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Imaging Modality Selection for Stress Fractures in Athletes: A Narrative Review

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ABSTRACT

Introduction. Bone stress injuries are common overuse injuries in athletes. Five imaging modalities are used – radiography, MRI, computed tomography, bone scintigraphy and ultrasound – and although MRI is regarded as the reference standard, no modality performs optimally at every anatomic site.

Aim. To synthesise evidence from 2016–2026 on the diagnostic performance and site-specific imaging recommendations for bone stress injury in athletes, and to determine whether a single imaging algorithm is adequate across the skeleton.

Material and methods. Narrative review. PubMed/MEDLINE and Google Scholar were searched (January 2016–September 2026, English language, case reports included); 45 references were included.

Results. MRI offers the highest sensitivity and specificity and the only well-validated severity grading, whereas radiography is poorly sensitive early. This hierarchy holds at most, but not all, sites. In the tibia and femoral neck, compression- versus tension-side location changes management independent of imaging grade. At the pars interarticularis the algorithm is inverted, with MRI preferred over radiography first-line. Site-specific grading systems show inconsistent prognostic value, and expert consensus cautions against using them in isolation. Evidence is uneven: for the pars, sacrum, ribs and upper extremity it is scarce or limited to case series, and several findings rest on single studies.

Conclusions. No single modality or algorithm is adequate across the skeleton. Radiography is a reasonable starting point at most sites and MRI the closest reference standard, but key decisions depend on site-specific evidence. Site-by-site reasoning should replace a universal rule; future work should standardise site-specific grading tools.

Key words: bone stress injury; stress fracture; magnetic resonance imaging; diagnostic imaging; athletes; sports medicine; radiography; return to sport

1. Introduction

Bone stress injuries (BSIs) remain among the most common overuse injuries in athletes. Presentation is often insidious and nonspecific, with symptoms that can mimic a range of other musculoskeletal complaints, and delayed diagnosis can prolong time away from sport and increase the risk of progression to complete fracture.[1,2] Therefore imaging plays a central role in confirming clinical suspicion and guiding management.

Most of these injuries are not, strictly speaking, "stress fractures" - a term that technically applies only when a visible fracture line is present. The majority instead represent an earlier-stage stress reaction, a distinction that matters clinically since it affects prognosis.[3] Recognising this, a 2025 international Delphi consensus of sports medicine experts chose "bone stress injury" as the preferred umbrella term, and this review adopts that terminology throughout.[4]

BSIs are conventionally described as a continuum ranging from early stress reactions to complete cortical fracture,[1,5] developing when repetitive mechanical loading outpaces bone's capacity for remodelling and microdamage accumulates faster than it can be repaired.[1,5] Unlike acute traumatic fractures, this process unfolds gradually, which frequently delays clinical recognition.[1]

These injuries impose a substantial burden in endurance and impact sports, with cross-country running, track and field, and military training among the most affected populations.[1,5] In cross-country, track and field and other running athletes, BSIs account for an estimated 15-20% of all musculoskeletal injuries.[5] Most occur in the lower extremity, where the tibia (approximately 49% of cases) and tarsal bones (approximately 25%) are the most commonly affected sites in endurance runners, though the precise distribution shifts with each sport's loading pattern — for example, the lumbar spine predominates in gymnasts and cricket fast bowlers, and the ribs in rowers.[1,5] This burden is not evenly distributed: female athletes sustain BSIs 1.8-2.3 times more often than male athletes,[1] and incidence appears to be rising, particularly among adolescents.[1,6]

Risk factors are conventionally divided into extrinsic contributors, such as training load, surface, and footwear, and intrinsic contributors, including bone mineral density, alignment, and hormonal status.[7] More recent work situates bone stress injury risk within the broader framework of Relative Energy Deficiency in Sport (REDs), a consensus model recognising chronic low energy availability as a distinct contributor to impaired bone health.[8] Supporting this, a systematic review found that athletes with low energy availability had significantly higher rates of bone stress injury across most included studies.[9]

Diagnosis is achieved through a combination of history, physical examination, and imaging used to confirm clinical suspicion.[1,2] Five modalities are in current clinical use: conventional radiography, magnetic resonance imaging (MRI), computed tomography (CT), nuclear bone scintigraphy, and diagnostic ultrasound. These differ considerably in sensitivity, specificity, radiation exposure, cost, and accessibility, and while MRI is generally regarded as the reference standard, no single modality performs optimally across every anatomic site or clinical context.[2,7]

The aim of this narrative review is to provide an updated, site-based synthesis of the evidence published between 2016 and 2026, specifically to: (1) describe BSIs and their epidemiology and risk factors in athletes; (2) compare the diagnostic performance of currently available imaging modalities; (3) evaluate the practical and clinical factors relevant to each modality; (4) map these considerations onto individual anatomic sites; and (5) identify emerging imaging technologies and persistent gaps in the literature.

