International Delphi consensus on bone stress injuries in athletes

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ABSTRACT

Bone stress injuries, commonly referred to as stress reactions and stress fractures, represent overuse injuries to bone. These injuries result in physical limitations in activity and can be career-ending for high-level athletes. While bone stress injuries have received increased attention in recent years, international consensus is lacking on definitions, risk factors and strategies for management and prevention. This study aimed to ascertain and improve the level of agreement on bone stress injuries by utilising a three-part modified Delphi approach on (1) pathophysiology, diagnosis, terminology and classification systems; (2) risk factors, screening and prevention; and (3) management and return to sport. A multidisciplinary steering committee initiated the consensus process. A panel of 41 members from six continents was formed to complete three rounds of voting, including experts (scientists and clinicians) and representatives (athletes and coaches). Thirty-three, 28 and 28 panel members completed Delphi rounds 1, 2 and 3, respectively. Consensus was reached on 41 out of 58 statements. Findings from this Delphi study outline a multifactorial approach to identify and manage bone stress injuries and to promote bone health in athletes. This includes recommendations for diagnostic workup and treatment to assist clinicians in caring for patients with bone stress injuries. Finally, this consensus process identifies knowledge gaps and provides a framework for future research to advance the clinical care and prevention of bone stress injuries.

INTRODUCTION

Bone is a viscoelastic tissue with a unique ability to withstand applied loads.[1] However, repetitive loading coupled with inadequate time for tissue recovery can result in overuse injuries to bone.[2] The phenotypes of these injuries vary and have collectively been referred to as bone stress injuries.[3]

In recent decades, communal efforts have contributed to an improved understanding of bone stress injuries.[2–7] Large epidemiological studies have shown that bone stress injuries, while infrequent in the general population (<1% of all injuries), are common (up to 20% of sports injuries) in athletes and military personnel who participate in activities involving repetitive impact loading, such as marching, running, jumping and dancing.[6 8] The diagnosis of a bone stress injury is typically made by history and physical examination combined with imaging.[4 9 10] Various risk factors have been described including those related to low energy availability,[11] biomechanics[7 12 13] and training load.[14 15] The management of bone stress injuries is guided by multiple factors such as the anatomical site, injury severity and level of sports participation.[2 4 5] Treatment approaches include activity modification, protected weight-bearing, immobilisation, physical therapy, nutritional counselling and, in some cases, surgical fixation.[2] Even with optimal treatment, bone stress injuries disrupt participation in sports and other physical activities, and full recovery may take many months.[4 5 7] Recognition that multiple risk factors may result in an elevated risk for future bone stress injury has led to interest in prevention strategies including diversifying sports participation during childhood and adolescence, training load management and aspects of nutrition including calcium, vitamin D intake and optimising energy availability.[11 14 16–20]

Prior terminology to describe bone stress injuries such as 'stress reactions,' 'bone marrow oedema syndrome' and 'stress fractures' lacks precision, and the need for universally accepted definitions result from inconsistent reporting measures across studies.[4 5] In addition, barriers to clinical care and advancing science may result from a lack of agreement on diagnostic approaches, risk factors and management strategies.[2] One solution to address these gaps in knowledge is the use of the Delphi method to establish consensus on clinically relevant topics.[21] The sports medicine community has utilised the Delphi consensus technique on topics of interest, including but not limited to tendinopathies, muscle injuries and femoroacetabular impingement.[22–24]

To date, no international consensus has been developed on the topic of bone stress injuries in athletes. The aim of this Delphi study was to ascertain the level of agreement among panellists on three topic areas of bone stress injuries including (1) pathophysiology, diagnosis, terminology and classification systems; (2) risk factors, screening and prevention; and (3) management and return to sport.

METHODS

Study design

The study reporting adheres to the ACcurate COnsensus Reporting Document (ACCORD; for ACCORD checklist, see online supplemental file 1).[25 26] Approval for the study was obtained from the Ethics Committee of the Medical Association of Hamburg (protocol number 2023–300375-WF) to perform a modified Delphi study on bone stress injuries. Other study registrations were not performed. An initial steering group was established to complete a literature review and to develop statements. The Delphi panel was assembled through a criteria-based identification and selection of international experts and stakeholders. A three-round electronic consultation was conducted between September 2023 and March 2024 using an institution-based software package (LimeSurvey, V.6.1.8, Hamburg, Germany).

Steering committee, search strategy and statement development

The Delphi study was initiated by a multidisciplinary steering committee (TH, KH, EK, KLP, MF, SJW, AST). Prior to the development of statements, a literature search was conducted in PubMed, Web of Science, Cochrane databases, SPORTdiscus and Google Scholar using the keywords 'stress fracture*', 'stress reaction*', 'bone stress injur*' and 'stress response'. Google Scholar was used in incognito mode. Further studies were identified through a forward ('cited by') and backward ('citation') search. Additional relevant publications that were not identified through the literature search were added manually based on recommendations from the steering group. The articles were reviewed non-systemically and used to publish a primer on bone stress injuries covering the topics of epidemiology, pathophysiology, diagnosis, screening, prevention, management, quality of life and outlook.[2] Based on this primer, the steering group of the current Delphi study identified three key areas requiring international consensus on bone stress injuries: (1) terminology, pathophysiology, diagnosis and classification; (2) risk factors, screening and prevention; and (3) management and return to sport.

Panel selection

An international expert and stakeholder panel was formed based on predefined criteria with the goal of recruiting at least 30 participants. The accuracy and reliability of Delphi results minimally improve with increasing sample size beyond 30 participants.[27] Members of the steering committee were excluded from serving as panellists.[28 29] Initially, panel experts were identified based on their scientific involvement in the study of bone stress injuries. No exceptions were made to this rule to avoid selection bias. Accordingly, a search on Medline (Pubmed) for peer-reviewed publications between April 2008 and March 2023 was performed using the following search string:

#1: bone stress injur*
#2: stress fracture
#3: stress reaction
#4: athlet*
#5: sport*
#1 OR ([#2 OR #3] AND ([#4 OR #5]).

All authors with four or more first or senior authorships were considered for invitation to serve as panellists. This criterion was based on preliminary searches, taking into account a substantial number of candidates not willing to participate.[22] Additional experts and stakeholders were then added to the panel to meet the strategic goal of promoting diversity among panel members.[29 30] The selection of additional panellists is outlined below in the sections *Equity, diversity and inclusion statement* and *Patient, public and clinical expert involvement*. The invited panel candidates were approached via email. All experts and stakeholders who initially agreed to serve as panellists were allowed to participate in each of the three Delphi rounds. All panellists were asked to assess only those statements related to their field of expertise.

Equity, diversity and inclusion statement

Additional scientific experts with fewer than four senior or first authorships but in the order of the search results were invited to serve as panellists based on predefined diversity criteria: (1) at least three experts per continent (except Antarctica) and (2) at least 40% female and male experts.

Patient, public and clinical expert involvement

To include perspectives beyond scientific knowledge, each identified expert was asked to nominate a non-scientific stakeholder (eg, clinician, coach, athlete) that should be included in the Delphi process. The recommended clinical experts and stakeholders were subsequently invited to participate in the Delphi study. Athletes and coaches were only counted as representatives if they have a currently active role in their sports without being a clinician or scientist (eg, clinicians and scientists who used to be athletes/coaches do not count as representatives). In addition, the involvement of athletes, coaches and public is planned in the dissemination of the study findings.

Modified Delphi process

A modified Delphi method was utilised. Specifically, in the first round, the steering group formulated preselected statements. Piloting of the survey instruments was not performed. For ordinal statements, a 5-point Likert scale was used (strongly agree, agree, neutral, disagree and strongly disagree). For each statement, an optional free-text box was provided with encouragement for panellists to add comments to support their decision or suggest modifications. Additionally, an open text box was implemented in the first round to gather information, from the panellists' point of view, on the lack of evidence and what additional categories would benefit from international consensus. All statements were sent to the panellists via email, with a reminder function integrated to reduce the attrition rate. No virtual or in-person meeting was held to ensure anonymity among panellists during the consensus process. All statements with agreement or disagreement of ≥80% were omitted for the subsequent rounds. All remaining statements were subjected to modification based on the panellists' feedback and were admitted to the next round. Anonymity was applied at all stages (blinding the identity of panellists to each other and votes). The second round consisted of all statements that did not achieve consensus in the first round. For each statement, the voting results from the previous round were provided (anonymous group voting results and the panellist's own vote). An example of the controlled feedback technique applied is provided in online supplemental file 2. This feature allowed every panel member to reflect on their own response from the previous round. The panellists were then asked to reconsider their previous ratings. Statements with ≥80% agreement or disagreement were excluded from the subsequent round. All other statements were subjected to modification based on the experts' feedback and admitted to the next round. Similarly, a third round containing the remaining statements was then sent to the experts for final voting.

