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Combined Core Stability and Short Foot Exercises Improve Medial Longitudinal Arch and Dynamic Balance More Than Short Foot Exercises Alone in Female Child Badminton Players with Pes Planus: A Randomized Controlled Trial

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Abstract

Background: Badminton involves rapid, multidirectional movements and unilateral landings that impose substantial mechanical stress on the foot–ankle complex. Athletes with pes planus are at an increased risk of instability and injury due to altered kinetic chain function. While short foot exercises (SFE) enhance medial longitudinal arch (MLA) integrity in individuals with flat feet, core stability training (CST) is increasingly incorporated into sports rehabilitation programs. However, the effects of CST on pes planus remain insufficiently explored. This study investigates the combined effects of CST and SFE on MLA integrity and dynamic balance in semi-professional female badminton players with pes planus.

Methods: In this randomized controlled trial, 30 female badminton players aged 9–12 years with mild to moderate pes planus (Staheli Arch Index [SAI]: 0.70–1.15) were randomly allocated to either a combined training group (CST + SFE) or a control group (SFE only). Following attrition, 24 participants (12 per group) completed the study and were included in the final analysis. Both groups trained three times per week for eight weeks under professional supervision. MLA function and dynamic balance were assessed using the Staheli Arch Index (SAI) and the Star Excursion Balance Test (SEBT), respectively. Between-group differences were analyzed using analysis of covariance (ANCOVA), with baseline values included as covariates.

Results: Both groups improved post-intervention, with the experimental group (SFE+CST) showing significantly greater enhancements than the control (SFE) in both foot arch structure (SAI decreased by 14% vs. 7.0%) and dynamic balance (SEBT composite increased by 5.22% vs. 1.86%). ANCOVA revealed a significant main effect for group on post-intervention SAI ($F(1,21)=611.74$, $P<0.001$, $\eta 2=0.97$, mean difference = 0.07) and SEBT composite score ($F(1,21)=3695.82$, $P<0.001$, $\eta 2=0.99$, mean difference = 3.36). Despite a violation of the homogeneity of regression slopes for SAI, pairwise comparisons confirmed the superior efficacy of the combined training over short foot exercises alone.

Conclusion: An eight-week combined CST and SFE program significantly improved MLA height and dynamic balance compared to SFE alone. It is recommended to integrate proximal (core) and distal (foot) exercises to enhance postural control, support the correction of pes planus, and enhance athletic performance in young badminton players.

Keywords: Core Stability, Short Foot Exercise, Pes Planus, Medial Longitudinal Arch, Dynamic Balance, Badminton

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Key Messages:

↑What is "already known" in this topic:

Pes planus is prevalent in children and may impair the structure of the medial longitudinal arch (MLA) and balance. Short foot exercises (SFE) improve intrinsic foot muscle function and arch integrity. Core stability training (CST) enhances proximal control; however, its effect on the foot arch remains unclear.

→What this article adds:

Combining CST with SFE results in greater improvements in MLA height and dynamic balance compared to SFE alone in young athletes with pes planus. A combined proximal–distal exercise approach may enhance postural control and support injury prevention in this population.

Introduction

Badminton is a globally popular, high-intensity racquet sport with over 200 million participants worldwide (1). Its dynamic movements—including lunging, braking, rapid directional changes, and frequent single-leg landings—demand high levels of postural control and neuromuscular coordination (1, 2). However, the repetitive and asymmetrical loading inherent to these actions places substantial mechanical stress on the foot–ankle complex, which may exacerbate altered kinetic chain function in individuals predisposed to structural deviations, thereby increasing the risk of injury in athletes with pes planus (flat feet), which affects approximately 25% of children and adolescents, according to recent meta-analytic evidence (3). A reduced medial longitudinal arch (MLA) compromises shock absorption, alters lower-limb kinematics, and impairs balance, thereby increasing the risk of overuse injuries in athletes (4).

