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The effect of running on foot muscles and bones: A systematic review

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ABSTRACT

Despite the widespread evidence of running as a health-preserving exercise, little is known concerning its effect on the foot musculature and bones. While running may influence anatomical foot adaptation, it remains unclear to what extent these adaptations occur. The aim of this paper is to provide a systematic review of the studies that investigated the effects of running and the adaptations that occur in foot muscles and bones. The search was performed following the PRISMA guidelines. Relevant keywords were used for the search through PubMed/MEDLINE, Scopus and SPORTDiscus. The methodological quality of intervention studies was assessed using the Downs and Black checklist. For cross-sectional studies, the Newcastle-Ottawa scale was used. Sixteen studies were found meeting the inclusion criteria. In general, the included studies were deemed to be of moderate methodological quality. Although results of relevant literature are limited and somewhat contradictory, the outcome suggests that running may increase foot muscle volume, muscle cross-sectional area and bone density, but this seems to depend on training volume and experience. Future studies conducted in this area should aim for a standard way of reporting foot muscle/bone characteristics. Also, herein, suggestions for future research are provided.

1. Introduction

Running is an important form of exercise because it is inexpensive, accessible, and it provides many health benefits (Lee et al., 2017); however, many of these benefits can only occur thorough repetitive loading of anatomical structures, and the effect of overload will lead to musculoskeletal injury and non-participation (Nohren, Davis, & Hamill, 2007; Pepper, Akuthota, & McCarty, 2006). Bones and muscles are adaptive tissues that develop in structure and function in response to mechanical load and metabolic demands, which is a demonstration of activity-dependant plasticity (Kiely & Collins, 2016). However, tissue can also be maladaptive. While repetitive load may cause a positive hypertrophic response in bone (Chen, Beaupré, & Carter, 2010) and muscles (Seynnes, de Boer, & Narici, 2007); the converse occurs with a reduction (or removal) of load – due to immobilization, physical inactivity, or microgravity exposure – resulting in tissue decay through the process of bone resorption (Holick, 2000; Kiratli, Smith, Nauenberg, Kallfelz, & Perkash, 2000) and muscle atrophy (Powers, Kavazis, & DeRuisseau, 2005). Runners can modulate the nature of the stresses experienced by bone and muscle by altering limb kinematics at impact (Li, Zhang, Gu, & Ren, 2017), or by selecting compliance variations in terrain surface and footwear substrates (Firminger, Fung, Loundagin, & Edwards, 2017); this is because both approaches will effect a change in the direction and magnitude of the external and internal forces applied to the lower limbs. In accordance with activity-dependent plasticity principle, there will exist certain kinematic-substrate combinations that lead to optimal

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adaptation of foot structure and function and help mitigate injury risk for runners, whereas other combinations will amplify risk. To adequately understand the pathological effect of maladaptive foot structure and function on running injury, a prerequisite step is to first understand the effect of repetitive running load on changes to foot anatomy. The motivation for this review is that this mechanistic effect remains largely unknown due to limited research exploration (Lee et al., 2017).

Repetitive stress injuries are very common among runners, especially stress fractures of the foot (van Gent et al., 2007). Around 55% of these fractures occur in the metatarsals – mostly second and third (Fetzer & Wright, 2006); the calcaneus, talus, navicular and sesamoid account for 6% (Groshar et al., 1997; Pelletier-Galarneau, Martineau, Gaudreault, & Pham, 2015). Long distance runners tend to be afflicted by metatarsal stress fractures more than other athletes (Brukner, Bradshaw, Khan, White, & Crossley, 1996). This high injury rate might be related to training distance (van Gent et al., 2007), training volume (Hreljac, 2004), and runners' biomechanical adaptations (Davis, Rice, & Wearing, 2017). During running, human locomotor system broadens the distribution of stress that arises from impact forces (Hart et al., 2017) by active modulation of muscle activity (Olin & Gutierrez, 2013) and hence joint torques and rotational energy (Lieberman et al., 2010). Because the foot is the most proximal aspect of the lower limb to the external ground forces, the effect of the stresses will be larger than elsewhere in the lower limb (Lieberman et al., 2010; Lieberman, 2012a, 2012b); furthermore, the foot may happen to have the most sensitive anatomy of the lower limb to exhibit activity-dependent plasticity (McKeon, Hertel, Bramble, & Davis, 2014).

Previous studies have shown an increased incidence in bone stress in runners who were transitioning from 'cushioned' footwear to minimal shoes (Johnson, Myrer, Mitchell, Hunter, & Ridge, 2016). The authors found that those who transitioned without negative effects to minimal shoes developed larger adductor halluces muscles, while those who developed bone stress had smaller foot muscles. Popp et al. (2017) investigated the association between tibial cortical bone density and stress fractures in runners, founding substantially weaker bones in the stress fracture group at the mid-shaft of the tibia. Results from the previous studies (although based on acute interventions) suggest that stronger foot muscles and bones may be protective, while weak feet may be more likely to be injured. However, the long-term effect of the loads generated in the foot bones and muscles during running remains unknown. This knowledge could be used to study the contribution of mechanical load to foot musculoskeletal development and health maintenance, which is essential information for devising methods of injury prevention and treatment.

Measuring bone and muscle adaptations is difficult *in vivo*. Even if bone strength can be approximated by dual-energy X-ray absorptiometry (DXA) (Cummings, Bates, & Black, 2002) and computed tomography techniques (Norton & Gamble, 2001), the problem remains that bone mineral density (BMD) is not the only determinant of bone strength. Innovative 3D analysis of high-resolution images can now provide an insight into bone microstructure and architecture; this technique has shown to be less dependent on bone density than DXA (Geusens et al., 2014), outperforming ultrasound and previous X-ray scanning techniques in terms of image resolution (up to 82 μm) and level of radiation exposure (< 3 μ Sievert) (Cheung et al., 2013). Muscles have been imaged by techniques other than conventional radiography, such as magnetic resonance imaging (MRI), and ultrasound scanning. Compared to the former, ultrasound imaging (US) is widely available and rather inexpensive, allowing valid measure of muscle size through real-time high-resolution imaging (Mickle, Nester, Crofts, & Steele, 2013).

