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Scaphoid Fractures in Athletes: Diagnostic Pitfalls and Return-to-Sport Strategies - a narrative review

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Abstract

Background. The scaphoid is the most frequently fractured carpal bone and is disproportionately common in athletes exposed to falls on an outstretched hand or direct impact to the wrist. Its retrograde, predominantly distal-to-proximal blood supply makes the fracture prone to diagnostic delay, nonunion, and avascular necrosis, while the athlete's imperative to return quickly to competition creates persistent tension between imaging accuracy, treatment choice, and timing of return to sport.

Aim. To synthesise, critically and comparatively, the diagnostic pathway, treatment options, and return-to-sport considerations for scaphoid fractures in athletic populations, with emphasis on the medical rationale behind imaging strategies, operative versus conservative management, and their documented functional consequences.

Materials and Methods. This narrative review draws on peer-reviewed epidemiological studies, cohort series, randomised controlled trials, systematic reviews and meta-analyses, diagnostic accuracy studies, artificial-intelligence validation studies, biomechanical studies, and international consensus statements.

Results. Diagnostic accuracy varies substantially across radiography, CT, MRI, bone scintigraphy, ultrasound, cone-beam CT and artificial-intelligence-assisted reading, with

important trade-offs in sensitivity, specificity, cost, and time to diagnosis. Surgical fixation generally accelerates radiographic union and return to sport relative to cast immobilisation, but the evidence for superior long-term functional outcomes is inconsistent, and nonunion, smoking status, and fracture displacement modify these effects.

Conclusions. Optimal management of the athlete with a suspected or confirmed scaphoid fracture requires individualised integration of imaging accuracy, fracture stability, sport-specific demands, and rigorously defined return-to-sport criteria, rather than a uniform diagnostic or therapeutic algorithm.

Keywords: scaphoid fracture; sports injury; wrist trauma; return to sport; diagnostic imaging; nonunion; internal fixation; athletes

1. Introduction

The scaphoid bridges the proximal and distal carpal rows and, by virtue of this unique anatomical and biomechanical position, is exposed to substantial stress during any activity that loads the wrist in extension and radial deviation [1,2]. It is the most commonly fractured carpal bone, accounting for 60–70% of carpal fractures and an estimated 2–7% of all skeletal fractures, with an annual incidence in Western populations of approximately five fractures per 10,000 inhabitants, although the true incidence is thought to be underestimated because of the diagnostic difficulty the fracture characteristically presents [1,3]. The typical patient is a young, active male between 15 and 30 years of age injured by a fall onto an outstretched hand, a mechanism that is itself intimately connected with athletic activity [2,4,5]. Sport-related trauma is estimated to account for roughly one-third of scaphoid fractures in some series, and specific sports characterised by high-velocity falls or direct wrist impact — American football, basketball, rugby, cycling, and skateboarding — carry a disproportionate share of this burden [2,5,6].

The clinical significance of the scaphoid fracture is inseparable from its vascular anatomy. Approximately 70–80% of the bone's surface is covered by articular cartilage, leaving a narrow non-articular corridor through which the dominant blood supply — retrograde branches of the radial artery entering at the dorsal ridge — must penetrate [1,3,5,7]. This anatomical arrangement means the proximal pole is nourished only via intraosseous flow from the distal pole, so a fracture at or near the waist interrupts the very supply on which proximal-pole healing depends [4,5,7]. The clinical consequence is a fracture that is unusually vulnerable to delayed union,

nonunion, and avascular necrosis, complications reported in a substantial minority of cases and capable of setting in motion a well-described, essentially inevitable progression toward degenerative wrist arthritis if the fracture is not recognised and adequately treated [1,4,7,8].

Two clinical realities compound one another in the athletic population. First, the diagnostic yield of the conventional first-line investigation — plain radiography — is limited: initial radiographs are reported to miss occult fractures in a substantial proportion of true cases, with occult-fracture rates ranging from single figures up to and beyond one-fifth of clinically suspected injuries depending on the population and reference standard used [2,9,10]. Second, athletes and their medical teams face powerful incentives to minimise time away from training and competition, which can encourage either premature return to play in a cast or, conversely, pressure toward surgical fixation on the assumption — not always borne out by the evidence — that operative treatment reliably shortens time to return [5,6,11]. These two pressures, diagnostic uncertainty and the drive for rapid return to sport, together define the central clinical problem that this review addresses.

The purpose of this narrative review is to synthesise, from a clinically oriented and comparative perspective, the diagnostic pathway for suspected scaphoid fractures in athletes, the evidence for and against the principal treatment strategies, and the criteria that inform safe and evidence-based return to sport. The review is structured to move from anatomy and epidemiology, through the comparative diagnostic accuracy of imaging modalities (including emerging artificial-intelligence tools), to fracture classification, conservative and surgical treatment, the management of nonunion, and finally the specific evidence base on return-to-sport rates and timing. Throughout, particular attention is paid to methodological heterogeneity across studies — differences in reference standards, definitions of union, follow-up duration, and study design — because these differences are frequently the explanation for apparently conflicting conclusions in the literature.

2. Materials and Methods

This article was conceived as a narrative review rather than a systematic review, and accordingly no review protocol was registered, no formal risk-of-bias instrument was applied across the included literature, and no quantitative pooling or meta-analytic synthesis was undertaken. The literature underpinning this review comprises peer-reviewed, predominantly English-language publications addressing scaphoid fracture diagnosis, classification, treatment, and outcomes,

including epidemiological and injury-surveillance studies, prospective and retrospective cohort and case series, randomised controlled trials, systematic reviews and meta-analyses, diagnostic accuracy and cost-effectiveness studies, artificial-intelligence validation and observer studies, a large-scale target-trial emulation using electronic health record data, biomechanical and histological investigations of fracture healing, consensus and protocol documents relevant to sports injury surveillance and reporting, and clinically oriented reviews and case reports illustrating athlete-specific management dilemmas. Sources were selected for their relevance to the diagnosis, treatment, and sport-specific outcomes of scaphoid fractures, prioritising methodological transparency and, where available, direct comparison between diagnostic or therapeutic strategies. Evidence was grouped thematically into the following domains: anatomy, epidemiology, and injury mechanism; clinical assessment and diagnostic accuracy of imaging modalities; the emerging role of artificial intelligence in fracture detection; classification systems and their prognostic implications; conservative management; surgical management and comparative trials; the specific problem of nonunion, its prediction, and its surgical correction; systemic and adjunctive interventions to promote union; injury-surveillance methodology relevant to return-to-sport reporting; and the athlete-specific evidence on return-to-sport rates, timing, and functional outcomes. Because source selection and thematic grouping were, by design, undertaken narratively rather than systematically, this review is subject to selection and emphasis bias, and its synthesis should be read as a clinically reasoned overview of the available evidence rather than an exhaustive or formally graded appraisal.

3. Anatomy and Biomechanics Relevant to Fracture Risk

Understanding why the scaphoid fractures the way it does, and why those fractures behave so unpredictably once they occur, requires attention to both its shape and its blood supply. The scaphoid links the proximal and distal carpal rows and, through this linkage, transmits load between the hand and forearm across nearly every position of wrist motion [1,5,7]. Its "boat-like" shape and oblique orientation mean that roughly 80% of its surface is covered in articular cartilage, a proportion consistently reported across independent anatomical descriptions, leaving only a narrow non-articular window — principally the dorsal ridge — through which nutrient vessels can enter [1,3-5,7].

The dominant vascular supply arises from the dorsal carpal branch of the radial artery, which enters at the dorsal ridge and, by retrograde flow, supplies an estimated 70–80% of the bone, including the entire proximal pole; a smaller palmar contribution from the superficial palmar arch enters via the distal tubercle and supplies mainly the distal pole independently [1,3-5,7]. Because the proximal pole has no independent arterial inflow and depends entirely on intraosseous flow travelling backward from the distal fragment, a fracture through the waist or proximal third of the bone can sever the only route by which the proximal fragment receives its blood, explaining the well-documented association between fracture level and risk of avascular necrosis and nonunion [1,3-5,7]. This vascular anatomy is not a minor technical detail: it is the single most important determinant of why scaphoid fractures, unlike most other carpal injuries, so often progress to nonunion when treatment is delayed or inadequate, and why proximal fractures are treated with a lower threshold for surgical intervention than waist or distal fractures across virtually every management algorithm discussed later in this review [4,5,7].

The typical injury mechanism — a fall onto an outstretched hand with the wrist in radial deviation and dorsiflexion — causes the scaphoid to impact against the concavity of the distal radius, generating tensile failure at the volar cortex that propagates dorsally in compression, with the fracture most often occurring near the waist [3-5,11]. Falls occurring with the wrist in greater abduction are associated with a higher likelihood of proximal-pole fracture, and axial loading through a clenched fist (as in a "boxer's" mechanism) has also been described as a contributing mechanism, alongside direct axial loading of the wrist more broadly [2,3,5]. Notably, the same fall-on-outstretched-hand mechanism that produces supracondylar humeral fractures in children and distal radius or other carpal fractures in older adults produces scaphoid fractures preferentially in young, skeletally mature adults, an age-dependent pattern attributed to the relative strength of the ligamentous and metaphyseal structures at different life stages [3].

4. Epidemiology in the Athletic Population

Scaphoid fractures predominantly affect young, active men, and this demographic overlap with competitive and recreational sport is central to understanding why the injury looms so large in sports medicine. Descriptive epidemiological work situates the mean age of injury in the range of 27–29 years across mixed civilian populations, with a clear male predominance and falls on the outstretched hand as the leading mechanism in roughly half to two-thirds of cases [4,5,12]. A

systematic review and meta-analysis of return to sport following scaphoid fractures, synthesising eleven studies published between 1979 and 2014, reported mean ages at injury ranging from 17.3 to 31.0 years across the different case series and cohorts included, with 77% of the 170 fractures in the pooled dataset occurring in male athletes; the most frequently represented sports were American football, soccer, baseball, and basketball [6].

Sport-specific series corroborate this pattern in more granular detail. A narrative account of scaphoid fractures in the athlete estimated that approximately one in one hundred athletes participating in collegiate American football will sustain a scaphoid fracture during their playing career, and identified football and basketball as sports in which high-impact loading of the wrist is a recurrent hazard [5]. A clinical review focused on epidemiology, anatomy, and diagnostic strategy similarly identified soccer, basketball, and cycling as sports with disproportionate representation among sport-associated scaphoid fractures, and further noted sex-specific patterns, with football, rugby, and basketball featuring prominently among men and roller-skating and skateboarding among women [2].

Beyond the wrist itself, injury-surveillance data from Major League and Minor League Baseball illustrate how scaphoid fractures fit within the broader landscape of hand and wrist trauma in professional sport. Across the 2011–2016 seasons, a centralised injury-tracking system recorded 4,478 hand and 1,748 wrist injuries across all Major League Baseball (MLB) and Minor League Baseball (MiLB) clubs, resulting in a cumulative 105,246 days out of play — equivalent to the length of 575 individual MLB player-seasons [13]. Within this dataset, scaphoid fractures were a comparatively rare but functionally significant diagnosis: only ten scaphoid fractures were recorded among wrist injuries (0.6% of all wrist diagnoses), yet these carried a mean of 73.5 days missed per injury (the longest mean time-loss of any listed wrist diagnosis in that series) and required surgical fixation in 60% of cases, second only to hook-of-hamate fractures (72.4% surgical rate) among wrist injuries in that cohort [13]. This dataset, while numerically small for scaphoid fractures specifically, offers an unusually rigorous, prospectively collected illustration of the disproportionate time-loss burden that even a small number of scaphoid injuries impose on a professional sporting organisation, and reinforces the broader point that most hand and wrist injuries in this population (72% hand versus 28% wrist in the same series) are contact-related and traumatic rather than degenerative in origin [13].

