scientific reports

OPEN

Differential effects of intrinsic-versus extrinsic-first corrective exercise programs on morphometric outcomes and navicular drop in pediatric flatfoot

Jafar Ketabchi[1], Foad Seidi[1✉], Shila Haghighat[2], Sue Falsone[3], Yousef Moghadas-Tabrizi[1] & Fatemeh Khoshroo[1]

Although the connection between muscular strength and flatfoot condition is well-established, the impact of corrective exercises on these muscles remains inadequately explored. This study aimed to assess the impact of intrinsic- versus extrinsic-first corrective exercise programs on muscle morphometry and navicular drop in boys with flexible flatfoot. Twenty-five boys aged 10–12 with flexible flatfoot participated, undergoing a 12-week corrective exercise program, with a shift in focus at six weeks. Ultrasound imaging measured muscle thickness and cross-sectional area (CSA), and the navicular drop test assessed flatfoot severity. The results demonstrated a significant interaction between exercise type and sequencing on muscle morphometry. Initiating with intrinsic exercises led to sustained improvement, even after transitioning to extrinsic exercises, while extrinsic-first exercises caused deterioration in intrinsic muscle morphometry, which was recovered after transitioning to intrinsic exercises. Statistical analysis revealed significant improvements in muscle thickness and CSA over time, particularly when initiating intrinsic exercises first. The intrinsic-first group also exhibited a more pronounced reduction in navicular drop. In conclusion, initiating corrective exercises with intrinsic muscles proved more effective in improving foot muscle morphometry and reducing navicular drop in boys with flatfoot. Therefore, commencing correction with intrinsic muscle exercises is recommended before progressing to extrinsic muscle exercises.

Flatfoot is a common pediatric foot abnormality[1] characterized by a reduced medial longitudinal arch (MLA), and a consequential navicular drop[2]. It also involves various complex morphological changes such as adduction and valgus of calcaneus, forefoot abduction, excessive pronation of the forefoot, subluxation of the talonavicular joint, adduction and plantar-ward movement of the talus, and abduction and dorsiflexion of the first metatarsal[3,4]. Flatfoot, whether symptomatic or asymptomatic, can have significant implications for individuals. Although asymptomatic flatfoot does not typically cause pain or discomfort, it can still affect foot alignment and overall quality of life. Research indicates that asymptomatic flatfoot may be a precursor to Progressive Collapsing Foot Deformity, suggesting it could serve as a risk factor for future foot-related issues[5]. Furthermore, studies have shown that children with asymptomatic flexible flatfoot report lower quality of life scores compared to their peers with normal foot structure, underscoring the condition's potential impact on well-being[6]. This highlights the importance of monitoring asymptomatic flatfoot, as it may not only influence current foot health but also predispose individuals to more serious complications in the future.

Various ligaments and fascia support the MLA, muscles also play an indispensable role in the maintenance of the MLA[7]. The intrinsic muscles such as the abductor hallucis (ABH) and flexor digitorum brevis (FDB), are anatomically situated with both origins and insertions in close proximity to the foot bones[8]. Conversely, the

[1]Health and Sports Medicine Department, Faculty of Sports Sciences and Health, University of Tehran, North Karegar St, P.O.B: 1439813117, Tehran, Iran. [2]Department of Physical Medicine and Rehabilitation, Isfahan University of Medical Sciences, Isfahan, Iran. [3]School of Osteopathic Medicine, A.T. Still University, Arizona, USA. ✉email: foadseidi@ut.ac.ir

extrinsic muscles—tibialis anterior (TA), tibialis posterior (TP), and flexor digitorum longus (FDL) provide vital reinforcement to the MLA[9]. Their leverage positions these muscles as dynamic mobilizers, crucial for the generation of propulsive forces during locomotion[10]. The nuanced collaborative mechanics of these muscle groups are integral to the sustainment of the MLA, thus highlighting the clinical pertinence of assessing their morphometry, namely thickness and CSA, as potential reflective markers for foot disorders such as flat foot[11,12].

Disparities in the CSA of intrinsic and extrinsic foot muscles among populations with healthy versus pronated feet in adulthood[13] imply potential morphometric remodifications, wherein extrinsic muscular adaptations are posited to compensate for intrinsic deficits[11]. This adaptation suggested by the research of Angin et al.[11], observing greater thickness and CSA in extrinsic foot muscles compared to intrinsic ones in individuals with pronated foot disorders, could potentially highlight a compensatory model of extrinsic-muscular hypertrophy in response to pronation stresses. Meanwhile, discrepancies in intrinsic muscle development between flat-footed individuals and their healthy counterparts have surfaced[14], fueling discussions on the role of exercises tailored to these muscles in preventing and potentially improving navicular drop[15,16]. Jung et al.[15] have reported that short foot exercises, combined with foot orthoses, can enhance the CSA of key intrinsic foot muscles like the ABH. Supporting this view, Mulligan and Cook[16] have suggested that short foot exercises might be effective in preventing navicular drop by strengthening the intrinsic foot muscles.

The concept of a 'foot core system'[7,10], extrapolated from Richardson and Hodges' lumbar stability model[17], offers an innovative perspective through McKeon's lens on foot musculature, conceptualizing intrinsic muscles as pivotal 'local core stabilizers' countered by 'global core stabilizers' represented by the extrinsic muscles[7,10]. This neurophysiological paradigm postulates that priming intrinsic muscles prior to their extrinsic counterparts may avert potential weakening of local musculature—a principle that, if substantiated, could revolutionize the approach to foot muscle rehabilitation.

Noninvasive modalities such as corrective exercises, categorized by their focus on either intrinsic or extrinsic muscle groups, have gained prominence for their efficacy on the MLA[16,18]. Contemporary literature on the intrinsic musculature of the foot lacks comparative exploration of intrinsic versus extrinsic muscle-focused training effects subject to different prioritizations on muscle morphometry[15,16,18,19]. Furthermore, the concept of a 'foot core system'[7,10] has not been explicitly tested in pediatric flatfoot based on the available research. Consequently, there needed to conduct an empirical study to figure out the muscular adaptations of the foot consequent to differential training methodologies involving both intrinsic and extrinsic muscle exercises, and thus recommend a counterbalanced exercise program for pediatric flat food. It should be noted that while intrinsic foot muscle exercises are essential, extrinsic foot muscle exercises are as equally important in providing support and maintaining the arch of the foot[20]. Weakness in extrinsic foot muscles can also result in instability in the midtarsal joint, contributing to the pronated appearance of the foot[20].

