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Review Article

Bone Quality in Competitive Athletes: A Systematic Review

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Abstract

The study objective was to assess bone quality measured by high resolution peripheral quantitative computed tomography (HR-pQCT) in competitive athletes. Medline, EMBASE and Sport Discus were searched through May 2022. Prior to submission, a follow-up database search was performed (January 2023). Studies of competitive athletes using HR-pQCT to assess bone quality were included. Athletes were aged between 14 and 45 years. Data extraction included study design and location (country), skeletal imaging modality and site, bone variables and any additional musculoskeletal-related outcome. Information identifying sports and athletes were also extracted. This review included 14 manuscripts and a total of 928 individuals (male: n=75; female: n=853). Athletes comprised 78% (n=722) of the included individuals and 93% of athletes were female. Assessment scores indicate the studies were good to fair quality. The athletes included in this review can be categorized into three groups: 1) healthy athletes, 2) athletes with compromised menstrual function (e.g., amenorrhoea), and 3) athletes with compromised bone health (e.g., bone stress injuries). When assessing bone quality using HR-pQCT, healthy competitive athletes had denser, stronger and larger bones with better microarchitecture, compared with controls. However, the same cannot be said for athletes with amenorrhoea or bone stress injuries.

Keywords: Bone Microarchitecture, Bone Mineral Density, Bone Strength, High Resolution Peripheral Quantitative Computed Tomography, Sport

Introduction

Health and injury prevention are critical to athlete performance and success. Low energy availability resulting from inadequate energy intake, relative to exercise energy expenditure may contribute to poor bone health in athletes including increased risk of stress fracture or injury[1]. In females, the interrelationship between low energy availability (with or without disordered eating), menstrual disturbance and low bone mineral density (BMD) is known as the Female Athlete Triad[2]. In male athletes, low energy availability including energy deficiency (with or without disordered eating), the suppression of the hypothalamic–pituitary–gonadal (HPG) axis and impaired bone health are known as the Male Athlete Triad[3,4]. In 2014, the International Olympic Committee introduced Relative Energy Deficiency in Sport (REDs)[5]. REDs is a syndrome that describes the relationship between prolonged and/or severe low energy availability and many interrelated aspects of physiological function, health, and athletic performance, irrespective of gender[5].

Both the Triad and REDs model recommend identifying individuals with low areal BMD using dual X-ray absorptiometry (DXA), where a Z-score of ≤-1.0 standard deviations below sex- and age-matched normative data warrants concern[2,5,6]. For this reason previous research exploring the bone health of athletes has generally relied on two-dimensional areal BMD, measured by DXA. However, in athletic populations, DXA has limitations due to its intrinsic influence by bone size[7,8] whereby athletes are often smaller or larger than the normal (non-athletic) population. For example, using DXA, an individual who is larger with thicker bones may receive a higher areal BMD score than a smaller individual, even if

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The authors have no conflict of interest.

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their true volumetric BMD is identical. This effect of size may underreport areal BMD in athletes such as gymnasts, figure skaters and ballet dancers. In addition, taller individuals such as basketball players are often too tall for DXA scanners, with technologists having to virtually remove the athlete's feet from the field of view, and consequently resulting in lowered reported areal BMD because the feet and resulting bone mass and area were removed from the analysis.

High resolution peripheral quantitative computed tomography (HR-pQCT) removes some of the limitations associated with DXA as it allows for the three-dimensional assessment of volumetric BMD and thus is not size dependent. Furthermore, HR-pQCT measures bone microarchitecture and strength, in addition to volumetric BMD, and can assess both the trabecular and cortical bone compartments at the distal ends of long bones, directly loaded through sports participation. Since its introduction in 2005, there are numerous studies that have used HR-pQCT to explore bone quality in athletes. Therefore, this systematic review aimed to assess bone quality measured by HR-pQCT in competitive athletes.

Methods

Search strategy

The search strategy consisted of three databases: Medline, EMBASE and Sport Discus. Databases were searched up to and including 27 May 2022. The search strategy included medical subject heading (MeSH) and subject headings, and can be seen in Supplementary Table 1. A combination of "bone," "bone density" and "bone strength," as well as "athlete," "sport" and "exercise" together with their synonyms and derivatives, was adopted. The term "high resolution peripheral quantitative computed tomography" was added as a multi-purpose (.MP) search across a range of different fields including title, abstract, keywords and text. Search terms were then combined with Boolean operators "OR" and "AND". Limitations included English language and human participants. Prior to manuscript submission, a follow-up database search was performed (16 January 2023).

Screening

References from the three databases were imported into Covidence, the Preferred Reporting Items for Systematic reviews and Meta-analyses (PRISMA) guidelines[9]. Within the Covidence platform, two researchers (PW & AM) independently examined the title and abstract of each article. At this stage researchers voted yes (the study is eligible), no (this study is ineligible) or maybe (eligibility unclear) for each potential manuscript. Subsequently, the full texts of potentially eligible articles, those voted yes or maybe were examined for evaluation based on the inclusion and exclusion criteria outlined below. Reference lists of included studies were manually searched for additional manuscripts. Disagreements were resolved by consensus following a group discussion (PW, AM & LB) and review of the manuscript.

Inclusion criteria

Identification of the included studies followed the participants, intervention, comparisons and outcomes (PICO) criteria[10]. Participants were competitive athletes. Interventions or exposure were current sport participation. Comparisons were made to another athlete cohort, or to a control group consisting of either non-athletes, sedentary individuals or to normative reference data. In some cases, intra-athlete comparisons were made (i.e., comparing dominant to non-dominant limb).

Studies of competitive athletes were included regardless of the type of sport the athletes were involved in. For this review athletes competing at a collegiate or varsity level (NCAA) were included as were professional athletes or individuals competing at the national, international, world championships or Olympic level. In cases where studies explored bone quality in athletes using HR-pQCT, but no description of competition level was given, a group average training load of ≥10 hours per week was used to include or exclude studies. The age range of athletes was between 14 and 45 years, both sexes and all races were included.

Exclusion criteria

The following exclusion criteria were used: (1) studies in languages other than English; (2) letter to the editor, case studies, review articles, dissertations, conference abstracts or similar articles that did not present data; (3) studies with animals; (4) studies that used the following imaging techniques without HR-pQCT: DXA, single photon absorptiometry, peripheral quantitative computed tomography (pQCT), magnetic resonance imaging (MRI), clinical CT, radiographs or ultrasound; (5) studies evaluating athletes under 14 or over 45 years old; (6) athletes training <10 hours per week. While army and military-based individuals are athletic, for the purposes of this review they were excluded.

Data extraction

One author (LB) independently extracted data from the included studies. Extracted data included study design and location (country), skeletal imaging modality and site, bone variables and any additional musculoskeletal-related outcomes measured (i.e., DXA, muscle strength, blood biomarkers). Additional information identifying the sports and athletes were also extracted (i.e., sport, level of competition, number of participants, training load and duration). Common HR-pQCT bone variables were identified at the distal radius and tibia and assembled into data tables. For each study, HR-pQCT bone data for athletes compared with controls and, where relevant, sub-classifications of athletes along with directionality have been extracted.

Quality assessment

The methodological quality of the included studies was assessed with the Newcastle–Ottawa Quality Assessment

Table 1. Methodology of included studies.

