to a mean of 633 ms (SD 70) in the symptomatic foot as well as from a mean of 700 ms (SD 116) to a mean of 633 ms (SD 47) in the asymptomatic foot at final follow-up.

At baseline, it was shown that the trajectory of the COP beneath the foot during the stance phase deviated to the lateral aspect of the foot in the symptomatic foot compared with the asymptomatic foot (Fig. 2). The COP trajectory became similar for the symptomatic foot and asymptomatic foot at final follow-up. It was demonstrated that the COP time in the hindfoot increased (symptomatic side: p = 0.038; asymptomatic side: p = 0.037, two-way ANOVA) after shockwave therapy in both the symptomatic foot and the asymptomatic foot, accompanied by a decrease in COP time of the midfoot (symptomatic side: p = 0.033; asymptomatic side: p = 0.016, two-way ANOVA). No differences could be detected in the COP time in the forefoot (symptomatic side: p = 0.560; asymptomatic side: p = 0.973, two-way ANOVA) or digit region (symptomatic side: p = 0.814; asymptomatic side: p = 0.714, two-way ANOVA).

Discussion

The most important finding in this study was that ESWT altered the distribution of foot pressure during gait, with the peak contact pressure in the forefoot increased, along with a decrease in contact area of the digits, in patients who suffered from PF. These results were comparable to those of Wearing et al[5] who found that patients with PF made a gait adjustment that resulted in reduced force beneath the rear foot and forefoot of the symptomatic foot. Thus, increasing forefoot peak pressure after ESWT contributed to a restoration of a more normal gait pattern, with a reduction in the VAS for pain. It has been suggested that the plantar fascia is most stretched during the pushing-off phase and PF patients have been shown to alter their gait by decreasing forefoot force and increasing digital force.[5,6,20] After treatment patients walked at a faster velocity accompanied by increased cadence that indicated functional improvement. The stance duration decreased 11% after shockwave therapy (asymptomatic side: p = 0.041; symptomatic side: p = 0.042, two-way ANOVA), which explained, at least in part, the decrease in the total foot impulse at the final follow-up.

In force-time curve analysis, the shockwave therapy resulted in a decrease in F2 that reversed the flattening of the normally double-peaked, vertical force-time curve that occurs in patients with PF.[21] This was also associated with increased walking speed that resulted in increased vertical acceleration of the body through the stride, which we believe was underwritten by the decrease in pain enabling the transfer of load.[22,23] In addition, a trend of decreased TF2 was also shown in the symptomatic foot after

