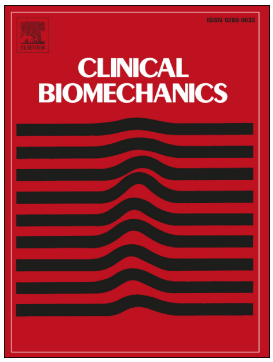
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The effects of foot core exercises and minimalist footwear on foot muscle sizes, foot strength, and biomechanics: a systematic review and meta-analysis

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Abstract

Background: Specific foot exercises and the use of minimalist shoes during running or daily life were suggested to strengthen the intrinsic foot muscles and to modify locomotion biomechanics. We aimed to review the effectiveness of these interventions to modify foot muscle sizes, foot strength, and biomechanical outcomes.

Method: PubMed, Embase, Cochrane Library and SportDiscus databases were searched (last update: 12 March 2024). Randomized controlled trials with intervention duration of four weeks or more were included. A random-effect meta-analysis was performed when at least two studies were available for an outcome. Standardized mean differences and corresponding 95% confidence intervals were reported. The certainty of the evidence was assessed by considering risk of bias, imprecision, inconsistency, and indirectness. The evidence not summarized in the meta-analysis was synthetised.

Findings: Twenty-eight trials (1399 participants) were included in the systematic review and seventeen meta-analyses were performed. From meta-analyses, minimalist shoes lead to greater strength of toes 2 to 5 (confidence interval = 0.02 to 0.76), and foot exercises resulted in lower medial longitudinal arch motion during running (confidence interval = 0.08 to 0.82). The certainty of the evidence was low to very low, mainly due to the limited number of available studies and high risk of bias. The systematic synthesis supported exercises and minimalist shoes to increase foot strength, but was conflicting for muscle sizes. The interventions occasionally modified walking and running biomechanical variables..

Interpretation: Foot exercises and minimalist shoes may be appropriate to increase foot strength and to induce biomechanical changes during dynamic tasks.

Keywords

Short foot exercise, Minimalist running shoe, Abductor hallucis, Ultrasound imaging, Biomechanical phenomena, Kinematics

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Introduction

The foot is a complex structure regulated by both the extrinsic and intrinsic foot muscles. The origins and attachments of the plantar intrinsic foot muscles (PIFMs) are located within the foot, and their resulting short moment arms designate them as local stabilizers for the foot.[1] As a result, the PIFMs contribute to maintaining medio-lateral balance during single-leg stance,[2] and during walking and running, they help attenuate foot impact upon landing and support foot stiffness during push-off.[3] Thicker PIFMs were observed in athletes compared to non-athletes.[4] In contrast, decreased PIFM sizes have been seen in various musculoskeletal disorders,[5-6] neurological and systemic diseases,[7-8] and among older individuals,[9] compared to healthy people. Common rehabilitation and return-to-sport approaches have given poor attention to interventions targeting the PIFMs.[10] These encompass foot exercises and specific footwear.[11] First, so-called foot muscle exercises – such as the short foot, foot doming, and the toe-spread-out exercises – were proved to activate the PIFMs.[12] Authors suggested to familiarize with these exercises through active-assisted contractions or with the aid of neuromuscular electrostimulation (NMES) targeting the medial foot muscles. They then recommend to combine the exercises into more global movements with the whole lower limb as progression.[10-11] Second, the use of minimalist running shoes (MRS) during running or daily life activities was also associated with hypertrophy and strengthening of the PIFMs.[13-14] MRS exhibit a high flexibility, lightweight construction, and a lack of stability features. As a result, they offer minimal interference between the foot and the surrounding environment.[15]

The strength of the foot refers to the ability of the intrinsic and extrinsic foot muscles to generate force. Foot muscle strength can be assessed directly through toe dynamometry, foot mobility under load and foot posture.[16] Indirect muscle strength assessment methods have also been described, using imaging techniques such as ultrasound or magnetic resonance imaging to measure muscle sizes.[16-18] Previous meta-analyses have demonstrated that PIFM exercises were linked to improved toe flexion strength, foot mobility, foot posture, and balance.[16, 19-22] Additionally, systematic reviews have outlined the growth in muscle sizes and modifications in lower limb biomechanics following these exercises,[9, 23] as well as following the use of MRS.[23-24] To our knowledge, no previous meta-analysis investigated the effects of PIFM exercises on PIFM sizes, and no meta-analysis of randomized

controlled trials investigated the benefits of MRS. Additionally, the existing meta-analyses and systematic reviews on foot strength and biomechanics have included a limited number of articles. This may be explained by their focus on specific PIFM exercises (e.g. the short foot exercise),[21-22] their population of interest, which is often pes planus, older people or asymptomatic participants,[9, 22-23] and search strategies that may have missed important synonyms.[9, 23, 25-26] Finally, the field of PIFM strengthening is rapidly evolving,[27-30] suggesting that more articles could be included into existing meta-analyses and that new meta-analyses may be feasible.

Therefore, the objective of this systematic review and meta-analysis was to thoroughly examine the effects of PIFM exercises and the use of MRS on PIFM sizes, foot strength, and biomechanics during dynamic tasks in both asymptomatic and symptomatic participants.

The hypotheses were that both foot exercises and MRS would result in increased PIFM sizes and foot strength. During running and walking, it was expected that these interventions would result in kinematic changes characterized by a forefoot strike pattern and a decreased medial longitudinal arch (MLA) mobility, along with kinetic and spatiotemporal changes.

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Methods

1. Study design

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). The protocol was prospectively registered in the PROSPERO database (CRD42023411084).

2. Sources and research strategy

PubMed (Medline), Embase, Cochrane Library and SportDiscus databases were consulted. The Cochrane Collaboration recommends at least searching in the three first databases,[31] while SportDiscus is more specific to sports medicine. Databases were searched using equations based on two search strings: The first included synonyms of PIFMs and the second synonyms of foot exercises alongside MRS. These terms were searched using Title, Abstract, Thesaurus, and Keyword fields, without filter. A team of librarians helped in creating this search strategy. The initial search was conducted on April 14, 2023, and subsequently updated on March 12, 2024, using the same search methodology (Supplementary file A). Additionally, a manual search was conducted within the reference lists of previous systematic reviews and meta-analyses.[9, 19-25, 32-33]

3. Eligibility criteria

Randomized controlled trials (RCT) with full texts available in English or French were included if their intervention lasted a minimum of 4 weeks and involved either PIFM exercises or the use of MRS during running or daily activities. The main outcomes were PIFM sizes as well as hallux, toes, and doming strength. Secondary outcomes included lower limb biomechanics during dynamic tasks such as walking, running, side-cutting, and jump-landing. Studies were included if at least one of these outcomes was assessed at baseline and immediately following the intervention.

4. Study selection

The search of available resources was conducted by two investigators (X.X. and X.X.) among the four databases. Duplicates were automatically removed using EndNote software, and the remaining articles were imported to Rayyan website where any remaining duplicate was manually removed. Two reviewers (X.X. and X.X.) independently selected articles based on titles and abstracts before resolving any disagreement. The articles were retrieved online, and authors were contacted whenever

necessary. Then, the same two reviewers, who were still blinded from each other, selected the retrieved articles through full-text reading and specified the reason for exclusion, such as language barrier, study design, intervention, outcomes, or the population. A third investigator (X.X.) was consulted to resolve any remaining disagreement.

5. Risk of bias assessment

Version 2 of Cochrane risk-of-bias tool for randomized trials (RoB2) was used to assess the risk of bias in RCT across five domains: (1) randomisation process, (2) deviations from intended interventions, (3) missing outcome data, (4) measurement of the outcomes, (5) and selection of the reported results. Two investigators (XX. and XX.) independently applied RoB2, and then met to reach consensus on the assessment of bias as "low risk", "some concerns", or "high risk".[34]

6. Data collection process and analysis of data

Data extraction from the selected articles was conducted by one reviewer (X.X.) using pre-established tables. The extraction covered study information, number of participants per group, demographics, intervention details (duration, frequency, volume in early and late intervention stages, and supervision), pre-and post-intervention results, adherence, study retention, and adverse events. Whenever possible, a meta-analysis was performed using RevMan web review manager (version 8.1.1.), considering two subgroups: PIFM exercises and MRS. For each outcome, a meta-analysis was conducted if two studies were available in a subgroup. A random effect model utilizing standardized mean differences (SMD) was applied to analyse post-intervention means and standard deviations. In case of missing means and standard deviation, they were calculated from medians and interquartile ranges or maximum and minimum values using the formulas provided by Wan et al. (2014).[35] Standard deviation was also calculated from standard error of the mean using formula (1).

(1) $SD_j = SEM \times \sqrt{n_j}$; where SDj is the standard deviation of the group, SEM is the standard error of the mean, and nj is the sample size of the group.