This study was hence designed to investigate the morphometric differences in selected intrinsic and extrinsic foot muscles contingent on the prioritization and timing of corrective exercises, and secondly, to ascertain the consequential variance in navicular drop amongst pediatric participants with flatfoot. It supports the hypothesis that initiation of corrective exercises program for individuals with flexible flat feet using intrinsic muscle training yields more favorable outcomes on the morphological characteristics of selected intrinsic muscles and navicular drop than starting with extrinsic muscle exercises after the first six weeks, and that intrinsic-first corrective exercise group (six weeks of intrinsic foot muscle exercises followed by six weeks of extrinsic foot muscle exercises) would show greater improvement in the morphological characteristics of selected intrinsic muscles and navicular drop after twelve weeks compared to the extrinsic-first corrective exercise group (six weeks of extrinsic foot muscle exercises followed by six weeks of intrinsic foot muscle exercises).The findings of this research endeavor aimed to clarify the optimal sequencing of corrective exercises, potentially steering a new course for future therapeutic strategies in the management of pediatric flatfoot.

Methods
Participants
Ethical clearance was granted by the Faculty of Physical Education and Sport Sciences at the University of Tehran (IR.UT.SPORT.REC.1399.008) and the Iranian Registry of Clinical Trials (IRCT20210818052223N1 on 08/09/2021). Prospective interventional trial with a within-subject crossover design was used. For the study, twenty-five boys presenting with flexible flat feet were enlisted from elementary schools, ranging in age from 10 to 12 years. Informed consent was secured from their parents or legal guardians. All methods were carried out in accordance with the Declaration of Helsinki[21].

During the exercise intervention, three participants opted out of the study due to a lack of interest in continuing the collaboration with the researchers, which left twenty-two subjects. These remaining participants were randomly assigned to two groups: the intrinsic-first corrective exercise group (n = 10, average age 10.8 ± 0.78 years, height 138.8 ± 7.22 cm, weight 40.7 ± 9.49 kg) and the extrinsic-first corrective exercise group (n = 12, average age 11 ± 0.85 years, height 143.1 ± 6.14 cm, weight 42.25 ± 9.05 kg). Computer-generated randomization was used in a 1:1 ratio, followed by a masked allocation by opening the sequentially numbered, checkmate, and secured envelopes. A card inside each envelope indicated the group where the participant was randomly allocated, i.e. intervention or control groups.

Candidates for the study met inclusion criteria of having an orthopedist-diagnosed asymptomatic flexible flatfoot and a navicular drop test score of ≥ 10 mm (mm). Exclusions were made for participants with any anatomical leg length discrepancies, a history of foot or leg surgery or injury, a diagnosis of rigid flatfoot, a positive tarsal coalition test, current use of insole orthotics, or congenital lower extremity deformities such as genu valgum or femoral anteversion.

Protocol

Images of the foot muscles, including the FDL, FDB, ABH, TA, and TP, were captured using an ultrasound system (US) (E-cube 9, Alpinion Medical Systems, Seoul, Korea) equipped with a 3–10 MHz linear wideband array transducer. A systematic review on the reliability of ultrasound measurements for the intrinsic foot muscles has reported strong intra- and inter-rater reliabilities for it[22]. The evaluation was focused on the participants' dominant limb during stance—the leg that each individual instinctively used when asked to perform a single-leg balance task. These assessments were carried out by a specialist examiner blinded to group allocation, adhering to a methodology laid out by Crofts et al.[12]. For accurate muscle thickness measurement, the probe was meticulously aligned parallel to the muscle fibers. To determine the CSA, the probe was pivoted by 90 degrees to lie perpendicular to the fibers at the muscle's thickest portion[12]. In the pursuit of precision, the mean value derived from three separate measurements was taken for each muscle to ensure robust statistical analysis. Figure 1 illustrates the probe positioning and sample images for all recorded measurements.

Measurement of navicular drop

According to Brody's methodology for the navicular drop test[23], participants were seated with the hips, knees, and ankles at 90-degree angles and the tibia perpendicular to the floor. The examiner, blinded to group assignments, used the thumb and index finger to palpate the anteromedial and anterolateral aspects of the talus. The participant's foot was rotated internally and externally to identify the subtalar joint's neutral position, where the talus was palpably centered between the examiner's fingers. The navicular bone's height from the floor was measured in this position using a digital caliper. Following this, the participant stood, ensuring an equal distribution of body weight and a perpendicular tibia to the floor; the navicular height was measured again. The difference between seated and standing measurements provided the navicular drop value. Mueller has suggested a borderline of 10 mm for the navicular drop test, indicating that values above this threshold may be considered indicative of flexible flatfoot conditions[24]. Navicular drop has been suggested to be a valid indicator of radiographic arch height indices[25,26]. Interrater and intrarater reliability of this technique has reported to be good to excellent[27].

Intervention

Participants underwent a 12-week corrective exercise program, comprising three 45-min sessions per week. The intrinsic-first group initially dedicated the first six weeks to performing exercises targeting the foot's intrinsic muscles. Subsequently, for the latter half of the program, they switched to focusing on extrinsic muscle exercises. Conversely, the extrinsic group commenced with extrinsic muscle exercises for the initial six weeks and switched to intrinsic ones for the remaining six weeks of the program.

Individuals attended three sessions a week for practice and trained in person, but they performed exercises daily under the supervision of their parents. In fact, they practiced every day: three days a week under my supervision and the rest at home with parental oversight. Each training session lasted about 45 min.

Intrinsic foot exercises

The intrinsic foot exercise program commenced with non-weight-bearing (unloaded) exercises, such as sitting, and advanced to weight-bearing (loaded) scenarios such as standing and single-leg stances once muscle activation proficiency was achieved[7]. Activities included short foot exercises, toe spreading, first toe extensions, and extensions of the second to fifth toes (Fig. 2). Gooding et al.[19] noted that these exercises led to heightened intrinsic muscle activation. Similarly, Jung et al.[28] found that short foot exercises elicited greater electromyographic activity in the ABH compared to conventional toe curls.