The MLA is primarily supported by the intrinsic foot muscles, which regulate arch height and contribute to both static and dynamic postural stability. Weakness or delayed activation of these muscles can lead to excessive pronation, reduced proprioceptive feedback, and impaired dynamic balance (5). Consequently, strengthening the intrinsic foot muscles has become a central component of both preventive and corrective training programs. The Short Foot Exercise (SFE) is recognized as one of the most effective and evidence-based approaches to enhancing intrinsic foot muscle activation, restoring MLA height, and improving balance performance (6).

In addition to local foot strengthening, numerous studies have demonstrated that Core Stability Training (CST) effectively improves spinal alignment, reduces musculoskeletal pain, and corrects postural deviations by enhancing neuromuscular control and segmental stability across the kinetic chain (7, 8). CST plays a critical role in maintaining optimal neuromuscular control and providing proximal stability for efficient force transmission throughout the kinetic chain (9). However, despite its well-documented effects on proximal postural alignment and lower-limb control, its potential to influence distal structures—particularly the MLA—remains insufficiently investigated and poorly established (7, 10).

Given the biomechanical and neuromuscular interdependence between the lumbopelvic region and the foot, it is plausible that enhancing proximal stability could improve distal alignment and load distribution through kinetic chain mechanisms (10). Therefore, integrating CST with SFE may yield synergistic adaptations by simultaneously enhancing both proximal and distal stability (9). This integration may provide a more comprehensive corrective strategy for young athletes with pes planus by improving local (foot) and global (core) components of postural control. Such a combined approach could facilitate more efficient load distribution and kinetic chain function, reinforce the MLA, and enhance dynamic balance—fundamental determinants of both performance and injury resilience in badminton athletes (9, 10).

Despite the theoretical rationale, empirical evidence remains limited (6, 10). Notably, no randomized controlled trial (RCT) has directly compared the combined CST + SFE approach with SFE alone in a pediatric athletic population. To date, no RCT has investigated whether the combination of CST and SFE produces superior effects on both MLA morphology and dynamic balance in badminton players with pes planus.

The present study aimed to investigate the effects of an eight-week combined CST and SFE program on the MLA and dynamic balance in semi-professional female badminton players with pes planus. It was hypothesized that the combined training program would yield greater improvements in both MLA height and dynamic balance compared to SFE alone, thereby supporting the integration of proximal and distal stabilization strategies in this population.

Methods

Study Design

This study was designed as a randomized controlled trial (RCT) with a pretest–posttest design and a control group. The reporting of this RCT was conducted in accordance with the Consolidated Standards of Reporting Trials (CONSORT) guidelines. The research protocol received approval from the Ethics Committee of the Faculty of Sport Sciences and Health at the University of Tehran (IR.UT.SPORT.REC.1404.073) and was registered in the Iranian Registry of Clinical Trials (IRCT20180727040609N5, registered on July 8, 2025) (11). Participant enrolment was conducted between July 6 and July 23, 2025. All participants and their legal guardians provided written informed consent prior to participation. To minimize measurement bias, all outcome assessments (SAI and SEBT) were conducted by trained assessors who were blinded to group allocation and had no involvement in the intervention sessions. The study adhered to the principles outlined in the Declaration of Helsinki.

Participants

A total of 30 semi-professional female badminton players aged 9–12 years were initially recruited from regional badminton training centers in Kish Island, Iran, using purposive sampling. Following eligibility screening, participants were randomly allocated into two groups of 15 individuals each: a combined exercise group (SFE + CST) and a control group (SFE only). During the intervention period, three participants from each group were lost to follow-up due to scheduling conflicts and an inability to attend training sessions consistently. No withdrawals were associated with adverse events or complications related to the intervention. Consequently, 12 participants remained in each group and were included in the final analysis (Figure 1).