5. Clinical Presentation and the Limits of Physical Examination

Clinicians confronted with an athlete after a fall on the outstretched hand must rely initially on history and examination, and the literature is consistent in describing a triad of findings — tenderness in the anatomical snuffbox, tenderness over the scaphoid tubercle, and pain on longitudinal compression of the thumb — as the principal clinical tests for suspected scaphoid fracture [2-4,7]. Reported sensitivities for these individual signs are frequently high: one review reported each of the three tests reaching a sensitivity as high as 100% in isolation, but with specificity falling as low as 9% for snuffbox tenderness, 30% for tubercle tenderness, and 48% for axial thumb compression, with combined-sign specificity improving to around 74% when all three are considered together [3]. A separate review of the athletic literature likewise reported that overall sensitivity of clinical examination is high but specificity approaches only 74–80%, with a reported positive predictive value as low as 21% [10]. Other reports of individual tests diverge further: one series found tenderness at the scaphoid tubercle to have a sensitivity of 95.2% and specificity of 74.1%, whereas anatomical snuffbox tenderness had a sensitivity of 85.7% but a specificity of only 29.6%, and axial compression performed worst of the three with sensitivity of 42.9% and specificity of 29.6% [10].

This spread of reported values across different series is itself instructive: it demonstrates that clinical examination, while excellent for excluding fracture when entirely negative (a point reinforced by the very high sensitivities reported), is a poor discriminator once a positive sign is elicited, because the specificity is consistently low regardless of which individual sign or combination is examined [2-4,10]. In practical terms, this means the athlete's initial clinical assessment reliably identifies who requires imaging, but does not by itself establish whether a fracture is truly present — the burden of diagnostic confirmation therefore falls almost entirely on imaging, a point the following section addresses in detail.

A separate diagnostic complication specific to sport is that athletes frequently continue competing after the injurious event, either because pain is initially tolerable or because of pressure — internal or external — to remain on the field, and this delayed presentation is repeatedly identified in case reports and reviews as a factor contributing to missed or delayed diagnosis [5,11]. A case report of a collegiate basketball player illustrates this pattern directly: the athlete continued to play after her injury, was initially diagnosed with a wrist sprain based on

radiographs read as negative at an outside facility, and only received a correct diagnosis of a displaced scaphoid waist fracture two months later when persistent pain prompted repeat evaluation [11]. Reviews addressing scaphoid fractures specifically in athletes note that this scenario — continued play, an initial radiographically "negative" wrist sprain diagnosis, and subsequent presentation with chronic pain — is a recurring and preventable pattern of delayed diagnosis in this population [5].

6. Diagnostic Imaging: Comparative Accuracy of Modalities

Table 1 summarises representative studies of diagnostic imaging accuracy for scaphoid fracture detection.

Table 1. Representative studies of diagnostic imaging accuracy for scaphoid fracture detection.

Source [ref]	Design	Population / focus	Principal findings
Neubauer et al. [1]	Retrospective diagnostic accuracy study	102 patients, CT vs radiography	CT sensitivity 93% (p=0.019), specificity 96% (p<0.001) vs radiography
Mallee et al. [14]	Cochrane systematic review and meta-analysis (11 studies)	Suspected fractures, negative initial radiographs	Bone scintigraphy sensitivity 0.99, specificity 0.86; CT sensitivity 0.72, specificity 0.99; MRI sensitivity 0.88, specificity 1.00
Bäcker et al. [10]	Systematic review and meta-analysis (42 studies, 2,507 patients)	Clinically suspected scaphoid fracture	MRI sensitivity 94.2%, specificity 97.9%; CT sensitivity 81.5%, specificity 96.0%; occult fracture rate 21.8%
Maciejowski et al. [1]	Systematic review (6	CBCT diagnostic	CBCT sensitivity

	studies, 335 patients)	performance	88.9–100%, specificity 96–100%; median effective dose 3.65–4.3 microsieverts
Kraus et al. [15]	Systematic review and diagnostic test accuracy meta- analysis (10 studies, 7 pooled)	AI/CNN detection on plain radiographs	Pooled sensitivity 0.80, specificity 0.89, SROC AUC 0.88; individual study AUC range 0.77–0.96
Hernández Ferrer et al. [16]	Real-world observational study	264 patients, straightforward vs complex diagnostic cases	AI assistance improved accuracy significantly only in diagnostically complex/occult cases
Hendrix et al.	Multicentre validation and observer study	219 cases, 5 musculoskeletal radiologists	AI AUC 0.88 vs radiologists' mean AUC 0.87; AI assistance reduced reading time but not accuracy for most readers
Dareez et al. [17]	Case series (3 patients)	DECT virtual non- calcium imaging	DECT VNCa detected bone marrow oedema in 2 of 2 true fractures, confirmed by MRI

6.1. Conventional radiography

Plain radiography remains the near-universal first-line investigation because of its low cost, wide availability, and low radiation dose, but its sensitivity for acute scaphoid fracture is limited and inconsistently reported across studies. A frequently cited figure places radiographic sensitivity at

approximately 70%, meaning that up to 30% of true scaphoid fractures may not be visible on initial films [3,4]. Other reviews report a comparable but slightly lower range of 66–81%, with occult fracture rates of up to 50% depending on which studies are pooled [15]. A systematic review and meta-analysis focused specifically on diagnostic accuracy across imaging modalities found a mean sensitivity of only 65–70% for plain radiography compared with bone scintigraphy, and reported an overall occult-fracture incidence of 21.8% (standard deviation 9.81) across 42 included studies encompassing 2,507 patients — an increase of 5.8 percentage points compared with earlier published estimates, which the authors attributed at least in part to genuine improvements in the sensitivity of comparator advanced-imaging techniques over time rather than to a true rise in the underlying occult-fracture rate [10].

Radiographic technique itself is a recognised source of variability. Standard teaching recommends at least four dedicated views — posteroanterior, lateral, oblique, and a dedicated scaphoid (ulnar-deviated posteroanterior) view — because a nondisplaced fracture will only be visualised if the X-ray beam happens to be oriented parallel to the fracture line [3,4]. Even with these dedicated views, a substantial proportion of radiographically negative but clinically suspected fractures will subsequently prove positive on further imaging or follow-up: in one prospective cohort of adults with acute wrist injury, sixty-eight of 893 patients (7.6%) were eventually diagnosed with a scaphoid fracture, and of these, fourteen (21%) were diagnosed only during follow-up rather than on initial radiographs [18].

6.2. Bone scintigraphy

Bone scintigraphy has historically been positioned as the most sensitive second-line test for occult scaphoid fracture, with sensitivities reported close to 100% in several series, but at the cost of lower and more variable specificity [3,10,14]. A Cochrane systematic review and meta-analysis of computed tomography, magnetic resonance imaging, and bone scintigraphy for clinically suspected fractures with negative initial radiographs pooled data from eleven included studies (four evaluating CT, five evaluating MRI, and six evaluating bone scintigraphy) and reported summary sensitivity and specificity of 0.99 (95% confidence interval [CI] 0.69–1.00) and 0.86 (95% CI 0.73–0.94) respectively for bone scintigraphy, compared with 0.72 (95% CI 0.36–0.92) and 0.99 (95% CI 0.71–1.00) for CT, and 0.88 (95% CI 0.64–0.97) and 1.00 (95% CI 0.38–1.00) for MRI [14]. Statistically, this Cochrane analysis found that the diagnostic odds ratio

of bone scintigraphy was significantly higher than both CT and MRI, reflecting its markedly superior sensitivity, even though its specificity was numerically the lowest of the three modalities [14]. The clinical implication of this trade-off is substantial: applying these pooled estimates to a hypothetical cohort of 1,000 patients with a median 20% prevalence of true fracture, the Cochrane review calculated that bone scintigraphy would miss only 2 fractures but generate 112 cases of unnecessary treatment, compared with 56 missed fractures and 8 unnecessary treatments for CT, and 24 missed fractures and 0 unnecessary treatments for MRI [14]. In other words, a modality selected purely to minimise missed fractures (bone scintigraphy) does so at the cost of a substantially higher rate of overtreatment than a modality selected to minimise false positives (MRI), and the "best" choice depends heavily on which error a given clinical service is more willing to tolerate.

A separate meta-analysis, updating and extending earlier reviews with the inclusion of six additional studies not previously analysed, similarly found bone scintigraphy to have the highest sensitivity of the four modalities compared (92.8%, standard deviation 11.4), narrowly ahead of MRI (94.2%, standard deviation 10.7) once the additional studies were incorporated, but with specificity for bone scintigraphy (90.9%, standard deviation 11.8) lower than that for both MRI (97.9%, standard deviation 4.7) and CT (96.0%, standard deviation 4.8) [10]. Practical drawbacks specific to bone scintigraphy — the need for intravenous radioactive isotope injection, a mandatory delay of at least 72 hours after injury to allow osteoblastic uptake to develop, higher radiation exposure than CT, and reduced suitability in children — are consistently identified across reviews as reasons the modality has fallen out of routine use despite its high sensitivity, with the same Cochrane review explicitly recommending against its use given these limitations combined with the substantial overtreatment burden imposed by its comparatively low specificity [3,10,14].

6.3. Computed tomography

Computed tomography (CT) offers rapid acquisition, wide availability in emergency settings, low cost relative to MRI, and excellent depiction of cortical involvement and displacement, which makes it particularly valuable for surgical planning once a fracture has been identified [3,4,7]. Diagnostic accuracy for detecting the fracture itself, however, is more modest than for MRI or bone scintigraphy. The Cochrane meta-analysis reported pooled CT sensitivity of 0.72 (95% CI

0.36–0.92), while a separate meta-analysis reported CT sensitivity of 81.5% (standard deviation 14.0), an improvement from the 72% previously reported in older syntheses, alongside a specificity of 96.0% (standard deviation 4.8) — the second-highest specificity of the four modalities compared, behind only MRI [10,14]. A further consideration for CT accuracy is imaging technique: comparing dedicated scaphoid-plane sequences against generic wrist CT protocols, one series reported sensitivity of only 33% and specificity of 89% for a general wrist CT protocol, compared with 67% sensitivity and 95% specificity when the CT was specifically reformatted along the longitudinal axis of the scaphoid, underscoring that CT accuracy figures reported in the aggregate literature likely understate the performance achievable with correct scaphoid-specific technique [10].

CT is also central to fracture healing assessment and surgical decision-making after initial diagnosis, given its superior depiction of trabecular bridging compared with plain film [4,5,7]. A comparative CT-versus-radiography study specifically addressing diagnostic accuracy for scaphoid fracture (rather than union assessment) reported sensitivity of 93% ($p=0.019$) and specificity of 96% ($p<0.001$) for CT in a retrospective analysis of 102 patients, representing a statistically significant improvement over standard radiography in the same cohort [1]. Cone-beam CT (CBCT), a technologically distinct low-dose variant of CT that uses a cone-shaped beam and flat-panel detector rather than the fan-beam geometry of conventional multidetector CT, has more recently emerged as a candidate technology combining much of the diagnostic accuracy of CT with a substantially lower radiation dose; this modality is addressed separately in Section 7, given the volume and specificity of the recent evidence base concerning it.

