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Combined Short Foot and Three-Dimensional PNF Ankle Exercises Improve Plantar Pressure, Ground Reaction Forces, and Postural Sway in Female Karate Athletes with Flexible Flatfoot

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ABSTRACT

Aims: Flexible flatfoot in athletes alters plantar pressure distribution, impairs postural control, and modifies ground reaction forces, elevating injury risk. This study compared SFE+3DAE versus SFE alone on these outcomes in female karate athletes with flexible flatfoot.

Method and Materials: Randomized controlled trial of 34 female karate athletes aged 17-25 years with flexible flatfoot, randomly assigned 1:1 to 8 weeks of Short Foot Exercises (SFE) alone or combined with three-Dimensional Ankle Exercises (3DAE). Plantar pressure distribution, postural control, and ground reaction forces were assessed pre- and post-intervention using pressure platforms. Within-group changes were analyzed using paired t-tests, while between-group differences were evaluated with ANCOVA, adjusting for baseline values.

Findings: Both groups demonstrated improvements in plantar pressure distribution, postural control, and ground reaction forces; however, the SF-3DAE group showed significantly greater reductions in first peak force and force depth ($\eta^2 = 0.151$, $p < 0.05$) and enhanced postural control, including major and minor axis lengths, COP path, and AP/ML sway (η^2 range: 0.176–0.734, $p < 0.05$). No significant changes were observed in symmetry indices between legs or forefoot-rearfoot distribution.

Conclusion: Integrating SFE with 3DAE provides a comprehensive rehabilitation approach for female karate athletes with flexible flatfoot, enhancing foot function, postural stability, and load distribution during dynamic activities. These results support the additive benefits of combining intrinsic foot muscle strengthening with ankle PNF exercises in athletic populations.

Keywords: Flatfoot, Exercise Therapy, Postural Balance, Three-Dimensional Exercises, Postural Control

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Introduction

Flatfoot, also known as pes planus, is a prevalent musculoskeletal condition characterized by a decreased or absent medial longitudinal arch, which alters normal foot biomechanics and is associated with abnormal plantar pressure distribution and impaired postural control [1,2]. Individuals with flexible flatfoot commonly demonstrate increased midfoot loading and compensatory movement strategies during gait and stance. These biomechanical alterations may predispose individuals to overuse injuries and performance impairments, particularly in activities that require dynamic balance and rapid force transmission[3,4].

Short Foot Exercise (SFE) has been widely used as a therapeutic approach to strengthen intrinsic foot muscles and provide active support to the medial longitudinal arch [5,6]. Previous studies have demonstrated that SFE can favorably modify plantar pressure distribution by reducing excessive midfoot pressures and redistributing loads toward more functional regions of the foot during static and dynamic tasks [7]. In addition, improvements in lower limb neuromuscular control and postural stability following short foot exercise have been reported[8]. However, most existing evidence is derived from general or non-athletic populations, with limited investigation in athlete cohorts where sport specific demands on balance and foot function are substantially higher. Effective foot

Function during athletic performance does not depend solely on intrinsic foot musculature but also on the integrity of proximal components within the lower limb kinetic chain [9].

The ankle joint plays a pivotal role in force transmission, postural regulation, and dynamic stability. Weakness or restricted mobility of the ankle musculature may limit the ability of intrinsic foot muscles to contribute effectively to postural control and propulsion, particularly in high demand sports. Accordingly, three dimensional ankle exercises that target muscle function across the sagittal, frontal, and transverse planes have been proposed to enhance lower limb stability and functional performance [10, 11].

Proprioceptive Neuromuscular Facilitation (PNF) techniques have been increasingly incorporated into ankle rehabilitation programs, with growing evidence supporting their effectiveness in improving muscle strength, coordination, and balance. Meta analytic findings indicate that PNF based interventions lead to superior improvements in balance and ankle muscle strength compared with conventional exercise approaches [12]. These findings suggest that PNF based three dimensional ankle exercises may complement intrinsic foot muscle training by enhancing neuromuscular integration throughout the lower limb.

Despite the established benefits of SFE and ankle focused neuromuscular training when applied independently, the combined effects of these interventions on plantar pressure distribution and postural control remain insufficiently explored. This gap is particularly evident in combat sport athletes such as karate practitioners, who are exposed to high demands on balance, agility, and foot ground interaction during training and competition. Therefore, the purpose of this randomized controlled trial was to investigate whether a combined program of SFE and PNF based three dimensional ankle exercises results in greater improvements in plantar pressure distribution and postural control than SFE alone in female karate athletes with flexible flatfoot.

