

Asymptomatic Bone Marrow Edema in Weight-bearing Bones in Athletes and Military Trainees: A Systematic Literature Review

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ABSTRACT

Asymptomatic bone marrow edema (aBME) is a non-specific radiographic finding often found in athletes. Although aBME may represent the body's physiological response to training load, the etiology, MRI characteristics, and natural history of aBME remain unknown. To better characterize aBME in the lower extremities of military trainees and athletes. A systematic literature review in accordance with PRISMA guidelines was performed to identify primary research articles reporting on aBME in the lower extremities of athletes and military trainees. We identified 347 unique articles and after applying inclusion and exclusion criteria, 10 articles were included for qualitative synthesis. There were a total of 444 patients with an average age of 28.4 ± 9.6 included. The most commonly used MRI sequences were proton-density with fat-saturation and T1-weighted imaging. The pattern of BME was inconsistently described, with various classification schemas used. The changes in aBME during longitudinal follow-up were dynamic and demonstrated both radiographic progression and regression. aBME is a highly prevalent and radiographically dynamic entity observed in high-level athletes and military trainees. Although follow-up was limited in the included studies, aBME may represent a natural, non-pathologic, reaction in response to specific biomechanical stressors.

Introduction

Bone marrow edema (BME) is a non-specific finding typically identified on magnetic resonance imaging and can often create a challenging dilemma for clinicians to interpret clinical relevance [1]. Although the radiographic findings correlate to a local process, histopathological analyses have suggested that BME may be a more dynamic process characterized by lymphocytic infiltration, fibrotic deposition, and increased vascularization [1, 2]. Due to this heterogeneity, BME has been replaced by some sources with more generic terms that do not necessarily suggest this histopathological

state, such as bone marrow lesions (BML) [3] and edema-like marrow signal intensity (ELMSI) [4].

BME that is associated with pain and disability may represent a bone stress injury driven by a biomechanical overload of joints, bone turnover, and trabecular fracture [5, 6]. Thus, BME is often detected in patients who are physically active such as athletes and military recruits due to the required and consistent axial loading on the lower extremities [6, 7]. BME from stress injury on MRI is generally described as a low-signal on T1-weighted MRI and a high-signal on fat-suppressed T2-weighted or short tau inversion recovery

ery sequences. Current classification systems for grading bone stress injuries such as the system described by Fredericson et al. [8] have been expanded to assist with further characterizing the presence of BME on fluid-sensitive MRI to identify the location of bone stress injuries. [6, 9]. These may become true stress fractures when identified on MRI as having linear high-signal on fluid-sensitive sequences or linear low-signal on T1. Even beyond the scope of stress injury, BME may also be associated with other concomitant injuries around joints such as osteochondral defects, osteoarthritis, enthesopathies, and tendonitis. Importantly, these all typically present with pain; thus, symptomatic BME (sBME) is associated with a host of pathologic processes.

In contrast, BME on MRI scans has also been found incidentally in asymptomatic athletes [10]. There are suggestions that these findings represent the body's normal physiological response to sports-specific training loads and is different from sBME and stress-related injury [11]. Due to its unclear etiology, the radiology literature describes these lesions as edema-like marrow signal intensity (ELMSI). However, clinicians have frequently characterized these findings as BME despite their lack of associated pain or pathologic processes. The etiology, unique MRI characteristics, and natural history of asymptomatic bone marrow edema (aBME) is unclear, with a paucity of evidence in the current literature pertaining to high level athletes and military personnel. At present, there are no clear management guidelines for these purely radiographic findings; particularly in situations where an MRI scan is done for an athlete with limb pain but the areas of BME noted on MRI do not correspond anatomically to where the athlete reports pain or has pain on physical exam [10]. Additionally, it is not known whether this radiographic finding progresses over time with continued training and possibly predisposes the athlete to stress injury.

An improved understanding of aBME would allow for better counseling of asymptomatic athletes regarding injury risks and hopefully, avoid significant restrictions on training or performance [1]. The purpose of this systematic review is to characterize the prevalence and natural history of asymptomatic BME (aBME) in the lower extremities of military trainees and high-level athletes based on (1) demographics including sport and gender, (2) MRI technique and classification methods of specific imaging findings, (3) location of edema signal at initial diagnosis and any progression over time during active sport or duty participation.