The load-related changes (adaptations) in foot muscle and bone may influence more variable running form and biomechanical solutions (Lieberman et al., 2015), resulting in minimisation of an accumulation of repeat stresses, however, solid evidence on the effect of running on the anatomical foot structure is needed to perorate this claim. Several original papers (Bobbert, Yeadon, & Nigg, 1992; Bramble & Lieberman, 2004; Bus, 2003; Davis et al., 2017; Gruber, Davis, & Hamill, 2011; Hasegawa, Yamauchi, & Kraemew, 2007; Hunter, Marshall, & McNair, 2005; Kasmer, Wren, & Hoffman, 2014; Lieberman et al., 2010, 2015; Lieberman, 2012a, 2012b, 2014; Nigg, 2010; Nigg, De Boer, & Fisher, 1995; Shu et al., 2015; Stefanyshyn & Nigg, 1997), as well as systematic reviews (Almeida, Davis, & Lopes, 2015; Hall, Barton, Jones, & Morrissey, 2013; Hollander, Heidt, Van Der Zwaard, Braumann, & Zech, 2017; Perkins, Hanney, & Rothschild, 2014; Schubert, Kempf, & Heiderscheit, 2014) analysed kinematics and kinetics of runners, with only some (Hollander et al., 2017; Shu et al., 2015) reporting findings on the long-term effect of running on foot morphology. The review by Hollander et al. (2017) concluded that habitual barefoot runners have wider feet and a reduced hallux angle than individuals that habitually wear shoes. However, most of the studies included in their review did not control for likely confounding variables such as body weight or running experience. Indeed, any structural change has also to be related to running volume and the amount of time spent resting between runs. Moreover, although they reported changes in foot morphology, the review by Hollander et al. (2017) focused on the differences between barefoot and shod populations, and they did not address adaptations to intrinsic foot muscle or bone. Therefore, the aim of the present paper is to review the evidence regarding the effect of running on foot musculoskeletal adaptations.

2. Methods

2.1. Search strategy

A systematic search of the literature was conducted in accordance with the PRISMA guidelines (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). PubMed/MEDLINE, Scopus, and SPORTDiscus databases were used to search for relevant literature from the inception of indexing up to the 1st November 2018. Combinations of the following keywords were used as search: running AND ("foot muscle" OR "foot muscles" OR "bone density" OR "bone strength" OR "bone composition" OR "muscle cross sectional area" OR "muscle volume" OR "foot morphology" OR "foot muscle morphology" OR "muscle strength" OR "foot strength"). Secondary searches were performed by checking the reference list of included articles as suggested by Greenhalgh and Peacock (2005). Forward citation tracking of the included studies was performed in Google Scholar.

2.2. Eligibility criteria

Studies were considered eligible if they met the following inclusion criteria: (1) published in English language; (2) published in a peer-reviewed journal; (3) included human participants; (4) used a randomized controlled trial (RCT), a case-control, a prospective cohort, or a cross-sectional study design; (5) measured foot muscle characteristics and/or foot bone characteristics; (6) at least one of the included groups was comprised of active runners. Exclusion criteria were studies reporting on groups or individuals with pre-existing medical conditions, such as metabolic diseases or foot anatomical deformation.

2.3. Coding of studies

The following information was extracted from the included studies: (i) sample size; (ii) groups description; (iii) main findings related to muscle/bone characteristics; and (iv) methods used to measure muscle/bone characteristics.

2.4. Methodological quality

Methodological quality of the included intervention studies was assessed using the validated Downs and Black scale (Downs & Black, 1998). For assessing cross-sectional studies, the modified Newcastle-Ottawa Scale was used (Wells et al., 1999). For the Downs and Black scale, studies scoring from 0 to 8 points were considered as being of poor methodological quality, studies scoring from 9 to 17 points were considered as being of moderate quality, and studies that scored 18 to 27 points were considered as being of high methodological quality. The maximum score on the Newcastle-Ottawa scale is 10 points. Based on the total score on the Newcastle-Ottawa Scale the studies were defined as either low quality (score ≤ 3 points), moderate quality (4–7 points), or high quality (score > 7 points). The datasets analysed during the current study are available from the corresponding author on reasonable request.

3. Results

3.1. Search results

The initial search resulted with 5487 search results. After the removal of duplicates, 3677 papers were screened, and excluded based on title, abstract, or in some cases, based on the full-text. In total, 41 full-text papers were read. Thirteen studies met the inclusion criteria (Best, Holt, Troy, & Hamill, 2017; Chen, Sze, Davis, & Cheung, 2016; Escamilla-Martinez et al., 2016; Fredericson et al., 2007; Fuller et al., 2018; Harber, Webber, Sutton, & MacDougall, 1991; Johnson, Myrer, Mitchell, Hunter, & Ridge, 2015; Kersting & Bruggemann, 1999; Laabes, Vanderjagt, Obadofin, Sendeht, & Glew, 2008; Lara et al., 2016; Miller, Whitcome, Lieberman, Norton, & Dyer, 2014; Senda et al., 1999; Zhang, Delabastita, Lissens, De Beenhouwer, & Vanwanseele, 2018). After screening the reference lists of the included studies, three additional studies were included (Drysdale, Collins, Walters, Bird, & Hinkley, 2007; Williams, Wagner, Wasnich, & Heilbrun, 1984). Forward citation tracking of the included studies did not result in the inclusion of additional studies. Thus, the total number of included studies was 16. Fig. 1 reports the flow diagram of the search process.