Randomization was performed using a block randomization method with a block size of four to ensure equal distribution across groups. A research assistant, who was not involved in the assessments or interventions, generat-

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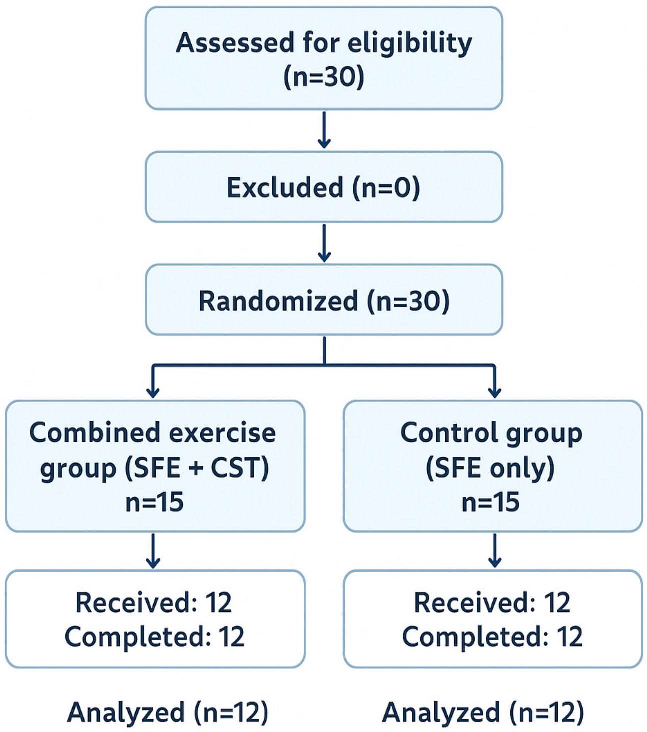

Figure 1. Flowchart of participant progression in the randomized controlled trial (RCT).

ed the randomization sequence using a computer-based random number generator. Allocation concealment was maintained through the use of sealed, opaque envelopes. A priori power analysis (G*Power 3.1) indicated that a total of 24 participants (12 per group) would achieve 80% power to detect a medium effect size ($f = 0.25$) at $\alpha = 0.05$ (12).

Inclusion and Exclusion Criteria

Participants were included if they met the following criteria: (a) female badminton players aged 9–12 years; (b) participation in semi-professional badminton training for a minimum of two years, with regular involvement in regional or national competitions; (c) a diagnosis of mild to moderate pes planus, defined by a Staheli Arch Index ranging from 0.7 to 1.15; (d) absence of pain or injury in the lower limbs, spine, or pelvis within the preceding six months; (e) no history of orthopedic, neurological, or vestibular disorders affecting gait or balance; and (f) willingness to complete the eight-week intervention and all pre- and post-intervention assessments.

The exclusion criteria were as follows: (a) non-adherence to more than two consecutive training sessions; (b) failure to complete either pre- or post-test assessments; (c) occurrence of any musculoskeletal pain, fatigue, or injury during the intervention period; (d) participation in other structured exercise programs targeting the lower limbs or core muscles during the study period; and (e) withdrawal of consent at any stage of the study.

Intervention Protocol

Both groups engaged in supervised exercise sessions three times per week for eight consecutive weeks, with each session lasting approximately 40 minutes. All sessions were conducted by a certified corrective exercise specialist.

Short Foot Exercise (SFE)

The SFE protocol (adapted from Zarali et al., 2015; Jung et al., 2011) (13, 14) consisted of five exercises targeting the intrinsic foot muscles and medial longitudinal arch (MLA) control: (a) standing arch depression, (b) towel roll, (c) toe extension excluding the hallux, (d) full toe extension, and (e) single-leg arch depression (Figure 2). Each exercise was performed in three sets of 10 repetitions, with 10-second contractions and 20-second rest intervals. Training intensity was monitored using a child-adapted RPE scale (6–8/10) (15). Progression followed a sequence from standing to unilateral to dynamic exercises over eight weeks.

Core Stability Training (CST)

The CST protocol (adapted from Akuthota et al., 2004; Hibbs et al., 2008) (16, 17) targeted deep lumbopelvic stabilizers, including the transversus abdominis, multifidus, pelvic floor, and diaphragm. The exercises included: (a) front plank, (b) superman, (c) glute bridge, (d) side plank, (e) crunches, and (f) prone hip extension (Figure 3). Each session lasted approximately 20 minutes and was conducted three times per week. Intensity was progres-

