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Effect of Adding Reactive Neuromuscular Exercises to Core Foot Training on Gait Kinetics in Girls with Flexible Flatfoot: A Single-Blind Clinical Trial

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Original Article

Abstract

Introduction: Flexible flatfoot is a common disorder during growth, characterized by a decreased medial longitudinal arch and altered gait patterns, which can lead to pain and chronic injuries. This study aimed to investigate the effect of combining core foot exercises (CFE) and reactive neuromuscular training (RNT) on gait kinetics in girls with flexible flatfoot.

Materials and Methods: A single-blind clinical trial with a pretest-posttest design was conducted involving three groups (two intervention groups and one control group). Forty-eight girls aged 12-15 years were randomly assigned into three groups of 16: CFE, CFE plus RNT (CFE + RNT), and control. Interventions were performed for eight weeks (three sessions per week). Kinetic data, including ground reaction force (GRF), time to peak GRF (T-Peak GRF), and center of pressure (COP) displacement, were recorded using a force plate. Normality of data distribution was assessed using the Shapiro-Wilk test, and homogeneity of variances was examined using Levene's test. One-way analysis of variance (ANOVA) was used to compare groups at pre-test, and analysis of covariance (ANCOVA) with Bonferroni post-hoc test was used for post-test comparisons after controlling for pre-test effects, at a significance level of 0.05. Data were analyzed using SPSS software.

Results: Eight weeks of training produced significant differences in GRF, T-Peak GRF, and COP ($P < 0.05$). The combined training group (CFE + RNT) experienced greater improvements in GRF, T-Peak GRF, and COP compared to the CFE group alone.

Conclusion: Adding RNT to CFE improves gait kinetics and enhances stability, representing a cost-effective and clinically effective approach for managing flexible flatfoot.

Keywords: Flexible flatfoot; Gait; Resistance exercises

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Introduction

The musculoskeletal system of the lower extremity, through the integration of bony, muscular, and ligamentous structures, plays a crucial role in weight-bearing, force absorption, and the production of efficient movements. The ankle-foot complex, as the terminal part of the kinetic chain, is responsible for distributing mechanical stresses, maintaining static and dynamic stability, and performing activities such as standing and walking (1, 2).

Flatfoot, characterized by the collapse of the medial longitudinal arch, forefoot abduction, and rearfoot valgus (3), is a prevalent abnormality during growth and is considered a risk factor for overuse injuries and functional foot disorders (4). The prevalence of this deformity is reported to be up to 42% in children and 15–23% in adults (5, 6). It can lead to complications such as plantar fasciitis, Achilles tendinopathy, chondromalacia patellae, and patellofemoral pain

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syndrome (7). This deformity can be accompanied by several postural adaptations, including hip anteversion, internal femoral rotation, external tibial rotation, knee valgus, and lumbar hyperlordosis (8).

Center of Pressure (COP) is a key indicator for quantifying the spatio-temporal distribution of applied forces, which manifests as the gait line path during the stance phase (9, 10). Individuals with flatfoot exhibit a more medial-lateral COP path; due to posterior tibial tendon dysfunction, changes in gait patterns occur, and the displacement and velocity of the COP during the stance phase are more distributed in the medial region (9, 11). Dynamic analysis of COP displacement is considered a comprehensive indicator for evaluating postural stability and neuromuscular function in the management of flatfoot deformity and for assessing the effectiveness of corrective protocols (12). Furthermore, Ground Reaction Force (GRF) components are key clinical indicators for identifying risk mechanisms, such as shock-absorption capacity and joint stability. Although the magnitude of these forces may be below the acute injury threshold, their repetitive nature over the long term leads to microtrauma and the development of chronic injuries within the lower limb kinetic chain (13). Excessive pronation during walking results in an unbalanced distribution of GRF and non-physiological gait patterns, leading to muscle fatigue and pain (14). Additionally, an increase in the vertical component and loading rate of GRF, along with an altered COP trajectory, indicates reduced shock-absorption capacity, decreased mechanical stability, and increased stress on tissues (15).