3.2. Study characteristics

Ten studies used a cross-sectional design (Best et al., 2017; Drysdale et al., 2007; Escamilla-Martinez et al., 2016; Fredericson et al., 2007; Harber et al., 1991; Kemmler et al., 2006; Laabes et al., 2008; Lara et al., 2016; Senda et al., 1999; Zhang et al., 2018) with a sample size ranged from 11 to 401 (median = 45). Four studies (Chen et al., 2016; Fuller et al., 2018; Johnson et al., 2015; Miller et al., 2014) used a RCT design, with sample sizes of $n = 20$, $n = 19$, $n = 18$ and $n = 33$, respectively, one study (Kersting & Bruggemann, 1999) used a 20-week long non-randomized intervention ($n = 8$), and one study (Williams et al., 1984) used a 9 months controlled before-and-after study design ($n = 7$). Two of the RCT studies (Johnson et al., 2015; Miller et al., 2014) were short in duration (10 and 12 weeks, respectively) while the study by Chen et al. (2016) had a 6-month transitioning program.

3.3. Sample characteristics

Overall, 624 males and 347 females (mean = 39M and 22F; median = 20M and 4F) were tested. Eight studies did not included female subjects while two did not included males. Runners ranged on average from 20 to 50 years old (mean = 32) and their body weight ranged from 46 to 78 kg (mean = 68) (Fig. 2A). Habitual training volume was quantified as km/week by ten studies (Best et al., 2017; Chen et al., 2016; Fuller et al., 2018; Johnson et al., 2015; Kemmler et al., 2006; Kersting & Bruggemann, 1999; Laabes et al., 2008; Lara et al., 2016; Miller et al., 2014; Zhang et al., 2018) and was on average 40 km/week (ranged from 25 to 69); whilst two studies (Kemmler et al., 2006; Laabes et al., 2008) reported training volume as kcal/kg/day (mean = 27 ± 12) and min/week (mean = 555 ± 129) respectively, making those studies incomparable with others (Fig. 2B).

Only three studies (Fredericson et al., 2007; Kemmler et al., 2006; Senda et al., 1999) included elite long distance runners, whose definition was not given by Fredericson et al. (2007); while Senda et al. (1999) defined 'elite level' using personal best time for the 3000 m run (mean 9 min and 19 s) and Kaup index (14.8–21.9). Kemmler et al. (2006) defined elite runners as those having a running history of at least 5 years and a running volume of 75 km/week and a time of less than 1.15 h for a half-marathon (or < 32:30 min for 10,000 m). The other studies involved 'recreational runners' whose definition was also inconsistent. For instance, Miller et al. (2014)

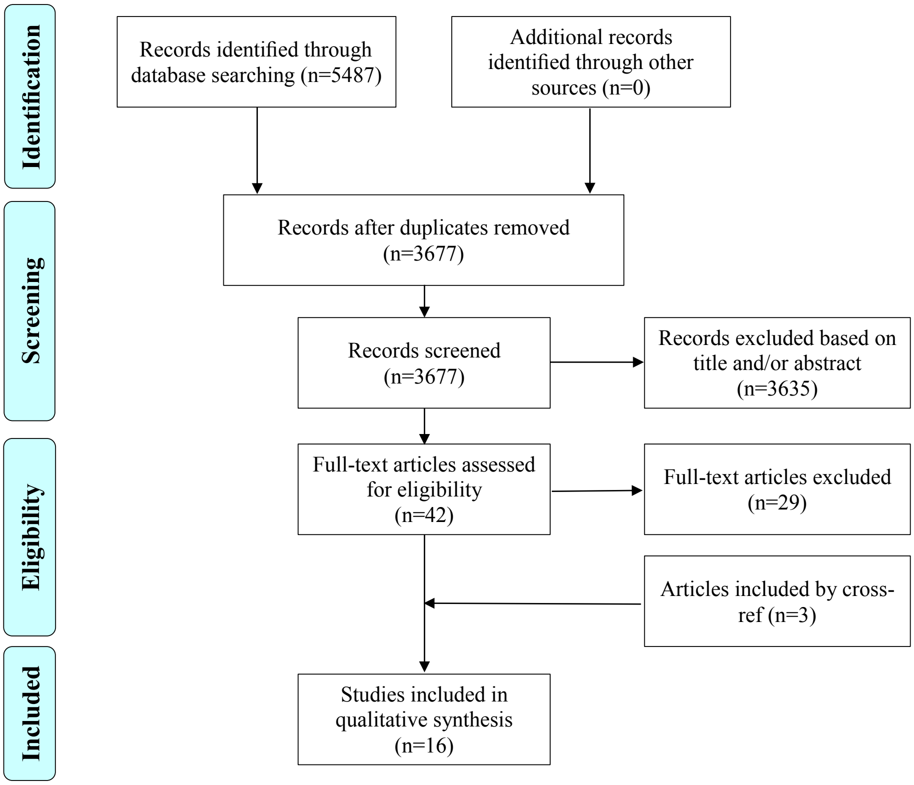

Fig. 1. Flow chart of the search strategy.

defined recreational as those who run an average of 30 miles per week (48.3 km) for a minimum of 12 months. Similarly, for Johnson et al. (2015) recreational was defined as an individual who runs an average of 24–48 km/week for the 6 months prior to the start of the study. However, Escamilla-Martinez et al. (2016) defined recreational runners as those who had been distance running as amateurs for at least five years and training at least three times per week with minimum per session duration of one hour.