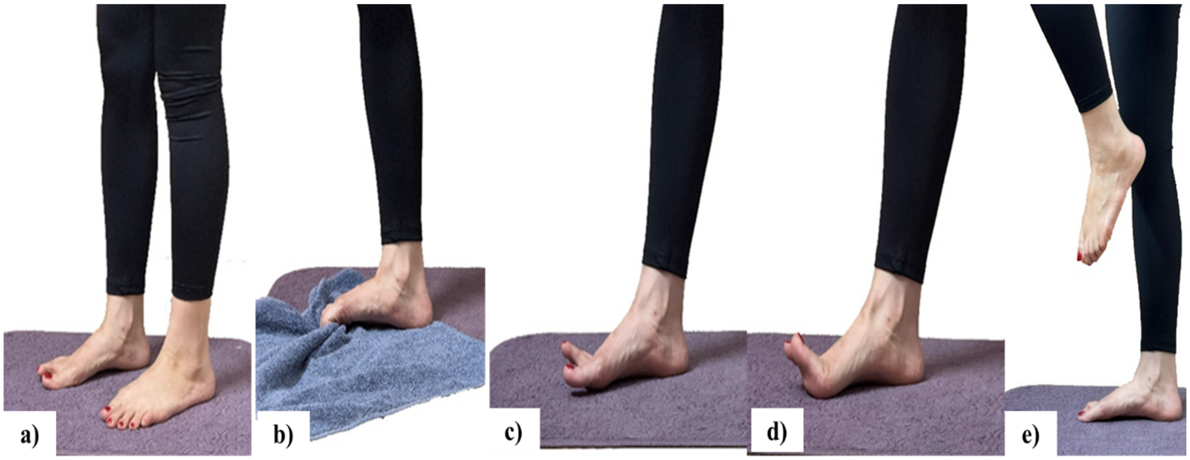

Figure 2. a) Standing arch depression; b) Towel roll; c) Toe extension (excluding the thumb); d) Toe extension; and e) Single-leg arch depression.

Figure 3. a) front plank, b) superman, c) glute bridge, d) side plank, e) crunches, and f) prone hip extension.

sively increased bi-weekly by modifying leverage, base of support, and contraction duration (from 10 to 20 seconds), and was monitored using the RPE scale (6–8/10) (15, 18). The combined group completed both CST and SFE during each session, while the control group performed SFE only.

Outcome Measures

1. Medial Longitudinal Arch (MLA)

Staheli's Arch Index was evaluated using footprint analysis, a straightforward, low-cost, and objective method for examining foot arch structure (19). This approach is recognized as both reliable and valid, rendering it suitable for flatfoot screening. Following the protocol described by Hernandez et al. (20), bilateral footprints were obtained. To determine the maximum midfoot width, a perpendicular line was drawn from the midpoint of a line connecting the medial borders of the heel and metatarsal areas. The maximum heel width was measured using a separate perpendicular line. The Staheli's Arch Index was calculated by dividing the midfoot width by the heel width, with a value exceeding 1.15 indicating flatfoot. A decrease in SAI values was interpreted as an improvement in MLA height.

2. Dynamic Balance

Dynamic balance was evaluated using the Star Excursion Balance Test (SEBT) in the anterior, posteromedial, and posterolateral directions, following the protocol described by Imai et al. (21). Participants stood barefoot on their dominant leg, reaching with the opposite leg along each line while maintaining balance and keeping their hands on the iliac crest. After six practice trials and a brief rest, three test trials were conducted for each direction in randomized order. The longest reach distance in each direction was normalized to leg length (measured from the anterior superior iliac spine to the medial malleolus) and used to calculate a composite score, which was derived from the sum of the three directions divided by three times the leg length, multiplied by 100.

Statistical Analysis

All analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Data normality was confirmed using the Shapiro–Wilk test, and homogeneity of variances was verified using Levene's test. Baseline differences between groups were examined using one-way analysis of variance (ANOVA). Post-intervention differ-

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ences between groups were analyzed using ANCOVA, controlling pre-test scores. Effect sizes were reported as partial eta squared (η^2), classified as small (0.01), medium (0.06), and large ($\geq$0.14). The level of statistical significance was set at $p < 0.05$. Data were analyzed using a per-protocol approach, including only participants who completed the intervention and both pre- and post-intervention assessments. No imputation was performed for missing data. The homogeneity of regression slopes assumption was evaluated for all ANCOVA models.