Subgroup SMD values with 95% confidence intervals (CI) and measures of heterogeneity (I^2) were reported.[36] The meta-analysis was non-significant if the CI of its SMD contained zero. For each meta-analysis, the certainty of the evidence was assessed using the Grading of Recommendations

Assessment, Development, and Evaluation (GRADE) methodology.[37] Because only RCT were included, the grading started at "high certainty of the evidence". It was then downgraded to moderate, low and very low certainty if serious (one level) or very serious (two levels) concerns were raised for the following criteria: (1) Risk of bias, i.e. one or more studies with two domains of RoB2 tool scored at "high risk", (2) imprecision, i.e. low sample size if there were less than 400 participants per group and/or contradictory findings under the CI (e.g. evidence of harm and evidence of benefits, with very small effect sizes regarded as "no effect"), (3) inconsistency, i.e. I^2 higher than 50% was regarded as "substantial",[36] (4) indirectness, i.e. only a restricted part of the research question was addressed, and (5) publication bias was investigated by funnel plots when at least 10 RCT were available.[37]

A synthesis of results (systematic review) was performed for data that could not be combined in the meta-analysis. Therefore, SMD were determined following Lakens' (2013) guidelines. Specifically, SMD values were calculated using Hedge's g_s (2), which is based on Cohen's d_s (3). Hedge's g values are considered more reliable for studies with small sample sizes. The SMD were interpreted as following: < 0.2 very small, < 0.5 small, < 0.8 medium, < 1.2 large, < 2 very large, and ≥ 2 huge.[38]

(2) Hedge's g = $Cohen's\ d \times (1 - \frac{3}{4\times(n_{IG}+n_{CG})-9})$;

(3) Cohen's d = $\frac{Mean_{IG}-Mean_{CG}}{\sqrt{\frac{(n_{IG}-1)\times SD_{IG}^2-(n_{CG}-1)\times SD_{CG}^2}{n_{IG}+n_{CG}-2}}}$;

Where, for equations (2) and (3), n is the sample size, SD is the standard deviation, IG refers to the intervention group, and CG refers to the control group.

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Results

1. Study selection

A total of 2485 references were identified through the databases, with 5 additional articles found among the reference lists (Figure 1).[39-43] After removing 668 duplicates, the title and abstract screening identified 89 articles for full-text review. Three articles were not retrieved,[29, 44-45] and one article was withdrawn between identification and screening.[46] Ultimately, 28 RCT were included in the systematic review, with 9 studies included in the meta-analyses for PIFM sizes, 9 for strength, and 10 for biomechanic parameters.

[INSERT HERE FIGURE 1: PRISMA FLOW CHART]

2. Risk of bias

The complete risk of bias assessment can be found in Supplementary file B. In total, 5 studies were classified as low risk, 4 as some concerns, and the remaining 19 as high risk of bias.

3. Characteristics of the studies

The characteristics of each study are summarized in Table 1. This systematic review includes the results from 1399 participants. Some studies did not provide enough information regarding the biological sex of participants.[47-52] Nevertheless, there was relative gender parity, with approximately half men and half women (male participation between 640 and 716 individuals).

Twenty-one studies implemented PIFM exercises. Suda et al. (2024) performed a subgroup analysis on the sample included in Matias et al.'s study.[27, 53] Six studies involved symptomatic participants.[30, 40, 54-57] Five studies included participants over the age of 60.[40, 42, 56-58] The intervention durations ranged from 1 and 6 months. The differences between the intervention and control groups were seen in the performance of PIFM exercises,[28, 30, 39, 50, 54-55, 59] including the short foot exercise carried out during wall squat,[28] as well as PIFM exercises combined with various interventions such as exercises targeting the extrinsic foot muscles,[14, 27, 42, 47, 53, 56, 60-61] physiotherapy oriented towards low-back pain,[55] and optimized podiatric treatment.[40] Adjuvant methods such as NMES, transcutaneous electrical nerve stimulation,[58, 62] electromyographic biofeedback, and electromyographically-controlled electrostimulation were used during the PIFM exercises,[57, 63] with NMES and transcranial direct current stimulation also being used as stand-alone technique.[48, 61]

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Besides, nine studies utilized MRS during running,[13, 41, 43, 48-49, 51, 64] or daily life activities.[14, 52] Three of these studies combined MRS during running along with exercises targeting the PIFMs and extrinsic foot muscles,[41, 43, 64] while one study included both a MRS group and a PIFM exercise group.[14] In one study, children aged 11 years old wore MRS during school hours.[52] The mean age of participants in the other eight studies ranged between 20 and 40 years old. The MRS interventions lasted between 1.5 and 9 months.

Adherence to the interventions was often high, but many RCT did not adequately report this outcome. Reported retention rates varied between 74 and 100%. Adverse events included injuries and overloading symptoms. For PIFM exercise studies, adverse events were reported in 5 participants of intervention groups versus 13 participants of control groups. For MRS studies, the adverse events affected 23 intervention versus 6 control participants. For more details on supervision, adherence, drop out rates, retention, and adverse events, see Supplementary file C.

[Insert here Table 1: Study population and intervention characteristics associated to the articles included in the systematic review and meta-analysis]

4. Summary of results

The results related to PIFM sizes and strength are summarized in Table 2. The results related to biomechanics are available in Supplementary file D. In both tables, data used in the meta-analyses are highlighted using "MA" in superscript.

[Insert here Table 2: Study results regarding muscle sizes and foot strength]

4.1. Plantar intrinsic foot muscle sizes

Meta-analyses were conducted for abductor hallucis, flexor digitorum brevis, and flexor hallucis brevis muscles (Figure 2). Therefore, volume, cross-sectional area (CSA), and thickness were used depending on availability in the articles. The CI crossed zero for abductor hallucis, with a SMD of 0.37 for PIFM exercises ([-0.07, 0.82], I^2 = 47%, p = 0.09) and 0.66 for MRS ([-0.03, 1.34], I^2 = 75%, p = 0.06). Similarly, there were no significant differences for flexor digitorum brevis between interventions and control (PIFM exercises: SMD = -0.16 [-0.61, 0.30], I^2 = 0%, p = 0.50 and MRS: SMD = 0.71 [-0.08, 1.50], I^2 = 81%, p = 0.08), as well as flexor hallucis brevis (PIFM exercises: SMD = -0.43 [-0.89, 0.04], I^2 = 0%, p = 0.07 and MRS: SMD = -0.01 [-0.50, 0.48], I^2 = 0%, p = 0.97).

The synthesis of data that could not be combined into the meta-analyses revealed the following: PIFM exercises did not result in increased CSA in the abductor hallucis, abductor digiti minimi, flexor digitorum brevis and flexor hallucis brevis muscles compared to a warm-up and stretching routine before running sessions.[60] The effect sizes for quadratus plantae CSA were moderate in favour of PIFM exercises in runners (SMD = 0.53, $p < 0.05$).[14] Individuals with low back pain experienced a significant increase in abductor hallucis CSA after PIFM exercises combined with other non-invasive interventions to the lumbar spine, compared to exercises with no expected effects (SMD = 2.29, $p < 0.001$).[55] Adding NMES or transcutaneous electrical nerve stimulation to PIFM exercises did not result in significant differences in abductor hallucis CSA compared to exercises with sham-NMES or sham-transcutaneous electrical nerve stimulation.[58, 62] The same was true for NMES alone compared to no intervention.[48] Regarding MRS, a six-month transition to MRS used during running combined with extrinsic foot muscle exercises did not lead to significantly increased total and forefoot muscle sizes compared to the group that ran in traditional footwear.[13] Similarly, an eight-week transition to MRS running did not significantly increase the abductor hallucis CSA compared to no intervention (median changes = 0.42cm² for MRS and 0.36cm² for control, $p = 0.203$).[48] A three-month transition to MRS running showed significant increases in abductor hallucis CSA, abductor digiti minimi CSA and volume – but not flexor digitorum brevis CSA – compared to running with traditional footwear (SMD ranging from 1.79 to 2.78).[51] Lastly, using MRS during daily activities significantly increased quadratus plantae CSA compared to no intervention, with a moderate effect size (SMD = 0.61, $p < 0.05$).[14]

[Insert here Figure 2: Meta-analyses for intrinsic foot muscle sizes]

4.2. Foot strength

Meta-analyses were conducted for hallux, toes 2-5 and metatarsophalangeal joint (MTPJ) flexion (Figure 3). The participants who used MRS showed significantly greater flexion strength in their toes 2-5 compared to control group (SMD = 0.39 [0.02, 0.76], $I^2 = 0\%$, $p = 0.04$), but this was not the case for PIFM exercises (SMD = 0.16 [-0.04, 0.37], $I^2 = 0\%$, $p = 0.12$). Hallux flexion strength did not change significantly between intervention and control groups (PIFM exercises: SMD = 0.04 [-0.17, 0.25], $I^2 = 0\%$, $p = 0.71$ and MRS: SMD = 0.33 [-0.03, 0.70], $I^2 = 0\%$, $p = 0.07$). Similarly, there was

no significant difference between the PIFM exercises and the control group for hallux and toes together (SMD = 0.41 [-0.16, 0.99], I^2 = 0%, p = 0.16) nor for MTPJ flexion (SMD = 1.16 [-0.23, 2.55], I^2 = 80%, p = 0.10).