For managing flatfoot, interventions such as orthotic insoles, taping, and exercise therapy have been reported with positive results (16). Exercise therapy has been introduced as an effective approach in treating flatfoot, and its combination with orthotic insoles is more effective than using insoles alone (17). Core-Foot exercises improve the medial longitudinal arch and enhance gait kinematic and kinetic parameters by strengthening the intrinsic foot muscles (18). Reactive Neuromuscular Training (RNT) also improves the balance and dynamic stability of the knee and ankle joints by correcting faulty movement patterns. It has shown favorable results in the rehabilitation of musculoskeletal disorders (19, 20).

Despite the individual effectiveness of these approaches, each has its own limitations. Core-Foot exercises primarily focus on strengthening local foot muscles, whereas Reactive Neuromuscular Training emphasizes proximal control (21). Since flatfoot is a multi-level disorder, it is hypothesized that the synergistic combination of these two approaches could more effectively improve gait kinetic parameters (22).

Given the limited number of previous studies focused on adults and the lack of investigation into combined interventions in children, a comprehensive protocol is needed. Since these two methods target the distal and proximal regions, respectively, their combination is expected to improve neuromuscular control and enhance gait kinetic parameters. Therefore, the purpose of the present study is to investigate the effect of adding Reactive Neuromuscular Training to Core-Foot exercises on gait kinetics in girls with flexible flatfoot.

Materials and Methods

This study was a single-anonymized clinical trial with a pretest-posttest design including two intervention groups and one control group. The research population consisted of female students aged 12 to 15 years with flexible flatfoot in Alborz Province. The sample size was calculated using G*Power software (G*Power 3.1.5 freeware, University of Düsseldorf, Düsseldorf, Germany) based on an effect size of 0.4, a test power of 0.8, and a significance level of 0.05; with a 20% dropout rate, 48 participants were required. Sampling was performed using a randomized block design, and eligible participants were randomly assigned to three groups of 16 individuals: Core-Foot exercises, combined Core-Foot and Reactive Neuromuscular Training (RNT), and the control group (Figure 1).

Ethical Considerations: This research was approved by the Research Ethics Committee of Kharazmi University (Code: IR.KHU.REC.1404.051) and was registered in the Iranian Registry of Clinical Trials (Code: IRCT20250610066157N1). Participants signed an informed consent form before entering the study.

Inclusion criteria included: girls aged 12 to 15 years with flexible flatfoot, normal Body Mass Index (BMI), a navicular drop of more than 10 mm during weight-bearing, positive results in Jack’s and Brody’s tests (23), no participation in similar training programs or use of orthotic insoles in the past 6 months, confirmation from a specialist physician, completion of the consent form, and voluntary participation.

Exclusion criteria were: absence from more than three training sessions, any acute lower limb injury during the study (such as ankle sprains, ligament tears, or severe muscle strains), presence of other musculoskeletal abnormalities in the lower limbs (including genu varum, genu valgum, or leg length discrepancy of more than one centimeter), a history of surgery, fracture, or dislocation in the lower limb joints, neuromuscular diseases, as well as expressing a lack of desire to continue cooperation at any stage of the study.