Extrinsic foot exercise

The extrinsic foot exercise program was structured to activate and strengthen the extrinsic foot muscles, with a particular emphasis on the posterior tibialis muscle due to its critical function in supporting the MLA[29]. It comprised exercises such as foot adduction, heel raises, and foot supination, which were performed both with an elastic band and against gravity, as illustrated in Fig. 3. Research by Kulig and colleagues[30] has demonstrated that the first three exercises are particularly effective in selectively engaging the extrinsic muscles of the foot, most notably the tibialis posterior. Initially, exercises were performed with minimal resistance, gradually incorporating heavier loads facilitated by an elastic band.

Progression of exercises

The exercises conducted in this study progressed through three phases of initial, improvement, and maintenance. In the initial phase, the goal was to familiarize individuals with the execution of the exercises and the activation of muscles, particularly within the intrinsic training group. During this phase, the load on the body should be minimized to facilitate the activation of intrinsic muscles in a weightless environment. The exercises designed in this phase emphasized increasing the duration of training.

In the second phase, the complexity of the exercises gradually increased, and along with the extension of practice time, a slight resistance was also introduced. The objective during this phase was to enhance the activity of the target muscles.

In the maintenance phase, it was essential to preserve the progress achieved thus far. Additionally, at the end of the development phase and the beginning of the maintenance phase, it was possible to incorporate weight-bearing positions based on individual progress. Consequently, during this phase, the duration of the exercises was reduced while the number of sets was increased.

To adjust the intensity of the exercises, it is crucial to recognize that each individual possesses different motor learning and physical literacy levels, and the activation of intrinsic foot muscles requires high levels

Fig. 1. Depiction of probe placement for ultrasonographic measurement: flexor digitorum longus thickness (**A1,A2**) and cross-sectional area (CSA) (**A3,A4**), flexor digitorum brevis thickness (**B1,B2**) and CSA (**B3,B4**), abductor hallucis thickness (**C1,C2**) and CSA (**C3,C4**), tibialis anterior thickness (**D1,D2**) and CSA (**D3,D4**), and tibialis posterior thickness (**E1,E2**) and CSA (**E3,E4**).

of control and motor learning. Therefore, a predetermined exercise protocol cannot be uniformly applied. However, the progression of the exercises can be tailored according to specific criteria. Initially, individuals in the intrinsic training group performed short foot exercises without weight-bearing. Once the participants were able to activate the intrinsic muscles, resistance bands were introduced to increase exercise intensity. Given that

Fig. 2. Illustration of intrinsic foot exercises: (**A**) short foot exercise, (**B**) extension of toes two to five, (**C**) first toe extension, (**D**) toe spreading.
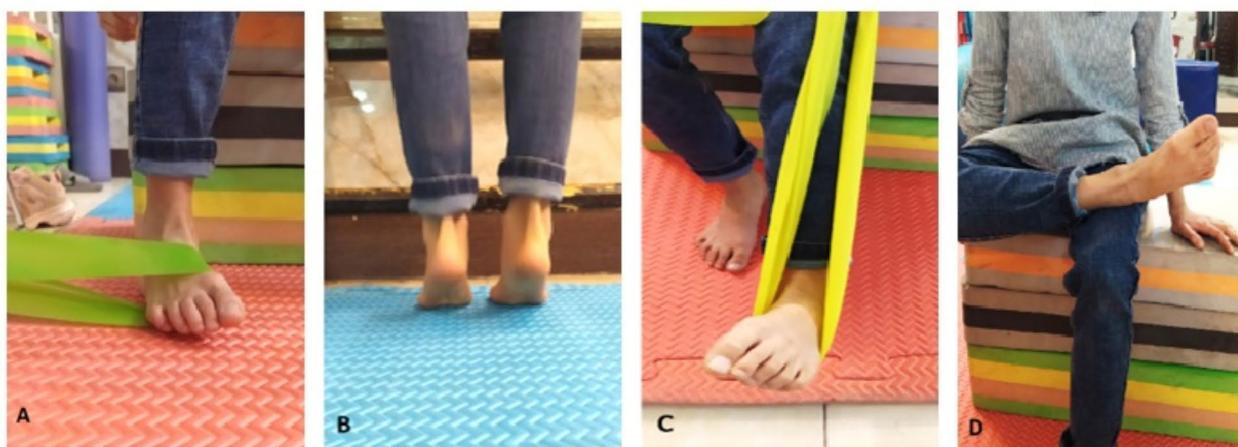
Fig. 3. Overview of extrinsic exercises performed: (**A**) foot adduction, (**B**) heel raises, (**C**) foot supination with an elastic band, (**D**) foot inversion against gravity.

intrinsic muscles are local and tonic, their endurance is prioritized over strength. Thus, the focus of the exercises was primarily on enhancing muscle endurance (increasing the duration of practice). After individuals could perform the non-weight-bearing exercises for a duration of two to four minutes, they could progress to weight-bearing exercises. The two to four-minute duration is ideal for activating tonic muscles[31]. The emphasis of these exercises was also on the endurance activation of intrinsic muscles.

For the progression of intrinsic exercises, two review studies were utilized[32,33]. In the short foot exercises, which form the basis of intrinsic training, participants were initially instructed on the execution of the exercises, holding each contraction of the intrinsic foot muscles without activating the extrinsic muscles for five seconds, repeated 100 times. In the first two weeks, the exercises were performed in a seated position, after which the exercises were generalized to functional positions[34]. To determine when each individual could transition to more challenging positions for further exercise progression, the criterion was the ability to perform three minutes of short foot exercises without inducing stiffness or discomfort in the relevant muscles[16].

To enhance the strength of extrinsic muscles, initial exercises included raising the body on the toes (calf raises) and strengthening the posterior tibialis muscle. These exercises were performed in four sets of ten repetitions. Initially, resistance bands with the tension of 170% of their original length were used[35], and once the exercises became manageable, higher resistance bands were employed. These exercises were also performed in four sets. The rest period between each exercise was 30 s, and the tempo of the exercise was 2–0-2 (concentric-isometric-eccentric)[35].

Statistical analysis

Data normality and variance homogeneity were ascertained using the Kolmogorov–Smirnov test before comprehensive statistical evaluation. In conducting two-way repeated measures ANOVA, all necessary assumptions were carefully considered to ensure the validity of the analysis. Observations were confirmed to be independent, and the normality of the dependent variable distributions was assessed Additionally, Mauchly's test was performed to evaluate the assumption of sphericity. A two-way repeated measures ANOVA examined the group effects (intrinsic and extrinsic), time effects (initial, the 6th week, the 12th week), and interaction effects (Group × Time) on the dependent variables of muscle thickness, CSA, and navicular drop. Bonferroni post hoc analysis was applied for pairwise comparisons at consecutive time points. P-values less than 0.05 were deemed statistically significant, with analyses performed using SPSS software (version 26.0; SPSS, Inc, an IBM Company, Chicago, IL).