The synthesis of data not included in the meta-analyses included strength exerted while flexing the hallux, the toes 2-to-5, the 5 toes together, and MTPJ, alongside foot doming strength. Adding PIFM exercises to in-person extrinsic exercises in older adults significantly increased hallux flexion (SMD = 0.38) and toes 2-to-5 flexion (SMD = 0.15) in the intervention group but not in the control group that performed similar exercises at home without increasing intensity.[56] PIFM exercises increased MTPJ strength with huge effect sizes (SMD = 2.03, p < 0.001) compared to no-intervention.[39] PIFM exercises combined with other exercises also increased doming strength compared to maintaining habitual running.[14] PIFM exercises combined with electromyographic-biofeedback increased toe grip strength compared to no biofeedback on the non-dominant side (SMD = 0.46, p = 0.029), but not for the dominant side.[63] Lastly, transcranial direct current stimulation was beneficial with small but significant effect sizes for toes 2-5 strength (SMD = 0.24, p = 0.015), and very large effect sizes for MTPJ strength compared to no intervention (SMD = 1.49, p = 0.008).[61] The use of MRS during daily activities improved foot doming strength compared to no intervention (SMD = 0.35, p < 0.05).[14] Besides, combining MRS during running with PIFM exercises and additional exercised increased MTPJ strength in the intervention group but not in the group that maintained habitual running.[64]

[Insert here Figure 3: Meta-analyses for foot strength]

4.3. Biomechanics

Meta-analyses of biomechanical outcomes are available in Supplementary file E. Meta-analyses were first conducted for MLA motion during walking and running as well as foot incidence at foot strike while running. MLA motion was significantly lower during running in the PIFM exercise group compared to the control group (SMD = 0.45 [0.08, 0.82], I^2 = 0%, p = 0.02), but not during walking (SMD = -0.01 [-0.59, 0.56], I^2 = 5%, p = 0.96). For foot incidence at foot strike after MRS compared to control, the CI lower bound was zero (SMD = 0.78 [0, 1.56], I^2 = 59%, p = 0.05). Meta-analyses were also conducted for vertical and horizontal ground reactions forces, ankle sagittal moment, and the first MTPJ sagittal moment. The PIFM exercise and control groups did not show significant

differences in vertical ground reaction forces during walking and running (respectively SMD = -0.09 [-0.60, 0.42], I^2 = 0%, p = 0.73 and SMD = 0.21 [-0.50, 0.93], I^2 = 64%, p = 0.56), anterior ground reaction forces during running (SMD = -0.03 [-0.39, 0.34], I^2 = 0%, p = 0.89), and the peak sagittal moments during running at the ankle and first MTPJ (respectively SMD = 0.07 [-0.87, 1.02], I^2 = 61%, p = 0.88 and SMD = -0.22 [-0.80, 0.35], I^2 = 0%, p = 0.45). Lastly, meta-analyses were performed on walking stance phase duration and time to lowest MLA height, which also did not show significant differences between the PIFM exercises and control (respectively SMD = -0.01 [-0.66, 0.63], I^2 = 41%, p = 0.97 and SMD = 0.54 [-0.03, 1.11], I^2 = 0%, p = 0.06).

The synthesis of data showed that PIFM exercises were found to be associated with biomechanical changes compared to the control groups during running and walking. During running, there was a significant increase in the shank-calcaneus inversion peak angle after PIFM exercises compared to warm-up and stretching (SMD = -0.37, p = 0.037).[53] Additionally, at 14km.h^{-1}, the control group showed a significantly higher increase in the first MTPJ sagittal plane range of motion (ROM) compared to the PIFM exercise group, and at 18km.h^{-1}, foot contact time was decreased.[47] Significant differences were observed using Statistical Parametric Mapping for Chopart dorsiflexion and inversion, calcaneus-metatarsals adduction, Lisfranc dorsiflexion, and first MTPJ abduction and dorsiflexion ($p < 0.05$).[53] Coordination of two joint couples – calcaneus-midfoot and midfoot-metatarsus – showed a significant increase following PIFM exercises compared to warm-up and stretching ($p < 0.05$), but not for the other joint couples.[27] During walking, PIFM exercises did not have significant impact on kinematic variables compared to control interventions. For walking kinetic variables, the medial ground reaction peak significantly decreased in PIFM exercise group compared to the control group (SMD = -0.66, p = 0.033). Walking peak plantar pressure and foot contact area were not significantly affected,[30] but centre of pressure excursion index was more laterally deviated in the intervention group.[28] Single-leg squat dynamic valgus index and jump (horizontal and vertical) kinetics did not show significant difference between groups.[39, 54]

Distinct biomechanical changes were also identified following MRS used during running. In a study implementing a 3-month transition to MRS running, there was a notable decrease in maximum MLA angle during rearfoot strike running compared to no intervention (p = 0.031), although no significant

changes were observed during a forefoot strike running task. During the rearfoot strike running task, the intervention group also exhibited significant changes in arch angle range of motion, arch height range of motion, and arch stiffness when compared to the control group, though no statistical significance was reported between groups.[64] In another 3-month transition to running in MRS combined with PIFM exercises, there was a significant increase in ankle range of motion while running shod, but not when running barefoot, along with a change in foot strike pattern (heel-toe latency) from rearfoot strike to forefoot strike pattern compared to the habitual running shoe group. Differences in knee kinematics were not statistically different between groups.[43] A third study of running in MRS also implemented PIFM and extrinsic foot muscle exercises. This intervention did not lead to significant changes in loading rate, impact peak force, vertical stiffness, stiffness of the knee and ankle during running in traditional shoes (between group p-values not available).[41] Exhaustive biomechanical findings are displayed in Supplementary file D.

5. GRADE rating for meta-analysis

The evidence of the meta-analysis assessing the impact of PIFM exercises on abductor hallucis muscle sizes was of low quality. The quality of the evidence was very low for all other meta-analyses (Table 3). This was mainly due to high risk of bias, low sample sizes and indirectness. Funnel plots could not be performed due to the limited number of RCT in each meta-analysis.

[Insert here Table 3: GRADE summary table]

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Discussion

This systematic review and meta-analysis aimed to investigate the impact of PIFM exercises and MRS on foot muscle sizes, foot strength, and biomechanical variables.

Out of the systematic review, performing foot muscle exercises seem to be appropriate to increase foot strength and it could increase the sizes of some PIFMs. Wearing MRS during running or during daily activities could be appropriate to increase the sizes of multiple PIFMs and may be helpful to increase foot strength. Biomechanical effects during walking and running were observed for both interventions. Besides, we conducted 17 meta-analyses and assessed the certainty of their evidence using GRADE methodology.[37] The uncertain to very uncertain evidence summarized in the meta-analyses revealed the following: First, PIFM exercises may have moderate effects on abductor hallucis size, all toes flexion strength, and metatarsophalangeal flexion strength. It may have trivial effects on hallux strength and toes 2-to-5 strength. Regarding the biomechanical variables, the meta-analyses revealed a decreased MLA mobility while running and decreased time to lowest MLA height while walking, with very low quality of evidence. Second, MRS may have a moderate effect on abductor hallucis size, flexor digitorum brevis size and foot strike pattern while running. It may also increase hallux flexion and toes 2-to-5 flexion strength.

Several experimental studies have highlighted the increased recruitment of the PIFM during specific exercises, including the short foot, toe-spread out, first toe extension, second-to-fifth toes extension,[12] toe grip, and metatarsophalangeal flexion exercises.[65] Also, PIFM were shown to be thicker after years of MRS used during daily life compared to wearing traditional footwear.[66] Therefore, several weeks to months of these interventions have the potential to generate hypertrophy and increased strength. However, the RCT included in this systematic review did not consistently report increased strength and muscle sizes. These RCT used ultrasound and magnetic resonance imaging to estimate PIFM sizes, as supported by various reliability studies.[18, 67] To estimate foot strength, hand-held and fixed dynamometers were used, as well as plantar pressure technologies, which are also reliable tools to estimate toe flexion and doming strength.[11, 68]