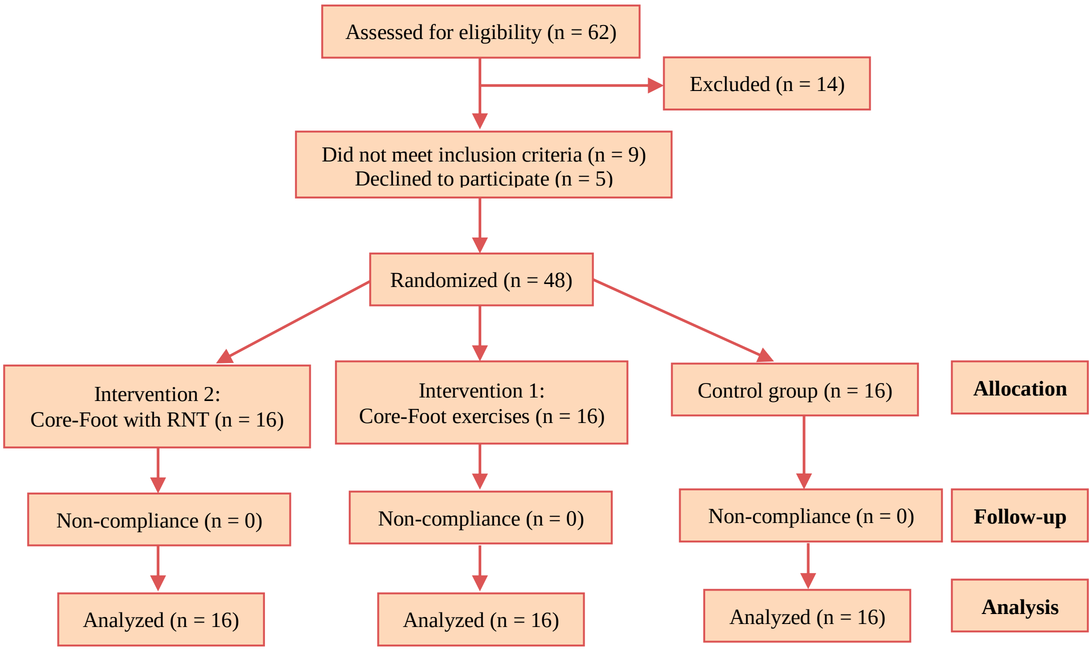

Figure 1. Randomization flowchart

Individuals with rigid flatfoot were rarely observed during the initial screening, but they were excluded from the study to prevent any potential negative impact.

Initially, the testing procedure and research design details were fully explained to the participants and their parents, and they were asked to complete and sign the consent and personal information forms before the tests began. Additionally, they were assured that their information would remain confidential and that they could withdraw from the study at any time. The force plate system was then calibrated according to the manufacturer's manual. Subsequently, the participants' height and weight were measured by the examiner using a digital scale and stadiometer and recorded in the personal information form.

In the pre-test phase, to measure kinetic variables, a Bertec force plate (Bertec Corporation, Model FP4060-10, USA, 1000 Hz) was placed in the center of a straight 8-meter walkway. The walkway surface was leveled and adjusted to minimize unevenness and interference with foot contact. This device can simultaneously measure vertical and shear forces (anteroposterior and mediolateral) during walking. Subsequently, before starting the dynamic test, a static test was first conducted for 5 seconds with the participant standing still in the center of the force plate to record baseline data for calibration and zero correction of the device (24). Furthermore, each participant was given five minutes of familiarization time with the walkway and the force plate before the test began.

To perform the main test, participants stood two steps behind the platform (facing it) and were asked to walk barefoot at their preferred speed while their kinetic data were recorded; a metronome was used to maintain a constant speed throughout the experiment (25). Walking speed was measured in meters per second (m/s) (mean: 1.05 ± 0.15 m/s, with no significant difference between groups: $P = 0.68$). The participants' starting position was determined so that the first step was taken with the non-dominant foot and the second step with the dominant foot, landing precisely on the force plate. The participant then continued for two more steps. The dominant foot was identified using the ball-kick test (26).

A successful trial was recorded when the participant placed their foot naturally in the center of the platform without altering their walking pattern. A 30-second rest period was provided between each repetition, and finally, the average of three successful trials for each lower limb was recorded (27). Subsequently, participants were randomly assigned to three groups of 16 individuals: 1- Core-Foot exercises, 2- Combined exercises (Core-Foot + Reactive Neuromuscular Training), and 3- the control group. The two intervention groups received 8 weeks of specific training, while the control group received none.

