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Spondylolysis and Spondylolisthesis in Adolescent Athletes: a narrative review

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Abstract

Background. Spondylolysis, a stress-induced fracture of the lumbar pars interarticularis, and its sequela spondylolisthesis are among the most frequent structural causes of low back pain in adolescent athletes, particularly those practising sports requiring repetitive hyperextension and rotation of the lumbar spine. Despite long clinical experience, heterogeneity persists regarding optimal imaging strategy, conservative treatment duration, bracing indications, and criteria for surgery.

Aim. To synthesise current evidence on the epidemiology, pathophysiology, diagnostic imaging, conservative and surgical management, and return-to-sport outcomes of spondylolysis and spondylolisthesis in adolescent athletes, while critically appraising the strength and consistency of the underlying evidence.

Materials and Methods. Narrative review of peer-reviewed English-language epidemiological studies, hospital and registry-based case series, systematic reviews and meta-analyses, randomised controlled trials, biomechanical and imaging-validation studies, and expert consensus statements on spondylolysis and spondylolisthesis in young and adolescent athletes.

Results. Spondylolysis accounts for a substantial proportion of low back pain presentations in adolescent athletes, with marked sport-specific variation in incidence and lesion distribution. Magnetic resonance imaging has progressively supplanted computed tomography and single-photon emission computed tomography as the preferred modality, balancing sensitivity against radiation exposure.

Conclusions. Early recognition, individualised imaging strategies, and staged conservative rehabilitation remain central to management, though gaps persist regarding optimal rest duration, bracing necessity, and long-term recurrence prevention.

Keywords: spondylolysis; spondylolisthesis; adolescent athletes; low back pain; pars interarticularis; return to sport

1. Introduction

Low back pain is a pervasive complaint among adolescent athletes, and among the identifiable structural causes, spondylolysis occupies a position of particular clinical importance. Spondylolysis is defined as a defect or fracture of the pars interarticularis, the segment of the vertebral arch bounded by the lamina, pedicle, and the superior and inferior articular processes [1]. When this defect becomes bilateral, it predisposes to spondylolisthesis, the anterior (or occasionally posterior or lateral) translation of one vertebral body relative to the subjacent segment [2]. Together these conditions represent the most frequently identified specific diagnosis in young athletes presenting with mechanical low back pain, with reported prevalence estimates in symptomatic adolescent athletes ranging as high as 47% in some series [3]. Low back pain in the broader athletic population - adolescent and adult alike - encompasses a wide range of underlying structural and non-structural causes, among which pars interarticularis injury is consistently highlighted as a leading and sport-relevant diagnosis requiring specific clinical consideration [4].

The clinical significance of spondylolysis in this population stems from several converging factors. First, the adolescent skeleton is undergoing active growth, with incomplete ossification of the posterior vertebral elements rendering the pars interarticularis particularly vulnerable to repetitive mechanical loading [1]. Second, many of the sports most popular among adolescents - gymnastics, cricket fast bowling, American football, diving, weightlifting, and dance - impose precisely the combination of hyperextension, axial loading, and rotational torque that biomechanical studies have identified as the principal driver of pars stress injury [1,5]. Third, the consequences of missed or delayed diagnosis are not trivial: progression from an early, potentially reversible stress reaction to a chronic, non-healing pseudarthrosis can result in prolonged time away from sport, recurrent symptoms, and in a minority of cases, the development of spondylolisthesis with attendant neurological risk [6].

Despite the condition's long recognition - spondylolysis was described in the orthopaedic literature as early as the mid-twentieth century - areas of genuine clinical uncertainty persist. There is no universal consensus on the optimal first-line imaging modality, with debate

continuing over the respective merits of plain radiography, computed tomography (CT), single-photon emission computed tomography (SPECT), and magnetic resonance imaging (MRI) in terms of diagnostic sensitivity, ability to stage lesion chronicity, and radiation exposure in a paediatric population [7]. Similarly, conservative management protocols vary considerably between institutions and countries regarding the necessity and duration of bracing, the permissible duration of rest from sport, and the criteria that should trigger consideration of surgical intervention [8]. The emergence of minimally invasive and motion-preserving direct pars repair techniques has further expanded the surgical armamentarium without yet producing a single agreed-upon algorithm for technique selection [9].

This narrative review aims to synthesise the current evidence addressing the epidemiology, pathophysiology, clinical presentation, diagnostic imaging, and management - both conservative and surgical - of spondylolysis and spondylolisthesis specifically in the adolescent athletic population. Particular emphasis is placed on critically comparing study designs and populations, identifying areas of persistent controversy, and highlighting gaps in the evidence base that limit the formulation of universally applicable clinical guidelines.

2. Materials and Methods

This article was conceived as a narrative review intended to provide a clinically oriented synthesis of the literature on spondylolysis and spondylolisthesis in adolescent athletes, rather than a systematic review or meta-analysis; accordingly, no review protocol was registered, and no formal risk-of-bias appraisal or quantitative pooling of data across studies was undertaken. The literature considered comprised peer-reviewed, English-language publications including epidemiological studies, hospital- and registry-based case series, systematic reviews and meta-analyses, randomised and non-randomised controlled trials, biomechanical and imaging-validation studies, cohort studies of conservative and surgical treatment outcomes, and international expert consensus statements (including Delphi-panel outputs) addressing the diagnosis, natural history, and management of lumbar pars interarticularis injury in young and adolescent athletes. Sources were selected for their direct relevance to the paediatric and adolescent athletic population, for their methodological standing within the available literature, and for their contribution to the clinical and biomechanical understanding of this condition. The material was grouped thematically into sections addressing epidemiology and risk factors; pathophysiology and biomechanics; clinical presentation and physical examination; diagnostic imaging modalities and classification systems; conservative management, including bracing, physical therapy, and activity modification; surgical management, including direct pars repair techniques and fusion; return-to-sport outcomes and recurrence; and sport-specific considerations. Because source selection and thematic grouping were, by design, narrative rather than systematic, the synthesis presented here may be subject to selection and emphasis bias, and its conclusions should be interpreted as a clinically reasoned overview rather than an exhaustive or formally graded account of all available evidence.

3. Epidemiology of Spondylolysis in Adolescent Athletes

The epidemiological burden of spondylolysis in young athletes varies considerably depending on the population studied, the imaging modality employed, and whether symptomatic or asymptomatic cohorts are assessed. In the general adult population, the prevalence of spondylolysis has been consistently reported at approximately 6%, with an incidence of 4.4% already detectable by six years of age, rising only modestly to adult levels thereafter, reflecting the condition's acquisition during childhood ambulation rather than at birth [6,10]. Against this background rate, athletic populations demonstrate substantially elevated prevalence. A systematic review and meta-analysis incorporating the largest published synthesis of sport-

related isthmic spondylolysis prevalence, drawing on 93 studies meeting inclusion criteria after screening 1864 records, calculated an overall pooled prevalence of 28% (95% CI 24-32%) among young athletes aged 10 to 19 years [11]. This same meta-analysis identified marked sport-specific variation, with the highest prevalence rates observed in baseball (45%, 95% CI 30-60%), hockey (43%, 95% CI 27-59%), track and field (36%, 95% CI 19-52%), and cricket (35%, 95% CI 23-47%), figures considerably higher than those seen in sports such as swimming, cycling, or archery [11].

A separate systematic review focusing specifically on pars interarticularis defects across the broader athletic population (not restricted to adolescents) similarly found elevated incidence relative to the general population, with diving athletes showing the highest reported incidence at 35.38%, followed by cricket at 31.97%, baseball/softball at 26.91%, rugby at 22.22%, weightlifting at 19.49%, sailing at 17.18%, table tennis at 15.63%, and wrestling at 14.74% [3]. This review, which retrieved 509 articles and incorporated quantitative data from 42 studies encompassing thousands of athletes across dozens of sports, is notable for the breadth of its sport-specific stratification and provides some of the most granular incidence estimates available, though it should be noted that sample sizes for individual sports varied considerably, from cohorts as small as single-digit numbers (e.g. motorcycling, n=8) to several hundred (e.g. American football, n=1720 pooled across studies) [3].

A further single-arm meta-analysis restricted specifically to athletes presenting with low back pain, pooling nine studies totalling 835 patients predominantly from Japan, the United States, and the United Kingdom, found a markedly higher pooled prevalence estimate of lumbar spondylolysis of 41.7% (95% CI 28-55%), reflecting the fact that this analysis selected for symptomatic athletes rather than unselected athletic cohorts, which inherently enriches for a condition that is a leading cause of such symptoms [12]. The considerable heterogeneity observed in this meta-analysis (I^2 = 95%, $p<0.01$) was partially explained by athlete gender, with male-predominant or male-only cohorts showing lower heterogeneity than mixed-gender cohorts, and by meta-regression on mean patient age, which revealed significant heterogeneity in incidence across different ages ($p=0.044$) [12].

Systematic review evidence addressing low back pain broadly in adolescent athletes, rather than spondylolysis specifically, provides important context for interpreting these spondylolysis-specific figures. A comprehensive systematic review and meta-analysis incorporating 80 studies found that the pooled incidence estimate of low back pain in adolescent athletes was 11% (95% CI 8-13%) over a two-year period, 36% (95% CI 4-68%) over twelve months, and 14% (95% CI 7-22%) over six months, while pooled prevalence estimates ranged from 16% for point prevalence to 42% for twelve-month prevalence [13]. Of the thirteen studies in this review that reported specific diagnoses underlying low back pain, spondylolysis and spondylolisthesis were the most commonly identified morphological finding, appearing in nine of the thirteen studies, followed by Schmorl's nodes, disc degeneration, and muscular strains [13]. This reinforces the status of spondylolysis as the single most frequently implicated specific pathology, even though the majority of adolescent low back pain overall remains non-specific or mechanical in nature, a conclusion broadly consistent with wider reviews of low back pain across the athletic population as a whole, which similarly emphasise the diversity of structural and non-structural contributors while identifying pars interarticularis injury as a disproportionately important specific cause in younger, skeletally immature competitors [4].

Risk factor analysis within these populations has identified several consistent associations. The systematic review of low back pain in adolescent athletes identified sport participation itself, sport volume or intensity, concurrent lower extremity pain, overweight or elevated body mass index, older adolescent age, female sex, and family history of low back pain as potential

associated factors, though notably female sex was associated with low back pain generally rather than specifically with spondylolysis, where male predominance is more typically reported [13]. A prospective cohort study of 189 male adolescent soccer players aged 12 to 14 years, using serial lumbar MRI with both short-tau inversion recovery and computed-tomography-like sequences, found that 28.5% of players demonstrated pathological progression of spondylolysis over a six-month follow-up period, with risk factors for progression including the presence of bone marrow oedema on baseline imaging, increased sacral slope relative to lumbar lordosis, greater sacral rotation angle, and restricted hip external rotation range of motion [8]. This study is particularly notable for being one of the few prospective cohort designs in this literature, as the majority of epidemiological data derive from cross-sectional or retrospective case series, a methodological limitation that constrains causal inference regarding risk factors for lesion onset versus progression.

Sport-specific biomechanical demands appear to drive not only the overall incidence but also the laterality and distribution of lesions. A retrospective comparative study examining 33 soccer players and 49 baseball players with symptomatic spondylolysis, all diagnosed via short-tau inversion recovery MRI, found that soccer players had significantly greater numbers of multiple lesions (63.6% versus 20.4%, $p<0.001$) and bilateral lesions (60.6% versus 18.4%, $p<0.001$) compared with baseball players, while in baseball players the side of the dominant hand used for pitching or batting correlated significantly with contralateral-side lesions ($p=0.001$) [14]. This finding, consistent with the broader biomechanical principle that unilateral, repetitive, sport-specific movements produce asymmetric loading patterns, illustrates how the same underlying pathology can present with meaningfully different lesion distributions depending on the specific athletic demands involved, a point further corroborated by observations in ice hockey players, where spondylolysis has been reported to occur on the shooting side in 73% of affected players [15].

Table 1 summarises representative prevalence estimates for spondylolysis across different athletic populations as reported in the reviewed literature, illustrating both the consistency of elevated risk relative to the general population and the substantial variability attributable to sport type, symptom status, and study design.

Table 1. Representative prevalence estimates of spondylolysis in athletic populations.