2. Diagnostic Performance of Imaging Modalities

The five modalities introduced above differ in sensitivity and specificity, how early each becomes positive relative to symptom onset, and their capacity to grade injury severity. Much of the pooled accuracy data below is drawn from lower extremity specific literature, reflecting both where these injuries are concentrated and where the evidence base is strongest; site-specific application beyond the lower extremity is addressed later in this review. Each modality is examined in turn below.

2.1 Conventional Radiography

Radiography's principal weakness is poor early sensitivity: 12%-56% against specificity of 88%-96%, with 60%-82% of radiographs negative at initial presentation and 46%-60% still negative on follow-up.[10,11] Sensitivity has been reported as low as 10%, at initial presentation.[7] By two weeks, sensitivity improves to roughly 40-50%,[12] but this reflects periosteal reaction and cortical thickening, reactive bone changes rather than a fracture itself. An actual fracture line is a distinct, later finding, appearing only in the minority of injuries that progress to a structural break; even then, it is often not visible on radiograph until four weeks or more after symptom onset.[12] This lag likely reflects the modality's dependence on structural, rather than functional, change: findings such as cortical thickening or sclerosis require the bone's remodelling response to be underway, not merely triggered.[7] Because of this lag, a normal radiograph cannot exclude a stress fracture, and persistent clinical suspicion warrants progression to MRI.[7,10,11]

2.2 Magnetic Resonance Imaging

MRI is the reference standard for stress fracture diagnosis, recommended when radiographs, discussed above, are negative but clinical suspicion persists.[7,13] Reported sensitivity ranges from 68% to 99% and specificity from 4% to 97%, a wide spread reflecting the heterogeneity of the underlying primary studies.[10] This combination of high sensitivity and specificity relative to the other modalities is echoed independently in more recent literature.[14] Fluid-sensitive sequences depict marrow and soft-tissue oedema at the earliest stage of injury, the property underlying MRI's high early sensitivity, while T1-weighted sequences can later show a discrete fracture line.[2,5] This staged appearance supports MRI-based grading systems: the widely used Fredericson classification progresses from periosteal oedema alone (grade 1), to periosteal and marrow oedema visible on fluid-sensitive sequences only (grade 2), to marrow oedema visible on both fluid-sensitive and T1-weighted sequences, indicating more extensive injury (grade 3), and finally to a visible fracture line (grade 4).[12] This staging carries real clinical weight: a meta-analysis of 560 injuries found higher MRI grade associated with longer return-to-sport time, from a mean of 41.7 days at grade 1 to 98.5 days at grade 4.[15] MRI is not without limitations, however: marrow oedema of uncertain significance has been reported in asymptomatic athletes, risking over-diagnosis when the modality is used without adequate clinical suspicion,[14] and cortical bone has traditionally been difficult to visualise on MRI due to its low proton density and short signal relaxation times,[16] a limitation for which specialised sequences are being investigated as a potential solution, discussed further below.

2.3 Bone Scintigraphy

Bone scintigraphy was historically the diagnostic gold standard on the strength of its high sensitivity, detecting increased osteoblastic activity days to weeks before radiographic change appears, and can identify both early stress reactions and established fractures.[10,12] Reported accuracy varies by study design. A single study, with an emphasis on the foot, reported sensitivity, specificity, and overall accuracy of 92.9%, 73.8%, and 83.3% respectively.[12] Across the broader literature, a systematic review found sensitivity ranging from 50% to 97% and specificity from 33% to 98%, with the lower end of the specificity range representing scintigraphy's persistent weakness.[10] Tracer uptake indicates bone turnover generally, not stress injury specifically. Any process that increases turnover, including infection, tumours such as osteoid osteoma, or other bone pathology, can also produce a positive scan, contributing to false-positive readings.[7,11,12] Combining planar scintigraphy with SPECT or SPECT/CT improves diagnostic accuracy over planar imaging alone, though even this refinement has not closed the gap with MRI's combination of high sensitivity and specificity.[12] With growing preference for MRI, scintigraphy's routine diagnostic role has narrowed, though it retains niche utility in settings where MRI is unavailable.[12,14]

2.4 Computed Tomography

CT cannot depict bone marrow oedema, the earliest imaging finding in bone stress injury, and is often uninformative in the first two weeks after symptom onset. A systematic review of multiple studies reported sensitivity as low as 32% to 38%, against a comparatively high specificity of 88% to 98%.[10] This reflects CT's underlying imaging mechanism: unlike MRI, its contrast depends on X-ray attenuation rather than tissue proton behaviour, making it comparatively insensitive to early marrow change but well suited to depicting the dense, calcified structure of cortical bone once it has been physically disrupted.[16] As a result, once sufficient time has passed, typically beyond two weeks, CT becomes informative through cortical disruption, periosteal reaction, and endosteal callus formation, and can outperform MRI for visualising longitudinal cortical fracture lines.[7,12] As with radiography, CT lacks a severity-grading system with the clinical validation of MRI's Fredericson classification. Because of this limited early utility and its associated radiation exposure, current clinical guidance classifies CT as usually not appropriate for initial imaging of suspected stress injury.[12-14] In practice, CT is best understood as a targeted, confirmatory study used once other findings raise suspicion, rather than a first-line or general-purpose modality.