The training program was developed based on the protocols of Sheng-Lohng Kao and Bin Shen, with necessary modifications made by a team of experts, including two physiotherapists, one PhD in sports rehabilitation, and one sports physiology specialist. This eight-week program consisted of three 40–70-minute sessions per week. The first two weeks focused on neuromuscular adaptation in a seated position; the middle three weeks were dedicated to standing and weight-bearing exercises with increasing difficulty; and the final three weeks focused on stabilizing single-leg movement patterns (28, 29). The exercises included hallux abduction, heel raises, heel raises on a step, towel curls with toes, arch lift (short foot), and toe spreading (Table 1).

Reactive Neuromuscular Training (RNT) was added to the Core-Foot program and was based on the protocols of Mozafaripour, Letafatkar, and Ford (30-32). The combined group met for three weekly 40–70-minute sessions. To maintain training volume consistency between the two intervention groups, the Core-Foot-only group performed basic training and stretching (including hamstring and calf stretches) for the same duration as the combined group (40-70 minutes) to control for training time as a confounding variable. Progressive overload was applied by increasing the resistance of the loop bands every two weeks, and resistance levels were increased only if the movements were performed correctly (33, 34). The RNT exercises included ankle inversion and dorsiflexion with resistance bands, squats and lunges with resistance bands, monster walks (side-stepping), single-leg deadlifts, and box step-downs with resistance bands, emphasizing improved neuromuscular control and motor reactions (Table 1). Since kinetic variables may be influenced by environmental factors or subjects' familiarity with laboratory conditions during the post-test phase, the control group served as a comparative reference to ensure that the observed improvements in the experimental groups resulted solely from the exercise interventions rather than from environmental or temporal confounding factors. The post-test phase was conducted 8 weeks later, using the same procedures and equipment as the pre-test.

After recording the raw data, the initial foot placement was first examined to confirm pressure symmetry in the anteroposterior and mediolateral axes. The raw data were filtered using a 4th-order low-pass Butterworth filter with a cutoff frequency of 20 Hz in MATLAB (R2022a, MathWorks, Natick, Massachusetts, USA) to remove high-frequency noise. The stance phase of gait was defined as the time interval between the moment of heel strike (vertical Ground Reaction Force (GRF) > 20 N) and the moment of toe-off (vertical GRF < 20 N). To facilitate comparison between subjects, the Center of Pressure (COP) displacement data were normalized to each participant's foot length, and vertical force values were normalized as a percentage of body weight (%BW) to neutralize the effect of weight in statistical analyses (23).

The kinetic variables examined in this study included GRF, time to peak ground reaction force (T-Peak GRF), and COP. GRF was defined as the maximum vertical and shear forces exerted by the ground on the foot during the stance phase of walking, and these values were normalized to body weight. This variable was measured in three components: anteroposterior, mediolateral, and vertical. Additionally, T-Peak GRF, an indicator of loading rate, was defined as the time elapsed from heel strike to peak vertical force and recorded in milliseconds. Finally, COP, which represents the displacement path of the point of application of the resultant vertical forces on the foot-ground contact plane, was calculated in both anteroposterior and mediolateral directions.

Table 1. Core-Foot and Reactive Neuromuscular Training (RNT) protocol over eight weeks

Exercises	Weeks 1-3	Weeks 4-5	Week 6-8
		Sets × Reps	
Core-Foot			
Hallux abduction	8×3	10×3	15×3
Heel raises	8×3	10×3	15×3
Bilateral heel raises on a step	8×3	10×3	15×3
Towel curls	8×3	10×3	15×3
Short foot exercise	8×3	10×3	15×3
Toe spreading	8×3	10×3	15×3
RNT			
Inversion and dorsiflexion with a resistance band	8×3	10×3	15×3
Squats with a resistance band around the knees	8×3	10×3	12×3
Side-stepping with the band	8×3	10×3	12×3
Single-leg deadlift with a resistance band around the knee	8×3	10×3	12×3
Modified forward lunge with resistance band	8×3	10×3	12×3
Forward step-down from a box with a resistance band	8×3	10×3	12×3

This variable was reported in millimeters and normalized to foot length; its primary application in this study was to evaluate postural fluctuations and dynamic stability during gait (24).