Statistical analysis and reporting

Levels of agreement to the Delphi statements are presented as percentage (%). Responses for 'strongly agree' and 'agree' were categorised as agreement, 'neutral' as undecided and 'disagree' or 'strongly disagree' as disagreement. Descriptive statistics were used to report demographic data of the participants. For each round, median and IQR voting results are presented. A χ^2 analysis was performed to investigate responses by demographics (number of cases treated per year). Statistical significance was defined as $p<0.05$. All statistical analyses were performed by using SPSS V.29.0 (IBM, Armonk, New York). Based on the previous reports,[11 28] consensus was defined *a priori* as agreement or disagreement of ≥80% for each statement. Three levels of agreement have been defined:

1. Full consensus: ≥80% of panellists agreed on the Delphi statement; no panellists disagreed.
2. Consensus with one or more disagreements: ≥80% of panellists agreed on the Delphi statement; one or more panellists disagreed.
3. Failure of consensus: <80% of panellists agreed on the Delphi statement.

RESULTS

Participants (Delphi panellists)

The initial literature search identified 94 experts who met criteria of lead or senior author publications on the topic of bone stress injuries. Two experts were not invited due to the absence of correspondence information. Of the remaining 92 experts, 38 agreed to participate (refused to participate: 9, no response: 45). The experts suggested additionally including eight stakeholders (clinicians without scientific experience, coaches and athletes). Of these, three stakeholders agreed to serve as panellists; one represented the athlete's voice, one the coach's voice and one the clinical expert without scientific experience in the field. This led to a total of 41 panellists agreeing to participate in the Delphi consensus. Of these, 33 panellists finished the first round ($n_{Dropout}$=8; response rate=80.5%), 28 panellists finished the second round ($n_{Dropout}$=13; response rate=68.3%) and 28 panellists finished the third round ($n_{Dropout}$=13 response rate=68.3%). The panel selection process is detailed in figure 1. The participant characteristics for each Delphi round are reported in table 1.

Delphi rounds and consensus process

The Delphi statements for each round are provided as supplementary material. The first, second and third round consisted of 59 (online supplemental file 3), 40 (online supplemental file 4) and 30 (online supplemental file 5) statements, respectively. The first round was started in September 2023, the second round in January 2024 and the third round in March 2024. The consensus process was divided into three parts. Table 2 presents the Delphi statements of part 1 on *pathophysiology, diagnosis, terminology and classifications*. Tables 3 and 4 present the Delphi statements of part 2 on *risk factors, screening and prevention*. Finally, tables 5 and 6 present the Delphi statements of part 3 on *management and return to sport*. Detailed voting results are provided in online supplemental files 6 and 7.

DISCUSSION

The purpose of this modified Delphi process was to ascertain the level of agreement among experts and stakeholders on key domains of bone stress injuries including (1) pathophysiology, diagnosis, terminology and classification systems; (2) risk factors, screening and prevention; and (3) management and return to sport. Agreement was reached on 41 out of 58 statements. Certain statements failed to reach international consensus; these statements may reflect topics that require future research.

Bone stress injury arises from cumulative microdamage, occurs on an injury continuum and may result in a complete bone fracture

The presumed underlying pathophysiology of bone stress injuries is an imbalance in bone metabolism favouring microdamage accumulation over its replacement via targeted bone remodelling.[2 31] The Delphi panel affirmed that with continued stress and strain, injuries may progress along a pathology continuum. It was collectively indicated by the panellists that local bone tissue weakening may result in a partial or complete bone fracture. The

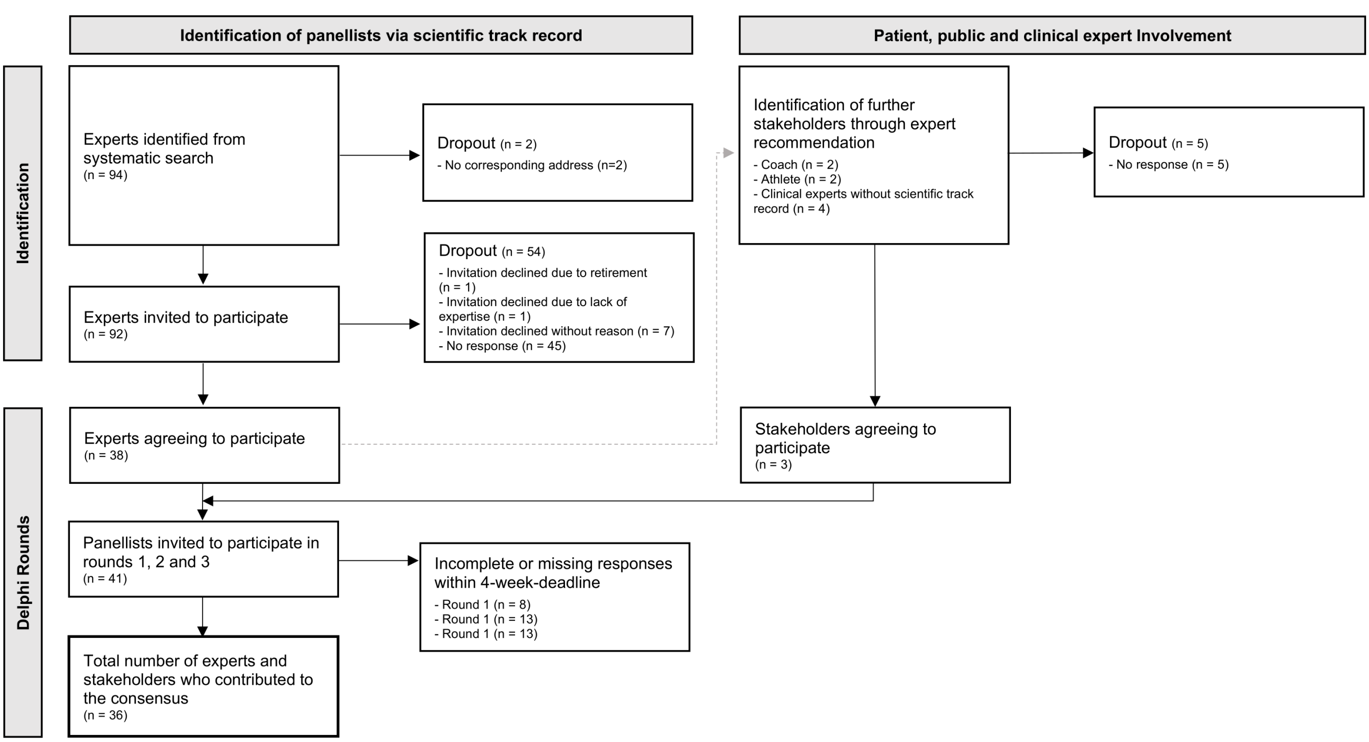

Figure 1 Flow diagram for panellist identification and patient, public and clinical expert involvement.

Table 1 Participant characteristics of the expert and stakeholder panel

Characteristic	Categories	Delphi round 1 (n=33)	Delphi round 2 (n=28)	Delphi round 3 (n=28)
Sex	(M:F)	19:14	17:11	18:10
Main profession	Physician: orthopaedic	6 (18.2%)	7 (25.0%)	8 (28.6%)
	Sports scientists or expert in biomechanics	6 (18.2%)	4 (14.3%)	4 (14.3%)
	Physician: primary care sports medicine	4 (12.1%)	3 (10.7%)	3 (10.7%)
	Physical therapist/physiotherapist	3 (9.1%)	3 (10.7%)	2 (7.1%)
	Physician: radiology	2 (6.1%)	2 (7.3%)	2 (7.1%)
	Sports dietitian	2 (6.1%)	2 (7.3%)	2 (7.1%)
	Podiatrist	2 (6.1%)	1 (3.6%)	2 (7.1%)
	Physiologist	2 (6.1%)	1 (3.6%)	1 (3.6%)
	Athletic trainer	1 (3.0%)	1 (3.6%)	1 (3.6%)
	Athlete	1 (3.0%)	1 (3.6%)	1 (3.6%)
	Coach	1 (3.0%)	1 (3.6%)	1 (3.6%)
	Endocrinologist	1 (3.0%)	1 (3.6%)	1 (3.6%)
	Not specified	2 (6.1%)	1 (3.6%)	0 (0.0%)
Sports affiliated with (multiple responses allowed)	Track and field/athletics	22 (66.7%)	17 (60.7%)	18 (64.3%)
	Road running/cross-country running	21 (63.6%)	17 (60.7%)	18 (64.3%)
	Soccer	17 (51.5%)	12 (42.9%)	14 (50.0%)
	Basketball	12 (36.4%)	10 (35.7%)	11 (39.3%)
	Triathlon	12 (36.4%)	10 (35.7%)	11 (39.3%)
	Gymnastics	9 (36.4%)	7 (25.0%)	7 (25.0%)
	Cricket	7 (21.2%)	5 (17.9%)	4 (14.3%)
	Baseball	6 (18.2%)	3 (10.7%)	4 (14.3%)
	Dancing	6 (18.2%)	5 (17.9%)	5 (17.9%)
	Other	22 (66.7%)	18 (64.3%)	18 (64.3%)
	Not applicable	2 (6.1%)	3 (10.7%)	3 (10.7%)
Bone stress injury cases managed per year	<6	2 (6.1%)	2 (7.1%)	2 (7.1%)
	6–12	2 (6.1%)	4 (14.3%)	4 (14.3%)
	13–24	5 (15.2%)	4 (14.2%)	3 (10.7%)
	25–36	4 (12.1%)	2 (7.1%)	4 (14.3%)
	37–52	5 (15.2%)	4 (14.3%)	4 (14.3%)
	52+	6 (18.2%)	6 (21.4%)	5 (17.9%)
	Not applicable	9 (27.3%)	6 (21.4%)	6 (21.4%)
Age	19 or younger	0 (0.0%)	0 (0.0%)	0 (0.0%)
	20–29	0 (0.0%)	0 (0.0%)	0 (0.0%)
	30–39	4 (12.1%)	4 (14.3%)	4 (14.3%)
	40–49	10 (30.3%)	7 (25.0%)	7 (25.0%)
	50–59	12 (36.4%)	9 (32.1%)	9 (32.1%)
	60 or older	7 (21.2%)	8 (28.6%)	8 (28.6%)
Continent of residence	North America	15 (45.6%)	14 (50.0%)	14 (50.0%)
	Europe	8 (24.2%)	6 (21.4%)	7 (25.0%)
	Asia	4 (12.1%)	4 (14.3%)	4 (14.3%)
	Oceania	4 (12.1%)	4 (14.3%)	3 (10.7%)
	South America	1 (3.0%)	0 (0.0%)	0 (0.0%)
	Africa	1 (3.0%)	0 (0.0%)	0 (0.0%)
Main workplace	Academic hospital or university medical centre	12 (36.4%)	13 (46.4%)	13 (46.4%)
	University (no medical position, for example, kinesiology)	9 (27.3%)	6 (21.4%)	6 (21.4%)
	Private clinic/non-academic affiliated	7 (21.2%)	5 (17.9%)	6 (21.4%)
	Other	5 (15.2%)	4 (14.3%)	3 (10.7%)
Race/ethnicity	White	26 (78.8%)	23 (82.1%)	23 (82.1%)
	Asian or Pacific Islander	4 (12.1%)	4 (14.3%)	4 (14.3%)
	Multiracial or Biracial	1 (3.0%)	0 (0.0%)	0 (0.0%)
	Black or African American	1 (3.0%)	0 (0.0%)	0 (0.0%)
	Native American or Alaskan Native	0 (0.0%)	0 (0.0%)	0 (0.0%)
	Hispanic or Latino	0 (0.0%)	0 (0.0%)	0 (0.0%)
	Other	1 (3.0%)	1 (3.6%)	1 (3.6%)