3.4. Measuring techniques characteristics

Methods used to measure foot muscle or bone characteristics also varied between the studies. Ultrasound-transmission velocity and broadband ultrasound attenuation were the main methods used to quantify bone density. Other techniques reported were photon absorptiometry, compton scattering technique, and peripheral instantaneous X-ray imaging. Only one study, (Best et al., 2017) used high resolution peripheral computed tomography to analyse trabecula characteristics of the calcaneus. For muscle measures, ultrasound and magnetic resonance imaging were most commonly used along with a custom toe dynamometer. Table 1 summarize the details of studies included in the analysis.

3.5. Methodological quality

Quality scores for the Downs and Black scale and the modified Newcastle-Ottawa Scale are reported in Table 2. The RCTs (Chen et al., 2016; Fuller et al., 2018; Johnson et al., 2015; Miller et al., 2014) had a score ≥18 points and were classified as being of high methodological quality. The non-randomized studies (Kersting & Bruggemann, 1999; Williams et al., 1984) scored 10 points and were classified as being of moderate methodological quality (Table 2A). Eight of the ten cross-sectional studies (Best et al., 2017; Escamilla-Martinez et al., 2016; Fredericson et al., 2007; Harber et al., 1991; Kemmler et al., 2006; Laabes et al., 2008; Lara et al., 2016; Senda et al., 1999) scored between 4 and 7 points on the Newcastle-Ottawa Scale, and, therefore, they were all classified as being of moderate quality (Table 2B). Only the Drysdale et al. (2007) and Zhang et al. (2018) studies were classified as of high quality (8 points).

4. Discussion

This systematic review summarises findings related to the effect of running on foot muscle and bone characteristics from 16 studies. The current body of evidence on this topic is limited, which highlights the need for future studies. In the next sections, we discuss the most significant findings and provide recommendations for future research in this area. Fig. 3 depicts the main findings of

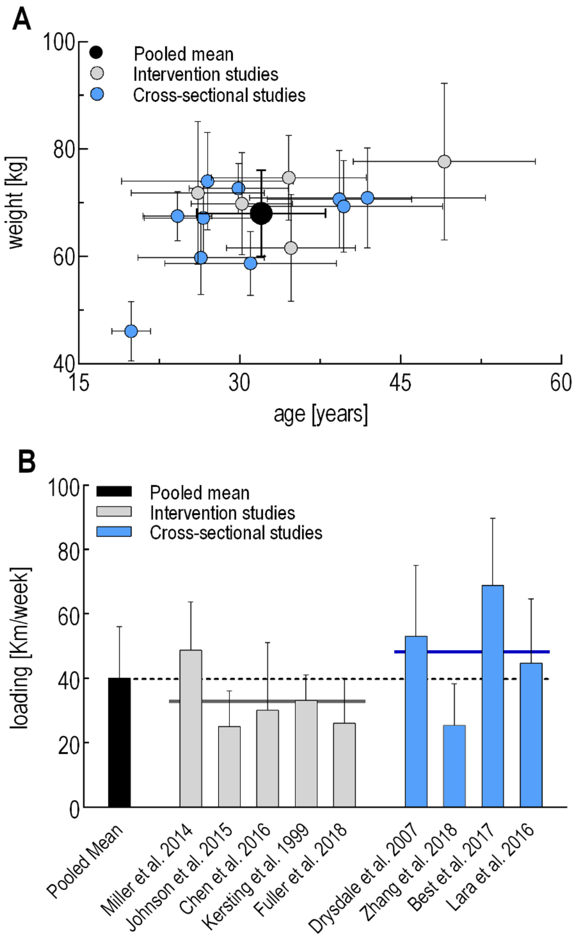

Fig. 2. (A) Sample age by weight distribution for all studies but Zhang et al. (2018) who did not report weight but body mass index; (B) training load for studies reporting load as km per week. Solid lines represent the mean of the group. Dotted line is the grand mean.

this review and what is still unknown.

4.1. Effect on muscles

Very limited evidence exists indicating that running is associated with increased foot muscle size. Chen et al. (2016) found a muscle growth (+8.8%, $p = 0.01$) in intrinsic foot muscles (measured as a whole) after a 6-month transitioning program to minimal shoes. However, a muscle-strengthening program was also part of the intervention, which may partially explain the change in muscle volume. The control group running in traditional shoes showed no change in foot muscle volume after the program.

Short training intervention may be more effective in increasing muscle size. Johnson et al. (2015) reported a significant increase (+10.6%, $p = 0.01$) in abductor halluces cross-sectional area after 10 weeks of training in minimal running shoes compared with the change (pre-post) in the control group (+1.8%) who were using traditional running shoes; however, no significant differences were found among all the other intrinsic muscles that were examined. Similarly, after a 12 weeks transitioning period, a +24.7% increase was found in the abductor digiti minimi muscle volume ($p = 0.009$) and a +18.0% increase in the abductor digiti minimi muscle cross-sectional area ($p = 0.007$) of recreational runners (Miller et al., 2014). For the other tested muscles no significant differences were found, and furthermore, no statistically significant differences were found between pre-and post-training in the control group running in traditional shoes.

Based on the limited evidence available, there is an indication that intrinsic muscle strength and muscle size may increase with running but this is dependent on type of footwear and the associated biomechanical changes (Davis et al., 2017; Lieberman, 2012a, 2012b). A stronger foot may better control loading redistribution at each step (McKeon et al., 2014) while reduced strength may limit the ability to control inter-joint movements resulting in increased soft tissue strain; therefore, greater foot strength may be a beneficial adaptation in response to the repetitive loading imposed on the foot during running, which may contribute to a decreased incidence of injuries (McKeon & Fourchet, 2015). When controlling for the shoe worn, loading seems to have less of an effect in stimulating muscle growth: while comparing 4 type of running shoes (neutral, motion control, minimalistic, and neutral with insoles), Zhang et al. (2018) found that among all intrinsic foot muscles selected, only abductor halluces showed a significant difference

Table 1
Characteristics of the included studies.