6.4. Magnetic resonance imaging

MRI is widely regarded across the literature as the single most accurate non-invasive modality for scaphoid fracture detection, and several reviews explicitly describe it as the reference or "gold" standard for ruling occult fracture in or out [3,7,10]. The systematic review by Bäckér and colleagues, pooling twelve studies encompassing 548 patients, reported MRI sensitivity of 94.2% (standard deviation 10.7) and specificity of 97.9% (standard deviation 4.7), both the highest values recorded among the four modalities compared in that synthesis, an improvement from the 88% sensitivity reported in prior reviews [10]. The Cochrane meta-analysis similarly found MRI specificity to approach unity (1.00, 95% CI 0.38–1.00), although its confidence interval for

specificity was notably wide, reflecting the smaller number of pooled studies for this modality [14].

Timing and technical parameters materially affect MRI's diagnostic yield. Studies comparing MRI performed within 24 hours of injury against imaging performed at approximately 10 days found no meaningful difference in sensitivity attributable to timing alone [10]. However, the choice of MRI sequence appears to matter considerably: one study comparing contrast-enhanced (gadolinium) against unenhanced MRI sequences found the enhanced protocol achieved sensitivity of 83% and specificity of 100%, compared with only 67% and 67% respectively for unenhanced sequences, a statistically significant difference [10]. False negatives on MRI have been attributed to short scanning protocols (as brief as seven minutes), diffusion of contrast agent from adjacent soft tissue mimicking a fracture signal, and misinterpretation of bone bruising or normal vascular channels for a fracture line [10]. Cost-effectiveness analyses have consistently found that despite its higher per-scan cost, immediate MRI reduces overall societal cost by avoiding unnecessary prolonged immobilisation, serial clinic visits, and repeat radiography in patients who ultimately prove not to have a fracture, with one randomised controlled trial (the SMaRT trial, discussed in detail in Section 6.6) directly quantifying this trade-off in a UK emergency-department population [7,10,19].

6.5. Ultrasound

Ultrasound occupies a smaller and more contested role in scaphoid fracture diagnosis than the other modalities discussed. The systematic review by Bäckér and colleagues pooled ten studies encompassing 589 patients and found ultrasound sensitivity of 81.5% (standard deviation 21.2) — statistically indistinguishable from CT sensitivity (81.5%, standard deviation 14.0) in the same analysis — but specificity of only 77.4% (standard deviation 18.5), significantly lower than that of MRI, CT, or bone scintigraphy [10]. The interpretation of ultrasound findings was noted to be strongly dependent on operator experience, and the modality's role in routine clinical diagnosis of occult fracture remains, by the authors' own characterisation, still under active investigation rather than established as a standard diagnostic tool [3,10]. The wide standard deviation around both sensitivity and specificity estimates for ultrasound, larger proportionally than for any of the other three modalities, itself signals substantial heterogeneity in how the technique is applied and

interpreted across different centres and operators, a caveat that should temper any confident clinical recommendation based on pooled ultrasound accuracy figures.

6.6. Comparative and health-economic considerations: the SMaRT trial

Beyond isolated diagnostic accuracy figures, the Scaphoid Magnetic Resonance Imaging in Trauma (SMaRT) trial offers a rare randomised, prospective, non-blinded comparison of an immediate-MRI diagnostic pathway against standard radiograph-only management in the emergency department, explicitly designed to quantify both clinical and cost implications [19]. In this trial, 132 patients with a suspected scaphoid fracture and negative initial radiographs were randomised either to a control pathway (radiographs only in the emergency department, with subsequent standard fracture-clinic follow-up) or to an intervention pathway receiving an additional immediate short-sequence MRI during the same emergency-department visit [19]. The trial found no statistically significant difference in the number of scaphoid fractures detected between groups (four of 65 in the control group versus seven of 67 in the intervention group, $p=0.372$), but a statistically significant increase in the detection of other (non-scaphoid) fractures in the MRI arm (five of 65 versus fifteen of 67, $p=0.019$), and markedly superior diagnostic accuracy for the immediate-MRI pathway, with accuracy for scaphoid fracture detection alone of 100.0% versus 93.8% for the control pathway, and accuracy for any fracture of 98.5% versus 84.6% [19].

Economically, mean cost per participant at three months was £542.40 in the control group versus £368.40 in the intervention group, a difference of £174 that did not reach statistical significance (95% CI -£30 to £378, $p=0.094$), but this difference widened and became statistically significant by six months (£266 per participant, 95% CI £3.30 to £528, $p=0.047$), because the upfront cost of immediate MRI was offset by avoided downstream costs of repeated consultations, further imaging, and unnecessary follow-up in patients who proved not to have a fracture [19]. Time to definitive diagnosis was dramatically shorter in the MRI arm (mean 1.7 days versus 10.2 days, $p<0.001$), and patient satisfaction trended higher in the intervention group across several domains, reaching statistical significance for overall experience of the study and for the perceived impact of participation on clinical care [19]. The SMaRT trial's findings are broadly consistent with an earlier cost-effectiveness analysis reporting that immediate MRI reduced unnecessary immobilisation duration compared with standard serial-radiograph follow-up, although that

earlier work found the intervention carried a higher direct per-patient cost that was not fully offset within the study's shorter follow-up window, illustrating that the economic case for immediate advanced imaging becomes more favourable the longer the time horizon over which downstream costs are captured [7,19].

7. Cone-Beam Computed Tomography: An Emerging Alternative

Cone-beam CT (CBCT) has been proposed as a technology capable of narrowing the gap between the diagnostic accuracy of MRI and the practical accessibility of conventional CT, chiefly by delivering high spatial resolution at substantially reduced radiation dose relative to multidetector CT [1]. A systematic review synthesising six studies and 335 patients (106 with confirmed fractures) reported CBCT sensitivity ranging from 88.9% to 100% and specificity between 96% and 100% across the individual studies, figures that place CBCT diagnostic performance in the same range typically reported for MRI [1]. Individual comparative studies cited within this review illustrate the range: a prospective study verifying CBCT findings against reference MRI within an average of 4.1 days post-injury found sensitivity of 94% and specificity of 97% for occult fractures, while a large retrospective analysis of 102 patients reported sensitivity of 93% ($p=0.019$) and specificity of 96% ($p<0.001$), a statistically significant superiority of CBCT over standard radiography in the same cohort [1].

The radiation dose profile is the most consistently cited advantage of CBCT relative to conventional CT: the median effective dose across the reviewed studies ranged from 3.65 to 4.3 microsieverts, meaningfully higher than the roughly 0.2 microsievert dose of conventional radiography, but substantially lower than standard multidetector CT [1]. A separate protocol paper on musculoskeletal CBCT dosimetry likewise emphasises that scanner design permits effective physical shielding of radiation-sensitive organs, an engineering feature not equally available with conventional CT gantry designs [1]. A direct comparison against high-resolution peripheral quantitative CT (HR-pQCT), a related low-dose extremity-imaging technology, found the latter capable of detecting 60% more scaphoid fractures than standard multidetector CT in trauma patients while achieving effective doses as low as 15 microsieverts, reinforcing the broader principle that purpose-built, dedicated extremity scanners can outperform general-purpose CT protocols for this specific anatomical target [1].

Beyond raw diagnostic accuracy, the clinical-pathway benefits of rapid CBCT access have been documented in a before-and-after interventional study evaluating an ambulatory CBCT pathway introduced in an emergency department: implementation of the dedicated pathway reduced the median time from patient presentation to CBCT imaging from 16.5 days to 2.0 days, increased the proportion of patients receiving definitive imaging within seven days from 11.1% to 91.8%, and produced a 71.9% reduction in unnecessary fracture-clinic attendances [1]. Aggregating across the reviewed studies, early access to CBCT allowed 94.1% of patients to receive a definitive diagnosis within 48 hours of injury [1]. These pathway-level findings echo, with a different technology, the same clinical and economic logic demonstrated by the SMaRT trial for immediate MRI: front-loading diagnostic certainty reduces downstream resource use, unnecessary immobilisation, and time to appropriate treatment [1,19].

Nevertheless, the same systematic review is candid about the limitations of the CBCT evidence base. CBCT excels at depicting cortical disruption but performs less well for purely trabecular fractures, which can occasionally be missed; the required acquisition time of approximately 15 seconds renders CBCT more susceptible to motion artefact than faster multidetector CT systems; and, perhaps most importantly, the methodological quality of the underlying studies is compromised by selection bias in several retrospective cohorts (in which patients with genuinely ambiguous initial radiographs may be preferentially referred for CBCT, artificially inflating its apparent "problem-solving" value while depressing the apparent performance of plain radiography in the same population), by inconsistent reference standards (some studies confirming fracture only via surgical exploration, which by definition excludes patients who did not require surgery and precludes calculation of specificity), and by delayed-imaging confounding in at least one study, where a median 15-day interval between initial radiography and CBCT — during which patients remained immobilised in a cast — raised the possibility that minor, nondisplaced fractures had already healed before the CBCT scan was performed, a limitation the study's own authors acknowledged [1]. Given these constraints, the reviewing authors concluded that CBCT is a promising and accessible alternative in the acute setting, but that further large-scale prospective studies are required before its diagnostic role can be considered fully established relative to MRI [1].

8. Artificial Intelligence in Scaphoid Fracture Detection

8.1. Rationale and diagnostic performance of AI models

Because up to one-fifth of scaphoid fractures are missed on initial plain radiographs, and because radiographic interpretation quality varies with reader experience and time of day, deep-learning convolutional neural networks (CNNs) have attracted considerable research interest as tools to assist — or potentially match — human readers in scaphoid fracture detection [15,16,20-23]. A systematic review and diagnostic test accuracy meta-analysis identified ten eligible studies published between 2020 and 2023, all retrospective, evaluating AI performance for scaphoid fracture detection on plain radiographs; seven of these studies, comprising a combined 3,373 images, were suitable for quantitative meta-analysis, which yielded a pooled sensitivity of 0.80 (95% CI 0.75–0.84) and pooled specificity of 0.89 (95% CI 0.82–0.94), with an overall area under the summary receiver operating characteristic (SROC) curve of 0.88 [15]. Individual model performance across the ten included studies spanned a wide range, from an area under the curve (AUC) of 0.77 up to 0.96, reflecting substantial heterogeneity in CNN architecture, training-dataset size, image-view configuration, and reference standard used to establish ground truth [15].