Table 2 Consensus statements on pathophysiology, diagnosis, terminology and classifications of bone stress injuries (part 1)

Nr.	Statement	Agreement	Undecided	Disagreement	Example of responses
1	Bone stress injuries result from the accumulation of bony microdamage	100%	0.0%	0.0%	However, microdamage is a normal process for the skeleton and is not inherently problematic.
2	Microdamage accumulates when loading induces microdamage formation at a rate that exceeds the ability to remove and replace microdamage via targeted remodelling (ie, the site-specific and sequential activity of bone-resorbing osteoclasts and bone-forming osteoblasts)	96.4%	3.6%	0.0%	I believe this to be true but have not seen hard evidence for this.
3	Accumulation of microdamage locally weakens the affected site leading to a heightened risk of an acute or complete bone fracture	100%	0.0%	0.0%	
4	Bone stress injuries occur on a pathology continuum (eg, the pathology can advance from one stage to the next if not diagnosed early and/or treated adequately)	93.1%	3.5%	3.5%	Pain might not be consistent across pathologies.
5	The terms 'stress reaction' and 'stress fracture' may be used when communicating with patients	92.3%	3.9%	3.9%	Use of multiple terms (BSI, stress reaction, stress fracture) confuses patients.
6	Stress reactions are bone stress injuries without a fracture line. Stress fractures are bone stress injuries with a visible fracture line (eg, on plain radiography or MRI)	81.5%	3.7%	14.8%	Fracture line can be present but not visible on imaging.
7	The term 'bone stress injury' is the preferred umbrella term for overuse injuries to bone in athletes	85.7%	0.0%	14.3%	There are too many different terms; bone stress injury should become the preferred umbrella term.
8	Bone stress injuries in athletes can be termed as low-risk or high-risk based on their anatomical location and risk for progression and/or healing complications	92.9%	7.1%	0.0%	Some injuries are high-risk but any bone stress injury can be problematic for ability to participate at highest level.
9	The term shin splints is imprecise and should be avoided	70.4%	14.8%	14.8%	Shin splints is imprecise but MTSS is a more defined clinical entity. However, it depends on who you're talking to. Athletes understand better to use the term shin splints rather than MTSS.
10	The term medial tibial stress syndrome is imprecise and should be avoided	32.0%	28.0%	40.0%	Shin splints is highly non-specific but MTSS is acceptable.
11	Medial tibial stress syndrome is a form of bone stress injury	72.0%	24.0%	4.0%	
12	When feasible or accessible, radiographic grading can help to guide decision-making and prognosis (eg, grading a bone stress injury can help guide an athlete's return to sport)	77.8%	18.5%	3.7%	Clinical decisions should not be made around classification alone. The clinical signs and symptoms are more important than imaging findings.
13	There is a need for one main classification system (agreed terminology and nomenclature)	86.2%	10.4%	3.5%	Easier said than done.
14	Classification systems should have consistent terminology	100%	0.0%	0.0%	Difficult to achieve consistent terminology that will be used globally.
15	The following aspects of a patient's history and physical examination should raise a high suspicion of the presence of bone stress injury:				
	Specific location of symptoms	96.6%	3.3%	0.0%	Being a strong risk factor for bone stress injuries does not mean that it must be present. These risk factors are important but you have to earn a bone stress injury. There is usually a loading error. It's important to discuss the overall life ecosystem with patients (eg, team/coach dynamics).
	Pain when load is applied to the bone	96.4%	3.6%	0.0%	
	Presence of worsening pain with weight bearing activity	88.9%	11.1%	0.0%	
	Absence of improved pain with activity ("warm-up" effect)	80.8%	3.9%	15.4%	
	Recent change in training volume or intensity	92.9%	7.1%	0.0%	
	History of a bone stress injury	85.7%	10.7%	3.6%	
	Type of activity	92.9%	7.1%	0.0%	
	Duration of symptoms	81.5%	18.5%	0.0%	
	Tenderness on palpation	79.3%	13.8%	6.9%	
	Symptoms are induced by provocative activities (eg, running, hopping)	92.9%	7.1%	0.0%	
	Presence of indicators of low energy availability state, including Female/Male Athlete Triad or Relative Energy Deficiency in Sport (REDs)	88.5%	7.7%	3.9%	
	Expression of subjective pain>6 (on a 0–10 scale)	84.6%	7.7%	7.7%	
	Change in footwear or running surface	80.8%	15.4%	3.9%	
	Psychological concerns leading to overtraining	92.3%	7.7%	0.0%	
	Psychological concerns with body image	88.5%	7.7%	3.9%	
16	It is reasonable to diagnose bone stress injuries clinically in select cases without further imaging to confirm presence of injury	73.1%	0.0%	26.9%	An accurate diagnosis needs imaging.
17	Plain radiography should be the initial imaging modality obtained	84.6%	7.7%	7.7%	X-ray is useful if you do not have quick access to MRI.

Continued

Table 2 Continued

Nr.	Statement	Agreement	Undecided	Disagreement	Example of responses
18	MRI represents the gold standard for diagnosis of bone stress injuries	85.7%	7.2%	7.2%	Though not perfect. Some fractures are not well seen on MRI. Also, MRI can be too sensitive (that is, detecting irrelevant bone findings that we didn't see before MRI became available).
19	Scintigraphy should not be used for assessing bone stress injuries, except in very select cases (eg, when MRI is not possible and other forms of imaging are inconclusive)	84.0%	16.0%	0.0%	We have great alternatives with MRI, for example, VIBE.
20	CT should not be used routinely for diagnosis but may be used in specific sites of injury (eg, tarsal navicular)	84.0%	12.0%	4.0%	Only required to detect a fracture if the MRI is equivocal (<10% of cases).
21	The presence of incidental bone marrow changes on MRI is of limited clinical or prognostic value in athletes if findings do not correspond with physical exam findings and/or clinical history	91.7%	0.0%	8.3%	Not enough research on this topic.
22	Diagnostic ultrasound is helpful to identify bone stress injuries in some cases	23.8%	28.6%	47.6%	Might point you in the right direction but is not diagnostic.

Consensus was defined *a priori* by≥80% agreement. Colouring indicates consensus reached without any votes of disagreement (■), consensus with one or more disagreement votes (■) and failure to reach consensus (■).
BSI, bone stress injury; MTSS, medial tibial stress syndrome; VIBE, volumetric interpolated breath-hold examination.

concept of overuse injuries to bone that exists on a continuum has been proposed by others[3 32 33] and is important to developing disease models that can advance treatment and prevention of these injuries.

The extent to which microdamage occurs is influenced by the magnitude, frequency, duration and direction of loading.[33] It is plausible that a generally low training workload may exceed the bone's tissue tolerance to stress and strain in athletes with impaired bone metabolism, thus considering these injuries as being multifactorial.[11] However, the exact mechanisms are not fully understood.[2] Greater understanding of the underlying pathophysiology is essential to inform prevention and treatment of bone stress injuries, for example, training interventions or pharmacological approaches.

