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Effect of plantar intrinsic muscle training on medial longitudinal arch morphology and dynamic function

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ABSTRACT

A specific training program emphasizing the neuromuscular recruitment of the plantar intrinsic foot muscles, colloquially referred to as "short foot" exercise (SFE) training, has been suggested as a means to dynamically support the medial longitudinal arch (MLA) during functional tasks. A single-group repeated measures pre- and post-intervention study design was utilized to determine if a 4-week intrinsic foot muscle training program would impact the amount of navicular drop (ND), increase the arch height index (AHI), improve performance during a unilateral functional reaching maneuver, or the qualitative assessment of the ability to hold the arch position in single limb stance position in an asymptomatic cohort. 21 asymptomatic subjects (42 feet) completed the 4-week SFE training program. Subject ND decreased by a mean of 1.8 mm at 4 weeks and 2.2 mm at 8 weeks ($p < 0.05$). AHI increased from 28 to 29% ($p < 0.05$). Intrinsic foot muscle performance during a static unilateral balancing activity improved from a grade of fair to good ($p < 0.001$) and subjects experienced a significant improvement during a functional balance and reach task in all directions with the exception of an anterior reach ($p < 0.05$). This study offers preliminary evidence to suggest that SFE training may have value in statically and dynamically supporting the MLA. Further research regarding the value of this exercise intervention in foot posture type or pathology specific patient populations is warranted.

1. Introduction

The role of the plantar fascia, calcaneonavicular (spring) ligament, posterior tibialis, and the closed pack nature of the subtalar joint (STJ) bony architecture in supporting the medial longitudinal arch (MLA) is well established (Saltzman et al., 1995; Donatelli, 1996; Carlson et al., 2000; Fuller, 2000) Less is known regarding the role of the intrinsic foot musculature in contributing to the stability, shock absorption, and force attenuation value of the smaller plantar muscles on the sole of the foot. Excessive pronation, represented by a loss of MLA height, is a common finding in many pathological conditions involving the lower extremity including, plantar fasciitis, patellofemoral pain syndrome, posterior tibialis tendinopathy, Achilles tendinopathy, and posterior and anterior tibialis overuse syndrome (Jung et al., 2011).

There are both passive and active systems that support the MLA. The passive support system includes the inherent shape of the MLA and its ligamentous support. The bony arch consists of the calcaneus, talus, navicular, medial cuneiform and the first metatarsal. The ligamentous support system includes the plantar aponeurosis, long and short plantar ligaments, and the spring ligament. The navicular bone serves as the keystone for the MLA and plays a pivotal role in STJ pronation and supination. Previous research has demonstrated that a modified low-Dye taping procedure can passively support the MLA and reduce the amount of navicular drop (ND) during a functional task (Holmes et al., 2002).

The active support system for the MLA includes the anterior and posterior tibialis, fibularis longus and the plantar foot intrinsic muscles. If any of these contractile structures fails, prolonged or excessive pronation that leads to an injury may occur. Many therapeutic activities focus on the extrinsic muscles to support the MLA. Conversely, short foot exercises target recruitment of the plantar intrinsic foot musculature yet few studies have been conducted on the effect of plantar foot intrinsic motor training to control the MLA.

Previously conducted electromyographic (EMG) studies have demonstrated that alteration or impairment of plantar foot intrinsic muscles influence the height of the navicular and shape of the MLA. A study by Fiolkowski et al. (2008), found that a tibial nerve block to ablate intrinsic muscle activity caused a large

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decrease in the EMG activity of the abductor hallucis which corresponded to a significant increase in ND. In another study, exercise-induced fatigue of the plantar intrinsics musculature correlated with a significant increase in ND (Headlee et al., 2008).

Short foot exercise (SFE) training is a specific exercise activity that has been shown to be an effective means to recruit the abductor hallucis and prevent excessive lowering of the MLA (Janda et al., 2007; Campbell et al., 2008; Sauer et al., 2011). The exercise aims to activate weakened or inhibited intrinsic plantar foot muscles by intensifying and optimizing the sole's contact with the floor. Plantar intrinsic muscles originate and insert within the foot itself and function to improve dynamic alignment, control the arch position, and stimulate proprioceptors on the sole of the foot to improve balance (Newsham, 2010).