The conflicting findings found in the included RCT could be explained by various sources of heterogeneity. First, the focus of this systematic review was on symptomatic and asymptomatic

participants. However, for MRS, no study included symptomatic participants, neither older people, so the evidence applies to young healthy participants transitioning from traditional to minimalist running shoes or wearing them during daily life activities. Contrarily, PIFM exercises were implemented in symptomatic participants (hallux valgus and low back pain with pes planus) and seemed to be effective at increasing PIFM sizes.[55, 59] These exercises were also implemented in older people and were more effective than active control to increase PIFM sizes, but not strength.[56] Adding electromyographic-biofeedback to PIFM exercises was also more effective on strength than the same exercises alone in older people,[57] suggesting that older people can benefit from these interventions in an attempt to decrease fall risk.[9] Second, the duration, frequency and volume of the interventions varied considerably. Durations varied from 1 to 9 months, and although strength already increases in the first few days of interventions primarily due to neuromuscular adaptations,[69] muscle hypertrophy requires more time and is not expected to occur before 4 or even 6 to 10 weeks of training.[70] Besides, training volumes varied from light (e.g. exercises performed once a week or MRS used less than an hour per week)[48, 63-64] to heavy (e.g. exercises performed or MRS used daily).[14, 39, 50, 55] Interestingly, PIFM sizes seemed to be increased following heavy training volumes,[2, 39, 50, 55] but not following lighter interventions.[48, 63] This relationship could also be true for foot strength, but less of these "light" or "heavy" training volume studies investigated that outcome. For example, Shen et al. implemented a transition to MRS worn less than one hour a week combined with PIFM exercises performed once a week,[64] and Ridge et al. included both a group wearing MRS daily and another performing various PIFM exercises at least 5 times per week.[14] Although Shen et al.'s intervention lasted 3 months, they reported increased strength for hallux flexion, but not for toes 2-to-5 flexion while Ridge et al.'s study, that lasted two months, resulted in benefits for both interventions over control for hallux flexion, toes 2-to-5 flexion and doming strength. Third, PIFM exercises were often included in blended interventions, for example combined with exercises known to recruit extrinsic foot muscles such as heel raises.[14, 40, 53, 56]

During walking and running, the PIFM help attenuate foot impact at landing through excentric contraction and support foot stiffness during push-off through rapid concentric contraction.[3] Sprint performance seem to be determined by toe strength,[71] and habitual running foot strike pattern

influences toe strength, with more strength developed in forefoot strikers.[72] Therefore, PIFM strengthening exercises, as well as walking and running MRS have the potential to modify dynamic task biomechanics. Other published meta-analyses showed that PIFM exercises resulted in decreased sit-to-stand navicular drop as well as a more supinated standing foot posture.[19-20, 22] These assessments of MLA mobility and foot posture are regarded as non-validated surrogate measures for PIFM strength.[11] Indeed, previous experiments highlighted that an increased activation of the PIFM results in a lower navicular drop and a more supinated foot posture.[73] Moreover, MLA mobility is correlated with abductor hallucis brevis and flexor hallucis brevis sizes,[74] and foot posture is partly explained by flexor hallucis brevis and flexor digitorum brevis muscle sizes.[75] Stronger PIFMs should thus theoretically result in a more elevated MLA and a more supinated foot posture, along with subsequent kinematic and kinetic changes during dynamic tasks. Evidence in favour of these hypotheses were found in some of the included RCT. First, PIFM exercises may result in less MLA mobility, a more plantarflexed Chopart joint, a more inverted shank-calcaneus joint,[53] and an increased vertical impulse during running.[60] Second, walking following PIFM exercises may be characterized by a more laterally oriented centre of pressure,[28] a decreased medial ground reaction force, and a decreased time to minimal MLA height.[63] Third, MRS transition consistently led to a foot strike pattern more oriented towards forefoot strike,[43, 51, 64] although this was biased in one study that assessed the intervention group in MRS and the control group in their habitual footwear.[51] However, one should admit the numerous non-significant findings associated with these interventions. Biomechanical changes are thus unpredictable and could be limited to isolated variables.

Transition to MRS can be associated with an increased risk of sustaining a running related injury.[76] Therefore, a safe transition requests a gradual increase in MRS use over a long period of time, in parallel with additional injury prevention exercises. These injury prevention programs typically include exercises oriented towards the foot muscles (intrinsic and extrinsic) and balance training.[77] Opposite to these recommendations, some of the included RCT implemented transitions to MRS over short periods of time and without injury prevention policy,[48-49, 51] which could partly explain the high rates of adverse events that some authors reported.[48-49] Contrarily, performing PIFM exercises does not seem to be associated with a particular risk of injury, as evidenced by the very low number of

adverse events reported. Even better, these PIFM exercises could decrease the rate of running related injuries.[78] Besides injury, adherence rates were sometimes low in the included RCT.[13, 40] Physiotherapists should be attentive to maintaining the motivation of their participants in order to promote the correct application of the interventions.

Although safe, exercises targeting the PIFM can be difficult to learn,[11] and activation of these muscles can also be obtained through functional exercises which are easier to perform and could result in benefits not only in the foot muscles.[79]

Limitations

The results of this systematic review with meta-analysis should be considered in light of its limitations. First, a single investigator performed systematic data extraction in the pre-established tables. Second, the limited quality of the evidence – mainly due to the very reduced number of study participants, the high risk of bias and the variety of interventions – prevents the recommendation of specific PIFM exercises and MRS transition programs as standalone interventions in clinical practice. Third, the evidence cannot be generalized to children for PIFM exercises and MRS used during running, nor can it be applied to older individuals or symptomatic people for MRS. Lastly, study durations were limited, especially for PIFM exercises, so effects of longer periods of interventions are unknown.

Perspectives

Future research should focus on the long-term effects of PIFM exercises and MRS, as well as the benefits of MRS used in children. In symptomatic populations, future studies on PIFM exercises should incorporate these interventions into existing rehabilitation. The feasibility and safety of using MRS could be evaluated in patients with specific musculoskeletal disorders. Besides, the outcomes of interest need to be assessed using reliable methods, with examinators blinded whenever possible.

Practical applications

Performing PIFM exercises or wearing MRS can be used in attempts to improve foot strength. Runners performing PIFM exercises can expect to have a less mobile medial longitudinal arch, and runners using MRS are likely to gradually change from a rearfoot to a forefoot strike pattern. PIFM

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the exercises appear to be safe, while MRS require a long transition period that should include strengthening exercises.

Conclusion

Exercises targeting the plantar intrinsic foot muscles seem to increase foot strength and could result in a more elevated medial longitudinal arch during running, but there is too much uncertainty regarding their effects on foot muscle sizes. The use of minimalist shoes during running or daily life seem to result in increased foot muscle sizes and foot strength, and a more forefoot-oriented strike pattern during running.

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Figure captions

Figure 1: PRISMA flow chart

Legend: N (sum of the number of articles), n (number of articles per category), PIFM (plantar intrinsic foot muscles).

Figure 2: Meta-analyses of plantar intrinsic foot muscle sizes

Legend: 2A: Abductor hallucis, 2B: Flexor digitorum brevis, and 2C: Flexor hallucis brevis. MRS (minimalist running shoes), PIFM ex. (exercises targeting the plantar intrinsic foot muscles), CI (confidence interval), SD (standard deviation), * (participants with a symptomatic status), ‡ (participants diagnosed with pes planus), ∀ (participants affected with another musculoskeletal disorder).

Figure 3: Meta-analyses of foot strength

Legend: 3A: Hallux flexion, 3B: Toes 2-to-5 flexion, 3C: Hallux and toes flexion, and 3D: Metatarsophalangeal flexion. MRS (minimalist running shoes), PIFM ex. (exercises targeting the plantar intrinsic foot muscles), CI (confidence interval), SD (standard deviation), * (participants with a symptomatic status), ‡ (participants diagnosed with pes planus).

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Table 1: Study population and intervention characteristics

	Study (Author, year)	**Study sample size (N) Participant characteristics**	**Intervention group** Group size (M:F ratio); mean age (SD) Intervention characteristics	**Control group** Group size (M:F ratio); mean age (SD) Intervention characteristics	**Duration** x frequency or volume Volume: Sets x reps (initial → … → final)
MRS during running or daily life	Chen et al. (2016)	N=38 Runners (≥20km/w) Asymptomatic	n=20 (11M:9F); 34.55 (6.62) Y Transition to MRS (Vibram® Five-fingers; 92% index) + calf strengthening + single-leg balance + rapid jogging in place	n=18 (11M:7F); 35 (5.39) Y Maintain running with habitual running shoes + calf strengthening + single-leg balance + rapid jogging in place	**6Mo** x *see below.* MRS: 2 to 3d/w → 5d/w (according to symptoms). 30min run/w + 2h walk/w → 1h50 run/w. Calf strengthening: 3d/w x 2 x 30: Stance → Single leg. Balance: 3d/w x 2: 10 reps lateral movements → 5 reps SEBT movements. Jogging in place: 3d/w x 2: 1.5min → 5

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					min.
	Johnson et al. (2016)	N=37 Runners (24 to 48km/w) Asymptomatic	n=18 (10M:8F); approx. 24.4 (6.2) Y Transition to MRS (Vibram® Five-fingers; 92% index)	n=19 (10 to 14M:9 to 5F); approx. 27.7 (6.2) Y Maintain running with habitual running shoes	**10w** x 24 to 48km/w MRS: 1.6 to 3.2km during w1 → increased by 1.6 to 3.2km/w for 3w → increased as tolerated (final distance ≥ 4.8km/w).
	Miller, E et al. (2014)	N=29 (13 to 17M:12 to 16F) Runners (≥48.3km/w) Asymptomatic	n=16 (M:F NA); approx. 30.5 (4.0) Y Transition to MRS (New Balance® Road Minimus 10; 72% index (*unsure)* or Merrel® Pace glove; 80% index) *n=14 were analysed for biomechanical outcomes*	n=13 (M:F NA); approx. 29.9 (5.5) Y Maintain running with habitual running shoes *n=12 were analysed for biomechanical outcomes*	**12w** x mean weekly distance of 48.3km (approx. 5 sessions/w) MRS: 3.2km during w1 → 20.9km during w11
	Quinlan, S et al. (2022)	N=64 Healthy children Asymptomatic	n=30 (15 to 19M:21 to 15F): 11.26 (0.76) Y MRS during school hours (shoe model NA; 46% index)	n=34 (15 to 17M:17 to 19F): 11.28 (0.83) Y Maintain wearing habitual shoes	**9Mo** x *see below.* MRS: 3d/w. = approx. 18h/w No progression.

