BMJ Open Sport & Exercise Medicine

New approach to identifying elite winter sport athletes' risk of relative energy deficiency in sport (REDs)

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To cite: Smith EM, Drager K, Groves EM, *et al*. New approach to identifying elite winter sport athletes' risk of relative energy deficiency in sport (REDs). *BMJ Open Sport & Exercise Medicine* 2025;**11**:e002320. doi:10.1136/bmjsem-2024-002320

► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/bmjsem-2024-002320).

Accepted 14 January 2025

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ABSTRACT

Objectives Relative energy deficiency in sport (REDs) is a syndrome resulting from problematic low energy availability (LEA). Low areal bone mineral density (aBMD) is a primary indicator of LEA, measured by dual X-ray absorptiometry (DXA). High-resolution peripheral quantitative CT (HR-pQCT) is an advanced imaging device that provides measures of volumetric BMD (vBMD), bone microarchitecture, geometry and strength. This study aimed to assess the prevalence of REDs in elite winter sport athletes and to observe the associations in bone parameters using HR-pQCT in athletes identified as at-risk or not at-risk of REDs.

Methods Participants included 101 elite athletes (24.1±4.4 SD years; 52% female). The REDs Clinical Assessment Tool (CAT2) was used to determine REDs risk. HR-pQCT scans of the non-dominant radius and left tibia were analysed on REDs risk grouping.

Results 17 athletes (17%; 71% female) were at-risk based on the REDs CAT2. After covarying for lean mass, OR suggested a higher likelihood of REDs risk classification for athletes with low cortical thickness, cortical area, total vBMD and bone strength.

Conclusions Impaired total vBMD, bone strength and cortical bone parameters were approximately twice as likely (OR: 1.9–3.0) in athletes at-risk of REDs. Results agree with the consensus statement that HR-pQCT may identify impaired bone health in athletes at-risk of REDs. Future directions should use HR-pQCT to explore REDs risk longitudinally, using bone change over time, as this may provide greater insight. Using advanced imaging to explore REDs risk in a population of winter high-performance athletes is novel.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Relative energy deficiency in sport (REDs) is a syndrome caused by low energy availability that negatively impacts bone health and athlete performance, with prevalence rates varying from 15–80% depending on sex and sport type.

WHAT THIS STUDY ADDS

⇒ This study highlights the utility of the REDs Clinical Assessment Tool V.2 and high-resolution peripheral quantitative CT (HR-pQCT) in assessing REDs risk, showing links between cortical bone impairments and REDs in elite winter sport athletes which is a population rarely studied. Results suggest a benefit of including both HR-pQCT and dual X-ray absorptiometry (DXA) for bone assessment in research and clinical settings to progress towards clinically relevant associations between REDs risk and bone health.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Findings suggest HR-pQCT's potential for advanced imaging indicators unique to REDs, paving the way for objective screening. Early identification through systematic screening could improve athlete health, particularly bone health, and reduce removal from sport due to severe REDs risk.

INTRODUCTION

Effects of low energy availability (LEA) pose risks to an athlete's health, wellness and sports performance.[1 2] LEA occurs when one's energy expenditure outweighs their energy intake[3] and can be especially detrimental to bone health.[4] Bone is a mechanosensitive tissue that requires adequate levels of physical stimulus and energy intake to induce positive adaptations[5 6] to maintain bone quality, including bone mineral density (BMD), strength, geometry, microarchitecture and tissue mineralisation. The relationship between bone health and LEA is well known,[7] leading to the development of models to describe this relationship, including relative energy deficiency in sport (REDs).[8 9] In 2023, REDs was redefined as 'a syndrome of impaired physiological and/or psychological functioning experienced by female and male athletes that is caused by exposure to problematic LEA'.[9] A primary indicator of REDs risk is the emphasis on impaired bone health, specifically low BMD, as defined in the REDs Clinical Assessment Tool V.2 (CAT2).[10]