Statistical Analysis: The Shapiro-Wilk test was used to assess normality, and Levene's test was used to evaluate homogeneity of variances. To ensure the absence of significant differences between groups at the beginning of the study, a one-way ANOVA was applied. Analysis of Covariance (ANCOVA) was utilized to analyze between-group differences at the post-test stage while controlling for the pre-test effect. If significant differences were found between groups, the Bonferroni post-hoc test was used to determine the exact location of the differences. The effect size was reported using the eta squared (η^2) index, with criteria based on Cohen's suggestions (small: 0.01, medium: 0.06, large: 0.14). Additionally, a paired t-test was used to assess within-group differences for each variable between the pre-test and post-test stages. The significance level for all tests was set at 0.05.

Results

The Shapiro-Wilk test confirmed normality, and Levene's test indicated homogeneity of variances. Furthermore, the one-way ANOVA results showed no significant differences in dependent variables between the groups at the pre-test stage (P > 0.05). Although there were non-significant differences in demographic variables (height, weight, age, and Body Mass Index) between the groups (P > 0.05), to more precisely control the impact of these potential differences on the primary results, Analysis of Covariance (ANCOVA) was employed by controlling for the pre-test effect and including BMI as a covariate in the statistical model.

Based on the findings from the statistical tests (ANCOVA and paired t-tests) reported in Table 2, the eight-week exercise intervention had varying effects on gait kinetic variables across the three groups: control, Core-Foot exercises, and combined exercises (Core-Foot + RNT). The results of the Analysis of Covariance (ANCOVA), controlling for the pre-test effect, showed a significant difference between groups in the anteroposterior axis of the Center of Pressure (F = 5.03, P = 0.00, η^2 = 0.19); however, the difference in the mediolateral axis was not statistically significant (P > 0.05).

The Bonferroni post hoc test indicated that the primary difference lay between the control group and the combined training group (Core-Foot + RNT), with the latter showing greater gait stability. The Core-Foot group also showed a reduction in Center of Pressure displacement, but the difference compared to the control group was not significant. The combined group exhibited a larger effect size in both Center of Pressure components than the Core-Foot group alone, confirming the clinical significance of these findings (Table 2).

Table 2. Results of ANCOVA and paired t-tests in pre-test and post-test for Center of Pressure (COP) indices, Ground Reaction Force (GRF), and Time to Peak GRF

Variable	Group	Pre-tes (mean ± SD)	Post-test (mean ± SD)	Between-group			Within-group		
				F	P	Effect Size	T	P	Effect Size
COP (mm)	CO	4.99 ± 1.55	4.80 ± 1.12	1.99	0.140	0.08	0.33	0.740	0.08
	CFE	5.12 ± 1.33	4.39 ± 1.03				2.06	0.050	0.53
	CFE+RNT	5.34 ± 1.26	4.09 ± 0.95				4.19	< 0.001*	1.08
COP Y (mm)	CO	19.88 ± 1.57	19.76 ± 1.52	5.03	0.010*	0.19	0.25	0.800	0.06
	CFE	21.74 ± 2.11	19.95 ± 1.17				4.65	< 0.001*	1.24
	CFE+RNT	21.63 ± 1.77	19.11 ± 0.76				6.94	< 0.001*	1.79
GRF X (%BW)	CO	5.77 ± 1.09	5.69 ± 1.66	3.50	0.030*	0.14	0.27	0.780	0.07
	CFE	6.39 ± 1.03	4.79 ± 1.61				3.33	< 0.001*	0.86
	CFE+RNT	6.38 ± 1.05	4.48 ± 1.50				4.21	< 0.001*	1.05
GRF Y (%BW)	CO	15.01 ± 1.95	13.93 ± 2.79	4.32	0.020*	0.17	1.65	0.120	0.42
	CFE	15.34 ± 1.54	12.75 ± 1.69				5.24	< 0.001*	1.03
	CFE+RNT	16.37 ± 1.47	12.38 ± 1.91				7.93	< 0.001*	2.04
GRF Z (%BW)	CO	98.56 ± 4.23	102.44 ± 7.24	8.16	< 0.001*	0.28	1.55	0.140	0.40
	CFE	102.80 ± 7.12	96.86 ± 8.08				2.24	0.040*	0.57
	CFE+RNT	100.76 ± 3.65	90.13 ± 8.80				4.28	< 0.001*	1.10
T-Peak GRF (% of stance phase)	CO	23.86 ± 2.47	23.80 ± 1.79	12.14	< 0.001*	0.37	0.11	0.910	0.02
	CFE	21.74 ± 1.81	26.12 ± 2.73				6.58	< 0.001*	0.95
	CFE+RNT	22.88 ± 2.45	25.91 ± 2.63				7.58	< 0.001*	1.70