The essentials of consistent terminology

The panel collectively accepted that, at present, *bone stress injury* is the preferred umbrella term. Until now, the clinical entity of activity-related, non-traumatic bone injuries has seen multiple terms, including stress reactions, stress fractures, fatigue fractures, hairline cracks, bone marrow oedemas or bone marrow lesions. To account for the broad spectrum of bone stress injuries, several classification systems have been described.[9 10 34] Two commonly applied classification systems are those by Arendt *et al*[9] and Fredericson *et al*,[10] and both use distinct imaging findings to assess the severity of bone stress injuries (eg, presence of a fracture line). The classification system described by Kaeding and Miller[34] is of interest for surgical decision-making as displaced fractures and non-unions are classified separately. A universally accepted bone stress injury classification system is yet to be developed, though recommended by the Delphi panel. The need for further international collaboration in this field stems from the potential benefits of grading bone stress injuries in informing decision-making and prognosis, particularly in high-level athletes.[4 5]

Improving recognition and accurate diagnosis of bone stress injuries through comprehensive case history, physical examination and MRI

In sports medicine, case history taking and clinical examination are key skills that can be taught and learnt.[35] The Delphi panel identified a number of features that may raise high suspicion of the presence of a bone stress injury, for example, recent changes in training volume or intensity. A comprehensive physical examination, including the observation of morphological variations (eg, pes cavus, bowlegs, pelvic tilt), is the basis for further clinical investigation.[2] Superficial bone stress injuries such as the tibial shaft allow for palpation of the injury site.[36] Depending on the injury location, specific tests have been described.[2 36] In a study of 80 adolescents with tibial bone stress injuries, the vertical single leg hop test demonstrated highest sensitivity as compared with tap/percussion test, vibration test, weight bearing lunge test and fulcrum test.[37] Notably, the authors highlighted that no individual test demonstrated high sensitivity or specificity. However, combining multiple tests resulted in higher likelihood for accurate diagnosis or exclusion of a bone stress injury. The limited physical exam features and characteristics to detect bone stress injuries remain a challenge for clinical evaluation.

Although patient history and clinical exam are critical components, imaging plays a crucial role in the diagnostic workup.[4 38 39] Plain radiography has the benefit of being widely accessible and is an agreed on initial imaging modality, however, MRI is considered the imaging modality of choice by most Delphi panellists. Other imaging modalities are of limited utility but may be used in selected cases.[2 4 5] Ultrasound was rarely considered useful by the panel in identifying bone stress injuries. Scintigraphy is less commonly used due to radiation exposure and its clear disadvantages as compared with MRI.[5] For detailed bone imaging, CT is a standard imaging technique worldwide although rarely used for assessing bone stress injuries. However, its use can be beneficial for differential diagnosis workup, aiding decision-making in high-risk bone stress injuries and for assessing fracture consolidation.[39–41] Newer imaging modalities are constantly evolving, and the use of volumetric interpolated breath-hold examination (VIBE) MRI, photon CT or dual-energy CT may offer new opportunities in the detection of bone stress injuries in the future.[39 42] However, increased accessibility to advanced imaging technology is not without disadvantage, that is, the misinterpretation/overdiagnosis of asymptomatic imaging findings.[43 44]

Risk factors for bone stress injuries are multifactorial and result from factors related to skeletal loading, underlying bone health and other health behaviours

The improved understanding of the underlying pathophysiology provides a clear explanation for the occurrence of bone stress injuries in athletes experiencing rapid transitions in training load,

Table 3 Ranked risk factors for the development of bone stress injuries in athletes (part 2a)

Nr.	Statement	Level of agreement
23	The following is a risk factor for the development of a bone stress injury:	
	Transitions in training load (eg, increases in training volume or intensity)	100%
	Previous history of a bone stress injury	96.3%
	Low body mass index	96.0%
	Poor bone health (eg, low bone mass)	92.9%
	History of eating disorder	92.6%
	Functional strength deficits	92.3%
	Early sport specialisation	92.0%
	Insufficient caloric intake to meet energy demands	88.9%
	Menstrual dysfunction (in females)	88.0%
	Low testosterone (in males)	87.0%
	Change in habitual footwear	84.6%
	Biomechanics (eg, foot overpronation, hip internal rotation during the stance phase of gait, low step rate)	84.6%
	Female sex	81.5%
	Low serum levels of vitamin D	80.8%
	Low calcium intake	80.8%
	Insufficient participation in ball sports (soccer/basketball) or jumping activities during childhood	73.1%
	Smoking and alcohol	70.8%
	Hard running surface (eg, pavement)	69.2%
	Inadequate sleep	68.0%
	Age	65.4%
	Lack of weight training	60.0%
	Vegetarian diet	60.0%
	Chronic use of NSAIDs	58.3%
	Psychological stress	52.0%
	Low carb diet	41.7%
	Previous history of a fracture from trauma	40.0%
	Non-cushioned shoes	38.5%
	"Supershoes / Technology Advanced Running Shoes" (those with carbon-fibre plate)	26.9%
	Hilly terrain	26.9%

Consensus was defined *a* priori by≥80% agreement. Colouring indicates consensus reached without any votes of disagreement (■), consensus with one or more disagreement votes (■) and failure to reach consensus (■).
NSAIDs, non steroidal anti inflammatory drugs.

for example, increases in training volume or intensity.[2] A suboptimal bone workload is present when the magnitude of loading cycles constantly surpasses the tissue's ability to withstand repetitive loads.[45] While in vivo microdamage accumulation is the driving force in the development of bone stress injuries,[46] the Delphi panellists recognise a clear association with risk factors related to bone health.

Prior work has characterised aspects of nutrition as contributing to bone stress injuries, including low energy availability.[11 47 48] Low energy availability is the cause of Relative Energy Deficiency in Sport (REDs) and is associated with higher rates of bone stress injuries.[48–51] Low energy availability is more common in female endurance athletes,[52] and female athletes have been suggested to have elevated risk for bone stress injuries.[53] Our panel identified similar risk factors for bone stress injury, and those related to low-energy availability include insufficient caloric intake to meet energy demands, history of eating disorder, low body mass index, low bone mass, menstrual dysfunction in women and low testosterone in men. Importantly, bone stress injuries may serve as the impetus for amateur athletes to consult a medical professional for the first time. Therefore, clinicians must be knowledgeable about the frameworks used for identifying REDs.[54]

Besides impaired bone health, probability of fracture is greater in the presence of increased stress and strain through abnormalities or variations in biomechanics and movement patterns.[33] Panellists agreed that change of habitual footwear represents a modifiable risk factor in athletes whose sporting activity includes high volumes of running (eg, distance runners, triathletes, orienteers). Introducing new footwear has been previously proposed as a risk factor for bone stress injury. For example, use of 'advanced footwear technology' containing carbon fibre plates and responsive midsole foam has been described in a small population of injured endurance athletes with bone stress injuries of the tarsal navicular[7] and resulted in calls to study this form of footwear.[55] Earlier work has shown that minimalist footwear (shoes with flexible midsole, minimal stack height and no foot arch support) may contribute to metatarsal injuries.[56] However, the Delphi panel did not agree that minimal shoes or advanced footwear technology increase the risk for bone stress injuries, such that specific footwear cannot currently be recommended to modify injury risk. Nevertheless, findings from the present consensus statement combined with earlier work suggest the need for athletes to use caution regarding changes in footwear.

Besides footwear, the panel was in agreement that intrinsic biomechanical patterns may contribute to risk of bone stress injury in running athletes. This is consistent with prior work published on clinical and musculoskeletal modelling studies, indicating that low step rates were associated with increased injury risk.[13 57] Accordingly, gait retraining interventions, such as adopting a higher step rate, have been previously suggested.[13] However, in line with the preferred movement pathway paradigm,[58] gait retraining in athletes is not routinely recommended by the Delphi panel. The panel though acknowledged that gait retraining may be a treatment intervention in athletes with a history of recurrent bone stress injuries.[59]

Clinical assessment of risk factors includes bone mass scanning and laboratory testing

Notably, a history of bone stress injury is seen to be among the strongest risk factors for developing a subsequent bone stress injury.[53 60] Thus, it is crucial to take steps to mitigate risk factors through sufficient energy intake, appropriate nutrition or training load monitoring.[11 36 59] Consensus was not reached for *routinely* obtaining a dual-energy X-ray absorptiometry study to measure bone mineral density (BMD) values in at-risk sports such as running if athletes are injury free. However, the threshold for defining low bone mass in athletes was agreed as BMD Z-score ≤ -1.0. A similar threshold has been previously proposed for male athletes[61] and for female athletes participating in weight-bearing sports by the American College of Sports Medicine.[62] However, the use of traditional bone health screening principles in sports medicine has been challenged, and new approaches such as sport-specific BMD Z-scores or bone microarchitecture assessment via high-resolution peripheral quantitative CT have been proposed.[47 63]

The panel reached consensus that laboratory testing is recommended to evaluate patients with bone stress injury with particular recommendations for screening for low serum vitamin D status. Further laboratory testing may be indicated and are similar to those proposed for

Table 4 Consensus statements on *risk factors, screening and prevention* of bone stress injuries (part 2b)

