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The Effects of a Comprehensive Exercise Program combined with Foot Orthoses on Foot Alignment and Dynamic Knee Valgus Kinematics in Individuals with Flexible Flatfoot :A Randomized Controlled Trial

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Abstract

Background: Flexible flatfoot is linked to changes in lower-limb alignment and increased dynamic knee valgus (DKV), which may predispose individuals to musculoskeletal disorders. Limited evidence exists comparing corrective exercises and custom foot orthoses on foot alignment and knee kinematics. **Methods:** Thirty male adolescents (12–15 years) with flexible flatfoot were randomly assigned to three groups: a combined comprehensive exercise program with custom-made orthoses, custom orthoses only, or a control group. Interventions lasted 6 weeks. Outcome measures included navicular drop, medial longitudinal arch angle, rearfoot eversion, and 3D lower-limb kinematic variables during a single-leg step down task. MANCOVA was used with baseline adjustments ($p \le 0.05$). **Results:** A significant multivariate group effect was observed (Wilks' Λ = .000, $F(14, 28) = 476.67$, $p < .001$, partial $\eta^2 = .996$). The combined intervention group showed greater improvements across all foot alignment variables and DKV kinematics compared to orthoses-only and control groups. Effect sizes were large ($0.14 < \eta^2$), and all changes exceeded MCID values. **Conclusion:** Combining a comprehensive exercise program with customized foot orthoses results in greater improvements in foot alignment and DKV kinematics than orthoses alone. This approach addresses both distal and proximal aspects of the kinetic chain and may benefit adolescents with flexible flatfoot. Long-term follow-up studies are recommended.

Keywords: flexible flatfoot, comprehensive exercises, foot orthoses, foot alignment, DKV kinematics

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Introduction

The foot is a complex structure with numerous articulations and various degrees of freedom, which are crucial for both static posture and dynamic activities (1). Poor posture in the arches of the feet can adversely affect foot health. One of the most prevalent foot deformities is flexible flatfoot. This deformity is typically defined by a partial or complete collapse of the foot's medial longitudinal arch (2-4). Research indicates that flexible flatfoot is prevalent across all age groups (5-7).

In accordance with the closed kinetic chain theory (8) of the lower extremity, a flexible flatfoot can impact foot misalignment of the foot, which can then be transferred to the upper portions of the lower extremity (9) during dynamic activity (10). This can result in medial tilting of the tibia with navicular drop, overpronation or valgus of the subtalar joint, rearfoot eversion, and dorsiflexion with forefoot abduction (2-4). This condition has often been identified as a risk factor for medial tibial stress syndrome or patellofemoral pain syndrome (11-13).

Studies have demonstrated that flexible flatfoot is linked to increased dynamic knee valgus (DKV) during functional movements (14, 15). In individuals with flexible flatfoot, DKV is observed as a compensatory movement strategy (16) and has the potential to result in patellofemoral joint dysfunction and anterior cruciate ligament injuries (17). DKV, which can lead to abnormal joint moments during weight-bearing activities, is a contributing factor to non-contact knee injuries, characterized by a combination of hip adduction and internal rotation, knee abduction, and ankle eversion (18, 19).

Previous research has employed a variety of methods for treating flexible flatfoot, such as different types of exercises (20), various foot orthoses (21), kinesio tape (22), non-steroidal anti-inflammatory drugs (23), and surgical correction (24).Therapists commonly prescribe noninvasive modalities like corrective exercises (active support) and foot orthoses (passive support) for the treatment of flexible flatfoot (25).

Foot orthoses, also known as arch support insoles, are commonly prescribed for flexible flat feet (26, 27). Different types of foot orthoses are utilized in clinical practice, including custom-made and prefabricated options (28). According to Cheung et al. (2011), custom-made foot orthoses have been found to be more effective than prefabricated ones (29). A previous study revealed that 50% of patients with flexible flatfoot deformities were treated with foot orthoses to elevate the medial longitudinal arch and address deformities (29, 30). The reasoning behind this approach is that personalized orthoses provide tailored treatment from therapists, leading to more effective correction of foot posture. Additionally, foot orthoses with a contoured medial arch have been demonstrated to prevent deformation of the medial longitudinal arch and reduce pronation during walking (31).