Materials and Methods

Literature search

A systematic literature review was performed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) 2009 guidelines [12]. A comprehensive literature review was conducted using PubMed, EBSCO host, Medline, and Google Scholar to identify all studies that evaluated outcomes and MRI findings in asymptomatic BME between 2002 and 2022. The search queried the aforementioned databases using the following terms: "(Bone marrow edema" OR "bones stress injury" OR "bone marrow edema lesions" OR "bone marrow edema like signal lesions") AND ("military" OR "athletes" OR "sports") AND ("lower limb" OR "lower extremities" OR "pelvis" OR "pelvic" OR "talus" OR

"femur" OR "femoral head" OR "foot" OR "Tibia") AND ("MRI" OR "magnetic resonance Imaging" OR "T1-weighted" OR "T1-weighted imaging" OR "T2-weighted imaging").

Study eligibility and selection

Inclusion and exclusion criteria were determined *a priori*, and two authors (A.K and M.E) completed the title and abstract screening while being blinded to each other's results. Any disagreements were adjudicated by a third author. We considered studies that met the following inclusion criteria: (1) full manuscript was written in English, (2) studies that included subjects that were either athletes or military personnel, (3) patients were diagnosed with asymptomatic BME localized at the level of the pelvis or lower in the leg, and (4) studies included MRI findings for a minimum of one timepoint. The exclusion criteria included: narrative reviews or systematic reviews, nonathletes or non-military members, patients under the age of 18, any duplicate studies among databases, and animal studies. Inclusion and exclusion criteria were applied by two reviewers, who were blinded to each other's results.

To rate the methodological rigor of all the included studies, we used the Joanna Briggs Institute (JBI) Critical Appraisal Tool for Systematic Reviews and Research Syntheses which addresses criteria such as presence of a representative sample, appropriate recruitment, adequate sample size, and objective measurement of the condition, among other aspects [13].

Data analysis

We utilized a systematic checklist to code study characteristics including the author, year, study design, patient demographics, MRI modality utilized, radiographic findings reported, and longitudinal radiographic changes, if available.