Nr.	Statements	Agreement	Undecided	Disagreement	Example of responses
24	Laboratory assessment (eg, serum vitamin D, parathyroid hormone) levels should be assessed in patients with a bone stress injury	84.0%	4.0%	12.0%	Depends on the healthcare system.
25	If feasible, bone mineral density normative values (BMD Z-score) should be collected to assess bone health status in athletes participating in elevated-risk activities (eg, running)	76.9%	11.5%	11.5%	For some advisable but not routinely.
26	Low bone mass in athletes should be defined by a Z-score≤−1.0	83.3%	12.5%	4.2%	Literature would probably support. However, it should be sport specific, and scan location should be referenced.
27	To reduce risk for bone stress injury, training intensity or volume should not be increased by more than 10% per week (10 percent rule)	68.0%	24.0%	8.0%	Overall sensible but why not 7.5% or 12.5%?
28	Participation in jumping sports and ball sports (eg, soccer and basketball) during youth reduces risk for future bone stress injury	82.1%	7.1%	10.7%	This has been demonstrated.
29	Supplementary resistance and impact training is beneficial to reduce risk of bone stress injury.	91.7%	8.3%	0.0%	
30	Bone stress injuries of the pelvis (including sacrum) or femoral neck are more suggestive for the presence of low energy availability (eg, REDs, Triad) than others	52.0%	48.0%	0.0%	

Consensus was defined *a priori* by≥80% agreement. Colouring indicates consensus reached without any votes of disagreement (■), consensus with one or more disagreement votes (■) and failure to reach consensus (■).
REDs, Relative Energy Deficiency in Sport.

assessing REDs.[11] The potential advantage of assessing bone biomarkers in response to acute or long-term exercise remains ambiguous.[64] The panel concluded that athletes with a bone stress injury should be provided nutrition counselling and supplemental vitamin D if serum levels are insufficient. Furthermore, the panel acknowledged that lifestyle factors including sleep and psychological stress may be important to address consistent with prior work suggesting these mechanisms being associated with rapid bone loss.[65]

Other instrumental assessments to identify risk factors may potentially comprise movement analyses in order to identify biomechanical abnormalities associated with an increased risk of bone stress injury.[12 66] Movement patterns in sports, such as running gait analysis, may be assessed clinically without advanced technology, but the use of camera-based systems or inertial measurement units provides higher accuracy, especially in high-speed motion analysis.[67]

Management of bone stress injuries depends on anatomical location and is mostly non-surgical

The anatomical location of bone stress injury should guide management. While most anatomical sites of bone stress injury are low risk, panel consensus on high-risk locations was achieved for the superior cortex of the femoral neck, anterior cortex of tibial diaphysis, navicular and base of fifth metatarsal. These anatomical locations of injury are fewer in number than prior definition for high-risk locations[68] but are consistent with literature describing the need to consider surgical management for injuries to the fifth metatarsal,[69] navicular,[41] femoral neck[70] and anterior tibial cortex.[71]

Standard fracture care may include periods of immobilisation and partial weight-bearing for lower extremity bone stress injuries. Elite athletes may consider surgery, particularly with the goal of facilitating early return to sport.[72] When considering surgical treatment, panellists may support the decision based on features including delayed union (no signs of union>3 months), non-union (no signs of union>6 months), recurrent injury, fracture displacement and injury site being prone to treatment complications.

The evolving role of shockwave, orthobiologics, shoe technology and antigravity treadmills in rehabilitation and fracture healing

The field of bone stress injury treatment has seen innovations and advancements in recent decades. Research has been conducted to identify strategies to promote faster bone healing with variable results, and similarly our panel did not reach consensus on adjuvant strategies to promote healing. No agreement was reached on prescription of low-intensity pulsed ultrasound, extracorporeal shockwave or electromagnetic stimulation. Minimally invasive interventions such as bone marrow aspirate injection or autologous platelet-rich technologies have been explored to expedite fracture healing[73]; our panel did not reach consensus on use of these treatments. Similarly, no conclusion on the potential role of (shock-absorbing) footwear or insoles can be made at present.[74] In rehabilitation, an increasing number of studies are currently investigating the role of modern treadmill technology (eg, antigravity or underwater treadmills).[75–77] While modern innovations certainly play an evolving role in clinical care of bone stress injuries, further evidence on their use or retention is warranted.

There is an unmet need for return to sports guidelines for athletes with bone stress injuries

Rehabilitation protocols should be provided through structured physical therapy.[78] A number of clinical criteria identified by the panel may guide return to sport. These include both the anatomical location and severity of injury and level of sport participation. Additionally, stepwise return to activity may be guided by pain-free status with sports and daily activities, with bone loading tests and with palpation over the injury site.

Table 5 Consensus statements on *management and return to sport* of bone stress injuries (part 3a)

Nr.	Statements	Agreement	Undecided	Disagreement	Example of responses
31	Clinicians should consider prescribing _______ to athletes with a bone stress injury:				
	Foot orthotics	73.1%	19.2%	7.7%	
	Changing to a minimalistic shoe	11.5%	26.9%	61.5%	
	Changing to a highly cushioned shoe	50.0%	30.8%	19.2%	
	Changing footwear (other than minimalistic or highly cushioned shoe)	53.8%	34.6%	11.5%	
	Converting to a different foot strike pattern	65.4%	19.2%	15.4%	
	Increasing running cadence	65.4%	26.9%	7.7%	
	Gait retraining (other than foot strike pattern or cadence)	69.2%	26.9%	3.9%	
	Electrical (electromagnetic) stimulation	22.7%	68.2%	9.1%	
	Low-intensity pulsed ultrasound	25.0%	58.3%	16.7%	
	Extracorporeal Shockwave	47.8%	34.8%	17.4%	
	Supplementation of Vitamin D (if insufficient serum levels)	83.3%	8.3%	8.3%	
	Recombinant parathyroid hormone (eg, teriparatide)	47.6%	38.1%	14.3%	
	Anti-sclerostin antibody agents	0.0%	52.9%	47.1%	
	Bisphosphonate medications excluding pre-menopausal women	14.3%	19.1%	66.7%	
	Transdermal oestrogen with cyclic progesterone (women)	57.1%	33.3%	9.5%	
	Nutritional counselling	88.0%	8.0%	4.0%	
	Addressing lifestyle factors including sleep and psychological stress	84.0%	12.0%	4.0%	
32	Clinicians should consider prescribing _______ to athletes with a repeated bone stress injury:				
	Foot orthotics	76.9%	15.4%	7.7%	
	Changing to a minimalistic shoe	11.5%	26.9%	61.5%	
	Changing to a highly cushioned shoe	46.2%	23.1%	30.8%	
	Changing footwear (other than minimalistic or highly cushioned shoe)	42.3%	42.3%	15.4%	
	Converting to a different foot strike pattern	61.5%	23.1%	15.4%	
	Increasing running cadence	76.9%	15.4%	7.7%	
	Gait retraining (other than foot strike pattern or cadence)	80.0%	12.0%	8.0%	
	Electrical (electromagnetic) stimulation	27.3%	63.6%	9.1%	
	Low-intensity pulsed ultrasound	45.8%	45.8%	8.3%	
	Extracorporeal Shockwave	47.8%	34.8%	17.4%	
	Supplementation of Vitamin D (if insufficient serum levels)	83.3%	8.4%	8.4%	
	Recombinant parathyroid hormone (eg, teriparatide)	52.4%	28.6%	19.1%	
	Anti-sclerostin antibody agents	0.0%	41.2%	58.8%	
	Bisphosphonate medications excluding pre-menopausal women	19.0%	14.3%	66.7%	
	Transdermal oestrogen with cyclic progesterone (women)	42.9%	42.9%	14.3%	
	Nutritional counselling	92.0%	3.9%	3.9%	
	Addressing lifestyle factors including sleep and psychological stress	83.3%	12.5%	4.2%	
33	Pharmacological interventions (excluding vitamin D, (supplemental calcium) or iron) should not be used as a first-line treatment	82.6%	13.0%	4.4%	Depends on the lab results.
34	Pharmacological interventions should be considered if initial non-pharmacological treatment was not successful (eg, activity modification, improving diet)	68.2%	27.3%	4.6%	Normal bone will heal itself.
35	Surgical management of bone stress injuries in select cases (eg, navicular, anterior tibia, fifth metatarsal) may allow for early return to sports and can be considered in elite athletes	83.3%	16.7%	0.0%	Indication for surgery should be better outcome rather than earlier return to play.
36	When treated surgically, orthobiologics (eg, bone marrow aspirate concentration, platelet-rich plasma) are a low-risk adjunct to the surgical procedure	41.2%	52.9%	5.9%	Additional cost.
37	Orthobiologic procedures / adjuncts provide superior results compared with non-orthobiologic treatment	5.6%	61.1%	33.3%	No high quality evidence yet.
38	Bone stress injuries at the femoral neck should be managed surgically if the fracture line is of>50% width of the femoral neck	81.0%	14.0%	5.0%	Rohena-Quinquilla classification should be considered here.
39	In general, bone stress injuries of the fifth metatarsal diaphyseal-metaphyseal region should be managed surgically in elite athletes	78.3%	21.7%	0.0%	If unresponsive to a period of non-surgical management.
40	If treated surgically, preferred surgical technique of bone stress injuries of the fifth metatarsal (non-displaced) is fixation using an intramedullary screw	82.4%	11.8%	5.9%	Head of a screw may irritate and cause ongoing problems.
41	For navicular bone stress injuries, decision-making on surgical vs non-surgical treatment should include fracture type (eg, classification by Saxena *et al*)	84.2%	10.5%	5.3%	In case of conservative treatment, casting and non-weightbearing for at least 6 weeks.

