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The relationship between static and dynamic foot posture and running biomechanics: A systematic review and meta-analysis

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ABSTRACT

Background: Medial longitudinal arch characteristics are thought to be a contributing factor to lower limb running injuries. Running biomechanics associated with different foot types have been proposed as one of the potential underlying mechanisms. However, no systematic review has investigated this relationship.
Research question: The aim of this study was to conduct a systematic literature search and synthesize the evidence about the relationship between foot posture and running biomechanics.
Methods: For this systematic review and meta-analysis different electronic databases (Pubmed, Web of Science, Cochrane, SportDiscus) were searched to identify studies investigating the relationship between medial longitudinal arch characteristics and running biomechanics. After identification of relevant articles, two independent researchers determined the risk of bias of included studies. For homogenous outcomes, data pooling and meta-analysis (random effects model) was performed, and levels of evidence determined.
Results: Of the 4088 studies initially identified, a total of 25 studies were included in the qualitative review and seven in the quantitative analysis. Most studies had moderate and three studies a low risk of bias. Moderate evidence was found for a relationship between foot posture and subtalar joint kinematics (small pooled effects: −0.59; 95%CI −1.14 to − 0.003) and leg stiffness (small pooled effect: 0.59; 95%CI 0.18 to 0.99). Limited or very limited evidence was found for a relationship with forefoot kinematics, tibial/leg rotation, tibial acceleration/shock, plantar pressure distribution, plantar fascia tension and ankle kinetics as well as an interaction of foot type and footwear regarding tibial rotation.
Significance: While there is evidence for an association between foot posture and subtalar joint kinematics and leg stiffness, no clear relationship was found for other biomechanical outcomes. Since a comprehensive meta-analysis was limited by the heterogeneity of included studies future research would benefit from consensus in foot assessment and more homogenous study designs.

1. Introduction

Foot and medial longitudinal arch characteristics have frequently been discussed as potential contributing factors to overuse injuries of the lower extremities [1,2]. Although the evidence is not conclusive [1,3,4], high arched feet are thought to be more rigid with less capacity for shock absorption [5,6]. This may lead to a higher incidence of ankle injuries, bony injuries (especially to the tibia or femur), and injuries to the lateral aspect of the lower limb [1]. Low arched feet in contrast appear to be related to more knee injuries, soft tissue injuries, and injuries to the medial aspect of the lower limb [1]. A recent systematic review aimed to identify this relationship and showed a slightly increased pooled odds ratio (OR = 1.23; 95% CI: 1.11, 1.37) for lower extremity injuries, when either high and low arch feet were present [4]. Some lower limb alignment characteristics have already been identified as being associated with running-related injuries [4,7].

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Altered biomechanics are also assumed to provide the link between medial longitudinal arch alignment and increased injury risk [1], and foot arch characteristics have been shown to influence kinematics and kinetics of running [8–10]. The flexibility of different medial longitudinal arch types has been suggested to contribute to differences in running biomechanics [11], i.e. influence the shock attenuation and plantar pressure distribution during running [1,12].

The relationship between foot posture and lower limb biomechanics in walking has already been investigated using a systematic approach by Buldt et al. [13]. A low level of evidence was found for a relationship between low foot arches and increased frontal plane motion of the rearfoot [13]. In contrast, the relationship between foot posture and running biomechanics has not been investigated using a systematic review approach. Therefore, the aim of this systematic review was to evaluate the relationship between different foot postures and running biomechanics.

2. Methods

This study was conducted and reported according to the PRISMA guidelines for reporting systematic reviews and meta-analysis [14] and as suggested by Harris et al. [15]. Prior to the start of the study, the review protocol was registered at the University of York, Centre for Reviews and Dissemination PROSPERO database: Registration number CRD42017069530 (http://www.crd.york.ac.uk/prospero/).

A systematic literature search was conducted in July 2017 and repeated in February 2018. Inclusion and exclusion criteria were determined a priori. All cohort, case-control, cross-sectional studies, and randomized controlled trials investigating healthy runners from different age groups were taken into consideration. The search was restricted to articles from peer-reviewed journals published in English, German, or Spanish languages. Furthermore, for inclusion, studies had to investigate the relationship between medial longitudinal arch characteristics and running biomechanics with an effect or regression analysis. Different methods of foot posture determination (static methods such as arch height index, foot posture index and navicular height as well as dynamic methods such as dynamic arch index and navicular drop) and running biomechanics analyses (over-ground and treadmill running, barefoot and shod) were eligible for inclusion. All studies solely investigating walking conditions or neuromuscular pathologies were excluded as well as studies investigating perturbations or any other activity such as stair climbing or hopping. The search strategy was applied to different databases (Pubmed, Web of Science, Cochrane, SportDiscus) and can be found in Table 1.

The databases were searched to identify a list of applicable studies based on the title and abstract. From this list two independent researchers (K.H. and J.S.) extracted relevant studies and tested them against the inclusion criteria first by title, then abstract and finally the full-text, if available. A third reviewer (A.Z.) was available for consensus decisions. The bibliographical information of included articles was examined for further relevant references. Citation tracking was performed using Web of Science® (Thomson Reuters). Reviews, systematic reviews, commentaries, case studies, and case series were not included.

2.1. Data extraction and quality analysis (Risks of bias in AND across studies)

The included articles were used to extract all temporal and spatial outcome measures, measurements of the center of gravity (including center of mass CoM and center of pressure CoP), and all kinetic and kinematic parameters. Further, information about participants, study objectives, independent and dependent variables, tested running conditions, statistical analyses and conclusions were collected.

Two independent reviewers (C.H., A.R.) with a third reviewer (K.H.) for consensus assessed the risk of bias using the Downs and Black quality index that has been found to be valid and reliable for randomized and nonrandomized studies [16] and has previously been used in a modified version for the quality assessment of biomechanical studies [17,18] (Supplemental Table 1). The identified quality score was used to determine a high (score, ≤ 6), moderate (score, 7–13), or low risk of bias (score ≥ 14) of the studies investigated [18].

Table 1
Search strategy.

Intervention		Outcomes		Exclusions
foot arch	AND	running	NOT	diabet*
OR		OR		OR
medial longitudinal arch		biomechanic*		ulcer
OR		OR		OR
longitudinal arch		kinetic*		fracture
OR		OR		OR
arch height		dynamic*		stroke
OR		OR		OR
AHI		kinematic*		cerebral palsy
OR		OR		OR
height index		EMG		orthosis
OR		OR		OR
arch index		cadence		osteoarthritis
OR		OR		
high arch*		step length		
OR		OR		
flat foot		ground reaction force*		
OR		OR		
low arch*		GRF		
OR		OR		
pes planus		lower limb		
OR		OR		
pes cavus		gait analysis		
OR		OR		
foot type		joint		
OR		OR		
foot anatomy		ankle		
OR		OR		
foot morphology		knee		
OR		OR		
foot characteristics		plantar pressure		
OR		OR		
foot metrics		video		
OR		OR		
foot length		mechanic		
OR				
foot width				
OR				
plantar pressure				

2.2. Data analysis

A meta-analysis was performed for available homogenous outcome data using Review Manager 5.3.5 (The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen, Denmark). Mean and standard deviation parameters were included for biomechanical outcomes when available from two or more studies using comparable methodology (e.g. barefoot running or running in cushioned running shoes). Authors were contacted for additional data or information on determination of kinematic data if needed. A random effects model was used to calculate standard mean differences for all numerical values ($p < 0.05$). I^2 statistics and χ^2 tests were used to test for statistical heterogeneity ($p < 0.05$). Pooled effect (PE) sizes were determined according to Barton et al. (2009) [19] as small (≤0.59), medium (0.60–1.19), or large (≥1.20).

2.3. Level of evidence

Levels of evidence (strong, moderate, limited, very limited or conflicting) were defined according to van Tulder et al. [20] as used in other systematic reviews on biomechanics before [17,18].