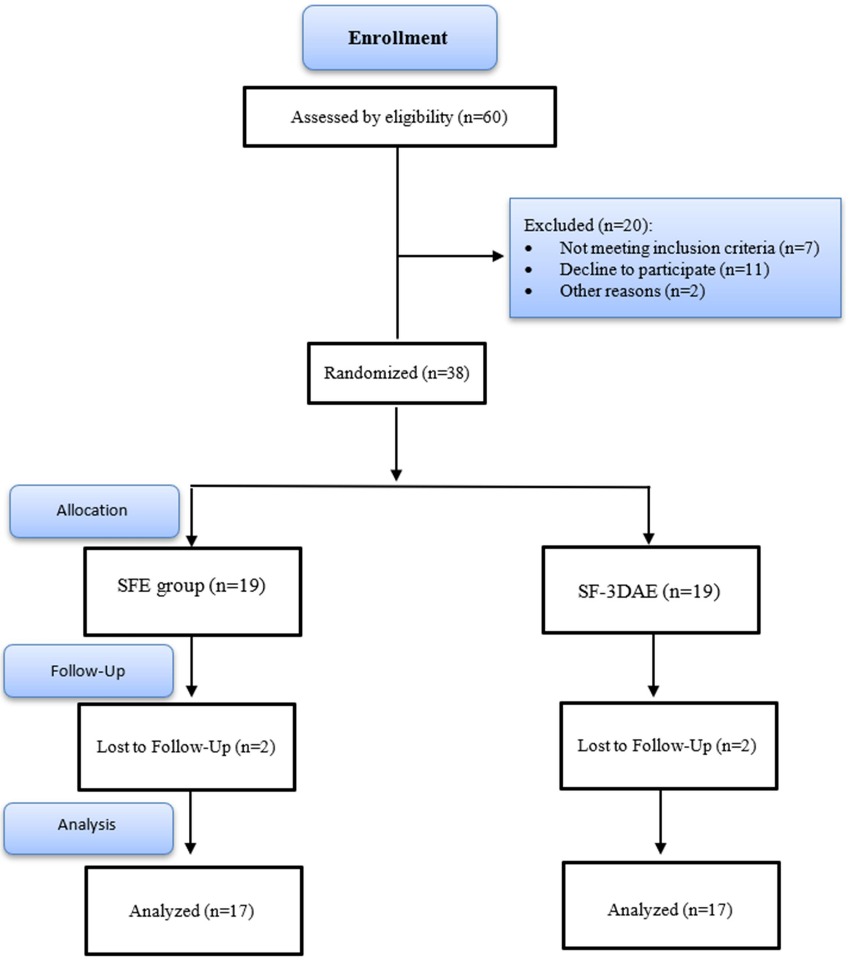
Method and Materials

This randomized controlled trial utilized a pre-test/post-test design with two intervention groups: the SFE group and the three-3 Dimensional Ankle Exercise (3DAE) group.

The study included female karate athletes aged 17 to 25 years, recruited through posters displayed in sports clubs and direct phone outreach to coaches. An initial assessment was conducted to measure navicular drop. Inclusion criteria were as age between 17 and 25 years, no history of lower limb musculoskeletal injuries or surgeries in the past year, a navicular drop exceeding 10 millimeters as measured by the standard navicular drop test, and no use of custom orthotics within the previous six months. Participants were excluded if they reported pain during the intervention or missed more than two training sessions. Of the 38 participants initially enrolled, four were excluded from the final analysis, including two due to missed training sessions and two who did not complete the post-intervention assessment, resulting in a total of 34 participants (17 per group) included in the final analysis.

The required sample size was calculated for detecting a large effect of SFE on midfoot peak plantar pressure. Based on previous studies, a Cohen's d of 0.9 was assumed for the difference between two independent groups[13]. Using a two-tailed t-test with an alpha level of 0.05 and a statistical power of 0.80, the analysis indicated that 16 participants per group were required, resulting in a total sample size of 32. To account for potential dropouts, 6 additional participants were recruited. Participants were then randomly allocated into two intervention groups: the SFE group and the SFE plus 3D ankle exercise (SF-3DAE) group.