Authors	Year	Country	Study Design	Imaging Modality	Skeletal site	Bone variables	Other methods
Ackerman	2011[12]	United States	Cross-sectional cohort study	HR-pQCT (82.0 µm), DXA, X-ray	HR-pQCT: radius, tibia; DXA: total body, hip, LS; X-Ray: bone age (hand)	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPm, TbN, TbTh, TbSp, TtAr, CtAr, TbAr; DXA: aBMD, BMAD, Z-score, lean mass, fat mass, %fat	Menstrual function; Energy expenditure: Bouchards 3-d activity record; Biomarkers: calcium, estradiol, 25OHD
Ackerman	2012[13]	United States	Cross-sectional cohort study	HR-pQCT (82.0 µm), DXA, X-ray	HR-pQCT: radius, tibia; DXA: total body, hip, LS; X-Ray: bone age (hand)	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPm, TbN, TbTh, TbSp, TtAr, CtAr, TbAr, FEA; DXA: aBMD, BMAD, Z-score, lean mass, fat mass, %fat	Menstrual function; Energy expenditure: Bouchards 3-d activity record; Biomarkers: 25OHD, P1NP, CTX
Ackerman	2015[14]	United States	Cross-sectional cohort study	HR-pQCT (82.0 µm), DXA, X-ray	HR-pQCT: radius, tibia; DXA: total body, hip, LS; X-Ray: bone age (hand)	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPm, TbN, TbTh, TbSp, TtAr, CtAr, TbAr, FEA; DXA: aBMD, BMAD, Z-score, lean mass, fat mass, %fat	Menstrual function; Energy expenditure: REE indirect calorimetry; Biomarkers: 25OHD, calcium
Burt	2016[21]	Canada	Cross-sectional cohort study	HR-pQCT (82.0 µm), DXA	HR-pQCT: radius, tibia; DXA: total body, hip, LS	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPo, TbN, TbTh, TbSp, TtAr, FEA; DXA: aBMD, %fat	Muscle strength: Biodex, grip strength; FFQ; IPAQ
Burt	2022[19]	Canada	Within subject controlled cross-sectional cohort study	HR-pQCT (60.7 µm)	HR-pQCT: radius, tibia	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPo, TbN, TbTh, TbSp, TtAr, CtAr, TbAr, FEA	Biomarkers: ferritin, total iron binding capacity, vitamin B12, 25OHD, estradiol, progesterone, testosterone; Skinfolds: muscle mass, fat mass, fat free mass, %Fat
Gehman	2022[17]	United States	Cross-sectional	HR-pQCT (82.0 µm), DXA	HR-pQCT: radius, tibia; DXA: hip, LS, total body	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTMD, CtTh, CtPo, CtPm, TbN, TbTh, TbSp, TtAr, CtAr, TbAr, FEA; DXA: aBMD, Z-score, lean mass, fat mass, %fat, appendicular lean mass/height^2	Menstrual function; Impact microindentation; Restrictive eating tendencies; EDE-Q
Liphardt	2015[24]	Canada	Cross-sectional cohort study	HR-pQCT (82.0 µm), DXA	HR-pQCT: radius, tibia; DXA: total body	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPo, TbN, TbTh, TbSp, TtAr, FEA; DXA: lean mass, fat mass, %fat	Muscle strength: Biodex, grip strength; FFQ; IPAQ
Mitchell	2015[15]	United States	Cross-sectional cohort study	HR-pQCT (82.0 µm), DXA	HR-pQCT: radius, tibia; DXA: total body, hip, LS	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPo, TbN, TbTh, TbSp, TtAr, TbAr, Individual trabecular separation, FEA; DXA: aBMD, Z-score, lean mass, fat mass, %fat	Menstrual function; Biomarkers: calcium, phosphate, 25OHD, PTH, IGH-1
Rudolph	2021[25]	United States	Cross-sectional	HR-pQCT (82.0 µm), DXA	HR-pQCT: tibia; DXA: hip, LS	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTMD, CtTh, CtPm, CtPo,TbN, TbTh, TbSp, bone robustness, FEA; DXA: aBMD, Z-score	Menstrual function
Schipilow	2013[23]	Canada	Cross-sectional cohort study	HR-pQCT (82.0 µm), DXA	HR-pQCT: radius, tibia; DXA: total body	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPo, TbN, TbTh, TbSp, TtAr, FEA; DXA: lean mass	Muscle strength: Biodex, grip strength; FFQ; IPAQ
Singhal	2019[16]	United States	Longitudinal observational study	HR-pQCT (82.0 µm), DXA, X-ray	HR-pQCT: radius, tibia; DXA: total body, hip, LS; X-Ray: bone age (hand)	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPm, TbN, TbTh, TbSp, TtAr, CtAr, TbAr, FEA; DXA: aBMD, BMC, Z-score, lean mass, fat mass, %fat	Menstrual function; Biomarkers: 25OHD, Calcium

Table 1. *(Cont. from previous page)*

Authors	Year	Country	Study Design	Imaging Modality	Skeletal site	Bone variables	Other methods
Sturznickel	2021[22]	Germany	Retrospective chart review (cross-sectional)	HR-pQCT (82.0 µm), DXA, CBCT	HR-pQCT: radius, tibia; DXA: hip, LS	HR-pQCT: CtBMD, TbBMD, CtTh, TbN, TbTh; DXA: Z-score	Biomarkers: BAP, Osteocalcin, Dpd, Ca, PTH, ALP, 25OHD; Fracture classification: clinical CT, X-ray, MRI
Warden	2021[20]	United States	Within subject controlled cross-sectional study	HR-pQCT (60.7 µm), DXA	HR-pQCT: radius, tibia; DXA: total body	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPo, TbN, TbTh, TbSp, TtAr, CtAr, TbAr, TbBV/TV, ConnD, FEA; DXA: aBMD, lean mass, fat mass	
Warden	2022[18]	United States	Cross-sectional cohort study	HR-pQCT (60.7 µm), DXA	HR-pQCT: radius, tibia; DXA: total body	HR-pQCT: TtBMD, CtBMD, TbBMD, CtTh, CtPo, TbN, TbTh, TbSp, TtAr, CtAr, TbAr, TbBV/TV, Imin, Imax, Ip, FEA; DXA: aBMD, lean mass, fat mass, Z-score, ASMI	HR-pQCT Imaging: diaphysis of the tibia, fibula, navicular and metatarsals; LEAF-Q

HR-pQCT: high resolution peripheral quantitative computed tomography; DXA: dual X-ray absorptiometry; LS: lumbar spine; TtBMD: total bone mineral density; CtBMD: cortical bone mineral density; TbBMD: trabecular bone mineral density; TbBV/TV: trabecular bone volume fraction; CtTh: cortical thickness; CtPo: cortical porosity; CtPm: cortical perimeter; TbN: trabecular number; TbTh: trabecular thickness; TbSp: trabecular separation; TtAr: total area; CtAr: cortical area; TbAr: trabecular area; ConnD: connectivity density; FEA: finite element analysis; Imin: minimum moment of inertia; Imax: maximum moment of inertia; Ip: polar moment of inertia; aBMD: areal bone mineral density; BMC: bone mineral content; BMAD: bone mineral apparent density; ASMI: appendicular skeletal muscle index; LEAF-Q: low energy availability in females questionnaire.

Scale (NOS) adapted for cross-sectional studies and cohort studies[11]. The scale consists of three domains: selection of study groups, comparability of study groups, and ascertainment of the outcome of interest. The highest score a study can receive is nine and studies were graded as being good, fair or poor quality. Good quality studies received three or four stars in the selection domain and one or two stars in the comparability domain and two or three stars in the outcome/exposure domain. Fair quality studies received two stars or more in the selection domain and one or two stars in the comparability domain and one star in the outcome/exposure domain. Poor quality studies received zero or one star in the selection domain or zero stars in the comparability domain or zero or one star in the outcome/exposure domain. One author (AM) performed the quality assessment on all studies.

Results

Selection and inclusion of studies

A total of 130 manuscripts were extracted from Ovid Medline, Embase, SPORTDiscus databases using our search criteria (Figure 1). Following the removal of duplicates (n=41), a total of 89 studies were screened. Seventy-two studies were deemed irrelevant following examination of title and abstract. The full text of 17 studies were assessed for eligibility and 11 met the inclusion criteria. Reasons for study exclusion are presented in Figure 1. The reference lists of the included studies were assessed for manuscripts that might fit the search criteria, and an additional two manuscripts were screened and included. In addition, one relevant manuscript had been published between May 2022 and January 2023 and was included. This systematic review is comprised of 14 manuscripts (Table 1).

Three authors were contacted and asked to confirm the level of competition or training load for the athletes in their studies. One author replied to data requests and study data were verified via personal written correspondence[12-16].