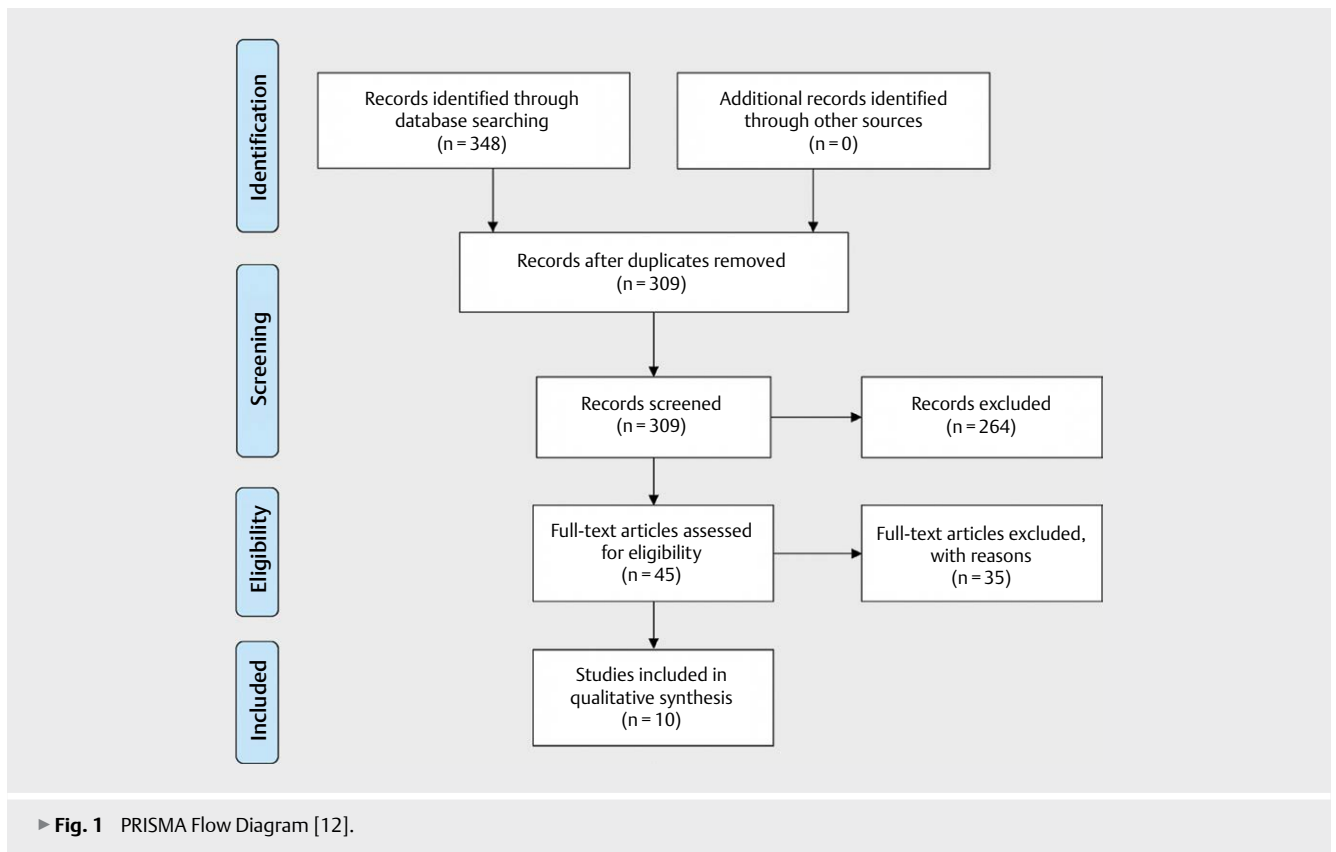
Data synthesis

A meta-analysis was not carried out since there were insufficient homogeneous comparison studies. In addition, the studies did not differentiate the results of the radiographs based on age or gender and as a result, analyses by age groups and gender were also not possible. For each study and result, all the data were gathered, and were narratively described.

Results

Study identification

The initial title and abstract query retrieved a total of 347 articles. Following the application of inclusion and exclusion criteria, 42 articles were included for abstract screening. Fifteen studies were included for full-text screening, of which, 10 were included for qualitative synthesis (► **Fig. 1**). Detailed study characteristics such as demographics, study design, and JBI critical appraisal score are highlighted in ► **Table 1**. Notably, there were three level 4 evidence studies, five level 3 evidence studies, and two level 2 evidence studies. The average JBI score was 7.4 with a standard deviation of 1.43. A total of 444 subjects with an average age of 28.4 ± 9.6 were included in our study, with a 65.8% (292) male predominance. All of the analyzed subjects were either athletes (367/444; 82.7%) or military recruits (77/444; 17.3%). In our systematic review, the largest



study included was by Horga et al. [14], 2019, which consisted of a total of 115 marathon runners. With respect to sports disciplines, there were 37 soccer athletes (9.5%), 256 marathon runners (65.8%), 16 middle and long-distance track runners (4.1%), 33 collegiate basketball players (8.5%), 25 high-level collegiate athletes participating in a variety of sports (6.4%), and 77 military recruits (77/444; 17.3%).

Imaging Modalities and BME Classification Criteria Used for Radiographic Assessment

There were nine different MRI sequences used to detect and diagnose aBME in the articles included. The sequences identified include T1-weighted, T2-weighted, fat saturated T2-weighted, proton-density-fat-saturated, turbo inversion recovery magnitude, short-tau inversion recovery, sampling perfection with application-optimized contrasts by using different flip angle evolution (SPACE), coronal and axial short inversion time inversion-recovery sequence and coronal gradient-echo in- and out-of-phase sequences. The most commonly used sequences were PD-FS and T1-weighted sequencing; although T1-weighted sequencing was often used in combination with other sequences such as T2-weighted sequencing. The majority of studies used 1.5 T scanners for radiological assessment at baseline (7/10; 70%) (► **Table 2**).

The pattern of BME is described inconsistently across the included articles (► **Table 2**). Eight studies included a definition or classification system to describe the aBME observed in the study participants. Three studies defined aBME as increased signal intensity on fat-suppressed T2-weighted MRI [15–17], while Bezuglov et al. con-

sidered BME as an area of low signal intensity on T1-weighted MRI and high signal intensity on PD-FS and TIRM sequences [18]. The remainder of the studies either classified BME according to various grading scales (5/10; 50%) or did not report how they defined BME (2/10; 20%). Hadid et al. used a grading system developed by Fredericson et al. for symptomatic bone stress injuries [19]. Tenforde et al. [6] used a modified grading system developed specifically for BME, which was proposed by Fredericson and Arendt and Yao et al. [17] used a grading system developed by Lazzarini et al. Varkas et al. [7] used the Spondyloarthritis Research Consortium of Canada (SPARCC) grading system, which is specific to symptomatic sacroiliitis. Horga et al. [20] used the scoring of hip osteoarthritis with an MRI (SHOMRI) grading system, which contains a subcategory describing BME severity.