Participants were randomly allocated into the two intervention groups using Random Number Generator Software. Allocation concealment was ensured using the Sequentially Numbered, Opaque, and Sealed Envelopes (SNOSE) method. The randomization was performed in two steps: first, each participant was assigned a unique number from 1 to 38, and then 19 numbers were randomly selected to assign participants to each group (Figure 1). Both groups received active exercise interventions, and participants were blinded to the specific type of exercise they were performing. Outcome assessors were also blinded to group assignments, resulting in a double-blind design. Therapists delivering the interventions were not blinded due to the nature of the exercises, but standardized instructions and procedures were applied to minimize potential bias.



SFE: Foot Exercise ; 3DAE: 3 Dimensional Ankle Exercise ()

Figure 1) CONSORT flow diagram from enrolment to analysis

Navicular drop was assessed using the Brody method, which has demonstrated high reliability for evaluating navicular height displacement (ICC = 0.94), with reported reliability and validity coefficients of 0.84 and 0.73, respectively [14]. The assessment was performed in two conditions: seated and standing. Initially, participants sat barefoot on a chair with the knee flexed at 90°. The examiner palpated the medial malleolus and used gentle inversion and eversion movements to identify the most prominent point of the navicular bone, which was then marked. The vertical distance from the marked point to the floor was measured using a ruler. Subsequently, participants assumed a relaxed, full weight-bearing standing position, and the vertical distance from the navicular bone to the floor was measured again. Each measurement was repeated three times under both conditions. The navicular drop was calculated by subtracting the standing measurement from the seated measurement, and the mean value of the three trials was recorded as the final navicular drop index [15]. Only participants with a navicular drop greater than 10 mm were included in the study. All participants presented with bilateral flatfoot; however, data from the dominant foot were used for the final analysis.

Foot dominance was determined by asking participants to kick a ball, with the kicking foot defined as the dominant limb.

Plantar Pressure Distribution. Plantar pressure assessment is a well-established method for evaluating foot function and load distribution. In the present study, plantar pressure distribution, postural sway, and ground reaction force were assessed using the PT-Scan system (Paya-Fanavaran, Mashhad, Iran). The system consists of a pressure-sensitive platform (50 × 50 cm) equipped with 2,300 sensors and operates at a sampling frequency of 165 Hz. The PT-Scan system has demonstrated good repeatability, with a reliability coefficient of 0.85 when compared with the Zebris plantar pressure distribution system [16].

Static variables, including bilateral foot symmetry and postural sway, were assessed while participants stood barefoot on the PT-Scan platform. Participants were instructed to maintain a comfortable upright stance with their arms relaxed at their sides and to fix their gaze on a point located two meters ahead at eye level to minimize postural adjustments. Each participant remained in this position for 20 seconds while plantar pressure data were recorded (Figure 2). Prior to the formal assessment, a practice trial was conducted to familiarize participants with the procedure. No verbal feedback was provided during data collection. Bilateral foot symmetry was quantified using the symmetry Index (SI), calculated as the proportion of force applied by the right foot relative to the total force exerted by both feet (Formula 1). An SI value of 50% represents perfect symmetry. Values below 50% indicate greater loading on the right foot, whereas values above 50% reflect increased loading on the left foot. The distribution of force between the forefoot and rear foot was evaluated using Formula 2. An SI value of 33% indicates an optimal force distribution between the anterior and posterior regions of the foot. Values below 33% suggest increased loading on the heel and rear foot, while values above 33% indicate greater force applied to the forefoot and toes [16].

Postural sway parameters were extracted using the PT-Scan software. The software outputs included Minor Axis Length, Major Axis Length, and center of pressure (COP) path length, the standard deviation of mediolateral sways, and the standard deviation of anteroposterior sways, providing a comprehensive assessment of postural control during quiet standing.

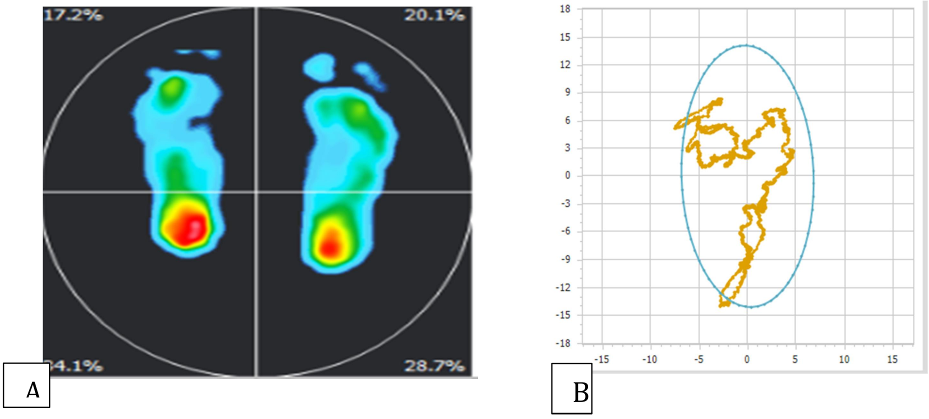


Figure 2) Static plantar pressure assessment: A. symmetry assessment. B. postural sway assessment