Source [ref]	Population / Design	Prevalence estimate	Notes
Riederer et al. [11]	Meta-analysis, 93 studies, athletes 10-19 years	28% overall (95% CI 24-32%)	Highest in baseball (45%), hockey (43%), track & field (36%), cricket (35%)
Tawfik et al. [3]	Systematic review, mixed athletic population, 42 quantitative studies	Up to 35.38% (diving)	Sport-specific incidence ranged from 0% to 35.38% depending on sport

Li et al. [12]	Single-arm meta-analysis, 9 studies, 835 symptomatic athletes with LBP	41.7% (95% CI 28-55%)	Restricted to athletes presenting with low back pain; high heterogeneity (I^2=95%)
Wall et al. [13]	Systematic review, 80 studies, adolescent athletes (general LBP)	Spondylolysis most common specific diagnosis (9/13 studies reporting diagnoses)	General LBP point prevalence 16%, 12-month prevalence 42%
General population (cited in [1,6])	Adult general population	~6%	Baseline comparator; incidence stable from childhood

The general population comparator of approximately 6% is drawn from foundational epidemiological descriptions reiterated across several of the reviewed sources [1,6], underscoring that athletic participation, and particularly participation in specific high-risk sports, is associated with a four- to sevenfold or greater increase in prevalence relative to the non-athletic population. However, direct comparison across these studies must be undertaken cautiously: differences in imaging modality (plain radiography versus CT versus MRI versus SPECT), in the inclusion of symptomatic versus asymptomatic athletes, and in age range and sex distribution all contribute substantially to the observed variability, and the marked heterogeneity reported in the pooled meta-analyses themselves (I^2 values frequently exceeding 90%) signals that these summary figures should be interpreted as broad indicators of relative risk rather than precise, generalisable point estimates.

4. Pathophysiology and Biomechanics

The pathophysiological basis of spondylolysis is now understood to represent a fatigue, or stress, fracture of the pars interarticularis rather than a congenital or developmental anomaly, a conclusion supported by several converging lines of evidence. Spondylolysis has never been demonstrated in neonates, and studies of non-ambulatory patients have found a 0% incidence of the condition, strongly implicating mechanical loading during upright locomotion and activity as the necessary precipitating factor [6,10]. Furthermore, the incidence of spondylolysis rises progressively through childhood, from 4.4% at six years of age to approximately 6% by adulthood, a pattern consistent with cumulative exposure to mechanical stress during the years of skeletal immaturity rather than a fixed congenital prevalence [6].

Biomechanical cadaveric and modelling studies have clarified the specific loading patterns responsible for pars stress. Early biomechanical analyses evaluating load and stress distribution across the lumbar vertebrae demonstrated that the pars interarticularis experiences the highest concentration of mechanical stress within the vertebral arch, with repetitive hyperextension identified as a particularly injurious movement pattern [1]. Fatigue-life studies of cadaveric lumbar vertebrae subjected to forces comparable to those experienced during activities of daily living demonstrated that repetitive sub-threshold loading causes minute, cumulative damage to

bone; when the rate of this microdamage exceeds the capacity for cellular repair, a fracture results [1]. These same cadaveric studies found that the strength of the neural arch continues to increase up to approximately 50 years of age, meaning that children and adolescents possess an inherently weaker, less fatigue-resistant posterior vertebral arch, compounding their vulnerability during the high-training-volume years of competitive youth sport [1].

The specific combination of lumbar hyperextension with concurrent rotation appears to be particularly deleterious. Repetitive loading in flexion increases pressure on the intervertebral discs and tension on the neural elements, while extension produces the converse effect, relieving tension on the dural sac and nerve roots but increasing the mechanical demand placed upon the posterior elements, including the pars interarticularis [2]. Different sports impose markedly different patterns of biomechanical stress: compressive loading predominates in American football and weightlifting, rotational or shear forces in the horizontal plane characterise throwing sports, golf, and baseball, and tensile stress from repetitive flexion-extension cycling characterises gymnastics, ballet, and cheerleading [2]. This sport-specific biomechanical signature likely explains much of the variation in incidence and lesion laterality described in the preceding section.

Hereditary and constitutional factors also appear to modulate individual susceptibility independent of loading history. First-degree relatives of patients with spondylolysis have been shown to have a substantially higher incidence of the condition (19%) compared with the general population, suggesting a genetic contribution, potentially related to inherited variation in pars morphology, trabecular architecture, or bone mineral density [1]. Male sex is a consistently reported risk factor, with incidence ratios of approximately 2:1 favouring males over females reported across multiple studies [3,5], though the biological basis for this sex disparity, whether hormonal, anatomical (e.g., differences in pelvic incidence or sacral morphology), or behavioural (differential participation rates in high-risk sports), remains incompletely characterised.

The classification of spondylolysis according to its stage of structural progression, first proposed in the context of describing fracture chronicity on advanced imaging, has become central to both prognostic counselling and treatment planning. Morita and colleagues' staging system, widely cited across the reviewed literature, divides pars defects into three progressive stages based on computed tomography appearance: an early stage, characterised by a hairline defect with focal bony resorption; a progressive stage, in which the defect widens and small bony fragments may be present; and a terminal stage, marked by sclerotic change indicative of an established pseudarthrosis [1,5]. A refined five- or six-grade classification incorporating MRI findings has subsequently been proposed, distinguishing a normal pars (grade 0), a stress reaction with bone marrow oedema but no cortical disruption (grade 1), an incomplete fracture with early cortical disruption (grade 2), an acute complete fracture (grade 3), and a chronic, established non-union without ongoing marrow oedema (grade 4) [5]. The clinical importance of this staging lies in its demonstrated correlation with healing potential: a retrospective study by Sakai and colleagues, cited extensively across the reviewed surgical and conservative-treatment literature, found a 100% bony healing rate in "very early" stage defects, declining to 93.8% in "early" stage defects, 80% in "progressive" stage defects, and essentially 0% in terminal-stage, pseudarthrotic defects, for which conservative healing was not even attempted in that series [5].

This staging framework also underpins the mechanistic distinction between acute and chronic pars pain. In acute lesions - stress reactions and early or progressive fractures - pain is thought to arise predominantly from local inflammation associated with the fracture process itself, whereas in chronic, terminal-stage defects, pain instead arises from communicating synovitis

at the fibrocartilaginous pseudarthrosis [5]. This distinction carries direct therapeutic implications: the treatment goal in acute or progressive lesions is to achieve bony union through immobilisation and activity restriction, whereas in terminal, non-healing defects, the therapeutic aim shifts toward symptomatic pain control, with bony union achievable, if at all, only through surgical intervention [5].

The progression from unilateral to bilateral spondylolysis, and subsequently to spondylolisthesis, follows a biomechanically coherent pathway. Approximately 80% of pars defects are reported to be bilateral, with the remaining 20% unilateral, and it has been proposed that a unilateral defect increases compensatory stress at the contralateral pars, explaining the eventual progression to bilateral involvement in many cases [5]. Once bilateral pars defects are established, approximately 75% of patients are estimated to progress to some degree of spondylolisthesis [5,16]. The classical Wiltse-Newman-Macnab classification system categorises spondylolisthesis by aetiology into six types: dysplastic (type I, arising from congenital dysplasia of the sacral or L5 articular processes permitting anterior translation), isthmic (type II, itself subdivided into IIA, a true pars stress fracture; IIB, pars elongation from repetitive microfracture and healing; and IIC, an acute traumatic fracture), degenerative (type III, arising from facet joint arthritis and ligamentous laxity), traumatic (type IV, resulting from high-energy fracture of posterior elements other than the pars), pathological (type V, secondary to bone disease such as tumour or infection), and iatrogenic (type VI, a sequela of prior spinal surgery) [1]. In the adolescent athletic population under consideration in this review, type IIA isthmic spondylolisthesis, arising directly from bilateral spondylolytic pars fractures, is overwhelmingly the most relevant subtype [1,16,17].

The severity of established spondylolisthesis is most commonly graded using the Meyerding classification, which quantifies the percentage of anterior translation of the cranial vertebral body relative to the subjacent vertebra on a standing lateral radiograph: grade I representing 0-25% slippage, grade II 26-50%, grade III 51-75%, grade IV 76-100%, and grade V (spondyloptosis) representing complete translation exceeding 100% [18]. A detailed classification-in-brief analysis of the Meyerding system notes that it demonstrates excellent intra-observer and inter-observer reliability (reported correlation coefficients of 0.94-0.95 and 0.78-0.93 respectively across validation studies), making it one of only a small number of radiographic measures in this domain shown to be consistently reproducible between examiners of varying experience levels [18]. However, the same analysis emphasises an important limitation: the Meyerding grade alone demonstrates poor correlation with symptom severity or progression risk, and must therefore be interpreted alongside aetiological classification, sagittal spinopelvic parameters, and clinical findings rather than used in isolation to guide treatment decisions [18].

5. Clinical Presentation and Physical Examination

Adolescent athletes with spondylolysis most commonly present with an insidious onset of activity-related low back pain, typically localised to the lower lumbar region and characteristically exacerbated by lumbar extension, impact loading (such as running or jumping), and sustained standing, while improving with rest [2,9]. The mean age at presentation across multiple cohort studies clusters around 15 to 16 years, coinciding with the adolescent growth spurt, during which the relative mismatch between rapid skeletal elongation and comparatively slower adaptation of surrounding musculature and connective tissue is thought to compound mechanical vulnerability [4,5]. A minority of patients present with a more acute onset, particularly in sports such as competitive cheerleading and gymnastics where a single traumatic hyperextension event can precipitate an acute pars fracture superimposed on pre-existing stress remodelling [2]. Radiating pain into the buttock or posterior thigh may occur,

but frank radicular symptoms or neurological deficits are distinctly uncommon in isolated spondylolysis without associated spondylolisthesis or disc pathology, and their presence should prompt consideration of alternative or concurrent diagnoses [2,9].

Physical examination findings, while useful in raising clinical suspicion, have been shown across multiple studies to possess limited diagnostic sensitivity and specificity when used in isolation. Decreased hamstring flexibility is reported as an almost universal finding in symptomatic athletes and may represent the only presenting sign in some cases, frequently accompanied by increased lumbar lordosis and relative weakness of the abdominal musculature [2]. The single-leg (or "one-legged") hyperextension test, in which the patient stands on one leg and extends the lumbar spine while the examiner observes for reproduction of ipsilateral pain, has historically been regarded as pathognomonic for spondylolysis, and is described as such in several of the reviewed sources [1,16,18]. However, more rigorous diagnostic-accuracy evaluation has substantially tempered this assumption: a study specifically assessing the one-legged hyperextension test against SPECT-confirmed spondylolysis found a sensitivity of only 50-55%, translating to very limited clinical utility as a standalone diagnostic tool [5]. This finding is corroborated by a separate evaluation reporting pain with back extension as having a sensitivity of 81% but a specificity of only 39.7% for radiographically confirmed spondylolysis in a cohort of 100 young athletes, indicating that while the absence of extension-related pain may have some value in reducing suspicion, its presence is a poor discriminator between spondylolytic and non-spondylolytic causes of mechanical back pain [1].

This recurring finding across independent studies - that clinical examination maneuvers classically taught as specific for spondylolysis in fact demonstrate only modest sensitivity and poor specificity - represents one of the more clinically important points of convergence (and caution) within this literature. It directly underpins the near-universal recommendation, articulated across multiple sources, that the diagnosis of spondylolysis cannot be reliably made on history and examination alone and necessitates appropriate imaging in any adolescent athlete with low back pain persisting beyond approximately two to three weeks [9,19]. Additional examination findings described in the literature, though similarly non-specific, include palpable tenderness over the affected segment, possible mild scoliosis, a palpable "step-off" of the spinous processes in cases with established spondylolisthesis, and in high-grade slips, compensatory postural changes including the Phalen-Dickson sign (a crouched gait with increased hip and knee flexion adopted to maintain sagittal balance) [2,17].

Several provocative tests directed at the sacroiliac joint and neural tension, including the FABER (flexion-abduction-external rotation) test and Gaenslen's sign, are described for differentiating sacroiliac-mediated pain from spondylolytic pain, though again these are reported with incomplete diagnostic accuracy data across the reviewed sources [2,9]. The straight-leg raise test is used primarily to screen for concurrent neural tension or disc pathology rather than to diagnose spondylolysis itself, and a positive result, particularly when accompanied by motor, sensory, or reflex abnormality, should prompt heightened suspicion for an alternative or coexisting diagnosis such as disc herniation or, in the context of established spondylolisthesis, nerve root compromise [2,9].