Individual studies illustrate this range in detail. A three-stage CNN pipeline that first localised the scaphoid, then screened for overt fracture, and finally applied a dedicated occult-fracture-detection network to images classified as negative by the earlier stages achieved an AUC of 0.955 for the primary fracture-detection step and 0.81 for the dedicated occult-fracture step, with the complete pipeline correctly identifying 90.9% of occult fractures in the validation set [15]. A two-step model (scaphoid localisation followed by fracture detection) using a DenseNet121 architecture and validated in an external, multi-hospital dataset achieved an AUC of 0.87, a performance level the study's authors judged comparable to that of eleven participating radiologists with varying levels of experience [15]. A subsequent, methodologically more elaborate validation of this same research group's pipeline, incorporating multiple radiographic views (posteroanterior, ulnar-deviated posteroanterior, oblique, and lateral) and tested against a held-out dataset of 219 cases (65 with fracture), found that algorithm performance improved incrementally as additional views were incorporated: AUC rose from 0.79 with posteroanterior views alone to 0.84 with the addition of ulnar-deviated posteroanterior views, to 0.85 with

oblique views added, and to 0.88 when all available views were combined, whereas the addition of lateral views alone did not produce a statistically significant improvement (AUC 0.83, $p=0.12$ versus posteroanterior alone) .

8.2. Comparison with human readers and effect of AI assistance

A central question for the clinical adoption of these tools is not merely whether they can detect fractures accurately in isolation, but whether they improve, are equivalent to, or potentially degrade the performance of practising radiologists and orthopaedic surgeons when used as a diagnostic aid. The evidence here is genuinely mixed. In the validation study by Hendrix and colleagues, comparing the algorithm's unassisted performance (AUC 0.88) against five musculoskeletal-expert radiologists reading without AI assistance (mean AUC 0.87, individual range 0.84–0.91), no statistically significant difference was found for any individual radiologist (p -values ranging from 0.32 to 0.90) . When these same radiologists were then given AI assistance, three of the five achieved statistically significant improvements in specificity and positive predictive value, five out of ten pairwise combinations of radiologists showed improved inter-observer agreement (average increase of 36.2%), and four of the five radiologists showed significantly reduced reading time (average reduction 49.4%, $p<0.001$ for all four) — yet, notably, sensitivity, overall accuracy, and AUC were not significantly improved for the majority of radiologists, and one radiologist's AUC actually fell significantly with AI assistance (0.81 versus 0.91 unassisted, $p=0.002$) . The authors concluded that AI assistance could meaningfully improve diagnostic efficiency (via reduced reading time and improved inter-rater consistency) without necessarily improving diagnostic accuracy for already-expert readers, a nuanced finding that resists simple summary as either "AI helps" or "AI does not help" .

A separate real-world observational study evaluating two different commercially available AI software packages (referred to by the study authors as SW1 and SW2) in the hands of non-specialist radiologists reached a more clearly favourable conclusion for AI assistance, but specifically in complex diagnostic scenarios [16]. In this study, patients were divided into a straightforward group (Group 1, where the original specialist radiologist report on plain radiographs alone was definitive, either positive or negative, $n=174$, with 80 confirmed fractures) and a complex group (Group 2, comprising indeterminate or persistently symptomatic cases that required subsequent CT confirmation, $n=90$, with 51 fractures confirmed on CT, including 29

initially read as radiographically negative and 22 initially read as doubtful) [16]. In the straightforward Group 1, AI performance (AUC 0.83 for SW1, 0.84 for SW2) was statistically indistinguishable from that of the non-specialist radiologists reading unassisted (AUC 0.88 and 0.90), and AI assistance did not produce a statistically significant improvement in either radiologist's overall diagnostic accuracy [16]. In the diagnostically complex Group 2, however, unassisted performance for both AI software and the non-specialist radiologists fell substantially (AI AUC 0.62–0.65; radiologist AUC 0.46–0.63), and AI assistance produced statistically significant improvements in sensitivity for both readers with SW1 (an increase of 21.5 percentage points for one radiologist, $p=0.013$, and 15.7 points for the other, $p=0.008$) and in overall diagnostic accuracy (AUC) for both radiologists with both software packages (p -values ranging from 0.003 to 0.030) [16]. The two AI packages also differed from one another in a clinically interpretable way: SW1 had higher sensitivity while SW2 had higher specificity, a trade-off the study authors suggested could inform selection of a particular tool depending on whether an emergency-department or specialist-radiology context is prioritising the avoidance of false negatives or false positives [16].

8.3. Methodological limitations of the AI evidence base

A dedicated critical review of the artificial-intelligence literature for scaphoid fracture detection, applying the CLAIM (Checklist for Artificial Intelligence in Medical Imaging) and PROBAST (Prediction Model Risk of Bias Assessment Tool) frameworks to nine included studies, concluded that current studies have "notable methodological flaws" and are at "high risk of bias," precluding meaningful, confident comparison with clinician performance as the current reference standard [21]. Specific deficiencies identified across the reviewed studies included frequently unreported or absent exclusion criteria (four of the nine studies reported no exclusion criteria at all), inconsistent and sometimes clinically inappropriate reference standards used to establish ground truth (ranging from plain radiographs alone, to CT, to a combination of imaging and clinical notes, with only some studies distinguishing between occult and overt fractures), small and variably sized test datasets (ranging from 53 to 688 patients, with the review noting that fewer than 100 cases in a test dataset falls below the minimum recommended by PROBAST), and — perhaps most tellingly for clinical translation — marked heterogeneity in the experience level and specialisation of the human comparator clinicians used to benchmark AI performance, with reported experience ranging from two to thirty years and a mixture of surgical and

radiological specialisations, making pooled comparisons across studies difficult to interpret meaningfully [21]. This same review scored overall adherence to CLAIM reporting items as low across most studies, with only three of nine studies reporting more than 70% of recommended items, and concluded that at the present stage of development, "it is not yet possible to meaningfully compare these models with clinicians" [21].

Taken together, the AI literature on scaphoid fracture detection illustrates a now-familiar pattern in diagnostic AI research more broadly: individual studies frequently report impressive point-estimate performance metrics, direct head-to-head comparisons with expert human readers often show approximate parity rather than clear AI superiority, real-world clinical benefit (where demonstrated) appears concentrated in improving efficiency and assisting less experienced readers in diagnostically ambiguous cases rather than in outright replacing expert judgement, and the underlying evidence base remains constrained by small sample sizes, inconsistent reference standards, and limited external validation across institutions [15,16,20-23]. This synthesis argues for cautious, targeted integration of AI tools — for instance, as a support for non-specialist or trainee readers facing genuinely difficult occult-fracture scenarios — rather than wholesale substitution for expert radiological or orthopaedic assessment.

9. Classification Systems and Their Prognostic Relevance

Three classification systems dominate the scaphoid fracture literature, each emphasising a different aspect of the injury and each carrying distinct implications for treatment selection. The Herbert classification, based on fracture stability, divides fractures into stable acute fractures (Type A: A1, fractures of the tubercle; A2, incomplete or nondisplaced waist fractures) and unstable acute fractures (Type B: B1, distal oblique fractures; B2, displaced or mobile waist fractures; B3, proximal pole fractures; B4, fracture-dislocations; B5, comminuted fractures), with Type C representing delayed union after prolonged immobilisation and Type D representing established nonunion, further subdivided into fibrous (D1) and sclerotic (D2) nonunion [3,7,24]. This classification is widely used precisely because it links directly to a treatment recommendation: stable Type A fractures are considered candidates for nonoperative management, while unstable Type B fractures are generally recommended for surgical fixation [7,24].

The Mayo (or anatomical location) classification instead divides fractures by their position along the length of the bone — proximal pole (approximately 10% of fractures), waist (approximately 70%), and distal (approximately 20%, itself subdivided into distal articular and distal tubercle fractures) — a scheme that maps directly onto the vascular anatomy discussed in Section 3 and therefore correlates strongly with union prognosis [3-5]. The Russe classification instead emphasises the orientation of the fracture plane, distinguishing horizontal oblique, transverse, and vertical oblique fracture lines; vertical oblique fractures, though accounting for fewer than 5% of scaphoid fractures, are considered the most biomechanically unstable because they generate the greatest shear forces across the fracture site, in contrast to horizontal oblique fractures, which are subjected predominantly to compressive rather than shear forces and are correspondingly more stable [3,7].

It is worth noting that a systematic review focused specifically on classification reliability found that inter- and intra-observer agreement for scaphoid fracture classification systems is imperfect, and that classification schemes, while clinically useful heuristics, may carry limited standalone prognostic value when applied inconsistently between observers [7]. This observation should temper the confidence with which any single classification is used as the sole determinant of treatment, and reinforces the more general principle — repeated throughout the surgical literature reviewed in later sections — that fracture location, displacement, stability, chronicity, and patient-specific factors such as smoking status must be considered together rather than derived from a classification label in isolation.

10. Conservative Management

Conservative treatment with cast immobilisation remains the standard of care for stable, nondisplaced fractures, and the evidence base supporting this approach is substantial in scope, if variable in specific detail across studies. Union rates with cast treatment alone for nondisplaced fractures are consistently reported in the range of 88–95% across multiple series [3-5], though the SWIFFT trial's five-year follow-up (discussed in detail in Section 11) found an even higher union rate of approximately 94% among conservatively managed patients when displacement was carefully restricted to two millimetres or less [9,12]. Duration of immobilisation is generally reported as 9–12 weeks for waist fractures, though this can extend considerably for proximal-pole

fractures given their compromised blood supply, while distal-pole fractures may unite within as little as 6 weeks [3-5].

The specific configuration of the cast — whether a short-arm or long-arm construct, and whether the thumb is included or left free — has been a recurring subject of investigation, and the accumulated evidence generally does not support the necessity of the more restrictive options. A meta-analysis comparing long-arm and short-arm thumb spica cast immobilisation, pooling four randomised controlled trials totalling 523 patients, found no statistically significant difference in nonunion rate between the two approaches, a finding cited approvingly across several subsequent reviews as evidence against the routine use of the more cumbersome long-arm cast for uncomplicated cases [5]. Similarly, whether the thumb is immobilised within the cast has been tested directly: a randomised prospective trial found that scaphoid fracture union rates were unaffected by inclusion or exclusion of the thumb from the cast, and this finding is echoed in the specific clinical protocol described in one detailed guideline, which recommends a standard short-arm cast without thumb immobilisation on the basis that this configuration preserves thumb opposition and pinch grip function without compromising fracture stability, since *in vivo* biomechanical studies have shown that control of wrist extension and ulnar deviation is what stabilises the fracture site, whereas immobilisation of forearm rotation or thumb metacarpophalangeal motion has little demonstrable impact on fracture-site stability [4,5].

A recent, methodologically rigorous meta-analysis by Alghwail and colleagues, restricting inclusion to four randomised controlled trial cohorts published from 2013 onward and totalling 559 patients, reinforces the case for conservative management as an appropriate default strategy for minimally displaced fractures, while also quantifying the genuine, if modest, advantage that surgery confers [9]. This analysis found that surgical fixation was associated with a statistically significant relative risk reduction for nonunion compared with cast immobilisation (risk ratio 0.35, 95% CI 0.15–0.82), but the absolute risk reduction was small (approximately 4%) because the pooled nonunion rate in the cast-immobilisation arm was itself low, at only 6% (95% CI 0.00–0.45), translating to a number needed to treat of 25 patients with surgery to prevent a single additional nonunion [9]. The same analysis found no statistically significant difference between surgical and conservative treatment in complication rates (high-certainty evidence) or in long-term Patient-Rated Wrist Evaluation (PRWE) scores at either one or five years (also high-certainty evidence, drawn principally from the SWIFFT trial) [9]. The authors' explicit

conclusion was that, given the high absolute union rate achievable with conservative management and the absence of a demonstrable long-term functional advantage for surgery, cast immobilisation should remain the standard first-line strategy for minimally displaced or undisplaced scaphoid waist fractures, with operative intervention reserved for confirmed non-unions, frankly displaced fractures, or patients with specific occupational demands necessitating a more rapid return to full function [9].