$$\text{Formula 1: SI}= \frac{\text{Right force}}{\text{Right force} + \text{Left Force}} * 100$$

$$\text{Formula 2: SI}= \frac{\text{Forward Force}}{\text{Forward Force} + \text{Backward force}} * 100$$

Dynamic assessment was conducted to evaluate ground reaction forces during walking using the PT-Scan system. Participants walked barefoot at a self-selected comfortable speed along an eight-meter walkway incorporating the pressure platform. To ensure steady-state gait at the time of foot contact, the starting point was positioned approximately seven steps before the platform. Ground reaction force data were recorded during the heel contact, mid-stance (full foot contact), and toe-off phases of gait and were expressed in Newtons. Measurements were obtained from the dominant foot only. Trials in which the foot did not fully contact the platform or demonstrated an atypical stepping pattern were discarded and repeated. Prior to the formal assessment, participants completed a familiarization trial to reduce learning effects. During data collection, they were instructed to look straight ahead and avoid directing their gaze toward the platform to minimize conscious gait alterations. Data collected from the dominant foot were used for subsequent statistical analysis. Key features of the vertical ground reaction force curve, including the initial peak, mid-stance minimum, and second peak forces, were extracted from the dominant foot for subsequent analysis (Figure 3).

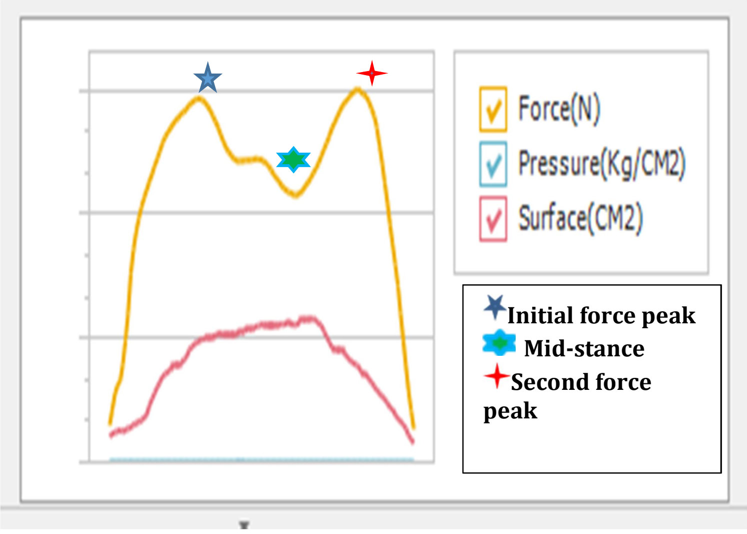


Figure 3) Vertical ground reaction force curve during walking

Participants assigned to SFE group completed a structured, supervised program targeting the intrinsic muscles of the foot, with the primary goal of enhancing medial longitudinal arch stability and improving foot muscle activation patterns. The exercises involved elevating the medial longitudinal arch, shortening the foot along the anteroposterior axis, and moving the head of the first metatarsal toward the heel while keeping the toes extended [17]. The SFE program was performed three times per week for eight weeks, with three sets of [12–15] repetitions per session, under the guidance of a certified exercise therapist. The training protocol progressed in difficulty: participants began in a seated position during weeks [1–2], advanced to double-leg standing during weeks [3–4], and finally performed exercises in a single-leg stance during weeks 5–8. Further details of the short foot exercise protocol are presented in Table 1.

Participants in the SF-3DAE group performed the SFE program alongside a three-dimensional foot–ankle exercise regimen, introduced from week 5 onward. The 3D exercises incorporated diagonal ankle movements in flexion and extension patterns (D1 and D2), performed alternately. These exercises are designed to improve multiplanar ankle mobility, neuromuscular control, and foot–ankle functional strength[11]. During weeks [5–6], the exercises were performed without external resistance, whereas elastic band resistance was introduced during weeks [7–8] to provide progressive overload. A detailed description of the 3D ankle exercise protocol is provided in Table 2.