Description of participants and study characteristics

A total of 928 individuals were included in this review (male: n=75; female: n=853, Table 2). Athletes comprised 78% (n=722) of the included individuals and 93% of athletes were female. None of the included studies encompassed a male only cohort and four studies included male and female athletes[19,22-24]. The remaining ten studies comprised female only cohorts[12-18,20,21,25]. Approximately half of the athletes participated in endurance based sports (running)[12-18]; the remainder included figure skaters[19], tennis players[20], trampolinists[21], track and field athletes[22], skiers[23,24], soccer players[23] and swimmers[23]. The mean age of the athletes was 23 years, training 16 hours per week with a training history of 15 years. While the mean age of athletes included in this review was over 18 years, some studies included

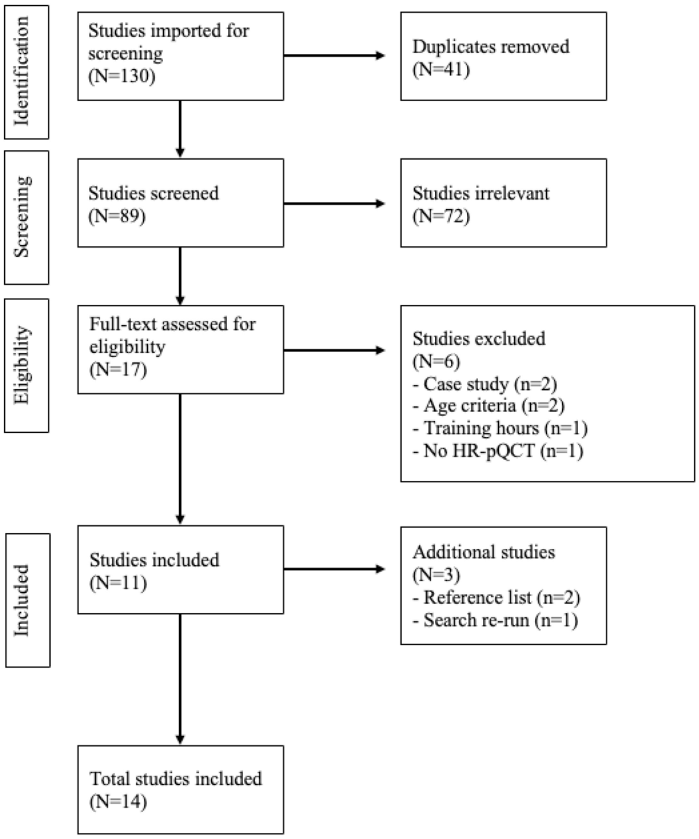

Figure 1. PRISMA study flow chart.

adolescent individuals younger than 18 years[12-15,19,21,23]. However, no comparisons were performed between those younger and older than 18 years. The controls were matched for sex and were sedentary or non-athletic with no training history in organized competitive sport[21,23,24], or participated in less than two hours per week of weight-bearing exercise and no organized team sports[12-16,25]. Five studies did not compare athletes to a control group[17-20,22], choosing instead to compare athletes with different loading patterns[18,20], or side-to-side (within athlete limb) comparisons[19,20]. Four studies compared athletes with normal (eumenorrheic) to compromised (amenorrheic or oligoamenorrheic) menstrual function[12,13,15,16]. Eumenorrhea was defined as at least nine menses in the preceding year with a cycle length of 21 to 35 days[12,13,15,16]. Amenorrhea was defined as the absence of menses for at least three months within a period of oligomenorrhea (cycle length >six weeks) for at least six months, or the absence of menarche at 15 years[16], 16 years or older[12,13] with a bone age of ≥14 years[15]. All studies exploring menstrual function excluded athletes with underlying causes of amenorrhea or oligomenorrhea. Four studies compared athletes with varying levels of bone stress injuries or stress fractures[14,17,22,25]. A self-report method was used for both classification of menstrual function and bone stress injuries for all studies with the exception of two studies where a physician recorded these data during participant interviews[14], or fracture was confirmed with imaging[22]. Finally, two studies compared athlete bone quality to normative reference data[19,22].

One longitudinal study was included in this review[16]. The remainder of included studies were cross-sectional in design. Publication date ranged from 2011 to 2022, with a mean year of 2017 (±4 SD). Studies were conducted in Canada[19,21,23,24] or the USA[12-18,20,25], with one study from Germany[22].

Bias assessment

The results of the NOS quality assessment scale are outlined in Table 2. Fifty-seven percent of studies were fair quality. Reasoning behind studies receiving fair quality included: lack of control group and inadequate time for outcome to occur.

Skeletal imaging assessment

Three studies acquired skeletal imaging using the newer second-generation HR-pQCT scanner (XtremeCTII, 60.7 μm Scanco Medical, Switzerland)[18-20]. All remaining

Table 2. Descriptive characteristics of included studies.

Authors	Year	Group	Sex	N	Age (years)	Training age (years)	Weekly training duration (hrs/wk)	Control group			Newcastle Ottawa Scale
								Yes/ No	Age (years)	N	
Ackerman	2011[12]	Eumenorrheic endurance athletes	F	18	18.7 (1.7)			Yes	19.4 (1.2)	15	Fair
		Amenorrheic endurance athletes	F	16	19.9 (1.7)						
Ackerman	2012[13]	Eumenorrheic endurance athletes	F	17	18.5 (1.6)			Yes	19.3 (1.2)	16	Fair
		Amenorrheic endurance athletes	F	17	19.8 (1.7)						
Ackerman	2015[14]	Oligoamenorrheic endurance athletes	F	100	19.7 (2.5)		10.5 (5.8)	Yes	19.8 (2.1)	40	Fair
		Eumenorrheic endurance athletes	F	35	18.9 (2.5)		10.0 (4.2)				
Burt	2016[21]	Trampolining	F	14	18.6 (2.6)	10.3 (4.8)	13.2 (2.3)	Yes	22.6 (3.9)	15	Good
Burt	2022[19]	Figure skating	M	9	25.2 (6.3)	15.9 (7.7)		No			Fair
			F	11	19.4 (4.9)	12.5 (6.2)					
Gehman[a]	2022[17]	MultiBSI	F	20	25.0 (3.3)			No			Good
		Controls	F	31	26.9 (4.6)						
Liphardt[b]	2015[24]	Skiing	M	12	25.5 (3.3)	17.7	22.7 (6.3)	Yes	M: 23.7 (3.6)	M: 16	Good
			F	10	22.7 (3.9)	14.7	24.3 (4.2)		F: 23.8 (3.2)	F: 10	
Mitchell	2015[15]	Eumenorrheic endurance athletes	F	32	19.1 (2.4)			Yes	20.1 (2.3)	32	Fair
		Amenorrheic endurance athletes	F	97	19.8 (2.4)						
Rudolph[b]	2021[25]	≥3 BSI endurance athletes	F	21	24.7 (3.5)		11.3	Yes	24.2 (1.9)	17	Fair
		≤1 BSI endurance athletes	F	63	26.3 (4.6)		10.3				
Schipilow[b]	2013[23]	Skiing	M	14	24.8 (3.5)	16.8	23.8 (10.2)	Yes	M: 23.7 (3.7)	M: 8	Good
			F	10	22.7 (3.9)	14.6	26.4 (9.8)				
		Swimming	M	7	21.8 (2.0)	12.8	24.0 (5.1)				
			F	13	21.5 (1.8)	13.3	20.5 (2.5)		F: 22.6 (3.9)	F: 15	
		Soccer	M	7	20.2 (1.5)	12.8	9.0 (2.2)				
			F	21	21.3 (2.0)	13.3	12.9 (4.1)				
Singhal	2019[16]	Oligoamenorrheic endurance athletes	F	27	19.2 (0.5)		10.0 (1.0)	Yes	19.7 (0.6)	22	Good
		Eumenorrheic endurance athletes	F	29	19.2 (0.5)		10.7 (0.9)				
Sturznickel	2021[22]	Pseudofractures	M	1	21.0 (5.0)			No			Fair
			F	3							
		MTSS	M	1	23.4 (9.6)						
			F	4							
Warden	2021[20]	Tennis	F	15	20.3 (1.2)	13.7 (2.5)		No			Fair
		Cross-country running	F	15	20.8 (1.2)						
Warden	2022[18]	Cross-country running	F	14	21.0 (1.6)	9.8 (2.3)		No			Good
		Cross-country running + multidirectional sport	F	18	20.6 (1.6)	8.9 (3.0)					

BSI: Bone Stress Injuries; MTSS: Medial Tibial Stress Syndrome (shin splints). [a] *Controls were runners with zero or one BSI and the MultiBSI group included runners with ≥ three BSI.* [b] *Data without SD values were calculated from data provided in respective manuscripts*

Table 3. HR-pQCT volumetric density, bone strength and total area for the distal radius.