Corrective exercises are frequently recommended for individuals with flexible flatfoot (20). Various types of exercises, such as short foot exercise (32), towel curling exercise (33), tibialis posterior strengthening exercise (34), gluteus training (35), and proprioceptive training (36), are commonly utilized in clinical settings. A network meta-analysis of randomized controlled trials comparing the efficacy of exercise therapy in adults with flexible flatfoot (20) found that various exercise therapies can enhance the arch shape and function of patients with this condition, particularly through hip muscle and lower limb muscle training. Current evidence suggests that strengthening the posterior tibial and plantar muscles along with gluteus muscle strengthening, neuromuscular movements focused on the buttocks, and lower limb proprioceptive neuromuscular facilitation (PNF) techniques are effective for improving the arch shape in flexible flatfoot patients. Additionally, centrifugal training of the posterior tibial muscle has been shown to improve foot function.

The correction of flat feet using exercise methods and medical orthotics has always been a topic of discussion. Therefore, in most cases an exercise program combined with medical insoles is more recommended (37). Previous studies on correcting flexible flatfoot deformities with exercise programs or foot orthoses have primarily focused on analyzing the static alignment of the foot, with no studies investigating DKV kinematics.

As a result, the research question for this randomized trial was: "What is the effect of a comprehensive exercise program combined with foot orthoses on foot alignment and DKV kinematics in individuals with flexible flatfoot?"

Materials and Methods

Study Design

This randomized clinical trial was registered with the Iranian Registry of Clinical Trials (IRCT20250506065623N1) on: 2025-08-25 and was carried out at the Laboratory of Medical Sciences Department, University of Shiraz. Ethical clearance was obtained from the Research Ethics Committee at the University of Tehran, Iran (IR.UT.SPORT.REC.1404.040). After posting an announcement of the research in a virtual space and at male high school students in Shiraz City, participants were chosen on the basis of the inclusion criteria implemented in this research. After our initial explanation of the research process, participants who were willing to participate were asked to sign an informed and voluntary consent form. The sample size needed for the F family using G*Power software (v3.1) for a repeated measures statistical test to analyze interactions within and between three groups over two measurement periods was calculated to be 27. This calculation was based on an effect size of 0.7, a test power of 0.8, and a significance level of 0.05 (38). Considering the potential for dropouts within the groups, we opted for a group size of 10 individuals (N = 30). Participants were randomly assigned by an impartial party to one of three groups: "Intervention Group 1," where individuals engage in comprehensive exercises with arch support insoles under the researcher's supervision; "Intervention Group 2," where individuals solely utilize arch support insoles. RandList software was used to select a code for each subject, and the codes were written on sheets that were then placed in opaque envelopes. After the pre-test, each of the participants was instructed to randomly choose one of the envelopes and was then assigned to the group corresponding to the chosen code. The medical insole being used is a custom-made insole tailored to each individual, created through the use of three-dimensional (3D) printing and computer-aided design/computer-aided manufacturing (CAD/CAM) technology with semi-rigid foam. "Control group": The control group did not partake in any of the intervention programs undertaken by the intervention group.

This study was conducted in accordance with the Declaration of Helsinki, approved by the ethics committee, and registered in the clinical trials database. The study was conducted in accordance with CONSORT guidelines. Prior to starting the exercises in the university's Sports Medicine laboratory, preliminary evaluations were conducted. Participants in each group were then briefed on the intended interventions to be carried out over a duration of six weeks. The allocation of participants was concealed from assessors and data analysts.

Participants

The study involved 30 male high school students aged 12 to 15 years who had flexible flatfoot and DKV. Inclusion criteria required a DKV angle <180°, determined by the single-leg step down test, as well as foot postural changes including navicular drop height >10 mm, medial longitudinal arch angle <130°, and rearfoot eversion angle >5°, measured using a ruler and goniometer, respectively. These measurements were conducted following established protocols (14, 39, 40). Exclusion criteria included congenital lower limb deformities, recent injuries within six months of the study, recent surgeries, and neurological deficits. The dominant foot of each participant was assessed, and individuals who did not complete the training sessions were excluded. Personal information of the participants was kept confidential from the evaluators and data analysts.