Results

Mixed ANOVA revealed significant interactions between the groups (Intrinsic, Extrinsic) and time (Initial, the 6th week, the 12th week) on the thickness of FDL ($F_{2,40}=7.215$, $P=0.002$, $\eta 2=0.26$, Cohen's f ≈ 0.59), FDB ($F_{2,40}=4.47$, $P=0.018$, $\eta 2=0.183$, Cohen's f ≈ 0.47), ABH ($F_{2,40}=4.865$, $P=0.035$, $\eta 2=0.47$, Cohen's f ≈ 0.42), TA ($F_{2,40}=5.156$, $P=0.010$, $\eta 2=0.205$, Cohen's f ≈ 0.51), and TP ($F_{2,40}=3.914$, $P=0.028$, $\eta 2=0.164$, Cohen's f ≈ 0.44). A significant main effect of time was observed for the following muscles: FDB ($F_{2,40}=10.026$, $P<0.001$, $\eta 2=0.334$, Cohen's f ≈ 0.71), ABH ($F_{2,40}=6.125$, $P=0.005$, $\eta 2=0.234$, Cohen's f ≈ 0.55), TA ($F_{2,40}=6.314$, $P=0.006$, $\eta 2=0.24$, Cohen's f ≈ 0.56), and TP ($F_{2,40}=3.324$, $P=0.046$, $\eta 2=0.143$, Cohen's f ≈ 0.41). No significant effects were detected for group differences in all muscle variables related to thickness ($P>0.05$).

Regarding the CSA, significant interactions were found for ABH ($F_{2,40}=4.80$, $P=0.014$, $\eta 2=0.194$, Cohen's f ≈ 0.49). A significant main effect of time was observed for the following muscles: FDB ($F_{2,40}=3.799$, $P=0.031$, $\eta 2=0.16$, Cohen's f ≈ 0.44), and TP ($F_{2,40}=3.695$, $P=0.034$, $\eta 2=0.156$, Cohen's f ≈ 0.43), indicating a temporal evolution in these measures. Conversely, no significant group effect was obtained in all muscle variables related to cross sectional area ($P>0.05$).

Additionally, for navicular drop, a significant effect of time was noted ($F_{2,40}=55.651$, $P<0.001$, $\eta 2=0.736$, Cohen's f ≈ 1.67), while group and interaction effects did not reach statistical significance ($P>0.05$). These effect sizes indicate not only statistical significance but also practical relevance, suggesting that the interventions had a meaningful impact on muscle thickness and function, particularly for the FDL and navicular drop measures.

Tables 1 and 2 present the mean values, results of post hoc analyses, and the percentage of change in outcome measures from baseline to follow-ups at 6th and 12th weeks for both groups.

Figures 4, 5, and 6 chart the trajectory of changes in outcome measures from baseline to 6 and 12-week follow-ups in both groups for the muscle thickness and CSA and navicular drop.

Variable	Group	Initial	6th week	12th week	P and % Change Initial to 6 weeks	P and % Change Initial to 12 weeks	P and % Change 6 weeks to 12 weeks	Interaction effect	Test time effect	Group effect
Flexor digitorum longus (cm)	Intrinsic	1.27 ± 0.44	1.08 ± 0.49	1.23 ± 0.61	P = 0.172 -15%	P = 1.00 -3%	P = 1.00 14%	F = 7.215 P = 0.002*	F = 2.31 P = 0.112	F = 2.58 P = 0.124
	Extrinsic	1.42 ± 0.40	1.79 ± 0.52	1.21 ± 0.49	P < 0.001 26%	P = 0.648 -15%	P < 0.001 -32%			
Flexor digitorum brevis (cm)	Intrinsic	0.72 ± 0.23	0.71 ± 0.34	0.78 ± 0.33	P = 1.00 -2%	P = 1.00 8%	P = 1.00 9%	F = 4.47 P = 0.018*	F = 10.026 P = 0.001*	F = 0.082 P = 0.778
	Extrinsic	0.67 ± 0.19	0.55 ± 0.17	0.90 ± 0.36	P = 0.009 -17%	P = 0.022 35%	P < 0.001 63%			
Abductor hallucis (cm)	Intrinsic	0.81 ± 0.24	0.93 ± 0.37	0.94 ± 0.38	P = 0.309 14%	P = 0.83 16%	P = 1.00 1%	F = 4.865 P = 0.013*	F = 6.125 P = 0.005*	F = 1.711 P = 0.206
	Extrinsic	0.73 ± 0.23	0.58 ± 0.14	0.95 ± 0.36	P = 0.079 -21%	P = 0.13 30%	P < 0.001 64%			
Tibialis anterior (cm)	Intrinsic	1.87 ± 0.41	1.74 ± 0.44	2.06 ± 0.58	P = 0.78 -7%	P = 0.47 10%	P = 0.012 19%	F = 5.156 P = 0.010*	F = 6.314 P = 0.004*	F = 3.714 P = 0.068
	Extrinsic	1.94 ± 0.29	2.30 ± 0.37	2.29 ± 0.34	P = 0.006 19%	P = 0.022 18%	P = 1.00 -0.2%			
Tibialis posterior (cm)	Intrinsic	2.08 ± 0.31	1.92 ± 0.39	2.29 ± 0.54	P = 0.79 -7%	P = 0.35 10%	P = 0.005 19%	F = 3.914 P = 0.028*	F = 3.324 P = 0.046*	F = 0.273 P = 0.607
	Extrinsic	2.03 ± 0.31	2.27 ± 0.44	2.22 ± 0.45	P = 0.21 12%	P = 0.36 9%	P = 1.00 -2%			
Navicular Drop (cm)	Intrinsic	1.54 ± 0.45	1.12 ± 0.33	0.81 ± 0.26	P < 0.001 -27%	P < 0.001 -47%	P = 0.003 -27%	F = 0.238 P = 0.789	F = 55.651 P < 0.001*	F = 0.769 P = 0.391
	Extrinsic	1.64 ± 0.58	1.25 ± 0.40	1.00 ± 0.34	P < 0.001 -24%	P < 0.001 -39%	P = 0.01 -20%			

Table 1. Mean (SD) changes in navicular drop and the thickness of selected muscles from baseline to follow-ups at 6th and 12th weeks. *Indicates difference ($P<.05$).