Clinically, the SFE emphasizes metatarsophalangeal and proximal interphalangeal joint flexion during balancing activities while minimizing distal interphalangeal flexion. This activity has been recommended as a means to improve neuromuscular control and intrinsic foot strength (Greenman, 2003; Rothermel et al., 2004; Jam, 2006; Prentice, 2009). The exercise is performed by the subject utilizing the intrinsic muscles of the foot to draw the metatarsal heads back toward the heel. The intent of this exercise is to "shorten the foot" without curling the toes. This motion should cause slight arch elevation without engaging the long toe flexors. The intensity of the exercise is submaximal in nature and emphasizes proper technique and the acquisition of new physical skill. This type of training was shown to challenge the abductor hallucis at 45% of a maximal voluntary isometric contraction in a sitting position that increased to 73% when the muscle was activated in a standing position (Jung et al., 2011).

The results of these studies seem to indicate that intrinsic plantar musculature may have an important role in supporting the MLA; however, to date, no studies have evaluated the ability of a specific intrinsic foot musculature (IFM) training program to decrease the ND, improve the arch height index (AHI), effect muscular balancing strategies in static stance, or impact function during a dynamic balancing activity. The purpose of this investigation was to evaluate the impact of a 4-week training program on the active support of the MLA and its ability to translate into dynamic control during functional tasks.

2. Methods

A pre-test-post-test design was used for this pilot study. The independent variable was a 4-week IFM training program. The dependent variables were ND, change in AHI, intrinsic foot musculature performance, and performance on the star excursion balance test (SEBT) as measured at baseline, 4 weeks, and 8 weeks.

2.1. Subjects

A sample of convenience of 21 subjects (representing 42 feet) volunteered for the study (3 men and 18 women). Demographic information regarding the study subjects is presented in Table 1.

Table 1
Demographic data.

Variable	Frequency	Mean ± SD	Range
Age ± SD (years)		26.1 ± 3.7	22–36
Gender	3 male 18 female		
Height ± SD (cm)		168.4 ± 7.11	160.0–182.9
Weight ± SD (Kg)		69.3 ± 13.55	52.3–113.2
Weekly training sessions ± SD (days/week)	5.94		

The study was approved by the institutional review board at the University of Texas Southwestern Medical Center in Dallas, TX and all subjects agreed via informed consent to participate in the investigation. Study exclusion criteria were any sign of foot pain, history of patellofemoral pain syndrome, plantar fasciitis, anterior or posterior tibialis dysfunction, or evidence of systemic or neurological disease within the past six months that would affect motor function. None of the subjects had previous personal experience with the specific plantar intrinsic foot training method utilized in the study.

2.2. Procedures

All baseline data was measured by one of the authors (PGC), an orthopedic physical therapy resident with one year of experience, who was blinded to all aspects of the exercise training intervention. ND was assessed in a manner similar to the methods described by Brody (1982), Sell et al. (1994), Allen and Glasoe (2000), Shrader et al. (2005), and Deng et al. (2010). All subjects were positioned on an elevated platform sitting in a chair with the hips and knees flexed to 90°. The subject stabilized their knee while the examiner palpated the position of the talus. The subtalar joint neutral (STJN) position was identified through palpation of the medial and lateral talar head while the subject pronated and supinated their STJ by elevating and collapsing their arch. The STJN position was defined as talonavicular congruency and manually determined by the position in which the talar head depth was symmetrically palpable on both sides. Once the STJN position was identified the examiner palpated the most anterior and inferior position of the navicular tuberosity and marked it with a washable fine tip marker. The subject was asked to hold that position while the height of the navicular tuberosity was measured with a digital caliper (Neiko 01407A, Neiko Tools USA) (Fig. 1). At the conclusion of the navicular height assessment the marking was rubbed off with an alcohol pad and the digital caliper was reset to zero.

Prior to the subject standing and while maintaining the STJN position additional measurements were taken to calculate the subject's AHI (Williams and McClay, 2000). Using a cloth tape measure, the total and truncated lengths of the foot were measured in a seated position with approximately 10% of the body weight on the foot. The total foot length was the distance from the most posterior aspect of the calcaneus to the tip of the longest toe. The truncated length was distance from the most posterior aspect of the calcaneus to the center of the first metatarsal head. Next, the height of the dorsum of the foot was measured with a modified carpenter's