Table 1) Short Foot Exercise

Week	Body Position	Sets × Repetitions	Rest Between Sets	Exercise Position
1–2	Sitting	3 × 15	2 s	Focus on intrinsic foot muscle activation
3–4	Standing on both legs	3 × 15	5 s	Progression to weight-bearing
5–8	Standing on one leg	3 × 15	7 s	Advanced balance and stability challenge

Short Foot Exercises: Doming, Doming on both legs, Doming on one leg, Lesser toe extension, Toe spread.

Table 2) Three-Dimensional Ankle Exercise Protocol

Week	Body Position	Exercise	Resistance	Sets × Repetitions	Rest
5–6	Sitting	Diagonal 1 flexion	None	3 × 12	30 s
5–6	Sitting	Diagonal 1 extension	None	3 × 12	30 s
5–6	Sitting	Diagonal 2 flexion	None	3 × 12	30 s
5–6	Sitting	Diagonal 2 extension	None	3 × 12	30 s
7–8	Sitting	Diagonal 1 flexion	Elastic band	3 × 12	30 s
7–8	Sitting	Diagonal 1 extension	Elastic band	3 × 12	30 s
7–8	Sitting	Diagonal 2 flexion	Elastic band	3 × 12	30 s
7–8	Sitting	Diagonal 2 extension	Elastic band	3 × 12	30 s

3D Ankle Exercise Patterns: D1 Flexion: From dorsiflexion-supination-inversion with toes extended to plantarflexion-pronation-eversion with toes flexed. D1 Extension: Reverse of D1 flexion. D2 Flexion: From dorsiflexion-pronation-eversion with toes extended to plantarflexion-supination-inversion with toes flexed. D2 Extension: Reverse of D2 flexion.

Normality of data was assessed using the Shapiro–Wilk test. Baseline differences between groups were evaluated with independent samples t-tests. ANCOVA, with pre-test scores as covariates, was used for between-group comparisons, while paired t-tests assessed within-group changes. Effect sizes were calculated using partial eta squared (η^2) and interpreted as small (0.01), medium (0.06), or large (0.14).[1] All analyses were conducted in SPSS version 26 (IBM Corp., Armonk, NY, USA), with significance set at" $\alpha < 0.05$.

Findings

A total of 38 participants were initially enrolled. Four participants did not complete the study due to withdrawal, leaving [17] participants per group for the final analyses. All analyses were conducted on a per-protocol basis, including only participants who completed the study. Descriptive statistics for demographic variables, including means and standard deviations for age, height, and weight, are presented in Table 3. No significant differences were observed between groups for any demographic characteristic (all p> 0.05, independent t-test). All subsequent analyses for outcome variables are presented in Table 4.

Table 3) Demographic Characteristics of Participants

Characteristic	SFE group	SF-3DAE group
	Mean ± SD	Mean ± SD
Age (years)	20.88 ± 3.01	20.71 ± 2.44
Height (cm)	168.71 ± 5.38	167.59 ± 4.52
Weight (kg)	60.59 ± 8.61	60.76 ± 9.75
BMI (kg/m2)	21.63 ± 3.16	22.51 ± 3.13
Navicular drop (mm)	12.04 ± 0.85	12.15 ± 0.79
Sport history (years)	8.29 ± 1.75	8.59 ± 1.80

SFE group = Short Foot Exercises; SF-3DAE group = Short Foot and 3D Ankle Exercise group.

Analyses of plantar pressure asymmetry indices revealed no significant within-group changes or between-group differences. The SI of right–left foot forces remained stable in the SFE group (50.48 ± 4.70 to 50.39 ± 3.84, t = –0.108, p = 0.916) and in the SF-3DAE group

(50.06 ± 4.40 to 50.57 ± 3.40, t = 0.720, p = 0.482). Similarly, forefoot–rearfoot SI for the right (SFE: 45.90 ± 8.56 to 43.77 ± 6.56, t = –1.58, p = 0.132; SF-3DAE: 46.28 ± 3.39 to 44.87 ± 3.83, t = –1.27, p = 0.220) and left foot (SFE: 45.94 ± 7.61 to 43.79 ± 7.71, t = –1.49, p = 0.155; SF-3DAE: 46.03 ± 6.05 to 44.13 ± 7.13, t = –1.66, p = 0.116) did not change significantly. Between-group ANCOVA also showed no significant differences for any plantar pressure variable (all $\eta^2 < 0.01$, all $p > 0.60$; Table 4).