Continued

Table 5 Continued

Nr.	Statements	Agreement	Undecided	Disagreement	Example of responses
42	Injuries of the anterior tibia with a "dreaded black line" should be managed surgically	63.6%	36.4%	0.0%	Needless delay in recovery without surgery.
43	If treated surgically, preferred surgical technique of bone stress injuries of the anterior tibia is tibial intramedullary nailing	76.5%	17.6%	5.9%	
44	If treated surgically, preferred surgical technique of bone stress injuries of the anterior tibia is tension plating	26.7%	20.0%	53.5%	Clinically, patients seem to struggle with the superficial location of the plate.
45	A rehabilitation protocol should be used with structured physical therapy following any bone stress injury	96.3%	3.6%	0.0%	Current rehab is not based on objective findings.
46	Multi-directional and/or osteogenic activities should be added to the rehabilitation process	88.0%	12.0%	0.0%	In a very gradual temporal sequence so as not to cause reinjury.
47	The following criteria are important to consider for return to running and return to sport progression:				
	Severity and location of the initial injury	100%	0.0%	0.0%	Rehab should focus on improving bone health/size/strength/balance. Load management is important.
	Time off from sports participation	100%	0.0%	0.0%	
	Level of sports participation (recreational vs elite athlete)	88.9%	7.4%	3.7%	
	Being pain-free during daily or sports activities	96.2%	3.7%	0.0%	
	Being pain-free during palpation of injury site (if palpation possible)	80.8%	15.4%	3.9%	
	Findings from repeated imaging	69.2%	19.2%	11.5%	
	Negative bone loading tests (eg, single-leg hopping test)	87.5%	8.3%	4.2%	
	Negative tests other than loading test (eg, muscular strength testing, proprioception)	79.2%	20.8%	0.0%	
48	Factors that should be considered to support surgical intervention include:				
	Recurrent injury	95.8%	0.0%	4.2%	
	Delayed union (no signs of union>3 month)	86.4%	4.6%	9.1%	
	Non-union (no signs of union>6 month)	95.5%	4.4%	0.0%	
	Fracture displacement	90.9%	9.1%	0.0%	
	Injury site prone to treatment complication (eg, non-union)	81.8%	13.6%	4.6%	
	Level of sport participation (eg, elite athlete)	82.6%	17.4%	0.0%	
49	The whole rehabilitation process should be agreed within a multidisciplinary team and have athlete engagement	100%	0.0%	0.0%	Patient preference for decision-making is utmost important.
50	The patient's sport and previous level of participation will impact the progression of exercise selection and ultimate return to activity	100%	0.0%	0.0%	Should use anti-gravity treadmill in elite athletes.
51	Pain with running at the injury site is not permissible when rehabilitating bone stress injuries	83.3%	8.3%	8.3%	If pain is 2-3/10 on VAS I'm less concerned than if it's a 7-8/10.
52	Pain with running is permissible when rehabilitating selected cases of bone stress injuries without major concerns for delayed or non-union	50.0%	8.3%	41.7%	Ok if it gets better with activity.
53	A repeated MRI exam for bone stress injury healing is not routinely recommended	82.6%	4.4%	13.0%	Not required for all but very helpful in others.
54	New rehabilitation guidelines for bone stress injuries are needed, and should include objective return to sport criteria with appropriate activities for each phase	100%	0.0%	0.0%	Clear milestones around when to progress intensity & volume of training are needed.
55	Compliance in addressing identified risk factors (eg, meeting with dietician, correcting errors in load management) should be considered when clearing for return to full activity	96.3%	3.7%	0.0%	Lots of variables impact decision-making, it's the total picture.
56	Repeated imaging findings can be helpful with return to sport decision-making in select cases (eg, femoral neck)	87.5%	8.3%	4.2%	Consensus on the best imaging modality for follow-up (not diagnosis) is warranted.

Consensus was defined *a priori* by≥80% agreement. Colouring indicates consensus reached without any votes of disagreement (■), consensus with one or more disagreement votes (■) and failure to reach consensus (■).

Multidisciplinary collaboration was recognised as a key aspect of managing bone stress injuries. In countries without a fully recognised sports medicine specialty, athletes may seek consultation with family doctors, orthopaedists, physiatrists and other healthcare professionals for assistance with sports injuries. As with any overuse injuries in athletes, the necessity for interdisciplinary collaboration becomes apparent. For example, orthopaedists may lack deep knowledge of concepts of low energy availability, while endocrinologists may lack knowledge of fracture care.

Future research areas

Some Delphi statements failed to achieve consensus, highlighting areas with a need for future research. Injury prevention requires the definitions and correction of both training errors and lifestyle risk factors. This includes a detailed understanding of how low-energy availability impacts bone health.[79 80] Implementing innovative strategies in the treatment and rehabilitation of bone stress injury is another field with a need for research.[2 48 73 77] This may comprise the use of shockwave or antigravity treadmills as well as surgical approaches.[2] The enthusiasm for new technological interventions is evident in the sports medicine community; however, evidence-based practices are paramount to ensure that the health and safety of our athletes remain a top priority. Nevertheless, future studies can benefit from new research methods such as finite element analysis, big data analyses and wearable technology.[2] Translational research may contribute to clinical care by investigating types of bony microdamage,

Table 6 High-risk and low-risk bone stress injuries (part 3b)

Injury site	Risk stratification	Management
	Level of agreement on statement nr. 57: A bone stress injury at the following anatomical locations is associated with higher rate of complications and should be classified as "high-risk"	Level of agreement on statement nr. 58 : Stress fractures (acute; with a clear fracture line present; non-displaced) of the following anatomical sites should be initially managed non-surgically.
Clavicle	27.8%	84.2%
Ribs	26.3%	100%
Scapula	16.7%	100%
Humerus	16.7%	95.0%
Radius	22.2%	85.0%
Olecranon	38.9%	80.0%
Hand/wrist	22.2%	90.0%
Pars interarticularis / vertebral arch region of the spine	57.1%	95.5%
Pubic ramus	40.9%	100%
Ilium	38.1%	100%
Sacrum	45.5%	100%
Superior cortex of the femoral neck ("tension-side")	91.3%	50.0%
Inferior cortex of the femoral neck ("compression-side")	47.8%	85.0%
Femoral shaft (diaphysis)	26.1%	85.0%
Distal femur (metaphysis)	17.4%	95.0%
Patella	39.1%	76.2%
Proximal tibia (metaphysis)	30.4%	90.5%
Anterior cortex of the tibial diaphysis	86.4%	72.7%
Posteromedial portion of the tibial diaphysis	34.8%	90.5%
Medial malleolus	60.9%	76.2%
Fibula shaft (diaphysis)	21.7%	95.2%
Lateral malleolus	27.3%	95.2%
Talus	50.0%	82.6%
Calcaneus	21.7%	90.5%
Navicular	87.0%	68.2%
Cuboid	31.8%	85.7%
Medial cuneiform	22.7%	95.2%
Middle cuneiform	18.2%	90.5%
Lateral cuneiform	18.2%	90.5%
Base of the second metatarsal	60.9%	82.6%
Shaft (diaphysis) of the second metatarsal	34.8%	90.5%
Base of the third metatarsal	39.1%	85.7%
Shaft (diaphysis) of the third metatarsal	17.4%	90.5%
Base of the fourth metatarsal	34.8%	90.5%
Shaft (diaphysis) of the fourth metatarsal	17.4%	90.5%
Base of the fifth metatarsal	82.6%	68.2%
Shaft (diaphysis) of the fifth metatarsal	43.5%	82.6%
Great toe/hallux sesamoids	65.2%	73.9%

Panellists rated on risk stratification and treatment recommendation for bone stress injuries of various injury sites. The level of agreement on high-risk stratification and non-surgical treatment recommendation is presented by injury site. Consensus was defined *a priori* by≥80% agreement. Colouring indicates consensus reached without any votes of disagreement (■), consensus with one or more disagreement votes (■) and failure to reach consensus (■).

mechanotransduction signalling pathways and fracture resistance mechanisms (eg, sacrificial bonding and dilatational band formation).[81–83]

Strength and limitations

The steering group invited a diverse group of experts and key stakeholders. To minimise risk of bias in voting members, experts were selected using objective criteria documented by peer-reviewed publications from multiple countries. The panel was supplemented by inviting stakeholders including athletes and coaches using pre-defined invitation criteria. However, a balanced view on the topic should not be taken for granted and the panel group may not necessarily reflect opinions of others. Also, differences in healthcare systems (eg, unequal access to modern imaging modalities) are a major challenge when defining universally accepted recommendations. To consider this limitation, terms like 'when accessible' or 'if feasible' were added to some consensus statements, acknowledging the varying healthcare resources around the globe. We used predefined criteria to improve diversity but did have more limited participation from certain geographic locations (eg, Africa and South America), coaches/athletes and from certain healthcare professions; in part, this reflects limited resources to publish on the topic. Furthermore, some topics such as the pathophysiology of bone stress injuries would benefit from in vivo studies, which represent higher evidence level as compared to expert consensus. Another limitation is the attrition in panellist participation, which may have been due to the length/comprehensiveness of the survey. This (modified) Delphi study differs from traditional approaches in that all 41 experts and stakeholders who agreed to participate in the consensus process were invited to vote in every round, regardless of their participation in previous rounds.