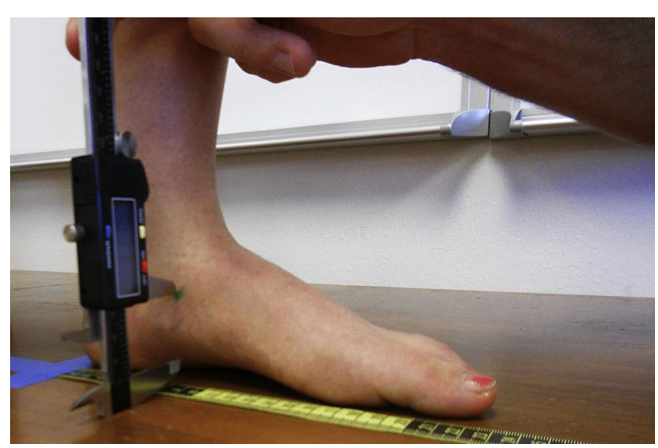

Fig. 1. Assessment of navicular height in subtalar joint neutral using digital caliper.

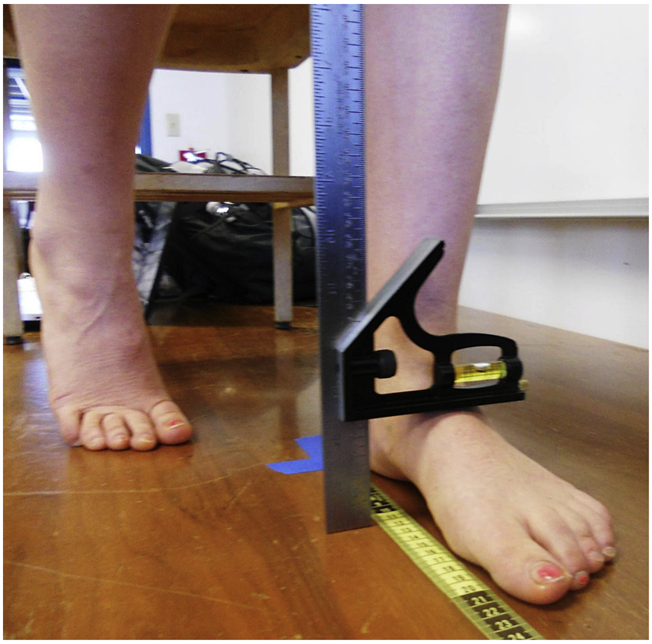

Fig. 2. Dorsal foot height measured at 50% of the foot length with a modified carpenter's square with a bubble level arm.

square with a bubble level arm (Fig. 2). The dorsum foot height was measured at 50% of the total foot length.

After both feet were measured each subject was asked to stand and assume a relaxed stance position. No attempt was made to place the STJ in a neutral position. The subject placed approximately 90% of their body weight on the measured extremity and allowed to stabilize their balance with a dowel rod in the opposite hand and toe-touch contact to the floor with the opposite lower extremity. The process of marking and measuring the navicular height position with a digital caliper as described above was repeated.

Following assessment of the relaxed navicular position the examiner used the modified carpenter's square to repeat the measurements to determine the AHI. The difference between the seated and standing navicular positions was defined as the ND. The AHI, a unitless measure, was calculated by dividing the dorsum foot height by the truncated length of the foot to form a ratio in both the seated and standing positions. Another ratio, the arch rigidity index, represents the structural mobility of the MLA. This ratio is calculated by dividing the standing AHI by the sitting AHI. Numbers closer to 1.00 represent a stiffer, more rigid MLA while increasing foot flexibility correlates with numbers that rise well above 1.00. Pilot testing on four individuals (8 feet) on consecutive weeks revealed an intrarater reliability of 0.84 for the AHI and 0.88 for the ND ($ICC_{2,1}$).

The subject's ability to functionally control the navicular position and utilize their intrinsic foot musculature was evaluated by an Intrinsic Foot Musculature Test (IFMT) described by Jam (2006). Prior to assessment the subjects were instructed in the purpose of the test and allowed practice trials to ensure comprehension of the task. The subject stood on a single limb with their arch in a modeled position with the metatarsal heads on the ground and the toes extended and relaxed. The subject was instructed to think of their foot as terminating at the balls of the feet so they would not curl their toes or grip the floor during the balancing performance trial. The subjects were allowed to lightly touch the wall if necessary to prevent a fall. The leg was to remain as still as possible without rotating the tibia or rolling the ankle in or out during the IFMT.