Authors	Year	Sport	Sex	TtBMD (mg HA/cm^3)	CtBMD (mg HA/cm^3)	TbBMD (mg HA/cm^3)	Failure Load (kN)	TtAr (mm^2)
Ackerman	2011[12]	AA	F	**298.2 ± 52.6**	825.8 ± 64.6	**158.1 ± 26.6**		265.4 ± 54.1
		EA	F	306.1 ± 46.8	815.5 ± 54.0	180.5 ± 30.5		286.2 ± 45.5
		Controls	F	352.8 ± 67.9	855.5 ± 53.1	188.8 ± 34.9		251.8 ± 42.8
Ackerman	2012[13]	AA	F		932.7 ± 44.3	**158.3 ± 25.8**		
		EA	F		911.5 ± 50.2	178.7 ± 30.5		
		Controls	F		937.6 ± 58.9	188.3 ± 35.0		
Ackerman	2015[14]	AA	F	**299.7 ± 56.5**	816.3 ± 67.5	165.4 ± 31.6	**3.7 ± 0.7**	263.7 ± 45.0
		EA	F	314.2 ± 51.5	824.6 ± 54.6	177.0 ± 37.0	4.0 ± 0.6	272.2 ± 42.1
		Controls	F	333.4 ± 63.6	845.2 ± 72.8	174.4 ± 35.8	4.0 ± 0.7	256.7 ± 40.7
Burt	2016[21]	Trampolining	F	324.0 ± 43.7	884.4 ± 69.8	185.3 ± 29.8	**2.5 ± 0.4**	**284.2 ± 39.3**
		Controls	F	315.4 ± 50.2	949.3 ± 37.5	154.9 ± 30.1	1.9 ± 0.3	263.6 ± 36.4
Burt	2022[19]	Single/Pair	M+F	301.7 ± 62.0	840.0 ± 100.1	164.8 ± 34.8	3.4 ± 1.1	307.4 ± 70.0
		Ice Dancers	M+F	306.0 ± 48.3	822.9 ± 86.5	187.4 ± 48.8	3.3 ± 1.1	372.7 ± 81.7
Gehman[a]	2022[17]	MultiBSI	F	365.1 ± 67.4	923.1 ± 35.7	143.9 ± 35.5	3.5 ± 0.5	208.2 ± 30.4
		Controls	F	375.7 ± 66.9	924.1 ± 41.0	149.7 ± 36.5	3.8 ± 0.7	214.2 ± 33.1
Liphardt	2015[24]	Skiing	M	335.9 ± 40.2	**859.0 ± 48.6**	**221.5 ± 17.8**	**4.2 ± 0.6**	**467 ± 66.2**
			F	320.7 ± 60.9	928.5 ± 41.4	**192.4 ± 337**	**2.7 ± 0.4**	**338 ± 52.9**
		Controls	M	320.0 ± 62.0	894.4 ± 32.1	189.1 ± 37.6	2.8 ± 0.4	362.5 ± 85.9
			F	305.8 ± 38.6	959.0 ± 41.3	162.1 ± 23.3	2.0 ± 0.3	258.2 ± 32.6
Mitchell	2015[15]	AA	F	298.5 ± 55.5	814.7 ± 69.4	164.2 ± 30.5	3.7 ± 0.7	263.2 ± 44.5
		EA	F	312.8 ± 53.6	823.8 ± 52.5	177.7 ± 38.4	4.1 ± 0.6	279.1 ± 43.8
		Controls	F	327.2 ± 67.1	842.9 ± 74.3	173.0 ± 35.0	3.9 ± 0.7	255.5 ± 42.1
Schipilow	2013[23]	Skiing	M	336.1 ± 42.6	864.1 ± 45.5	**218.1 ± 20.4**	**3.9 ± 0.7**	459.7 ± 67.3
			F	320.7 ± 60.9	928.3 ± 41.4	192.4 ± 33.7	2.9 ± 0.7	**338.7 ± 52.8**
		Swimming	M	291.0 ± 44.3	846.5 ± 38.5	176.1 ± 26.4	2.2 ± 0.2	402.4 ± 54.0
			F	294.4 ± 53.5	930.1 ± 45.9	158.7 ± 35.0	2.5 ± 0.5	327.4 ± 48.4
		Soccer	M	335.5 ± 46.3	863.6 ± 29.6	215.6 ± 36.8	2.4 ± 0.4	381.2 ± 41.1
			F	307.6 ± 42.1	917.3 ± 26.3	168.0 ± 32.6	2.3 ± 0.4	291.7 ± 41.6
		Controls	M	340.8 ± 50.5	873.6 ± 73.3	200.2 ± 29.5	2.7 ± 0.5	353.9 ± 73.7
			F	315.4 ± 50.3	949.3 ± 37.5	154.9 ± 30.2	2.5 ± 0.7	263.6 ± 36.5
Singhal	2019[16]	OA	F				3.5 ± 0.1	
		EA	F				3.8 ± 0.1	
		Controls	F				3.9 ± 0.2	
Warden[b]	2021[20]	Tennis	F	269 ± 36	863 ± 31	155 ± 32	3.17 ± 0.6	302 ± 30
		Running	F	284 ± 45	860 ± 49	168 ± 28	3.57 ± 0.7	297 ± 43
Warden	2022[18]	Running	F				5.33 ± 0.7	
		Running + MDS	F				5.83 ± 1.0	

TtBMD: total bone mineral density; CtBMD: cortical bone mineral density; TbBMD: trabecular bone mineral density; TtAr: total area; AA: amenorrheic athletes; EA: eumenorrheic athletes; OA: oligoamenorrheic athletes; BSI: bone stress injuries; MDS: multidirectional sport. F: female; M: male. [a] Controls were runners with zero or one BSI and the MultiBSI group included runners with ≥ three BSI; [b] non-dominant limb. Bold values are significantly different from controls ($p<0.05$)

studies used the first-generation scanner (XtremeCT, 82.0 µm Scanco Medical, Switzerland). The distal radius and tibia were measured in all studies except for one, where the tibia alone was evaluated[25]. One study assessed both the distal as well as the diaphysis radius and tibia, and scanned common bone stress injury skeletal sites including the fibula, second metatarsal (base and diaphysis), fifth metatarsal (proximal diaphysis) and the navicular[18]. Typically, a unilateral scanning protocol was used, with two studies performing bilateral scans[19,20]. Most studies scanned the non-dominant limb with

Table 4. HR-pQCT volumetric density, bone strength and total area for the distal tibia.