Variable	Group	Initial	6th week	12th week	*P* and % Change Initial to 6 weeks	*P* and % Change Initial to 12 weeks	*P* and % Change 6 weeks to 12 weeks	Interaction effect	Test time effect	Group effect
Flexor digitorum longus (cm)	Intrinsic	2.52 ± 1.65	2.43 ± 1.73	2.68 ± 1.65	$P=1.00$ -4%	$P=1.00$ 6%	$P=0.993$ 10%	$F=0.388$ $P=0.681$	$F=0.792$ $P=0.460$	$F=2.638$ $P=0.120$
	Extrinsic	1.60 ± 0.51	1.90 ± 0.59	1.99 ± 0.41	$P=0.944$ 19%	$P=0.873$ 24%	$P=1.00$ 5%			
Flexor digitorum brevis (cm)	Intrinsic	1.47 ± 0.86	1.58 ± 0.83	1.64 ± 0.76	$P=1.00$ 7%	$P=1.00$ 11%	$P=1.00$ 4%	$F=1.762$ $P=0.185$	$F=3.799$ $P=0.031*$	$F=0.088$ $P=0.770$
	Extrinsic	1.42 ± 0.57	1.28 ± 0.53	1.75 ± 0.43	$P=1.00$ -10%	$P=1.00$ 24%	$P<0.001$ 37%			
Abductor hallucis (cm)	Intrinsic	1.34 ± 0.59	1.59 ± 0.80	1.67 ± 0.80	$P=0.15$ 19%	$P=0.10$ 25%	$P=1.00$ 5%	$F=4.800$ $P=0.014*$	$F=2.429$ $P=0.101$	$F=0.079$ $P=0.782$
	Extrinsic	1.55 ± 0.55	1.29 ± 0.53	1.54 ± 0.53	$P=0.10$ -17%	$P=1.00$ -1%	$P=0.041$ 18%			
Tibialis anterior (cm)	Intrinsic	5.80 ± 1.86	5.26 ± 1.74	5.65 ± 2.24	$P=0.231$ -9%	$P=1.00$ -3%	$P=0.159$ 7%	$F=1.80$ $P=0.179$	$F=1.135$ $P=0.332$	$F=0.001$ $P=0.977$
	Extrinsic	5.68 ± 1.51	5.68 ± 1.20	5.40 ± 1.06	$P=1.00$ 0%	$P=1.00$ -4%	$P=0.392$ -4%			
Tibialis posterior (cm)	Intrinsic	3.71 ± 0.69	3.83 ± 0.50	4.63 ± 0.75	$P=1.00$ 3%	$P=0.17$ 25%	$P=0.24$ 21%	$F=2.356$ $P=0.108$	$F=3.695$ $P=0.034*$	$F=0.983$ $P=0.333$
	Extrinsic	4.08 ± 1.56	4.94 ± 1.85	4.59 ± 1.68	$P=0.008$ 21%	$P=0.72$ 12%	$P=1.00$ -7%			

Table 2. Mean (SD) changes in the CSA of selected muscles from baseline to follow-ups at 6th and 12th weeks. *Indicates difference ($P<.05$).

Discussion

In the investigation of intrinsic- versus extrinsic-first corrective exercise programs for pediatric flexible flatfoot, the current study adeptly explored the hypothesis that not only the kinds of exercises but also their sequence of implementation may significantly impact the morphometry of foot muscles and the degree of navicular drop. The study results indicated that intrinsic corrective exercises, like short foot exercises, during the initial six weeks for the intrinsic-first group led to an improvement in the muscle thickness and CSA of intrinsic muscles such as ABH (increase of 14%, 19%) and FDB (decrease of 2%, increase of 7%). These findings suggest that intrinsic-first strategy to the corrective exercise program does not adversely affect the morphometry of either intrinsic or extrinsic foot muscles. Even, subsequent implementation of extrinsic corrective exercises in the latter six-week period (from weeks 6 to 12) resulted in continued improvements in intrinsic foot muscles, evidenced by FDB (9%, 4%) and ABH (1%, 5%) gains in addition to enhanced muscle thickness and CSA of extrinsic muscles, including TA (19%, 7%) and TP (19%, 21%). In other words, training these muscles seems to provide a stable base for the extrinsic muscles to function more effectively. Hence, the initial focus on intrinsic muscle exercises improved the morphometry of these smaller muscles which was preserved through the subsequent development of extrinsic muscles. This finding is a compelling endorsement of the foot core system theory, positing that a proximodistal approach to foot muscle rehabilitation may yield the most favorable outcomes in managing pediatric flatfoot[7,10].

Our investigation also revealed that extrinsic corrective exercises during the initial six-week phase contributed to an adverse alteration in the morphometry of intrinsic muscles (muscle thickness and CSA), while exerting beneficial effects on extrinsic musculature. Specifically, the muscle thickness and CSA of the intrinsic muscles, such as FDB (decreased by 17%, 10%) and ABH (decreased by 21%, 17%), exhibited declines, whereas the respective indices for extrinsic muscles, such as FDL (increased by 26%, 19%), TA (increased by 19%, unchanged), and TP (increased by 12%, 21%) incremented. This finding pivotally emphasized the potential negative impact of extrinsic-first strategy to the corrective exercise program. This sequence showed reduced morphometric benefits for the intrinsic muscles, a discovery that resonates with the foundational principles of neuromuscular rehabilitation, suggesting a potential interference effect where early extrinsic-muscle-training emphasis may overshadow intrinsic muscle development[17].

Initiating a training regimen with intrinsic foot muscle exercises can lead to sustained improvements in intrinsic foot muscle morphometry and function, even after transitioning to extrinsic exercises, due to several biological mechanisms. Intrinsic foot muscle exercises, such as short foot and toe spread out, promote specific adaptations in intrinsic foot muscle activity and morphology, including increased muscle fiber recruitment and enhanced neuromuscular coordination of key intrinsic foot muscles like the ABH and flexor hallucis brevis[36,37]. These adaptations provide a strong foundation for subsequent extrinsic training and demonstrate superiority compared to three-dimensional foot–ankle exercises in maintaining a favorable ABH/adductor hallucis ratio[38]. Furthermore, intrinsic foot muscle exercises create a favorable inflammatory environment that supports muscle repair and growth, which can be maintained even after transitioning to extrinsic exercises, whereas extrinsic exercises may induce inflammation that negatively impacts recovery[39].