Radiographic Findings at time of Assessment

All of the included studies reported evidence of pelvic or lower extremity aBME in their cohorts at the time of first MRI analysis. Tenforde et al. found evidence of BME in seven metatarsals from five of the 16 athletes at the beginning of the athletic season, with three metatarsals having Grade 1 lesions (mild marrow edema exclusively on STIR images), two metatarsals having Grade 2 lesions (moderate marrow edema exclusively on STIR images), and two metatarsals having Grade 3 lesions (severe marrow edema or severe periosteal edema on both T1-weighted images and STIR without a fracture line); the first four metatarsals were affected, with BME seen mostly in the first and third metatarsals [6]. Kornaat et al. reported that 88% of athletes in their cohort had evidence of BME before the start of the season, with 69%

► **Table 1** Study Characteristics

Author, Year	Study Design	Sports/Participants	Sample Size (N)	Sex (%male)	Mean Age	JB1 score (out of 11)
Bezuglov [18], 2021	Case Series, Single Center, Russia	Elite soccer athletes	N = 37	Male (100 %)	25.5 ± 4.3	9
Hadid [19], 2014	Longitudinal, prospective, cohort study, Single Center, Israel	Military recruits	N = 55	Male (100 %)	18.6	9
Horga [20], 2021	Longitudinal, prospective, cohort study, Single Center, United Kingdom	Amateur marathon runners	N = 28	Male (50 %)	32.4	9
Horga [14], 2019	Longitudinal, prospective, cohort study, Single Center, United Kingdom	Amateur marathon runners	N = 115	Male (44.45 %)	44	8
Kornaat [15], 2014	Cohort Studies, Single Center, Netherlands	Middle and long-distance professional track runners	N = 16	Male (81.25 %)	22.9 ± 2.7	8
Major [16], 2002	Cohort Study, Single Center, USA	Collegiate basketball players	N = 17	Male (70.59 %)	N/A	6
Mandalia [21], 2020	Cohort Study, Single Center, United Kingdom	High level collegiate athletes	N = 25	Male (48 %)	21	6
Tenforde [6], 2022	Cohort Study, Single Center, USA	Collegiate basketball players	N = 16	Male (100 %)	20	5
Varkas [7], 2018	Observational Cohort study, Single Center, Belgium	Military recruits	N = 22	Male (86.4 %)	N/A	7
Yao [17], 2021	Case Series, Single Center, China	Amateur marathon runners	N = 113	Male (55.75 %)	43.1	7

of these lesions localized to the ankle joint and foot [15]. Across 183 analyzed ankles, Yao et al. found that 12 (6.6 %) had evidence of BME with four Grade 1 (increased signal intensity involving < 25 %), six Grade 2 (increased signal intensity involving 25 %-50 %), and two Grade 3 (increased signal intensity involving > 50 %) [17]. Major et al. found that BME was observed in 14 of the 34 radiographically analyzed knees, with seven lesions in the medial femoral condyle, two in the lateral femoral condyle, and two in the lateral tibial plateau [16]. Similarly, the study by Mandalia et al. reported evidence of BME in eight knees, with five localized to the medial femoral condyle, two in the lateral tibial plateau, and one in the trochlea [21]. The study by Horga et al. showed that 58 out of 142 knees scanned before a marathon showed evidence of BME with the most common lesion location being patellofemoral [14]. In another study, also by Horga et al., six out of 42 hip joints displayed evidence of subchondral BME, and four lesions were Grade 1 (BME size ≤ 0.5 cm), one lesion was Grade 2 (BME size > 0.5 and ≤ 1.5 cm), and one was a Grade 3 (BME size > 1.5 cm) [20]. This study was unique in that subchondral lesions were still considered aBME despite evidence suggesting that changes in the signal of subchondral bone marrow may suggest large cartilage lesions [20]. The study by Varkas et al. showed that even before a 6-week intense training regimen, nine out of 22 military recruits displayed radiographic evidence of BME [7]. Finally, the study by Hadid et al. showed that before basic training, 26 recruits displayed radiographic evidence of BME [19]. A summary of the main radiographic findings from all the studies is shown in ► **Table 2**.