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MRS combined with PIFM ex.	McCarthy et al. (2013)	N=19 (100% F) Recreational runners (>15km/w) Asymptomatic	n=9; 29 (3) Y Transition to MRS (Vibram FiveFingers; 92% index) + running with habitual shoes + PIFM ex.	n=10; 30 (4) Y Maintain running with habitual running shoes	**12w** x 3/w MRS: walk → walk and run → run (3x5min → 3x30 min → individually-adapted)
	Shen, B et al. (2022)	N=26 (100% M) Recreational runners (mean approx. 30km/w) Asymptomatic	n=13; 25.2 (4.8) Y Transition to MRS (Vibram® Five-fingers; 92% index) while running with a forefoot strike + PIFM ex. (towel curls, foot doming, TSO) + heel raises + balance board + foot auto-massage	n=13; 23.8 (1.7) Y Maintain running with habitual shoes	**12w** x *see below.* Total running: ≥20km/w FFS running in MRS: 3d/w x 5 min/d → 48 min/w All ex.: 1d/w (*unsure*) Towel curls: 3x10 → 3x15 Doming and TSO: 2x10 → 4x25 Heel raises: bipedal (1x10 → 2x15) → bipedal on step (2x20 → 3x30) + unipedal on step (1x10 → 3x15)

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					Balance board: 2x20s → 3x40s
	Warne et al. (2017)	N=24 (100% M) Runners (≥40km/w) Asymptomatic	n=12; 36 (7) Y Transition to MRS (Vibram FiveFingers; 72% index) + conventional shoe running (Asics GEL-Columbus; 16% index) + gait retraining (step rate increased by 10%, forefoot strike pattern, upright posture, soft landing) + towel curls + heel raises + single leg balance + ankle mobility	n=12; 34 (9) Y Conventional shoe running (Asics GEL-Columbus; 16% index) + same interventions as IG except MRS.	**6w** x *see below.* MRS: 3/w x (5-8 min → 30 - 40 min) Exercises: 3 → 2/w x 3x15 reps per ex. Balance: 60s
MRS or PIFM ex.	Ebrecht et Sichting (2018)	N=59 (23 to 37M:23 to 37F); approx. 25.3 (7.2) Y Healthy, Asymptomatic	**IG1** n=32 (M:F NA): Transition to MRS (Leguan® Aktiv; 88% index) (<10km/h="beginners"; ≥10km/h="advanced") *n=11 were analysed for muscle sizes* **IG2** n=15 (M:F NA): NMES in sitting without active contraction *n=7 were analysed for muscle sizes*	n=12 (M:F NA)*:* Maintain habitual running *n=5 were analysed for muscle sizes*	**8w** x 2d/w MRS: 10 or 15 min (beginners and advanced runners, respectively). Duration increased (unclear). NMES: 75 reps (15 min). Intensity individually increased (unclear).

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	Ridge et al. (2019)	N=57 Runners (24.1 to 28.3km/w) Asymptomatic	**IG1:** n=19 (9M:10F): 22.9 (3.3) Y MRS during daily life (Inov-8® Bare-XF 210; 86% index or Bare-XF 260; 76% index) (not used during running) **IG2:** n=19 (10M:9F); 22 (1.8) Y Towel curls + TSO + toe squeeze + doming (bipedal and hopping) + heel raises	n=19 (11M:8F); 22.6 (2.7) Y Maintain running with habitual shoes	**8w** x *see below.* MRS: 2500 steps/d → 5000 steps/d (w3 and w4) → 7500 steps/d. All exercises except doming while hopping: ≥5d/w; 3 sets x 10 to 20 reps → 30 reps. Doming while hopping (in place → in square): 3x10 → 3x20 Heel raises (stance → single leg stance; flat surface → edge of step)
Exercises targeting muscle	Day and Michael (2019)	N=20 Elite runners (≥50km/w), Asymptomatic	n=11 (M:F NA); 24 (6) Y SFE + foot curl + eccentric band curl + concentric band curl + range of motion (*unclear*). *n=9 were analysed for biomechanics at 14km/h and*	n=9 (M:F NA); 30 (12) Y Maintain habitual training *n=7 were analysed for biomechanics at*	**10w** x 3d/w Range of motion: 30 Each other ex.: 3 x 10 Bands of greater resistance

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			18km/h, and n=8 were analysed at 22km/h.	*14km/h and 18km/h, and n=5 were analysed at 22km/h.*	
	Elsayed, W et al. (2023)	N=40 Flexible pes planus (ND≥1 cm and forefoot abduction), Symptomatic	n=20 (7M:13F); 26.8 (6.5) Y SFE with towel + shoe insoles	n=20 (5M:15F); 24.9 (4.7) Y Shoe insoles	**6w** x *see below.* SFE: 7d/w x 3 x 10 Sit → stance → <u>single leg stance</u> (every 2w) Insoles: 8h/d
	Goldmann et al. (2013)	N=27 (100% M) Healthy Asymptomatic	n=15; 24 (4) Y Isometric metatarsophalangeal joint flexion contractions	n=12; 26 (2) Y No intervention	**7w** x 4/w IG: 4 sets x 5 reps (3s contraction – 3s relaxation) at 90% of maximal voluntary contraction
	Hartmann et al. (2009)	N=56 Older adults Asymptomatic (*probably*)	n=28 (10M:18F); 75.9 (5.5) Y In-person and home-sessions: Same as CG + moving toes + spreading toes + grabbling small objects + calf stretching.	n=28 (11M:17F); 75.9 (5.4) Y In-person: Warm-up + 15 min aerobic + resistance training (knee and hip) +	**12w** x *see below.* In-person session: 2/w Resistance training: 2-3 sets x 12 reps Home-session: 7/w x 10 min

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				stretching	Stretching: 2 x 30 s per stretch
	Jung et al. (2011)	N=28 (*gender NA)* Pes planus (≥4° calcaneal eversion while standing; ND>1.3cm) Asymptomatic	n=14 (M:F NA); 22.36 (2.41) Y SFE + foot orthoses	n=14 (M:F NA); 21.93 (2.73) Y Foot orthoses	**8w** x *see below.* SFE (single leg stance): 7d/w x 2/d x 3 sets x *unknown* reps of 5s (per foot) → 5 reps of 10s Foot orthoses: during outdoor walking (duration NA)
	Kim, H et al. (2022)	N=48 Patello-femoral pain syndrome (>3Mo) and ≥6° calcaneal eversion at rest), Symptomatic	**IG1** n=16 (7M:9F); 21.81 (2.29) Y SFE **IG2** n=16 (8M:8F); 22.69 (2.77) Y SFE + talonavicular joint mobilization	n=16 (6M:10F); 21.38 (1.82) Y Talonavicular joint mobilization	**4w** x 3d/w SFE: 2 x 5 min (5s per contraction). Sit → stance (from w3) Mobilization: 2 x 5 min (frequency 1/s)
	Kim, M et al. (2015)	N=24 (13M:11F) Hallux valgus (>15°) Symptomatic status NA	n=12 (M:F NA); 22.2 (2.04) Y TSO + orthoses	n=12 (M:F NA); 22.8 (2.83) Y Orthoses	**8w** x *see below.* TSO: 4d/w x 20 min/d Orthoses: >8h/d
	Mahmoud, W	N=46 (100% M) Low back pain +	**IG1**: n=15; 50.28 (8.28) Y SFE	n=14; 47.64 (7.76) Y	**6w** x *see below.* SFE: 7d/w x 30

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	(2022)	flexible pes planus (FPI≥10 and ND>1cm) Symptomatic	**IG2**: n=17; 47.42 (7.10) Y SFE + walking + stretching (hamstring, calf, plantar fascia) + TENS (lumbar) + massages (lumbar)	MTP joint and ankle DF/PF without load	x 30s (10s rest). Sit → stance and half-squat (from w4). Walking: 2d/w x 20 min. Stretching: 2d/w x 5 x 60s. TENS: 3d/w x 20 min (intensity according to tolerance). Massages: 3d/w x 15 min. CG: 1/d x 5 sets (for ankle and MTP joints) x 30s.
	Matias et al. (2022)	N=87 Runners (20 to 100km/w) Asymptomatic	n=41 (17M:24F); 40.3 (7.7) Y (A) In-person: PIFM ex. (toes abd-adduction, SFE, plantar arch raises, ball grabbing, squeeze toe separators) + heel raises + ex. with rubber bands (abduction, toes and ankle flexion) + ex. sitting (inv- and eversions,	n=46 (25M:19F); 40.3 (6.1) Y Warm up and static stretching before each running practice	**8w** x 4d/w PIFM ex: total=50 reps; approx. 15 min. Sit → stance → single leg stance Heel raises: 1 x 30 → 2 x 30 → 2 x 40 reps. Ex. with rubber band: 10 per ex.