Muscle

Study	Total sbj	Design	Grouping	Age (y) – BW (kg)	Footwear Foot-strike	Training volume	Intervention duration	Muscle measures	Method	Findings
Senda et al. (1999)	49	Cross-sectional	12 top level marathon runners – 37 healthy control	19.9 ± 1.8 y – 46.1 ± 5.5 kg	//	//	//	Total toe flexors power, abductor power of 1st and 5th	TD	Running (in conventional running shoes) decreases total flexor power
Miller et al. (2014)	33	Randomized control study	Control (recreational runners; n = 16) – recreational runners + intervention (n = 17)	30.2 ± 4.7 y – 69.8 ± 9.5 kg	TRS	48.7 ± 15 km/week	12-Week training regime	MV and CSA of the FDB, abductor digiti minimi (ADM), and ABDH	MRI	Running in minimal shoes (with 4 mm offset or less) strengthen the foot
Johnson et al. (2015)	37	Randomized control study	Sex-blocked randomization. 19 control (recreational runners) – 18 recreational runners + intervention	26.1 ± 6.2 y – 71.8 ± 13.3 kg	TRS	25 ± 11 km/week	10-Week transition period	ABDH CSA (cm^2)-FDB CSA (cm^2)-FHB thickness (cm)-EDB thickness (cm)	MRI, USI	Significant 10.6% increase in abductor hallucis cross-sectional area in the Vibram FiveFingers™ group compared with the control group ($p = 0.01$)
Chen et al. (2016)	38	Randomized, single-blinded control study	Control (training program in TRS; n = 18) – intervention (training program in MRS + transition exercises + transitioning tips; n = 20)	34.8 ± 6 y – 61.6 ± 9.9 kg	TRS (heel-toe drop > 5 mm)	30.4 ± 21.3 km/week	6-Month transition period	IFM volume	MRI	MRS group had significantly larger foot ($p = 0.01$, Cohen's $d = 0.62$) muscles after transition. The forefoot mainly contributed to foot muscle growth

(continued on next page)

Table 1 (*continued*)

Muscle										
Study	Total sbj	Design	Grouping	Age (y) – BW (kg)	Footwear Foot-strike	Training volume	Intervention duration	Muscle measures	Method	Findings
Zhang et al. (2018)	38	Cross-sectional	Neutral shoes (n = 11); motion control shoes (n = 10); minimalistic shoe (n = 7); insole (n = 10)	26.3 ± 6.9 y – 22 ± 2.1 BMI	Mixed shoe models	25.4 ± 13 km/week	//	ABDH CSA (mm^2) and thickness (mm)-FDB CSA (mm^2) and thickness (mm)-FHB thickness (mm)	US	Runners in minimal shoes had the thickest abductor halluces
Bone										
Study	Total sbj	Design	Grouping				Intervention duration	Bone measures	Method	Findings
Williams et al. (1984)	30	Controlled before-and-after study	Consistent runners (n = 7); inconsistent runners (n = 13); control (n = 10)	49.1 ± 8.5 y – 77.7 ± 14.6 kg	//	//	9 Months	Calcaneal bone mineral content	PA	Calcaneal bone mineral content is dependent on training volume. Post intervention, subject training more than 16 km per month has significantly ($p < 0.05$) higher bone mineral content than control
Harber et al. (1991)	42	Cross-sectional	Group A (eumenorrheic normoactive females) n = 14 subjects who reported 9 or more months per year and who exercised fewer than 3 times per week but did not participate in any formal exercise; Group B (eumenorrheic athletes) n = 17 runners who reported 9 or more menses per year and who trained 7–12 times per week. Group C (amenorrheic athletes) n = 11 runners who reported no menses in the last 12 months and who trained 7–12 times per week	26.4 ± 5.9 y – 59.8 ± 6.9 kg	//	//	//	Calcaneal density	CST	Amenorrhea in athletes is not associated with any reduction in heel bone density. However, bone turnover rate is significantly greater in athletes

(*continued on next page*)

Table 1 (*continued*)