Interventions

This study utilized a comprehensive exercise program previously presented by Tanya et al (41). In this study, we enhanced the process of conducting these comprehensive exercises using insights from prior research (42-44). The comprehensive exercise program included warm-up, active exercises such as foot dorsiflexion and plantarflexion, short foot exercises like lesser toe extension, toe spread, doming, and hallux extension, gluteal muscle strengthening exercises such as hip abduction and hip extension, hip external rotation, oyster exercise, isometric gluteal muscles and foot contraction, Modified lunges, modified one leg squat as well as calf stretches. The exercises were modified after 2 weeks by changing the position (e.g., sitting, standing, single-leg stance, side lying, prone lying with and without elastic band) and/or increasing the hold time and number of repetitions. The intervention consisted of three sessions per week for a duration of 6 weeks, with the sessions scheduled for Monday, Wednesday, and Friday (Table 1) (Figures 1-17).

In this study, all scientific principles of exercise were taken into consideration when implementing comprehensive exercise routines. Six weeks which is deemed as a reasonable duration for both neuromuscular and physiological adaptations (45, 46), improves the sensorimotor abilities (parametric and primary proprioceptive abilities) in the initial phase by giving necessary feedback and helping them to them passively positioned each participant into the appropriate alignment (47). Next, the progression of exercise load occurred during the improvement phase (3–6 weeks) to produce necessary tissue adaptations (48). During maintenance phase, exercises progressed functionally to provide an adequate challenge for sensorimotor adaptation. It was highly emphasized that participants maintained the proper alignment of the involved segment and all other body segments during exercises and functional movement patterns. Besides, different kinds of visual, oral, and tactile feedback were provided. Indeed, the researcher continuously provided verbal cues on proper alignment in their performance. If necessary, the researcher would have modeled the exercise movements or used a mirror so that participants could identify their errors or even touched and directed them how to perform the exercises accurately.

The participants in experimental group 1 received comprehensive exercises while wearing custom-made orthoses fabricated from individual foot impressions and fitted by a qualified podiatrist, designed to provide medial arch support and limit excessive pronation (Figure 18). This group was instructed to wear their allocated footwear for at least 6–8 hours daily throughout the 6-week period. These insoles are specifically crafted with an internal longitudinal arch that matches each individuals foot arch size using three-dimensional (3D) printing and computer-aided design/manufacturing (CAD/CAM) technology with semi-rigid foam. Additionally, utilizing 3D printed foot orthoses provides flexibility in adjusting the corrective level and can positively impact individuals with pes flexible flatfoot (31). Previous studies concluded that custom-made foot orthoses are more effective compared to prefabricated options (29, 49). This is attributed to the personalized approach that enables therapists to tailor the correction to each person's foot posture. Furthermore, research indicates that foot orthoses incorporating a contoured medial arch can help prevent deformation of the medial longitudinal arch and reduce foot pronation during walking (31).

The second experimental group was instructed to wear their assigned footwear for a minimum of 6 to 8 hours daily over the six week period.

The control group engaged in their usual daily activities and did not take part in any exercise programs and received standard commercially available footwear matched for size and comfort but lacking orthotic modifications for at least 6–8 hours daily throughout the 6-week period. Following the completion of the study, the control group was provided with the intervention protocol due to ethical considerations.

Table 1: Content and progression of the experimental group intervention.

Exercises	Weeks	Position	Contraction duration (s)	Volume	Frequency (sessions/wk)
Warm-up	1 to 6	-	-	7 min	3
Active exercise: dorsiflexion plantarflexion	1 to 6	sitting	10	15 reps × 2 sets	3
Short foot exercises: toe spread hallux extension doming lesser toe extension	1 to 2	sitting	5	15 reps × 2 sets	3
	3 to 4	standing	10		
	5 to 6	single leg stance	15		
Gluteal muscle strengthening: hip abduction hip extension	1 to 2	side lying prone lying	0	8 to 10 reps × 2 sets	3
	3 to 4	side lying	5	10 to 12 reps	

		prone lying		× 2 sets	
	5 to 6	side lying prone lying	10	10 to 12 reps × 2 sets	
Cool down: range of motion exercises calf stretches	1 to 6	-	-	7 min	3

The three sessions per week were prescribed to occur on Monday, Wednesday and Friday. Min = minutes, reps = repetitions.