Areal BMD (aBMD) is measured using dual X-ray absorptiometry (DXA); however, relying solely on DXA may be restrictive

as the technology has limited ability to analyse bone strength and microarchitecture. High-resolution peripheral quantitative CT (HR-pQCT) is an advanced imaging technology that measures total, cortical and trabecular BMD, bone microarchitecture, geometry and estimated strength using finite element analysis (FEA). Cortical bone microarchitecture and geometry may play a critical role in the development of bone stress injuries (BSIs) in athletes with menstrual dysfunction.[11–13] Compromised bone strength and cortical bone have been observed in amenorrhoeic athletes compared with both eumenorrhoeic athletes and non-athletes.[14] Thus, associated decrements in strength and microarchitecture could suggest REDs risk. Additionally, estimated strength derived by HR-pQCT and FEA has been shown to predict fracture risk independent of aBMD[15 16] which is crucial in preventative assessment for the longevity of an athlete's career. The growing utility and emerging potential of HR-pQCT has led to the inclusion of this modality in the possible assessment of REDs risk, though further research is needed.[17 18]

Bone quality measured by HR-pQCT in athletes at-risk of REDs is poorly understood, especially among winter sport athletes. However, limited work suggests that bone health appears poorer in athletes at-risk of REDs compared with not at-risk athletes.[19] Research on REDs risk primarily includes endurance athletes, who tend to be more susceptible to REDs.[20 21] The ability to use HR-pQCT in addition to DXA in identifying REDs risk is relatively unknown; however, assessing bone microarchitecture and strength[18] may provide greater detail and implications of impaired bone health.

This study aimed to determine the prevalence of winter sport athletes at-risk of REDs using the REDs CAT2. In addition, we explored the likelihood and association of HR-pQCT derived bone density, microarchitecture, geometry and estimated strength parameters observed in athletes at-risk versus not at-risk of REDs, based on the REDs CAT2. It was hypothesised that athletes considered at-risk of REDs would have inferior bone quality via HR-pQCT than those not at-risk of REDs.[22]

METHODS

Participants

Data collection for this cross-sectional study occurred between November 2019 and January 2024. Participants were recruited through collaborative efforts with the Canadian Sport Institute Alberta based on the following eligibility criteria: affiliation with the Canadian Sport Institute, competing at either elite/international (Tier 4) or world-class (Tier 5)[23] level in a winter sport recognised as part of the Olympic Winter Games, at least 14 years old, and have not experienced pregnancy/lactation in the year before data collection. All participants provided informed consent before participating in the study. Individuals under 18 were assessed and treated as mature minors and signed their own consent forms.

Questionnaires

Participants completed electronic questionnaires capturing relevant information pertaining to REDs risk, including the age at which athletes began training, fracture and BSI prevalence and missed or modified training due to injury/fracture. For females, age of menses, cycle frequency/duration and use of contraception were collected. The REDs CAT2 Step 2[10] was used to assess an athlete's risk of REDs. Athletes within this cohort were classified into two rather than four groups: at-risk of REDs (yellow/'mild', orange/'moderate' or red/'severe') or not at-risk of REDs (green/'none'). The REDs CAT2 captures blood-based data (ie, testosterone, triiodothyronine and cholesterol) and mental health screening (ie, disordered eating, anxiety and/or depression). These variables were omitted as we did not have this data.

Dual X-ray absorptiometry

DXA (GE Lunar iDXA, GE Healthcare) was used to measure aBMD (g/cm^2) of the left hip (femoral neck (FN) and total hip (TH)) and lumbar spine (LS). In addition to aBMD, sex-matched, age-matched and weight-matched Z-scores were calculated (iDXA, enCORE V.18, GE Lunar). Total body DXA scans were conducted to obtain anthropometric measures, including lean mass (ie, skeletal muscle, organs and connective tissue), fat-free mass (ie, bone, skeletal muscle, organs and connective tissue), fat mass and percent body fat. Precision errors of aBMD for DXA sites ranged from 0.51% to 1.14%.[24]

High-resolution peripheral quantitative CT

Participants completed unilateral HR-pQCT scans of the distal non-dominant radius and left tibia at a nominal isotropic resolution of 61 µm (XtremeCT II, Scanco Medical, Brüttisellen, Switzerland). The left tibia was chosen to align with the left hip of the DXA scan, based on standard imaging protocols. If either site could not be scanned due to a previous fracture or metal artefact, the contralateral limb was scanned. Scans captured a 10 mm length totalling 168 slices and were located 9.5 mm and 22.5 mm proximal to the reference line for the radius and tibia, respectively.[25] Technicians performed and analysed all scans using the standard manufacturer's method[25] and subsequent fully automatic segmentation was applied before quantitative analysis.[26] All scans were graded 1–5 for motion artefacts: a scan scoring '1' had no motion and a scan scoring '5' was subject to severe blurring and discontinuities.[27] Any scan with a motion score of '4' or greater was excluded from analyses. Precision scores for HR-pQCT ranged from<2.4% for density to<3.3% for microarchitecture parameters, except for cortical porosity (CtPo) (<13.7%).[28]