CONCLUSIONS

This Delphi study addresses key domains and topics in the field of bone stress injuries that required consensus due to recent advancements in research, for example, aspects of imaging modalities, training load monitoring, the interaction of low-energy availability with bone health and technological advancements in rehabilitation. In total, 36 experts and stakeholders from six continents reached consensus on 41 statements. Key areas of consensus include the terminology of bone stress injuries, assessment of underlying risk factors including those related to low energy availability, the risk stratification into low-risk and high-risk injuries and proposed treatment and rehabilitation algorithms. This consensus paper has placed emphasis on translational and clinical aspects. It outlines a multifactorial approach aiming to reduce risk of bone stress injuries and to promote bone health in athletes. Furthermore, clinical strategies for diagnosis, treatment and return to sport are presented. Finally, given that several topics (eg, psychosocial risk factors, pharmacological treatment strategies) failed to reach consensus, this study provides a framework for future bone stress injury research.

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REFERENCES

1 Seeman E, Delmas PD. Bone quality—the material and structural basis of bone strength and fragility. *N Engl J Med* 2006;354:2250–61.
2 Hoenig T, Ackerman KE, Beck BR, *et al*. Bone stress injuries. *Nat Rev Dis Primers* 2022;8.
3 Warden SJ, Hoenig T, Sventeckis AM, *et al*. Not all bone overuse injuries are stress fractures: it is time for updated terminology. *Br J Sports Med* 2023;57:76–7.
4 Hoenig T, Tenforde AS, Strahl A, *et al*. Does Magnetic Resonance Imaging Grading Correlate With Return to Sports After Bone Stress Injuries? A Systematic Review and Meta-analysis. *Am J Sports Med* 2022;50:834–44.
3 Hoenig T, Eissele J, Strahl A, *et al*. Return to sport following low-risk and high-risk bone stress injuries: a systematic review and meta-analysis. *Br J Sports Med* 2023;57:427–32.
6 Kelly S, Waring A, Stone B, *et al*. Epidemiology of bone injuries in elite athletics: A prospective 9-year cohort study. *Phys Ther Sport* 2024;66:67–75.
7 Tenforde A, Hoenig T, Saxena A, *et al*. Bone Stress Injuries in Runners Using Carbon Fiber Plate Footwear. *Sports Med* 2023;53:1499–505.
8 Rizzone KH, Ackerman KE, Roos KG, *et al*. The Epidemiology of Stress Fractures in Collegiate Student-Athletes, 2004-2005 Through 2013-2014 Academic Years. *J Athl Train* 2017;52:966–75.
9 Arendt E, Agel J, Heikes C, *et al*. Stress injuries to bone in college athletes: a retrospective review of experience at a single institution. *Am J Sports Med* 2003;31:959–68.
10 Fredericson M, Bergman AG, Hoffman KL, *et al*. Tibial stress reaction in runners. Correlation of clinical symptoms and scintigraphy with a new magnetic resonance imaging grading system. *Am J Sports Med* 1995;23:472–81.
11 Mountjoy M, Ackerman KE, Bailey DM, *et al*. 2023 International Olympic Committee's (IOC) consensus statement on Relative Energy Deficiency in Sport (REDs). *Br J Sports Med* 2023;57:1073–98.
12 Nunns M, House C, Rice H, *et al*. Four biomechanical and anthropometric measures predict tibial stress fracture: a prospective study of 1065 Royal Marines. *Br J Sports Med* 2016;50:1206–10.
13 Kliethermes SA, Stiffler-Joachim MR, Wille CM, *et al*. Lower step rate is associated with a higher risk of bone stress injury: a prospective study of collegiate cross country runners. *Br J Sports Med* 2021;55:851–6.
14 Soligard T, Schwellnus M, Alonso J-M, *et al*. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med* 2016;50:1030–41.
15 Schwellnus M, Soligard T, Alonso J-M, *et al*. How much is too much? (Part 2) International Olympic Committee consensus statement on load in sport and risk of illness. *Br J Sports Med* 2016;50:1043–52.
16 Tenforde AS, Sayres LC, McCurdy ML, *et al*. Identifying sex-specific risk factors for stress fractures in adolescent runners. *Med Sci Sports Exerc* 2013;45:1843–51.
17 Milgrom C, Simkin A, Eldad A, *et al*. Using bone's adaptation ability to lower the incidence of stress fractures. *Am J Sports Med* 2000;28:245–51.
18 Fredericson M, Ngo J, Cobb K. Effects of ball sports on future risk of stress fracture in runners. *Clin J Sport Med* 2005;15:136–41.
19 Nieves JW, Melsop K, Curtis M, *et al*. Nutritional Factors That Influence Change in Bone Density and Stress Fracture Risk Among Young Female Cross-Country Runners. *PM&R* 2010;2:740–50.