Fig. 1. Short foot exercises: a. hallux extension, b. doming, c. lesser toe extension, d. toe spread, **Fig. 2.** Warm up, **Fig. 3**. Active exercise: dorsiflexion, plantarflexion, pronation and supination, **Fig. 4.** Active exercise with elastic band: dorsiflexion, plantarflexion, pronation and supination, **Fig. 5.** Short foot exercises with isometric hip abduction during sitting, standing, single leg standing, **Fig. 6.** Short foot exercises with hip abduction with elastic band during sitting on, standing, single leg standing, **Fig. 7.** Hip external rotation during prone lying, **Fig. 8.** Oyster exercise during side lying, **Fig. 9.** isometric gluteal muscles and foot contraction, **Fig. 10.** Modified hip adduction during side lying, **Fig. 11.** Modified hip extension during prone lying, **Fig. 12.** Modified hip adduction/external rotation, **Fig. 13.** isometric hip adduction/external rotation, **Fig 14.** Pelvic resisted rotation, **Fig. 15.** Modified one leg squat, **Fig. 16.** Modified one leg squat, **Fig. 17.** Cool down: range of motion exercises, calf stretches and **Fig. 18.** Custom made orthoses fabricated.

Data collection and outcome measurement

Data were collected at the biomechanics laboratory of Shiraz University of Medical Sciences. Individuals who met the study eligibility criteria were required to sign a consent form if they agreed to participate. Upon their arrival at the lab, the researcher measured their basic demographic characteristics and instructed them to complete a questionnaire. The dominant leg was identified for each participant by asking which leg they used to kick a ball. The basic demographic characteristics included age, gender, height, weight, and body mass index. Foot and ankle assessment through physical examinations and functional tests involved gathering data on key variables such as the DKV angle, navicular drop height, medial longitudinal arch angle, and rearfoot eversion angle. These variables were measured following protocols from previous literature (14, 39, 40). Fourteen reflective markers were placed on anatomical landmarks in accordance with the Plug-in Gait method: ASISs, PSISs, lateral sides of thighs, lateral epicondyles of the knees, lateral sides of shanks, lateral malleolus, and center of the calcaneus. Participants were instructed to perform single-leg squat trials to approximately 60° of knee flexion while maintaining a rhythm of 2 seconds for both ascending and descending phases. Each participant stood on their dominant leg, with toes pointing straight forward, the non-weight-bearing leg in the position used during the screening test (90° knee flexion and 45° hip flexion), and hands clasped behind their backs. They were then asked to perform three sequential trials of the single-leg squat to approximately 60° of knee flexion. The lower extremity kinematic data were recorded at the maximum knee flexion angle for each participant, and the average of the three trials was calculated. The acceptable range of the knee flexion angle for each trial was from 50° to 70°. The test-retest reliabilities for all kinematic measures were above 0.80 in a pilot study. Three-dimensional trajectory data for DKV were collected using a 6-camera motion analysis system (VICON; Oxford Metrics LTD, Oxford, UK). Trajectory data were digitally recorded using Nexus software (Windows Version 2.6.1) and sampled at 240 Hz. The Butterworth filter was used to filter the kinematic data using a low-pass, zero lag, and fourth-order with a 10-Hz cut-off frequency to obtain smooth and coordinated data (50). ISB recommendations on the definitions of joint coordinate systems were followed for kinematic variable measurements (51).

Dynamic knee valgus test

The DKV angle was measured during a single-leg step down test. Participants wore fitted dark shorts, and the dominant leg of each subject was tested barefoot. Four retroreflective circular markers (14 mm in diameter) were placed at both anterior superior iliac spines (ASIS), the center of the patella, and the second metatarsophalangeal joint. Subjects performed the single-leg step down from a 15-cm step box (52, 53) (Fig. 19). They were instructed to lower the non-dominant leg until the heel lightly contacts the floor and then return to the initial position. Subjects were asked to clasp their hands behind their backs to accurately capture each ASIS marker and avoid compensatory motions such as using the upper extremities. The mean values of the measurements obtained in the two trials were used for data analysis. A regular smartphone (Galaxy S10e; Samsung Inc., Seoul, Korea) with a video recording application (4K, 3,840 × 2,160 pixels at 60 fps) was placed on a tripod 60 cm in height and 250 cm in front of the step box. The video recording data were analyzed using available software package Kinovea® (version 0.8.15; Kinovea, Bordeaux, France). The method for measuring the frontal plane projection angle was standardized as in a previous study by Harput et al (54). The frontal plane projection angle was calculated via the intersection of a line connecting the ASIS and the center of the patella and a line connecting the center of the patella and the middle of the ankle joint. The alignment was considered neutral at 180°; a DKV angle less than 180° indicated knee valgus alignment (14).