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			foot taps, toe mobilisation, plantar self-massage, ball slide. (B) At-home: slight differences.		Ex. sitting: approx. 4min CG: 5 minutes Volume and difficulty increased each w. Further details: see article protocol.
	Mickle et al. (2016)	N=68 Older people Both symptomatic and asymptomatic	n=36 (8M:28F); 70.6 (5.6) Y In-person: Warm-up + short-foot + heel raises + ex. against band (toe flexion, hallux flexion, hallux adduction, ankle dorsiflexion, inversion and eversion) + calf and plantar fascia stretching. *n=16 were analysed for muscle sizes*	n=32 (11M:21F); 69.5 (6.0) Y Home-based: Warm-up + ex. without resistance: toe squeezes, toe pulls, marble pickups, towel pulls and short foot exercise *n=13 were analysed for muscle sizes*	**12w** x 3/w IG: 45 min Short foot: 3 x 5 reps x 5 s → <u>5 x 5 reps x 10s</u> Other ex.: 1 x 10 reps → <u>2 to 3 x 10 reps</u> CG: no progression.
	Namsawang, J et al. (2019)	N=36 Flexible pes planus (criteria NA) Asymptomatic	n=18 (8M:10F); 20.17 (1.20) Y SFE + NMES	n=18 (4M:14F); 19.78 (1.59) Y SFE + "sham" NMES	**4w** x 3d/w SFE: 30 x 5s (sitting). NEMS: 30min (maximal

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					intensity without discomfort) during stance.
	Namsawang, J. et al. (2022)	N=68 Sedentary older adults (age criteria NA) Asymptomatic	n=34 (6M:28F); 68.6 (4.6) Y SFE + TENS	n=34 (6M:28F); 68.7 (4.0) Y SFE + sham TENS	**4w** x 3d/w SFE: 30 x 5sec during stance. TENS (standing): 30 min (maximal intensity without discomfort) No progression.
	Okamura et al. (2020)	N=17 Older adults (≥65 Y) Both symptomatic and asymptomatic	n=9 (9M:0F); 79.1 (4.4) Y SFE + TSO with EMG biofeedback	n=8 (7M:1F); 79.6 (4.2) Y SFE + TSO	**6w** x 2d/w SFE: 3 x 10 x 5s TSO: 40 x 3 to 5s SFE and TSO: Sit → <u>Stance</u>
	Okamura et al. (2020b)	N=20 Pes planus (FPI≥6) Asymptomatic	n=10 (1M:9F); 19.7 (0.9) Y SFE + EMG biofeedback + EMG-controlled electrostimulation	n=10 (2M:8F); 20.2 (1.5) Y No intervention	**8w** x 3d/w 3 x 10 x 5s Sit → stance → <u>single leg stance</u>
	Spink et al. (2011)	N=305 Older adults with disabling foot pain and increased risk of	n=153 (47M:106F); 74.2 (6.0) Y Foot orthoses + provision of footwear + education in falls prevention + home-based	n=152 (47M:105F); 73.6 (5.7) Y Continue current podiatry	Total duration is 12Mo but outcomes were assessed at **6Mo** x *see below.*

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		falling Symptomatic	ex.: toe flexion strength, ankle ROM, ankle strength (eversion, inversion, dorsiflexion, heel raises), calf and hallux stretching.	treatment	Home-based ex.: 3/w x 30 min (<u>increase reps and resistance</u>) Strengthening ex.: 3x10 Stretching: 2-3 x 20s
	Suda et al. (2024)	This is a secondary analysis of the data of Matias et al. (2022). We refer the reader to the description of this article upper in this table.			
	Taddei, U et al. (2020)	N=28 Recreational runners (20 to 100km/w) Asymptomatic	**IG:** n=14 (5M:9F); 41.9 (7.4) Y; **CG:** n=14 (9M:5F); 41.6 (6.0) Y This is a proof-of-concept article using the same interventions as Matias et al. (2022). We refer the reader to the description of this article upper in this table.		
	Utsahachant et al. (2023)	N=45 Flexible pes planus (ND>10mm) Asymptomatic	**IG1**: n=15 (5M:10F); Median (IQR): 21.0 (21; 29) Y SFE **IG2**: n=15 (5M:10F); Median (IQR): 21.0 (20; 22) Y SFE during wall squat	n=15 (5M:10F); Median (IQR): 21.0 (21; 26) Y No intervention	**6w** x 7d/w IG1: 3→<u>4</u> sets x 10 reps x 3→<u>5s</u> (sit → stance → <u>single leg stance</u>) IG2: 3→<u>4</u> sets x 10 reps x 3→<u>5s</u> (sit → wall squat → <u>unilateral wall squat</u>)
	Xiao et al. (2022)	N=36 (100% M) Healthy	**IG1:** n=12; 22.7 (2.0) Y SFE + TSO with toe squeeze	n=12; 23.5 (1.5) Y	**4w** x 3d/w SFE and TSO: 2

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		sedentary adults Asymptomatic	+ towel curls + balance board training. **IG2:** n=12; 21.9 (2.1) Y tDCS	No intervention	x 10 → 3 x 20 Towel curls: 3 x 10 → 3 x 15 with 0.5kg additional weight Balance board: 2 x 20s → 3 x 30s tDCS: 20 min

Legend: /w (per week), approx. (approximately), CG (control group), d (day), DF (dorsiflexion), EMG (electromyography), ex. (exercise), F (female), FFS (fore foot strike), FPI (foot posture index), IG (intervention group), IQR (interquartile range), M (male), min (minutes), Mo (month), MRS (minimalist running shoes), MTP (metatarsophalangeal), N (sample size included in the analyses), n (sample size of the group), NA (non-available), ND (navicular drop), NMES (neuromuscular electrostimulation), PF (plantarflexion), PIFM (plantar intrinsic foot muscle), SD (standard deviation), SEBT (star excursion balance test), SFE (short foot exercise), tDCS (transcranial direct current stimulation), TENS (transcutaneous electrical nerve stimulation), TSO (toe spread out exercise), w (week), w1 (first week after the beginning of the study), and Y (year).

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Table 2: Study results regarding foot muscle sizes and foot strength

	Outcome domain	**Study** ***Instrument***	**Outcome (units)**	**Intervention group** Mean (SD), within-group p-value	**Control group** Mean (SD), within-group p-value	**Between group** p-value Effect size
MRS during running or daily life	PIFM sizes	Chen et al. (2016) *MRI*	Total foot muscle volume (cm^3)	Pre: 4566.96 (753.51) Post: 4973.51 (766.5); **p<0.01***	Pre: 4613.94 (723.98) Post: 4739.53 (914.34); p=0.38	p: NA, g=0.27
			Rearfoot muscle volume (cm^3)	Pre: 2592.21 (630.42) Post: 2764.32 (531.33); p=0.10	Pre: 2526.27 (485.81) Post: 2647.36 (660.84); p=0.33	p: NA, g=0.19
			Forefoot muscle volume (cm^3)	Pre: 1974.27 (303.23) Post: 2209.64 (417.21); **p<0.01***	Pre: 2087.66 (333.13) Post: 2092.16 (330.48); p=0.95	p: NA, g=0.30
		Johnson et al. (2016) *USI*	AbH CSA (cm^2)^{MA}	Pre: 2.29 (0.45) Post: 2.53 (0.40); p: NA	Pre: 2.22 (0.55) Post: 2.26 (0.48); p: NA	**p=0.01*** (IG>CG), g=0.60
			FDB CSA (cm^2)^{MA}	Pre: 2.04 (0.37) Post: 2.04 (0.39); g=0	Pre: 2.12 (0.56) Post: 2.03 (0.49)	p=0.22, *g=0.02*
			FHB thickness	Pre: 1.01 (0.17)	Pre: 1.07	p=0.08, *g=-0.05*