Results

Descriptive Statistics

Twenty-four semi-professional female badminton players aged 9–12 years participated in the study and were included in the final analysis. Participants were randomly allocated to either a combined exercise group (SFE + CST, n = 12) or a control group (SFE only, n = 12). Baseline demographic variables (age, height, weight, and BMI) were analyzed using one-way analysis of variance (ANOVA), revealing no significant between-group differences at baseline. These findings indicate that the control and experimental groups were comparable prior to the intervention (all P>0.05; Table 1).

Primary Outcomes

Descriptive statistics for medial longitudinal arch height (Staheli Arch Index; SAI) and dynamic balance (SEBT composite score) are presented in Table 2. Both groups showed improvements following the intervention, with more pronounced changes observed in the combined training group. In the control group, SAI decreased from 1.00 ± 0.06 to 0.93 ± 0.05, indicating an improvement in medial longitudinal arch structure, while SEBT composite scores increased from 65.16 ± 1.40 to 67.02 ± 1.44. In the experimental group, SAI decreased from 1.01 ± 0.04 to 0.87 ± 0.04, accompanied by an increase in SEBT composite scores from 65.30 ± 1.07 to 70.52 ± 1.07.

Figure 4 illustrates the percentage improvement in SAI and dynamic balance following the intervention in both groups. The experimental group demonstrated greater improvements than the control group, achieving a 14.0% improvement in foot arch index and an 5.22% improvement in dynamic balance, compared to 7.0% and 1.86%, respectively, in the control group.

Inferential Statistics

Following attrition, baseline characteristics remained comparable between groups (P>0.05). Data normality was verified using the Shapiro–Wilk test (P>0.05). The assumptions of ANCOVA were examined prior to the analysis. Levene's test confirmed the homogeneity of variances for SAI (F=0.20, P=0.655) and dynamic balance (F=0.84, P=0.367). The homogeneity of regression slopes assumption was tested by examining the interaction between group and pre-test scores. For dynamic balance, the interaction was not significant ($F(1,20)=0.20$, P=0.654), indicating that this assumption was satisfied. However, for

Table 1. Baseline demographic characteristics of participants

Variable	Group	Mean ± SD	Min	Max
Age (years)	Control	10.75 ± 1.05	9.00	12.00
	Experimental	10.58 ± 1.04	9.00	12.00
Height (cm)	Control	140.84 ± 3.67	135.0	147.0
	Experimental	142.17 ± 3.08	138.0	147.0
Weight (kg)	Control	35.13 ± 2.66	30.8	39.1
	Experimental	35.09 ± 2.55	30.9	39.2
BMI (kg/m²)	Control	17.70 ± 1.02	15.91	19.52
	Experimental	17.34 ± 0.60	16.25	18.39

Abbreviations: BMI, Body Mass Index; SD, Standard Deviation; Min, Minimum; Max, Maximum

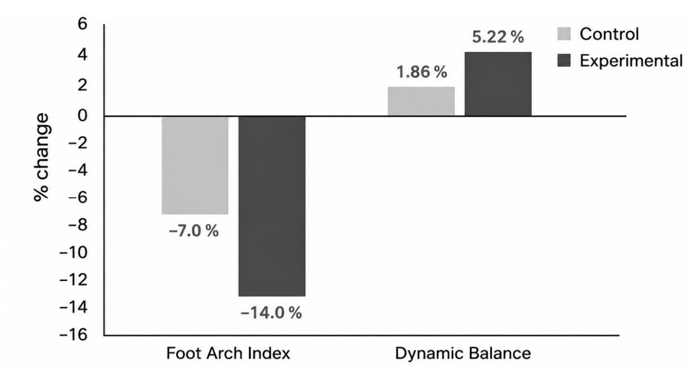

Figure 4. Changes in the foot arch index (Staheli Arch Index; SAI) and dynamic balance (Star Excursion Balance Test; SEBT composite score) from pre- to post-intervention in the control (SFE only) and experimental (SFE + CST) groups are presented. Values are expressed as mean ± standard deviation (SD). The percentage change (%) reflects the relative change from baseline (pre-test to post-test values). A decrease in SAI indicates an improvement in medial longitudinal arch height, while an increase in the SEBT composite score signifies improved dynamic balance performance.