Significant improvements in postural control were observed in both groups. Major Axis Length decreased from 21.78 ± 8.98 to 15.61 ± 5.84 in the SFE group (t = 5.08, $p < 0.001$) and from 21.14 ± 8.35 to 10.38 ± 2.00 in the SF-3DAE group (t = 5.19, $p < 0.001$), with a significant between-group effect ($\eta^2 = 0.366$, $p < 0.001$). Minor Axis Length, anterior–posterior sway, medial–lateral sway, COP path length, and COP area all showed similar within-group improvements and between-group advantages favoring SF-3DAE ($\eta^2 = 0.176–0.734$, all $p < 0.05$).

Ground reaction forces decreased from pre- to post-intervention in both groups, indicating reduced vertical impact. The reductions in first peak force and force depth were significantly greater in the SF-3DAE group compared with the SFE group, whereas second peak force also decreased in both groups but without a significant between-group difference (Table 4). Overall, these findings suggest that the combined SF-3DAE intervention effectively reduced vertical ground reaction forces.

Table 4) Within- and between-group comparisons of plantar pressure, postural control, and ground reaction force variables

Variable	SFE group				SF-3DAE group				Between group		
	Mean ± SD		t	pa	Mean ± SD		t	pa	F	Pb	η^2
	Pre-test	Post-test			Pre-test	Post-test					
Plantar pressure asymmetry index											
SI for right- left foot forces (%)	50.39±3.84	50.48±4.70	-0.108	0.916	50.57±3.40	50.06±4.40	0.720	0.482	0.280	0.601	0.009
Forefoot-back foot forces SI for right foot (%)	43.77±6.56	45.90±8.56	-1.58	0.132	44.87±3.83	46.28±3.39	-1.27	0.220	0.81	0.778	0.003
Forefoot-back foot forces SI for left foot (%)	43.79±7.71	45.94±7.61	-1.49	0.155	44.13±7.13	46.03±6.05	-1.66	0.116	0.008	0.931	0.000
Postural control variable											
Major Axis Length (mm)	21.78±8.98	15.61±5.84	5.08	<.001*	21.14±8.35	10.38±2.00	5.19	<.001*	15.00	<.001*	0.366
Minor Axis Length (mm)	9.05±4.41	7.08±3.68	4.97	<.001*	9.03±3.80	5.64±1.99	4.70	<.001*	5.55	0.026*	0.176
Anterior-Posterior postural sway (mm)	2.47±1.00	1.94±0.60	2.78	0.016*	3.11±1.46	1.50±0.26	4.70	<.001*	11.89	0.002*	0.314
Medial-lateral postural sway (mm)	3.12±1.31	2.38±0.63	3.14	0.013*	3.64±1.33	2.11±0.58	5.22	<.001*	6.41	0.018*	0.198
COP path length (mm)	412.59±108.23	387.37±107.41	2.70	0.006*	452.64±108.97	234.79±22.65	9.02	<.001*	71.84	<.001*	0.734
COP area (mm^2)	77.10±29.75	70.1931±26.69	2.76	0.014*	79.01±30.99	35.56±11.38	6.26	<.001*	37.67	<.001*	0.592
Ground reaction force variable											
first peak force (N)	230.52±56.25	171.83±43.56	7.27	<.001*	251.74±42.66	157.51±23.42	7.32	<.001*	5.16	0.031*	0.151
force depth (N)	187.27±58.25	147.12±48.05	4.54	<.001*	192.89±48.05	125.11±28.71	6.69	<.001*	5.17	0.030*	0.151
second peak force (N)	228.32±54.47	169.92±58.81	4.13	<.001*	256.46±53.62	171.75±42.54	7.49	<.001*	0.775	0.386	0.026

SFE = Short Foot Exercises; SF-3DAE = Short Foot and three Dimensional Ankle Exercise. ES = Effect Sizes (η^2) for ANCOVA
Pa = P value for within-group comparisons (paired t- test); Pb = P value for between group comparison (ANCOVA)

Discussion

The present study investigated the effects of combining SFE with 3DAE versus SFE alone on plantar pressure distribution, postural control, and ground reaction forces in female karate athletes with flexible flatfoot. The findings showed that the combined SFE and 3DAE intervention produced greater improvements in plantar pressure distribution compared with SFE alone.