Muscle										
Study	Total sbj	Design	Grouping	Age (y) – BW (kg)	Footwear Foot-strike	Training volume	Intervention duration	Muscle measures	Method	Findings
Kersting and Bruggemann (1999)	26	Non-randomized intervention	3 groups. running shoes of similar construction but different midsole hardness: 45° (n = 9), 53° (n = 9) and 61° (n = 8)	34.6 ± 7.2 y – 74.7 ± 7.9 kg	RFS	33.8 ± 8.2 km/week	20-Week training regime	Calcaneal density	SOS, MRI	No relationship between midsole hardness and external or in-shoe impacts. Bone parameters showed specific differences for all groups which are pronounced in runners with intermediate impacts
Kemmler et al. (2006)	31	Cross-sectional	Endurance trained male runners (n = 20), BMI-matched control (n = 11) aged 20–35 years	26.6 ± 5.5 y – 67.2 ± 6.7 kg	//	555 ± 129 min/week	//	Calcaneal density	SOS, BUA	Runners displayed significantly higher SOS and BUA than control
Drysdale et al. (2007)	401	Cross-sectional	Marathon runners (n = 401; 217 M, 184F), control group from previous studies (n = 601; 267 M, 334F).	41.9 ± 11 y – 70.9 ± 9.3 kg	//	53.8 ± 22.3 km/week	//	Calcaneal density	BUA	The rate of decline of BMD appeared to be reduced significantly in marathon runners compared with the normative group
Fredericson et al. (2007)	45	Cross-sectional	Elite male soccer players (n = 15), elite male long-distance runners (n = 15) and sedentary male controls (n = 15) aged 20–30 years	24.2 ± 3.2 y – 67.5 ± 4.6 kg	//	//	//	Total and regional bone mineral density	DXA	Running is associated with higher BMD at directly loaded sites (the calcaneus) but not at relatively unloaded sites (the spine)
Laabes et al. (2008)	102	Cross-sectional	Football (n = 68), running (n = 15), handball (n = 7), taekwondo (n = 6), cycling (n = 2), judo (n = 1), badminton (n = 1) and high jump (n = 1)	31 ± 8 y – 58.7 ± 6 kg	//	27 ± 12 kcal/kg/d (runners only)	//	Calcaneal bone stiffness index	BUA	Repetitive skeletal loading at the heel has the potential to improve bone density in black male athletes. The magnitude of increase may be higher in medium impact sports such as soccer and running compared with low or non-impact sports
Escamilla et al. (2016)	95	Cross-sectional	Amateur runners (n = 33); control (n = 62)	39.3 ± 6.7 y – 70.7 ± 9.1 kg	RFS	//	//	Calcaneal density	BUA	Distance running seems to have a negative effect on calcaneal bone mass density during the course of a 700-km training season

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Table 1 (*continued*)

Muscle										
Study	Total sbj	Design	Grouping	Age (y) – BW (kg)	Footwear Foot-strike	Training volume	Intervention duration	Muscle measures	Method	Findings
Fuller et al. (2018)	39	Randomized control study	Minimal shoes (n = 19); conventional shoes (n = 20)	27 ± 8 y – 74 ± 9.1 kg	TRS and MRS	26 ± 14 km/week	20-Week training regime	Calcaneal and metatarsal (1st to 5th) mineral density (g cm^2)	DXA	Minimalist shoes did not affect bone mineral density after 20 weeks follow-up
Best et al. (2017)	18	Cross-sectional	FFS (n = 6); RFS (n = 6); control (n = 6)	29.9 ± 4.6 y – 72.7 ± 4.6 kg	TRS and MRS	68.8 ± 20.9 km/week	//	Calcaneal volumetric density, trabecular thickness, number, distance between; DA	HRpQCT	Trabecular thickness and mineral density were greatest in forefoot runners with strong effect sizes (< 0.80). Trabecular thickness was positively correlated with weekly running distance ($r^2 = 0.417$, $p < 0.05$) and years running ($r^2 = 0.339$, $p < 0.05$). individuals with the greatest summative loading stimulus had, after body mass adjustment, the thickest trabeculae
Lara et al. (2016)	278	Cross-sectional	Long-distance runners (n = 122); short distance runners (n = 81); control (n = 75)	39.7 ± 9.2 y – 69.3 ± 8.5 kg	//	44.7 ± 20 km/week	//	Calcaneal bone stiffness	BUA, SOS	Long distance runners and short distance runners presented higher values than sedentary counterparts in SOS ($P < 0.05$), and calcaneus stiffness ($P < 0.05$). However, there were no significant differences between longer distance and shorter distance runners

MV muscle volume, CSA cross-sectional area, FDB flexor digitorum brevis, ADM abductor digiti minimi, ABDH abductur halluces, FHB flexor hallucis brevis, EDB extensor digitorum brevis, TD toe dynamometer, PA photon absorptiometry, CST Compton scattering technique, MRI magnetic resonance imaging, USI ultrasound imaging, TRS traditional running shoes, RFS rear foot strike, FFS fore foot strike, MRS minimalist running shoes. IFM intrinsic foot muscles, SOS speed of sound, BUA broadband ultrasound attenuation, DXA dual-energy x-ray absorptiometry, HRpQCT high resolution peripheral computed tomography, DA degree of anisotropy.

Table 2
Methodological quality evaluation using (A) the Downs and Black methodological quality assessment, and (B) the adapted Newcastle-Ottawa Scale.

A – Non cross-sectional	Scale items																											
Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	Total
Williams et al. (1984)	*1*	*1*	*0*	*1*	*0*	*1*	*1*	*0*	*0*	*1*	*0*	*0*	*0*[a]	*0*	*0*	*1*	*0*[a]	*1*	*0*	*0*	*0*[a]	*1*	*0*	*0*	*1*	*0*	*0*	10
Kersting and Bruggemann (1999)	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*0*	*0*	*1*	*0*[a]	*0*[a]	*0*[a]	*0*[a]	*0*[a]	*0*	*0*[a]	*1*	*0*[a]	*1*	*0*[a]	*0*[a]	*0*	*0*	*0*[a]	*0*[a]	*0*	10
Miller et al. (2014)	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*0*	*1*	*1*	*0*	*0*[a]	*0*	*1*	*0*	*0*[a]	*1*	*1*	*1*	*1*	*1*	*1*	*0*[a]	*0*	*1*	*0*	18
Johnson et al. (2015)	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*0*	*0*	*0*	*1*	*1*	*1*	*1*	*1*	*0*	*1*	*1*	*1*	*0*[a]	*1*	*1*	*1*	22
Chen et al. (2016)	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*0*	*1*	*1*	*1*	*0*	*0*[a]	*1*	*1*	*0*	*0*[a]	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*0*	*1*	*0*	20
Fuller et al. (2018)	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*0*[a]	*0*[a]	*0*	*0*[a]	*1*	*1*	*1*	*1*	*1*	*1*	*0*	*1*	*0*[a]	*1*	*1*	*1*	21