COP X = Anteroposterior Center of Pressure; COP Y = Mediolateral Center of Pressure; GRF X = Anteroposterior Ground Reaction Force; GRF Y = Mediolateral Ground Reaction Force; GRF Z = Vertical Ground Reaction Force; T-Peak GRF = Time to Peak Ground Reaction Force; CO = Control Group; CFE = Core-Foot Exercise Group; CFE+RNT = Core-Foot Exercise + Reactive Neuromuscular Training Group.
*Significance level (P < 0.05)

After controlling for the pre-test, significant differences were observed across all three GRF axes: anteroposterior ($F = 3.50$, $P = 0.03$, $\eta^2 = 0.14$), mediolateral ($F = 4.32$, $P = 0.02$, $\eta^2 = 0.17$), and vertical ($F = 8.16$, $P = 0.00$, $\eta^2 = 0.28$). Post-hoc testing indicated that the primary difference lay between the control and combined groups. The combined group experienced 30% reductions in the anteroposterior and mediolateral axes, and a 10% reduction in the vertical component. In comparison, the Core-Foot group showed reductions of 25% and 6% in the same axes, though some components did not reach statistical significance compared to the control group. These results suggest reduced mechanical stress on the lower limb joints, improved alignment of movement, and enhanced shock absorption in the combined group.

Furthermore, a significant difference between groups was observed in T-Peak GRF ($F = 12.14$, $P = 0.00$, $\eta^2 = 0.37$). Specifically, the Core-Foot group experienced a 20% increase and the combined group a 13% increase, indicating a more gradual loading rate and a reduction in sudden impacts on foot structures. Post-hoc tests confirmed that these changes were significantly different between the two training groups and the control group. In contrast, the large effect size in the combined group underscores its clinical importance.

In summary, although Core-Foot exercises alone led to improvements in most variables, the combined group (Core-Foot + RNT) showed superior improvements across all indices, with significant differences from the control group in COP Y, GRF X, GRF Y, GRF Z, and T-Peak GRF. This highlights the superiority of the combined approach in enhancing dynamic stability, reducing mechanical stress, and optimizing gait loading patterns in girls with flexible flatfoot (Table 2).

Discussion

The present study aimed to investigate the effect of adding reactive neuromuscular training (RNT) to Core-Foot exercises on gait kinetic variables, including Center of Pressure (COP), Ground Reaction Force (GRF), and Time to Peak vertical force (T-Peak GRF) in girls aged 12 to 15 years with flexible flatfoot. The primary findings of this research indicated that both exercise protocols (Core-Foot and combined) led to significant improvements in most kinetic variables; however, the combined group (Core-Foot + RNT) demonstrated more substantial and consistent improvements across all indices compared to the Core-Foot group alone. These findings are clinically significant, as they suggest that a multi-level therapeutic approach targeting both the intrinsic foot muscles and the proximal kinetic chain can further enhance gait efficiency in this population.