Fig. 19. Measurement of frontal plane projection angle during the single-leg step down

Navicular drop

The Brody method was utilized to assess the navicular bone's height in the dominant leg. A participant was instructed to sit in an adjustable chair with their hips and knees bent at 90 degrees. The second toe and knee were positioned to ensure the subtalar joint was in a neutral, non-weight-bearing alignment. The neutral position of the subtalar joint was defined as achieving equal palpation of the medial and lateral aspects of the talus head in relation to the navicular (55). Anatomical landmarks, including the navicular tuberosity, were identified through palpation and marked with a CD/DVD marker. The distance from the ground to the navicular tuberosity was measured and then remeasured in a weight-bearing stance, where participants stood with their feet shoulder-width apart. The difference between these two measurements was calculated as the Navicular Drop (ND) (56) (Fig. 20). The evaluation was repeated three times, and the mean of these repetitions was used to generate the final data. The vertical distance from the floor to the navicular tuberosity was measured using a ruler. Sell et al (57) reported an Intraclass Correlation Coefficient (ICC) ranging from 0.73 to 0.96 for both intertester and intratester reliability. Menz et al (58) found a significant association between Navicular Height (NH) and the corresponding radiographic measure, with a Pearson correlation coefficient of 0.79.

Fig. 20. Navicular height with the foot in subtalar neutral position.

Medial longitudinal arch angle

A participant was seated in an adjustable chair with their hips and knees bent at 90-degree angles. The second toe and knee were positioned so that the subtalar joint was in a neutral, non-weight-bearing state. The neutral position of the subtalar joint was defined as equal palpation of the medial and lateral aspects of the talus head concerning the navicular bone. Anatomical landmarks, including the center of the medial malleolus, navicular tuberosity, and the head of the first metatarsal bone, were identified through palpation and marked with a pen (CD/DVD marker, Relief). The goniometer's center (ProTerapi A/S) was aligned with the navicular tuberosity, and its ends followed the landmarks at the center of the medial malleolus and the head of the first metatarsal. The angle (LAA) between the lines from the medial malleolus to the navicular tuberosity and from the navicular tuberosity to the head of the first metatarsal bone on the ground was measured and recorded in the weight-bearing position, with the participants having their feet shoulder-width apart. This evaluation was conducted three times, and the average of the measurements was used to derive the final data (Fig 21). Dahle et al (59) reported a Kappa value of 0.72 for inter-tester reliability in visually assessing LAA, while Jonson et al (60) reported intratester and intertester ICC values of 0.90 and 0.81, respectively.

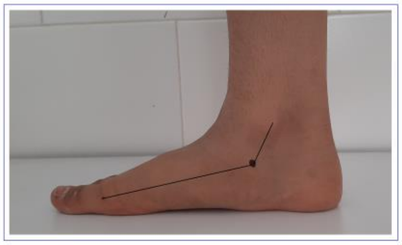

Fig. 21. Longitudinal arch angle with the foot in subtalar neutral position.

Rearfoot angle

Measurement of the rearfoot angle is a clinical method widely accepted in numerous studies (60, 61). This measurement evaluates calcaneal eversion or heel valgus and determines the level of foot pronation. Kanatli et al (62) emphasized that the rearfoot angle and MLA foot arch height should be evaluated separately in the assessment of flat feet. To measure the rearfoot angle, the subject is positioned lying prone with the foot and ankle extended 10 cm off the bed. A longitudinal line is drawn along the back of the lower third of the leg with a pen, and then the subject stands on both feet. The rearfoot angle is measured using a goniometer to determine the angle between the calcaneus and the lower third of the leg. In the double-limb standing position with full weight bearing, the rearfoot angle is measured with a two-arm goniometer. This angle is formed by the bisecting line of the distal one-third of the leg and a longitudinal line bisecting the back of the calcaneus (60) (Fig. 22). In our study, an excessive valgus heel alignment is defined as a rearfoot angle of more than 5°.