B – Cross-sectional	Selection				Comparability	Outcome		Total
Study	1	2	3	4	1	1	2	
Harber et al. (1991)	*0*	*0*	*0*	*2*	*1*	*2*	*1*	6
Senda et al. (1999)	*0*	*0*	*0*	*1*	*1*	*2*	*0*	4
Kemmler et al. (2006)	*0*	*0*	*0*	*2*	*2*	*2*	*1*	7
Drysdale et al. (2007)	*1*	*0*	*1*	*1*	*2*	*2*	*1*	8
Fredericson et al. (2007)	*0*	*0*	*1*	*1*	*1*	*2*	*1*	6
Laabes et al. (2008)	*0*	*0*	*0*	*1*	*1*	*2*	*1*	5
Escamilla-Martinez et al. (2016)	*0*	*0*	*0*	*1*	*2*	*2*	*1*	6
Lara et al. (2016)	*1*	*0*	*0*	*1*	*2*	*2*	*0*	6
Zhang et al. (2018)	*1*	*1*	*0*	*1*	*2*	*2*	*1*	8
Best et al. (2017)	*1*	*0*	*0*	*1*	*2*	*2*	*1*	7

Items 1–10 are related to reporting, items 11–13 are related to external validity, items 14–26 are related to internal validity, item 27 is related to statistical power.
1 criteria met, *0* criteria not met.
[a] Item was unable to be determined, scored 0.

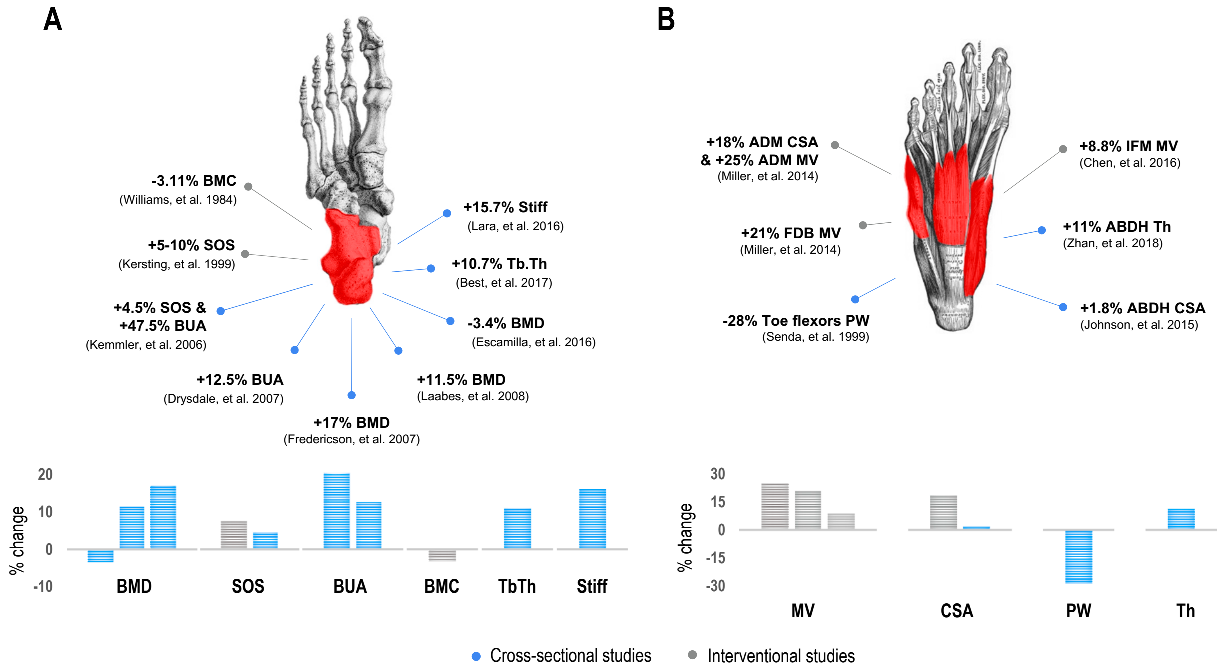

Fig. 3. Results summary of the effect of running on foot bones (A) and foot muscles (B). BMC bone mineral content; SOS speed of sound; BUA broadband ultrasound attenuation; BMD bone mineral density; Tb.Th trabecular thickness; Stiff bone stiffness. CSA cross-sectional area; MV muscle volume; Th thickness; PW power; ADM abductor digiti minimi; FDB flexor digitorum brevis; Abd Hal abductur halluces; IFM intrinsic foot muscles.

between groups. Runners using minimalistic shoes had the thickest abductor halluces. More cushioning and restrictive design of traditional shoes may neutralize the action of the intrinsic foot muscles making runners relying more on extrinsic foot muscles for loading redistribution (Murley, Landorf, Menz, & Bird, 2009). Muscle imbalance could explain the lower (−28%) global foot power recorded in marathoners compared against a control group (Senda et al., 1999). Long-term, muscle imbalance may cause foot deformity (Kwon, Tuttle, Johnson, & Mueller, 2009) and increase risk of injury (Nigg et al., 2017; Page, Frank, & Lardner, 2010).

4.2. Effect on bones

A number of studies (Pocock, Eisman, Yeates, Sambrook, & Eberl, 1986; Strope et al., 2015; Whitfield, Kohrt, Gabriel, Rahbar, & Kohl, 2015) suggest that increased physical activity can result in an increase in bone mineral density (BMD) in common skeletal loading sites. In long-distance runners the calcaneus showed greater (+17%, $p = 0.002$) BMD compared with sedentary controls (Fredericson et al., 2007), greater (+3.1%) mineral content in 'consistent' (> 16 km/month) runners compared with a control group ($p < 0.05$) (Williams et al., 1984), and greater (+12%) stiffness compared to sedentary counterparts (Lara et al., 2016). Greater (+11.5%) calcaneus BMD was also reported in male runners (sprinters, middle distance and marathoners) when compared with athletes from low or no-impact disciplines; running was a significant ($p < 0.001$) determinant of BMD and independent of age and body weight (Laabes et al., 2008).