20 Sonneville KR, Gordon CM, Kocher MS, *et al*. Vitamin d, calcium, and dairy intakes and stress fractures among female adolescents. *Arch Pediatr Adolesc Med* 2012;166:595–600.
21 Yousuf MI. Using experts' opinions through Delphi technique. *Pract Assess Res Eval* 2007;12.
22 Paton BM, Court N, Giakoumis M, *et al*. London International Consensus and Delphi study on hamstring injuries part 1: classification. *Br J Sports Med* 2023;57:254–65.
23 Vicenzino B, de Vos R-J, Alfredson H, *et al*. ICON 2019—International Scientific Tendinopathy Symposium Consensus: There are nine core health-related domains for tendinopathy (CORE DOMAINS): Delphi study of healthcare professionals and patients. *Br J Sports Med* 2020;54:444–51.
24 Dijkstra HP, Mc Auliffe S, Ardern CL, *et al*. Oxford consensus on primary cam morphology and femoroacetabular impingement syndrome: part 1-definitions, terminology, taxonomy and imaging outcomes. *Br J Sports Med* 2022;57:325–41.
25 Gattrell WT, Logullo P, van Zuuren EJ, *et al*. ACCORD (Accurate COnsensus Reporting Document): A reporting guideline for consensus methods in biomedicine developed via a modified Delphi. *PLoS Med* 2024;21:e1004326.
26 Logullo P, van Zuuren EJ, Winchester CC, *et al*. ACcurate COnsensus Reporting Document (ACCORD) explanation and elaboration: Guidance and examples to support reporting consensus methods. *PLoS Med* 2024;21:e1004390.
27 Clayton MJ. Delphi: a technique to harness expert opinion for critical decision-making tasks in education. *Educ Psychol (Lond)* 1997;17:373–86.
28 Shrier I. Consensus statements that fail to recognise dissent are flawed by design: a narrative review with 10 suggested improvements. *Br J Sports Med* 2020.
29 Blazey P, Crossley KM, Ardern CL, *et al*. It is time for consensus on consensus statements. *Br J Sports Med* 2022;56:306–7.
30 Hayes V, O Donovan J. Women in Sports and Exercise Medicine: where are we now? *Br J Sports Med* 2023;57:498–9.
31 McBrydeJR AM. Stress fractures in athletes. *J Sports Med* 1975;3:212–7.
32 Hughes JM, Popp KL, Yanovich R, *et al*. The role of adaptive bone formation in the etiology of stress fracture. *Exp Biol Med (Maywood)* 2017;242:897–906.
33 Edwards WB. Modeling Overuse Injuries in Sport as a Mechanical Fatigue Phenomenon. *Exerc Sport Sci Rev* 2018;46:224–31.
34 Kaeding CC, Miller T. The Comprehensive Description of Stress Fractures: A New Classification System. *J Bone Joint Surg Am* 2013;95:1214–20.
35 Goodwin J. The importance of clinical skills. *BMJ* 1995;310:1281–2.
36 Hegedus EJ, Mulligan EP, Beer BA, *et al*. How Advancement in Bone Science Should Inform the Examination and Treatment of Femoral Shaft Bone Stress Injuries in Running Athletes. *Sports Med* 2023;53:1117–24.
37 Nussbaum ED, Gatt CJ Jr, Bjornarra J, *et al*. Evaluating the Clinical Tests for Adolescent Tibial Bone Stress Injuries. *Sports Health* 2021;13:502–10.
38 Nattiv A, Kennedy G, Barrack MT, *et al*. Correlation of MRI grading of bone stress injuries with clinical risk factors and return to play: a 5-year prospective study in collegiate track and field athletes. *Am J Sports Med* 2013;41:1930–41.
39 Beekman KM, Kuijer P, Maas M. Imaging of Overuse Injuries of the Ankle and Foot in Sport and Work. *Radiol Clin North Am* 2023;61:307–18.
40 Rolvien T, Krause M, Zustin J, *et al*. Intra-articular osteoid osteoma accompanied by extensive bone marrow edema. A clinical and micro-morphological analysis. *J Bone Oncol* 2019;18:100256.
41 Saxena A, Fullem B, Hannaford D. Results of treatment of 22 navicular stress fractures and a new proposed radiographic classification system. *J Foot Ankle Surg* 2000;39:96–103.
42 Katakura M, Mitchell AWM, Lee JC, *et al*. Is it time to replace CT with T1-VIBE MRI for the assessment of musculoskeletal injuries? *Bone Joint J* 2020;102-B:1435–7.
43 Kiuru MJ, Niva M, Reponen A, *et al*. Bone stress injuries in asymptomatic elite recruits: a clinical and magnetic resonance imaging study. *Am J Sports Med* 2005;33:272–6.
44 Tenforde AS, Outerleys J, Bouxsein ML, *et al*. Metatarsal Bone Marrow Edema on Magnetic Resonance Imaging and Its Correlation to Bone Stress Injuries in Male Collegiate Basketball Players. *Orthop J Sports Med* 2022;10:23259671211063505.
45 Warden SJ, Edwards WB, Willy RW. Preventing Bone Stress Injuries in Runners with Optimal Workload. *Curr Osteoporos Rep* 2021;19:298–307.
46 Burr DB, Martin RB, Schaffler MB, *et al*. Bone remodeling in response to in vivo fatigue microdamage. *J Biomech* 1985;18:189–200.
47 Stürznickel J, Hinz N, Delsmann MM, *et al*. Impaired Bone Microarchitecture at Distal Radial and Tibial Reference Locations Is Not Related to Injury Site in Athletes With Bone Stress Injury. *Am J Sports Med* 2022;50:3381–9.
48 Torstveit MK, Ackerman KE, Constantini N, *et al*. Primary, secondary and tertiary prevention of Relative Energy Deficiency in Sport (REDs): a narrative review by a subgroup of the IOC consensus on REDs. *Br J Sports Med* 2023;57:1119–26.
49 Heikura IA, Uusitalo ALT, Stellingwerff T, *et al*. Low Energy Availability Is Difficult to Assess but Outcomes Have Large Impact on Bone Injury Rates in Elite Distance Athletes. *Int J Sport Nutr Exerc Metab* 2018;28:403–11.
50 Tenforde AS, Carlson JL, Chang A, *et al*. Association of the Female Athlete Triad Risk Assessment Stratification to the Development of Bone Stress Injuries in Collegiate Athletes. *Am J Sports Med* 2017;45:302–10.
51 Roche M, Nattiv A, Sainani K, *et al*. Higher Triad Risk Scores Are Associated With Increased Risk for Trabecular-Rich Bone Stress Injuries in Female Runners. *Clin J Sport Med* 2023;33:631–7.
52 Loucks AB. Low energy availability in the marathon and other endurance sports. *Sports Med* 2007;37:348–52.
53 Wright AA, Taylor JB, Ford KR, *et al*. Risk factors associated with lower extremity stress fractures in runners: a systematic review with meta-analysis. *Br J Sports Med* 2015;49:1517–23.
54 Stellingwerff T, Mountjoy M, McCluskey WT, *et al*. Review of the scientific rationale, development and validation of the International Olympic Committee Relative Energy Deficiency in Sport Clinical Assessment Tool: V.2 (IOC REDs CAT2)-by a subgroup of the IOC consensus on REDs. *Br J Sports Med* 2023;57:1109–18.
55 Hoenig T, Saxena A, Rice HM, *et al*. Navigating the challenges and opportunities with 'super shoes': balancing performance gains with injury risk. *Br J Sports Med* 2023;57:1472–3.
56 Ridge ST, Johnson AW, Mitchell UH, *et al*. Foot bone marrow edema after a 10-wk transition to minimalist running shoes. *Med Sci Sports Exerc* 2013;45:1363–8.
57 Edwards WB, Taylor D, Rudolphi TJ, *et al*. Effects of stride length and running mileage on a probabilistic stress fracture model. *Med Sci Sports Exerc* 2009;41:2177–84.
58 Nigg BM, Baltich J, Hoerzer S, *et al*. Running shoes and running injuries: mythbusting and a proposal for two new paradigms: 'preferred movement path' and 'comfort filter.' *Br J Sports Med* 2015;49:1290–4.
59 Warden SJ, Edwards WB, Willy RW. Optimal Load for Managing Low-Risk Tibial and Metatarsal Bone Stress Injuries in Runners: The Science Behind the Clinical Reasoning. *J Orthop Sports Phys Ther* 2021;51:322–30.
60 Kelsey JL, Bachrach LK, Procter-Gray E, *et al*. Risk factors for stress fracture among young female cross-country runners. *Med Sci Sports Exerc* 2007;39:1457–63.
61 Barrack MT, Fredericson M, Tenforde AS, *et al*. Evidence of a cumulative effect for risk factors predicting low bone mass among male adolescent athletes. *Br J Sports Med* 2017;51:200–5.
62 Nattiv A, Loucks AB, Manore MM, *et al*. American College of Sports Medicine position stand. The female athlete triad. *Med Sci Sports Exerc* 2007;39:1867–82.
63 Jonvik KL, Torstveit MK, Sundgot-Borgen J, *et al*. Do we need to change the guideline values for determining low bone mineral density in athletes? *J Appl Physiol (1985)* 2022;132:1320–2.
64 Dolan E, Dumas A, Keane KM, *et al*. The Bone Biomarker Response to an Acute Bout of Exercise: A Systematic Review with Meta-Analysis. *Sports Med* 2022;52:2889–908.
65 Ben-Sasson SA, Finestone A, Moskowitz M, *et al*. Extended duration of vertical position might impair bone metabolism. *Eur J Clin Invest* 1994;24:421–5.
66 Novacheck TF. The biomechanics of running. *Gait & Posture* 1998;7:77–95.
67 Van Hooren B, Jukic I, Cox M, *et al*. The Relationship Between Running Biomechanics and Running Economy: A Systematic Review and Meta-Analysis of Observational Studies. *Sports Med* 2024;54:1269–316.
68 Boden BP, Osbahr DC. High-risk stress fractures: evaluation and treatment. *J Am Acad Orthop Surg* 2000;8:344–53.
69 Roche AJ, Calder JDF. Treatment and return to sport following a Jones fracture of the fifth metatarsal: a systematic review. *Knee Surg Sports Traumatol Arthrosc* 2013;21:1307–15.
70 Rohena-Quinquilla IR, Rohena-Quinquilla FJ, Scully WF, *et al*. Femoral Neck Stress Injuries: Analysis of 156 Cases in a U.S. Military Population and Proposal of a New MRI Classification System. *Am J Roentgenol* 2018;210:601–7.
71 Chaudhry ZS, Raikin SM, Harwood MI, *et al*. Outcomes of Surgical Treatment for Anterior Tibial Stress Fractures in Athletes: A Systematic Review. *Am J Sports Med* 2019;47:232–40.
72 Oji DE. Foot and Ankle High-Risk Injuries. New York: Springer Publishing Company, 2021:81–100.
73 Miller TL, Kaeding CC, Rodeo SA. Emerging Options for Biologic Enhancement of Stress Fracture Healing in Athletes. *J Am Acad Orthop Surg* 2020;28:1–9.
74 Lavigne A, Chicoine D, Esculier J-F, *et al*. The Role of Footwear, Foot Orthosis, and Training-Related Strategies in the Prevention of Bone Stress Injuries: A Systematic Review and Meta-Analysis. *Int J Exerc Sci* 2023;16:721–43.
75 Liem BC, Truswell HJ, Harrast MA. Rehabilitation and return to running after lower limb stress fractures. *Curr Sports Med Rep* 2013;12:200–7.
76 Tenforde AS, Watanabe LM, Moreno TJ, *et al*. Use of an Antigravity Treadmill for Rehabilitation of a Pelvic Stress Injury. *PM&R* 2012;4:629–31.
77 Vincent HK, Madsen A, Vincent KR. Role of Antigravity Training in Rehabilitation and Return to Sport After Running Injuries. *Arthroscopy Sports Med Rehab* 2022;4:e141–9.
78 Warden SJ, Davis IS, Fredericson M. Management and prevention of bone stress injuries in long-distance runners. *J Orthop Sports Phys Ther* 2014;44:749–65.
79 Ihle R, Loucks AB. Dose-response relationships between energy availability and bone turnover in young exercising women. *J Bone Miner Res* 2004;19:1231–40.
80 Fensham NC, Heikura IA, McKay AKA, *et al*. Short-Term Carbohydrate Restriction Impairs Bone Formation at Rest and During Prolonged Exercise to a Greater Degree than Low Energy Availability. *J Bone Miner Res* 2022;37:1915–25.
81 Hendrickx G, Fischer V, Liedert A, *et al*. Piezo1 Inactivation in Chondrocytes Impairs Trabecular Bone Formation. *J Bone Miner Res* 2021;36:369–84.
82 Thompson JB, Kindt JH, Drake B, *et al*. Bone indentation recovery time correlates with bond reforming time. *Nature New Biol* 2001;414:773–6.
83 Burr DB, Forwood MR, Fyhrie DP, *et al*. Bone Microdamage and Skeletal Fragility in Osteoporotic and Stress Fractures. *J Bone Miner Res* 1997;12:6–15.