Authors	Year	Sport	Sex	TtBMD (mg HA/cm^3)	CtBMD (mg HA/cm^3)	TbBMD (mg HA/cm^3)	Failure Load (kN)	TtAr (mm^2)
Ackerman	2011[12]	AA	F	308.1 ± 39.6	**870.7 ± 31.3**	192.3 ± 24.7		**700.6 ± 104.6**
		EA	F	337.8 ± 45.3	876.6 ± 36.4	213.1 ± 29.2		**708.4 ± 107.8**
		Controls	F	353.9 ± 68.6	902.4 ± 8.5	202.6 ± 34.2		585.3 ± 117.0
Ackerman	2012[13]	AA	F		951.0 ± 30.9	193.1 ± 24.2		
		EA	F		955.2 ± 40.4	212.3 ± 29.8		
		Controls	F		976.1 ± 42.9	205.9 ± 33.2		
Ackerman	2015[14]	AA	F	328.1 ± 46.9	**867.4 ± 37.0**	203.1 ± 28.4	**11.4 ± 1.5**	**669.8 ± 102.8**
		EA	F	334.8 ± 52.3	874.4 ± 36.2	208.4 ± 34.6	12.1 ± 1.7	698.7 ± 91.5
		Controls	F	335.1 ± 58.2	893.0 ± 40.5	192.5 ± 33.2	10.6 ± 1.6	615.8 ± 99.0
Burt	2016[21]	Trampolining	F	357.3 ± 32.5	926.6 ± 49.2	**227.6 ± 23.7**	**7.2 ± 1.1**	**663.1 ± 85.6**
		Controls	F	326.2 ± 32.7	956.4 ± 38.8	184.9 ± 27.2	6.0 ± 0.8	659.2 ± 86.1
Burt[a]	2022[19]	Single/Pair	M+F	358.3 ± 49.6	890.6 ± 60.0	214.4 ± 29.1	11.2 ± 2.6	740.0 ± 176.6
		Ice Dancers	M+F	302.5 ± 56.5	894.9 ± 86.8	177.9 ± 40.5	10.7 ± 2.9	893.4 ± 241.5
Gehman[b]	2022[17]	MultiBSI	F	350.5 ± 53.3	909.1 ± 28.3	179.8 ± 33.0	10.2 ± 1.4	569.4 ± 60.0
		Controls	F	349.4 ± 50.9	906.2 ± 31.8	182.6 ± 35.2	10.7 ± 1.4	593.9 ± 79.9
Liphardt	2015[24]	Skiing	M	336.1 ± 39.8	898.3 ± 0.1	**229.7 ± 24.7**	**9.5 ± 1.0**	1011.7 ± 118.1
			F	**348.0 ± 38.8**	**961.5 ± 18.4**	**223.6 ± 25.2**	**7.8 ± 0.8**	**775.6 ± 86.3**
		Controls	M	316.1 ± 59.4	925.6 ± 41.6	201.3. ± 27.1	7.7 ± 1.2	894.1 ± 206.9
			F	314.1 ± 19.6	987.6 ± 28.7	186.6 ± 16.3	6.1 ± 0.8	672.3 ± 96.1
Mitchell	2015[15]	AA	F	328.5 ± 46.5	868.4 ± 36.4	202.9 ± 28.1	**11.3 ± 1.5**	**665.1 ± 108.7**
		EA	F	337.2 ± 53.2	875.1 ± 35.5	**211.9 ± 34.4**	**12.3 ± 1.7**	**702.7 ± 89.1**
		Controls	F	329.1 ± 61.9	890.9 ± 41.3	190.6 ± 32.2	10.2 ± 1.3	605.8 ± 101.7
Rudolph	2021[25]	≥ 3 BSI	F	266 ± 39	875 ± 40	201 ± 28	10.5 ± 1.5	833 ± 85
		≤ 1 BSI	F	274 ± 42	866 ± 44	210 ± 33	10.9 ± 1.6	839 ± 111
		Controls	F	273 ± 50	872 ± 34	207 ± 39	11.1 ± 2.0	858 ± 101
Schipilow	2013[23]	Skiing	M	339.4 ± 37.8	892.6 ± 33.2	**232.3 ± 23.7**	**9.6 ± 1.16**	1012.9 ± 131.6
			F	**348.0 ± 38.8**	961.3 ± 18.5	**223.6 ± 25.2**	**7.8 ± 0.8**	**776.1 ± 86.3**
		Swimming	M	291.0 ± 20.4	902.0 ± 28.4	193.6 ± 16.3	6.9 ± 1.2	913.9 ± 109.9
			F	280.0 ± 38.7	951.1 ± 27.1	178.4 ± 24.0	6.2 ± 0.6	797.9 ± 114.7
		Soccer	M	353.1 ± 34.8	896.4 ± 27.9	233.0 ± 30.7	**8.9 ± 0.8**	886.2 ± 98.5
			F	**345.7 ± 32.4**	944.4 ± 35.0	**209.1 ± 24.6**	**7.1 ± 0.8**	718.5 ± 86.2
		Controls	M	350.0 ± 40.9	914.6 ± 44.9	216.4 ± 22.1	7.6 ± 1.0	794.6 ± 144.4
			F	326.2 ± 32.7	956.4 ± 38.8	184.9 ± 27.3	6.0 ± 0.9	659.3 ± 86.2
Singhal	2019[16]	OA	F				10.9 ± 0.3	
		EA	F				**11.9 ± 0.4**	
		Controls	F				10.7 ± 0.4	
Warden[c]	2021[20]	Tennis	F	347 ± 38	936 ± 22	212 ± 33	12.2 ± 1.9	**706 ± 66**
		Running	F	360 ± 44	930 ± 38	219 ± 28	11.1 ± 1.8	635 ± 105

TtBMD: total bone mineral density; CtBMD: cortical bone mineral density; TbBMD: trabecular bone mineral density; TtAr: total area; AA: amenorrheic athletes; EA: eumenorrheic athletes; OA: oligoamenorrheic athletes; BSI: bone stress injuries; MDS: multidirectional sport. F: female; M: male. [a] take-off leg; [b] Controls were runners with zero or one BSI and the MultiBSI group included runners with ≥ three BSI; [c] non-dominant limb. Bold values are significantly different from controls (p<0.05).

three choosing to scan the dominant limb[21,23,24]. Four studies used a percent offset scanning location rather than fixed distance[17,18,20,25].

In addition to HR-pQCT, all but one study included DXA assessment of bone density[19]. Several studies used X-ray to report bone age at the hand/wrist[12-14,16] and one study identified pseudofractures (local, radiolucent cortical defects) using additional imaging modalities of X-ray, clinical CT, cone beam computed tomography and/or MRI[22].

The athletes included in this review can be categorized into three groups: 1) healthy athletes[19-21,23,24], 2) athletes with compromised menstrual function (e.g., amenorrhoea)[12,13,15,16],

Table 5. Trabecular and cortical HR-pQCT bone geometry and microarchitecture at the distal radius.