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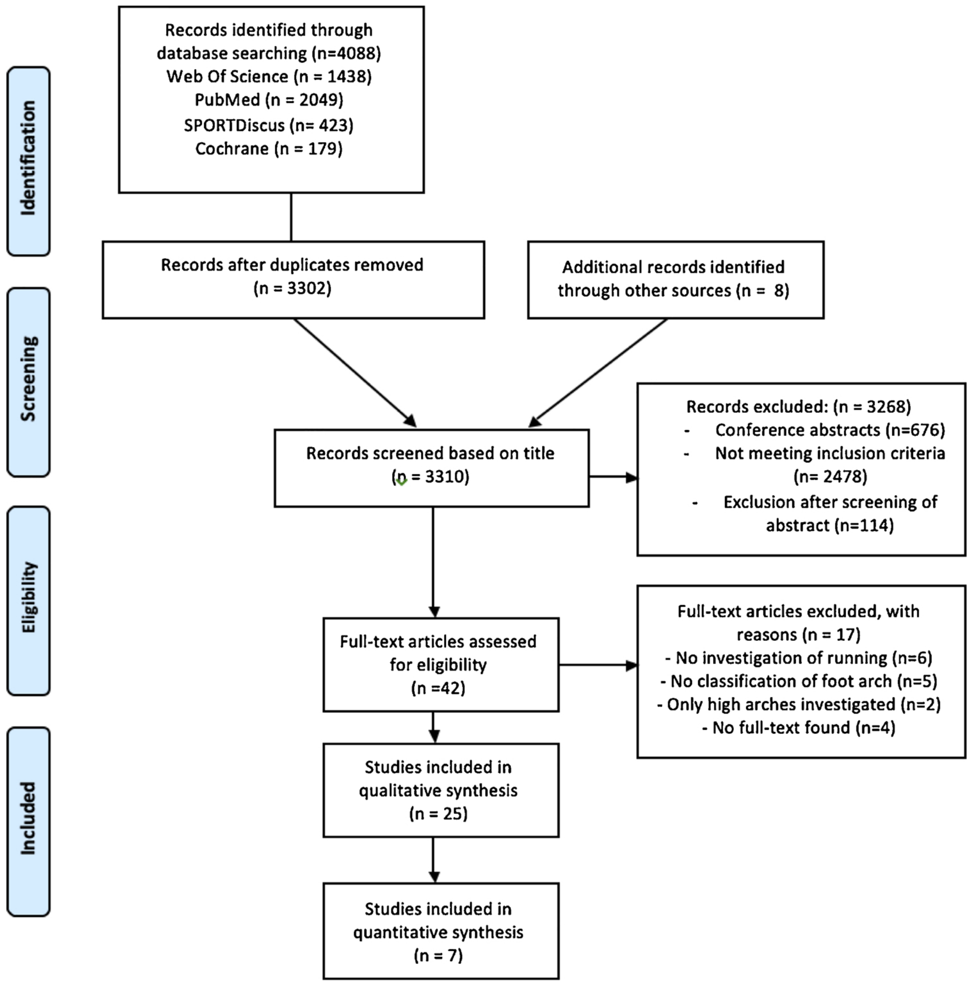

Fig. 1. Prisma Flow Chart.

3. Results

3.1. Study selection and study characteristics

3.1.1. Search results

The initial search resulted in 4088 studies, of which 787 duplicates were excluded. Additionally, eight studies were identified through other sources (forward and backward search). A total of 42 studies were assessed for eligibility, of which 17 needed to be excluded for various reasons (no investigation of running condition, no classification of foot type, no full-text found, no comparison group). Finally 25 studies were included in the qualitative analysis and seven studies in the quantitative analysis. The full selection process is displayed in Fig. 1.

3.1.2. Characteristics of included studies

Study characteristics of all included studies are summarized in Tables 2 and 3 and Fig. 2 [8–10,21–40]. Most participants were adults, over 18 years of age. Fifteen studies investigated barefoot running (Table 2) [9,10,21,22,24–27,29–33,35,39] and 10 studies focused on shod running biomechanics (Table 3) [8,23,28,34,36–38,40–42]. Due to the influence of footwear on biomechanics [17,43,44], the results of shod and barefoot running were analysed separately. Thirteen studies investigated recreational runners [10,21,27,29–32,35,39–41], while 11 studies included healthy adults and did not report the running experience [9,22–26,28,34,36,38,42]. Only one of the identified studies included children aged 10–14 years [33]. The sample size varied from 12 to 215 participants. Inclusion criteria were mostly recreational athletes, during an injury free interval, with no lower limb abnormalities and with no history of surgery to the foot and ankle. Four studies analysed only female participants [10,29–31] and four other studies included exclusively male participants [9,24,25,38]. For two studies only habitually rearfoot-striking participants were included [21,22], while for two other studies only non-rearfoot-striking participants were considered [30,33]. Recruitment was mostly done from local communities and university campuses. One study recruited children from a local sports club [33].

3.1.3. Risk of bias results

There were no randomized controlled trials found. All studies had a cross-sectional study design. A priori power-calculations were performed in 5 studies [9,38,40–42]. The risk of bias score of included studies can be found in Supplemental Table 2. None of the studies had a high risk of bias, most (n = 22) were rated with a moderate risk of bias and three studies had a low risk of bias (=high quality). For reporting, most studies achieved full points, with the highest risk of bias in the description of the distribution of confounders (question 5). While internal validity regarding bias was good among the studies, internal validity regarding confounding showed the lowest quality. Information on recruitment population (question 21) was missing in 44% of the studies and recruitment time (question 22) was missing in all included studies. Furthermore, in 80% of the studies no adjustment for possible confounders (question 25) or an a priori power analysis (question 27) was performed.

3.1.4. Determination of foot type and running conditions

The included articles showed a heterogeneous assessment of the

Table 2
Study characteristics and main results of all included studies investigating barefoot running.