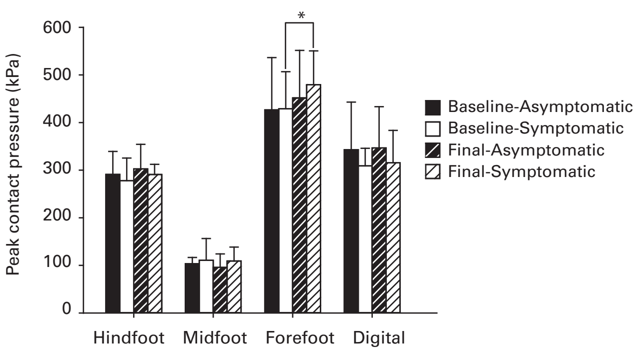

Fig. 3a

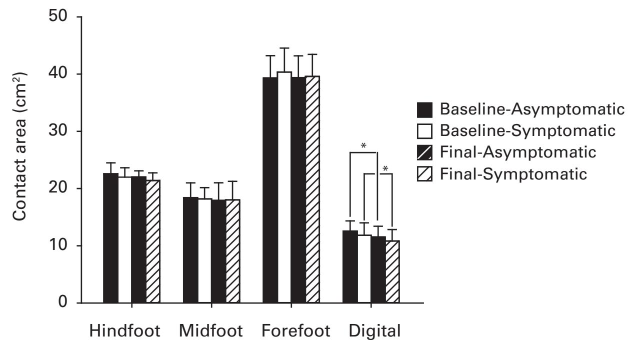

Fig. 3b

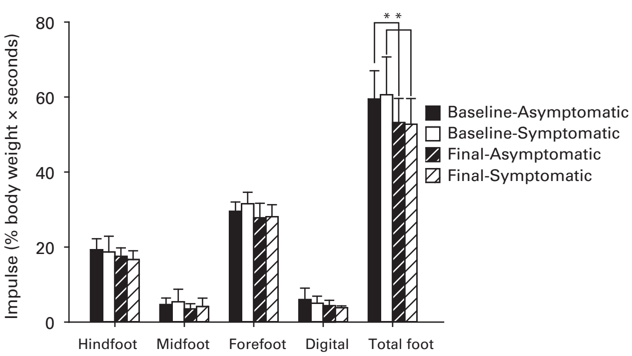

Fig. 3c

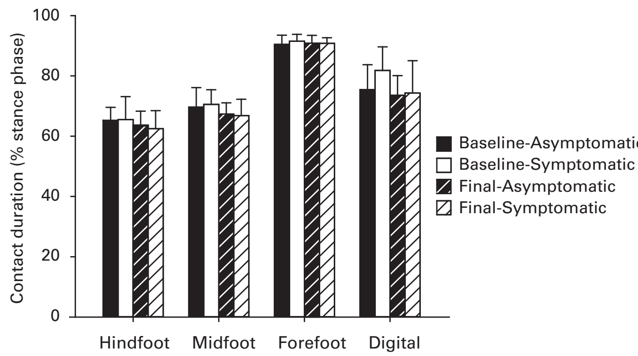

Fig. 3d

Histograms showing a) the mean peak contact pressure and b) mean contact area, at each site of the foot region, c) mean impulse (* p = 0.022 and p = 0.028, significant differences between baseline and final follow-up in asymptomatic and symptomatic side limbs by two-way ANOVA) and d) mean contact duration at each site of the foot region as well as the total foot in the symptomatic foot and asymptomatic foot before and after shockwave therapy. It was shown that peak contact pressure increased in the forefoot after shockwave therapy (* p < 0.05, between baseline and final follow-up). The error bars denote standard error.

Table II. Comparison of force-time curve parameters between baseline and final follow-up (BW, body weight; ST, stance phase)

	Baseline			**Final follow-up (SD)**			**p-values (baseline *vs* follow-up)**	
Mean (SD) parameters	**Asymptomatic**	**Symptomatic**	**p-value**	**Asymptomatic**	**Symptomatic**	**p-value**	**Asymptomatic**	**Symptomatic**
F1 (%BW)	97 (6)	99 (8)	0.613	99 (5)	101 (6)	0.502	0.673	0.601
TF1 (%ST)	31 (3)	29 (5)	0.370	27 (5)	26 (5)	0.834	0.066	0.181
F2 (%BW)	85 (6)	85 (7)	0.971	78 (5)	78 (6)	0.850	0.003*	0.031*
TF2 (%ST)	52 (4)	51 (8)	0.749	48 (4)	48 (6)	0.911	0.115	0.059
F3 (%BW)	105 (8)	105 (13)	0.949	106 (11)	104 (3)	0.677	0.627	0.896
TF3 (%ST)	77 (1)	76 (3)	0.455	78 (2)	77 (4)	0.841	0.296	0.563
Stance duration (ms)	700 (116)	710 (87.8)	0.161	633 (47.1)	632 (69.9)	0.432	0.041*	0.042

* p < 0.05, significant difference between baseline and final follow-up by two-way analysis of variance

shockwave therapy. It has been suggested that TF2 increases in PF patients when they attempted to delay the transfer of load onto the symptomatic limb by increasing the period of initial double support or by reducing the instantaneous walking speeds.[5] The trend of decreasing TF2 after treatment in the current study implied a smooth vertical acceleration and faster roll over process.

There were no differences in the arch index either between the symptomatic foot and asymptomatic foot or between initial and final follow-up evaluation. Wearing et al[24] suggested that neither abnormal shape nor movement of the arch in the sagittal plane are associated with chronic PF. However, footprint-based estimates of arch structure have been limited because of confounding body composition in adults.[25] The COP path spatial-temporal characteristics might represent dynamic functional behaviour,[19,26,27] which is supported by our work. We found the COP trajectory shifted laterally during progression on the symptomatic foot compared with the asymptomatic foot. The lateral shift of the COP trajectory indicated a functional high arch in adjusted gait pattern for PF patients because these patients walked on their symptomatic foot using an inversion moment and adducted foot position during walking and therefore displayed higher and more supinated feet.[28] At final follow-up, the COP trajectory had been restored to a similar pattern in both feet and the COP time decreased in the hindfoot of the symptomatic foot compared with the asymptomatic foot prior to treatment. A rapid movement of the COP away from the heel would be consistent with an antalgic gait response.[8] Increases in the COP time over the hindfoot after shockwave therapy provided a more symmetrical gait. The COP time seemed a more sensitive parameter in PF patients than the contact duration revealed by the Tekscan software.

There were several limitations in the current study. First, the number of patients was small, while the comparison within the same patient provided an advantage of repeated measurement in this study design. Second, biomechanical parameters were evaluated at only three weeks after the final session of shock wave therapy. However, this time period suggests an early remodelling phase that is important for subsequent tendon healing.[29] ESWT has been shown to result in controlled internal fascial tissue micro-disruption that initiates a healing response after a transient swelling of the tendon with a minor inflammatory reaction.[12,30-33] The inflammatory phase usually subsides within one week and enters an early remodelling phase at around three weeks after the intervention.[29]

In conclusion, ESWT not only decreases the pain VAS but also improve the gait parameters in the symptomatic foot of PF patients at three weeks following repetitive treatment.

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