Center of Pressure (COP) Displacement: COP is a valid index for assessing postural control and dynamic stability during gait (35). Due to intrinsic foot muscle weakness and proprioception impairment, individuals with flatfoot often exhibit greater COP displacement, particularly in the mediolateral axis, indicating lateral instability (36). In the present study, both intervention groups showed a significant reduction in the mediolateral COP axis; however, the combined group demonstrated a clear advantage with a very large effect size and a significant difference compared to the control group. This finding aligns with the results of Cao et al. (2024), who showed that Core-Foot exercises alone can reduce COP range (37). Nevertheless, the superiority of the combined group in our study suggests that adding reactive neuromuscular training increases proximal stability by improving neuromuscular control at the hip and knee joints, subsequently reducing distal fluctuations (38). This finding is consistent with research by Yulinti et al. (2023), which demonstrated that weak proximal control is directly related to foot instability in children with flatfoot (39).

Along the anteroposterior COP axis, although both intervention groups showed reductions, the difference between groups was not statistically significant. This may be because anteroposterior control of the center of pressure is more dependent on ankle strategies than on hip and pelvic strategies (40), and both protocols engaged the ankle dorsiflexors and plantarflexors to a similar extent. This finding corresponds with the study by Russ et al. (2013), which indicated that localized foot exercises have a greater impact on lateral control than on anteroposterior control (41).

The Effect of Interventions on Ground Reaction Force (GRF): Ground Reaction Force (GRF) is a reflection of the mechanical loads applied to the musculoskeletal system during foot-to-ground contact (42). In individuals with flatfoot, excessive pronation increases the medial and vertical components of GRF and reduces shock absorption capacity (43, 44). In the present study, the combined group showed a greater reduction in all three GRF components than the Core-Foot group. Specifically, the combined group observed reductions of 32% in the anteroposterior component, 26% in the mediolateral component, and 11% in the vertical component of GRF. In contrast, the Core-Foot group alone experienced reductions of 22%, 7%, and 5% in these components, respectively. These findings align with research by Otsahachant et al. (2023), which showed that combining Core-Foot exercises with lower limb training has a greater impact on foot dynamics (45), as well as with the study by Zarei and Hemmati (2022), which emphasized the role of neuromuscular training in improving force distribution (46).

The physiological mechanism for this improvement can be explained at two levels: 1) Distal Level: Core-Foot exercises strengthen the arch-supporting muscles, such as the flexor digitorum brevis and abductor hallucis, increasing the dynamic stiffness of the medial longitudinal arch and preventing its excessive collapse (47, 48). According to findings by Okamura et al. (2019), the activation of intrinsic foot muscles has the capacity to support the medial longitudinal arch and can alter foot kinematics during gait (49). 2) Proximal Level:* Reactive Neuromuscular Training (RNT) stabilizes the kinetic chain by improving the activation patterns of the muscles surrounding the hip joint (particularly the gluteal muscles and external rotators) and controlling knee valgus. This results in a more balanced distribution of shear and vertical forces throughout the entire lower limb (50, 51). Ford et al. (2015) demonstrated that neuromuscular training focused on the hip can reduce dynamic lower limb valgus and improve neuromuscular control (52). The synergistic effect of these two levels of intervention explains the significant superiority of the combined group.

The Effect of Interventions on Time to Peak Vertical Force (T-Peak GRF): Time to peak vertical force is a sensitive index of the loading rate. An increase in this time signifies a more gradual distribution of force and a reduction in sudden impact on the foot and ankle structures, which serves as a crucial protective factor against overuse injuries such as plantar fasciitis and stress fractures (52). Our findings showed that both intervention groups experienced a significant increase in T-Peak GRF (Core-Foot group: 18%; combined group: 14%), and the ANCOVA indicated a highly significant difference between the exercise groups and the control group.