Fig. 22. Eversion angle with the foot in subtalar neutral position.

Data Analysis

Statistical analyses were conducted using SPSS version 27.0, with the significance level set at $p \leq 0.05$. Baseline demographic characteristics were compared across groups using a one-way analysis of variance. Post-test outcomes were evaluated using multivariate analysis of covariance, adjusted for corresponding pre-test values. All assumptions for multivariate analysis of covariance were assessed and met, including normal distribution of residuals (Shapiro–Wilk test, $p > 0.05$), homogeneity of variances (Levene's test, $p > 0.05$), homogeneity of regression slopes, linearity between covariates and dependent variables, and equality of covariance matrices (Box's M test, $p > 0.05$). Effect sizes were calculated using partial eta-squared (ηp^2), and interpreted as small (0.01), medium (0.09), or large (0.14) (63). The minimal clinically important difference (MCID) was estimated using a distribution-based method, defined as 0.5 times the baseline standard deviation (SD), calculated as follows: MCID = SD × 0.5 (64).

Results

All 30 participants successfully completed the programs, and their data were included in the analysis. There were no dropouts or loss to follow up in any study group. Additionally, no adverse events occurred during or outside of the training sessions. Furthermore, no statistically significant differences were found in the baseline demographic characteristics and dependent variables among the groups (P > 0.05). The demographic and general characteristics of the subjects are detailed in Table 2.

Table 2. Demographic and General Characteristics of the Subjects (N=30)

Groups	N	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m²)
Comprehensive exercises with Foot orthoses	10	12.96±0.50	50.60±3.74	156.60±3.86	20.60±0.36
Foot orthoses	10	13±0.44	50.68±3.66	156.29±3.84	20.64±0.35
Control	10	12.93±0.54	50.39±4.57	156.19±4.40	20.62±0.35
P-value		0.957	0.989	0.973	0.971

A multivariate analysis of covariance (MANCOVA) was conducted to compare the intervention and control groups while controlling for pre-test scores. Before the main analysis, we assessed the assumptions of MANCOVA. The Shapiro–Wilk test confirmed that variables across all groups followed a normal distribution ($p > .05$). Levene's test indicated that variances were homogeneous across groups ($p > .05$). The assumption of homogeneity of regression slopes was also met, as the interaction between the covariate and the group variable was not significant ($p > .05$). Furthermore, a linear relationship was observed between the covariate and each dependent variable, confirming the linearity assumption. Box's M test showed no violation of the homogeneity of variance-covariance matrices ($p > .05$). Overall, the data met all the assumptions necessary for MANCOVA.

The MANCOVA analysis showed a statistically significant multivariate main effect for the intervention groups, with Wilks' $\Lambda = .000$, $F(14, 28) = 476.67$, $p < .001$, partial $\eta^2 = .996$. This indicates that the Comprehensive Exercises with foot orthoses group and the foot orthoses group produced significantly different effects of the dependent variables after controlling for the covariates. Subsequent univariate analyses demonstrated significant differences between the two intervention groups on all dependent variables. Detailed results of the MANCOVA comparing these groups are presented in Table 3.

Table 3. Univariate Tests Following MANCOVA

Source	Dependent Variable	Type III SS	df	MS	F	p	Partial η^2
Group	Navicular drop (post-test)	.981	2	.491	2024.725	.000	.995
	Medial longitudinal arch (post-test)	204.343	2	102.171	480.619	.000	.980
	Rearfoot eversion (post-test)	47.638	2	23.819	1762.717	.000	.994
	Knee varus (+) / valgus (−) (post-test)	249.804	2	124.902	4160.259	.000	.998
	Femur abduction/adduction (post-test)	113.573	2	56.787	3564.156	.000	.997
	Femur medial/lateral rotation (post-test)	188.477	2	94.239	3599.984	.000	.997
	Tibial medial/lateral rotation (post-test)	222.793	2	111.396	12148.875	.000	.999

Post hoc analyses revealed that the group undertaking Comprehensive exercises with foot orthoses experienced the most significant improvements across all variables, while the group using only foot orthoses exhibited slight, non-significant enhancements. The control group displayed no significant changes over the course of the study. Group disparities were highlighted by Bonferroni post hoc tests in Appendix Table 4.