In the study by Bezuglov et al., 64 out of the 74 analyzed ankle joints (86.5 %) had evidence of degenerative joint disease, and 13 out of the 74 ankle joints (17.6 %) had Grade 3 (multiple osteophytes, definite joint space narrowing, sclerosis, and possible bony deformity) or Grade 4 (large osteophytes, marked joint space narrowing, severe sclerosis, and definite bony deformity) cartilage lesions based on a modified version of the Noyes-Stabler classification [22], with all 13 lesions also showing evidence of BME at time of first radiographic assessment [18]. Mandalia found that six of the

BME lesions were isolated while two of them showed a high signal in the meniscus without tear [21]. Horga et al. found that in one patient with aBME also had concomitant partial thickness cartilage defect (present before the marathon) and another patient had a preexisting psoas bursa [20].

Radiographic Changes

Only six studies (6/10; 60 %) included a longitudinal radiographic assessment of the region of interest. Five of the aforementioned studies reported alterations in the observed BME signals at the time of second radiographic evaluation, despite the subjects remaining asymptomatic [6, 7, 14, 15, 20]. Hadid et al. had nine of their subjects become symptomatic, six in subjects who had BME at baseline and three in subjects who were clear at baseline [19]. Eight of 26 recruits (30.8 %) who had positive results at time 0 showed full resolution after 4 months of training, while four recruits (15.4 %) experienced worsening of their BME [19]. Tenforde et al. showed that of the 13 participants who completed the season, six (46 %) had aBME that included two new cases since the initial pre-season imaging [6]. Notably, of the four subjects with previously identified aBME, the grade improved in one, worsened in one, and was stable in the remaining two [6]. Kornaat et al. found that during the course of the season, 26 out of the 45 (58 %) assessed lesions had fluctuations in the T2-weighted signal intensity, with old lesions disappearing in 10 cases (22 %) [15]. Both studies by Horga et al. had similar findings which showed fluctuation in BME signal between the beginning and end of the marathon [14, 20]. In the 2019 study, 53 % (26/49) of knees imaged post-marathon showed new or worsening BME at the patellofemoral region (19/26) or the tibiofemoral region (7/26) [14]. The remaining 23 runners showed improvement at either the patellofemoral region (2/23) or tibiofemoral region (21/23) [14]. Finally, Varkas et al. found that after the intense training regimen, 11 of the 22 recruits presented with a SPARCC score ≥ which was higher by two cases from baseline [7]. A summary of reported radiographic changes is shown in ► **Table 3**.

► **Table 2** Radiographic findings at baseline.

Author, Year	Imaging Modality	BME Classification	Radiographic Findings at Presentation	Longitudinal Radiographic Changes	Concomitant findings
Bezuglov [18], 2021	-T1-weighted and T2-weighted MRI -1.5-T scanners -PD-FS and TIRM	-BME was defined as an area of low signal intensity on T1-WI and an area of high signal intensity on PD-WI FAT SAT and TIRM.	- 64/74 (86.5%) of the analyzed ankle joints had evidence of DJD. -13/74 (17.6%) of the ankle joints had BME.	-N/A	-The ankle joints with BME either had grade 3 or 4 cartilage lesions (based on modified Noyes and Stabler classification)
Hadid [19], 2014	-T1-weighted and T2-weighted MRI -coronal and axial short inversion time inversion-recover sequences. -coronal gradient-echo in- and out-of-phase sequences -0.5-T and 3.0-T scanners	-The MR images were evaluated for the grade of stress reaction according to the grading system of Fredericson et al	- 26/55 (47.2%) of recruits had bone stress changes at the tibia - Grade 1: 1 - Grade 2: 25	- 27/55 (49.1%) of recruits had bone stress changes - 9 newly discovered BME - 8 BME seen at baseline were resolved. - 4 BME progressed; all of which were either 100 mm or greater at baseline. - 6 recruits with BME at baseline developed symptomatic bone stress injury - 3 recruits with no BME at baseline developed symptomatic bone stress injury	-N/A
Horga [20], 2021	-PD-FS turbo spin echo MRI -3.0 T scanners.	-BME defined according to the SHOMRI grading system	-At timepoint one, 6/42 (14%) of the hip joints displayed evidence of subchondral BME. -Grade 1: 4 -Grade 2: 1 -Grade 3: 1	-At timepoint two, 2 BME lesions progressed -One lesion progressed from Grade 0 to Grade 2 -The other lesion progressed from Grade 1 to 2. -Both patients were asymptomatic.	-1 patient with aBME also had concomitant partial thickness cartilage defect (present before the marathon) -1 patient had a preexisting psoas bursa with aBME.
Horga [14], 2019	-PD-FS MRI -3.0 T scanners	-N/A	-Pre-marathon MRI showed BME in 58/142 (41%) of knees. -Most common lesion location was patella-femoral.	-49 knees were analyzed from those who completed the marathon. -26 showed new or worsening BME at the patella-femoral region (19) or tibio-femoral region (7). -23 showed improving BME at the patello-femoral region (2) or tibio-femoral region (21).	-N/A
Kornaat [15], 2014	-T2-weighted MRI and SPACE fat-suppressed images -1.5-T scanners	-BME was defined as an ill-defined area of increased signal intensity on T2-weighted-MRI.	-14/16 (88%) of the athletes had BME lesions before the start of the season. -31/45 (69%) of the lesions located in the ankle joint and foot.	-During the course of the season, 26/45 (58%) of the BME lesions showed evidence of fluctuation on MRI. -New lesions appeared in 9/45 (20%) of locations -Old lesions disappeared in 10/45 (22%) of the locations.	-N/A
Major [16], 2002	-fast-spin echo T2-weighted MRI and spin-echo PD-FS -1.5 T scanners	-BME was defined as an area of high signal on fat-suppressed fast spin-echo images.	-BME was observed in 14/34 (41%) of the knees at the following locations: -medial femoral condyle:7 -lateral femoral condyle: 2 -lateral tibial plateau: 2 Patella: 3	-N/A	-N/A