Study	Objective	Participants	Independent Variable	Running Condition	Dependent Variable	Modified D&B Score (Max. 20 Points)
Anbarian et al. [21]	Plantar pressure distribution in HA vs LA	Habitual rearfoot striking adult runners (n = 42)	AHI; cut-off values: > 0.365 for HA and < 0.275 for LA	Barefoot, overground at 3.3 m/s ± 5%; running induced fatigue protocol	Plantar pressure: maximum pressure, peak forces (BW %), and impulses in 10 different areas	11
	Groups					
	High arch (n = 21)	12 male: 21.8 ± 3.2 years, 182.9 ± 4.5 cm, 71.2 ± 4.4 kg, AHI 0.419 ± 0.044 9 female: 24 ± 1.3 years, 172.6 ± 6.5 cm, 63.2 ± 4.4 kg, AHI 0.409 ± 0.034				
	Low arch (n = 21)	3 male: 21.1 ± 3.0 years, 179.1 ± 4.2 cm, 73.8 ± 7.3 kg, AHI 0.264 ± 0.006 8 female: 25.3 ± 2.7 years, 167.6 cm, 63.5 ± 6.5 kg, AHI 0.257 ± 0.015				
	Main findings: Significant and different effects of fatigue on plantar loading distribution in HA and LA runners.					
De Cock at al. [22]	Influence of foot types (three groups: HA, LA and normal arch) on centre of pressure trajectories	Healthy adults (physical education students), only RFS, no information on running experience (n = 215)	Arch Index: HA (arch index ≤ 15.2%), NA (15.2 < arch index < 24.1%) and LA (arch index ≥ 24.1%).	Barefoot, overground at 3.3 ± 0.17 m/s, only RFS	Kinetics: Displacement of COP line	13
	Groups					
	Female (n = 86)	18.2 ± 0.7years, 166.9 ± 5.6 cm, 59.3 ± 7.1 kg, arch index 18.3 ± 6.8%				
	Male (n = 129)	18.3 ± 1.2 years, 179.5 ± 5.9 cm, 69.0 ± 7.2 kg, arch index 19.5 ± 6.1%				
	Main findings: Center of pressure course more lateral for LA runners.					
Eslami et al. [9]	Relationship between navicular drop and running kinetics and kinematics	Healthy male adults, injury free (n = 16)	Navicular drop (average 7.13 mm (SD = ± 2.92), range 3 and 12 mm)	Barefoot, overground at 170 steps/minute	Rearfoot eversion, tibial internal rotation, peak ankle inversion moment, peak knee abduction moment	11
	Groups					
	Correlation analysis, no groups	Participants characteristics: weight 81.5 ± 10.4 kg, height 179.1 ± SD 5.4 cm and heel-toe length 26.0 ± 6.70 cm				
	Main findings: Significant correlation between navicular drop and peak knee adduction moment and peak ankle inversion moment.					
Hernández-Gervilla et al. [35]	Correlation between foot posture and running kinematics	Recreational runners (n = 25)	Foot Posture Index: 3 groups (supination, normal, pronation)	Barefoot, treadmill at 2.43 m/s	Contact time, flight time, stride time and stride frequency	13
	Groups					
	60% (n = 15) normal foot, 32% (n = 8) pronated foot, 8% (n = 2) supinated foot	15 men and 10 women, age 28 ± 9.1 years, 67 ± 13.3 kg weight, height 1.69 ± 0.08 m, BMI 23.2 ± 3.2 kg/m^2)				
	Main findings: Foot posture index was not significantly associated with contact time, flight time, stride time and stride frequency.					
Hollander et al. [33]	Relationship between dynamically measured arch index and running biomechanics	Children 10-14 (local schools / sport clubs), injury free, no neurological or neuromuscular abnormalities, all RFS	Dynamic arch index (contact area middle third to whole foot in %)	Barefoot, self-selected speed	Foot strike pattern	16
	Groups					
	Correlation analysis, no groups. Dynamic arch index [°]: mean 0.18 (SD 0.069)	45.5% females, mean ± SD age 12 ± 1.3 years, height 156.9 ± 10.4 cm, weight 45.7 ± 9.6 kg, BMI 18.4 ± 2.2				
	Main findings: Significant association between dynamic arch index and foot progression angle. A higher dynamic arch index (=flatter arch) was associated with a higher foot progression angles (=external rotation).					
Langley et al. [24]	Prediction of longitudinal arch motion during running through static arch measures	Healthy males from university and local sports clubs (n = 15)	Foot posture index (> 5 vs. 0-5 v.s < 0), rear foot angle (≥3° valgus vs. ≤ 2° valgus to ≥2° varus vs. ≤ 3° varus) and medial longitudinal arch angle (< 130° vs.130-150° vs. > 150°)	Barefoot, treadmill at a self-selected pace (2.8 ± 0.5 m/s)	Medial longitudinal arch deformation and angle at contact, midstance and toe-off	13
	Groups					
	Pronated, neutral, supinated feet. Predictive model, distribution only	27 ± 5 years, 177 ± 4 cm, 80 ± 10 kg, FPI-6: mean 4 (SD 4), min − 4, max 12 / MLAA mean 132° (SD 13°), min 108°, max 151° / RFA mean 4° valgus (SD 5°), min 17° valgus, max 3° varus				
	Main findings: Significant prediction of medial longitudinal arch angle during stance phase by different foot type measures.					

(*continued on next page*)

Table 2 (*continued*)

Study	Objective	Participants	Independent Variable	Running Condition	Dependent Variable	Modified D&B Score (Max. 20 Points)
Lee et al. [25]	Correlation between arch height and max. rearfoot eversion	Healthy males, injury free (min. 6 months)	Dynamic and static arch height (Navicular height/truncated foot length)	Barefoot, overground at 4.5 m/s, only rearfoot strike	Max. rearfoot eversion (stance)	9
	Groups					
	Static arch height (H/L) Dynamic arch height (H/L)	All: mean: 0.201 (SD 0.041), high: n = 9 mean 0.22 (SD 0.053), low n = 8 mean 0.18 (SD 0.036)				
	Main findings: High correlation between dynamic arch height and static arch height, plantar fascia tension and maximum rearfoot eversion.					
Lees et al. [26]	Relationship between medial longitudinal arch and ground reaction forces	Athletic adults, clinically normal feet, no further specifications (n = 18)	Arch index (radiographically): navicular height/foot length	Barefoot, overground at 3 m/s ± 5%	Ground reaction forces & dynamic load rate: Peak vertical force (1 magnitude) body weight normalized	11
	Groups					
	No groups, correlation	Arch index: mean 0.170 (SD 0.036), BMI 74.8, SD 16.2				
	Main findings: No correlation between arch index and ground reaction force or load rate peaks.					
McPoil & Cornwall [27]	Relationship between static and dynamic arch angle	Healthy, experienced runners (n = 17)	Longitudinal arch angle (static)	Barefoot, overground at self-selected speed ± 5%	Longitudinal arch angle (dynamic during mid-support)	12
	Groups					
	No groups, correlation	Mean Longitudinal Arch Angle (n = 34) standing: 138.4 (SD 7.7), midstance walking: 135.2 (SD 7.2), mid-support running: 128.7 (SD 7.7)				
	Main findings: Standing posture longitudinal arch angle predicted the dynamic posture of the foot that occurs at mid-support during running.					
Ogon et al. [39]	Relationship between arch height and impact loading	Healthy recreational runners, no information on sex.	Medial longitudinal arch height (navicular height/foot length)	Barefoot and shod, stand. footwear, overground at 1.5 m/s ± 15%	Ground reaction forces: initial loading rate	12
	Groups					
	High arch and low arch	Age: 32.9 ± 7.9 years, 174.4 ± 7.6 cm, 73.1 ± 15.8 kg, navicular height 31.4 ± 3.2 cm, arch height index 0.149 ± 0.017				
	Main findings: HA: Higher acceleration amplitude and rate at the lower back compared to LA runners. Slight negative correlation between arch height and initial anterior-posterior and vertical loading rate, and slight positive correlation between arch height and initial medial loading rate.					
Powell et al. [29]	Biomechanical characteristics under different dynamic loading conditions	Recreational female runners (n = 20)	AHI (+/- 1.5 SD)	Barefoot, overground at self-selected speed ± 5%	3D Foot kinematics: peak eversion angle, time to peak eversion, eversion excursion	13
	Groups					
	High arch (n = 10) Low arch (n = 10)	20.8 ± 2.5 years, 162 ± 7 cm, 58.3 ± 5.4 kg, AHI > 0.377 21.1 ± 2.3 years, 162 ± 7 cm, 58.9 ± 10.9 kg, AHI < 0.283				
	Main findings: Significant smaller peak ankle eversion angles and peak mid-forefoot eversion angles in HA compared to LA runners.					
Powell et al. [31]	Dynamic joint stiffness and joint work of the ankle during the total stance phase	Recreational female runners (n = 20)	AHI (+/- 1.5 SD)	Barefoot, overground at self-selected speed ± 5%	Dynamic joint stiffness, net. Ankle & propulsive work, ankle braking	12
	Groups					
	High arch (n = 10) Low arch (n = 10)	18-30 years, 162 ± 7 cm, 58.3 ± 5.4 kg, AHI 0.386 ± 0.010 18-30 years, 163 ± 7 cm, 58.9 ± 10.9 kg, AHI0.259 ± 0.043				
	Main findings: Significant greater ankle dynamic joint stiffness significant and smaller net and propulsive work in HA compared to LA runners.					
Powell et al. [10]	Knee abduction moments in HA compared to LA athletes during walking and running	Recreational female runners (n = 20)	AHI (+/- 1.5 SD)	Barefoot, overground at self-selected speed ± 5%	Kinetics: knee abduction moments	13
	Groups					
	High arch (n = 10) Low arch (n = 10)	18-30 years, 162 ± 7 cm, 58.3 ± 5.4 kg, AHI 0.386 ± 0.010 18-30 years, 163 ± 7 cm, 58.9 ± 10.9 kg, AHI0.259 ± 0.043				
	Main findings: Significant smaller peak knee abduction moments in HA compared to LA runners.					