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Table 2. Pre- and post-intervention values of medial longitudinal arch height (SAI) and dynamic balance (SEBT composite score) in the control (SFE) and experimental (SFE + CST) groups.

Variable	Group	Pre-test Mean ± SD	Post-test Mean ± SD	Estimated Post Mean (95% CI)	% Absolute Change	Between-group Mean Difference (95% CI)	F (ANCOVA)	*P*-value	partial η²
Foot Arch Index (SAI)	Control	1.00±0.06	0.93±0.05	0.931 (0.927–0.934)	- 7.0%		611.74	<0.001	0.97
	Experimental	1.01±0.04	0.87±0.04	0.864 (0.861–0.868)	- 14.0%	0.066 (0.061–0.072)			
Dynamic Balance (SEB_	Control	65.16±1.40	67.02±1.44	67.088 (67.007–67.169)	+1.86%		3695.82	<0.001	0.99
	Experimental	65.30±1.07	70.52±1.07	70.445 (70.364–70.526)	+5.22%	3.357 (3.242–3.472)			

Abbreviations: SAI, Staheli Arch Index; SEBT, Star Excursion Balance Test; SD, Standard Deviation; partial η², partial eta squared.

SAI, the interaction between group and baseline values was significant ($F(1,20)=12.64$, $P=0.002$), indicating a violation of the homogeneity of regression slopes assumption. Therefore, the ANCOVA model for SAI was interpreted with consideration of this interaction effect, and the results were reported with caution.

Foot Arch Index (SAI)

The results of the ANCOVA revealed a significant effect of the pre-test SAI as a covariate (F1,21=945.43, $P<0.001$, $\eta 2 = 0.98$). After adjusting for baseline differences, a significant main effect was observed for the study groups (F1,21=611.74, $P<0.001$, partial $\eta 2=0.97$), indicating a substantial difference in post-intervention SAI between the two groups. The very large effect sizes reflect the combination of low within-group variability and strong covariate adjustment in a tightly controlled sample. Pairwise comparisons with Bonferroni adjustment showed that the mean difference between groups was 0.07 ($P<0.001$, 95% CI: 0.06 to 0.07). These findings suggest that the combined intervention was more effective in reducing the SAI—reflecting an improvement in the medial longitudinal arch—compared to short foot exercises alone. Given the violation of the homogeneity of regression slopes assumption for SAI, the subsequent ANCOVA results should be interpreted with caution (Table 2; Figure 4).

Dynamic Balance (SEBT Composite Score)

The ANCOVA demonstrated that the overall model was statistically significant for post-intervention dynamic balance ($F(2,21)=2974.24$, $P<0.001$), with a very large effect size (partial $\eta^2=0.996$). The covariate, pre-intervention balance, was identified as a significant predictor of post-intervention balance ($F(1,21)=2252.66$, $P<0.001$, partial $\eta^2 = 0.99$). After adjusting for baseline balance, a significant between-group difference was observed ($F(1,21)=3695.82$, $P<0.001$, partial $\eta^2=0.99$). The very large effect sizes reflect the combination of low within-group variability and strong covariate adjustment in a tightly controlled sample. Bonferroni-adjusted pairwise comparisons indicated that the Experimental group achieved significantly higher post-intervention balance scores compared to the Control group (mean difference = 3.36, 95% CI: 3.24 to 3.47, $P<0.001$).

Discussion

The present study demonstrates that an eight-week combined core stability training (CST) and short foot exercise (SFE) program significantly enhances medial longitudinal arch (MLA) height and dynamic balance in young female badminton players with pes planus, compared to SFE alone. These results indicate that integrating proximal (core) and distal (foot) stabilization exercises elicits superior neuromuscular and biomechanical adaptations compared to isolated intrinsic foot training. Specifically, the experimental group exhibited a 14.0% decrease in foot arch index (SAI) and a 5.22% improvement in SEBT composite scores, surpassing the 7.0% and 1.86% gains observed in the control group. This demonstrates a statistically significant improvement in both structural and functional outcomes. The substantial reduction in SAI in the experimental group indicates an improvement in medial longitudinal arch structure and supports the notion that enhancing core stability may indirectly influence distal structures through improved kinetic chain function. CST is suggested to improve trunk stiffness and anticipatory postural adjustments, which may contribute to more efficient force transmission from the proximal segments to the foot–ankle complex, thereby potentially reducing compensatory loading patterns.