2.5 Diagnostic Ultrasound

Ultrasound identifies indirect signs of stress injury, including periosteal elevation, cortical disruption, and soft-tissue oedema, with power Doppler used to assess vascularity as a marker of injury acuity.[17] Because these vascular and periosteal changes reflect the earliest inflammatory response to bone injury, ultrasound may detect abnormalities within the first week after symptom onset.[17] Sensitivity has been reported from 43% to 99% and specificity from 13% to 79%,[10] a similarly wide range restated in a review of the ultrasound literature.[17] The modality's central limitation is structural rather than statistical: because sound waves cannot penetrate cortical bone, ultrasound can only assess the bone surface and surrounding soft tissue, and is unable to assess deeper structures such as bone marrow oedema. The direct evidence base for bone stress injury specifically also remains modest in scale relative to the other modalities discussed here: a dedicated systematic review for this population drew on 119 participants across eight studies, and a direct comparison against MRI involved 37 patients.[18,19] Serial ultrasound has instead shown promise in a monitoring role distinct from primary diagnosis, tracking the healing trajectory of bone stress injury and correlating sonographic findings, notably hyperaemia, with pain and return to sport in a small cohort of 30 patients.[20]

2.6 Summary

No single modality is superior across every context, and even MRI, the strongest performer, carries a real risk of over-diagnosis without adequate clinical suspicion. Radiography and CT are poorly sensitive early in the disease course, and neither has a validated severity-grading system comparable to MRI's; scintigraphy is highly sensitive but nonspecific; ultrasound may detect change early, but is structurally unable to assess deeper bone and rests on a comparatively modest evidence base; and MRI combines the strongest overall sensitivity and specificity with the only well-validated capacity to grade severity. The practical and clinical factors underlying these trade-offs, and how they combine with site-dependent evidence to guide modality selection, are addressed in the sections that follow.

3. Practical Clinical Factors

Where two or more modalities offer comparable diagnostic value, the choice of which to use in practice is often determined not by accuracy alone but by cost, radiation exposure, accessibility, and turnaround time. Radiation exposure deserves particular attention here, since a large share of athletes are young adults or adolescents, and radiation accumulated from medical imaging earlier in life carries greater long-term cancer risk.[21,22] Combined with the frequent need for serial imaging to monitor healing, this makes radiation dose a clinically relevant consideration in this population.[13]

3.1 Conventional Radiography

Among the three modalities that involve ionising radiation, radiography carries by far the lowest dose: reference dosimetry places a typical knee radiograph at approximately 0.005 mSv, several orders of magnitude below a full-region CT scan or bone scintigraphy.[11] It is also inexpensive and widely accessible,[6,14] available in most clinical settings, and typically provides same-day results. This combination of low cost, minimal radiation, and wide accessibility underlies its consistent recommendation as the first-line study for suspected stress fracture across multiple sources, despite its limited diagnostic sensitivity.[10,13,23]

3.2 Magnetic Resonance Imaging

MRI involves no ionising radiation, which is a meaningful advantage for repeated imaging. Despite substantial growth in extremity MRI use in recent decades, its cost and relatively limited accessibility remain the primary reasons why it is often not performed first in clinical practice — even for injuries it depicts optimally. This pattern is reported even in countries with a comparatively large number of MRI scanners.[23] Acquisition times are also longer than for radiography or CT, meaning MRI is more commonly scheduled in advance than performed as an immediate, same-visit study. MRI is generally among the most expensive of the five modalities discussed here,[17,23] a factor that compounds its more limited accessibility outside well-resourced or tertiary settings.

3.3 Bone Scintigraphy

Unlike radiography or CT, which are typically confined to the region of clinical concern, bone scintigraphy involves systemic radiotracer uptake and generally images the entire skeleton in a single study; reference dosimetry reports an effective dose of approximately 6.3 mSv for a standard technetium-99m bone scan.[11] Access is more limited than for radiography, CT, or

ultrasound, since scintigraphy requires a nuclear medicine facility and radiopharmaceutical handling. Despite this infrastructure requirement, it is generally less expensive than MRI, which partly explains its continued use in settings where MRI access is constrained. Its turnaround is inherently slower: a three-phase scan takes approximately three to four hours to complete.[11]

3.4 Computed Tomography

CT also involves ionising radiation, but unlike radiography or bone scintigraphy, its dose varies substantially depending on the body region scanned, with reported effective doses generally ranging from approximately 2 to 8 mSv depending on the area imaged.[6] Because stress fracture imaging is typically confined to the symptomatic region rather than the whole body, the radiation cost of a given CT study depends heavily on which anatomic site is being evaluated — smaller peripheral sites generally carrying a substantially lower dose than central or axial regions such as the pelvis or spine, a distinction addressed further when individual sites are discussed. Cost and accessibility are generally intermediate: CT is widely available in hospital-based settings but less so in outpatient sports-medicine clinics. The scan itself is rapid, but access in non-emergency settings typically requires scheduling and physician referral rather than point-of-care use.