The aim of this functional task was to maintain the arch shape and navicular height without recruiting muscles extrinsic to the foot. Once the instructions were understood the examiner passively placed the foot in an STJN position and asked the subject to maintain this position while actively recruiting muscles in the arch of the foot. Once the opposite leg was lifted from the ground the examiner observed the performance of the test for 30 s. At the completion of the test the examiner graded the performance on a 3-point ordinal scale using the criteria listed in Table 2 (Jam, 2006). Pilot testing of this performance test showed an agreement of 70% between examiners with a Kappa coefficient of 0.55 indicating the test has moderate reliability.

The final dependent variable used to evaluate the effect of short foot training was the SEBT conducted in a manner similar to that described by Kinzey and Armstrong (1998), Hertel et al. (2000), Plisky et al. (2006), and Munro and Herrington (2010). In this task the subjects were asked to reach as far as possible with the non-weight bearing foot in five different directions relevant to the stance limb – anterior, anteromedial, medial, posteromedial, and posterior. Cloth tape measures were fixed to the floor in each of the 5 directions to measure the maximal distance reached.

During the test the subjects had to keep both hands on their hips throughout the duration of the reach and the return to the starting position while maintaining their balance. If the subject touched the ground with their reaching extremity they were required to repeat the test. After practice trials, a single effort was used to determine the reaching distance.

Pre-baseline assessment of the examiner's SEBT intratester reliability showed reliability consistent with other studies Kinzey and Armstrong (1998), Hertel et al. (2000), Plisky et al. (2006), and Munro and Herrington (2010). Pilot testing produced intraclass correlation coefficients of 0.87 for the anterior reach, 0.88 for the anteromedial reach, 0.76 for the medial reach, 0.87 for the posteromedial reach and 0.86 for the posterior reach ($ICC_{2,1}$).

2.3. Intervention

All subjects were required to attend a one-hour training session prior to baseline assessment. This training session explained the research design, provided the intervention and assessment timeline, and taught the subjects the correct technique for performing and progression of the SFE. Each subject had to demonstrate appropriate technique without compensatory extrinsic muscle contributions before completing the training session.

Each subject performed an unsupervised short foot sensorimotor training session for up to three minutes each day for four weeks at home. Each repetition was held for five seconds and

Table 2
Performance grading criteria for IFMT.

Performance Grade[a]	Steadiness of the navicular height	Tendency for over activity or compensation by extrinsic musculature
(3) – Good	Always	Never
	Able to maintain relatively steady navicular height with minimal compensation from extrinsic musculature	
(2) – Fair	Sometimes	Periodic
	Navicular position periodically fluctuated with inconsistent use of the intrinsic musculature requiring some contribution by the extrinsic musculature	
(1) – Poor	Never	Always
	Quickly lost navicular position and could not hold position without compensatory extrinsic muscular recruitment.	

IFMT – Intrinsic Foot Muscle Test.
[a] Performance grading criteria adapted from Jam (2006).

repeated for up to three minutes (approximately 30 repetitions). The exercise difficulty was progressed when the subject felt they could perform the exercise correctly for the entire three minute exercise period without significant muscle soreness the following day. The exercise training began in a sitting position and progressed to a double, then single leg stance position. 20 of the 21 subjects were able to progress the exercise training program to a unilateral stance position during the four weeks of training at an average of 19 days (range of 6–28 days and SD = 6.4). Variables the subjects utilized to fine tune the difficulty or complexity of the exercise included altering their vision status and the surface stability on which they trained.

Intervention compliance was monitored with an exercise log in which the subjects recorded the position in which they exercised, the need for balance assistance, visual status (eyes open or closed), stabile or labile training surface, and any contralateral limb movements used during the short foot hold position. Subjects were asked to maintain their regular levels of activity and not introduce any new fitness training routines during the study. The exercise intervention only lasted the first four weeks of the study and subjects were asked to discontinue the training sessions during the next four weeks so as to assess for any carryover effect from the training.

3. Data analysis

The amount of ND and the distance reached on the SEBT were both analyzed by repeated measures analysis of variance (ANOVA) to determine if statistically significant differences existed between measurements taken at baseline, 4 weeks post-intervention, and at 8 weeks post-intervention. To protect against Type I error, Tukey tests were used to ensure the alpha levels ($p < 0.05$) identified the probability that one or more of the pairwise comparisons would be falsely declared significant. The Friedman repeated measures ANOVA on ranks was used to analyze the ordinal classification of intrinsic muscle function during unilateral stance. The AHI and two of the SEBT reach tests (anteromedial and posterior) were also evaluated by the Friedman repeated measures ANOVA on ranks as the subject data failed the Shapiro–Wilk normality test that ensures a normal distribution in the study population. SigmaPlot 12 software (Systat Software, Inc., San Jose, CA) was used for all statistical analysis.