Authors	Year	Sport	Sex	TbAr (mm^2)	TbN (1/mm)	TbTh (mm)	TbSp (mm)	CtAr (mm^2)	CtTh (mm)	CtPo (%)
Ackerman	2011[12]	AA	F	212.3 ± 53.3	1.96 ± 0.26	0.07 ± 0.01	0.45 ± 0.07	47.9 ± 13.2	**0.71 ± 0.20**	
		EA	F	**231.3 ± 44.9**	2.04 ± 0.22	0.07 ± 0.01	0.42 ± 0.05	49.5 ± 9.3	**0.71 ± 0.15**	
		Controls	F	191.7 ± 41.7	2.07 ± 0.21	0.08 ± 0.01	0.41 ± 0.05	56.6 ± 12.8	0.86 ± 0.18	
Ackerman	2012[13]	AA	F	218.0 ± 52.7				50.3 ± 11.9	0.81 ± 0.82	0.71 ± 0.62
		EA	F	234.9 ± 45.1				52.7 ± 8.5	0.82 ± 0.14	0.70 ± 0.45
		Controls	F	203.4 ± 46.0				57.5 ± 10.5	0.94 ± 0.18	0.63 ± 0.44
Ackerman	2015[14]	AA	F						**0.70 ± 0.20**	**1.2 ± 0.8**
		EA	F						0.75 ± 0.16	0.8 ± 0.4
		Controls	F						0.83 ± 0.25	0.8 ± 0.5
Burt	2016[21]	Trampolining	F		2.07 ± 0.20	0.074 ± 0.008			0.95 ± 0.15	1.92 ± 1.01
		Controls	F		2.02 ± 0.24	0.064 ± 0.011			0.92 ± 0.18	1.12 ± 0.37
Burt	2022[19]	Single/Pair	M+F	249.9 ± 66.7	1.47 ± 0.14	0.22 ± 0.02	0.64 ± 0.07	61.2 ± 15.0	0.99 ± 0.22	0.58 ± 0.36
		Ice Dancers	M+F	307.1 ± 76.1	1.53 ± 0.24	0.24 ± 0.14	0.61 ± 0.11	69.9 ± 13.1	0.99 ± 0.15	1.00 ± 1.10
Gehman[a]	2022[17]	MultiBSI	F	152.7 ± 34.9	1.81 ± 0.29	**0.066 ± 0.01**	0.50 ± 0.10	57.6 ± 8.1	1.06 ± 0.16	0.60 ± 0.34
		Controls	F	156.4 ± 31.6	1.74 ± 0.34	0.072 ± 0.01	0.53 ± 0.12	59.8 ± 10.1	1.08 ± 0.23	0.76 ± 0.43
Liphardt	2015[24]	Skiing	M	**376.7 ± 69.2**	2.15 ± 0.21	**0.087 ± 0.010**	0.38 ± 0.04	**95.8 ± 29.1**	1.00 ± 0.16	2.7 ± 1.2
			F	**278.3 ± 56.3**	**2.13 ± 0.17**	0.075 ± 0.014	**0.40 ± 0.04**	**62.7 ± 9.7**	0.89 ± 0.19	1.2 ± 0.6
		Controls	M	289.4 ± 84.2	2.12 ± 0.21	0.074 ± 0.013	0.40 ± 0.05	71.3 ± 11.5	0.95 ± 0.18	2.0 ± 1.0
			F	209.3 ± 29.7	1.89 ± 0.31	0.072 ± 0.008	0.47 ± 0.10	53.3 ± 13.0	0.83 ± 0.15	0.9 ± 0.5
Mitchell	2015[15]	AA	F	211.8 ± 45.2	1.96 ± 0.26	0.070 ± 0.010			0.70 ± 0.20	**0.94 ± 0.60**
		EA	F	221.5 ± 45.1	1.97 ± 0.28	0.075 ± 0.013			0.75 ± 0.17	0.83 ± 0.43
		Controls	F	201.5 ± 44.5	2.00 ± 0.24	0.072 ± 0.013			0.79 ± 0.21	0.62 ± 0.38
Schipilow	2013[23]	Skiing	M		2.17 ± 0.20	0.084 ± 0.011	0.38 ± 0.03		1.05 ± 0.22	2.7 ± 1.0
			F		2.13 ± 0.17	0.075 ± 0.014	0.40 ± 0.04		0.89 ± 0.19	1.2 ± 0.6
		Swimming	M		2.02 ± 0.21	0.073 ± 0.011	0.43 ± 0.05		0.91 ± 0.13	3.0 ± 0.5
			F		2.04 ± 0.33	0.065 ± 0.011	0.44 ± 0.10		0.86 ± 0.17	1.5 ± 0.8
		Soccer	M		**2.3 ± 0.18**	0.078 ± 0.01	**0.36 ± 0.04**		1.0 ± 0.13	3.0 ± 1.4
			F		2.0 ± 0.30	0.070 ± 0.01	0.44 ± 0.08		0.89 ± 0.12	1.3 ± 0.4
		Controls	M		1.95 ± 0.2	0.086 ± 0.013	0.43 ± 0.05		1.02 ± 0.13	2.9 ± 2.3
			F		2.03 ± 0.24	0.064 ± 0.011	0.44 ± 0.06		0.92 ± 0.18	1.1 ± 0.4
Warden[b]	2021[20]	Tennis	F	257 ± 32	1.61 ± 0.16	0.212 ± 0.15	0.58 ± 0.66	50.0 ± 5.5	0.80 ± 0.11	
		Running	F	250 ± 42	1.53 ± 0.13	0.217 ± 0.11	0.60 ± 0.64	51.0 ± 6.8	0.85 ± 0.14	
Warden	2022[18]	Running	F						0.88 ± 0.16	
		Running + MDS	F						0.91 ± 0.13	

TbAr: trabecular area; TbN: trabecular number; TbTh: trabecular thickness; TbSp: trabecular separation; CtAr: cortical area; CtTh: cortical thickness; CtPo: cortical porosity; AA: amenorrheic athletes; EA: eumenorrheic athletes; OA: oligoamenorrheic athletes; BSI: bone stress injuries; MDS: multidirectional sport. F: female; M: male; [a] Controls were runners with zero or one BSI and the MultiBSI group included runners with ≥ three BSI; [b] non-dominant limb. Bold values are significantly different from controls ($p<0.05$).

Table 6. Trabecular and cortical HR-pQCT bone geometry and microarchitecture at the distal tibia.

Authors	Year	Sport	Sex	TbAr (mm²)	TbN (1/mm)	TbTh (mm)	TbSp (mm)	CtAr (mm²)	CtTh (mm)	CtPo (%)
Ackerman	2011[12]	AA	F	**583.9 ± 106.0**	**1.77 ± 0.26**	0.09 ± 0.02	**0.48 ± 0.07**	116.1 ± 20.5	1.14 ± 0.22	
		EA	F	**577.9 ± 105.8**	2.04 ± 0.20	0.09 ± 0.01	0.41 ± 0.04	130.5 ± 17.9	1.27 ± 0.18	
		Controls	F	464.0 ± 120.7	1.97 ± 0.25	0.09 ± 0.02	0.43 ± 0.06	120.2 ± 20.1	1.30 ± 0.26	
Ackerman	2012[13]	AA	F	**601.1 ± 102.4**				100.1 ± 17.4	1.05 ± 0.20	**1.40 ± 0.52**
		EA	F	**589.1 ± 101.0**				111.9 ± 13.8	1.17 ± 0.18	**1.44 ± 0.71**
		Controls	F	494.4 ± 118.7				106.9 ± 16.7	1.22 ± 0.25	0.92 ± 0.37
Ackerman	2015[14]	AA	F	**547.6 ± 106.2**					1.22 ± 0.25	**1.9 ± 1.1**
		EA	F	568.6 ± 94.4					1.27 ± 0.23	1.7 ± 0.9
		Controls	F	494.3 ± 101.0					1.25 ± 0.24	1.4 ± 1.0
Burt	2016[21]	Trampolining	F		1.84 ± 0.21	**0.104 ± 0.013**			1.32 ± 0.13	2.88 ± 1.94
		Controls	F		1.83 ± 0.23	0.085 ± 0.013			1.33 ± 0.14	2.31 ± 1.24
Burt[a]	2022[19]	Single/Pair	M+F	591.1 ± 165.0	1.46 ± 0.15	0.28 ± 0.01	0.65 ± 0.07	154.2 ± 28.1	1.74 ± 0.29	1.76 ± 1.00
		Ice Dancers	M+F	751.6 ± 235.7	1.32 ± 0.14	0.26 ± 0.03	0.73 ± 0.09	147.8 ± 31.8	1.48 ± 0.32	1.28 ± 0.83
Gehman[b]	2022[17]	MultiBSI	F	450.5 ± 62.7	1.76 ± 0.35	0.086 ± 0.014	0.50 ± 0.10	122.7 ± 21.2	1.44 ± 0.27	2.67 ± 1.01
		Controls	F	472.9 ± 80.9	1.70 ± 0.27	0.090 ± 0.014	0.51 ± 0.09	124.7 ± 13.8	1.43 ± 0.20	3.04 ± 1.62
Liphardt	2015[24]	Skiing	M	841.1 ± 129.5	**2.06 ± 0.29**	0.094 ± 0.009	**0.40 ± 0.06**	**164.1 ± 22.3**	1.39 ± 0.22	**4.2 ± 1.1**
			F	632.5 ± 91.3	**2.03 ± 0.18**	0.092 ± 0.012	**0.40 ± 0.04**	**131.5 ± 17.9**	1.30 ± 0.22	2.1 ± 0.8
		Controls	M	748.6 ± 218.1	1.86 ± 0.18	0.091 ± 0.015	0.45 ± 0.05	137.1 ± 19.6	1.24 ± 0.26	2.5 ± 1.4
			F	55.5 ± 91.0	1.64 ± 0.28	0.960 ± 0.017	0.53 ± 0.08	109.5 ± 9.8	1.15 ± 0.07	2.0 ± 0.7
Mitchell	2015[15]	AA	F	545.1 ± 107.6	1.90 ± 0.27	**0.090 ± 0.011**			1.22 ± 0.25	**1.94 ± 0.96**
		EA	F	**572.9 ± 92.6**	1.99 ± 0.21	0.089 ± 0.013			1.28 ± 0.24	**2.18 ± 1.29**
		Controls	F	489.8 ± 105.6	1.92 ± 0.24	0.083 ± 0.014			1.20 ± 0.25	1.21 ± 0.86
Rudolph	2021[25]	≥3 BSI	F	752 ± 89	2.08 ± 0.27	0.081 ± 0.012	0.408 ± 0.061	86.0 ± 16.8	0.78 ± 0.18	3.88 ± 1.01
		≤1 BSI	F	754 ± 112	2.10 ± 0.23	0.084 ± 0.013	0.398 ± 0.052	88.6 ± 13.7	0.79 ± 0.14	4.78 ± 1.70
		Controls	F	769 ± 107	2.23 ± 0.24	0.077 ± 0.012	0.375 ± 0.048	93.3 ± 16.8	0.84 ± 0.19	4.46 ± 1.59
Schipilow	2013[23]	Skiing	M		2.03 ± 0.28	0.096 ± 0.01	0.403 ± 0.058		1.38 ± 0.2	4.1 ± 1.1
			F		2.03 ± 0.18	0.092 ± 0.012	0.403 ± 0.037		**1.30 ± 0.22**	2.1 ± 0.8
		Swimming	M		1.75 ± 0.23	0.093 ± 0.012	0.487 ± 0.063		1.13 ± 0.15	3.5 ± 0.8
			F		1.77 ± 0.28	0.085 ± 0.013	0.494 ± 0.091		1.05 ± 0.15	2.7 ± 0.9
		Soccer	M		**2.13 ± 0.18**	0.092 ±0.011	0.382 ± 0.041		1.47 ± 0.17	3.5 ± 0.9
			F		1.95 ± 0.21	0.090 ± 0.011	**0.429 ± 0.05**		**1.36 ± 0.15**	2.7 ± 1.1
		Controls	M		1.80 ± 0.32	0.103 ± 0.018	0.469 ± 0.087		1.44 ± 0.19	3.8 ± 1.3
			F		1.83 ± 0.23	0.085 ± 0.013	0.469 ± 0.07		1.33 ± 0.14	2.3 ± 1.2
Warden[c]	2021[20]	Tennis	F	577 ± 68	1.57 ± 0.21	0.260 ± 0.014	0.599 ± 0.010	134 ± 18	1.51 ± 0.22	
		Running	F	513 ± 103	1.52 ± 0.17	0.270 ± 0.025	0.602 ± 0.072	127 ± 19	1.54 ± 0.26	