3.5 Diagnostic Ultrasound

Ultrasound shares MRI's advantage of using no ionising radiation, while being, in most settings, among the least expensive and most portable of the five modalities.[6] It can be performed point-of-care, including in field-side or training settings, without the need for a dedicated imaging suite. Its diagnostic use is nonetheless fundamentally constrained by what it can physically visualise: ultrasound cannot assess structures deep to the bone cortex, such as bone marrow oedema, meaning injuries confined to deeper or subcortical bone may go undetected.[6] Beyond this structural limitation, image quality and interpretation are also operator-dependent, with inter-sonographer variability and a steep learning curve for clinicians.[6]

3.6 Summary

Taken together, radiation exposure, accessibility, and turnaround time divide the five modalities into three practical tiers. MRI and ultrasound involve no ionising radiation at all,

but differ sharply in cost, accessibility, and turnaround: ultrasound is the more affordable, portable, and immediate of the two, while MRI is among the most expensive modalities and is typically scheduled rather than performed same-visit. Radiography carries a very low but nonzero radiation dose and remains the cheapest, most accessible, and fastest modality, providing same-day results in most clinical settings. CT and bone scintigraphy carry the greatest radiation burden of the five, though their turnaround differs sharply: the CT scan itself is rapid, with its dose depending heavily on the region scanned, but non-emergency access typically requires scheduling and physician referral; scintigraphy is inherently the slower of the two, requiring several hours to complete and a dedicated nuclear medicine facility regardless of the site of injury. These practical trade-offs do not operate independently of the diagnostic-accuracy patterns described earlier: a modality that is cheap and accessible is of limited value if it is insensitive at the site in question, and vice versa. How accuracy and practicality combine to favour a particular modality at a particular anatomic site is addressed next.

4. Site-Based Modality Recommendations

Diagnostic accuracy and practical factors do not apply uniformly across the skeleton; each site's underlying anatomy, vascular supply, and functional demands shape which modality performs best there. Bone stress injury can occur at many different locations, and this section does not attempt to cover all of them; instead, it focuses on those most commonly encountered in clinical practice, with rarer ones addressed together in a final, combined section. The tibia is consistently the most common site, accounting for an estimated 19-54% of total injuries by anatomical distribution,[6] a range that includes the 49% reported among endurance runners in the Introduction. Among runners, the tarsal bones, metatarsals and femur follow the tibia in frequency,[2,7] while the lumbar spine predominates in some sports, such as gymnastics and cricket fast bowling.[1,5] Anatomical site also predicts prognosis: a meta-analysis of 76 studies found that the femoral neck, anterior tibial shaft and tarsal navicular were associated with increased complication rates and longer return-to-sport timelines.[24] This variation in risk by location is one reason accurate, timely imaging matters more in some cases than others, a distinction developed further below.

4.1 Tibia

The tibia is not a single homogeneous site: injury to the posteromedial (compression-side) cortex behaves very differently from injury to the anterior (tension-side) cortex. The posteromedial pattern is associated with a comparatively short mean return-to-sport time of 44 days (95% CI 27-61 days), while the anterior pattern is associated with some of the highest treatment complication rates of any site in the body.[4,24] MRI is the most practical way to distinguish these two patterns soon after presentation, given its established early sensitivity to marrow and periosteal change relative to radiography, discussed above.[13] Radiography's sensitivity at the tibia scales closely with underlying injury severity rather than being reliable at any single stage: in one military cohort, the proportion of patients with a positive radiograph rose from 4% at the mildest injury grade to 100% at the most severe, meaning radiography only becomes dependable once the injury has already progressed substantially.[25] CT may offer an advantage over MRI for the less common longitudinal stress fracture, a subtype particularly prone to being missed: one study reported CT sensitivity of 82% against 73% for MRI, and this preference has also been noted in a subsequent review.[6,26] Ultrasound also has a role, though a limited one: because it depends on superficial access, its evidence base and clinical utility are concentrated at the distal tibia rather than more proximal or deeper regions.[17] Taken together, MRI remains the preferred modality at the tibia primarily for its ability to characterise the anterior-versus-posteromedial distinction early and reliably. CT can be a useful adjunct when a longitudinal fracture pattern is suspected, radiography's reliability depends heavily on how far the injury has already progressed, and ultrasound's role remains largely limited to superficial sites such as the distal tibia.

4.2 Tarsal Bones

Stress injury is not distributed evenly across the seven tarsal bones (the talus, calcaneus, navicular, cuboid, and three cuneiforms). The navicular is among the most commonly affected, with estimates of up to 35% of all foot and ankle stress fractures, and correspondingly receives most of the clinical and research attention in this category.[27] Its presentation is often vague, and radiography performs particularly poorly here, missing the fracture in as many as 66% of cases.[27,28] This combination carries a real cost: in a multicentre adolescent cohort, 44% of patients were not diagnosed until they had already developed a visible fracture line, the most severe stage on MRI, rather than being identified earlier while still at the more treatable stress-reaction stage.[29] Reflecting this severity, the navicular carries the longest mean return-to-sport time of any site in a cross-site meta-analysis, 127 days (95%