Previous studies have confirmed the critical role of intrinsic foot muscles in maintaining medial longitudinal arch (MLA) height. Karpińska et al. (2018) emphasized that the Short Foot Exercise (SFE) activates intrinsic plantar muscles responsible for proper arch formation and improves proprioception, positively affecting foot morphology (22). Unver et al. (2019) reported that six weeks of SFE significantly reduced navicular drop, improved foot posture, decreased pain and disability, and increased medial midfoot plantar forces (23). Similarly, Iram et al. (2025) demonstrated that SFE reduced pain and improved foot posture in adults with flexible pes planus, highlighting the importance of intrinsic muscle training for MLA stability (24). Okamura et al. (2020) found that eight weeks of SFE improved static foot alignment and shortened the time for navicular height to reach its minimum during gait, suggesting enhanced windlass mechanism function (25). Collectively, these studies confirm that SFE effectively restores MLA height, and the current findings

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indicate that these effects are substantially amplified when combined with proximal core stabilization.

Consistent with these findings, Zarali et al. (2024) reported that the integration of isometric hip abduction with SFE led to greater reductions in navicular drop, improved static foot parameters, and decreased postural sway compared to SFE alone or combined strengthening and balance exercises (13). This underscores the significance of proximal hip and trunk stabilization in modulating distal foot mechanics, which aligns with the superior improvements observed in the CST + SFE group.

Moreno-Barriga et al. (2023) demonstrated a positive correlation between internal oblique activity and dynamic postural control across various medial foot arch types, thereby supporting the rationale for combining CST with SFE (26). Enhanced recruitment of proximal muscles may facilitate control of distal joints, providing a plausible explanation for the superior postural stability observed in the experimental group.

Soni et al. (2025) and Karadeniz & Develi (2025) further support the additive effects of combining proximal and distal interventions. Soni et al. reported improvements in medial arch height and foot function, with core training demonstrating slightly superior functional outcomes (27). In contrast, Karadeniz & Develi found that foot core exercises combined with arch-supported insoles enhanced balance, navicular drop, and vertical jump performance more than insoles alone (28). Matias et al. (2016) also highlighted the effectiveness of foot–ankle exercise protocols in improving intrinsic foot muscle strength and lower-limb biomechanics (29). The present study extends this evidence by demonstrating that coupling these exercises with CST further enhances dynamic stability and functional performance.

Dynamic balance, assessed via the SEBT, improved more significantly in the combined training group compared to the control group. This improvement may be attributed to enhanced neuromuscular coordination, improved proprioceptive integration, and more efficient feedforward activation patterns resulting from CST. Prior studies confirm that CST enhances postural control, sensorimotor integration, and lower-limb coordination (7, 8, 16, 17). When combined with intrinsic foot muscle activation, these adaptations likely enable athletes to maintain balance more effectively during dynamic, sport-specific tasks.

However, these mechanisms should be regarded as plausible explanations rather than definitive physiological mechanisms, as trunk stiffness, kinetic-chain alignment, and neuromuscular adaptations were not directly measured in the present study. Consequently, any interpretations regarding these factors should be considered theoretical and hypothesis-driven rather than confirmed mechanisms.

Although improvements in SEBT performance have been previously associated with enhanced dynamic stability and reduced injury risk—supporting the practical relevance of the observed changes—the interpretation of clinical meaningfulness should be approached with caution. Currently, there are no established minimal clinically important difference (MCID) values for the Staheli Arch Index (SAI) or the Star Excursion Balance Test (SEBT), particularly in pediatric athletic populations. Consequently, defining a precise threshold for clinically meaningful change is challenging. Nevertheless, the magnitude of improvements observed in both structural (MLA) and functional (dynamic balance) outcomes, along with the significant between-group differences, suggests that the intervention may hold practical relevance. However, these interpretations should be regarded as exploratory and based on statistical significance and effect magnitude rather than confirmed clinical meaningfulness. Future studies are necessary to establish MCID values for these measures to facilitate a better interpretation of clinical significance.