6. Differential Diagnosis

Given the limited specificity of both history and physical examination, a broad differential diagnosis must be entertained in any adolescent athlete presenting with persistent low back pain, encompassing both intrinsic spinal pathology and extraspinal causes. Among intrinsic causes, Scheuermann's disease (juvenile kyphosis) represents an important alternative or coexisting diagnosis, particularly in its atypical thoracolumbar form, which has itself been

associated with sports involving repetitive flexion-extension cycling such as gymnastics, weightlifting, rowing, and wrestling [2,20]. Scheuermann's disease is diagnosed radiographically according to Sørensen's criteria, requiring thoracic kyphosis exceeding 40 degrees in combination with anterior wedging of at least 5 degrees across three or more contiguous vertebrae, and is itself associated with Schmorl's nodes and vertebral endplate irregularities that may occasionally be mistaken for, or coexist with, spondylolytic changes [20]. A narrative review focusing specifically on Scheuermann's disease notes that conservative management, including physiotherapy and selective bracing, is successful in the majority of cases, with surgical intervention reserved for curves exceeding 70 degrees or those with persistent, refractory pain, broadly paralleling the staged management philosophy applied to spondylolysis itself [20].

Lumbar disc herniation, while considerably less common in the paediatric and adolescent population than in adults, must also be considered, particularly when radicular symptoms, positive straight-leg raise testing, or neurological deficit are present [2,9]. Vertebral ring apophyseal avulsion fractures, a paediatric-specific injury pattern arising from the biomechanically weak cartilaginous junction between the vertebral body and its apophysis, can present with acute flexion-related lumbar pain and may mimic or coexist with posterior element injury, particularly in weightlifting and wrestling populations [9]. Posterior element overuse syndrome (also termed hyperlordotic or mechanical low back pain), representing a constellation of muscle-tendon, ligamentous, and facet-joint overuse injuries without a demonstrable pars defect, is identified as the second most common cause of adolescent low back pain after spondylolysis itself, and shares a very similar clinical presentation of extension-related pain, underscoring the necessity of imaging to distinguish between the two [9]. Sacroiliac joint dysfunction, scoliosis (addressed further in Section 15), and, in rare but important cases, discitis, vertebral osteomyelitis, and spinal or paraspinal neoplasm must also be considered, particularly in the presence of constitutional symptoms, night pain, or examination findings inconsistent with mechanical pathology [2,9]. A broader review of low back pain across the athletic population underscores the same principle, cataloguing muscular strain, disc pathology, apophyseal injury, and inflammatory or neoplastic causes alongside pars interarticularis injury within the differential diagnostic framework that should be applied whenever an athlete of any age presents with persistent mechanical back pain [4].

7. Diagnostic Imaging: Modalities and Comparative Accuracy

The selection of appropriate imaging represents one of the most actively debated aspects of spondylolysis management in adolescent athletes, reflecting a fundamental tension between diagnostic sensitivity, the ability to stage lesion chronicity and healing potential, and the imperative to minimise cumulative ionising radiation exposure in a paediatric population with decades of subsequent life expectancy.

Plain radiography, comprising anteroposterior, lateral, and oblique views of the lumbosacral spine, remains the conventional first-line investigation in most published protocols, owing to its wide availability, low cost, and ability to identify chronic, established defects via the classic "Scotty dog with a collar" appearance on oblique views [1,16]. However, the diagnostic sensitivity of plain radiography is consistently reported as inadequate for detecting early-stage lesions. Standing anteroposterior and lateral radiographs have been reported to demonstrate a sensitivity of approximately 75% for established spondylolysis, substantially lower than the 90% sensitivity attributed to CT scanning in the same comparative analysis [5]. Furthermore, several sources note that oblique radiographic views, long considered standard owing to their visualisation of the pars defect in profile, provide no meaningful incremental diagnostic value over anteroposterior and lateral views alone while incurring additional radiation exposure,

leading many contemporary protocols to discourage their routine use except in the specific circumstance of suspected upper lumbar spondylolysis [5,17].

Computed tomography offers substantially superior visualisation of cortical bony anatomy and remains, in the view of several authors, the most reliable modality for precisely staging lesion chronicity (distinguishing an acute, non-sclerotic fracture from an established, sclerotic pseudarthrosis) and for monitoring bony healing during the course of conservative treatment [5]. Sagittal reconstructed CT imaging is specifically recommended for optimal visualisation of early-stage defects isolated to the ventral-caudal aspect of the pars, the anatomical location at which tensile stress is concentrated according to biomechanical modelling [5]. The principal disadvantage of CT is, self-evidently, its substantial radiation burden; a large-scale study of over 680,000 individuals exposed to CT scanning during childhood or adolescence found an incidence rate ratio of 1.13 for all-type cancers attributable to spine CT scanning specifically, a finding that has driven increasing efforts toward dose-reduction protocols and a broader shift toward non-ionising imaging modalities where diagnostically feasible [5].

Single-photon emission computed tomography, frequently combined with CT as SPECT-CT, was historically regarded by many clinicians as the gold-standard investigation owing to its exceptional sensitivity for detecting early metabolic bone stress reactions, often preceding any visible structural fracture on CT or plain radiography [2,9]. However, SPECT carries its own significant limitations: it cannot reliably distinguish an acute stress reaction from a chronic, non-healing lesion, generates false positives from other causes of increased radiotracer uptake such as facet arthropathy or infection, and detects only approximately 17% of chronic defects when used in isolation, alongside carrying a substantial radiation dose, estimated at approximately 5 mSv for SPECT alone and 10 mSv for combined SPECT-CT [5]. Reflecting these limitations, several contemporary reviews now recommend that SPECT be essentially reserved for cases in which MRI findings are non-diagnostic, or for circumstances requiring particularly expedited diagnosis in elite athletes with persistent symptoms beyond three weeks [5].

Magnetic resonance imaging has progressively emerged across the reviewed literature as the preferred advanced imaging modality for the majority of adolescent athletes, reflecting its combination of diagnostic accuracy and absence of ionising radiation. Early concerns regarding the sensitivity of MRI for spondylolysis detection have been substantially allayed by the development of thin-slice, pars-specific imaging protocols; contemporary MRI sequences incorporating fat-suppressed, fast-spin T2-weighted imaging in the sagittal plane have been reported to achieve sensitivities as high as 92-98% for spondylolysis detection, approaching parity with CT and SPECT while eliminating radiation exposure entirely [5]. The short-tau inversion recovery (STIR) sequence in particular has been repeatedly validated as highly sensitive for detecting the bone marrow oedema that characterises an early, metabolically active stress reaction, a finding of considerable prognostic importance given its association with superior healing potential under conservative management, discussed further in Section 10 [5,8,14]. A 2002 classification scheme proposed by Hollenberg and colleagues, cited across multiple sources in this review, grades MRI appearance on a five-point scale analogous to the CT-based staging described in Section 4: grade 0 (normal), grade 1 (stress reaction with marrow oedema, intact cortex), grade 2 (incomplete fracture), grade 3 (acute complete fracture), and grade 4 (chronic, established defect without active oedema) [5,16].

Despite this progressive shift toward MRI, important caveats are consistently raised. One investigation directly comparing MRI, CT, and SPECT concluded that MRI demonstrated high accuracy for grades 0, 3, and 4 lesions but showed relative limitation in reliably distinguishing a stress reaction (grade 1) from an incomplete fracture (grade 2), a distinction that nonetheless

carries meaningful prognostic and therapeutic implications [5]. Furthermore, a retrospective review specifically examining the adequacy of MRI in a cohort of adolescents with back pain found that spondylolysis was "frequently missed" by MRI alone, implying that in certain clinical contexts a combined or sequential imaging approach, beginning with radiography and MRI but escalating to CT when clinical suspicion remains high despite negative or equivocal MRI findings, may still be warranted [19]. This recommendation is echoed in a broader review of lumbar spine injuries in sport, which explicitly advises incorporating both CT and plain radiography into screening protocols for persistent adolescent low back pain rather than relying on MRI as a sole investigation [19].

The practical diagnostic algorithms proposed across several reviewed sources converge on a broadly stepwise approach: plain radiography as an initial, low-cost screening investigation, followed by MRI (incorporating dedicated bone-sensitive and marrow-oedema-sensitive sequences) as the preferred advanced imaging modality for most adolescent athletes, with CT reserved for cases requiring precise structural staging, preoperative planning, or monitoring of bony union, and SPECT reserved for selected cases in which MRI findings remain non-diagnostic despite ongoing clinical suspicion [1,2,5,9]. It is notable, however, that none of the reviewed sources describe this algorithm as having been formally validated in a prospective, head-to-head comparative trial specifically within the adolescent athletic population; the recommendations instead derive from a synthesis of diagnostic-accuracy studies, expert opinion, and considerations of radiation stewardship specific to paediatric patients.

8. An Alternative Diagnostic Paradigm: Deferred or Selective Imaging

A notable counterpoint to the imaging-forward diagnostic philosophy described in Section 7 emerges from a pilot non-randomised controlled trial evaluating a physical-therapist-guided functional progression model of care, explicitly designed to challenge the prevailing assumption that advanced imaging must precede treatment initiation in adolescent athletes with extension-based low back pain [21]. In this study, sixteen adolescent athletes were allocated to either a conventional "biomedical model," in which physicians sought to obtain a specific pathoanatomical diagnosis via advanced imaging before commencing treatment, or an alternative "physical therapy first" model, in which patients began a structured, criterion-based (rather than time-based) exercise progression immediately, with advanced imaging reserved only for those failing to progress through the programme within a defined timeframe [21].

The results of this pilot trial were striking in their implications for resource utilisation: the physical-therapy-first model reduced the use of advanced imaging by 88% relative to the biomedical model, while achieving broadly comparable improvements in pain and functional outcome (as measured by the Micheli Functional Scale) between the two groups [21]. All patients in the physical-therapy-first group and 88% of patients in the biomedical model group ultimately achieved a full return to sport. Notably, however, the two models diverged substantially in time-to-return-to-sport depending on injury type: among patients who did not sustain a confirmed vertebral injury, those in the biomedical model (who had the reassurance of a normal scan) returned to sport considerably sooner than those in the physical-therapy-first group (3.4 days versus 51 days), whereas among those with a diagnosed or presumed vertebral injury, the biomedical model group took longer to return to sport than the physical-therapy-first group (131 days versus 71 days) [21]. Two adverse events were recorded in the biomedical model group (one case of worsening pain ultimately attributed to a herniated disc requiring surgical intervention, and one case of significant pain exacerbation during therapy following a bilateral spondylolysis diagnosis), while no adverse events were recorded in the physical-therapy-first group, though the authors appropriately caution that this pilot study was underpowered for formal statistical comparison of safety outcomes [21].

This single pilot trial stands in some tension with the broader weight of the reviewed literature, which generally favours an imaging-based diagnostic approach, particularly given the demonstrated limitations of clinical examination discussed in Section 5. The authors of the pilot trial themselves frame their findings as hypothesis-generating rather than practice-changing, explicitly calling for a larger, adequately powered, ideally randomised trial before the physical-therapy-first model could be recommended for widespread adoption [21]. Nonetheless, this study is valuable in illustrating that the optimal balance between diagnostic certainty and resource/radiation stewardship in this population remains an area of genuine ongoing investigation rather than settled consensus, and it provides supporting context for the subsequently discussed international expert consensus effort (Section 14), which likewise grappled with disagreement regarding the necessity and timing of imaging relative to the initiation of physical therapy.

9. Conservative Management: General Principles

The overwhelming majority of adolescent athletes diagnosed with spondylolysis, and a substantial proportion of those with low-grade (Meyerding grade I or II) spondylolisthesis, are managed successfully with conservative, non-operative treatment, a conclusion that recurs with remarkable consistency across virtually every source addressing management outcomes in this review [1,2,4-6,9,16,22]. The core components of conservative management, while varying in specific detail between protocols, typically comprise a period of relative rest or activity restriction from the provoking sport, a structured physical therapy programme emphasising abdominal and core strengthening, hamstring and lumbar flexibility, and antilordotic postural retraining, and, in many but not all protocols, a period of thoracolumbosacral bracing [2,5,9].