CI 102-151 days).[24] Bone scintigraphy offers high sensitivity but poor specificity here as elsewhere, while MRI is considered the benchmark, better able to detect early oedema and medullary extension than CT.[27] The stakes of this distinction are reflected in outcomes: a meta-analysis of 315 fractures found operative management achieved a higher 97.9% success rate against 78.1% for conservative management, although the return-to-play rate did not differ significantly.[30] Once a fracture is confirmed, CT remains useful for characterising the fracture pattern and guiding surgical planning.[27] Beyond the navicular, the calcaneus stands out as a genuinely frequent site, ranking as the second most common foot stress fracture in men and the most common in women in one military cohort, most often affecting the posterior calcaneus; as with the navicular, radiographs are often negative and MRI is the primary diagnostic tool.[28] The talus, by contrast, is seen far less often, typically involving the talar head, and a positive finding here frequently coincides with a fracture at an adjacent bone, the calcaneus or navicular.[28] The cuboid and cuneiforms are documented only in isolated case reports; at the cuboid, radiographs are often negative and CT has a helpful diagnostic role.[28]

4.3 Metatarsals

Metatarsal stress injury accounts for a substantial share of lower-limb stress fractures overall, with the second and third metatarsals most commonly affected.[28] As at most sites, radiography performs poorly early in the disease course, and MRI is considered the reference standard, with radiographs often falsely negative.[28] The fifth metatarsal deserves separate attention: unlike the second and third metatarsals, its proximal portion carries a genuine risk of delayed union, attributed to a comparatively vulnerable blood supply at the metaphyseal-diaphyseal junction, and its base is independently recognised as a high-risk site in clinical practice guidelines.[4,13,31] The widely used Lawrence-Botte classification divides fifth metatarsal fractures into three zones by location: (1) the tuberosity, typically an avulsion injury; (2) the metaphyseal-diaphyseal junction, the classic Jones fracture; and (3) the proximal diaphysis, where genuine stress fractures occur. This zonal distinction carries real treatment implications, since management strategies differ significantly by zone.[31] Interobserver reliability of the overall zonal system, which mixes these acute and stress-type patterns, has been reported as only moderate, and at least one newer classification has been proposed with improved reliability.[31] Clinically, plain radiographs remain the first-line study even at the fifth metatarsal, though MRI can visualise much more subtle findings, such as early periosteal and marrow change, and is used when radiographic findings are equivocal or

clinical suspicion remains high.[31] Because metatarsal injuries occur at a relatively superficial, accessible site, ultrasound has also shown promising diagnostic accuracy here: a small prospective cohort (37 patients) comparing ultrasound directly against MRI, with most patients injured at the metatarsal or tibia, found 80% sensitivity and 71% specificity.[19]

4.4 Femoral Neck

Femoral neck stress injury represents up to 7% of all stress fractures,[13] yet carries some of the highest stakes of any site: a meta-analysis found it among the sites with disproportionately high complication rates and a mean return-to-sport time of 107 days (95% CI 79-135 days), more than double that of the tibia's posteromedial cortex.[24] Location on the femoral neck itself determines this risk: lateral, tension-type fractures are inherently unstable and prone to displacement, while medial, compression-type fractures are comparatively low-risk.[13] The Delphi consensus likewise classified the superior (tension side) cortex of the femoral neck as high-risk.[4] Radiographs are frequently unhelpful, with 90% of initial films negative and half still negative on repeat imaging four to six weeks later.[32] Bone scintigraphy offers high sensitivity here too, reported at 93% to 100%, with specificity of 76% to 95% and a false-positive rate as high as 32%; now that MRI is widely available, bone scintigraphy has become a largely historical tool at this site.[32] In one retrospective study, CT and MRI performed comparably when used alone, but combining both modalities significantly improved detection over either alone, though this specific finding has not been independently replicated.[33] MRI is now considered the benchmark at the femoral neck, and its value extends beyond detection into prognosis: the Rohena-Quinquilla grading system developed specifically for this site distinguishes low-grade injury, limited to endosteal marrow oedema without a visible fracture, from high-grade injury, where a macroscopic fracture line spans much of the femoral neck's width, and the presence of a hip effusion on initial MRI has been associated with an eightfold higher risk of fracture progression and subsequent surgery in fractures with a fracture line under 50% of the neck width.[32]

4.5 Pars Interarticularis

Unlike most sites discussed in this review, radiography is not recommended as the first-line study at the pars interarticularis. The earliest stage of injury involves marrow oedema alone, before any structural change to the bone, meaning it can be occult not only on radiographs but even on CT; on this basis, at least one systematic review has explicitly recommended that radiography be discouraged in favour of MRI as the first-line investigation.[34] In these

comparative studies, CT or SPECT-CT was used as the reference standard against which MRI's own accuracy was measured, rather than a symmetric comparison of both modalities: MRI's sensitivity against CT was reported at 97-98%,[34,35] and against SPECT-CT at 80-88%,[34] with specificity generally exceeding 90%. One included review noted that MRI performed comparably to CT for fully formed fractures specifically, while offering additional insight during follow-up, since marrow oedema on MRI can indicate ongoing healing even once the cortical bone itself appears intact on CT.[34] SPECT-CT's own reliability as a reference standard has been questioned, since abnormal tracer uptake has been reported at asymptomatic, non-painful sites in 34-45% of athletes, reflecting normal bone turnover rather than injury.[34] A large cohort of 902 patients also found that 9.1% of injuries involved the upper lumbar spine (at or above L3), a notably higher proportion than previously reported, suggesting imaging protocols should not be anchored solely to the traditionally assumed lower-lumbar predominance.[36]