From a practical standpoint, integrating CST with SFE offers a comprehensive, cost-effective, and feasible intervention for youth athletes with pes planus. While SFE alone enhances intrinsic foot muscle function and MLA height, the addition of CST optimizes proximal control, thereby improving postural stability, functional performance, and potentially reducing the risk of lower-limb injuries.

The findings of this study should be interpreted within the context of the specific population examined. Limitations of this study include a small sample size restricted to female semi-professional badminton players aged 9–12 years, which limits generalizability, despite being supported by a priori power analysis. Furthermore, the inclusion of only female semi-professional badminton players aged 9–12 years from a single geographic region restricts the external validity of the results. Therefore, these findings may not be directly applicable to males, non-athletes, individuals from other age groups, or broader pediatric clinical populations with varying activity levels or underlying conditions. However, this homogeneity was intentionally maintained to reduce variability related to growth, maturation, and sport-specific training. The relatively large effect sizes observed in this homogeneous sample should be interpreted with caution and validated in larger, more heterogeneous populations. Future studies should include larger and more diverse populations to determine the extent to which these results can be generalized. The intervention duration was eight weeks, and the long-term retention of adaptations remains unknown. Additionally, differences in sex, maturation status, and training background may influence neuromuscular adaptations to both proximal and distal interventions. Future studies should include longer follow-ups, male athletes, participants from different sports, and objective measures such as electromyography or imaging to further elucidate neuromuscular and morphological adaptations (30). The use of a per-protocol analysis and the presence of a 20% attrition rate may introduce potential attrition bias. Although baseline comparability was maintained after participant loss and dropouts were unrelated to the intervention, the findings should be interpreted with caution. Future studies are encouraged to apply intention-to-treat analyses to further strengthen the robustness of the results.

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Despite these limitations, the randomized controlled design enhances internal validity, while the simple, low-cost, functional exercise protocols provide practical relevance for coaches, clinicians, and rehabilitation professionals. A methodological strength of this study is the implementation of assessor blinding, which reduces the risk of measurement bias in outcomes that involve examiner judgment, such as footprint analysis and SEBT. The present study included a relatively small sample of female semi-professional badminton players aged 9–12 years from a single geographical region, which limits the generalizability of the findings. Therefore, the results should be interpreted as preliminary and specific to this population, and future multicenter trials with larger and more diverse samples are warranted.

Conclusion

An eight-week combined CST + SFE program significantly improved MLA height and dynamic balance when compared to SFE alone. The greater reductions in SAI (indicating enhanced arch structure) and SEBT scores suggest superior structural and functional adaptations resulting from integrated proximal and distal stabilization training. These findings support the implementation of combined CST and SFE in young female badminton players with pes planus.

Acknowledgment

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Conflict of Interests

The authors declare that they have no competing interests.

Authors' Contributions

A.K. and S.Z. made substantial contributions to the conception and design of the study. B.S.R., a M.Sc. graduate student, was responsible for data acquisition, analysis, and interpretation. A.K. and B.S.R. drafted the manuscript. S.Z. supervised the study, critically revised the manuscript, and served as the corresponding author. All authors have read and approved the final manuscript and contributed equally to its preparation.

Ethical Considerations

This study was approved by the Ethics Committee of the Faculty of Sport Sciences and Health, University of Tehran (IR.UT.SPORT.REC.1404.073). Written informed consent was obtained from all participants and their legal guardians. The study adhered to the principles of the Declaration of Helsinki.

Trial Registration:

Iranian Registry of Clinical Trials (IRCT), IRCT20180727040609N5, registered on 8 July 2025 (https://irct.behdasht.gov.ir/search/result?query=IRCT20180727040609N5).

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Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

AI Use Statement

The authors confirm that this manuscript does not contain any AI-generated content. All sections of the manuscript were written and prepared solely by the authors, and the work represents original research.

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