Table 4. Results of Bonferroni Post-Hoc Tests for Pairwise Comparisons ns among Experimental Groups.

Variable	Comparison	Mean Difference (I–J)	SE	P value	95% CI Lower	95% CI Upper
Navicular drop	Comprehensive exercises with foot orthoses - Foot orthoses	-0.154	0.009	< .001	-0.177	-0.131
	Comprehensive exercises with foot orthoses - Control	-0.574	0.009	< .001	-0.598	-0.550
	Foot orthoses - Control	-0.420	0.009	< .001	-0.444	-0.396
Medial longitudinal arch	Comprehensive exercises with foot orthoses - Foot orthoses	1.903	0.258	< .001	1.228	2.577
	Comprehensive exercises with foot orthoses - Control	8.197	0.274	< .001	7.480	8.913
	Foot orthoses - Control	6.294	0.270	< .001	5.589	6.999
Rearfoot eversion	Comprehensive exercises with foot orthoses - Foot orthoses	-1.002	0.065	< .001	-1.172	-0.832
	Comprehensive exercises with foot orthoses - Control	-3.981	0.069	< .001	-4.162	-3.800
	Foot orthoses - Control	-2.979	0.068	< .001	-3.157	-2.802
Knee varus/valgus	Comprehensive exercises with foot orthoses - Foot orthoses	3.393	0.097	< .001	3.140	3.647
	Comprehensive exercises with foot orthoses - Control	9.339	0.103	< .001	9.070	9.609
	Foot orthoses - Control	5.946	0.101	< .001	5.681	6.211
Femur adduction / abduction	Comprehensive exercises with foot orthoses - Foot orthoses	-2.019	0.071	< .001	-2.204	-1.835
	Comprehensive exercises with foot orthoses - Control	-6.254	0.075	< .001	-6.451	-6.058
	Foot orthoses - Control	-4.235	0.074	< .001	-4.428	-4.042
Femur internal / external rotation	Comprehensive exercises with foot orthoses - Foot orthoses	-2.073	0.091	< .001	-2.310	-1.837
	Comprehensive exercises with foot orthoses - Control	-7.940	0.096	< .001	-8.191	-7.688
	Foot orthoses - Control	-5.867	0.095	< .001	-6.114	-5.619
Tibial internal / external rotation	Comprehensive exercises with foot orthoses- Foot orthoses	1.977	0.054	< .001	1.837	2.117
	Comprehensive exercises with foot orthoses - Control	8.556	0.057	< .001	8.407	8.705
	Foot orthoses - Control	6.579	0.056	< .001	6.433	6.725

Note. SE = Standard Error; CI = Confidence Interval.

The results of the MCID calculation indicate that the difference observed in the effect of the protocol on research variables surpasses the values required for the minimum clinical difference. In other words, the differences noted in the study are also clinically significant (see Table 5).

Table 5. The Results of the MCID

Variable	Minimum required changes calculated by the formula	The amount of observed changes
Navicular drop	0.0665	0.5670
Medial longitudinal arch	0.9307	7.4
Rearfoot Eversion	0.3799	3.84
Knee varus (+)/valgus (−) (degree)	0.5868	9.1480
Femur adduction (+)/ abduction (−) (degree)	0.4388	6.1130
Femur medial(+)/lateral rotation(−) (degree)	0.5479	7.8270
Tibial medial (+)/lateral rotation (−) (degree	0.4978	8.360

Discussion

This study investigates the effects of a six-week comprehensive exercise program combined with custom foot orthoses on foot alignment and DKV kinematics in adolescent males with flexible flatfoot. The primary finding was that the combined intervention resulted in significantly greater improvements in both static foot posture and dynamic lower extremity alignment compared to using foot orthoses alone.

Our findings support previous research that demonstrates the effectiveness of both exercise and orthotic interventions in improving measures of static foot alignment, such as navicular drop, medial longitudinal arch angle, and rearfoot eversion (20, 26, 27, 41). The observed advantage of the combined approach can be attributed to the synergistic interaction between active neuromuscular training and passive mechanical support. The comprehensive exercise regimen, with a particular focus on incorporating short foot exercises, likely improved the activation and endurance of the intrinsic foot muscles (e.g., abductor hallucis, flexor digitorum brevis). These muscles play a critical role in stabilizing the medial longitudinal arch during weight-bearing activities (41). At the same time, the customized foot orthoses provided immediate biomechanical correction by supporting the arch and reducing excessive subtalar pronation, thus relieving strain on the muscular structures and promoting a more neutral foot position (29, 31). This combination seems to create a conducive environment where passive support encourages optimal alignment, while active exercises develop the neuromuscular capacity to sustain this alignment dynamically.