(*continued on next page*)

Table 2 (*continued*)

Study	Objective	Participants	Independent Variable	Running Condition	Dependent Variable	Modified D& B Score (Max. 20 Points)
Powell et al. [30]	Muscular and skeletal contributions to leg stiffness during running and step off landing tasks	Recreational female runners (n = 20)	AHI (+/- 1.5 SD)	Barefoot, overground at self-selected speed ± 5%	Three-dimensional kinematics and kinetics, leg stiffness	14
	Groups					
	High arch (n = 10)	20.8 ± 2.50 years, 162 ± 7 cm, 58.3 ± 5.4 kg, AHI 0.386 ± 0.010				
	Low arch (n = 10)	21.1 ± 2.3 years, 163 ± 7 cm, 58.9 ± 10.9 kg, AHI0.259 ± 0.043				
	Main findings: Significant greater leg stiffness and skeletal stiffness in HA compared LA runners. No differences in muscular stiffness.					
Sinclair et al. [32]	Differences in frontal plane subtalar joint angles between individuals with pes planus or pes cavus before and after a 45 minute run.	Healthy runners (n = 34)	Medial longitudinal arch angle LA: 90-130°, HA 150-180°	Barefoot, treadmill at 12 km/h before and after 45 min of shod running	Calcaneus vertical angle (calcaneus to ground)	14
	Groups					
	Low arch (35 feet)	20 female, 14 male, 36.7 (22-55) years, 173 (144-198) cm, 67 (44-86) kg, BMI 22.6 (18.7-26) kg/m*m				
	High arch (30 feet)					
	Main findings: No significant differences before running between both groups regarding the calcaneus vertical angle (frontal plane), but after running LA group exhibited higher eversion compared to HA runners.					

Abbreviations: EMG electromyography, HA high-arched, LA low-arched, SD standard deviation.

medial longitudinal arch. Most commonly, in 11 studies, the arch height index (AHI) established by Williams and McClay [45] was used to differentiate between a low or high arched foot [8,10,21,25,29–31,37,38,40,41]. Three studies calculated an arch index based on the contact area of the foot [23,26,33]. Arch height was assessed in three other studies [28,36,39]. Arch index [22,23], the foot posture index [24,35], the (medial) longitudinal arch angle [27,32], and navicular drop [9,42] were used in two studies each. One study assessed the feet radiographically [26], and one study graded the feet based on the visual assessment of an orthopaedic surgeon [34].

Most studies (15) evaluated barefoot running conditions at a self-selected speed either overground or on a treadmill. Seven studies used standardized footwear, two studies examined the interventional effect of motion control vs. cushioned shoes [40,41], one study used minimalist footwear [38].

Analysis of the included participants, independent variables, running conditions, and published data identified seven studies that allow pooling of the data for a meta-analysis.

3.1.5. *Statistical reporting*

Of all included studies, fourteen studies used either ANOVA [21,22,28,29,34,38–41] or t-tests [8,10,30,31,37] to compare means. Of these, only three studies calculated effect sizes [8,30,38]. Four studies compared their data using a Pearson product-moment correlation [9,25–27] as well as Spearman or intraclass correlation coefficients [32,35]. Regression analysis was used in four other studies [23,24,36,42], while one study analysed the data using generalized linear mixed models [33].

3.1.6. *Overview of variables and results of studies*

The overview of biomechanical outcomes investigated in the included studies is summarized in Fig. 3. The assessed variables included rearfoot eversion (n = 8 studies), ground reaction forces (n = 7), plantar pressure (n = 4), tibial and leg rotation (n = 4), spatial–temporal measures (n = 3), forefoot eversion and abduction (n = 3), leg stiffness (n = 3), ankle kinematics (n = 2), ankle inversion moments (n = 2), knee abduction moments (n = 2), tibia shock (n = 2), plantar fascia tension (n = 1) and tibia acceleration (n = 1).

3.1.7. *Kinematics*

3.1.7.1. Subtalar joint. Rearfoot eversion was assessed in eight studies [8,9,23,25,29,32,38,40] using different techniques, mostly with markers on the rearfoot, either directly on the skin or attached to the shoe. One study used the calcaneal vertical angle with video capture [32].

Pooling was able to be conducted for eversion excursion showing a small pooled effect (-0.94; 95% CI −1.74 to − 0.014) for increased eversion excursion angles during shod running for low-arched runners reflecting moderate evidence (Fig. 4, Table 4). For barefoot running, no pooled effect was found (Fig. 4, Table 4).

Very limited or conflicting evidence was found with regards to other rearfoot kinematics. Two studies, examining barefoot running and running with minimal footwear, did not find a significant difference between rearfoot eversion in low arch (LA) or high arch (HA) runners [9,38]. Three other studies showed significant differences in low vs. high arch runners with regards to the rearfoot motion. Williams et al. found a significantly higher eversion for LA runners at footstrike and eversion velocity in shod running [8], while Powell et al. report smaller peak ankle eversion angles for HA runners in barefoot running [29]. Lee et al. [25] were able to show a significant correlation between dynamic arch height and maximum rearfoot eversion motion in barefoot running. Sinclair and colleagues showed a significantly higher eversion during mid-stance in LA runners when compared to HA runner after a 45 min run [32].

3.1.7.2. Forefoot motion and foot positioning. When looking at foot

Table 3
Study characteristics and main results of all included studies investigating shod running.