The precise duration of required activity restriction, however, demonstrates considerable variability across the literature, and this variability is itself a recurring theme of methodological critique within several of the reviewed systematic reviews. A systematic review specifically evaluating nonoperative treatment in lumbar spondylolysis and spondylolisthesis, screening studies published between 1966 and 2012, identified only ten studies meeting rigorous inclusion criteria (comparative design, inclusion of at least one nonoperative treatment arm), and concluded that "no consensus can be reached on the role of nonoperative versus surgical care because of limited investigation and heterogeneity of studies reported," further noting that studies of nonoperative care options "suffered from lack of blinding of assessors and control groups and decreased patient compliance with exercise programs" [6]. This review found that, among studies directly comparing different exercise-based approaches, flexion-based exercise programmes were associated with significantly better outcomes (less pain, better return to work, higher self-rated recovery) than extension-based programmes in patients with established spondylolisthesis, though it should be noted that the populations studied in these particular comparative trials skewed toward older adult patients rather than adolescent athletes specifically [6].

Return-to-sport rates following conservative management are, nonetheless, consistently reported as favourable across multiple independent cohort studies, even where the specific protocols employed differ considerably. A case-series study from the United Kingdom following 104 elite adolescent athletes (predominantly cricket fast bowlers) treated with activity restriction and physical therapy over a mean duration of symptoms before diagnosis of several weeks found that 87.5% returned to sport following conservative measures [23]. A Japanese retrospective cohort study examining 180 pediatric athletes (147 male, 33 female, mean age 13.6-14.4 years) managed according to one of two distinct conservative treatment strategies - a "bone union" (BU) strategy employing a hard trunk brace with complete cessation of sports activity, versus a "pain management" (PM) strategy involving a soft corset and activity as

tolerated by pain - found a return-to-sport rate exceeding 95% in both groups, specifically 98.9% in the BU group and 97.6% in the PM group [22]. This study is particularly informative because it directly compared two fundamentally different conservative philosophies within a single institutional cohort: the mean time to return to sport was significantly longer in the bone-union group (4.7 ± 1.9 months) than in the pain-management group (1.8 ± 1.7 months, $p<0.01$), a difference attributable to the additional time required for radiographic bony healing in the former strategy, yet recurrence rates after return to sport were broadly similar between the groups (7.4% in the BU group versus 4.8% in the PM group) [22]. The authors of this study interpret their relatively low recurrence rates, compared with the 26.1% recurrence rate reported by an earlier study (Sakai et al.) in which patients returned to sport based on radiographic confirmation of union alone without structured physical rehabilitation, as evidence for the importance of a dedicated rehabilitation programme targeting thoracic mobility and hamstring/quadriceps flexibility, rather than bony union status alone, in minimising recurrence risk [22].

A meta-analysis specifically addressing return-to-play rates in adolescent athletes with symptomatic spondylolysis without associated listhesis, pooling data from eleven studies encompassing 376 patients (245 managed non-operatively, 131 managed operatively across both operative subgroups reported), found that return to athletic competition, calculated via logit event rate analysis, was statistically favoured following both nonoperative (92.2%) and operative (90.3%) treatment, with no significant heterogeneity among the nonoperatively treated studies ($Q=4.99$, $I^2=0\%$) [23]. This remarkably low heterogeneity for the nonoperative treatment arm stands in notable contrast to the substantial heterogeneity reported in several of the epidemiological prevalence meta-analyses discussed in Section 3, and the authors of this meta-analysis attribute this consistency to their use of a single, well-defined, binary outcome measure (return to play, yes or no) rather than the more heterogeneous outcome definitions (varying pain scales, functional indices, imaging-based healing criteria) that complicate cross-study comparison in much of this literature [23].

10. Bracing: Evidence and Controversy

The role of thoracolumbosacral bracing within conservative management protocols represents one of the most persistently debated aspects of spondylolysis treatment in adolescent athletes, with the reviewed literature reflecting genuinely divergent institutional philosophies rather than a settled consensus.

Proponents of bracing argue that external immobilisation, by restricting lumbar extension and rotation, reduces mechanical stress across the healing pars defect and may thereby promote bony union, particularly in earlier-stage lesions. Multiple sources describe the historical and continued use of rigid thoracolumbosacral orthoses, typically worn for a period of approximately eight to twelve weeks, often as part of a staged protocol in which bracing is used preferentially for early or progressive-stage defects while pain-management-oriented soft corsets or no bracing at all are reserved for terminal, pseudarthrotic lesions unlikely to achieve union regardless of immobilisation strategy [5,22,24]. A detailed narrative review addressing management of lumbar bone stress injury specifically in cricket fast bowlers describes an approach in which unloading from bowling is continued, with or without bracing, until serial MRI with bone-window sequencing demonstrates complete bony healing, a process the authors note typically requires three to six months rather than the shorter six-to-ten-week period that would be dictated by symptom resolution alone [24]. This same review explicitly frames its approach as "structural" management, in contrast to the "functional" management (treating according to symptoms rather than imaging-confirmed structural healing) more commonly recommended for low back pain in middle-aged adults, arguing that the specific demands of

elite youth fast bowling justify this more conservative, imaging-dependent strategy given anecdotal observations of apparently longer subsequent career longevity among bowlers who achieve bony union compared with those who develop chronic pars defects [24].

Countervailing evidence, however, questions whether bracing confers meaningful additional benefit beyond the activity restriction it inherently enforces. A meta-analysis of the conservative management of spondylolysis with grade I spondylolisthesis specifically did not find a significant difference in return-to-sport rates or clinical outcomes between patients treated with versus without bracing [24]. The cricket-focused review itself acknowledges this uncertainty directly, stating that "while the application of a brace to limit lumbar extension and rotation logically should promote healing, there is a lack of strong evidence to support a clear advantage in all athletes," and suggests that bracing may be of selective benefit principally in patients with persisting rest pain, exaggerated lumbar lordosis, clinical features suggesting delayed or non-union, or established bilateral stress fractures, rather than as a universal component of management [24]. Reflecting this uncertainty in practice, the same authors note that in their own clinical experience with full-time professional athletes, braces are generally not prescribed, with the pragmatic rationale for bracing instead reserved for scenarios such as a schoolchild who might otherwise continue informal twisting sport at school despite having agreed to formally rest from organised competition [24].

This divergence of opinion regarding bracing is further corroborated by the international expert consensus Delphi study discussed in Section 14, which explicitly identified the usage of bracing for spondylolysis management as one of the areas lacking sufficient high-quality evidence to guide definitive recommendations, calling specifically for "higher-quality studies on the benefits of bracing" as a priority for future research [25]. Taken together, the reviewed literature suggests that while bracing remains in widespread clinical use, particularly for earlier-stage or higher-risk lesions, the evidence supporting its incremental benefit over activity restriction and physical therapy alone remains genuinely unresolved, and bracing decisions in contemporary practice appear to be guided substantially by individual clinician philosophy and specific patient risk factors rather than by high-level comparative trial evidence.

11. Adjunctive Conservative Modalities: Low-Intensity Pulsed Ultrasound

Low-intensity pulsed ultrasound (LIPUS) has emerged as a notable adjunctive therapy within conservative management protocols, specifically targeting enhancement of bony union rates in progressive-stage spondylolysis defects where conventional immobilisation alone yields comparatively modest healing rates. The foundational description of this condition's natural history and treatment, reviewing the broader spondylolysis and spondylolisthesis literature, describes a controlled comparison in which an experimental group of nine adolescent patients with progressive-stage spondylolysis received twenty minutes of daily LIPUS in addition to conventional conservative treatment, achieving a union rate of 66.7% over a mean treatment duration of 3.8 months, compared with a union rate of only 10% over an identical treatment duration in a control group of ten adolescent patients receiving conventional conservative treatment alone [1]. A broader meta-analysis of LIPUS across various fracture types (not restricted to spondylolysis), pooling three trials encompassing 158 fractures, found an average reduction in time to healing of 64 days in the LIPUS-treated group compared with controls, lending some external corroboration to the biological plausibility of this intervention, though the authors of the spondylolysis-specific review caution that "larger studies need to be undertaken regarding the effectiveness of LIPUS in treating spondylolysis conservatively" before it can be considered a standard of care [1].

This cautiously optimistic assessment is echoed in a separate, more recent review specifically addressing acute and chronic pars fractures, which similarly describes LIPUS as "a technique that has recently emerged with promising results for increasing bony union rates, particularly in progressive stage pars fractures," citing the same clinical study demonstrating an increase in bony union from 10% with conventional treatment to 67% with LIPUS in progressive-stage fractures demonstrating high-signal change (bone marrow oedema) on MRI [5]. This same review additionally cites a separate prospective study in athletes with spondylolysis reporting that LIPUS reduced the time required to return to sport by 72%, from a mean of 167 days with conventional treatment to 61 days with the addition of LIPUS [5]. These two independently cited figures (the 66.7%/67% union rate improvement and the 72% reduction in time to return to sport) derive from what appear to be related but not necessarily identical study populations across the two reviewing sources, and the overall body of LIPUS-specific evidence in this population remains limited to a small number of relatively small studies, such that while the results are consistently described as encouraging across the reviewed literature, neither source elevates LIPUS to the status of an established standard-of-care intervention, and both explicitly flag the need for further confirmatory research before broader adoption.

12. Prognostic Factors for Bony Union Under Conservative Treatment

Beyond the staging classification described in Section 4, several additional clinical and radiological factors have been specifically investigated as predictors of successful bony union under conservative management, with direct implications for patient counselling and the tailoring of rehabilitation intensity.

A retrospective study of pediatric and adolescent athletes with spondylolysis, analysing 227 individual pars defects across 127 patients treated with a standardised conservative protocol (activity cessation, bracing, and a structured rehabilitation programme emphasising abdominal strengthening and hamstring stretching), found an overall bony union rate of 66.5% (151 of 227 defects) at the level of individual lesions and 70.1% (89 of 127 patients) at the patient level [26]. Multivariate logistic regression in this study identified three factors independently and significantly associated with bony union: the stage of the ipsilateral pars interarticularis defect (odds ratio 0.26, p=0.0027, indicating that higher defect stage substantially reduces the odds of union), the stage of the contralateral pars interarticularis defect (odds ratio 0.51, p=0.00026, indicating that a more advanced contralateral defect similarly reduces union probability even at the index level), and performance on the straight-leg-raising test as a measure of hamstring flexibility (odds ratio 1.06, p=0.028, indicating that greater flexibility, i.e., a higher achievable SLR angle, was associated with increased odds of union) [26]. Notably, in this same analysis, other commonly measured flexibility parameters, including finger-floor distance and heel-buttock distance, as well as trunk strength as measured by a modified Kraus-Weber test, did not reach statistical significance as independent predictors, suggesting that hamstring-specific flexibility, rather than generalised trunk flexibility or strength, carries particular prognostic weight [26]. The authors of this study interpret their findings as supporting the biomechanical hypothesis that tight hamstrings limit hip rotation and pelvic mobility, thereby transferring additional compensatory mechanical stress to the lumbar spine during functional movement and impeding the mechanical environment necessary for fracture healing even when sports participation itself has been formally discontinued [26].

These findings regarding the prognostic significance of unilateral versus bilateral and contralateral defect status are consistent with, and extend, the pattern described in the earlier prospective cohort study of adolescent soccer players, in which bone marrow oedema status, sacral slope relative to lumbar lordosis, sacral rotation angle, and hip external rotation range of motion were similarly identified as significant predictors of progression (rather than specifically

of union, as the soccer-player study examined worsening rather than healing as its primary outcome) [8]. Taken together, these two studies, despite examining somewhat different outcomes (healing in one case, progression in the other) and different sport-specific populations, converge on a broader thematic conclusion: both local structural factors (defect stage, laterality, presence of marrow oedema) and more distal biomechanical or flexibility-related factors (hamstring tightness, hip rotational range of motion, sacropelvic alignment) appear to jointly influence the trajectory of spondylotic lesions under conservative management, lending support to rehabilitation protocols that explicitly target hip and pelvic girdle flexibility and alignment rather than focusing exclusively on core or lumbar-specific strengthening.

13. The Role of Immediate versus Delayed Physical Therapy

A particularly important and clinically actionable body of evidence addressed in this review derives from a recent, well-designed multicentre randomised controlled trial directly comparing the timing of physical therapy initiation in adolescent athletes with active lumbar spondylolysis, representing one of the higher-quality experimental designs available within this literature [27]. This trial randomised sixty-four adolescent athletes (median age 14.2 years, 40% female) with MRI-confirmed active spondylolysis (defined as oedema at the pars interarticularis with or without a fracture line) to either an "immediate physical therapy" group, in which structured therapy began within seven days of diagnosis, or a "rest before physical therapy" group, in which therapy was deferred until symptoms had resolved, with subsequent progression then based on a predetermined time-based protocol rather than functional criteria [27].