The repetitive high forces generated during running should theoretically increase foot bone density (Hart et al., 2017); Kersting and Bruggemann (1999) speculated that impact forces are constantly, and directly, regulating calcaneal bone adaptations. For example, Kemmler et al. (2006) compared high volume runners (> 75 km/week) with BMI-matched controls (≤2 h exercise/week) and reported that runners display a significantly higher calcaneal density. Similarly, in a large cross-sectional study involving marathon runners ($n = 401$; 217 men and 184 women) the rate of decline of BMD appeared to be reduced significantly in marathon runners compared with a normative group (Drysdale et al., 2007).

Overall, runners have higher calcaneus BMD than sedentary population; however, due to their continued practice the accelerated bone turnover (Harber et al., 1991) would inevitably decrease bone mass (Hetland, Haarbo, & Christiansen, 1993). For instance, Escamilla-Martinez et al. (2016) reported distance running to have a negative effect on calcaneal BMD during a 700-km training season in amateur runners ($n = 33$); similarly, Fuller et al. (2018) found no differences ($p \geq 0.319$) at the 20-week follow-up of a minimalist training intervention. Regular high volume of running may therefore decrease foot bone strength, increasing the risk of osteopenia and/or stress fracture.

4.3. Research limitations

The main limitations of the included studies are (i) the inconsistency on the dependent variable chosen as a proxy for foot muscles strength, (ii) primarily only one site (the calcaneus) was chosen to investigate foot bone characteristics, (iii) the inconsistency on the methodology used to measure muscles and bone properties, and (iv) the incomplete information regarding the footwear, pattern of foot strike (heel vs. fore foot), physical activity background (training volume) of participants of the studies.

Experimental devices have been designed to measure foot muscles strength (Goldmann & Brüggemann, 2012; Senda et al., 1999); however, no device is able to distinguish between intrinsic and extrinsic muscles. Moreover, other biomechanical factors such as the moment arms of intrinsic foot muscles and muscle-tendon length may also influence the capacity of these muscles to generate force. An accurate measure of intrinsic foot muscles may provide valuable insight into their ability to produce force; however, such a technology still needs to be developed.

Although the calcaneus is considered an important peripheral site for osteoporosis assessment (Frost, Blake, & Fogelman, 2000; Glüer et al., 2004), prediction of the risk of hip fracture (Ross et al., 2000), and often used as a representation of skeletal status (Baroncelli, 2008; Langton & Langton, 2000), foot accounts for 26 bones with a unique shape that varies the magnitude and direction of the load they are subjected to. The choice of the calcaneus as an indicator of bone characteristics is questionable as this bone seems to be less affected by stress fractures than others. For example, the evidence indicates that sites of high risk stress fractures include the tarsal navicular, base of the fifth metatarsal, talus, base of the second metatarsal, sesamoids, and medial malleolus (Boden & Osbahr, 2000). While low-risk factures in the foot and ankle include the calcaneus, and the second through fifth metatarsals (Boden, Osbahr, & Jimenez, 2001).

Moreover, bone density is only a proxy of bone strength that also depends on bone geometry, bone quality (metabolism and collagen cross-linking), cortical and trabecular morphology (Ammann & Rizzoli, 2003; Saito et al., 2010; Seeman, 2008). Only one study (Best et al., 2017) investigated trabecular characteristics using high resolution peripheral quantitative computed tomography – HR-pQCT; they found trabecular thickness to be positively correlated to weekly running distance ($r^2 = 0.417$, $p < 0.05$) and experience ($r^2 = 0.339$, $p < 0.05$). Clearly, more study of other foot bones and their specifics, other than density, may unveil new perspective on the effect of running on foot bones. Furthermore, bone density is not only influenced by mechanical external stresses (i.e. physical activity level), but also by age, diet, hormonal characteristics and genotype (Herbert et al., 2018), these internal physiological mechanisms together are suggested to explain around 50–85% of bone density; it is therefore important for future studies to consider those possible confounding variables when seeking to explain the effect of exercise (i.e. running) on bone density.

Finally, no standard protocols to investigate foot muscles and bones characteristics have been developed that would allow comparison between studies. These limitations could be addressed in future. Besides the comparison of runners and nonrunners, it would be interesting to compare foot anatomical characteristics in individuals with similar running experiences (i.e. weekly mileage and years of running) but different footwear choices. Despite the generalized perception that running is good for health, there are still questions that need to be answered: what is the impact of running on foot health? Do the shoes worn affect the potential benefits associated with running?

5. Conclusion

The present review systematically appraises the current level of knowledge on the effect of running on foot anatomical structures. Due to the moderate-quality and small sample size (and possible low statistical power) of the majority of the included studies, caution must be used when attempting to generalize their results to the wider population. The limited body of evidence suggests that running may increase foot muscles size and calcaneal BMD, but this seems to depend on training volume, running experience, and footwear.

The lack of details on the shoes worn by participants involved does not allow any inference on the contribution of footwear (and the associated biomechanical changes) on foot anatomical adaptations. It is evident that the role of footwear in 'modelling' the foot has not received enough attention and further experimental investigations are warranted. Future research should therefore, more closely, examine the links between running and foot musculoskeletal adaptations.

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Author contribution

The authors (AG and ST) conducted the search and coding process independently. AG performed methodological quality assessment, while ST checked the accuracy of the data. All authors were involved in drafting and reviewing the manuscript.

Additional information

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