For the athletic population specifically, the principal drawback of conservative management is not a deficiency in ultimate union rate but the duration of immobilisation itself, and the associated period during which return to competitive sport is either impossible or, at best, limited to activities compatible with cast-protected play [5,6,11]. This trade-off — comparable union outcomes but a longer interval to functional recovery — is precisely the tension that has motivated the shift toward operative management in many athletic and occupational settings, and it is the specific evidence for and against this shift that the following section examines.

11. Surgical Management: Techniques and Comparative Trials

Table 2 summarises comparative outcomes of surgical versus conservative management for scaphoid waist fractures.

Table 2. Comparative outcomes of surgical versus conservative management for scaphoid waist fractures.

Source [ref]	Design	Population	Principal findings
Dias et al. [12]	RCT protocol (SWIFFT)	439 adults, UK, minimally displaced waist fractures	Primary outcome PRWE at 52 weeks; powered for 6-point difference
Al-Ajmi et al. [25]	Meta-analysis (8 RCTs, 399 patients)	Acute undisplaced/minimally displaced fractures	Surgery: better grip strength, function at 2–4 months, faster return to work (−6.01 weeks, $p<0.001$); no difference in

			complications or long-term function
Alghwail et al. [9]	Systematic review and meta-analysis (4 RCT cohorts, 559 patients)	Acute, ≤ 2 mm displacement	Surgery: RR for nonunion 0.35 (95% CI 0.15–0.82); absolute risk reduction ~4%; no difference in PRWE at 1 or 5 years
Zhang et al. [26]	Target-trial emulation (EHR data, 6,769 patients)	Chinese tertiary hospitals, bicortical waist fractures	Surgery: DASH –4.2 points at 52 weeks ($p < 0.001$); nonunion halved (8.4% vs 17.5%); complications sevenfold higher (14.1% vs 2.0%)
Goffin et al. [6]	Systematic review and meta-analysis (11 studies, 170 fractures)	Athletes, scaphoid fractures	Surgery: RRS 98% vs 90% conservative ($p = 0.045$); RTS 7.3 vs 9.6 weeks ($p = 0.002$); union 97% vs 85% ($p = 0.030$)

11.1. Rationale and surgical approaches

The theoretical case for surgical fixation of scaphoid fractures rests on the observation that rigid internal fixation permits earlier controlled mobilisation, potentially accelerates radiographic union, and may reduce complications associated with prolonged immobilisation such as joint stiffness and disuse muscle atrophy [4,5,7]. Contemporary fixation predominantly employs percutaneous or open placement of a headless compression screw, introduced by Herbert and Fisher and subsequently refined into cannulated designs that permit minimally invasive, image-guided insertion [24]. Surgical approach is dictated by fracture location: distal and waist fractures

are generally approached volarly, both for adequate exposure and to preserve the dorsal blood supply, whereas displaced proximal-pole fractures are more often approached dorsally to allow more accurate screw placement into the small, retrograde-dependent proximal fragment [3,7]. Arthroscopically assisted fixation has also been described, offering the theoretical advantages of minimal soft-tissue disruption, direct visualisation of fracture reduction, and the ability to detect concomitant intercarpal ligament injury, though this technique is technically demanding and requires substantial dedicated experience with wrist arthroscopy [4,7,24].

11.2. Randomised and observational comparisons of surgery versus casting

The comparative literature on surgery versus conservative management for acute, nondisplaced or minimally displaced scaphoid fractures is extensive but has, until relatively recently, been characterised by small individual trials with divergent conclusions. A meta-analysis by Al-Ajmi and colleagues, synthesising eight randomised controlled trials with a combined 399 patients (182 surgical, 196 conservative) published between 2001 and 2015, found that surgical treatment produced statistically significantly better functional scores at 2 and 4 months post-treatment, significantly greater grip strength at 2, 4, 6, and 12 months and beyond 12 months, and a significantly shorter time to return to work (weighted mean difference -6.01 weeks, 95% CI -9.16 to -2.87 , $p < 0.001$) [25]. However, this same meta-analysis found no statistically significant difference between the two treatment groups in range of motion at any time point, in functional scores at 6 months, 1 year, or beyond 1 year, in pinch strength beyond 1 year, or — critically — in the overall complication rate, which included malunion, nonunion, osteoarthritis, need for further surgery, avascular necrosis, and infection, none of which differed significantly between groups ($p = 0.754$ for the pooled complication analysis) [25]. The authors of this meta-analysis were explicit that, despite the statistically significant advantages identified for several secondary outcomes, "there is insufficient evidence to provide a definitive conclusion that surgery is a better option," citing substantial heterogeneity in patient populations (including one trial conducted exclusively in full-time military personnel with atypically rapid return-to-duty timelines), variable duration of follow-up ranging from 8 weeks to 12 years across the included studies, and inconsistent methods of confirming radiographic union (only two studies used the more reliable CT-based assessment rather than plain radiography) [25]. This conclusion — that surgery offers real but modest and inconsistently demonstrated advantages, chiefly in time-dependent outcomes such as return to work, without clearly superior long-term function or fewer

complications — echoes almost precisely the conclusion reached independently by the more recent Alghwail meta-analysis discussed in Section 10, lending it additional credibility through convergent evidence from two methodologically distinct syntheses conducted several years apart [9,25].

The largest and most methodologically rigorous single trial in this literature is the Scaphoid Waist Internal Fixation for Fractures Trial (SWIFFT), a pragmatic, multicentre, UK National Health Service-based randomised controlled trial that recruited 439 adults across 31 hospitals, randomising them to either headless compression screw fixation or below-elbow cast immobilisation (with delayed surgical fixation reserved for those who developed confirmed nonunion) [9,12]. The trial's published protocol specifies a primary outcome of the Patient-Rated Wrist Evaluation (PRWE) score at 52 weeks, powered to detect a clinically meaningful difference of six points, with secondary outcomes including radiological union assessed by CT and radiograph, quality of life, grip strength, range of motion, and complications [12]. At 52 weeks, the SWIFFT trial found no clinically or statistically meaningful difference in PRWE score between the surgical and conservative arms (adjusted mean difference reported elsewhere in this review as -2.1 , 95% CI -5.8 to 1.6), and this finding of equivalence was confirmed at five-year follow-up (mean difference 0.6 , 95% CI -2.4 to 3.6) [26]. The SWIFFT trial's baseline nonunion rates were markedly lower than in most other published series — approximately 0.5% in the surgical arm and 1.8% in the conservative arm — a discrepancy the trial investigators and subsequent commentators attribute to the trial's strict enrolment criteria, which excluded fractures with displacement greater than two millimetres, thereby selecting a population of predominantly stable, favourable-prognosis fractures less representative of the full spectrum of scaphoid injury encountered in general or athletic practice [12,26].

11.3. Target-trial emulation: generalisability across healthcare systems

A recent target-trial emulation study explicitly designed to test the generalisability of the SWIFFT findings outside the UK healthcare context offers an instructive methodological complement to the original trial [26]. Using electronic health record data from three Chinese tertiary teaching hospitals and a clone-censor-weight design with inverse probability weighting to emulate randomisation, this study analysed 6,769 patients (2,544 surgical, 4,225 conservative) meeting broadly similar eligibility criteria to SWIFFT (bicortical scaphoid waist fracture,

displacement $\leq 2\text{mm}$, presentation within 14 days of injury) [26]. With a sample size more than fifteen times larger than the original SWIFFT trial, this emulation detected a statistically significant, though modest, functional advantage favouring surgery on the Disabilities of the Arm, Shoulder, and Hand (DASH) score at 52 weeks (adjusted mean difference -4.2 points, 95% CI -4.9 to -3.5 , $p < 0.001$) — a difference the study authors themselves characterise as falling below the commonly cited minimal clinically important difference threshold of 10–15 points for the DASH instrument, though it approaches lower proposed thresholds of 7–10 points, particularly at the earlier 6- and 12-week assessment points, where the surgical advantage was considerably larger (mean differences of -16.2 and -9.2 points respectively) and narrowed progressively over the following year [26].

Beyond the primary functional outcome, this emulation found that surgery approximately halved the risk of nonunion (8.4% versus 17.5%, risk ratio 0.48, 95% CI 0.41–0.55) but was associated with a sevenfold increase in overall complication rate (14.1% versus 2.0%, risk ratio 7.10, 95% CI 5.63–8.95), predominantly screw-related problems such as prominence, malposition, and the need for revision surgery [26]. Strikingly, nearly one in five conservatively managed patients (18.1%) ultimately required surgical conversion, the overwhelming majority (91.5%) for confirmed nonunion, a crossover rate that itself carries important implications for how conservative-arm outcomes should be interpreted and counselled to patients [26]. Prespecified subgroup analyses found a larger surgical benefit among patients with displaced (rather than undisplaced) fractures and among current smokers, both subgroups facing a substantially elevated baseline risk of nonunion under conservative management [26]. The authors reasonably attribute the markedly higher absolute nonunion rates observed in this Chinese cohort compared with SWIFFT (17.5% versus 1.8% in comparable conservative arms) to the substantially higher smoking prevalence in the study population (42.4% current smokers, roughly double the smoking rate among UK men during the SWIFFT recruitment period) combined with the inclusion of some genuinely displaced fractures (Herbert B2, up to 2mm) within the study's eligibility window [26]. This comparison across two large, methodologically distinct studies conducted in different healthcare systems illustrates a point of real clinical importance: the near-equivalence between surgery and casting demonstrated in SWIFFT may be, at least in part, a consequence of the specific, favourable-risk population that trial recruited, and the incremental benefit of surgery

may be considerably larger in populations — or individual patients — carrying elevated baseline risk factors for nonunion such as smoking or greater fracture displacement [9,12,26].

11.4. Studies specific to athletic populations and military cohorts

Several studies bearing more directly on athletic and physically active populations reinforce the theme that surgery's principal, most consistently demonstrated advantage lies in accelerating the return to physically demanding activity rather than in improving ultimate functional outcome. A trial conducted exclusively in military personnel — a population selected, like competitive athletes, for high baseline physical demands and strong institutional pressure toward rapid return to full duty — found that patients randomised to percutaneous screw fixation returned to full military duties seven weeks sooner than those treated conservatively, and achieved radiographic union eight weeks sooner, although by two-year follow-up there was no difference between groups in wrist range of motion or grip strength [5]. A separate randomised comparison found that operative patients achieved earlier return of wrist range of motion and grip strength beginning at eight weeks postoperatively compared with conservatively managed patients, but that ten of forty-four (23%) conservatively managed patients in that same trial developed delayed union at 16 weeks requiring subsequent surgical intervention, and by one-year follow-up there was no difference between the originally randomised groups [5]. The consistent thread across these athlete- and military-relevant comparisons is that surgery offers a real, reproducible acceleration of early functional milestones and time to union, of direct practical relevance to an athlete under pressure to return to competition, but this early advantage does not translate into superior ultimate long-term function once conservatively managed fractures that go on to unite are compared against surgically fixed fractures at extended follow-up [5,9,25,26].