4.6 Other Sites: Sacrum, Ribs, and Upper Extremity

Sacrum. Radiography has low sensitivity at the sacrum, and current guidelines recommend MRI or CT over bone scintigraphy once the initial radiograph is negative.[13] Bone scintigraphy does have one distinctive, named finding here: the "Honda" or "H" sign, which carries a strong 94% positive predictive value when present, but is only seen in 63% of confirmed sacral insufficiency fractures, meaning its absence cannot exclude a fracture.[13] MRI is generally considered the gold standard, though not infallible: one systematic review noted it missed the fracture in a small number of reviewed cases.[37] Ultrasound has a narrower, more specific role than at other sites, with some evidence supporting its use specifically for visualising posterior sacral fractures, without the radiation exposure of CT or bone scintigraphy, although the guideline rates it as usually not appropriate and cautions against delaying definitive diagnosis.[13] A dedicated MRI-based grading system, the Bakker classification, exists for this site, though one case series of 13 athletes found good return-to-sport outcomes with nonoperative management even among higher-grade fractures, leading its authors to caution against using this classification as the sole basis for surgical decision-making.[38]

Ribs. Rib stress injury, particularly of the first rib, is frequently underrecognised, and radiographs are often falsely negative early in the disease course. A practical imaging detail is worth noting here: a standard shoulder radiograph visualises only 46% of the first rib,

compared with 97% on a cervical spine radiograph, meaning the choice of radiographic view, not just the choice of modality, materially affects diagnostic yield at this site.[39] MRI remains the sensitive standard beyond radiography, though it can only capture the anatomy at rest. A single case report has also explored dynamic ultrasound, performed during active movement rather than at rest, as a complementary tool for characterising the functional mechanics of rib stress injury.[40]

Upper Extremity. Stress injury of the upper extremity follows a broadly similar diagnostic pattern to the rest of the skeleton, but rests on a comparatively thin quantitative evidence base overall. Return-to-sport decisions here should not be based on elapsed time alone; current guidance recommends a multidimensional assessment incorporating imaging findings alongside symptoms and functional testing.[41]

4.7 Summary

Table 1 consolidates the recommended first-line study and preferred definitive modality, together with the key clinical consideration driving that choice, for each anatomic site discussed in this section. Radiography is the recommended first-line study almost everywhere, and MRI the preferred definitive modality at nearly every site, but the pars interarticularis and the tibial longitudinal fracture subtype are notable exceptions: at the former, radiography is actively discouraged, and at the latter, CT retains a supporting role. The rationale and evidence behind each entry, along with its limitations, are set out in the corresponding subsection above.

Table 1. Site-specific imaging modality recommendations for bone stress injury

Anatomic Site	Recommended First-Line Study	Preferred Definitive Modality	Key Clinical Consideration
Tibia – posteromedial cortex	Radiography	MRI	Low risk pattern; short return-to-sport time
Tibia – anterior cortex	Radiography	MRI	High-risk pattern; among the highest complication rates of any site

Tibia – longitudinal fracture subtype	Radiography	MRI, with CT as a possible adjunct	CT preference rests on a single older study; evidence limited
Navicular	Radiography	MRI	High-risk; 66% radiographic miss rate; delay linked to worse-grade presentation at diagnosis
Calcaneus	Radiography	MRI	Genuinely common (2nd most frequent in men, most frequent in women); radiographs often negative
Talus, cuboid, cuneiforms	Radiography	No established preference (CT noted as helpful at cuboid)	Rare; talar injury often co-occurs with calcaneal or navicular fracture
Metatarsals (2nd/3rd, typical shaft)	Radiography	MRI (reference standard); ultrasound shows reasonable accuracy	Radiographs often falsely negative
Metatarsals (5th, Jones-type)	Radiography	MRI for complex/equivocal cases	Zone-dependent risk of nonunion (Lawrence-Botte classification)
Femoral neck — tension-side	Radiography	MRI	Unstable, high-risk pattern
Femoral neck — compression-side	Radiography	MRI	Comparatively low-risk pattern

Femoral neck (general)	Radiography (90% initially negative)	MRI	Hip effusion on MRI associated with 8-fold higher risk of fracture progression and surgery (fracture line <50% of neck width); bone scan now largely historical
Pars interarticularis	MRI (radiography discouraged)	MRI	Early oedema-only stage occult on both radiography and CT; radiation avoidance prioritised in this young population
Sacrum	Radiography (low sensitivity)	MRI	Honda sign on bone scan has strong PPV (94%) but limited sensitivity (63%); ultrasound useful for posterior fractures specifically
Ribs (first rib)	Cervical spine radiograph, not shoulder view	MRI	Shoulder view visualises only 46% of the first rib vs. 97% on cervical spine; dynamic ultrasound emerging for functional assessment