► **Table 2** Continued.

Author, Year	Imaging Modality	BME Classification	Radiographic Findings at Presentation	Longitudinal Radiographic Changes	Concomitant findings
Mandalia [21], 2020	-T1-weighted MRI and PD-FS imaging -1.5 T scanners	-N/A	-8 knees displayed BME at the following locations: -medial femoral condyle: 5 -lateral tibial plateau: 2 -trochlea: 1–6/8 lesions were isolated -2/8 lesions showed association with high signal in the meniscus without tear.	-N/A	-2/8 lesions showed association with high signal in the meniscus without tear.
Tenforde [6], 2022	-STIR and long-axis T1-weighted MRI -1.5-T scanners	-BME was defined according to the modified MRI grading system proposed by Fredericson and Arendt.	-Preseason MRI showed BME in 7 metatarsals from 5 of the 16 participants. -Grade 1 BME: 3 -Grade 2 BME: 2 -Grade 3 BME: 2	-Postseason MRI showed metatarsal BME in 6 of 13 participants -4 participants had persistent BME -2 participants developed de-novo BME -Of the 4 participants with 4 preseason metatarsal BME: -MRI BME grade improved in 1, worsened in 1, and was stable in 2.	-N/A
Varkas [7], 2018	-T1-weighted turbo spin echo and STIR -1.5 T scanners	-BME defined according to the SPARCC grading system.	-At baseline, 9/22 of the recruits had SPARCC score of ≥ 1 in the sacroiliac joint	-After 6 weeks, 11/22 of the recruits presented with a SPARCC score ≥ 1 in the sacroiliac joint	-N/A
Yao [17], 2021	-T1-weighted MRI, FS-T2-weighted MRI, FS-PDWI -1.5 T scanners	-BME signal intensity was defined according to a grading scale adopted from Lazzarini et al.	-MRI showed BME in 12/183 ankles -Grade 0 BME: 171 -Grade 1 BME: 4 -Grade 2 BME: 6 -Grade 3 BME: 2	-N/A	-N/A
Abbreviations: Bone marrow edema (BME), Proton-density-fat-saturated (PD-FS), turbo inversion recovery magnitude (TIRM), sampling perfection with application-optimized contrasts by using different flip angle evolution (SPACE), short tau inversion recovery (STIR), Fat-suppressed Proton Density-weighted Imaging (FS-PDWI), Scoring hip osteoarthritis with MRI (SHOMRI), Bone Marrow Edema (BME), Spondyloarthritis Research Consortium of Canada (SPARCC), and Degenerative Joint Disease (DJD).					