A key and innovative contribution of this study is its demonstration of significant improvements in DKV kinematics. Although the association between flexible flatfoot and increased DKV has been established in previous studies (14, 15), few have assessed the effectiveness of interventions on this specific parameter. Our findings indicate that the combined intervention not only enhanced foot alignment but also led to considerable positive changes in knee varus/valgus, femoral adduction/abduction, and tibial rotation, with large effect sizes ($0.14 < \eta 2$). This implies that addressing the foot deformity has a profound impact upstream on the entire kinetic chain.

The reasons for this improvement likely go beyond just the foot. The comprehensive exercise routine involved strengthening the gluteal muscles, focusing on the hip abductors and external rotators. Weakness in these muscles is a known factor in dynamic knee valgus (52, 64-67), as it can lead to excessive femoral adduction and internal rotation when performing daily activities (15). By strengthening these core stabilizers, our treatment likely aided in controlling hip and pelvic movements, thereby reducing the compensatory shift towards knee valgus. This holistic approach to correcting issues in both the distal (foot) and proximal (hip) parts of the body's kinetic chain offers a strong rationale for the better results seen in the combined group.

Impaired movement patterns have been linked to functional reorganization within the cerebral cortex (68). Consequently, re-establishing appropriate muscle activation can be achieved by applying neuromuscular training and motor learning principles, including movement education and varied forms of feedback, which help restore optimal muscle recruitment strategies (47, 69). Several studies have also demonstrated that incorporating feedback and movement instruction within an intervention can affect lower limb kinematics (70, 71). Therefore, accurate execution of exercises throughout all phases along with providing diverse types of feedback and movement education may explain the observed improvements in participants' movement patterns (72), and subsequently in lower extremity kinematics and muscle strength.

The practical implications of these discoveries are significant. Since excessive dynamic knee valgus (DKV) is a known risk factor for conditions like patellofemoral pain syndrome and noncontact anterior cruciate ligament (ACL) injuries (17, 18), an intervention that effectively addresses DKV in individuals with flexible flatfoot can have a meaningful impact on prevention and rehabilitation. Clinicians should thus consider going beyond a singular approach and embrace a multi-faceted strategy that combines tailored foot orthoses for immediate biomechanical aid with a gradual exercise program focusing on both intrinsic foot muscles and proximal hip stabilizers.

Finally, the results of the MCID calculation indicated that the amount of difference observed in the effect of Comprehensive exercises with foot orthoses protocol on research variables was higher than the values required for the minimum clinical difference. In other words, the observed changes were not only statistically, but also clinically significant after applying the Comprehensive exercises with foot orthoses protocol which verifies the effectiveness of this program in the present study.

Our study has several limitations. Firstly, the exclusive inclusion of adolescent males restricts the generalizability of our findings to females and other age groups. Future studies should aim to include a more diverse population. Secondly, the lack of long-term follow-up prevents us from determining the durability of the observed improvements. Research with extended follow-up periods is necessary to assess the long-term efficacy and potential for lasting neuromuscular adaptation. Lastly, investigating the effects of this combined protocol on functional performance measures and actual injury incidence would be a valuable next step.

Conclusion

In conclusion, a six-week intervention that combines a comprehensive exercise program with custom foot orthoses leads to significantly greater improvements in foot alignment and DKV kinematics compared to using orthotics alone for individuals with flexible flatfoot. This study highlights the significance of a multidimensional, kinetic chain-based approach in managing flexible flatfoot, addressing both the static deformity and its dynamic consequences. We recommend this combined protocol as an effective strategy for clinicians seeking to enhance lower limb biomechanics and potentially reduce injury risk in this population.

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Ethical consideration

Ethical considerations in terms of honesty and integrity in texts and sources have been observed.

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Conflict of interest

None

Authors' contributions

All authors contributed equally to the preparation of this article.

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