Intrinsic corrective exercises in the following six-week period led to substantial enhancements in the thickness and CSA of the intrinsic muscles, evidenced by increments in FDB (63%, 37%) and ABH (64%, 18%). Contrary to lumbar stability model[17], this intriguing result suggests that initiating training with the extrinsic foot muscles
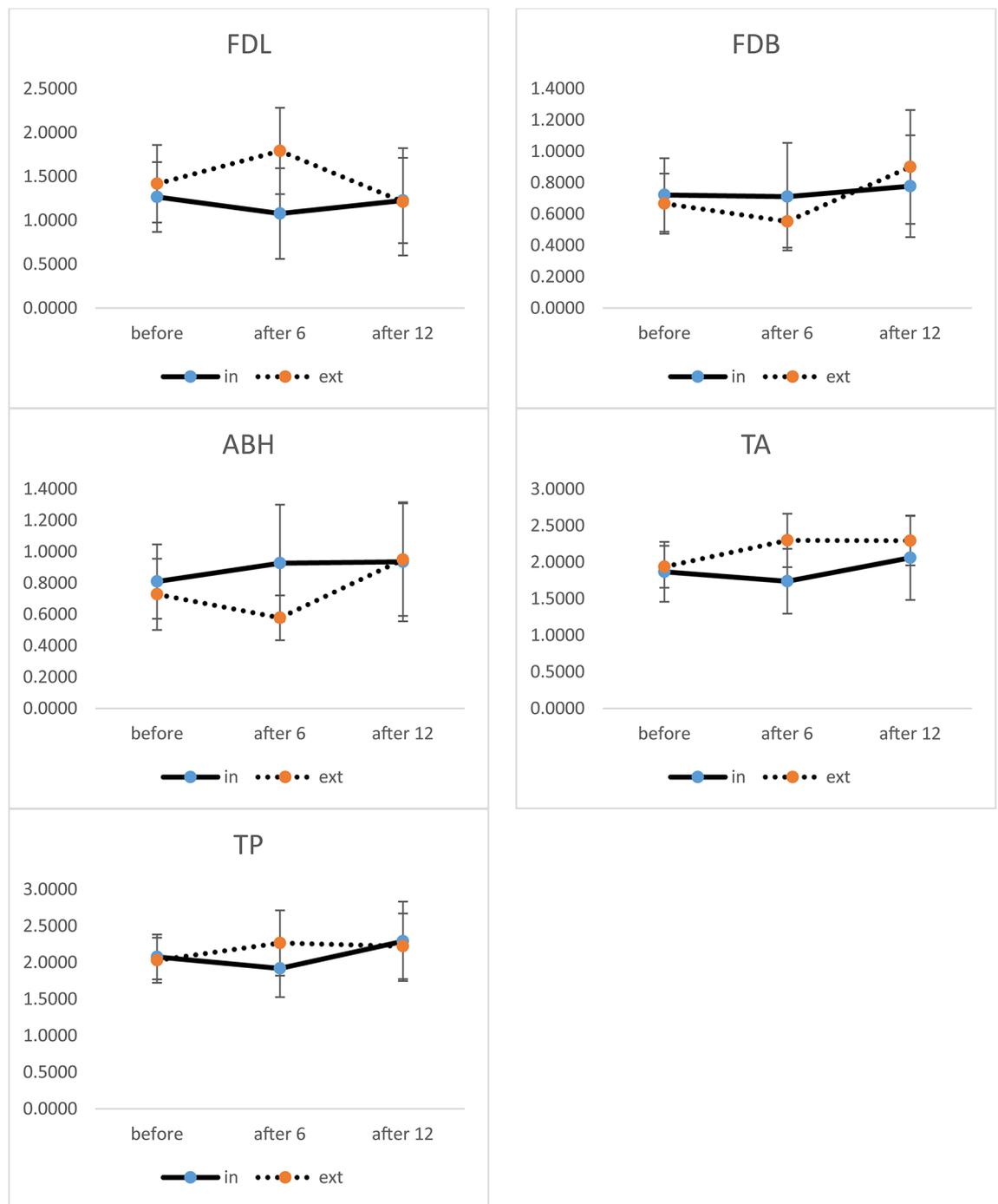
Fig. 4. Illustration of the variance in muscle thickness for both intrinsic and extrinsic exercise groups, from pre-test (before) to post-test (after 12 weeks).

did not yield significantly different outcomes from commencing with intrinsic muscle emphasis. It should be noted that the six-week training period may not have been sufficient to fully differentiate the effects of training the intrinsic versus extrinsic foot muscles. Extending the duration of the training periods and incorporating longitudinal assessments could provide more comprehensive insights into the temporal dynamics of muscle adaptation in the lower extremities. Moreover, the divergence observed in the training sequence effects on foot musculature may stem from the distinct roles of the intrinsic foot muscles and the inner core unit. The intricate functions of the intrinsic foot muscles, specifically in supporting the foot arches and facilitating proper foot mechanics, may deviate from the sequential training efficacy proposed for the core musculature.

Integrating intrinsic and extrinsic foot muscle exercises in pediatric flatfoot showed significant benefits in morphometric outcomes and navicular drop reduction . Studies focusing on intrinsic foot muscle training have also demonstrated improvements in foot function, including decreased navicular drop and improved balance
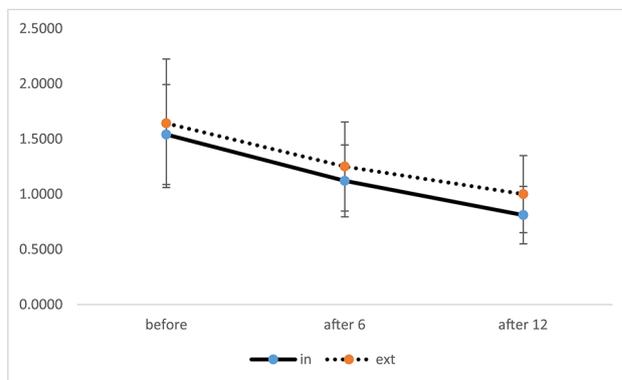
Fig. 5. Illustration of the variance in navicular drop for both intrinsic and extrinsic exercise groups, from pre-test (before) to post-test (after 12 weeks).

and strength[40]. In contrast, the study by Elsayed et al. found that combining short foot exercises with shoe insoles resulted in improved pain, function, and altered foot pressure distribution in individuals with symptomatic flexible flatfoot, with no significant difference in navicular drop between groups[41]. Furthermore, a meta-analysis by Huang et al. reinforced the advantages of short foot exercise, demonstrating that participants in the short foot exercise group experienced notable reductions in navicular drop test values and foot posture index scores compared to those receiving alternative interventions, such as shoe insoles and muscle strengthening exercises[33]. Integrating intrinsic and extrinsic exercises in pediatric flatfoot management aligns with the broader benefits observed in foot function and postural control across various studies, emphasizing the significance of a comprehensive approach to foot muscle training in pediatric populations.