4. Results

The subjects reported a daily exercise compliance of 85% or an average of 5.9 training sessions per week. At baseline the subjects had a mean ND of 12.7 mm ± 6.0 mm which had a significant decrease to 10.9 ± 5.5 mm drop ($p = 0.04$) at 4 weeks and 10.5 ± 5.7 at 8 weeks ($p = 0.01$) (Fig. 3). There was not a significant change between the ND findings at 4 and 8 weeks after the exercise training ceased ($p > 0.05$). AHI and IFMT also had a significant change from baseline to 4 and 8 weeks post-intervention ($p < 0.05$). Again, there was no change in AHI or IFMT between weeks 4 and 8 ($p > 0.05$). There was a significant improvement in reach distance at 4 and 8 weeks from baseline on the SEBT for all directions ($p < 0.05$) with the exception of the anterior reach where $p = 0.075$. With the exception of the posteromedial reach there were no significant changes between weeks 4 and 8 for any direction of reach on the SEBT (Table 3). Table 4 represents the frequency of IFMT performance grade scores at baseline and at 4 and 8 weeks follow-up. 25

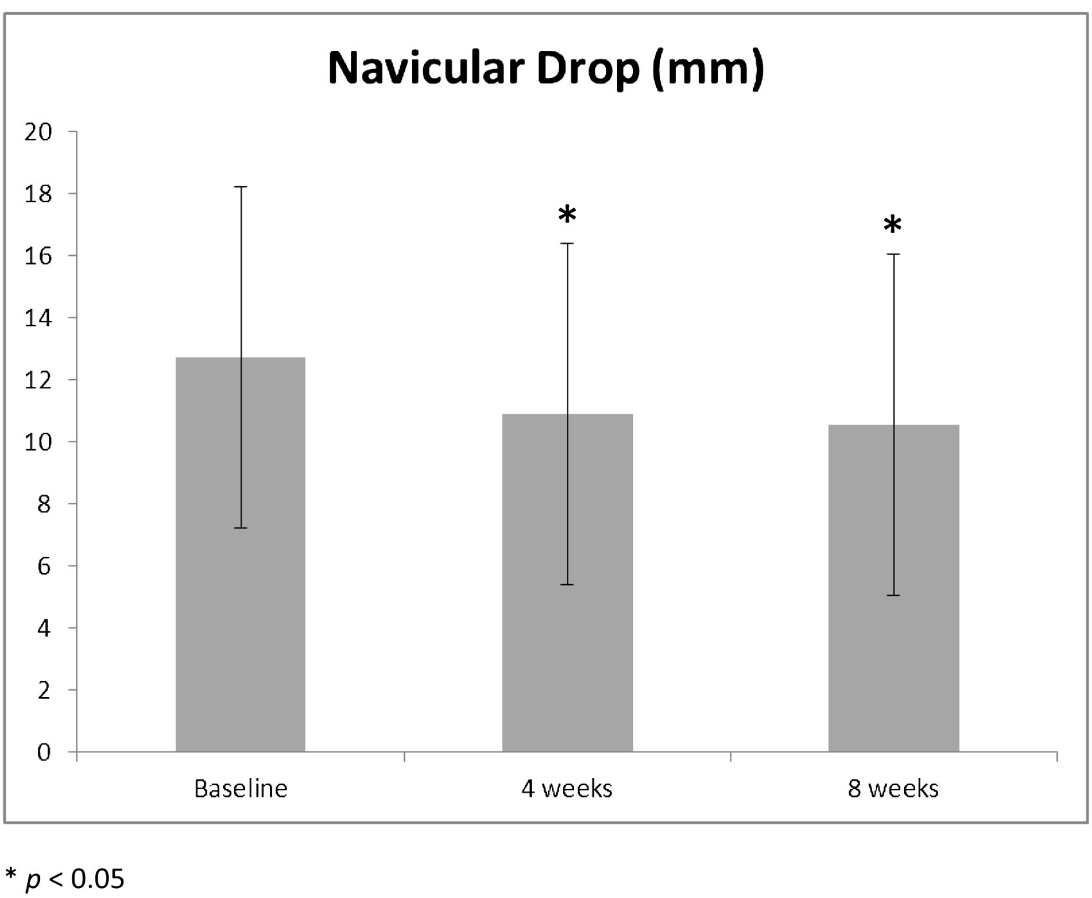

Fig. 3. Mean navicular drop (mm) at baseline compared to 4 and 8 weeks post exercise training intervention.