Bone parameters including total (TtBMD; mg hydroxyapatite (HA)/cm^3) and trabecular volumetric BMD (mg HA/cm^3), trabecular number (mm^{-1}), trabecular thickness (mm), trabecular separation (mm) and trabecular area (mm^2) were assessed using the standard morphological analysis.[25] Cortical parameters, including cortical

volumetric BMD (mg HA/cm^3), cortical thickness (CtTh; mm), cortical area (CtAr; mm^2) and CtPo (%), as well as total cross-sectional area (mm^2) were determined using an automated segmentation method.[29 30] Image analysis was performed using Scanco Image Processing Language (V.6.6).

Estimated bone strength was determined via simulated failure load (FL) using FEA software (FAIM, V.9.0, Numerics88 Solutions, Calgary, Canada).[31] An axial compression test was simulated using a 1% compressive strain, Young's modulus of 8748 megapascals (MPa) and a Poisson's ratio of 0.3.[32] The primary estimate of bone strength was FL (kilonewtons (kN)) based on 2% of the elements exceeding 7000 microstrains.[33] Precision errors are<2% (coefficient of variation (CV) <1%) for estimates of stiffness and FL.[34]

Equity, diversity and inclusion

Recruitment of male and female athletes in similar numbers was important to applying the REDs CAT2, as males are often neglected in REDs research. Our team comprises academic researchers, exercise physiologists and a dietitian from all career stages with kinesiology, engineering and radiology backgrounds.

Patient and public involvement

Patients or the public were not involved in any aspect of this research.

Statistical analysis

The sample size was based on large effect sizes (0.9) previously observed between eumenorrhoeic and amenorrhoeic athletes and between athletic sporting groups using HR-pQCT.[35 36] A minimum of 42 participants was required to achieve 80% power with a confidence level of 95% (α=0.05). Data were analysed using R Statistical software (V.4.0.0). Continuous data were presented using mean, SD and categorical data using numbers and percentages. Data were checked for normality using Shapiro-Wilk tests and visually checked with Q–Q plots and histograms. Demographic information was displayed for all athletes and split by sex, where two-sample t-tests were used to explore differences between at-risk and not at-risk groups. The primary outcome variables of this study included TtBMD and FL at both the radius and the tibia.

HR-pQCT and FEA results were compared with age-matched and sex-matched controls using freely available normative data (Normative, https://www.normative.ca) developed and maintained by the Bone Imaging Laboratory at the University of Calgary and Z-scores were produced for each variable. Normative data was not sport-specific. OR used Z-scores for each HR-pQCT parameter and were used to determine the likelihood and association between REDs risk and HR-pQCT parameters, where higher ORs represent a greater likelihood of observing a lower measure of each parameter (eg, OR>1: odds of observing low values of a parameter are greater in the at-risk group than in the not at-risk group). These models were adjusted for lean mass a priori as studies have found positive correlations between lean mass and aBMD.[37] Due to sample size limitations, multiple variable logistic regression was performed but restricted to a maximum of two variables, including the independent variable (eg, TtBMD) and one covariate (ie, lean mass).

Research checklist

This study was reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology checklist to ensure rigorous and transparent reporting of observational research methods and findings.

RESULTS

Demographics

101 elite winter sport athletes (52% female) participated in this study. They were associated with the following winter sports: biathlon, cross-country skiing, long-track speed skating, figure skating and ski cross. Demographic and sport affiliation information are presented in table 1. This cohort was 24.1±4.4 SD years old with an average training age of 13.2±6.3 SD years.

Athletes had DXA scans of the TH, FN and LS and HR-pQCT scans of the radius and tibia; however, two athletes were without scans at the radius due to reported bilateral fractures. No scans were removed due to motion artefacts.