Upper extremity (general)	Radiography	MRI	Comparatively thin evidence base; return-to-sport should rest on multidimensional assessment, not imaging alone

Source: Compiled by the authors from the sources cited in Section 4

5. Emerging Imaging Technologies and Persistent Gaps

Several imaging techniques beyond the five modalities discussed above are being explored for bone stress injury, though most remain at an early or investigational stage. High-resolution peripheral quantitative CT and ultrashort echo time MRI allow direct assessment of bone microarchitecture and cortical bone quality, respectively, at peripheral anatomic sites, with potential application to fracture-risk screening in athletes rather than confirmatory diagnosis of an established injury. HR-pQCT in particular remains confined to a handful of specialised centres and has not yet moved into routine clinical use.[42] A different application of CT technology: dual-energy CT, using virtual non-calcium reconstruction, has demonstrated pooled sensitivity of 86% and specificity of 93% for detecting bone marrow oedema across the appendicular skeleton in a meta-analysis of 20 studies and 790 patients, comparable to MRI and potentially addressing CT's traditional inability to depict this early finding; this technique has been validated in general appendicular trauma but not yet directly in bone stress injury specifically.[43] Artificial intelligence, particularly deep learning, has also been applied to radiographs for automated detection and grading of lower-extremity fatigue fractures: one retrospective multicentre study reported detection sensitivity above 90% and performance comparable to experienced radiologists on internal testing, though overall diagnostic accuracy fell substantially on external validation (from 78.5% to 62.9% for the tibia and fibula), underscoring the need for broader, prospective validation before clinical adoption.[44] Both dual-energy and photon-counting CT have separately been identified by an international expert panel as promising future directions for bone stress injury imaging specifically.[4]

Persistent gaps remain alongside these technical advances, and the field has begun to formally address them. Terminology has long been inconsistent, with more than thirty different diagnostic terms identified for overuse injury of a single bone[6]; this is not merely semantic, since only around one in five athletes presenting with a bone stress injury has a true fracture line on imaging, with the remainder representing earlier-stage stress reactions.[3] This problem was explicitly identified as needing resolution,[3] and has since been addressed by a three-part international Delphi consensus involving a panel of over thirty experts and stakeholders, which reached full agreement that classification systems should use consistent terminology and strong majority agreement on the need for a single, unified classification system.[4] The same panel cautioned that wider access to advanced imaging technology carries its own risk of overdiagnosis and misinterpretation of incidental, asymptomatic findings.[4] The underlying evidence base also remains methodologically uneven: a meta-analysis of return-to-sport outcomes pooling 76 studies and nearly 3,000 injuries found the large majority of included studies were retrospective and focused on a single anatomic site, with methodological quality ranging from very low to high.[24] Taken together, the unproven clinical role of the emerging techniques above, and the still-recent efforts to standardise terminology and strengthen the evidence base, represent the principal frontiers for future research in stress fracture imaging.

6. Discussion

Taken as a whole, this review's findings resist reduction to a single algorithm. Radiography remains a reasonable default starting point at nearly every site, and MRI is, with only a handful of genuine exceptions, the closest thing to a universal reference standard. However the details that actually influence clinical decisions, which cortex is involved, how much time has passed, which bone within a cluster of anatomically similar bones is affected, sit entirely in the site-specific evidence reviewed above, not in the general modality comparisons that opened this review. This tension is not unique to the present synthesis: an international Delphi consensus of experts in this field addressed a broadly similar problem, highlighting a lack of agreement on diagnostic approaches, risk factors and management strategies, and reaching a strong agreement (86.2%) on the need for one main classification system.[4]

Grading systems illustrate this problem clearly. This review has discussed at least four site-specific systems in detail: the Fredericson classification at the tibia, the Rohena-Quinquilla

and related systems at the femoral neck, the Bakker classification at the sacrum, and the Lawrence-Botte zonal system at the fifth metatarsal. These are not isolated examples: grading and classification tools have proliferated across the bone stress injury literature without a corresponding consensus on which to prioritise, a pattern that mirrors the terminological fragmentation described earlier.[3] Yet this review's own findings suggest that more systems have not necessarily translated into more reliable prognostic tools. At the tibia, one paediatric cohort found no significant difference in recovery time across Fredericson grades,[45] in tension with the broader pattern established elsewhere[15]; at the sacrum, a case series found favourable outcomes even among higher-grade fractures, leading its authors to explicitly caution against using the Bakker classification as a sole surgical decision-making tool.[38] Grading systems appear most useful when tied to a specific, validated prognostic marker, such as the femoral neck's hip effusion finding, and least reliable when applied as a general severity scale extrapolated across populations or institutions.