Discussion

To the best of our knowledge, this represents the first systematic review to report on the MRI signal characteristics, relevant MRI classification systems, and natural history of asymptomatic bone marrow edema (aBME). Our goal was to provide a unifying definition of aBME as it relates to the specific MRI characteristics that distinguish it from a true pathological process and what happens with these areas of bone edema over time with continued athletic or military duty participation. Additionally, our aim was to determine significant sport-specific and demographic factors associated with the aBME observed and whether these lesions become symptomatic over time. We were able to determine that asymptomatic BME (aBME) is highly prevalent and radiographically dynamic in the lower extremities of athletes and military recruits. The existing literature frequently presents these MRI findings in the presence of associated pathologic abnormalities (i. e. cartilage injury), but in cases of asymptomatic patients the literature falls short of providing adequate qualitative descrip-

tions of the signal characteristics or pattern on MRI. Currently available studies imply that these lesions remain asymptomatic despite continued high-impact activity.

We observed that the majority of studies defined aBME as increased signal on T2-weighted and STIR sequences, with some reports noting additional findings or decreased signal on T1-weighted sequences without a linear pattern. Importantly, no studies clearly described the signal in terms of qualitative characteristics (e. g. ill-defined signal, no clear margins, etc.) and the location within the bone (subchondral, intracortical or trabecular). Studies also utilized different scanners and validated MRI grading systems to categorize the aBME lesions observed in their cohort, suggesting lack of consensus regarding this radiographic entity. Notably, only three studies utilized 3.0 T scanners to detect aBME, with the remainder using 1.5 T scanners, and one study also used 0.5 T scanners. Notably, all the studies discussed aBME on MRI qualitatively, which is inherently subjective. Future directions should focus on

► **Table 3** Radiographic findings after follow-up period.

Author, Year	Radiographic Findings
Bezuglov [18], 2021	N/A
Hadid [19], 2014	Bone stress changes were seen in 35 of 55 recruits in 26 recruits at time 0 and in nine recruits after basic training. The size of the lesion at time 0 demonstrated a significant relationship with its advancement. The majority of BME findings less than 100 mm resolved or did not change, whereas the majority of BME findings greater than 100 mm advanced.
Horga [20], 2021	There were 2 cases out of 21 who competed the marathon with a small area of bone marrow edema appearance in the femoral heads: 1 progressed from a grade of 0 to 2, and the other progressed from a grade of 1 to 2
Horga [14], 2019	Before the marathon, subchondral bone marrow oedema (BME) was present in 58 knees (41%), of those that went on to finish the marathon, with over half of the lesions in the patella-femoral joint (54%). After the marathon, the patellofemoral joint had the highest number of new/worsened lesions (19 lesions, although of no statistical significance. However, improvement was noted in the medial compartment BME with 10 lesions improved in the tibia and nine lesions improved in the femur. In non-marathon runners, nine out of 22 knees (41%) had BME before training. After training, there were three additional patellar lesions and three other lesions improved.
Kornaat [15], 2014	More than half (58%; 26/45) of the BME lesions fluctuated during the season, with new lesions occurring and other lesions disappearing. None of the lesions were associated with clinical complaints in the elite runners. Therefore, an incidental BME lesion seen on MRI in the asymptomatic athlete did not predict clinical complaints at the conclusion of an intensive running season of 7 months.
Major [16], 2002	N/A
Mandalia [21], 2020	BME was associated with an increased training duration in the regression model.
Tenforde [6], 2022	Preseason MRI demonstrated metatarsal BME in 5 of the 16 participants, and postseason MRI demonstrated metatarsal BME in 4 of the 13 participants. All 4 of the participants with postseason BME had MRI findings of BME in the same metatarsals. Compared to those without BME, participants with metatarsal BME had a shorter history of basketball exposure, and those with postseason BME had started playing at an older age.
Varkas [7], 2018	After 6 weeks of intense standardized physical training the number of military members with BME increased from 9 to 11 members.
Yao [17], 2021	The risk factor for BME-like signal intensity in amateur marathon runners was a rearfoot strike pattern
Abbreviations: Bone marrow edema (BME)	

the use of quantitative MRI techniques such as T2 maps, diffusion-weighted imaging (DWI), or MR fingerprinting to characterize the presence and degree of BME more precisely [4, 23–25]. Furthermore, Foti et al. demonstrated that dual-energy computed tomography (DECT) is another modality that can accurately identify BME when compared to MRI [26].