REDs prevalence

Within this cohort, 17% of athletes (71% female) were considered at-risk of REDs and 83% (49% female) were not at-risk by use of the REDs CAT2 risk. Of the 17% at-risk athletes, 88% (67% female) were considered a yellow risk, 12% (100% female) were considered an orange risk and zero were considered a red risk. Due to sample size restrictions, yellow, orange and red risk were considered 'at-risk' in our study. The prevalence of REDs risk by sport type is displayed in online supplemental table 1 and the prevalence of each REDs CAT2 indicator for this cohort is displayed in table 2. Most athletes at-risk of REDs were from biathlon (29%) and cross-country skiing (26%). Information for athletes in each risk group, split by sex, is displayed in table 3.

Bone quality parameters

Adjusted ORs revealed that athletes with lower CtTh (OR radius: 2.1, p=0.021; tibia: 1.9, p=0.037) and CtAr (OR radius: 3.0, p=0.007; tibia: 2.7, p=0.006) were approximately two to three times more likely to be at-risk of REDs. Similarly, at the tibia, it was observed that athletes with lower TtBMD (OR tibia: 2.1, p=0.030) and FL (OR tibia: 2.2, p=0.033) were approximately twice as likely to be observed in the at-risk group. The OR results are displayed in figure 1 and online supplemental table 2.

DISCUSSION

In our cohort, 17% of athletes were considered at-risk of REDs despite not being initially screened for risk.[10]

Table 1 Demographic information for all athletes and proportion of athletes by sport

Demographics	All (n=101) Mean (SD)	Male (n=48) Mean (SD)	Female (n=53) Mean (SD)
Age (years)	24.1 (4.4)	24.0 (4.3)	24.2 (4.6)
Height (cm)	175.1 (8.6)	180.8 (6.0)	170.0 (7.3)
Weight (kg)	72.0 (10.2)	78.4 (7.9)	66.2 (8.4)
Body mass index (kg/m^2)	23.4 (2.2)	24.0 (2.3)	22.8 (1.9)
Lean mass (kg)	56.4 (9.3)	64.3 (5.6)	49.3 (5.3)
Fat mass (kg)	12.7 (4.1)	11.0 (3.0)	14.2 (4.3)
Per cent fat (%)	17.7 (5.2)	13.9 (2.8)	21.1 (4.5)
Fat-free mass (kg)	59.4 (9.7)	67.6 (5.9)	52.0 (5.6)
Age of menarche (years)	NA	NA	13.4 (1.4)
Training age (years)	13.2 (6.3)	12.8 (5.6)	13.5 (6.9)
Participants by sport	Number (%)	Number (%)	Number (%)
Biathlon	14 (13.9)	5 (10.4)	9 (17.0)
Cross-country skiing	23 (22.8)	12 (25.0)	11 (20.8)
Figure skating	10 (9.9)	4 (8.3)	6 (11.3)
Long-track speed skating	33 (32.7)	17 (35.4)	16 (30.2)
Luge	6 (5.9)	2 (4.2)	4 (7.5)
Ski cross	15 (14.9)	8 (16.7)	7 (13.2)

Data are presented as mean (SD) for continuous variables and number (%) for discrete variables.

Previous research reports REDs prevalence between 15–80% depending on the sport,[9 38] where leanness (or aesthetic) based sports and endurance sports tend to have higher prevalence due to the associated energy demands.[20 39 40] This study included both endurance (ie, cross-country skiing, biathlon and long-track speed skating) and impact (ie, figure skating, luge, ski cross) sports, and there was a higher percentage of athletes in the endurance-based sports considered at-risk. However, the small sample size was underpowered to evaluate sport-type differences. Including endurance and impact sports may have contributed to the lower prevalence we report; however, we chose to include all sport types because studies involving winter sports are lacking. Notably, athletes within this cohort were supported by a multidisciplinary team at the Canadian Sport Institute Alberta, including performance dieticians and exercise physiologists, who are educated in REDs prevention strategies, possibly helping mitigate overall REDs risk.

Primary indicators for REDs include an aBMD Z-score<−1.0 SD at the LS, TH or FN and a recent (ie, within two years) history of high-risk and/or multiple low-risk BSI.[10] This cohort had a relatively small prevalence (8%) of athletes with low aBMD via DXA, zero with a recent high-risk BSI and only 3% with a low-risk BSI. This differs from other studies which report 11–39% of athletes with low aBMD[22 41] and up to 20% sustained at least one BSI per season.[42] These disparities may be partially due to unique energy demands and loading patterns associated with winter sports compared with those usually studied (ie, runners) and may also be partially attributed to the support this cohort received.