Study	Objective	Participants	Independent Variable	Running Condition	Dependent Variable	Modified D&B Score (Max. 20 Points)
Barnes et al. [38]	Fore-, rearfoot kinematics, and tibial shock in HA vs LA	Male participants, no information in habitual foot strike or running experience (n = 30)	AHI; at 90% of BW: LA below 1 st quartile, HA above the 4th quartile	Minimalist footwear (gait sandals), overground at 3.5 m/s ± 5%	Peak tibial acceleration, fore- and rearfoot kinematics	13
	Groups					
	High arch (n = 15)	19.0 ± 1.2 years, 178.3 ± 4.3 cm, 77.3 ± 11.3 kg, AHI (90%) 0.383 ± 0.016				
	Low arch (n = 15)	21.6 ± 2.8 years, 180.2 ± 5.5 cm, 77.1 ± 6.5 kg, AHI (90%) 0.320 ± 0.013				
	Main Findings: Significant effect of foot type on forefoot abduction excursion and forefoot abduction velocity (both higher in HA runners). No effects on tibial acceleration, tibial shock, forefoot eversion excursion and forefoot eversion velocity.					
Butler et al. [40]	Interaction of arch type and footwear on rearfoot mechanics and loading variables	Recreational runners from the local community (n = 40)	AHI (+/- 1.5 SD)	Motion control and cushioned footwear, overground at 3.5 m/s ± 5%	3D Kinematics & Tibial acceleration	15
	Groups					
	High arch (n = 20)	11 female, 9 male, 22.3 ± 4.4 years, 171 ± 7 cm, 70.8 ± 10.1 kg, AHI 0.390 ± 0.015				
	Low arch (n = 20)	10 female, 10 male, 22.8 ± 4.7 years, 171 ± 10 cm, 66.8 ± 8.0 kg, AHI 0.291 ± 0.018				
	Main findings: Significant interaction between footwear and foot type. HA lower instantaneous loading rate in cushioned running shoe, LA lower instantaneous loading rate in motion control shoe.					
Butler et al. [41]	Running mechanics over a prolonged run with different shoe types in HA vs LA	Recreational runners (n = 24)	AHI (+/- 1.5 SD)	Motion control and cushioned footwear, overground at self-selected pace	Lower extremity kinematics and tibial acceleration	13
	Groups					
	High arch (n = 12)	20.9 ± 3.0 years, 170 ± 7 cm, 68.4 ± 5.8 kg, AHI 0.390 ± 0.011				
	Low arch (n = 12)	21.8 ± 3.2 years, 173 ± 11 cm, 70.0 ± 7.3 kg, AHI 0.296 ± 0.019				
	Main findings: Different interaction between footwear and foot type. LA: peak tibial internal rotation decreased in motion control shoes, increased in cushioned running shoes.					
Chuckpaiwong et al. [34]	Differences in plantar pressure between walking and running and between subjects with a normal and a low arch feet	Healthy adults, no information on sex, foot strike patterns or running experience (n = 50)	Navicular height < 37 mm, arch angle < 46°; Rearfoot angle < 9° and clinical examination (orthopaedic surgeon)	Shod, no information on footwear, overground at 3.3 m/s ± 5%	Kinetics: Insole kinetics during stance phase (contact area, peak pressure, maximum force, and the force-time integral in 8 different areas)	12
	Groups					
	Normal arch (n = 43)	24.7 ± 4.3 years, 177 ± 8 cm, 81.5 ± 17.5 kg				
	Low arch (n = 16)	25.2 ± 3.3 years, 177 ± 9 cm, 74.8 ± 13.2 kg				
	Main findings: Significant interaction between foot type and contact area in the medial midfoot and maximum force and peak pressure in the lateral forefoot. LA: maximum force and peak pressures.					
Kernozek et al. [23]	Relationship between arch type, foot placement angle and rearfoot motion	Healthy women, from university fitness class (n = 20)	Arch Index (are of midpart): HA (AI ≥ 0.26 cm2), NA (0.21 < AI < 0.26 cm^2) and LA (AI ≤ 0.21cm^2)	Shod, standardized footwear, overground at 3.5 m/s ± 5%	Kinematics: Rearfoot angle and foot placement angle (=foot progression angle)	11
	Groups					
	No groups, correlation analysis	18-30 years, mean weight 57.0 ± 3.1 kg, mean AI 0.23 cm2 +/- 0.05 cm2 (normal arch type across all subjects)				
	Main findings: Arch type was related to rearfoot motion: Normal arched runners exhibit less rearfoot motion than LA and HA.					
Lee & Hertel [42]	Correlation between arch height and plantar pressure	Healthy and physically active adults	Navicular drop	Shod, standardized footwear, treadmill at 2.6 m/s ± 5%	Insole plantar pressure: max. pressure (+ time to), pressure–time integral (diff areas)	12
	Groups					
	Correlation analysis, no groups	8 male, 17 female, 21.4 ± 2.3, 170.4 ± 7.4 cm, 59.5 ± 5.6 kg, navicular drop: rear-foot alignment: 3.56° ± 1.50°, 1.28° ± 1.43°, and 4.99 ± 2.47 mm				
	Main findings: Rear-foot alignment was a significant predictor of maximum plantar pressure and pressure–time integral in the medial rear-foot and midfoot regions					
Nachbauer & Nigg [28]	Effect of arch height and arch flattening on selected ground reaction force-variables	Adult subjects from university campus (n = 37)	Arch height (Caliper) and Arch flattening (Video)	Shod, standardized footwear, rearfoot strike only, overground at 4 m/s ± 10%	Ground reaction forces	15
	Groups					
	3 groups: LA, normal arch, HA	18 female, 19 male, age 19-48 years, 152-185 cm, 49-90kg arch height per group: LA 1.86 ± 0.23 cm, Normal arch 2.57 ± 0.14 cm, HA 3.27 ± 0.16 cm				
	Main findings: No correlation between arch height and arch flattening. Initial medial force peak occurred later in LA runners.					
Nigg et al. [36]	Influence of arch height on lower limb kinematics	Healthy adults from university campus (n = 30)	Arch height (full weight baring) in cm	Shod, standardized footwear, rearfoot strike only, overground at 4 m/s ± 10%	Kinematics: eversion, internal leg rotation and transfer coefficient	13
	Groups					

(*continued on next page*)

Table 3 (*continued*)

Study	Objective	Participants	Independent Variable	Running Condition	Dependent Variable	Modified D&B Score (Max. 20 Points)
	No groups, correlation	15 female, 15 male, 30.4 ± 7.6 years, 170.5 ± 8.5 cm, 66.4 ± 10.7 kg; arch height 2.64 ± 0.43 cm				
	Main findings: Arch height did not influence maximal eversion moments or maximal internal leg rotation during stance, but arch height influences the transfer of eversion to internal leg rotation.					
Williams et al. [1]	Relationship between arch type rearfoot eversion and tibial rotation and vertical ground reaction forces	Runners with injury history, (n = 40)	AHI (+/- 1.5 SD)	Shod, standardized footwear, rearfoot strike only, overground at 3.35 m/s ± 5%	Kinematics and ground reaction forces: Eversion excursion, Eversion to tibial internal rotation ratio, eversion to knee internal ratio. eversion velocity, peak knee flexion, loading rate	14
	Groups					
	High arch: n = 20	10 female, 10 male, 172 cm, 66.5 kg, AHI 0.367 ± 0.013				
	Low arch: n = 20	12 female and 8 male, 174 cm, 72.1 kg, AHI 0.271 ± 0.023), 27.8 ± 8.1 years				
	Main findings: LA had increased rearfoot eversion excursion, eversion to tibial internal rotation ratio and rearfoot eversion excursion. HA runners had increased vertical loading rate compared to LA runners.					
Williams et al. [37]	Compare leg stiffness between HA and LA	Runners with no injury history, n = 40	Arch height index (+/- 1.5 SD)	Shod, standardized footwear, rearfoot strike only, overground at 3.35 m/s ± 5%	Leg stiffness, knee stiffness, vertical loading rate and lower extremity support moment, EMG	11
	Groups					
	High arch: n = 20	10 female, 10 male, 172 cm, 66.5 kg, AHI 0.367 ± 0.013				
	Low arch: n = 20	12 female and 8 male, 174 cm, 72.1 kg, AHI 0.271 ± 0.023), 27.8 ± 8.1 years				
	Main findings: Significant increase in leg stiffness and vertical loading rate, as well as decrease in knee flexion excursion during stance and earlier onset of M. vastus medials for HA compared to LA runners.					

Abbreviations: EMG: electromyographiy, HA: high-arched, LA: low-arched, SD: standard deviation.

kinematics, very limited evidence exists for higher forefoot abduction excursion and velocity [38] and midfoot-forefoot eversion [29] for HA runners compared to LA when running barefoot. Furthermore, for children, limited evidence was found for an association of low arches with higher foot progression angles (= 'dynamic' external rotation) [33].

3.1.7.3. Ankle kinematics. Sagittal plane ankle kinematics for barefoot running were reported in two of the included studies [31,33]. Powell et al. [31] observed less plantarflexion at ground contact, less peak dorsiflexion and less range of motion during stance phase in HA barefoot running trials. However, they did not present sufficient statistical analysis for their reports. Sagittal ankle angles at foot strike and corresponding foot strike patterns were investigated in another study on 10–14 years-old children and were not reported to be significantly associated with medial longitudinal arch characteristics [33]. Therefore, limited evidence can be assumed for no association of medial longitudinal arch characteristics and sagittal plane ankle kinematics at least in children.

3.1.7.4. Tibial rotation and leg rotation. Four studies investigated tibial and leg rotation. While no effect of foot type on peak tibial rotation and tibial internal rotation excursion was reported in one study [40], another study showed only an interaction effect between footwear and foot type regarding peak tibial rotation [41]. LA runners exhibited reduced peak tibial internal rotation in a motion control shoe and increased peak tibial internal rotation in a cushioned running shoe over the course of the prolonged run [41]. Very limited evidence was, respectively, found for a correlation between navicular drop and tibial internal rotation excursion [9], as well as between arch height and internal leg rotation [36].

3.1.7.5. Tibial acceleration and tibial shock. No effect of foot type on peak positive tibial acceleration or peak-to-peak positive tibial acceleration was reported by Butler et al. [40], representing limited evidence. Furthermore, very limited evidence exists for no differences between LA and HA regarding tibial shock variables [38], and lower tibial shock values in HA runner after prolonged shod running [41].

3.1.8. Spatial–temporal variables

Three studies investigated spatial-temporal variables, of which two only reported them as secondary outcomes. Williams and colleagues [37] reported a statistically significant reduction in contact time for shod running in HA runners, while Hernández-Gervilla et al. [35] did not find any correlations between foot posture index and contact time, flight time, stride time or stride frequency for barefoot running. For children, no association between dynamic arch index and spatial-temporal variables were found for barefoot running [33]. Therefore, conflicting evidence is present for a relation between medial longitudinal arch characteristics and spatial-temporal variables.