At the primary one-month endpoint, the immediate physical therapy group demonstrated significantly superior pain and functional outcomes, with a mean difference on the Micheli Functional Scale of 21.3 points (95% CI 28.7 to 13.9, $p<0.001$) favouring immediate therapy [27]. Patients in the immediate physical therapy group also returned to sport significantly sooner, with a median time to meeting return-to-sport criteria of 74 days (95% CI 64-85) compared with 112 days (95% CI 92-132) in the rest-before-physical-therapy group ($p<0.001$), and experienced a substantially lower rate of low back pain recurrence over twelve months of follow-up (3% versus 29%, $p=0.01$) [27]. Importantly, no adverse events were reported in either treatment arm, directly addressing the theoretical concern that early loading of an unhealed pars defect might precipitate worsening injury or impede structural healing [27].

This latter concern regarding structural healing was directly addressed in a subsequent secondary analysis of the same trial cohort, specifically examining bony healing outcomes on three-month follow-up MRI as a function of treatment timing [28]. This analysis, encompassing the fifty-three participants who completed both baseline and three-month follow-up imaging, found no statistically significant difference in the proportion demonstrating MRI healing between the immediate physical therapy group (84%) and the rest-before-physical-therapy group (79%, $p=0.30$), nor in rates of no change (8% versus 7%) or worsening findings (8% versus 14%) [28]. Multivariate logistic regression confirmed that treatment group allocation was not a significant predictor of healing on three-month MRI (odds ratio 1.8, 95% CI 0.4-7.3, $p=0.30$), and none of several secondary baseline variables examined (lesion laterality, stage of injury, vertebral level, patient sex, or age) achieved statistical significance as independent predictors of healing in this particular cohort, in some contrast to the prognostic factors identified in the retrospective Japanese cohort discussed in Section 12, though the authors note this discrepancy may reflect the smaller sample size and shorter (three-month) follow-up interval of the randomised trial relative to the five-month-or-longer follow-up typically employed in the retrospective cohort studies [26,28].

Consistent with the primary trial's clinical findings, this secondary MRI analysis reported that regardless of treatment group allocation, participants whose three-month MRI demonstrated healing were significantly more likely to be pain-free at that time point (97.6% pain-free) compared with those whose imaging showed no change or worsening (67% pain-free, p=0.01), and were significantly less likely to experience recurrence of low back pain within twelve months (7.3% recurrence versus 50% recurrence in those without MRI-confirmed healing, p=0.02) [28]. These two linked studies together provide what is arguably the strongest level of evidence within this entire review regarding a specific, actionable management question: they directly challenge the traditional dogma of mandatory prolonged rest preceding physical therapy initiation, demonstrating that immediate, criterion-based physical therapy neither impairs structural bony healing nor increases adverse events, while conferring meaningful advantages in time to symptom resolution, time to return to sport, and recurrence prevention. The authors of both reports explicitly attribute at least part of the benefit observed with immediate physical therapy to differential effects on the lumbar multifidus musculature, noting a significant between-group difference in multifidus functional cross-sectional area change (an increase of 7.0% in the immediate physical therapy group versus a 1.4% decrease in the rest-before-physical-therapy group, p=0.03), consistent with previously described associations in the broader low back pain literature between multifidus cross-sectional area and the subsequent development of chronic or recurrent pain [27].

14. International Expert Consensus on Diagnosis and Management

Reflecting the persistence of genuine clinical uncertainty across multiple domains of spondylolysis management discussed in the preceding sections, a formal Delphi consensus study was undertaken by a dedicated spine and spondylolysis research interest group, convening thirty-five expert panellists (thirty primary care sports medicine physicians and five pediatric spine surgeons) across two structured rounds of iterative rating, following an initial open-ended round generating 107 closed-ended statements for subsequent voting [25]. This structured methodology is notable within the reviewed literature as one of the few explicitly formal attempts to systematically characterise the degree of expert agreement (or disagreement) across the full spectrum of diagnostic and management questions addressed throughout this review, using a predefined 80% agreement threshold on a nine-point Likert scale to determine consensus.

Of the 107 items initially generated, thirty-three achieved consensus in the first round and a further nine in the second round, leaving sixty-five items (approximately 61% of all statements considered) without consensus even after two full rounds of structured deliberation among recognised content experts [25]. Items that did achieve consensus provide useful confirmation of several points already established across the individually reviewed primary studies: panellists agreed on the diagnostic importance of pain reproduced with lumbar extension (97% agreement), the presence of marrow oedema at the pars on MRI (97% agreement), the value of obtaining two-view lumbar radiographs (86% agreement), and the importance of avoiding CT scanning where possible (86% agreement) given radiation considerations [25]. Regarding management, panellists reached consensus that patients do not need to wait eight to twelve weeks of rest before beginning physical therapy (83% and 80% agreement against mandating eight and twelve weeks of rest respectively), a finding directly corroborating the randomised trial evidence discussed in Section 13, and agreed on beginning physical therapy with a neutral or flexion-based protocol, avoiding extension until pain-free, and focusing on core strength (86-97% agreement across these related items) [25].

Critically, however, the panel explicitly failed to reach consensus on several questions of substantial clinical importance that have been highlighted as areas of controversy throughout

this review, including the optimal specific timing for beginning physical therapy (beyond the general agreement that prolonged mandatory rest is not required), and notably, the usage of bracing in spondylolysis management, an item the consensus report specifically flags by name as an area where "higher-quality studies on the benefits of bracing and other specific management strategies would be beneficial in optimizing care for young athletes with spondylolysis" [25]. Regarding return-to-sport decision-making, the panel did achieve strong consensus that being pain-free on examination (97% agreement), demonstrating progression through physical therapy (97% agreement), being able to run without pain (94% agreement), and achieving good core stability (88% agreement) were all important considerations guiding return-to-sport clearance, providing a useful, broadly accepted clinical framework even in the continued absence of consensus on several upstream management questions [25].

This consensus exercise, considered alongside the companion epidemiological meta-analysis from the same research interest group discussed in Section 3 [11], represents a particularly valuable contribution to this review precisely because it transparently documents the boundaries of genuine expert agreement, distinguishing clearly established clinical principles (the diagnostic value of extension-provoked pain and MRI oedema, the lack of necessity for prolonged pre-therapy rest, core return-to-sport criteria) from areas that remain legitimately unresolved even among dedicated subspecialists (optimal bracing strategy, precise physical therapy timing beyond the general principle of avoiding unnecessary delay), thereby providing an evidence-informed roadmap for the research priorities articulated further in the Limitations and Conclusions sections of this review.

15. Surgical Management: Indications and Direct Pars Repair Techniques

Surgical intervention is reserved, across virtually all reviewed sources, for the minority of adolescent athletes who fail an adequate trial of conservative management, variably defined as persistent, functionally limiting pain after six to twelve months of structured nonoperative treatment, progressive spondylolisthesis exceeding established thresholds (commonly cited as progression beyond 50% slippage or progression of more than one Meyerding grade), the development of neurological deficit, or radiographically confirmed pseudarthrosis unlikely to achieve union through any further period of conservative management [1,4,5,17-19]. Estimates of the proportion of symptomatic adolescent athletes ultimately requiring surgical intervention are consistently reported as low, generally in the range of 5-15% across multiple sources, reinforcing the primacy of conservative management as first-line treatment in this population [5,17,18].

For isolated spondylolysis or low-grade (Meyerding grade I) spondylolisthesis without significant disc degeneration, direct pars repair, rather than spinal fusion, has become the preferred surgical approach specifically because it preserves segmental motion, avoiding the biomechanical consequences of fusion (loss of range of motion and the well-documented risk of accelerated adjacent-segment degeneration) that are of particular concern in a young, otherwise healthy patient population with an anticipated several further decades of spinal loading and, frequently, continued athletic ambition [3,4,29]. A detailed comparative narrative review systematically evaluating all seven principal direct pars repair techniques described in the literature - Buck's screw technique, Scott's tension-band wiring, the Morscher hook-screw system, pedicle screw-based constructs, the V-rod/U-rod (Gillet) technique, the "smiley face" rod construct, and the dual-stability construct - provides the most comprehensive comparative synthesis available within this review regarding technique selection [29].

This comparative review, drawing on pooled data from multiple prior meta-analyses and individual case series, reports that pedicle screw-based techniques demonstrated the highest

fusion rate among the classical (longest-established) techniques at 90.2% (pooled from 240 patients across 14 studies), with a complication rate of 12.8% and favourable clinical outcomes in 80.1% of patients [29]. Buck's technique, involving direct lag-screw compression across the pars defect, demonstrated a fusion rate of 83.5% (pooled from 372 patients across 27 studies), with complications occurring in 13.4% and favourable outcomes in 84.3% [29]. Scott's tension-band wiring technique achieved an 81.6% fusion rate but was associated with a substantially higher complication rate of 22.4%, nearly double that of Buck's technique, predominantly attributable to wire-related complications such as breakage [4,29]. The Morscher hook-screw system demonstrated the lowest fusion rate (77.7%, pooled from 193 patients across five studies) and the highest complication rate among the four classically compared techniques (27.4%), a finding the review's authors attribute substantially to hook-related hardware loosening, reported in as many as 57% of patients in some individual series, leading the authors to explicitly recommend that this technique be reserved as a salvage option only, for cases in which pedicle screw and Buck's technique trajectories are both anatomically precluded [29].

More recently developed constructs - the V-rod/U-rod technique, the smiley face rod construct, and the dual-stability construct - are reported in the same comparative review to show fusion rates in available case series ranging from approximately 85% to 93%, with complication rates generally in the range of 11-15%, broadly comparable to or modestly exceeding the outcomes achieved with pedicle screw-based fixation, though the authors explicitly caution that evidence for these newer constructs derives predominantly from smaller case series with shorter follow-up, such that direct, confidently weighted comparison against the more extensively studied classical techniques remains premature [29]. A specific case report describing a combined approach using a dual-headed pedicle screw system to simultaneously perform transforaminal lumbar interbody fusion at one level (L4 isthmic spondylolisthesis with associated foraminal stenosis) and a motion-preserving smiley-face-rod direct pars repair at an adjacent level (L5 spondylolysis without associated slippage) in a 59-year-old former competitive softball player, illustrates the clinical reasoning increasingly applied in selecting fusion versus motion-preserving repair on a level-specific basis within the same patient, successfully achieving bony union at both levels and enabling the patient's full return to softball participation at two years postoperatively without evidence of adjacent-segment disease [30]. While this patient falls outside the strict adolescent age range that is the principal focus of this review, the case nonetheless usefully illustrates the broader surgical decision-making framework (motion preservation where feasible, fusion reserved for levels with established slippage or disc degeneration) that is directly applicable to younger patients requiring surgery for isolated, non-slipped spondylolysis at one level in the context of coexisting slipped disease at an adjacent level.

Age emerged as a consistently identified, powerful determinant of surgical success across the comparative review of direct pars repair techniques, with success rates in the 85-100% range reported for patients younger than 25 years across all techniques examined, declining markedly in patients older than 35 years regardless of the specific fixation method employed [29]. This age-dependent pattern of outcomes directly corroborates the emphasis, recurring throughout this review, on the particular favourability of the adolescent and young-adult skeleton for both conservative healing (as discussed in relation to pars staging in Section 4) and surgical fusion or repair, likely reflecting both superior biological healing capacity and the generally more favourable disc and facet joint status typically present at this younger age, in contrast to the degenerative changes that frequently complicate pars repair in older patients.

A separate, dedicated comparative analysis specifically evaluating minimally invasive versus conventional (open) direct repair techniques across sixteen studies encompassing 150 patients

(46 treated with minimally invasive approaches, 104 with conventional open repair) found that patients in the minimally invasive group achieved significantly higher rates of complete pain resolution ($p<0.001$), along with shorter hospital stays (mean 1.67 days versus data not directly comparable in the open cohort studies, which more frequently reported only 3.2 days for the subset reporting this outcome) and, in the limited subset of studies reporting this outcome, apparently faster return-to-sport times, with three minimally invasive studies reporting return-to-sport intervals of 1.4 months, 3 months, and as briefly as 3 weeks, compared with a mean of 5.6 months (range 4-6 months) across the studies reporting return-to-sport time in the conventional repair group [4]. The authors of this comparative review candidly acknowledge substantial limitations constraining confidence in these findings, noting that the minimally invasive patient population was, on average, more than ten years older than the conventionally treated population, potentially reflecting a general trend toward reduced surgical morbidity with minimally invasive techniques expanding candidacy to older patients rather than representing a directly age-matched comparison, and that inconsistency in reported outcome metrics across the included studies precluded more rigorous quantitative statistical analysis [4].