Primary amenorrhoea and prolonged secondary amenorrhoea are defined in the REDs CAT2 as severe indicators of REDs for females.[10] Previous studies report HR-pQCT differences in bone quality between athletes with and without menstrual dysfunction[12 14 36 43] and between athletes with and without BSIs.[43] The development of BSIs in athletes with menstrual dysfunction has been linked to compromised cortical bone microarchitecture, geometry and estimated strength,[11–13] suggesting justification for HR-pQCT monitoring in athletes at-risk of REDs. These results are consistent with our findings whereby differences in HR-pQCT derived bone density (TtBMD), microarchitecture (CtTh), geometry (CtAr) and estimated bone strength (FL) were observed in athletes at-risk versus not at-risk of REDs. In our study, athletes with lower parameters were approximately twice as likely to be at-risk of REDs, supporting our hypothesis.

The current study did not observe differences between at-risk groups for trabecular bone; however, some studies have shown poorer quality of trabecular bone (ie, higher separation, lower density, number and thickness) are observed in athletes with amenorrhoea and/or LEA.[14 36] The metabolic activity of trabecular bone makes it highly adaptive to mechanical loading, resulting in a high

Table 2 Prevalence of REDs CAT2 indicators used in severity classification among athletes considered at-risk of REDs

Risk factors*	All (n=101) Number (%)	Male (n=48) Number (%)	Female (n=53) Number (%)
All athletes risk factors			
Primary indicators			
History of high-risk and/or multiple low-risk BSIs	0 (0)	0 (0)	0 (0)
Absence of>6 months from training due to BSIs	0 (0)	0 (0)	0 (0)
BMD Z-score<–1.0 SD at the LS, TH or FN	8 (8)	5 (10)	3 (7)
Secondary indicators			
History of 1 low-risk BSI within the previous 2 years	3 (3)	3 (6)	0 (0)
Absence of<6 months from training due to BSIs	3 (3)	3 (6)	0 (0)
Female risk factors			
Severe primary indicators			
Primary amenorrhoea/prolonged secondary amenorrhoea	NA	NA	10 (19)
Primary indicators			
Secondary amenorrhoea	NA	NA	1 (2)
Secondary indicators			
Oligomenorrhoea caused by FHA	NA	NA	2 (4)

Data are presented as numbers (percentages).
*Definitions for the risk factors are available in the REDs CAT2.[10]
BMD, bone mineral density; BSI, bone stress injury; CAT2, Clinical Assessment Tool V.2; FHA, functional hypothalamic amenorrhoea; FN, femoral neck; LS, lumbar spine; REDs, relative energy deficiency in sport; TH, total hip.

potential for bone remodelling.[44] The predominant gliding motion of these sports, in addition to the impact loading of some, may have masked or mitigated some of the negative effects of LEA on trabecular bone. It is also possible that changes in trabecular bone may be more affected by hormonal changes related to oestrogen, as

Table 3 Demographics by REDs risk comparison for all athletes and by sex for at-risk and not at-risk groups

	All athletes			Male			Female		
	Not at-risk (n=84) Mean (SD)	At-risk (n=17) Mean (SD)	P value	Not at-risk (n=43) Mean (SD)	At-risk (n=5) Mean (SD)	P value	Not at-risk (n=41) Mean (SD)	At-risk (n=12) Mean (SD)	P value
Age (years)	23.9 (4.2)	25.3 (5.8)	0.346	24.1 (4.4)	22.8 (3.0)	0.339	23.6 (3.9)	26.4 (6.4)	0.195
Height (cm)	175.6 (8.4)	172.7 (9.1)	0.248	180.8 (6.1)	180.3 (5.4)	0.358	170.1 (6.8)	169.6 (8.6)	0.896
Weight (kg)	**73.3 (10.0)**	**65.5 (7.5)**	**<0.001**	**79.2 (7.9)**	**71.7 (2.6)**	**<0.001**	67.2 (8.4)	62.9 (7.3)	0.092
BMI (kg/m^2)	**23.7 (2.2)**	**21.9 (1.5)**	**<0.001**	**24.2 (2.3)**	**22.1 (1.8)**	**0.002**	**23.2 (2.0)**	**21.8 (1.4)**	**0.009**
Lean mass (kg)	**57.3 (9.5)**	**51.7 (6.6)**	**0.006**	**64.9 (5.6)**	**59.0 (1.9)**	**<0.001**	49.4 (5.1)	48.7 (5.3)	0.712
Fat mass (kg)	**13.0 (4.2)**	**11.1 (2.7)**	**0.027**	11.1 (3.1)	10.0 (1.7)	0.810	**14.9 (4.4)**	**11.6 (2.9)**	**0.005**
Percent fat (%)	17.8 (5.5)	17.0 (3.5)	0.460	13.9 (2.9)	13.8 (2.1)	0.232	**21.9 (4.5)**	**18.3 (3.2)**	**0.005**
FFM (kg)	**60.4 (9.9)**	**54.4 (6.8)**	**0.005**	**68.2 (5.9)**	**61.8 (1.9)**	**<0.001**	52.2 (5.3)	51.3 (5.6)	0.681
Menarche (years)	NA	NA	NA	NA	NA	NA	**12.9 (1.1)**	**15.1 (1.3)**	**<0.001**
Training age (years)	**12.2 (5.3)**	**17.6 (8.7)**	**0.017**	11.2 (4.4)	11.8 (5.4)	0.784	**13.4 (6.0)**	**20.0 (8.7)**	**0.022**