3.1.9. Kinetics

3.1.9.1. Ground reaction force. Seven studies reported on ground reaction force (GRF) data, of which four studies used an effect analysis [8,28,37,40], two studies a correlation analysis [26,39] and one study a linear mixed model analysis [33].

LA runners exhibited a lower vertical loading rate combined with a lower initial peak occurring over a longer time in shod running [8,37]. Pooling was possible for these two GRF-related outcomes. One study had to be excluded from the pooling of loading rate due to duplicate representation of results [8,37]. After pooling, no statistically significant differences were found for loading rate (p = 0.27) or impact peak (p = 0.32) in shod running between HA and LA runners (Fig. 4, Table 4).

Differences in instantaneous loading rates regarding footwear use were reported by Butler et al. [40], with LA runners showing a lower

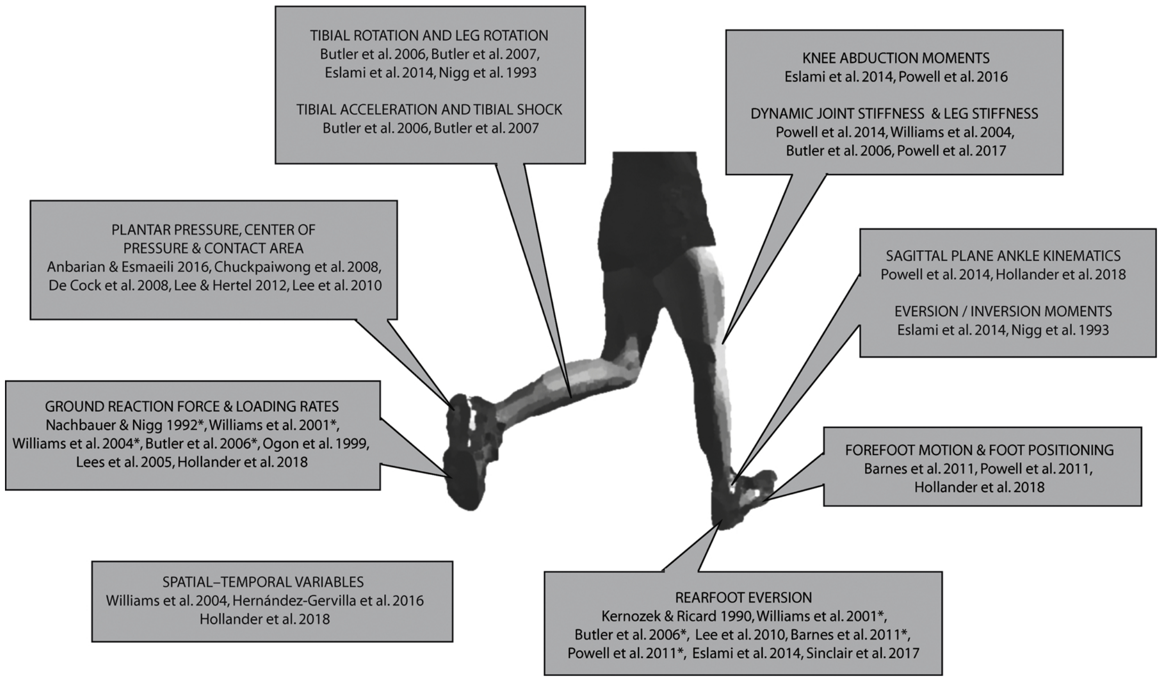

Fig. 2. Graphical abstract of includes studies. Asterisk annotates the studies included into the meta-analysis.

instantaneous loading rate in motion control shoes and HA runners had a lower instantaneous loading rate in normal cushioned running shoes. Furthermore, there was a negative correlation between medial longitudinal arch height and initial loading rate in anterior-posterior and vertical directions, as well as a positive correlation with initial loading rate in the medial direction [39]. Another study reported the initial medial force peak to occur later in LA runners running shod [28]. For children, an association between dynamic arch index and maximum

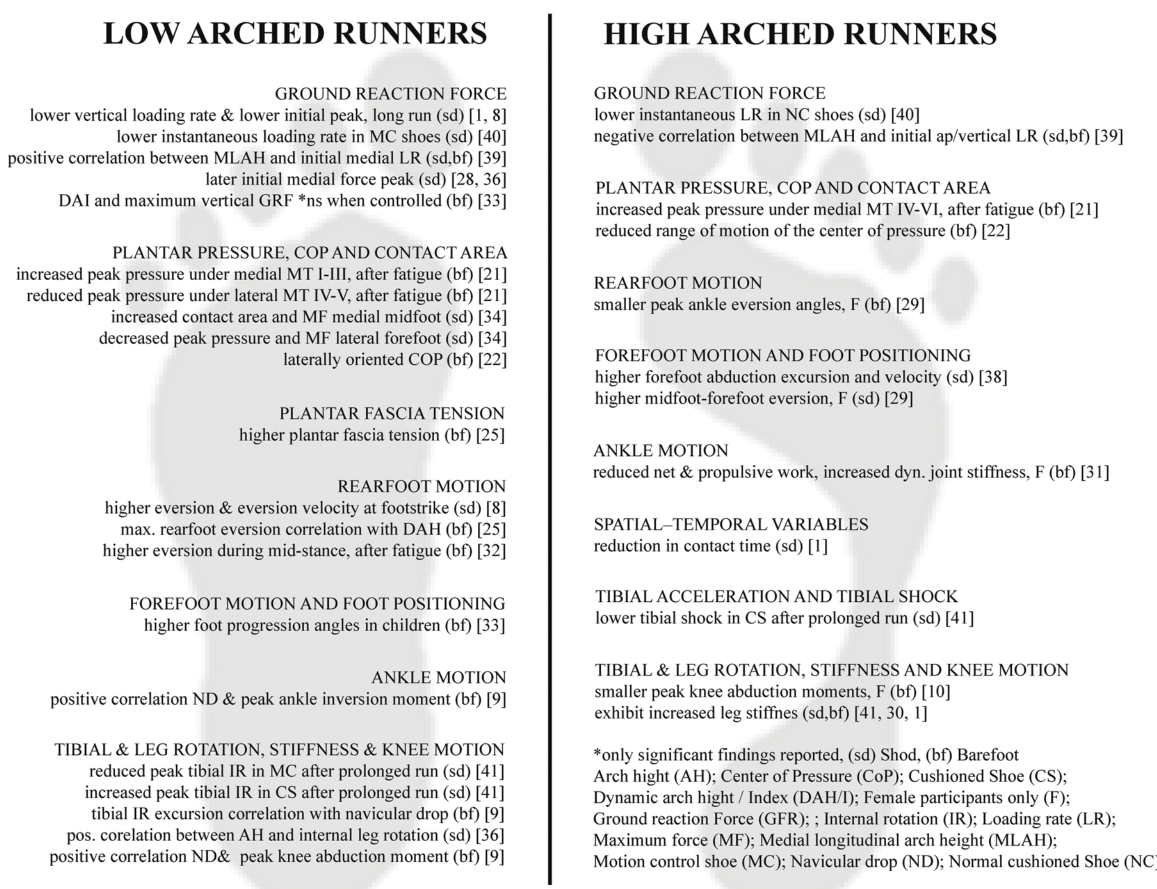

Fig. 3. Summary of significant biomechanical findings for low arched and high arched runners.