16. Surgical Management: Posterolateral Fusion and Spondylolisthesis

For higher-grade spondylolisthesis, or for cases of spondylolysis complicated by significant disc degeneration, facet arthropathy, or established vertebral slippage precluding direct pars repair, spinal fusion - whether posterolateral, interbody, or circumferential - remains the standard surgical approach, though this too has been subject to evolving refinement over recent decades [16,17,31].

Long-term outcome data for posterolateral in situ fusion specifically in adolescent and young patients with low-grade spondylolisthesis are reported as generally favourable: a cohort study of 108 young patients treated with in situ posterolateral fusion for low-grade spondylolisthesis, with a mean follow-up of 20.8 years, reported satisfactory long-term outcomes as measured by the Oswestry Disability Index and Scoliosis Research Society questionnaire [31]. For high-grade spondylolisthesis, a separate long-term cohort of sixty-nine young patients treated with posterolateral, anterior, or circumferential in situ fusion, followed for a mean of 17.2 years, likewise reported generally good Oswestry Disability Index scores, with the subgroup receiving circumferential (combined anterior-posterior) fusion demonstrating somewhat superior outcomes compared with those receiving posterolateral fusion alone [31]. However, a recognised disadvantage of fusion that recurs across multiple sources is the loss of segmental motion at the fused level, with associated concern for adjacent-segment stress and degeneration, reported in one series to necessitate additional surgery at adjacent levels in up to 36% of patients during long-term follow-up [31].

The question of whether vertebral slippage should be reduced toward anatomical alignment prior to fusion, or whether fusion should instead be performed in situ (accepting the existing degree of slippage), remains an area of ongoing debate within the broader spondylolisthesis surgical literature, with proponents of reduction citing improved sagittal balance and biomechanical fusion surface area, and critics citing increased risk of neurological injury from traction on lumbosacral nerve roots during the reduction manoeuvre [17,29]. A meta-analysis comparing in situ fusion against reduction followed by fusion for isthmic spondylolisthesis found that both approaches achieved favourable clinical outcomes overall, though reduction was associated with a higher fusion rate, improved radiographic alignment, and shorter hospital stays, without a statistically significant increase in neurological complication rate, suggesting that reduction may be preferable where surgical expertise and appropriate neuromonitoring are available, though this meta-analysis's specific patient population skewed toward adult rather than exclusively adolescent cohorts [17].

Regarding the specific choice between posterior lumbar interbody fusion (PLIF) and transforaminal lumbar interbody fusion (TLIF) techniques when interbody fusion is indicated, a systematic review and meta-analysis of seven comparative studies found that while PLIF was associated with a higher overall complication rate and longer operative time than TLIF, there was no significant difference between the two techniques in clinical outcomes, patient satisfaction, or radiographic fusion rate, broadly corroborating the general trend across multiple individual comparative studies toward preferring TLIF's unilateral, less nerve-root-retraction-dependent approach where feasible, while acknowledging that both techniques can achieve comparably successful fusion [17].

17. Return to Sport: Criteria, Timing, and Outcomes Across Treatment Modalities

Return-to-sport decision-making represents an area of recurring emphasis across virtually all sources reviewed, reflecting its centrality as both the primary clinical goal for the adolescent athlete and family, and the outcome measure most consistently reported across the heterogeneous study designs comprising this literature.

Across conservative management studies, the criteria most consistently described for clearing an athlete to return to sport include achievement of pain-free range of motion through all cardinal lumbar movements, restoration of normal core and hip strength, completion of a graduated, sport-specific functional progression without symptom recurrence, and, in protocols emphasising structural healing, radiographic or MRI confirmation of bony union, though as discussed in Section 9, the relative weighting placed on imaging-confirmed union versus purely symptom- and function-based criteria varies substantially between the "bone union" and "pain management" philosophies described in the Japanese cohort study [22], and between the structural and functional management paradigms contrasted in the cricket fast bowling review [24]. The international expert Delphi consensus discussed in Section 14 achieved strong agreement (88-97%) on a core set of return-to-sport criteria centred on being pain-free on examination, demonstrating satisfactory progression through physical therapy, ability to run without pain, and achievement of good core stability, providing perhaps the most broadly endorsed, consensus-derived framework available within this body of literature [25].

Mean time to return to sport under conservative management is reported with considerable consistency in the 3.7 to 5.9 month range across multiple independent sources: the meta-analysis of pars interarticularis defects across varied athletic populations reported a mean return-to-play time of 3.7 months following conservative therapy [3]; the ice hockey-specific case series reported an average return-to-play time of 8 weeks (approximately 2 months), notably shorter than most other reported series, potentially reflecting the specific, relatively lower-grade injury profile of acutely presenting junior hockey players in that cohort [15]; and the Japanese pediatric cohort study, as discussed, reported mean times of 4.7 months in the bone-union protocol group versus 1.8 months in the pain-management protocol group [22]. Following surgical treatment via direct pars repair, return-to-sport timelines are reported as somewhat longer, with the comparative review of minimally invasive versus conventional repair techniques reporting a mean of 2.7 months (range 0.75-6.0 months) following minimally invasive repair, compared with a mean of 5.6 months (range 4-6 months) following conventional open repair [4], while following fusion for spondylolisthesis, return-to-sport (where permitted at all for higher-impact or collision sports) is generally reported to require 6-12 months, with surveys of spine surgeons indicating considerably greater reluctance to clear athletes for return to high-impact collision sports (such as American football, rugby, or ice hockey) following fusion compared with return to lower-impact, non-contact activities [31].

This pattern - of surgeons permitting earlier and more unrestricted return to non-contact and contact sports than to specifically "collision" sports following fusion - emerges as a particularly consistent finding across the specific literature addressing pediatric spinal fusion outcomes more broadly (encompassing fusion performed both for spondylolisthesis and for other indications such as adolescent idiopathic scoliosis, discussed further in Section 19), with survey-based evidence indicating that only approximately 27-36% of surveyed spine surgeons permit return to collision sports at one year following spondylolisthesis fusion, compared with 51-66% permitting return to contact or non-contact sports at the same time point [31]. The most important factors reported to influence surgeons' return-to-sport decision-making in this context were radiographic appearance of fusion and elapsed time since surgery, though notably, this same survey-based evidence found considerable disagreement among respondents even regarding fundamentally important questions such as whether return to any collision sport should ever be permitted following fusion for spondylolisthesis, underscoring that this remains an area where individual surgeon judgement, rather than firm evidence-based guideline, continues to predominate [31].

18. Sport-Specific Considerations

The considerable variation in both the incidence and the specific biomechanical pattern of spondylolysis across different sports, established in Section 3, carries direct implications for sport-specific prevention strategies and management nuance, and several of the reviewed sources address particular sports in sufficient depth to merit dedicated consideration.

Cricket fast bowling represents one of the most extensively characterised sport-specific contexts within this review, reflecting both the exceptionally high reported incidence of spondylolysis in this population (ranging from 10.98% to 55% across various pooled estimates) and the sport's unique biomechanical demands [3,24]. The specific bowling action - combining lumbar flexion, hyperextension, and pronounced lateral and rotational trunk motion, compounded by ground reaction forces at front- and back-foot contact that have been measured to substantially exceed body weight during delivery - has been identified as the principal biomechanical driver of this elevated risk, with the specific bowling technique (a "mixed" action combining front-on and side-on elements) associated with higher risk than either pure front-on or pure side-on techniques [3]. The specialist review of lumbar bone stress injury management specifically in cricket bowlers provides one of the most detailed accounts available of the historical evolution of imaging and management philosophy in this population, tracing the transition from an era in which X-ray-only diagnosis meant most fast bowlers accumulated spondylolysis (or progressed to spondylolisthesis) essentially inevitably over a career, through the introduction of SPECT-CT enabling earlier detection but still associated with persistently high rates of non-union, to the current MRI-based era in which serial bone-window imaging allows genuinely individualised monitoring of healing progress and, the authors argue, has contributed to apparently longer subsequent Test-match bowling careers among modern bowlers who achieve bony union under this more structurally-oriented management approach [24]. This review's explicit framing of its recommended approach as deliberately departing from the "functional" management paradigm advocated for general adult low back pain (as exemplified in contemporary clinical practice guidelines emphasising minimal reliance on imaging) represents one of the more conceptually interesting tensions surfaced across this entire review: the authors argue explicitly that the specific demographic (adolescent/young adult, high-demand, structurally vulnerable athletes) and the specific pathology (a genuinely structural, potentially healable stress fracture rather than the predominantly degenerative findings typical of adult back pain) together justify a management exception to the generally imaging-averse philosophy now standard in adult back pain care [24].

Gymnastics similarly features prominently across multiple sources as a particularly high-risk sport, with the repetitive "ubiquitous arch" (the back-bend motion fundamental to numerous gymnastic skills) identified as a characteristic biomechanical exposure, performed potentially thousands of times over the course of a competitive career [32]. A dedicated review focusing specifically on scoliosis in young gymnasts, while centred primarily on spinal deformity rather than spondylolysis per se, nonetheless explicitly identifies spondylolysis, alongside Scheuermann's disease and intervertebral disc pathology, as among the recognised "overuse" injuries affecting the posterior spinal elements in this population, and notes the biomechanically plausible contribution of generalised joint hyperlaxity (frequently assessed via the Beighton scale), delayed skeletal maturity, and asymmetric loading patterns (the latter particularly pronounced in rhythmic gymnastics, where athletes reportedly spend approximately 75% of training time using a dominant hand or side for implement control) to the elevated injury risk observed in this population [32]. This same review raises an important nuance regarding causal interpretation in the gymnastics-spondylolysis (and gymnastics-scoliosis) literature: it describes a "morphesthesia" hypothesis, whereby individuals with pre-existing musculoskeletal characteristics conferring greater flexibility and joint laxity - potentially including a predisposition toward posterior element vulnerability - may be preferentially selected into, or self-select toward, gymnastics specifically because these same characteristics confer competitive advantage in a sport rewarding extreme ranges of motion, meaning that the observed association between gymnastic participation and posterior element injury may reflect a combination of genuine causal mechanical injury and pre-existing selection bias rather than purely the former [32].

Soccer, baseball, and ice hockey each demonstrate distinctive patterns as discussed in Section 3, with soccer associated with a greater tendency toward multiple and bilateral lesions (attributed to the relatively more symmetric bilateral lower-limb loading inherent in running and the use of both the dominant and non-dominant foot for kicking), in contrast to the more frequently unilateral, contralateral-to-dominant-hand lesion pattern observed in baseball (attributed to the strongly lateralised, repetitive nature of pitching and batting mechanics) [14]. Ice hockey players, in the dedicated case series reviewed, demonstrated a strong association between spondylolysis laterality and shooting-hand side (73% of affected players demonstrating ipsilateral spondylolysis relative to their shooting side), with the majority of affected players in this cohort being forwards rather than defensemen, a finding the study's author links to the specific, repetitive, powerful shooting and twisting motions characteristic of the forward position [15]. This same case series, examining medical records across nine hockey seasons within a single elite junior-level programme, found that 44% of players presenting with low back pain were ultimately confirmed to have spondylolysis, with the majority of cases presenting during the athlete's first year within the program, suggesting that an initial period of adaptation to markedly increased training volume or intensity, rather than cumulative exposure over multiple years, may represent a particularly vulnerable window for injury onset [15].

Weightlifting and American football, discussed somewhat more briefly across the reviewed sources but nonetheless consistently identified among the higher-risk sports, are characterised predominantly by axial compressive loading mechanisms, in contrast to the rotational and flexion-extension mechanisms predominating in throwing, kicking, and gymnastic sports [2,3]. The consistency with which specific biomechanical loading patterns (axial compression versus rotational torque versus repetitive flexion-extension cycling) recur as explanatory mechanisms across these varied sport-specific discussions reinforces the broader biomechanical understanding, established in Section 4, that the pars interarticularis is a structure specifically vulnerable to a combination of extension and rotational stress, with the precise sport-specific pattern of injury (laterality, single versus multiple level involvement, severity) substantially

shaped by the particular combination and relative proportion of these loading vectors characteristic of each individual sport's technical demands.