TbAr: trabecular area; TbN: trabecular number; TbTh: trabecular thickness; TbSp: trabecular separation; CtAr: cortical area; CtTh: cortical thickness; CtPo: cortical porosity; AA: amenorrheic athletes; EA: eumenorrheic athletes; OA: oligoamenorrheic athletes; BSI: bone stress injuries; MDS: multidirectional sport. F: female; M: male. [a] take-off leg; [b] Controls were runners with zero or one BSI and the MultiBSI group included runners with ≥ three BSI; [c] non-dominant limb.

Table 7. Summary of the differences between sporting groups at the distal radius and tibia.

	Distal Radius	Distal Tibia
TtBMD	No differences	Ski > Swim [23] Soccer > Swim [23] Run + MDS > Run [18]
CtBMD	No differences	Swim > Soccer [23]
TbBMD	EA > AA [12] <2 BSI > 2 or more BSI [14]	Ski > Swim [23] Soccer > Swim [23] Run + MDS > Run [18]
TbN	Soccer > Swim [23]	EA > AA [12] Soccer > Swim [23]
TbTh	No BSI > BSI [14]	Run + MDS > Run [18]
TbSp	Swim > Soccer [23]	AA > EA [12] Swim > Ski [23] Swim > Soccer [23]
CtTh	No differences	Ski > Swim [23] Soccer > Swim [23] Run + MDS > Run [18]
CtPo	AA > EA [14]	Soccer > Ski [23]
TtAr	Ski > Swim [23] <2 BSI > 2 or more BSI [14]	Tennis > Run [20]
CtAr	No differences	Run + MDS > Run [18]
TbAr	No differences	No differences
Failure Load	EA > AA [14,15] <2 BSI > 2 or more BSI [14] Ski > Soccer [23] Ski > Swim [23] Run + MDS > Run [18]	EA > AA [14,15] <2 BSI > 2 or more BSI [14] Ski > Swim [23] Soccer > Swim [23]

TtBMD: total bone mineral density; CtBMD: cortical bone mineral density; TbBMD: trabecular bone mineral density; TbN: trabecular number; TbTh: trabecular thickness; TbSp: trabecular separation; CtTh: cortical thickness; CtPo: cortical porosity; TtAr: total area; CtAr: cortical area; TbAr: trabecular area; AA: amenorrheic athletes; EA: eumenorrheic athletes; MDS: multidirectional sport.

and 3) athletes with compromised bone health (e.g., bone stress injuries)[14,17,22,25].

Bone density

Volumetric bone density data at the distal radius and tibia are presented in Table 3 and Table 4. Comparing normal healthy athletes to controls, total and trabecular volumetric BMD was generally higher for athletes[21,23,24]. On the other hand, amenorrheic athletes had lower trabecular volumetric BMD than controls[12,13]. Lower cortical volumetric BMD was reported for skiers and amenorrheic athletes compared with controls[12,24] with no difference indicated for the remaining studies.

Bone microarchitecture

Trabecular and cortical bone microarchitecture are presented in Table 5 (radius) and Table 6 (tibia). Comparing normal healthy athletes to controls, trabecular number and thickness were higher for athletes than controls[21,23,24] whereas trabecular separation was lower for athletes than controls[23,24]. Amenorrheic athletes had lower trabecular number with a higher trabecular separation than controls[12]. In the cortical compartment, cortical porosity was higher for athletes than controls[24], as well as for eumenorrheic and amenorrheic athletes compared with controls[13,15].

Bone geometry

Larger bone size (total and/or trabecular area) was reported in normal healthy athletes compared with controls[21,23,24], and eumenorrheic and amenorrheic athletes compared with controls[12,15].

Bone strength

Failure load was consistently higher in normal healthy athletes compared with controls[16,21,23,24]. However, compromised bone strength was observed in amenorrheic athletes[14] compared with controls.

Side to side differences

Two studies reported side to side differences comparing the dominant to non-dominant limbs[20] or the landing and takeoff leg[19]. Among tennis players, bone microarchitecture, geometry, and strength at the diaphysis were different between the dominant and non-dominant limbs favouring the dominant side[20]. Similar results were observed at the distal sites with the addition of bone benefits observed in density when comparing the dominant and non-dominant limbs of tennis players[20]. Alternatively, runners had no differences between dominant and non-dominant limbs except for higher cortical volumetric BMD in the dominant radius[20].

Additional comparisons

Comparisons between sports, menstrual function and bone stress injury status are shown in Table 7. Skiers and soccer players had denser total and trabecular volumetric BMD at the tibia than swimmers[23]. Furthermore, they had lower trabecular separation, higher cortical thickness and stronger bones than swimmers[23]. Additionally, total and trabecular volumetric BMD and cortical area were higher for runners with a history of multidirectional sport (soccer or basketball) participation than those without[18]. Athletes with more than two bone stress injuries had lower trabecular volumetric BMD and total area than athletes with less than two bone stress injuries[14] and trabecular number was lower for athletes with previous bone stress injuries compared to those without previous bone stress injuries[14].