12. Nonunion: Prediction, Prevalence, and Prognostic Modelling

12.1. Prevalence and consequences

Scaphoid nonunion is widely regarded as the injury's most feared complication because of its close mechanistic link to progressive carpal collapse and posttraumatic osteoarthritis. Reported nonunion prevalence varies considerably depending on fracture location, initial displacement, delay to treatment, and the population studied, with figures ranging from approximately 5–10% for all scaphoid fractures up to 12–15% in some series, and rising substantially — to as high as 46–50% — for displaced or proximal-pole fractures managed nonoperatively [1,3,7,8,27]. A

broader review of extremity nonunion across all fracture types situates the scaphoid at particularly high relative risk, reporting a scaphoid-specific nonunion rate of 15.5%, the highest of any individual bone examined, ahead of the lower leg (14%) and femur (13.9%) [8]. The same review notes that scaphoid nonunion carries not merely a biomechanical but a substantial health-economic and quality-of-life burden characteristic of nonunion in general: affected patients report Health-Related Quality of Life scores below those reported for many chronic systemic diseases, and Time Trade-Off utility values (a measure of the fraction of remaining life expectancy a patient would sacrifice for immediate restoration of full health) averaging only 0.68 in one cohort — lower than reported utility values for type 1 diabetes (0.88), post-stroke status (0.81), or AIDS (0.79) — while treatment of nonunion imposes costs approximately 350% higher than treatment of a fracture that unites without complication, and a typical treatment course lasting an average of 45 weeks [8].

12.2. Risk factors and predictive tools

Given these consequences, considerable research effort has been directed toward identifying patients at elevated risk of nonunion early enough to modify management. The most robust and consistently identified modifiable risk factor across the literature is smoking. A retrospective multicentre UK study of 462 bone-graft surgeries for established scaphoid nonunion found that smoking at the time of surgery was independently associated with a near-doubling of the odds of persistent nonunion after grafting (adjusted odds ratio 1.8, 95% CI 1.0–3.1), a finding the study authors note is consistent with two earlier, smaller studies reporting union rates of 82–88% in non-smokers compared with only 40–57% in smokers undergoing the same procedure [28]. The same UK multicentre study identified a second, independently significant risk factor: the time interval between the original acute fracture and definitive nonunion surgery, with delays of one to two years associated with a 40% higher adjusted odds of persistent nonunion (odds ratio 1.4) and delays exceeding two years associated with a 140% higher odds (odds ratio 2.4) relative to surgery performed within three to six months of injury [28]. Notably, in this same dataset, the type of bone graft used (vascularised versus non-vascularised, or iliac crest versus distal radius donor site) did not significantly influence outcome once smoking and delay-to-surgery were accounted for, a finding consistent with two independent systematic reviews that similarly reported comparable union rates for vascularised and non-vascularised grafts (approximately 92% and 88% respectively in one pooled analysis) [28].

Beyond these clinical and behavioural risk factors, a broader review of nonunion prediction across all skeletal sites (not scaphoid-specific but directly relevant given the scaphoid's disproportionate representation in that literature) surveys the accuracy of biomarker, imaging, and computational approaches to early nonunion risk stratification, and reaches a broadly sobering conclusion [8]. Systemic bone-turnover markers such as bone alkaline phosphatase and inflammatory markers including C-reactive protein and interleukin-6 show statistically significant associations with subsequent nonunion in cohort studies but exhibit substantial inter-individual variability driven by age, sex, smoking, diabetes, and other comorbidities, such that no single marker currently has adequate standalone predictive value for routine clinical use [8]. Clinical heuristic judgement — the ability of experienced surgeons to predict nonunion based on risk-factor review and postoperative imaging — was found in one study to carry excellent negative predictive value (87.7% postoperatively), meaning clinicians are reliable when they predict a fracture will unite, but comparatively poor positive predictive value (35.5% postoperatively), meaning that a clinical prediction of eventual nonunion is frequently wrong, an asymmetry the review's authors describe as demonstrating that "clinical judgement alone is insufficient for accurately identifying risks" [8]. Machine-learning models applied to nonunion prediction in a separate skeletal site (distal clavicle fracture) achieved a superior area under the receiver operating characteristic curve of 0.863 but still carried a comparatively modest positive predictive value of only 55.3%, which the review's authors interpret as meaning that, at current performance levels, nearly half of patients flagged by such an algorithm as high-risk would in fact go on to achieve union, a false-positive rate the authors argue is too high to justify basing surgical decisions on algorithmic output alone [8]. The review's overarching conclusion — that single-modality prediction, whether biomarker-based, heuristic, or algorithmic, remains inadequate, and that effective prediction will likely require integration of multimodal clinical, imaging, and computational data within prospective, centralised registries — is directly applicable to the scaphoid, given that fracture is the single bone type most heavily represented in the underlying nonunion literature this review synthesises [8].

12.3. Imaging correlates of nonunion healing capacity

A histological and CT correlation study specifically addressing scaphoid nonunion offers valuable mechanistic insight into why certain nonunions respond better to surgical bone-grafting than others, and provides an evidence-based framework for selecting between vascularised and

non-vascularised graft options [29]. In this study of 29 patients undergoing nonunion surgery, three CT-based structural parameters of the proximal fragment — presence of a normal trabecular grid pattern, presence of sclerosis, and presence of fragmentation — were correlated with a quantitative histological "bone healing capacity" (BHC) score derived from direct tissue sampling at the time of surgery [29]. Cases demonstrating preserved trabecular structure had significantly higher BHC scores at the proximal fragment (5.3 versus 0.9 in cases without trabecular structure, $p<0.001$) and achieved significantly faster time to union (3.4 versus 5.2 months, $p<0.001$), whereas the presence of fragmentation was associated with significantly lower BHC (1.3 versus 4.3, $p=0.036$), reflecting essentially disintegrated, biologically inert bone [29]. Sclerosis alone, by contrast, did not correlate significantly with BHC score but was associated with a significantly longer time to union (4.3 versus 3.4 months, $p=0.038$), leading the study authors to conclude that sclerosis reflects reduced fragment vascularity rather than true biological death of the tissue, distinguishing it mechanistically from fragmentation, which the authors regard as the only truly avascular-necrotic pattern warranting the most aggressive graft option [29]. The study further found that nonunions located within the completely intra-articular proximal pole (a zone the authors term "white-white," lacking any independent ligamentous or capsular blood-supply attachment) had significantly lower BHC and significantly longer time to union than nonunions located more distally at the waist, where at least partial extra-articular vascular attachment is preserved, directly reflecting the vascular anatomy principles described in Section 3 [29]. Based on these correlations, the authors proposed a treatment algorithm in which the presence of trabecular structure supports the use of a simpler non-vascularised graft regardless of anatomical zone, whereas absence of trabecular structure combined with fragmentation, or location in the white-white proximal zone, favours a vascularised graft — an evidence-based decision framework grounded directly in objective CT parameters rather than surgeon intuition alone [29].

13. Surgical Treatment of Established Nonunion and Advanced Technique

When nonunion is confirmed, surgical reconstruction combining bone grafting with rigid internal fixation is the standard approach, but the specific technique — vascularised versus non-vascularised graft, and single- versus dual-screw fixation — remains an area of active technical refinement. A retrospective single-surgeon series of arthroscopically assisted treatment for both unstable acute fractures and established nonunion, using two headless compression screws with a distal radius bone graft for nonunion cases, reported bone union in all 23 patients (13 acute

unstable fractures, 10 nonunions) at a mean of 11.6 weeks (range 8–20 weeks), alongside statistically significant improvements from preoperative to postoperative assessment in wrist extension, visual analogue pain score, grip strength, and multiple validated wrist-function questionnaires (the Modified Mayo Wrist Score, the Patient-Rated Wrist Evaluation score, and the Disability of the Arm, Shoulder and Hand score), with no fixation failures or other postoperative complications recorded [24]. This study's authors situate their dual-screw technique within a broader biomechanical literature demonstrating, via finite-element analysis and cadaveric testing, that two headless compression screws provide significantly greater rotational stability, stiffness, and resistance to interfragmentary displacement than a single screw, and comparable stability to a dedicated scaphoid plate construct, translating in clinical series to higher reported union rates with dual- versus single-screw fixation for both acute unstable fractures and established nonunion [24].

The choice of bone graft donor site and vascularity — distal radius versus iliac crest, vascularised versus non-vascularised — remains, as discussed in Section 12.2, an area where the accumulated systematic-review evidence has not identified a clearly superior single approach across the general nonunion population, with the UK multicentre retrospective study finding no significant outcome difference by graft type once smoking and time-to-surgery were controlled for [28]. This finding, together with the CT-histological correlation work discussed above, supports a case-selection approach — reserving vascularised grafting for nonunions demonstrating radiographic and, where feasible, intraoperative evidence of poor proximal-fragment vascularity or biological inertness, rather than routine application of the more technically demanding vascularised technique to every nonunion regardless of its individual biological characteristics [28,29].

14. Adjunctive and Systemic Interventions to Promote Union

For fractures at risk of delayed union, or for patients seeking to avoid surgery, low-intensity pulsed ultrasound (LIPUS) has been investigated as a non-invasive adjunct intended to accelerate bone healing. A case series specifically addressing LIPUS for delayed-union scaphoid fractures treated 29 male patients (predominantly injured during sport, most commonly a fall on an outstretched hand) with daily 20-minute sessions of pulsed ultrasound delivered through a window cut into a thumb spica cast, dividing patients into an "early diagnosed" group (fracture

identified at a mean of 5.5 days post-injury, with LIPUS added after three months of unsuccessful cast immobilisation) and a "late diagnosed" group (fracture identified at a mean of seven months post-injury, with LIPUS begun immediately at diagnosis) [30]. Overall, 22 of 29 fractures (76%) healed with LIPUS treatment, but the healing rate differed considerably by timing of diagnosis: 12 of 13 fractures (92%) in the early-diagnosed group healed, compared with only 10 of 16 (63%) in the late-diagnosed group, a difference that approached but did not reach conventional statistical significance ($p=0.06$) in this modestly sized case series [30]. By fracture location, 9 of 11 proximal-pole fractures (82%) and 12 of 17 waist fractures (71%) achieved union with LIPUS, a difference the authors reported as not statistically significant given the small subgroup sizes [30].

The authors of this case series situate their findings against a separate, frequently cited retrospective study of 933 delayed unions across multiple bone types treated with LIPUS, which reported considerably higher scaphoid-specific healing rates of 94% for delayed unions (mean fracture age 150 days) and 100% for established nonunions (mean fracture age 755 days), figures the authors of the more recent, scaphoid-specific case series note may reflect a heterogeneous patient population that included some surgically augmented cases, rather than a directly comparable cohort [30]. A separate, earlier randomised controlled trial comparing LIPUS plus cast immobilisation against cast immobilisation alone in 30 patients with acute (not delayed) scaphoid fractures found a statistically significant 30% reduction in time to radiographic union in the LIPUS-treated group, a finding of direct relevance to acute rather than delayed-union management, though the case series authors note this earlier trial addressed a biologically distinct clinical scenario (fresh fracture healing acceleration) rather than rescue of an already-stalled union [30]. The case-series authors are explicit about several important limitations of their own study: the absence of a concurrent control group (since spontaneous healing was not anticipated in these delayed unions, every patient effectively served as their own historical comparison against expected natural history), the inseparability of the LIPUS effect from the concurrent, prolonged cast immobilisation each patient also received (meaning the relative contribution of ultrasound versus continued splinting to the observed healing cannot be disentangled from this study design alone), and a lack of standardised imaging criteria for declaring treatment failure across the several treating physicians involved [30]. Taken as a whole, this evidence supports LIPUS as a plausible, low-risk adjunct particularly attractive to patients wishing to avoid surgery,

with a more favourable prognosis when applied earlier in the delayed-union timeline, but the trial evidence base remains too limited in size and methodological rigour to establish it as a routine substitute for either continued conservative management or surgical intervention in cases of confirmed nonunion.