Data are presented as mean (SD). P values represent the difference between at-risk and not at-risk groups for all athletes, males and females.
*Bold values indicate statistical significance (p<0.05).
BMI, body mass index; FFM, fat-free mass; REDs, relative energy deficiency in sport.

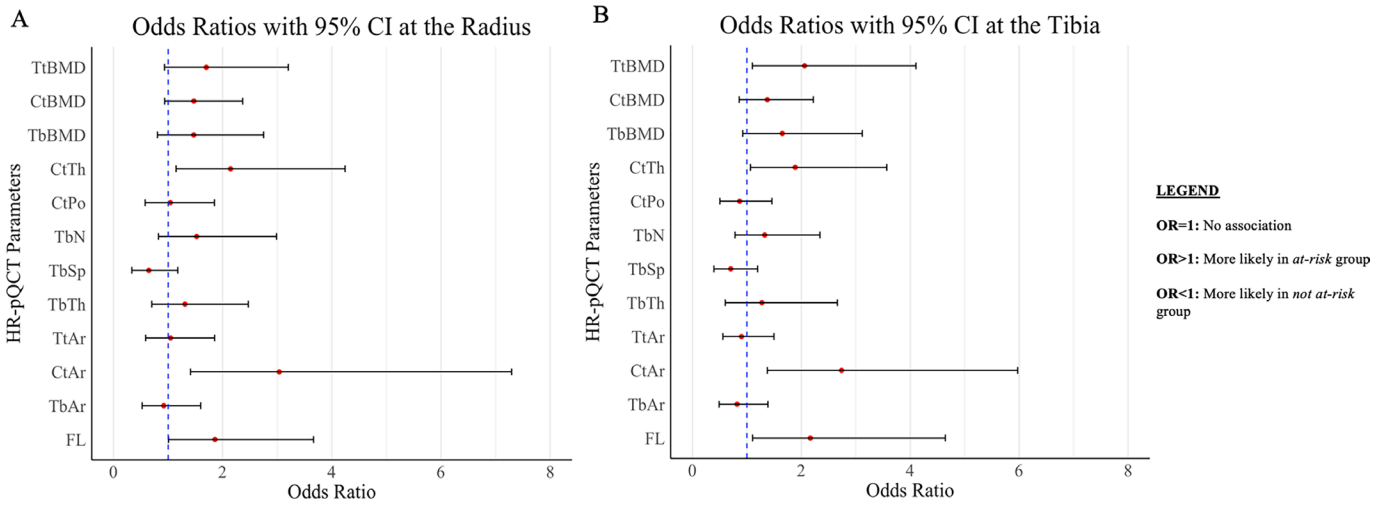

Figure 1 ORs for REDs risk at the radius (A) and tibia (B). OR values>1 are associated with *lower* observed parameters (eg, lower TtBMD, CtTh, CtAr, FL) in the REDs at-risk group. CtAr, cortical area; CtBMD, cortical bone mineral density; CtPo, cortical porosity; CtTh, cortical thickness; FL, failure load; HR-pQCT, high-resolution peripheral quantitative CT; REDs, relative energy deficiency in sport; TbAr, trabecular area; TbBMD, trabecular bone mineral density; TbN, trabecular number; TbSp, trabecular spacing; TbTh, trabecular thickness; TtAr, total area; TtBMD, total bone mineral density.

seen in amenorrhoeic athletes.[36 45 46] In contrast, in our cohort, only one at-risk athlete was classified based on secondary amenorrhoea which might be most associated with an athlete's current menstrual function.[46] Notably, 70% (n=37) of the female athletes within this cohort were using contraceptives. Thus, the observance of secondary amenorrhoea or oligomenorrhoea in a natural cycle was not possible.