Discussion

When assessing bone quality using HR-pQCT, healthy competitive athletes had denser, stronger and larger bones with better microarchitecture, compared with controls. However, the same cannot be said for athletes with amenorrhoea or bone stress injuries as several bone parameters (e.g., trabecular BMD, trabecular number, bone strength) were lower in these individuals.

The higher bone density and microarchitectural parameters illustrated in healthy athletes compared with controls were observed in the total and trabecular bone compartment[21,23,24]. The same bone compartments reported differences between landing and takeoff legs in figure skaters[26] and the dominant to non-dominant arm in tennis players[20], benefiting the landing leg and dominant arm. The cortical compartment also reported differences between athletes involved in different sports. For example soccer players had higher cortical thickness than swimmers[23]. However, differences in the cortical compartment were not always positive (i.e., thicker cortices). Compared with controls, skiers had lower cortical density and higher cortical porosity[24], and soccer players had higher cortical porosity than skiers[23]. While the mechanism for lower cortical density in athletes remains unclear[20], some studies have reported the same findings in athletes using pQCT[27,28]. Higher cortical porosity likely explains the lower cortical density, indicating the bone is in a higher state of remodeling, attempting to improve the mechanical properties of the bone. While bone turnover markers were not assessed in studies included in this review and cannot confirm these findings[23,24], previous literature found periods of higher bone resorption throughout a competition season in elite athletes[29,30].

Many sports included in this review loaded the lower extremity and as a result observed better bone quality at the tibia for healthy athletes compared with controls. In addition to the tibia, skiers also reported larger and stronger bones at the radius compared with controls[24]. Skeletal differences observed between athletes and controls at the upper and lower extremity, or the weight bearing and non-weight bearing limbs, are likely the result of sport-specific impact loading. No bone density, microarchitecture or strength differences were observed between swimmers and controls[23]; yet, differences between tennis players and runners[20] as well as skiers, soccer players and swimmers[23] were reported. Furthermore, discipline dependent skeletal adaptations were found in figure skaters when single and pair skaters (jumpers) were compared with ice dancers[19]. Several studies using other imaging modalities have shown similar differences between athletes and controls based on the loading requirements of the sport[31-33] as well as discipline or player position differences[34-36]. Athletes participating in non-impact sports such as swimming or cycling may have similar[37,38] or lower[39,40] bone density compared with controls, whereas athletes involved in high impact and odd impact sports tend to result in better bone quality[41], supported by the skiers (high impact), soccer and tennis players (odd impact) in this review.

Unlike the healthy athletes mentioned above, athletes with compromised menstrual status (amenorrhea) had lower total[12,14] and trabecular[12,13] bone density with poorer trabecular microarchitecture[12] resulting in lower bone strength[13], compared with controls. Like healthy athletes, amenorrheic athletes also had higher cortical porosity; however, no significant differences were observed in cortical density[13,15], and rather than a thicker cortex, these athletes had lower cortical thickness[12,13]. It is speculated that the lower cortical thickness accompanied by larger trabecular area is the result of increased bone resorption (enhanced trabecularization) at the endocortical region, driven by inadequate estradiol[13]. The amenorrheic athletes included in this review likely had varying states of estrogen and energy availability, both of which could have influenced bone turnover. Several studies have shown that reduced or low energy availability have a negative impact on short- and long-term bone health[42]. Furthermore, it has been suggested that while exercising women with compromised menstrual status will suffer from estrogen deficiency, their menstrual disturbances are a manifestation of energy deficiency that may amplify the detrimental effects of low energy availability on bone[43].

HR-pQCT studies exploring bone quality in athletes with bone stress injuries are mixed with some finding no difference in bone density, microarchitecture and strength[17,25], and another finding a dose-response relationship with poorer bone quality associated with higher number of bone stress injuries[14]. The two studies finding no difference in bone quality using HR-pQCT[17,25], are supported by a systematic review reporting no difference between athletes with and without a history of bone stress injuries using DXA and pQCT[44]. It is possible the differences observed in the study by Ackerman and colleagues were because of the compromised menstrual status in the athletic cohort. When the amenorrheic athletes were divided into those with and without bone stress injuries, minimal differences were observed[14], leading us to assume the driving factor for the compromised bone quality might be the amenorrhea resulting from low energy availability.

Exploring bone strength in amenorrheic athletes is particularly important as lower bone strength may be indicative of increased risk of stress fracture, identified as a moderate risk according to the REDs Clinical Assessment Tool[45] and the Female Athlete Triad Cumulative Risk Assessment Criteria[46]. Amenorrhea is an independent risk factor for stress fracture occurrence in endurance athletes[47], although not all females with compromised menstrual function report stress fractures[14]. Low energy availability in males and females has known negative effects on reproductive function and metabolic hormones, both of which influence bone quality.

The most important indicator of skeletal health is bone strength, which is influenced by bone density, microarchitecture and geometry[48]. While the biomechanical behavior of cortical bone is rather stable, trabecular bone shows a wide variability in strength and stiffness[49]. Both the distribution and orientation of two major types of trabeculae – plates and rods – play critical and distinct roles in determining the predicted strength and failure of trabecular bone[50]. During the ageing process, when bone resorption dominates, plates become more rod-like and plate connectivity with rods declines, contributing to lower bone strength. It is possible similar changes to the trabecular morphology occur in young amenorrheic athletes as plate bone volume fraction and plate number were lower in amenorrheic compared with eumenorrheic athletes[15]. Again, estrogen deficiency is likely a driving factor in trabecular morphology differences in these young athletes, as it is in menopausal women. However, better tracking of hormonal and bone turnover biomarkers are needed in athletic populations.

Some caution should be taken when interpreting the findings of this review. The same athletes were included in several studies by the same authors, and while sample size improved over time, increasing the power, most of the research comes from North America. Multi-centre studies including international participation are needed to better understand whether sociocultural differences in bone quality exist among competitive athletes. Furthermore, supplementary analyses should be performed on those athletes under 18 years compared with those over 18 years. Additional longitudinal data is required to determine changes in bone quality with changes in energy consumption, hormones, menstruation and bone stress injury status, both during an athlete's career and upon retirement from sport. While one study explored bone accrual rates over 12 months, no catch-up in bone accrual was observed for athletes with compromised compared with normal menstrual status despite ongoing counseling to optimize caloric intake, and menses resumption in almost 40% of participants over the study duration[16]. Due to the limited number of males included in this review sex comparisons were not explored. Unlike other areas in sport science research where males dominate the literature[51], females are more likely to have their bone quality assessed using HR-pQCT. Future work in this field should include male athletes, trabecular plate-rod morphometric analysis as well as bone quality changes resulting from stress fracture, healing and return to play/participation. Other limitations that should be considered include the bias associated with self-report as this technique was used for assessment of menstrual status and bone stress injuries for most of the included studies within this review. Finally, this review only explored HR-pQCT, excluding studies that used the lower resolution and single slice pQCT for bone health quantification[52,53]. Differences between the two scanning modalities have been published and for bone microarchitectural analyses HR-pQCT is the modality of choice due to its three-dimensional capability[54].

It is well accepted that normal healthy athletes have better bone quality than controls and that impact loading activity offers skeletal benefits. However, the skeletal health of athletes with compromised bone (e.g., bone stress injuries) or menstrual health (e.g., amenorrhea) may present examples where this assumption is incorrect. Not all studies assess energy intake, reproductive function, metabolic and hormonal biomarkers. It takes time for the bone to respond to low energy availability and variation might occur depending on when the bone stress injury occurred relative to the skeletal site measured. However, we do know the deleterious effects associated with impaired hormone function on bone quality may be clearer at the radius than the tibia, since detrimental changes at the tibia may be countered to some degree by sport-specific impact loading. We recommend longitudinal monitoring to ensure athletes are not losing bone density or are at increased risk of bone stress injuries. Furthermore, to account for differences in bone quality based on sport type (e.g., impact loading verses weight supported) within-sport comparisons should be made. Finally, caution should be taken by all practitioners working with female athletes with suspected low energy availability, reproductive dysfunction, and/or those who present with bone stress injuries.

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