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			(cm)[MA]	Post: 1.00 (0.18)	(0.22) Post: 1.01 (0.22)	
		Quinlan, S et al. (2022) *USI*	AbH CSA (% of foot length)[MA]	Pre: 6.53 (2.05) Post: 7.32 (2.35)	Pre: 6.29 (1.92) Post: 6.77 (1.53)	p=0.1, g=0.28
			FDB CSA (% of foot length)[MA]	Pre: 6.42 (1.01) Post: 6.82 (1.05)	Pre: 6.27 (1.37) Post: 6.36 (1.23)	p=0.09, g=0.40
	Foot strength	Quinlan, S et al. (2022) *Fixed hand-held dynamometer*	Hallux flexion (% of BMI)[MA]	Pre: 2.33 (1.06) Post: 2.58 (0.86)	Pre: 2.15 (0.99) Post: 2.20 (0.72)	p=0.10, g=0.48
			Toes 2-to-5 flexion (% of BMI)[MA]	Pre: 2.18 (1.01) Post: 2.26 (0.75)	Pre: 1.91 (0.83) Post: 1.85 (0.76)	p=0.10, g=0.54
MRS + PIFM ex.	Foot strength	Shen, B et al. (2022) *Dynamometer, except MTPJ flexion with force sensors*	Hallux flexion ($N.kg^{-1}$)[MA]	Pre: 1.43 (0.39) Post: 1.74 (0.44); **p=0.001***	Pre: 1.67 (0.44) Post: 1.7 (0.5); p=0.762	**p=0.036*,** g=0.08
			Toes 2-to-5 flexion ($N.kg^{-1}$)[MA]	Pre: 0.94 (0.21) Post: 1.29 (0.43)	Pre: 0.98 (0.34) Post: 1.05 (0.46)	p>0.05, g=0.52
			MTP joint flexion (all toes) ($N.kg^{-1}$)	Pre: 1.17 (0.39) Post: 1.55 (0.4); **p=0.006***	Pre: 1.58 (0.6) Post: 1.54 (0.6); p=0.813	p NA, g=0.02

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MRS or PIFM ex.	PIFM sizes	Ebrecht et Sichting (2018) *USI*	AbH CSA (cm²)	*Pre-post changes (median and IQR)* [λ]: **IG1**: 0.42 (0.53; 0.87); **IG2**: 0.32 (0.35; 0.56)	*Pre-post changes (median and IQR)* [λ]: 0.36 (0.32; 0.57)	p=0.203, g NA
		Ridge et al. (2019) *USI*	AbH CSA (cm²)[MA]	**IG1**: Pre: 2.08 (0.61); Post: 2.22 (0.54); **p<0.05*** **IG2**: Pre: 1.98 (0.57); Post: 2.19 (0.55); **p<0.05***	Pre: 2.22 (0.45) Post: 2.20 (0.42); p=0.704	**p<0.001*,** g=0.04 (IG1>CG) and **p<0.05*,** g=-0.02 (IG2>CG)
			FHB thickness (cm)[MA]	**IG1:** Pre: 1.56 (0.20); Post: 1.61 (0.20); **p<0.05*** **IG2**: pre: 1.33 (0.22); Post: 1.52 (0.23); **p<0.05***	Pre: 1.60 (0.23) Post: 1.60 (0.22); p=0.516	**p<0.05***, g=0.05 (IG1>CG) and **p<0.05***, g=-0.35 (IG2>CG)
			FDB CSA (cm²)[MA]	**IG1**: pre: 2.06 (0.35); Post: 2.17 (0.35); **p<0.05*** **IG2**: pre: 1.83 (0.46); Post: 2.04 (0.50); **p<0.05***	Pre: 2.05 (0.22) Post: 2.04 (0.23); p=0.687	**p<0.05***, g=0.43 (IG1>CG and), **p<0.05***, g=0 (IG2>CG)
			QP CSA (cm²)	**IG1**: pre: 1.84 (0.41); Post: 2.02 (0.46); **p<0.05*** **IG2:** pre: 1.70 (0.35); Post: 1.95 (0.33); **p<0.05***	Pre: 1.76 (0.45) Post: 1.75 (0.41); p=0.875	**p<0.05***, g=0.61 (IG1>CG) and **p<0.05***, g=0.53 (IG2>CG)

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	Foot strength	Ridge et al. (2019) *Dynamometer*	Hallux flexion (kg)[MA]	**IG1** pre: 4.68 (0.97); Post: 6.98 (2.35); **p<0.05*** **IG2**: pre: 5.27 (2.34); Post: 7.14 (3.99); **p<0.05***	Pre: 6.03 (2.90) Post: 6.38 (2.35); p=0.483	**p<0.05*,** g=0.25 (IG1>CG) and **p<0.05*,** g=0.23 (IG2>CG)
			Toes 2 to 5 flexion (kg)[MA]	**IG1**: pre: 4.62 (1.91); Post: 5.70 (1.80); **p<0.05*** **IG2:** pre: 5.13 (2.27); Post: 6.85 (3.22); **p<0.05***	Pre: 5.81 (2.33) Post: 5.87 (2.27); p=0.477	**p<0.05*,** g=-0.08 (IG1>CG) and **p<0.05***, g=0.34 (IG2>CG)
			Doming (kg)	**IG1**: 6.28 (3.03); Post: 9.47 (4.16); **p<0.05*** **IG2:** pre: 4.98 (2.10); Post: 10.28 (4.31); **p<0.05***	Pre: 7.53 (2.26) Post: 8.14 (3.31); p=0.082	**p<0.05***, g=0.35 (IG1>CG) and **p<0.05***, g=0.55 (IG2>CG)
Exercises targeting the PIFM	PIFM sizes	Jung et al. (2011) *USI*	AbH CSA (cm^2)[MA]	Pre: 2.36 (0.66) Post: 2.63 (0.65); **p<0.001***	Pre: 2.49 (0.41) Post: 2.62 (0.44) **p<0.001***	**p=0.008*** g=0.02
		Kim, M et al. (2015) *USI*	AbH CSA (cm^2)[MA]	Pre: 2.04 (0.43) Post: 2.52 (0.66); **p<0.05***	Pre: 2.04 (0.62) Post: 1.93 (0.51); p>0.05	**p<0.05*** g=0.97

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		Mahmoud, W (2022) *USI*	AbH CSA (mm^2)[MA]	**IG1**[MA]: Pre: 216.63 (17.15); Post: 233.5 (11.59); **p=0.001**[*] **IG2**: Pre: 220.79 (21.68); Post: 256.75 (17.59); **p<0.001**[*]	Pre: 211.55 (21.5) Post: 212.45 (20.33); p=0.216	**p=0.038*,** g=1.25 (IG1>CG) **p<0.001**[*]**,** g=2.29 (IG2>CG)
		Mickle et al. (2016) *MRI*	AbH CSA (mm^2)	Pre: 13.5 (1.0) Post: 15.1 (1.0); p=0.27	Pre: 13.9 (0.6) Post: 12.8 (0.6); p=0.2	**p=0.0016*,** g=2.26
			FDB CSA (mm^2)	IG: Pre: 14.9 (1.0) Post: 16.4 (1.1); p=0.3	Pre: 12.1 (0.6) Post: 13.7 (0.7); p=0.08	p=0.9881, g=2.78
			AbDM CSA (mm^2)	Pre: 10.5 (0.5) Post: 12.4 (0.5); **p=0.007***	Pre: 11.4 (0.6) Post: 11.3 (0.7); p=0.9	**p=0.001*,** g=1.79
			AbH muscle volume (mm^3)[MA]	Pre: 688.5 (61.0) Post: 838.4 (62.8); p=0.1	Pre: 711.3 (39.3) Post: 729.3 (42.5); p=0.76	**p=0.0011***, g=1.94
			FDB muscle volume (mm^3)[MA]	Pre: 125.1 (8.2) Post: 152.3 (8.5); **p=0.03***	Pre: 111.1 (6.4) Post: 133.8 (6.9); **p=0.03***	p=0.5542, g=2.30

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			AbDM muscle volume (mm^3)	Pre: 398.3 (24.6) Post: 496.8 (25.3); **p=0.009***	Pre: 429.1 (26.2) Post: 441.3 (31.0); p=0.77	**p=0.0256*,** g=1.93
		Namsawang, J et al. (2019) *USI*	AbH CSA (mm^2)	Pre: 218.66 (53.23) Post: 256.96 (NA); **p<0.05***	Pre: 225.97 (64.10) Post: 244.36 (NA); p>0.05	p>0.05, g=0.21
		Namsawang, J. et al. (2022) *USI*	AbH CSA (cm^2)	*Median (IQR)* Pre: 1.86 (1.61 – 2.31) Post: 2.05 (1.76 – 2.53); **p<0.05***	*Median (IQR)* Pre: 1.79 (1.56 – 2.20) Post: 2.16 (1.77 – 2.50); **p<0.05***	p=0.49, g=-0.05
		Okamura et al. (2020b) *USI*	AbH thickness (mm)[MA]	Pre: 12.3 (2.4) Post: 13.4 (3.7)	Pre: 12.2 (1.7) Post: 13.2 (2.1)	p>0.05, g=0.06
			FDB thickness (mm)[MA]	Pre: 7.3 (1.0) Post: 7.1 (1.1)	Pre: 7.7 (1.7) Post: 7.6 (1.6)	p>0.05, g=-0.35
			FHB thickness (mm)[MA]	Pre: 13.9 (1.6) Post: 14.0 (1.3)	Pre: 14.3 (1.4) Post: 14.7 (1.1)	p>0.05, g=-0.56
		Taddei, U et al. (2020) *MRI*	AbH CSA (mm^2)	Pre: 135.8 (64.4) Post: 141.2 (58.5)	Pre: 157.7 (79.8) Post: 145.2 (64.6)	p=0.1, g=-0.06
			AbDM CSA (mm^2)	Pre: 105.4 (36.1) Post: 112.8 (31.4)	Pre: 119.3 (33.7)	p=0.256, g=-0.03