The evidence base underlying these recommendations is also markedly uneven across sites, a fact this review has tried not to obscure. Some sites rest on a genuinely substantial foundation: the tibia and femoral neck each draw on multiple, moderately sized studies[6,25,32,33,45] and, in the femoral neck's case, independent corroboration from both a clinical guideline[13] and international expert consensus.[4] Others do not. The pars interarticularis literature was explicitly characterised by its own authors as "scarce and low in quality".[34] The sacrum, ribs, and upper extremity rest substantially on case series and case reports rather than comparative cohorts. And even within better-studied sites, several individual findings, the CT advantage for longitudinal tibial fractures, the benefit of combining CT and MRI at the femoral neck, rest on a single study apiece, with no independent replication identified in the course of this review. None of these findings should be dismissed on that basis alone, but they should be weighted accordingly, and flagged as priorities for future research rather than treated as settled practice.

This unevenness has a direct practical consequence, developed in Section 4: the general radiography-first algorithm established from cost, accessibility, and radiation considerations holds at most sites, but not at all of them. The pars interarticularis represents a genuine inversion of this default, with at least one systematic review explicitly recommending that radiography be discouraged in favour of MRI as the first-line study, given how early in the disease process this site becomes occult even to CT.[34] The navicular and calcaneus,

meanwhile, do not invert the general algorithm outright: current guidelines still list radiography first even at high-risk sites, but the documented cost of delay at these two sites arguably justifies a lower threshold for escalating to MRI than the practical factors discussed in isolation would suggest.[13] These are precisely the exceptions a purely modality-level or purely practicality-level analysis would miss, and precisely why this review adopted a site-based structure rather than stopping at the general comparisons established earlier.

Several limitations of the underlying literature, rather than of this review specifically, are worth stating plainly. Terminology inconsistency, discussed at length in the Introduction, likely affects not only clinical communication but the evidence base itself: studies using older or nonstandard terms for the same underlying pathology may be missed by systematic searches built around newer, preferred nomenclature, and the true evidence base at several sites may therefore be somewhat larger, or somewhat more fragmented, than what this review was able to identify. Population heterogeneity is a related concern; this review encountered genuine, unresolved discrepancies between paediatric, adult, and military cohorts at the same anatomic site, most notably at the tibia, where a paediatric MRI-grading study and a military scintigraphy-grading study reached opposite conclusions about whether grade predicts recovery time. Whether this reflects a true population difference, a modality difference, or simply the play of chance in two individually small studies cannot be resolved from the literature currently available.

This review carries its own limitations as well. As a narrative rather than a systematic review, source selection was not governed by a pre-registered search protocol, and while considerable effort was made to verify every substantive claim against primary text, the possibility of selection bias, toward more accessible, English-language, or more recent literature, cannot be excluded. The 2016-2026 window, while defensible given the pace of change in this field, necessarily excludes foundational older work except where cited for historical attribution or where directly referenced within an included source. Readers should treat the site-specific sections of this review as a current, carefully sourced synthesis, not as a substitute for a formal systematic review or clinical practice guideline.

Looking forward, the emerging technologies discussed earlier in this review, dual-energy and photon-counting CT, HR-pQCT, AI-assisted radiograph interpretation, may eventually help close some of the practical gaps identified at individual sites in Section 4, particularly where CT's radiation burden currently limits its use despite genuine diagnostic value. But technology

alone will not resolve the more fundamental issue this Discussion has raised: the same international consensus process that produced unified BSI terminology could plausibly be extended to imaging pathways themselves, consolidating the proliferation of site-specific grading systems and diagnostic algorithms identified in this review into a smaller number of validated, prospectively tested tools, applied consistently rather than in isolation.

7. Conclusion

Bone stress injuries are a common overuse injury among athletes, disproportionately affecting endurance and military populations and accounting for an estimated 15-20% of musculoskeletal injuries in running athletes. Risk is shaped by extrinsic training factors and intrinsic contributors such as low energy availability, and burden is not evenly distributed by sex or age.

Comparing the five available modalities, MRI combines the highest overall sensitivity and specificity with the only well-validated capacity to grade severity, while radiography remains poorly sensitive early in the disease course, improving only gradually over the following weeks. Ultrasound can detect the early inflammatory changes but is limited to superficial tissues. Scintigraphy and CT each retain narrow, complementary roles.

Beyond diagnostic accuracy, modality choice in practice is shaped by cost, radiation exposure, accessibility, and turnaround time, considerations that carry particular weight given the young, radiation-sensitive population typically affected and the frequent need for serial imaging to monitor healing.

Mapping these general and practical considerations onto individual anatomic sites, however, shows that no single imaging algorithm is adequate across the skeleton. The tibia and femoral neck each carry a location-dependent risk split that changes management independent of imaging grade and the pars interarticularis inverts the general algorithm outright, with radiography explicitly discouraged in favour of MRI as the first-line study.

Emerging technologies like dual-energy and photon-counting CT, HR-pQCT, as well as AI-assisted radiograph interpretation, may change imaging approach in the future. However,

currently the field's most fundamental gaps lie in inconsistent terminology and an evidence base whose methodological quality remains highly uneven.

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