Table 3.
Mean change in navicular drop, AHI, IFMT, and SEBT from baseline to 4 and 8-week follow-up.

Variable	Initial	4 wk FU	8 wk FU	p value Initial to 4 wks	p value Initial to 8 wks	p value 4 to 8 wks
Navicular drop ± SD (cm)	12.7 ± 6.0	10.9 ± 5.5	10.5 ± 5.7	$p = 0.04$	$p = 0.01$	NS
AHI ± SD (%) in standing	28 ± 2	29 ± 2	29 ± 2	$p = 0.03$	$p = 0.03$	NS
IFMT (ordinal grade median value)	2.0	3.0	3.0	$p = 0.00$	$p = 0.00$	NS
Anterior reach ± SD (cm)	37.0 + 4.1	37.9 ± 4.2	38.6 ± 6.0	NS	NS	NS
Anteromedial reach ± SD (cm)	45.7 ± 6.0	48.2 ± 5.3	48.9 ± 7.2	$p = 0.00$	$p = 0.00$	NS
Medial reach ± SD (cm)	57.8 ± 7.4	61.6 ± 6.6	62.0 ± 6.6	$p = 0.00$	$p = 0.00$	NS
Posteromedial reach ± SD (cm)	71.2 ± 9.2	75.4 ± 8.8	78.1 ± 10.4	$p = 0.00$	$p = 0.00$	$p = 0.04$
Posterior reach ± SD (cm)	91.2 ± 10.8	94.8 ± 9.9	94.3 ± 9.9	$p = 0.00$	$p = 0.00$	NS

AHI – arch height index; IFMT – intrinsic foot muscle test; FU – follow-up; SD – standard deviation.
NS $-p > 0.05$.

feet (59%) improved their grade, 15 feet (36%) did not change, and 2 feet (5%) had lower scores at the 4-week reassessment.

5. Discussion

Our initial findings support that a simple training program has an impact on ND, arch height morphology, foot intrinsic function in static stance, and dynamic balance and reach abilities in an asymptomatic population. These findings are similar to others that have found that alterations in IFM activity impact navicular positioning (Fiolkowski et al., 2008; Campbell et al., 2008; Headlee et al., 2008). These results correlate with previous EMG studies that suggest IFM function has a supportive role in the maintenance of the MLA. Not only do these muscles prevent increased ND they may have the capacity to alter the AHI with a simple exercise regimen. Significant change takes as little as four weeks and the benefit is maintained at least another 4 weeks without further exercise training. This result is similar to the impact of a three week training program reported by Campbell et al. (2008). It is unknown if this effect lasts longer than eight weeks.

These results are in contrast to a recent randomized controlled trial in which SFE training was compared to a 4-week course of towel-curl exercise training (Lynn et al., 2012). In this study there were no significant post-training differences between the exercise groups in regards to navicular height in relaxed stance; however, the total range of movement in the non-dominant limb's center of pressure during a dynamic reaching task was smaller for the group that underwent SFE training. The difference in navicular position may be attributable to the authors using a modified navicular drop test in which the relaxed position of the navicular's height was used as a dependent variable as opposed to the change in navicular height from a neutral to relaxed position as was used in this study.

It is important to note that this study is an indirect assessment of the influence of plantar intrinsic foot muscle training as there are currently no gold standards of measuring isolated intrinsic foot muscle strength (Soysa et al., 2012). Instead we have evaluated the effect of plantar intrinsic foot muscle training in its ability to impact navicular position and influence dynamic capabilities during tasks with increased postural demands (Kelly et al., 2012).

The clinical relevance of these changes has yet to be established with metric assessment of the minimal detectable change (MDC) values. Allen and Glasoe (2000) and Shrader et al. (2005) found that the standard error of measurement (SEM) for the navicular drop is in the range of 1–2 mm which computes to an MDC of approximately 6 mm. This value is substantially less than 2 cm change that we observed between baseline and 4 weeks. McPoil et al. (2009) reported an SEM for measuring the weight-bearing dorsal arch height in the range of 10–20 mm which represents approximately the 1% change in AHI ratio given the average foot length of the subjects in this study.