With respect to classifying bone edema seen, only four of 10 studies used a previously reported classification schema to grade the MRI findings. Importantly, these classification systems were originally designed to describe symptomatic edema with an identifying cause such as bone stress injury and osteoarthritis. Hadid et al. used a grading scale proposed by Fredericson et al. [8], which follows as: Grade 1 (periosteal edema or reaction only), Grade 2 (bone marrow edema on T2-weighted fat-suppressed image), Grade 3 (high signal intensity in the marrow on T2-weighted fat-suppressed images and low signal intensity in the marrow on gradient-echo T1-weighted image) and Grade 4 (fracture line) [19]. Tenforde et al. used a modified scale proposed by Fredericson et al. and Arendt et al. [27] for bone stress injury based on radiographic findings on STIR and T1-weighted imaging, which graded bone stress injury based on the severity of the marrow edema as well as the presence of a fracture line [6]. Yao et al. used the Lazzarini scale [11] to determine the severity of BME, and it is the only grading system that we found to describe BME without being fundamentally based on an associated pathologic process. Grade was determined by the percentage of bone with high signal intensity [17]. Varkas et al. used a grading system that is specific to the sacroiliac joint, SPARCC. In that grading system, six

continuous planes displaying the synovial joint are selected; the sacroiliac joint is divided into four quadrants, and points are assigned based on the presence of high signal intensity and depth of the edema, for a maximum score of 72 [7]. Finally, Horga et al. used the SHOMRI grading system, which is designed to classify osteoarthritis, although there is a subcategory for BME that grades BME based on size [20]. Overall, there was limited evidence to suggest that aBME can be found in this population in the absence of additional and possibly pathological MRI findings.

Despite the different grading systems, the studies reviewed suggest that aBME is present in a substantial portion of the athletic and military population at baseline. In the athlete population, aBME was present in 37.9% of participants, and in the military population, aBME was present in 45.5% of participants. In the follow-up MRI screenings only, the study by Hadid et al. suggested a clinically significant pattern for progression of the BME. They reported that any BME less than 100 mm did not progress in their subjects [19]. The variability seen within studies would suggest that there does not appear to be a predictable course for these areas of aBME that locations and characteristics can change throughout a training period or competitive season.

Importantly, in those studies that followed MRI scans longitudinally, study duration was typically one year and reportedly only four participants (0.9%) developed symptoms despite resolution or progression of bone marrow edema. So it can be inferred that athletic individuals can continue participation with low risk and not be restricted with respect to activities in the shorter term of a sea-

son or year. Despite being only discussed by one study [17], it is worth noting the impact that biomechanics, such as foot strike pattern, may have on BME-like MRI signals. Specifically, a non-rearfoot strike pattern is implicated in a lower ground reaction force compared to a rearfoot strike pattern, and therefore may be associated with less repetitive pressure injury to the ankle joint [17, 28]. On MRI, this may translate to less BME signal being noted, although further research needs to be done to determine the factors that might impact the longer-term clinical trajectory and radiographic changes associated with aBME areas.

Limitations

Our study has several limitations. Firstly, due to the heterogeneous nature of the data and the few numbers of studies that met our inclusion and exclusion criteria, we were unable to perform a meta-analysis. Second, the included articles had moderate and weak levels of evidence with an average JBI score of 7.4 and a standard deviation of 1.43, which is related to the fact that most of the studies were cohort or case series lacking any control groups. In addition, most of the studies contained only small sample sizes with unaccounted confounding factors such as age, diet, and amount of training. Nonetheless, there is still a very small database for aBME studies in athletes and military recruits that provides useful prevalence and location data, which is the reason we decided to include these studies. Finally, MRI reporting involves a certain level of bias that could impact the reliability of the studies included.

Conclusion

In conclusion, asymptomatic BME (aBME) is a painless buildup of excessive fluid in associated bone marrow structures that is highly prevalent and radiographically dynamic in high-level athletes and military trainees in the lower extremities. These aBME areas may represent a metabolic, physiological footprint of sorts, representing the unique forces distributed about the bone in certain sports and military disciplines and the bone's reaction to them. However, the available literature lacks sufficient qualitative descriptions of the MRI findings and frequently describes them in the presence of potentially pathologic findings (i. e. cartilage injury). Available longitudinal studies suggest that these lesions remain asymptomatic during high-level performance but are limited to one year of follow-up. Clinicians can use this data to reassure patients that in the short term they can continue the same level of activity without concern for the development of worsening MRI findings or clinical symptoms. Future studies should seek to provide more detailed descriptions of aBME imaging characteristics, include quantitative imaging techniques, and exclude subjects with bone marrow edema found in the setting of concomitant and potentially confounding pathologies.

Conflict of Interest

The authors declare that they have no conflict of interest.

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