19. Coexisting and Related Spinal Pathology in the Adolescent Athlete

Given that spondylolysis does not occur in biomechanical or clinical isolation, several of the reviewed sources address its relationship to other spinal pathologies prevalent in the adolescent athletic population, providing important context for the differential diagnostic considerations introduced in Section 6.

Scheuermann's disease, as discussed briefly in Section 6, shares sufficient biomechanical and clinical overlap with spondylolysis - both conditions being associated with sports demanding repetitive flexion-extension cycling, and both presenting with activity-related back pain in the adolescent growth-spurt years - that the two conditions are frequently considered together within differential diagnostic frameworks for adolescent back pain [2,9,20]. The conservative management philosophy for Scheuermann's disease, as detailed in a dedicated narrative review, mirrors that applied to spondylolysis closely: physiotherapy emphasising flexibility and core strengthening as first-line treatment, selective bracing for skeletally immature patients with kyphosis exceeding approximately 50 degrees, and surgical intervention reserved for curves exceeding 70 degrees, severe persistent pain, or documented progression [20]. This review notably reports that most athletes with Scheuermann's disease and kyphosis below 50 degrees who have completed a course of physiotherapy are able to return to full, unrestricted sporting activity, a return-to-sport threshold and philosophy broadly analogous to that applied in low-grade spondylolisthesis management [20].

Scoliosis represents a further area of overlap, both as a potential direct consequence of asymmetric, unilateral spondylolysis-related paraspinal muscle spasm and compensatory postural adaptation, and as an independently occurring condition in the same at-risk adolescent athletic population, particularly within gymnastics. The dedicated review of scoliosis in young gymnasts reports markedly elevated prevalence of "scoliosis suspected status" (determined via Adam's forward bend test and scoliometer measurement) in competitive gymnastic cohorts, reaching 28.8% in one large multidisciplinary screening study, compared with general population prevalence estimates for adolescent idiopathic scoliosis typically cited in the range of 0.47% to 5.2% [32]. While this review's primary focus is scoliosis rather than spondylolysis, it explicitly identifies spondylolysis as occurring alongside scoliosis within the broader constellation of posterior-element overuse injuries affecting young gymnasts, and notes that spondylolisthesis itself has been separately reported to demonstrate a notably elevated co-occurrence with scoliosis, with one cited incidence figure of 15-48% co-occurrence between spondylolisthesis and scoliosis in affected patients [1]. The mechanistic relationship proposed to explain this association involves asymmetric paraspinal muscle guarding or spasm secondary to unilateral or asymmetric spondylolytic pain producing a secondary, functional scoliotic curve, distinguishing this entity from idiopathic scoliosis occurring independently of posterior element pathology, though the reviewed sources do not provide definitive evidence clearly distinguishing causal direction in this association within the adolescent athletic population specifically [1].

The broader relationship between adolescent sports participation (independent of the specific diagnosis of spondylolysis) and lifelong skeletal health is addressed by a review examining the impact of physical activity on osteoporotic fracture risk across the lifespan, which, while not focused on spondylolysis specifically, provides relevant contextual evidence regarding the generally protective, bone-density-enhancing effect of weight-bearing physical activity during adolescence and young adulthood, alongside the countervailing observation that excessive

training volume, particularly in combination with low energy availability, can predispose to stress fractures at various skeletal sites [33]. This broader context is relevant to understanding spondylolysis as occupying a position along a spectrum of bone stress injury that shares underlying risk factors (training volume, load, nutritional status, skeletal maturity) with stress fractures occurring at other anatomical sites in young athletes, even though the specific anatomical and biomechanical vulnerability of the pars interarticularis renders it a disproportionately common site of such injury in this population [1,33].

20. Discussion

This review has synthesised a body of literature characterised by considerable methodological heterogeneity, ranging from large pooled meta-analyses and a small number of well-designed randomised controlled trials, through numerous retrospective cohort and case-series studies, to expert consensus statements explicitly designed to document areas of ongoing disagreement, as well as broader reviews of low back pain in athletes that help situate spondylolysis within the wider differential diagnostic landscape [4]. Several overarching themes merit synthesis.

First, regarding epidemiology, the evidence consistently establishes markedly elevated spondylolysis prevalence in adolescent athletes relative to the general population, with figures ranging from approximately 28% across all athletic sports pooled together [11] to over 40% when restricted specifically to symptomatic athletes presenting with low back pain [12], figures that must nonetheless be interpreted against the substantial heterogeneity (I^2 frequently exceeding 90%) reported within the underlying meta-analyses themselves, reflecting genuine variation attributable to sport type, imaging modality, symptom status, age, and sex composition of the populations studied, rather than representing a single, precisely estimable population parameter. The sport-specific gradient in risk, from relatively low-risk sports such as swimming and cycling to markedly elevated risk in diving, cricket fast bowling, baseball, and gymnastics, is consistently reproduced across independent analyses [3,11] and is biomechanically coherent given the specific loading patterns (hyperextension, axial compression, rotational torque) characteristic of these higher-risk activities [1,2].

Second, regarding diagnostic imaging, the literature reveals a clear trajectory of evolution from plain radiography and CT, through SPECT, toward MRI as the now generally preferred modality, driven primarily by considerations of radiation stewardship in a paediatric population but tempered by persistent, specifically documented limitations in MRI's ability to reliably distinguish early stress reactions from incomplete fractures [5], and by at least one study documenting that spondylolysis can be "frequently missed" by MRI alone in some clinical contexts [19]. This represents a genuine area of continuing refinement rather than settled practice, and the pilot evidence regarding a deferred, criterion-based imaging strategy [21] further illustrates that even the fundamental question of whether advanced imaging should precede treatment initiation at all remains incompletely resolved.

Third, and perhaps most clinically significant given the strength of the underlying evidence, the question of physical therapy timing relative to rest has been directly and rigorously addressed by a well-designed multicentre randomised controlled trial [27] and its companion MRI-healing analysis [28], both converging on the conclusion that immediate, criterion-based physical therapy confers meaningful clinical benefit (faster symptom resolution, faster return to sport, lower recurrence) without compromising structural bony healing or increasing adverse events, directly challenging the traditional, widely taught practice of mandating a prolonged period of rest preceding the initiation of rehabilitation. This finding is corroborated by the international expert consensus panel's agreement that prolonged mandatory rest before beginning physical

therapy is not required [25], representing one of the clearer, better-supported practice-change messages emerging from this body of literature.

Fourth, the question of bracing remains genuinely unresolved, with the reviewed literature reflecting a spectrum of institutional philosophies from routine, structurally-oriented bracing protocols extending for months pending imaging-confirmed healing [22,24], through more selective bracing strategies reserved for specific risk-factor profiles [24], to institutional practices eschewing bracing for full-time professional athletes entirely [24]. The international expert Delphi panel's explicit identification of bracing efficacy as an area requiring higher-quality research [25], combined with the absence of a definitively positive randomised comparative trial specifically examining bracing versus no bracing within an otherwise standardised conservative protocol, indicates that this remains a legitimate area of clinical equipoise rather than simply inadequate dissemination of an already-established evidence base.

Fifth, regarding surgical management, the evidence supports a clear hierarchical preference for motion-preserving direct pars repair over fusion wherever anatomically feasible for isolated spondylolysis or minimally slipped (grade I) spondylolisthesis, with pedicle screw-based and several newer rod-construct techniques demonstrating the most favourable combination of fusion rate and complication profile among the techniques directly compared [29], while fusion remains reserved, with generally favourable long-term outcomes, for higher-grade slippage or cases with significant coexisting disc or facet pathology precluding motion preservation [17,31]. The remarkably consistent finding that patient age below approximately 25 years is one of the strongest predictors of surgical success across virtually every technique examined [29] underscores the particular biological favourability of the adolescent and young-adult skeletal environment for both conservative and surgical healing, a point of considerable reassurance when counselling this specific patient population, even as it raises corresponding caution regarding the direct extrapolation of outcomes data derived substantially from younger cohorts to the comparatively less frequently studied subset of adolescent athletes approaching skeletal maturity at the upper boundary of this age range.

Finally, the sport-specific analyses reviewed in Section 18 collectively illustrate that spondylolysis, while sharing a common underlying pathophysiological mechanism (fatigue fracture of a biomechanically vulnerable structure during skeletal immaturity), manifests with genuinely distinct lesion distribution, laterality, and presumably also somewhat distinct optimal prevention strategies depending on the specific sport-technical demands involved, suggesting that future prevention and rehabilitation protocols may benefit from greater sport-specific tailoring (for example, targeting bilateral core and hip strengthening symmetrically in soccer players versus specifically addressing side-dominant asymmetric loading patterns in baseball pitchers or ice hockey forwards) rather than applying a single, generic protocol uniformly across all affected athletes regardless of their specific sport.

21. Limitations of the Evidence Base

Several important limitations characterise the evidence base synthesised in this review and merit explicit acknowledgement. First, the overwhelming majority of included studies are retrospective cohort studies or case series, frequently drawn from single institutions or single sporting programmes, with inherent risks of selection bias, incomplete follow-up, and limited generalisability to broader or more diverse adolescent athletic populations; genuinely prospective cohort designs [8] and adequately powered randomised controlled trials [27,28] remain comparatively rare within this literature, a limitation explicitly acknowledged within several of the reviewed systematic reviews themselves [6,23].

Second, considerable heterogeneity in outcome definition and measurement persists across studies, encompassing variable definitions of "healing" (ranging from purely symptomatic resolution, through radiographic appearance on plain films or CT, to specific grading systems applied to MRI bone-window and marrow-oedema sequences), variable and often non-validated functional outcome measures, and inconsistent follow-up durations ranging from a few months to multiple decades, all of which substantially complicate direct cross-study comparison and almost certainly contribute to the very high statistical heterogeneity (I^2 frequently exceeding 90%) reported in several of the pooled meta-analyses addressed in this review [11-13].

Third, the available evidence regarding several clinically important management questions - most notably the specific efficacy of bracing, the optimal duration of activity restriction where restriction is employed at all, and the comparative long-term outcomes of different direct pars repair constructs - derives substantially from small case series or from meta-analyses pooling such case series, rather than from adequately powered, directly comparative trials, a limitation explicitly and repeatedly acknowledged by the authors of the primary sources themselves [4,6,24,25,29]. The international expert consensus Delphi panel's explicit failure to achieve agreement on fully sixty-five of 107 proposed statements after two structured rounds of deliberation among dedicated content experts provides perhaps the clearest available quantification of the genuine extent of unresolved clinical uncertainty within this field [25].

Fourth, this review itself is narrative rather than systematic in design; source selection and thematic synthesis were undertaken by the reviewing authors without a pre-registered protocol, formal dual-reviewer screening, or quantitative risk-of-bias appraisal, meaning that the relative emphasis placed on different studies and findings throughout this review may reflect subjective judgement regarding clinical relevance and methodological quality rather than a fully reproducible, systematic weighting scheme. Readers should therefore interpret the conclusions offered here as a clinically informed synthesis intended to orient further reading and clinical reasoning, rather than as a definitive, exhaustively validated summary of the entirety of the available evidence.

Fifth, the geographic and demographic representation within the reviewed literature is skewed toward specific national contexts (notably Japan, the United States, the United Kingdom, and Australia) and toward specific, relatively well-resourced sporting institutions (elite junior hockey programmes, national cricket academies, tertiary paediatric sports medicine centres), raising legitimate questions regarding the generalisability of reported incidence figures, management protocols, and outcomes to adolescent athletes participating in less formally structured or more resource-limited sporting contexts globally. A general review of low back pain across athletic populations of varying age and competitive level similarly cautions that findings derived from elite, well-resourced cohorts may not translate directly to recreational or lower-resource athletic settings, where access to advanced imaging and structured rehabilitation may be considerably more constrained [4].