Toe curling exercises (towel crunches, marble pick-ups) are often prescribed to strengthen intrinsic foot strength however these exercise activities tend to recruit the long toe flexors (flexor hallucis and digitorum longus) as opposed to the intrinsic foot muscles. Conversely, SFE training targets the plantar intrinsic muscles of the foot. These intrinsic muscles may have a similar functional role as the deep core stabilizers of the spine. They work at segmental levels to stabilize the MLA and have an important neuromuscular role in fine tuning the position of the arch during weight-bearing functional activities. These findings may be of value to clinicians who attribute excessive pronation as a contributing factor to lower extremity injuries.

The subjects in this study were asymptomatic with a wide range of ND (0–21 mm) but post hoc analysis revealed a significantly greater impact on navicular height drop in those feet whose baseline ND was greater than 15 mm as compared to those with less than 15 mm. This amount of ND was chosen as this value is a commonly accepted standard as proposed by Brody (1982) as being abnormal or excessive. The overall mean change in ND for the study population was approximately 2 mm but closer to 6 mm in the subjects that had a baseline ND of greater than 15 mm. Conversely, subjects in the normal range of a 6–9 mm drop saw essentially no change in their ND after 4 weeks of short foot training. Using the somewhat arbitrary, but commonly accepted standard of greater than a 10–15 mm ND one could speculate that this exercise training may have a more specific impact on subjects with abnormal STJ hyperpronation compensation tendencies. Further research in this area may benefit from controlling this potentially confounding variable by evaluating the impact of plantar intrinsic foot muscle training in subjects with different scores on the foot posture index (Redmond et al., 2006).

The results of this study also offer preliminary evidence to suggest that SFE training in normal subjects may have an impact on muscular recruitment strategies during unilateral stance and improve contralateral limb reaching abilities in an anteromedial, medial, posteromedial, and posterior direction. While subjects were educated on minimizing extrinsic muscle activity during the exercise training it is not possible to exclude the potential for enhancements in dynamic balance being attributable to improved subtalar joint control via increased awareness and control of the posterior tibialis and fibularis muscles.

A limitation of this study is that it evaluated the response of short foot training in a relatively small sample of paired feet in an asymptomatic population with narrow demographic

Table 4
IFMT score for all 42 feet at baseline, 4 week, and 8 week follow-up.

Variable	Baseline	4 wk FU	8 wk FU
IFMT performance grade 1 – poor	14	5	5
IFMT performance grade 2 – fair	17	12	5
IFMT performance grade 3 – good	11	25	32

characteristics and somewhat homogenous abilities in their dynamic, functional movement tasks. The study also assumes that excessive ND and alterations in AHI are accurate composite predictors of compensatory STJ pronation and changes in the MLA (Mueller et al., 1993; Menz, 1998; Hannigan-Downs et al., 2000; Williams and McClay, 2000; Shrader et al., 2005). Furthermore, this study presumes that alterations in MLA may contribute to lower extremity injury. Even if plantar intrinsic foot musculature strength contributes to MLA height we do not know to what degree this variable would impact a multifactorial movement event in a symptomatic population. However, reversal of plantar intrinsic contractile impairments may have an important role in the absence of other arch maintenance disabilities.

Another potential source of bias is that the subjects were instructed in the short foot exercises immediately prior to the baseline assessment. It is possible this initial training session may have activated dormant muscle awareness and influenced the baseline dynamic measurements of the IFMT and SEBT.

Future investigations need to look at the impact of IFM training on pathological populations to see if changes in MLA morphology correlate with improvements in pain or function. There are suggestions from the literature that a variety of pathological conditions such as posteromedial shin pain (Garth and Miller, 1989; Sherman, 1999), chronic ankle instability (Drewes and Hertel, 2009), and plantar fasciitis (Chang et al., 2011) may be associated with deficits in plantar intrinsic foot strength. This pilot study suggests that it may be possible to influence some of the common structural compensations and functional impairments that are commonly associated with these injuries. Further study in a foot posture type or pathology specific population is warranted.

6. Conclusion

A four week training program emphasizing recruitment of the plantar intrinsic muscles may have value in dynamically supporting the MLA. IFM training may have an adjunctive role in preventing excessive ND, influencing dynamic control during functional tasks, and have potential value as part of a comprehensive approach to addressing abnormal hyperpronation mechanics in a selected subset of subjects.

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