15. Advanced Imaging in the Assessment of Suspected Fracture and Occult Injury: Dual-Energy CT

A further technological development relevant to the diagnostic pathway, distinct from both conventional CT and CBCT discussed above, is dual-energy CT (DECT) using virtual non-calcium (VNCa) post-processing, a technique that exploits differential tissue attenuation at two distinct X-ray energy levels to subtract the calcified trabecular bone signal and thereby visualise the relative water content characteristic of bone marrow oedema — the radiological correlate of an acute, otherwise radiographically occult, fracture [17]. A small case series describing three patients with clinically suspected but radiographically negative or equivocal scaphoid trauma illustrates the technique's potential: in two of the three patients, conventional CT bone-window images showed either no visible fracture line or only a very subtle cortical discontinuity, yet the corresponding DECT VNCa images clearly demonstrated a green-coded region of increased water-equivalent attenuation consistent with bone marrow oedema, a finding subsequently confirmed by MRI in both cases as low T1 signal intensity with corresponding high signal intensity on fluid-sensitive sequences, the classical MRI appearance of an acute nondisplaced fracture [17]. In the third patient, both DECT VNCa and subsequent MRI were concordantly negative, correctly excluding fracture [17].

The authors of this case series situate their observations within a small but growing body of comparable DECT VNCa validation work in other anatomical regions using MRI as the reference standard: studies in knee trauma have reported sensitivity of 86.4% and specificity of 94.4–95.5% for detecting post-traumatic bone bruise, studies in ankle trauma have reported sensitivity of 90% but more modest specificity of 81.6%, studies in occult hip fracture have reported sensitivity as high as 90–100% but specificity as low as 40%, and studies in vertebral compression fracture have reported sensitivity ranging from 63% to 92% (improving to 92% when quantitative CT-number measurement was combined with visual assessment) alongside consistently high specificity around 98–99% [17]. This pattern — generally high sensitivity but more variable and,

in several anatomical regions, disappointingly low specificity — mirrors closely the trade-off profile already discussed for bone scintigraphy in Section 6.2, and the authors of the scaphoid-specific case series are appropriately cautious in their conclusions, explicitly framing DECT VNCA as "a promising technique" warranting further dedicated study of its accuracy specifically in the scaphoid, rather than as an already-validated diagnostic tool ready for routine clinical deployment [17]. The principal practical attraction the authors identify is that DECT VNCA images can, in principle, be generated from the same acquisition as a standard emergency-department CT scan, at no additional radiation dose and with a substantially shorter scan time than MRI, offering a potential pathway to same-visit exclusion of occult fracture in centres where MRI access is delayed or unavailable — though this promise, on the evidence of only three illustrative cases, remains to be confirmed in a properly powered diagnostic accuracy study [17].

16. Injury Surveillance Methodology and Its Relevance to Return-to-Sport Reporting

Before examining the specific return-to-sport evidence in detail, it is important to consider the methodological standards that underpin how sports injury and time-loss data are collected and reported, because inconsistencies in these definitions are a recurring, explicit limitation acknowledged across the return-to-sport literature discussed in the following section. The International Olympic Committee (IOC) consensus statement on methods for recording and reporting epidemiological data on injury and illness in sport provides the foundational framework most sports-medicine journals now expect authors to follow, and it makes several definitional distinctions directly relevant to interpreting scaphoid fracture return-to-sport studies [31]. The consensus statement distinguishes an "injury" as tissue damage resulting from rapid or repetitive transfer of kinetic energy during sport, and further distinguishes "time-loss" injuries (those preventing completion of the current or a future training session or competition) from "medical-attention" injuries (those prompting a clinical encounter but not necessarily any missed participation), a distinction of direct relevance to scaphoid fractures given that, as discussed in Section 6.1, many athletes continue competing for a period after the injurious event before eventually being sidelined [31]. The consensus statement further specifies that severity should ideally be reported as the number of days between the day after injury onset and the day the athlete returns to full, unrestricted training and competition participation, using standardised severity categories (for example, 0 days, 1–7 days, 8–28 days, and more than 28 days), and explicitly cautions that this time-loss metric, while the most widely used severity measure in

sports medicine, systematically underestimates the burden of conditions — such as gradual-onset overuse injuries — where an athlete may continue participating, in modified form, without ever formally missing a session [31].

A football-specific extension of this same IOC consensus framework refines the definition of "return to sport" still further, specifying it as the date on which an injured player returns to full, unrestricted team training without modification of duration or activity content, distinguishing this endpoint explicitly from the later milestones of first competitive match participation and eventual return to pre-injury performance level, and cautioning that studies which fail to specify precisely which of these distinct endpoints they are measuring cannot be validly compared with one another [32]. This same extension also recommends specific, more granular severity time-bins (0 days, 1–3 days, 4–7 days, 8–28 days, 29–90 days, 91–180 days, and more than 180 days) explicitly to better communicate the consequences of more severe injuries — a category into which most scaphoid fractures, particularly those managed operatively or complicated by nonunion, self-evidently fall, given typical return-to-sport intervals measured in weeks to months rather than days [32]. An empirical illustration of how time-loss data behave in a large, prospectively collected professional-sport cohort comes from a 16-year follow-up analysis of the UEFA Elite Club Injury Study, encompassing 22,942 index and recurrent injuries across 494 team-seasons of professional football, which found that even among common upper-extremity contusion and sprain-type injuries with generally short absences, injuries recorded as recurrences carried a significantly longer mean absence than the corresponding index injury for the majority of diagnoses examined, and that median rather than mean absence duration was the more statistically appropriate summary measure given the strongly right-skewed distribution of time-loss data typical of musculoskeletal injury [33]. This methodological point — that time-loss distributions in sports injury are skewed, and that mean values can therefore be misleading unless accompanied by median and interquartile-range figures — is directly pertinent to interpreting the wide, and sometimes divergent, mean-versus-median time-loss figures reported across the individual scaphoid return-to-sport studies synthesised in the following section [6,33].

17. Return to Sport: Rates, Timing, and Comparative Effectiveness

17.1. Systematic review evidence

The most comprehensive dedicated evidence on return-to-sport outcomes specifically following scaphoid fracture comes from a systematic review and meta-analysis by Goffin and colleagues, which identified eleven eligible studies (two randomised controlled trials, six retrospective cohort studies, and three case series) published between 1979 and 2014, collectively reporting on 170 scaphoid fractures in athletes, of which follow-up data on return to sport were available for 160 (94.1%) [6]. Of these 160 fractures, 77 were managed conservatively and 83 surgically; within the conservative group, 28 patients were permitted to return to sport while still in a cast and 49 were required to complete cast treatment before returning, while within the surgical group, 50 were treated with open reduction and internal fixation and 33 with percutaneous screw fixation [6].

Pooled analysis found an overall return-to-sport rate of 90% (69 of 77) for conservatively managed athletes and 98% (81 of 83) for surgically managed athletes, a difference the meta-analysis found to be statistically significant (risk ratio 1.09, 95% CI 1.00–1.18, $p=0.045$) [6]. The mean time to return to sport was 9.6 weeks for the conservative group overall and 7.3 weeks for the surgical group, also a statistically significant difference (mean difference 2.3 weeks, 95% CI 0.79–3.87, $p=0.002$), and fracture union rates were significantly higher (97% versus 85%, risk ratio 1.14, 95% CI 1.01–1.28, $p=0.030$) and significantly faster (mean 9.8 versus 14.0 weeks, mean difference 4.2 weeks, 95% CI 3.94–4.36, $p<0.001$) in the surgically managed group [6]. Within the surgical subgroup, percutaneous screw fixation achieved a marginally faster mean return-to-sport time than open reduction and internal fixation (6.5 versus 7.9 weeks), an advantage the review's authors attribute to reduced tissue dissection and typically shorter postoperative immobilisation with percutaneous technique, despite both approaches achieving comparable union rates (97% and 98% respectively) [6].

17.2. The problem of premature return to sport in a cast

A critically important, and clinically cautionary, finding emerges specifically from the subgroup of conservatively managed athletes permitted to return to sport while still immobilised in a cast: this subgroup achieved a numerically very short mean return-to-sport time of only 1.9 weeks — a figure that dramatically, and misleadingly, improves the overall pooled "conservative" mean

return time when included in the aggregate analysis — but at a substantial cost in fracture healing, with an associated nonunion rate of 15% (compared with 14% and 8% nonunion in individual studies contributing to this figure), and the review's authors explicitly attribute this elevated failure rate to excessive movement at the fracture site during premature return to competitive activity [6]. All three of the studies contributing to this "return-in-cast" subgroup were published more than three decades before the review itself, and the review's authors are explicit that this practice — permitting return to sport before cast-protected immobilisation is complete — is "currently not recommended" and should be "actively discouraged" given the disproportionate nonunion risk it appears to generate [6]. When the mean return-to-sport time for the conservative group is instead calculated using only the subgroup that completed full cast treatment before returning to sport (the clinically appropriate comparator), the mean rises to 13.9 weeks — considerably longer than the pooled surgical mean of 7.3 weeks, and the difference between appropriately managed conservative treatment and surgical treatment is therefore substantially larger than the headline pooled figures suggest once this confound is corrected for [6].

17.3. Return to pre-injury level of performance

Beyond simple return-to-sport rates and timing, return to the athlete's pre-injury competitive level is arguably the more clinically and functionally meaningful outcome, and the same systematic review reported this endpoint where available: 88% of conservatively managed athletes and 96% of surgically managed athletes returned to their pre-injury level of sport, a numerically favourable difference for surgery consistent with the pattern observed for the simpler return-to-sport-at-all metric [6]. Complication profiles differed meaningfully between the two treatment approaches within this athlete-specific dataset: conservatively managed patients who returned to sport in cast experienced non-union rates of 8–21% across the individual contributing studies and, in one series, a 14% rate of delayed surgical intervention for confirmed nonunion, while conservatively managed patients who completed cast treatment before returning to sport experienced complications including nonunion (15–17%), avascular necrosis (7%), complex regional pain syndrome (4%), malunion (11%), radioscaphoid osteoarthritis (4%), and, in one contributing study, persistent radial-sided wrist pain in fully half of surgically-comparator patients receiving percutaneous fixation with a shorter period of postoperative splinting [6]. Surgically managed patients experienced a distinct complication profile, including peri-operative breakage of the

cannulated screwdriver (7% in one contributing study using percutaneous fixation), symptomatic retained metalwork (4%), scar sensitivity (6% in one study using open reduction and internal fixation), and, notably, superficial radial nerve neuropraxia in 40% of patients in one small case series of open reduction and internal fixation, a strikingly high complication rate for a single technique that the review's authors do not further contextualise but which underscores the importance of surgical technique and approach selection in minimising iatrogenic morbidity [6].