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					Post: 113.9 (31.7)	
			FDB CSA (mm^2)	Pre: 116.9 (45.5) Post: 116.7 (30.8)	Pre: 128.3 (44.4) Post: 122.0 (44.1)	p=0.169, g=-0.14
			FHB CSA (mm^2)	Pre: 143.3 (38.9) Post: 147.2 (42.3)	Pre: 174.9 (37.6) Post: 166.2 (52.2)	p=0.053, g=-0.39
			AbH volume (cm^3)^{MA}	Pre: 11.0 (6.1) Post: 13.7 (6.3); p NA	Pre: 15.4 (8.1) Post: 13.3 (6.3); p NA	**p=0.019*,** g=0.06
			AbDM volume (cm^3)	Pre: 9.2 (5.0) Post: 11.2 (4.8); p NA	Pre: 12.5 (4.6) Post: 12.0 (4.6); p NA	**p=0.013*,** g=-0.17
			FDB volume (cm^3)^{MA}	Pre: 10.4 (4.6) Post: 12.5 (4.7); p NA	Pre: 14.0 (4.6) Post: 13.3 (4.3); p NA	**p=0.039*,** g=-0.17
			FHB volume (cm^3)^{MA}	Pre: 9.1 (4.8) Post: 10.2 (4.4); p NA	Pre: 12.6 (3.6) Post: 12.0 (4.1); p NA	**p=0.009*,** g=-0.41
	Foot strength	Day and Michael (2019) *Biodex dynamometer*	5-toes flexion ($N.kg^{-1}$)^{MA}	Pre $^{\lambda}$: 2.6 (0.6) Post $^{\lambda}$: 3.3 (0.9); **p=0.006***	Pre $^{\lambda}$: 2.6 (0.6) Post $^{\lambda}$: 2.6 (0.9); p=0.607	**p=0.002***, g=0.74
		Goldmann et al. (2013)	MTP joint flexion moment	Pre: 0.24 (0.06) Post: 0.40 (0.08);	Pre: 0.25 (0.05)	**p<0.001***, g=1.86

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		Dynamometer	(all toes) ($Nm.kg^{-1}$), right side[MA]	**p<0.001***	Post: 0.26 (0.06); p=0.11	
			MTP joint flexion moment (all toes) ($Nm.kg^{-1}$), left side	Pre: 0.21 (0.06) Post: 0.38 (0.07); **p<0.001***	Pre: 0.24 (0.04) Post: 0.25 (0.05); p=0.12	**p<0.001***, g=2.03
		Jung et al. (2011) *Fixed dynamometer*	Hallux flexion (kgf)[MA]	Pre: 6.35 (2.98) Post: 8.14 (3.17); **p<0.001***	Pre: 6.38 (3.53) Post: 7.26 (3.24); **p<0.001***	**p=0.008*,** g=0.27
		Mickle et al. (2016) *Pressure platform*	Hallux flexion (% BW)	Pre[λ]: 9.1 (4.3) Post [λ]: 10.9 (4.9); **p<0.001***	Pre [λ]: 9.3 (5.0) Post [λ]: 9.3 (3.1); p=0.92	p NA, g=0.38
			Toes 2 to 5 flexion (% BW)	Pre[λ]: 5.3 (2.5) Post [λ]: 7.3 (2.9); **p<0.05***	Pre [λ]: 7.1 (4.5) Post [λ]: 6.9 (2.4); p>0.05	p NA, g=0.15
		Okamura et al. (2020) *Dynamometer*	5-toes flexion (grip), seated, dominant (N)	Pre: 12.2 (4.2) Post: 13.8 (3.8)	Pre: 13.1 (4.5) Post: 14.4 (5.4)	p>0.05, g=-0.12
			5-toes flexion (grip), seated, non-dominant (N)	Pre: 9.8 (4.3) Post: 13.1 (4.9); **p=0.0008***	Pre: 9.6 (4.6) Post: 10.7 (4.9); p>0.017	**p=0.029*,** g=0.46
		Spink et al. (2011) *Hand-held dynamometer*	Hallux flexion (N)[MA]	Pre: 68.23 (26.97) Post: 69.69 (30.15); p NA	Pre: 68.95 (27.98) Post: 69.86	p=0.85; g=0.0

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					(28.16); p NA	
			"Lesser toe" flexion (N)[MA]	Pre: 68.00 (25.06) Post: 74.11 (30.04); p NA	Pre: 67.95 (27.18) Post: 70.13 (27.11); p NA	p=0.13; g=0.14
		Taddei, U et al. (2020) *Pressure platform*	Isometric 5-toes flexion (% BW)	Pre: 19.95 (6.24) Post: 27.31 (9.33)	Pre: 23.46 (4.86) Post: 25.61 (7.4)	p=0.707, g=0.20
		Xiao et al. (2022) *Dynamometer*	MTP joint flexion (all toes) ($N.kg^{-1}$)[MA]	**IG1**[MA]: pre: 3.03 (0.87); Post: 3.37 (1.05) **IG2**: pre: 3.63 (1.21); Post: 4.17 (1.71)	Pre: 2.91 (0.99) Post: 2.88 (0.95)	**p=0.027*,** g=0.47 (IG1>CG); **p=0.008*,** g=1.49 (IG2 > CG)
			Toes 2 to 5 flexion ($N.kg^{-1}$)[MA]	**IG1**[MA]**:** pre: 1.76 (0.70); Post: 1.99 (0.79) **IG2:** pre: 1.76 (0.49); Post: 1.90 (0.52)	Pre: 1.72 (0.72); Post: 1.74 (0.74)	p>0.05, g=0.32 (IG1 vs CG) and **p=0.015*,** g=0.24 (IG2 > CG)

Legend: AbDM (abductor digiti minimi), AbH (abductor hallucis), BMI (body mass index), **Bold *** (significant p-value at p<0.05 or lower if it results from a post-hoc test), CG (control group), CSA (cross-sectional area), ex. (exercise), FDB (flexor digitorum brevis), FHB (flexor hallucis brevis), g (Hedge's g effect size), IG (intervention group), IQR (interquartile range), kgf (kilogram force), [MA] (data included in the meta-analysis), MRI (magnetic resonance imaging), MRS (minimalist running shoes), MTP (metatarsophalangeal), NA (non-available), p (p-value), PIFM (plantar intrinsic foot muscle), Post (post-intervention), Pre (pre-intervention), QP (quadratus plantae), SD (standard deviation), USI (ultrasound imaging), and [λ] (data was estimated from graph).

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Table 3: Summary of findings for plantar foot muscle exercises or minimalist shoes

	Outcome	Risk of bias	Imprecision	Inconsistency	Indirectness	Publication bias	Certainty of the evidence
Plantar foot muscle exercises	Abductor hallucis sizes	0	-1[b]	0	-1[f]	0[h]	Low
	Flexor digitorum brevis sizes	-1[a]	-2[b, c]	0	-1[f, g]	0[h]	Very low
	Flexor hallucis brevis sizes	-1[a]	-2[b]	0	-1[f, g]	0[h]	Very low
	Hallux flexion strength	-1[a]	-1[b]	0	-1[f, g]	0[h]	Very low
	Toes 2-to-5 flexion strength	-1[a]	-1[b]	0	-1[f]	0[h]	Very low
	Hallux and toes strength	0	-2[b]	0	-1[f, g]	0[h]	Very low
	Metatarsophalangeal flexion	-1[a]	-2[b, c]	-1[d]	-1[f, g]	0[h]	Very low
Minimalist shoes	Abductor hallucis sizes	-2[a]	-1[b]	-1[d, e]	-1[f, g]	0[h]	Very low
	Flexor digitorum brevis sizes	-2[a]	-1[b]	-1[d, e]	-1[f, g]	0[h]	Very low
	Flexor hallucis	-2[a]	-2[b, c]	0	-1[f, g]	0[h]	Very

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	brevis sizes					low
	Hallux flexion strength	-2[a]	-2[b]	0	-1[f, g]	0[h]	Very low
	Toes 2-to-5 flexion strength	-2[a]	-2[b]	0	-1[g]	0[h]	Very low

Legend: [a] (-1 if one article has 2 high risk domains and -2 if most articles have 2 high risk domains), [b] (small sample size), [c] (overall confidence interval includes contradictory findings), [d] (substantial heterogeneity), [e] (confidence intervals do not overlap), [f] (blended interventions in the intervention groups), [g] (restricted population with respect to the research question), and [h] (funnel plot could not be performed due to the limited number of studies). For each outcome, the corresponding meta-analysis can be seen in Figure 2 for muscle sizes and in Figure 3 for strength.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Highlights

- Foot muscle exercises may increase foot strength
- Foot muscle exercises may decrease medial longitudinal arch mobility during running
- Minimalist shoes could be appropriate to increase foot muscle sizes and strength
- Runners using minimalist shoes may switch from rearfoot- to forefoot strike pattern

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