Notably, the within-group effect size for the combined group (d = 1.70) was larger than that of the Core-Foot group (d = 0.95), indicating greater stability and consistency of these changes in the combined group. This finding is comparable to research by Padron et al. (2023), which showed that individuals with flatfoot have longer contact times during the stance phase (53), and also to the study by Karimzadeh et al. (2022), which indicated that Core-Foot exercises alone may not be capable of significantly altering the kinetic parameters of the foot (54). However, the superiority of the combined group in terms of effect size suggests that improved neuromuscular control at the hip and pelvis level (achieved through reactive training) contributes to more precise heel-strike timing and gradual weight transfer. This results in a reduced loading rate and an increased time to peak force (55, 56).

From a clinical perspective, the findings of this study are significant as they demonstrate that adding reactive neuromuscular training to Core-Foot exercises is a cost-effective and efficient therapeutic strategy for managing flexible flatfoot in adolescent girls. Large to very large effect sizes (ranging from 0.57 to 2.04 for within-group effects and from 0.14 to 0.37 for between-group effects) confirm that these improvements are significant not only statistically but also clinically (based on Cohen's criteria). Gradually reducing applied forces and gradually increasing the loading rate can decrease the risk of secondary injuries, such as patellofemoral pain, Achilles tendinopathy, and plantar fasciitis, in this population (57).

Limitations

This study has several limitations that should be considered when interpreting the results. First, the relatively small sample size (n = 48) and the restriction of the study population to girls aged 12 to 15 limit the generalizability of the findings to boys, other age groups, and patients with rigid flatfoot. Second, daily physical activity levels and the type of footwear used by the participants throughout the study period were not fully controlled, which may have acted as confounding variables. Third, important mediating variables—such as the isometric and isokinetic strength of the intrinsic and extrinsic foot muscles, medial longitudinal arch height (measured via more precise methods like radiography or 3D scanning), electromyographic (EMG) activity of key muscles (e.g., posterior tibialis, peroneus longus, and gastrocnemius), and pain levels (using standardized scales)—were not measured in this study. Fourth, no long-term follow-up was conducted to evaluate the durability of the training effects after the intervention ended.

Recommendations

Based on the findings and limitations of this study, the following suggestions are proposed: 1) Conducting similar studies with larger sample sizes, including both genders and broader age groups. 2) Simultaneous measurement of kinetic variables alongside electromyographic (EMG) and kinematic variables to better understand the underlying neuromuscular mechanisms of the improvements. 3) Designing studies with follow-up periods of at least 3 to 6 months to evaluate the stability and durability of the training effects. 4) A direct comparison of the effects of reactive neuromuscular training (RNT) alone versus Core-Foot exercises and the combined approach in a three-arm clinical trial to identify the most effective therapeutic intervention. 5) Investigating the impact of these training protocols on functional variables related to daily activities, such as dynamic balance, jumping power, and proprioception.

Conclusion

The results of this study indicated that while Core-Foot exercises alone can improve certain gait kinetic variables in girls with flexible flatfoot, the combined approach (Core-Foot paired with reactive neuromuscular training) is significantly more effective. This integrated strategy yields greater improvements in dynamic stability (reduced COP), reduced detrimental mechanical loads (decreased GRF in all three directions), and optimized loading pattern (increased T-Peak GRF). From a clinical standpoint, these findings underscore that the effective management of flexible flatfoot in children and adolescents necessitates a comprehensive, multi-level approach that simultaneously addresses both localized foot impairments and neuromuscular dysfunctions within the proximal segments of the kinetic chain.

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Authors' Contribution

Project design and conce ptualization: Ghazal taghizadeh, Seyed Sadredin Shojaedin
Attracting financial resources to carry out the project: Seyed Sadredin Shojaedin
Project support, scientefic and executive service: Seyed Sadredin Shojaedin
Providing equipment and statistical samples: Ghazal taghizadeh, Seyed Sadredin Shojaedin
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Conflict of Interest

The authors did not have a conflict of interest.

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