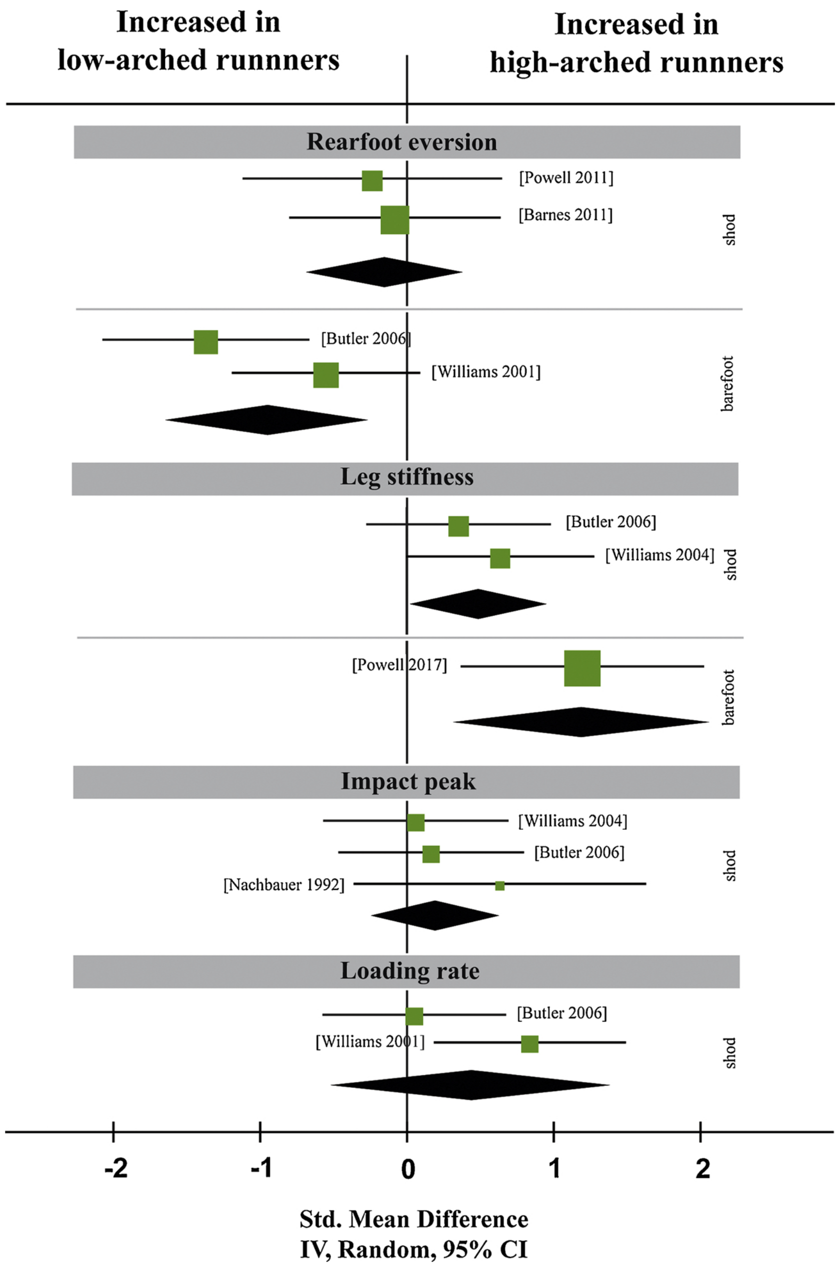

Fig. 4. Forrest plot displaying the pooled effects of high-arched and low-arched runners on the variables that were included in the meta-analysis (rearfoot eversion excursion during stance phase of running, loading rate of ground reaction force curves during running, impact peak of ground reaction force curves during running, leg stiffness during running). CI, confidence interval; df, degrees of freedom; IV, instrumental variable; SD, standard deviation; Std, standard.

vertical GRF was reported, which was not evident when possible confounders (BMI, height and running velocity) were controlled for [33]. No further effects or correlations between medial longitudinal arch and GRF were reported.

3.1.9.2. Plantar pressure, shift of the center of pressure and contact area. Four studies investigated the influence of the medial longitudinal arch on plantar pressure, of which two used an insole device [34,42] and two used barefoot running over a pressure detection interface [21,22]. One study implemented a fatigue protocol in order to investigate differences in plantar pressure distribution before and after a prolonged run [21]. After the fatigue protocol LA runners showed increased peak pressure under the medial metatarsal bones (I-III) and a reduced peak pressure under the lateral metatarsal bones (IV-V). In HA runners the opposite was found, namely increased peak pressure under the fourth and fifth metatarsal bones [21]. Chuckpaiwong et al. [34] investigated shod running using insole devices. For LA individuals compared to normal feet, they reported an increased contact area and maximum force beneath the medial midfoot, as well as decreased peak pressure and maximum force beneath the lateral forefoot. When investigating the center of pressure, De Cock et al. [22] found significant effects of foot types on displacement of the center of pressure. Namely, LA runners exhibited a more laterally oriented COP course than HA, while HA runners showed a reduced range of motion in their center of pressure during forefoot contact phase. No differences between foot types were found for force-time integrals [34] or pressure outcomes beneath the medial aspect of the foot [42]. Altogether, only very limited evidence for different plantar pressure distribution after running and displacement of the COP between HA and LA participants.

3.1.9.3. Plantar fascia tension. Very limited evidence exists from one study investigating plantar fascia tension for an association (negative

Table 4
Meta-analysis results.

		High-arched runners			Low-arched runners				
	Rearfoot eversion								
	Study	Mean	SD	Total	Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
shod	Butler 2006	9.8	2.9	20	13.7	2.7	20	48.4%	−1.36 [−2.06, −0.67]
	Williams 2001	11.9	3.73	20	13.96	3.63	20	51.6%	−0.55 [−1.18, 0.08]
	Total (95% CI)			**40**			**40**	**100%**	**−0.94 [−1.74, -0.14]**
barefoot	Powell 2011	−7.5	2.6	10	−6.7	3.3	10	39.8%	−0.26 [−1.14, 0.62]
	Barnes 2011	13.2	3.3	15	13.6	4.2	15	60.2%	−0.10 [−0.82, 0.61]
	Total (95% CI)			**25**			**25**	**100%**	**−0.16 [−0.72, 0.39]**
	Leg stiffness								
	Study	Mean	SD	Total	Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
shod	Butler 2006	8.9	1.8	20	8.3	1.5	20	50.9%	0.35 [−0.27, 0.98]
	Williams 2004	7.17	1.16	20	6.46	1.01	20	49.1%	0.64 [0.00, 1.28]
	Total (95% CI)			**40**			**40**	**100%**	**0.49 [0.05, 0.94]**
barefoot	Powell 2017	29.3	11.3	10	20.6	3.7	10	100%	1.19 [0.37, 2.02]
	Total (95% CI)			**10**			**10**	**100%**	**1.19 [0.37, 2.02]**
	Impact peak								
	Study	Mean	SD	Total	Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
shod	Williams 2004	1.47	0.28	20	1.45	0.33	20	41.8%	0.06 [−0.56, 0.68]
	Butler 2006	1.76	0.25	20	1.71	0.33	20	41.6%	0.17 [−0.45, 0.79]
	Nachbauer 1992	1.97	0.41	9	1.72	0.33	8	16.6%	0.63 [−0.35, 1.62]
	Total (95% CI)			**49**			**49**	**100%**	**0.20 [−0.20, 0.60]**
	Loading rate								
	Study	Mean	SD	Total	Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
shod	Williams 2004	62.48	13.62	20	52.05	10.79	20		Not estimable
	Butler 2006	84.5	24.5	20	83.4	25.9	20	50.8%	0.04 [−0.58, 0.66]
	Williams 2001	62.48	13.62	20	52.05	10.79	20	49.2%	0.83 [0.18, 1.48]
	Total (95% CI)			**40**			**40**	**100%**	**0.43 [−0.34, 1.20]**

correlation) between the plantar fascia tension and the dynamically measured arch index, representing a higher fascia tension in LA runners [25]. Furthermore, the dynamic arch index was better in predicting plantar fascia tension than static arch height [25].

3.1.9.4. Ankle and knee moments. Two studies investigated knee abduction moments during barefoot running revealing conflicting evidence [9,10]. One study found a positive correlation between navicular drop and peak knee abduction moment [9], while for females, HA runners tended to have smaller peak knee abduction moments when compared to LA female runners [10].