The limited empirical researches in this field presents challenges to directly correlating current findings with established literature. Nevertheless, it appears that both intrinsic and extrinsic foot muscles follow a consistent response pattern to both extrinsic-muscle-targeted exercises and certain pathophysiological conditions. Notably, Angin et al.[11] documented a decrease in the thickness and CSA of the ABH, flexor hallucis brevis, and the peronei longus and brevis, while reporting an increase in these metrics for the FDL and peronei muscles in flatfooted conditions. These findings suggest potential compensatory adaptation by the extrinsic muscles to uphold the MLA when intrinsic muscle functionality is compromised due to anomalous foot structure. The same compensatory response of extrinsic foot muscles—the increase in thickness and CSA—to both early extrinsic-muscle-training interventions over a controlled period and natural pathological conditions (i.e., flat feet) not only entails the adoption of more conscious intrinsic-first strategy to the corrective exercise program, but also seems to be indicative of a complex interplay between the intrinsic and extrinsic muscles, a phenomenon that can either support or undermine the structure and function of the foot, depending on the scenario.

The results suggest a potential interference effect, where early emphasis on extrinsic muscle training may negatively impact the improvement of intrinsic muscles. Strengthening extrinsic foot muscles, which originate on the leg and insert on the foot, can potentially lead to intrinsic foot muscle atrophy due to a phenomenon known as "muscle imbalance" or "disuse atrophy"[42]. When extrinsic muscles are strengthened, they may take over the functions that intrinsic muscles typically perform, such as supporting the arch and aiding in foot movements. This can lead to underuse of the intrinsic muscles, which may then weaken and atrophy over time[43]. When extrinsic muscles become stronger or more dominant, the intrinsic muscles may not receive the necessary stimulus to maintain their strength and function, leading to atrophy[38].

It is also worth delving deeper into the anatomy underlying these observations. Intrinsic muscles, acting as local stabilizers, have shorter lever arms and are tailored for fine-tuned support of the MLA[10]. Indeed, intrinsic foot muscles have been shown to provide afferent information and a stable base of support for balance, changing the shape of the foot according to the loading[38]. However, they are more prone to atrophy or functional impairment when not adequately prioritized in rehabilitative processes[44]. Conversely, training intrinsic foot muscles can play a crucial role in enhancing not only the intrinsic muscles but also the extrinsic muscles indirectly[45]. For instance, increased muscle activity in the intrinsic foot muscles has been associated with increased foot stiffness, which is beneficial for propulsion during gait[46] performed partly by TP[47].The enhancement of extrinsic muscle morphometry following intrinsic muscle training could suggest a neuromuscular adaptation that aligns with a foundational before functional training paradigm[17]—a concept embraced widely in core stabilization literature.

The differential impact on the navicular drop—a chief metric in assessing flatfoot severity—furthers the discourse on the importance of exercise sequencing. Participants subjected to intrinsic-first training showed a more substantial reduction in navicular drop (47%), though not statistically significant, compared to the extrinsic group (39%) over a 12-week training period, elevating the intrinsic-first strategy as a potentially superior strategy not only for muscle morphometry but also for functional foot correction.

Numerous studies have reported improvements in the stability of the MLA following the strengthening of the intrinsic foot muscles[16,48,49]. Lucas et al. (2017) has asserted that exercises aimed at strengthening the intrinsic muscles of the foot are effective in enhancing the windlass mechanism and reducing the rate of navicular drop[50]. Although the primary factors affecting this mechanism are traditionally associated with the plantar fascia, the researchers believe that due to the extensive adhesions of the intrinsic foot muscles to the plantar fascia,
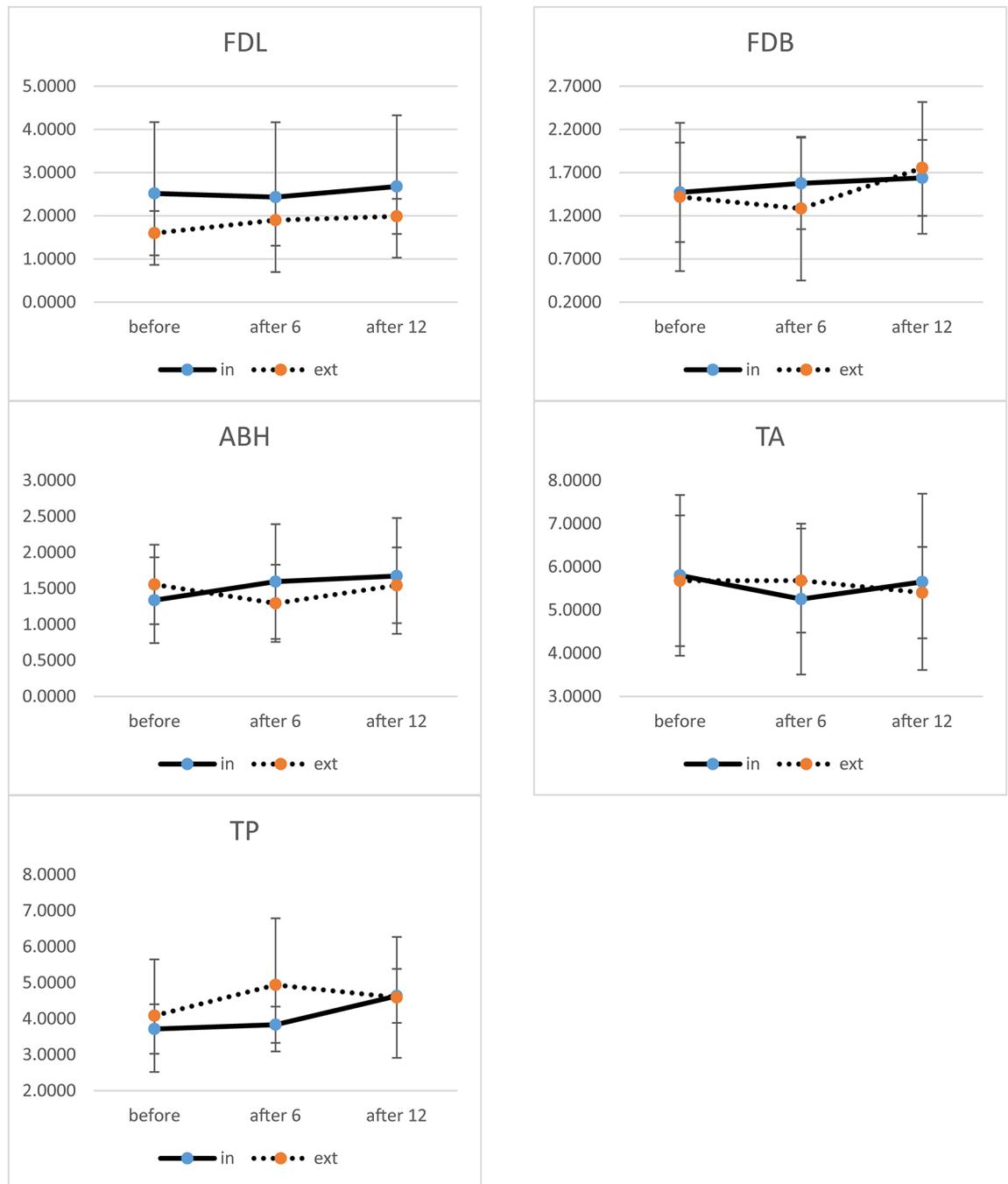
Fig. 6. Illustration of the variance in CSA for both intrinsic and extrinsic exercise groups, from pre-test (before) to post-test (after 12 weeks(.