17.4. Synthesis: reconciling return-to-sport data with the broader treatment literature

Read alongside the broader surgical-versus-conservative literature synthesised in Sections 10 and 11, the athlete-specific return-to-sport evidence presents a coherent and clinically actionable picture, even though — as with the general adult scaphoid fracture literature — no single study is definitive. Surgery reliably and reproducibly accelerates the interval to appropriately supervised return to sport by a clinically meaningful margin (on the order of six weeks when premature, in-cast return is excluded from the conservative comparator), and this acceleration is achieved alongside, rather than at the expense of, a higher rather than lower union rate in the pooled athlete-specific data — a pattern that stands in some tension with the general-population evidence discussed in Sections 10 and 11, where union rates with appropriately managed conservative treatment were reported as comparably high (SWIFFT: approximately 94% at five years; Alghwail meta-analysis: pooled 94% union in the conservative arm) [6,9,26]. This apparent discrepancy most plausibly reflects differences in the underlying study populations and eras: the athlete-specific systematic review drew on studies spanning 1979–2014, including several older case series and cohort studies predating the refinement of both cast-immobilisation protocols and CT-based union assessment that characterises the more recent, larger randomised trials and target-trial emulations discussed in Section 11, and it is entirely plausible that historical conservative-arm union rates in athlete cohorts were genuinely lower than those achieved with contemporary technique, imaging-guided monitoring, and stricter case selection [6,9,12,26]. This observation itself illustrates a recurring theme of this review: apparent disagreements between studies in the scaphoid fracture literature are frequently attributable not to a genuine biological inconsistency in how the injury behaves, but to differences in study era, imaging technology available for confirming both diagnosis and union, case-selection criteria (particularly regarding fracture displacement), and the specific outcome definitions and reference standards each study employed.

18. Discussion

Read as a whole, the evidence synthesised in this review supports a nuanced, comparative rather than categorical conclusion about the diagnosis and management of scaphoid fractures in athletes. On the diagnostic side, the literature converges on the recognition that plain radiography, while an appropriate and necessary first-line investigation, cannot by itself exclude a clinically significant fracture, with occult-fracture rates consistently reported in the range of one-fifth to one-quarter of clinically suspected cases even in contemporary series [10,15]. The choice of confirmatory second-line investigation is not a matter of identifying a single "best" modality but of matching the accuracy-cost-speed trade-off of each option to the specific clinical context: bone scintigraphy maximises sensitivity at the cost of substantial overtreatment and practical inconvenience [10,14]; MRI offers the most balanced combination of high sensitivity and high specificity but at greater cost and, in many health systems, reduced immediate accessibility [7,10,19]; CT and its emerging cone-beam variant offer faster, more accessible, and — in the case of CBCT — lower-dose alternatives with diagnostic accuracy approaching that of MRI, though the CBCT evidence base remains constrained by selection bias and heterogeneous reference standards in several included studies [1,10]; and artificial-intelligence-assisted reading, while approaching expert-level accuracy in aggregate, delivers its clearest, most reproducible clinical benefit not by outperforming expert radiologists in straightforward cases but by improving efficiency and supporting less experienced readers specifically in diagnostically ambiguous, occult-fracture scenarios [16,21]. The randomised evidence from the SMaRT trial, demonstrating that an immediate-MRI diagnostic pathway becomes cost-saving by six months despite a higher upfront cost, exemplifies how the "best" diagnostic strategy in this condition is inseparable from a health-economic, whole-pathway perspective rather than an isolated sensitivity-and-specificity comparison [19].

On the therapeutic side, the most striking pattern across the two largest and most methodologically rigorous bodies of comparative evidence — the SWIFFT trial and its Chinese target-trial emulation, and the two independent meta-analyses of surgery versus conservative management — is a remarkable degree of convergence: surgical fixation reduces nonunion risk and accelerates early return to function, but this advantage is modest in absolute terms, is not consistently accompanied by superior long-term patient-reported functional outcomes, and is achieved at the cost of a substantially higher complication rate, predominantly related to

hardware [9,12,25,26]. The athlete-specific return-to-sport literature complicates this general-population picture somewhat, suggesting a larger apparent surgical advantage in union rates within older athletic cohorts, a discrepancy this review attributes most plausibly to differences in study era and imaging technology rather than to any biological distinction unique to athletes [6]. The clinical implication that emerges consistently across this literature is that the decision between surgical and conservative management should not be made reflexively in favour of surgery merely because the patient is an athlete under pressure to return quickly, but should instead be individualised according to fracture displacement, smoking status, occupational and sporting demands, and — as the histological-CT correlation work on nonunion demonstrates — objective structural imaging characteristics of the fracture fragment itself where nonunion has already occurred [9,26,28,29].

A further theme worth foregrounding is the repeated observation, across multiple independent lines of evidence in this review, that apparent nonunion or premature-return risk is frequently attributable to modifiable factors — continued smoking, delay to definitive treatment, and premature return to unprotected activity — rather than to immutable characteristics of the fracture itself [6,26,28]. This is a clinically actionable finding: unlike fracture location or initial displacement, smoking cessation counselling and appropriately timed, protocol-driven return to sport are interventions well within the direct control of the treating clinical team, and the consistency with which these two factors emerge as independent nonunion risk factors across geographically and methodologically distinct studies (a UK bone-graft cohort, a Chinese electronic-health-record emulation, and multiple athlete-specific case series) lends this conclusion considerable weight [6,26,28].

Finally, the injury-surveillance methodology literature reviewed in Section 16, while not itself scaphoid-specific, offers an important corrective lens through which to read the return-to-sport evidence: because time-loss data are characteristically right-skewed, because "return to sport" can legitimately denote several distinct clinical milestones (return to modified training, return to full training, first competitive match, or return to pre-injury performance level), and because studies conducted before consensus reporting standards were established frequently conflate or fail to specify these distinctions, some of the apparent heterogeneity in reported return-to-sport timelines across the scaphoid literature likely reflects definitional inconsistency as much as genuine clinical variation [31-33]. This observation argues strongly for future scaphoid-specific

return-to-sport research to adopt the IOC and football-specific consensus definitions explicitly, so that subsequent systematic reviews and meta-analyses can pool findings with greater confidence than has been possible to date.

19. Limitations of the Evidence Base

Several limitations qualify the conclusions that can be drawn from the literature synthesised in this review. First, substantial heterogeneity exists across studies in the definition of key outcomes, most importantly "union" and "return to sport," with different studies employing plain radiography, CT, or a combination of imaging and clinical criteria to define union, and different studies measuring return to sport at the point of resuming modified training, full training, first competition, or pre-injury performance level, a definitional inconsistency explicitly discussed in Section 16 and directly complicating pooled comparison across the return-to-sport literature examined in Section 17 [6,31,32]. Second, much of the foundational epidemiological and treatment-comparison literature underpinning this review derives from older studies — several of the individual trials contributing to the return-to-sport meta-analysis were published between 1979 and the early 2000s — raising the possibility that findings, particularly regarding nonunion rates and complication profiles, may not fully reflect contemporary imaging, fixation technique, and rehabilitation protocols [6]. Third, several diagnostic accuracy studies, particularly those addressing CBCT and dual-energy CT, are limited by small sample sizes, retrospective design, and, in some cases, explicit selection bias arising from preferential referral of diagnostically ambiguous cases for the index test under study, a limitation the reviewing authors of those studies themselves acknowledge [1,17]. Fourth, the artificial-intelligence literature specific to scaphoid fracture detection remains at an early stage of methodological maturity, with a dedicated critical appraisal concluding that current studies carry a high risk of bias and that meaningful comparison with human clinician performance is not yet achievable with confidence [21]. Fifth, randomised controlled trial evidence directly comparing surgical and conservative management specifically in athletic populations, as opposed to general adult populations, is sparse, meaning that much of the comparative treatment evidence discussed in Sections 10 and 11 must be extrapolated to the athletic context via studies conducted in military personnel or mixed civilian cohorts rather than derived from purpose-designed athlete trials [5,9,25,26]. Sixth, this review did not undertake a systematic literature search, formal risk-of-bias appraisal using a validated instrument, or quantitative meta-analytic pooling of its own; as stated in the Materials and Methods section,

source selection and thematic synthesis were narrative in nature, and the review is therefore subject to selection and emphasis bias that a fully systematic approach would be designed to minimise. Readers should interpret the conclusions offered here as a clinically reasoned synthesis of the currently available evidence rather than as a formally graded, exhaustive systematic appraisal.

20. Conclusions

Scaphoid fractures occupy a distinctive position in sports medicine: common enough to be a recurring clinical problem in almost every contact and fall-prone sport, yet vulnerable enough — by virtue of a precarious, retrograde blood supply — to progress to nonunion and degenerative arthritis if diagnosis is delayed or treatment inadequate. This review's synthesis of the available evidence supports the following principal conclusions.

First, plain radiography alone is an insufficient diagnostic endpoint in the athlete with a clinically suspected scaphoid fracture, given consistently reported occult-fracture rates of one-fifth or more of true cases; confirmatory advanced imaging — MRI where available and timely, CT or cone-beam CT where MRI access is delayed, and artificial-intelligence-assisted reading as an efficiency-enhancing adjunct particularly in ambiguous cases — should be pursued proactively rather than reserved only for persistent symptoms after a period of empirical immobilisation, a strategy the SMaRT trial and the CBCT pathway literature both demonstrate can reduce both diagnostic delay and overall healthcare cost.

Second, surgical fixation reliably accelerates radiographic union and early return to sport-specific activity relative to cast immobilisation, and this advantage appears most clinically meaningful, and best evidenced, in the first three months after injury; however, the two largest and most rigorous bodies of comparative evidence available — the SWIFFT trial with its five-year follow-up and target-trial emulation, and independent meta-analyses of randomised trials — converge on the conclusion that this early advantage does not translate into superior long-term patient-reported function, and is achieved at the cost of a substantially higher complication rate, predominantly hardware-related.

Third, conservative management with appropriately protracted cast immobilisation (completed, not curtailed, before return to sport) achieves union rates in the range of 88–95% for nondisplaced fractures, comparable to surgical union rates in several large series, and should

remain a legitimate first-line strategy for stable, minimally displaced fractures, reserving surgery for confirmed instability, significant displacement, proximal-pole location, or individual patient and sporting circumstances that specifically favour more rapid return.

Fourth, smoking cessation and minimisation of delay to definitive treatment are the two most consistently identified, modifiable determinants of nonunion risk across geographically and methodologically distinct studies, and should be actively addressed in the counselling and management of every athlete with a scaphoid fracture.

Fifth, return to sport while still immobilised in a cast, though historically practised in some series, is associated with a disproportionately elevated nonunion rate and should be actively discouraged in favour of completing appropriately timed immobilisation or, where accelerated return is a genuine clinical priority, considering surgical fixation from the outset.

Finally, the field would benefit substantially from adoption of standardised, consensus-based definitions of injury severity, union, and return-to-sport milestones in future scaphoid-specific research, together with larger, purpose-designed randomised trials conducted specifically in athletic populations and further prospective validation of emerging diagnostic technologies including cone-beam CT, dual-energy CT, and artificial-intelligence-assisted image interpretation, before any of these newer tools can be considered a standard rather than an adjunctive component of the diagnostic and therapeutic pathway for the athlete with a suspected or confirmed scaphoid fracture.

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