At the ankle, very limited evidence was found for HA female runners having reduced net work and propulsive work, as well as increased dynamic joint stiffness when compared to LA female runners during barefoot trials [31]. Conflicting evidence was found for a correlation between foot types and eversion/inversion moments. While Eslami et al. [9] found a positive correlation between navicular drop and peak ankle inversion moment during barefoot running, Nigg et al. [36] did not find a correlation between arch height and eversion moment during shod running.

3.1.9.5. Leg stiffness. Moderate evidence from three studies [30,37,40] was found for HA runners to exhibit increased leg stiffness when running barefoot or shod (Fig. 4, Table 4). When synthesized, a small pooled effect size was found for shod running (0.49; 95%CI 0.05 to 0.94).

4. Discussion

The aim of this study was to systematically synthesize the relationship between medial longitudinal arch characteristics and running biomechanics. Overall, some evidence was found for a relationship between the medial longitudinal arch and rearfoot kinematics, leg stiffness, mid- and forefoot kinematics, tibial rotation, tibial acceleration/shock, plantar pressure distribution (peak pressures, center of pressure course) and ankle kinetics (net work, propulsive work, dynamic joint stiffness moments). However, even though 25 studies investigating this relationship were identified, only seven studies could be used to pool data. For the other studies it was not possible to pool data and conduct a meta-analysis due to the high heterogeneity of participants, foot type assessments, biomechanical outcomes and statistical strategies, as well as different states of fatigue. The included studies were grouped according to their biomechanical outcomes and will be discussed accordingly.

4.1. Association between foot posture characteristics and biomechanical outcomes

Overall, some evidence was found for an association between medial longitudinal arch characteristics and kinematic, spatial-temporal and kinetic outcomes.

An association between the medial longitudinal arch and subtalar joint kinematics and tibial rotation can be assumed due to anatomical constraints [9,29,32,36,38]. No evidence was found relating medial longitudinal arch characteristics to sagittal ankle kinematics, only very limited evidence for tibial acceleration or tibial shock. However, after a prolonged run in footwear, HA runner showed reduced tibial shock in cushioned running shoes without motion control [41]. The interaction of foot type and footwear regarding biomechanics [40] and injury epidemiology [46,47] is likely only one part of the multifactorial etiology of running related injuries [48,49]. However, except for the rearfoot eversion excursion, the associations found in this systematic review are too heterogeneous to provide evidence or clinical guidance. Other research designs (prospective cohort studies or randomized controlled trials) are needed to clarify this question.

Only one study reported a reduction of contact time in HA runners [37]. In this study it was accompanied by a higher leg stiffness and vertical loading rate compared to LA individuals. Moderate evidence was found for higher leg stiffness in high-arched runners. This could be associated with a stiffer arch due to intrinsic muscle activation [37,50]. Furthermore, Powell et al. [30] showed that in high-arched runners the skeletal contribution to leg stiffness is higher than in low-arched runners. The higher leg stiffness in HA runners is associated with increased knee and ankle joint stiffness.

This moderate evidence for increased leg stiffness for HA runner [30,37,40] could also contribute to the expected differences in GRF characteristics. LA runners showed lower vertical loading rates than HA counterparts [8,37]. This was argued to be due to lower initial peaks over a longer time, which is in accordance with the findings of Nachbauer & Nigg [28]. However, the meta-analysis revealed non-significant differences for loading rate and impact peaks. Furthermore and contrary to these findings, a slight negative correlation between arch height and vertical loading rate was reported by Ogon et al. [39]. These opposite findings might be explained by different experimental setups. All studies tested overground running, but one study [39] used a rather slow speed (1.5 m/s), while a faster velocity of 3.35 m/s was used in the other studies [8,37]. Furthermore, Ogon et al. [39] included barefoot and shod testing and did not restrict inclusion to rearfoot-striking runners. It is known that speed and footwear influence foot strike patterns and it is well documented that foot strike pattern influences vertical loading rates [17,51–53]. Additionally, there was an interaction effect of different footwear (cushioned and motion control) and vertical loading rates reported in one of the included studies [40]. Therefore, it is difficult to draw valid conclusions on the relationship between the medial longitudinal arch and vertical loading rates from these studies. Furthermore, recent research has demonstrated that vertical loading rates can be altered in multiple ways, for example by changing footwear, footstrike patterns or using gait retraining or habituation [43,54–57].

For plantar pressure, LA runners had decreased peak pressures under the lateral forefoot which further decreased after a fatiguing run [21,34]. This observation was accompanied by an increased contact area and maximum force values in the medial midfoot and a more laterally oriented center of pressure course [22]. In accordance with this, HA runners showed increased peak pressures under the lateral forefoot and a reduced range of motion of their center of pressure during forefoot contact [21,22]. These findings can be interpreted in accordance with reported injury patterns which seem to occur more laterally in HA runners and more medially in LA runners [1]. This has been related to increased stress on the, respectively, lateral or medial lower limb [1]. However, the number of participants (n = 40) and accordingly the number of injuries (n = 134) were relatively small to draw conclusive clinical or preventive recommendations from these finding.

4.2. Limitations and methodological considerations of current research

4.2.1. Risk of bias

All studies showed moderate or low risk of bias, with major problems in internal validity, such as reporting of recruitment strategies, adjustments for confounding factors and a priori power analysis. These problems are simple to overcome, and should ideally be improved upon in future studies. Possible confounders that should be kept in mind are internal factors such as weight, height, BMI, sex, age, and changes related to growth [58–60], as well as external factors such as running surface, speed, footwear and habituation to footwear [17,18,52,61].

Only few studies provide information on running background of participants, such as competitive or recreational level, personal bests or weekly mileage. Therefore, no differentiations for competitive vs. recreational populations were possible. However, the level of experience and competitive level is important to interpret running biomechanics [62,63]. For this systematic review, only generally valid conclusions for overall running were able to be drawn.

4.2.2. Methods of foot (arch) type classification

In the included studies, there was a high heterogeneity for independent (medial longitudinal arch characterizations) and dependent (running biomechanics) variables. Similar difficulties have recently also been documented by a systematic review comparing medial longitudinal arch characteristics and plantar pressure distribution of gait [64]. While in the clinical setting an x-ray may be considered as the gold standard of assessing medial longitudinal arch morphology, there is currently no gold standard for assessing medial longitudinal arch characteristics in scientific settings, where the ionizing radiation is not always justified. In the included studies, there were several dynamic and static assessments of the foot, such as arch height index, (dynamic) arch index, the (medial) longitudinal arch angle, the foot posture index, as well as radiographical or visual assessments by an orthopaedic surgeon. Sometimes the same term was used for different assessments, such as the 'dynamic arch index'. The pedobarographically assessed dynamic arch index is inversely correlated with arch height [33], while the video determined arch index is directly correlated to arch height [25]. This might lead to confusion in the interpretation of results, and a consensus for the terminology is desirable. The arch height index developed by Williams & McClay [45] was the predominant foot assessment used. However, different cut-off values (quartiles, 1.5 SD or fixed values) were used to determine high or low arched feet. Furthermore, there is conflicting evidence about the comparability of different foot assessments to each other [65,66] and other studies also showed the importance of differentiating between dynamic and static arch measurements [25,58,67]. Due to these differences in evaluation, it was only possible to pool data for few studies and outcomes. If we want to give clear evidence about the impact of medial longitudinal arch characteristics on biomechanics, it is suggested that a consensus on terminology and foot type assessment in biomechanical research is needed.

5. Conclusion

There is evidence for a relationship between medial longitudinal arch characteristics and running biomechanics, especially for subtalar joint kinematics, leg stiffness, ankle kinetics and tibial shock. Even though this relationship has been discussed as an underlying mechanism for running-related injuries, it is difficult to draw conclusive practical or clinical guidance from the current literature. Future research would benefit from higher internal validity and a consensus on medial longitudinal arch characterization to provide more homogenous comparisons. Both points would be helpful to generalize, compare and synthesize findings.

Conflict of interest statement

There are no conflicts of interest among any of the authors of this article.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.05.031.

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