Future studies would benefit by exploring the use of HR-pQCT in longitudinal analyses to observe REDs risk and associated changes in bone microarchitecture that may not otherwise be observed by DXA,[17 47] as a negative change in aBMD Z-scores is also considered indicative of REDs risk.[9 10] Additionally, further work should be done to include more impact or non-endurance sports for REDs CAT2 development.[48]

Clinical implications

The release of the REDs CAT2 has provided clinicians with a means to assess athletes for REDs risk despite REDs remaining a diagnosis by exclusion. This study contributes to the application required for such a tool by applying it to a diverse group of athletes and sports. Based on these data, even with incomplete data for all indicators, the REDs CAT2 was used to identify athletes as being at-risk of REDs in a cohort that was not recruited for their REDs risk nor was initial screening completed as per the REDs CAT2 Step 1.[10] These results suggest that even mild REDs risk may lead to impairments in bone quality which may result in increased fracture risk. These data suggest an added benefit for the inclusion of HR-pQCT, in addition to DXA, for bone assessment in both research and clinical settings, to progress towards clinically relevant associations between REDs risk and bone health.

Strengths/limitations

This is the first study to apply the REDs CAT2 to winter sport athletes. This work contributes to the potential usage of HR-pQCT for studying various health outcomes, especially bone health, associated with REDs.[9] However, the small number of athletes in the at-risk group and the incomplete panel of REDs CAT2 indicators limit the applicability and generalisability of these findings. Even with this tool, diagnosis is limited as all other potential clinical conditions must be systematically ruled out before confirming the presence of REDs.[9 10] Without a single universal identifier, risk classification is inherently challenging. Additionally, this study compared bone quality by measure of HR-pQCT in a cohort where many had already been stratified as having low aBMD via DXA based on the REDs CAT2. While aBMD and HR-pQCT-derived parameters are not linearly related in athletes,[35] the reliance on aBMD to classify REDs risk may have confounded the results. However, not all athletes with low aBMD values had low HR-pQCT values. Future studies should examine the relationship between DXA and HR-pQCT skeletal outcomes and consider first stratifying athletes based on HR-pQCT parameters and subsequently evaluated for REDs risk. Finally, the cross-sectional nature of this study is limiting as bone metabolism may fluctuate throughout a competitive season[49] and longitudinal data may be more representative of athlete bone health.

CONCLUSION

Athletes with lower cortical geometry and microarchitecture at both the radius and tibia and lower total density and estimated strength at the tibia were more likely to be identified as at-risk of REDs. Results from this study agree with the IOC consensus statement that HR-pQCT may identify impaired bone health in athletes at-risk of

REDs. By using HR-pQCT prospectively and screening all athletes for REDs risk, the incidence of removal from sport due to extreme REDs risk classification may be reduced, increasing the athlete's longevity.

Acknowledgements The authors would like to thank the athletes for participating in this work. They would also like to thank the staff at the McCaig Institute for Bone and Joint Health, University of Calgary, for their role in data scheduling and collection. They also wish to acknowledge the cooperative efforts of the Canadian Sport Institute Alberta in making this work possible.

Contributors LAB devised the study, assisted in data analysis and interpretation of results, and provided supervision throughout the study. LAB is the guarantor. EMS contributed to athlete recruitment, data analysis, manuscript drafts and the creation of tables and figures. KD helped with athlete recruitment and provided insight for study design and interpretation of results. LG helped provide insight for statistical analysis and interpretation of results. EMG was involved in the study design and interpretation of results. SKB assisted with data analysis and provided supervision throughout the study. All authors contributed to the revision of this manuscript.

Funding This research received no grant or funding from any agency. Trainee funding (EMS) was provided by the Dr. Cy Franke Trainee Award in Nutrition for Bone, Joint and Muscle Health awarded by the McCaig Institute for Bone and Joint Health.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval Ethics was obtained from the Conjoint Health Research and Ethics Board at the University of Calgary (REB19-1078). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request.

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