The observed improvements in plantar pressure distribution can be explained through several biomechanical and neuromuscular mechanisms. SFE enhances activation of intrinsic foot muscles, which are essential for maintaining the Medial Longitudinal Arch (MLA) and absorbing shock during weight-bearing activities [18]. Strengthening these muscles likely improves pressure distribution across the foot, reducing excessive loading on the medial forefoot and rearfoot. Additionally, 3DAE enhances dynamic ankle stability, which helps control pronation and supination during movement [19]. This increased stability may reduce compensatory movements common in flexible flatfoot, leading to a more neutral foot alignment and improved plantar pressure distribution. Together, SFE and 3DAE likely promote better neuromuscular coordination between the foot and ankle, facilitating adaptation to external forces during dynamic activities such as karate.

Significant improvements were also observed in postural control parameters, including major axis length, minor axis length, COP path length, and anterior-posterior and medial-lateral sway. These measures reflect better control of the center of pressure (COP), reducing sway and enhancing balance. The combined exercises demonstrated greater improvements, suggesting that targeting both intrinsic foot muscles and ankle stability provides a more comprehensive strengthening program. This is particularly relevant for karate athletes who require high balance for performance and injury prevention. These findings are consistent with previous studies: Previous study reported that combining visual feedback with SFE shifted plantar pressure from the medial to lateral foot and supported MLA formation [20]. Existed evidence found that combined strengthening of intrinsic and extrinsic foot muscles reduced foot pressure in adults with flexible flatfoot [21]. Another study demonstrated that combining SFE with lower extremity exercises led to greater improvements in the COP index during walking than SFE alone [22]. Similarly, the other study reported that SFE combined with shoe insoles improved pain, function, and plantar pressure distribution more than insoles alone in patients with symptomatic flatfoot [23].

Regarding Ground Reaction Forces (GRF), both exercise interventions reduced first peak force and force depth, with greater reductions in the SF-3DAE group, indicating improved shock absorption during initial contact and better maintenance of force during mid-stance. No significant differences were observed for second peak force between groups, suggesting that the push-off phase, primarily driven by gastrocnemius and soleus muscles, was not differentially affected. These results align with study conducted by Owen et al. (2021), who reported that SFE can modulate GRFs during landing, particularly in unhealthy or injured populations [24]. Overall, the combined intervention appears more effective for landing and mid-stance phases, while additional interventions targeting calf strength may be necessary to influence the push-off phase.

The study found no significant effects on symmetry indices, including right-left leg forces and forefoot-rearfoot symmetry. This lack of change may be due to the exercises being applied bilaterally, maintaining pre-existing symmetry. As flexible flatfoot is often a bilateral condition, the exercises may enhance overall foot function rather than alter symmetry.

Several limitations should be noted. The relatively small sample size and inclusion of only female karate athletes may limit generalizability. The absence of long-term follow-up prevents conclusions regarding the sustainability of effects. Functional outcomes such as gait, sport-specific performance, and detailed electromyography analyses were not assessed, limiting insight into mechanisms and clinical relevance. Moreover, test–retest reliability for individual plantar pressure variables was not available, precluding calculation of clinically meaningful change indices such as SEM, MDC, or MCID. Future studies incorporating biomechanical and EMG analyses and diverse populations are warranted.

Conclusion

In conclusion, combining SFE with 3DAE leads to greater improvements in plantar pressure distribution, postural control, and shock absorption than SFE alone in female karate athletes with flexible flatfoot. These findings underscore the importance of a comprehensive rehabilitation approach targeting both intrinsic foot muscles and ankle stability, supporting functional foot performance and injury prevention.

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Not applicable.

Author Contributions:

YGH: Data curation, Investigation, Methodology, Resources, Writing, original draft. FS: Conceptualization, Data curation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing, original draft, Writing, review & editing. FG: Conceptualization, Data curation, Methodology, Writing, review & editing.

Conflicts of Interest

There is no confilict of interest for this study.

Ethical Permission

Ethical approval information: We confirm that this study was conducted in full compliance with the principles outlined in the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee of Bu-Ali Sina University (IR.BASU.REC.1401.025), and the study was registered in the clinical trial system under the identifier IRCT20221215056826N1. Written informed consent was obtained from all participants.

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