strengthening these muscles could potentially increase tension in the fascia which in turn, may contribute to the improvement of the MLA, particularly during dynamic activities[50,51]. During the gait cycle, substantial forces impact the foot and especially the MLA, thus strengthening the mechanism resistance to these forces can help the arch function as a stronger lever to maintain stability against external forces[29].

The interplay between foot structures and muscular function seem to further account for the way musculature influences foot configuration. Empirical studies suggest that the weakening of both extrinsic and intrinsic foot muscles, such as TP and ABH, precipitates a decrease in MLA height[52,53]. Investigating static foot alignment through the navicular drop test and arch height index, Mulligan et al.[16] established that short-foot exercise yielded improvements within four weeks. Complementarily, Sulowska et al.[18] substantiated the positive effects of intrinsic muscle-strengthening exercises, reporting enhancement in the static foot alignment of long-distance runners after a six-week period of short-foot training, as assessed by the Foot Posture Index.

Based on findings, extrinsic-first muscle training also seems to significantly improve navicular drop. Considering the insertion points of the extrinsic muscles, particularly the TA and the TP muscles—the former attaching from above and the latter from the inferomedial aspect—it can be posited that these muscles may also exert considerable effects on controlling navicular drop. As such, no significant difference was observed between the two groups in terms of navicular drop. Therefore, it is deduced that both intrinsic and extrinsic muscles can contribute to the improvement of navicular drop and the control of foot pronation.

The findings of this study suggest that corrective exercise programs for pediatric flexible flatfoot should prioritize intrinsic foot muscle exercises before progressing to extrinsic muscle exercises. Initiating with intrinsic exercises appears to be more effective in improving intrinsic muscle morphometry and reducing navicular drop. Specifically, beginning with intrinsic foot muscle exercises results in greater improvements in intrinsic muscle thickness and cross-sectional area compared to starting with extrinsic muscles first. The intrinsic-first group showed sustained improvements in intrinsic muscle morphometry even after transitioning to extrinsic exercises in the second half of the program, while the extrinsic-first group experienced deterioration in intrinsic muscle morphometry that was later recovered after switching to intrinsic exercises. Additionally, the intrinsic-first group exhibited a more pronounced reduction in navicular drop, a key indicator of flatfoot severity.

These results provide empirical evidence supporting the concept of a "foot core system", where intrinsic foot muscles act as local stabilizers and should be targeted first in rehabilitation. This aligns with the principle that priming intrinsic muscles before extrinsic muscles may prevent potential weakening of local musculature. Clinicians should consider incorporating this approach into their treatment protocols to optimize outcomes and potentially prevent the progression of flatfoot deformities.

The study acknowledges several limitations, including lack of long-term follow-up, the relatively small sample size and the lack of control for participants' physical activity levels, which may limit the external validity and generalizability of the findings. Additionally, the study relied solely on static measures like the navicular drop test to assess changes in foot structure, and future research should incorporate more comprehensive dynamic assessments to provide a more complete picture of foot function. The potential for selection bias in the participant recruitment process and not including girls is another limitation that could impact the interpretation of the results. Addressing these limitations in future studies, such as increasing the sample size, controlling for baseline activity levels, long-term follow-up, and employing a more diverse set of outcome measures, would strengthen the conclusions drawn from this research.

Future research should also focus on conducting longitudinal studies to investigate the long-term effects of this exercise sequencing on foot function and overall quality of life in children with flatfoot. Additionally, expanding the participant demographics to include girls and various age groups will enhance the generalizability of the findings. Investigating the underlying mechanisms that contribute to the observed improvements, as well as comparing the efficacy of intrinsic-first exercises against other treatment modalities, will provide further insights. Lastly, replication studies in different settings will be crucial for validating these results and refining exercise protocols for clinical application.

Conclusion

In conclusion, the study impeccably postulates an intrinsic-first rehabilitative strategy as a cornerstone in managing flexible flatfoot in children, with findings that could revolutionize current therapy protocols. The detailed investigation into the interrelationship between intrinsic and extrinsic muscle training offers a valuable lens through which future researches can refine and corroborate these results. It sets the stage for a new direction in therapeutic interventions—one that favors a bottom-up approach in musculoskeletal rehabilitation, aiming not only for symptomatic relief but also for the optimized structural and functional development of the foot.

Data availability

Data is provided within the manuscript.

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Acknowledgements

Author contributions

JK: Conceptualization, methodology, implementation. FS: Supervision, Project administration, statistical analysis. SH: Supervision and implementation of tests. SF: participation in the design of the study and interpretation. YMT: project administration. FK: writing, substantial revision, edition, and participation in statistical analysis.

All authors contributed to the manuscript writing. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to F.S.

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