22. Conclusions

Spondylolysis and spondylolisthesis constitute the most frequently identified specific structural diagnoses underlying low back pain in adolescent athletes, with prevalence substantially elevated above general-population baseline rates and exhibiting marked sport-specific variation attributable to the distinctive biomechanical demands of individual athletic disciplines. The pathophysiological understanding of the condition as a fatigue fracture of the pars interarticularis, modulated by skeletal immaturity, cumulative mechanical loading, and likely hereditary predisposition, is well established and consistently corroborated across the

biomechanical and epidemiological literature reviewed. Diagnostic imaging has evolved substantially, with magnetic resonance imaging now generally favoured over computed tomography and single-photon emission computed tomography for most adolescent patients, balancing diagnostic sensitivity against the imperative to minimise cumulative radiation exposure, though important limitations in MRI's ability to fully characterise lesion chronicity persist and continue to justify selective use of CT in specific clinical circumstances.

Conservative management, encompassing activity modification, structured physical therapy, and selective bracing, remains the appropriate first-line approach for the great majority of affected athletes, achieving favourable return-to-sport rates generally exceeding 85-95% across the reviewed cohort studies and meta-analyses. Within this conservative paradigm, recent high-quality randomised trial evidence has meaningfully challenged the traditional practice of mandating prolonged rest before initiating physical therapy, demonstrating that immediate, criterion-based rehabilitation confers superior clinical outcomes without compromising structural healing or increasing adverse events, a finding that merits incorporation into updated clinical practice recommendations. The role of bracing, by contrast, remains genuinely unresolved, as does the optimal rehabilitation strategy for addressing the biomechanical risk factors - including hip and hamstring flexibility, sacropelvic alignment, and core stability - that have been independently associated with both lesion progression and failure of bony union.

Surgical intervention, required in only a minority of cases, has progressively favoured motion-preserving direct pars repair techniques over fusion for appropriately selected patients with isolated spondylolysis or minimally slipped spondylolisthesis, with pedicle screw-based and contemporary rod-construct techniques demonstrating the most favourable balance of fusion rate and complication profile, while fusion remains appropriately reserved for higher-grade slippage or cases complicated by significant coexisting disc or facet pathology. Across both conservative and surgical management pathways, younger patient age consistently predicts superior outcomes, reinforcing the particular biological favourability of early, accurate diagnosis and appropriately timed intervention within this population.

Future research priorities, substantially informed by the explicit gaps identified through the international expert consensus process reviewed here, should prioritise adequately powered randomised trials specifically examining the efficacy of bracing, further prospective characterisation of sport-specific and biomechanical risk factors for lesion progression and non-union, standardisation of imaging and outcome-reporting criteria to permit more robust cross-study synthesis, and longer-term follow-up studies addressing recurrence risk and functional outcomes extending into adulthood. Until such evidence accumulates, management of spondylolysis and spondylolisthesis in adolescent athletes should continue to be guided by individualised clinical judgement, integrating the available evidence on imaging selection, staged conservative rehabilitation, and judicious application of surgical techniques within a framework that prioritises both safe return to sport and long-term spinal health.

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References

1. Gagnet P, Kern K, Andrews K, Elgafy H, Ebraheim N. Spondylolysis and spondylolisthesis: a review of the literature. Journal of Orthopaedics. 2018;15(2):404–407. DOI: https://doi.org/10.1016/j.jor.2018.03.008

2. Patel DR, Kinsella E. Evaluation and management of lower back pain in young athletes. Transl Pediatr. 2017;6(3):225–235. DOI: https://doi.org/10.21037/tp.2017.06.01

3. Tawfik S, Phan K, Mobbs RJ, Rao PJ. The incidence of pars interarticularis defects in athletes. Global Spine Journal. 2020;10(1):89–101. DOI: https://doi.org/10.1177/2192568218823695

4. Kolcun JPG, Chieng LO, Madhavan K, Wang MY. Minimally-invasive versus conventional repair of spondylolysis in athletes: a review of outcomes and return to play. Asian Spine J. 2017;11(5):832–842. DOI: https://doi.org/10.4184/asj.2017.11.5.832

5. Linton AA, Hsu WK. A review of treatment for acute and chronic pars fractures in the lumbar spine. Curr Rev Musculoskelet Med. 2022;15(4):259–271. DOI: https://doi.org/10.1007/s12178-022-09760-9

6. Garet M, Reiman MP, Mathers J, Sylvain J. Nonoperative treatment in lumbar spondylolysis and spondylolisthesis. Sports Health: A Multidisciplinary Approach. 2013;5(3):225–232. DOI: https://doi.org/10.1177/1941738113480936

7. Vanti C, Ferrari S, Guccione AA, Pillastrini P. Lumbar spondylolisthesis: STATE of the art on assessment and conservative treatment. Arch Physiother. 2021;11(1):19. DOI: https://doi.org/10.1186/s40945-021-00113-2

8. Tsutsui T, Sakamaki W, Takei S, Ikegami N, Torii S. Physical factors associated with stage progression of lumbar spondylolysis: a prospective cohort study in male adolescent soccer players. Orthopaedic Journal of Sports Medicine. 2026;14(1):23259671251401599. DOI: https://doi.org/10.1177/23259671251401599

9. Purcell L, Micheli L. Low back pain in young athletes. Sports Health: A Multidisciplinary Approach. 2009;1(3):212–222. DOI: https://doi.org/10.1177/1941738109334212

10. Mortazavi J, Zebardast J, Mirzashahi B. Low back pain in athletes. Asian J Sports Med. 2015;6(2). DOI: https://doi.org/10.5812/asjsm.6(2)2015.24718

11. Riederer M, Hollabaugh W, Achar S, Gregory A, MacDonald J, MacEachern M, McHorse K, Pomerantz A, Selhorst M, Rizzone K, Sweeney E, Teramoto M. The prevalence of isthmic spondylolysis in young athletes: a systematic review and meta-analysis. Orthopaedic Journal of Sports Medicine. 2026;14(6_suppl5):2325967126S00217. DOI: https://doi.org/10.1177/2325967126s00217

12. Li J, Liang J, Xu Y, Du D, Feng F, Shen J, Cui Y. Incidence of lumbar spondylolysis in athletes with low back pain: a systematic evaluation and single-arm meta-analysis. Medicine. 2023;102(38):e34857. DOI: https://doi.org/10.1097/md.0000000000034857

13. Wall J, Meehan WP, Trompeter K, Gissane C, Mockler D, van Dyk N, Wilson F. Incidence, prevalence and risk factors for low back pain in adolescent athletes: a systematic review and meta-analysis. Br J Sports Med. 2022;56(22):1299–1306. DOI: https://doi.org/10.1136/bjsports-2021-104749

14. Yokoe T, Tajima T, Sugimura H, Kubo S, Nozaki S, Yamaguchi N, Morita Y, Chosa E. Comparison of symptomatic spondylolysis in young soccer and baseball players. J Orthop Surg Res. 2020;15(1):378. DOI: https://doi.org/10.1186/s13018-020-01910-4

15. Donaldson LD. Spondylolysis in elite junior-level ice hockey players. Sports Health: A Multidisciplinary Approach. 2014;6(4):356–359. DOI: https://doi.org/10.1177/1941738113519958

16. Lima MVD, Caffaro MFS, Santili C, Watkins IV RG. Espondilólise e espondilolistese em atletas. Rev Bras Ortop (Sao Paulo). 2024;59(01):e10-e16. DOI: https://doi.org/10.1055/s-0043-1777435

17. Dragosloveanu S, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania, Department of Orthopedics, Foisor Clinical Hospital of Orthopedics, Traumatology and Osteoarticular Tuberculosis, Bucharest, Romania, Nedelea DG, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania, Department of Orthopedics, Foisor Clinical Hospital of Orthopedics, Traumatology and Osteoarticular Tuberculosis, Bucharest, Romania, Vulpe DE, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania, Department of Orthopedics, Foisor Clinical Hospital of Orthopedics, Traumatology and Osteoarticular Tuberculosis, Bucharest, Romania, Gherghiceanu F, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania, Capitanu BS, Department of Orthopedics, Foisor Clinical Hospital of Orthopedics, Traumatology and Osteoarticular Tuberculosis, Bucharest, Romania, Stoica IC, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania, Department of Orthopedics, Foisor Clinical Hospital of Orthopedics, Traumatology and Osteoarticular Tuberculosis, Bucharest, Romania. Surgical and non-surgical management of spondylolisthesis: a comprehensive review. JMedLife. 2025;18(3):196–207. DOI: https://doi.org/10.25122/jml-2025-0039

18. Koslosky E, Gendelberg D. Classification in brief: the meyerding classification system of spondylolisthesis. Clin Orthop Relat Res. 2020;478(5):1125–1130. DOI: https://doi.org/10.1097/corr.0000000000001153

19. Ball JR, Harris CB, Lee J, Vives MJ. Lumbar spine injuries in sports: review of the literature and current treatment recommendations. Sports Med - Open. 2019;5(1):26. DOI: https://doi.org/10.1186/s40798-019-0199-7

20. Ćwiek HJA, Kołodziej-Sieradz M, Terlecka AM, Gryz PK, Komorowski K, Pilarska KJ, Szwankowska AA, Baczyńska A, Boruszczak BAE, Rożenek AW. Scheuermann's disease: a

narrative review of treatment standards. Qual Sport. 2026;54:70483. DOI: https://doi.org/10.12775/qs.2026.54.70483

21. Selhorst M, Rodenberg R, Padgett N, Fischer A, Ravindran R, MacDonald J. An alternative model of care for the treatment of adolescent athletes with extension-based low back pain: a pilot study. International Journal of Sports Physical Therapy. 2021;16(1). DOI: https://doi.org/10.26603/001c.18715

22. Kasamasu T, Ishida Y, Sato M, Mase Y, Sairyo K. Rates of return to sports and recurrence in pediatric athletes after conservative treatment for lumbar spondylolysis. Spine Surg Relat Res. 2022;6(5):540–544. DOI: https://doi.org/10.22603/ssrr.2021-0242

23. Overley SC, McAnany SJ, Andelman S, Kim J, Merrill RK, Cho SK, Qureshi SA, Hecht AC. Return to play in adolescent athletes with symptomatic spondylolysis without listhesis: a meta-analysis. Global Spine Journal. 2018;8(2):190–197. DOI: https://doi.org/10.1177/2192568217734520

24. Orchard J, Saw R, Kountouris A, Redrup D, Farhart P, Sims K. Management of lumbar bone stress injury in cricket fast bowlers and other athletes. SA J Sports Med. 2023;35(1). DOI: https://doi.org/10.17159/2078-516x/2023/v35i1a15172

25. Sweeney E, Petersen S, Agnew M, Kliethermes S, Rizzone K. Diagnosis and management of adolescent isthmic spondylolysis: a delphi study. Orthopaedic Journal of Sports Medicine. 2026;14(6_suppl5):2325967126S00202. DOI: https://doi.org/10.1177/2325967126s00202

26. Yamazaki K, Kota S, Oikawa D, Suzuki Y. High defect stage, contralateral defects, and poor flexibility are negative predictive factors of bone union in pediatric and adolescent athletes with spondylolysis. J Med Invest. 2018;65(1.2):126–130. DOI: https://doi.org/10.2152/jmi.65.126

27. Selhorst M, Sweeney E, Martin LC, Yang J, Benedict J, Brna M, Spondylolysis Physician Group, Fischer AN. Immediate physical therapy is beneficial for adolescent athletes with active lumbar spondylolysis: a multicentre randomised trial. Br J Sports Med. 2026;60(2):125–132. DOI: https://doi.org/10.1136/bjsports-2025-110606

28. Sweeney EA, Fischer A, Brna M, Martin L, Yang J, Selhorst M. Rest before physical therapy is not necessary to achieve bony healing of lumbar spondylolysis in adolescent athletes. Orthopaedic Journal of Sports Medicine. 2026;14(4):23259671261421595. DOI: https://doi.org/10.1177/23259671261421595

29. KOSE KLC, IBRAHIM M, HADEN NCD, AFOLAYAN J, ANWAR H. Direct pars repair techniques for lumbar spondylolysis: a comparative literature review . Turkish Journal of Medical Sciences. 2026;56(4):946–955. DOI: https://doi.org/10.55730/1300-0144.6338

30. Tatsumura M, Ikezawa S, Okuwaki S, Gamada H, Funayama T. Combined transforaminal lumbar interbody fusion and smiley face rod technique using dual-headed pedicle screws for L4 isthmic spondylolisthesis and L5 spondylolysis. Cureus. 2024. DOI: https://doi.org/10.7759/cureus.60756

31. Christman T, Li Y. Pediatric return to sports after spinal surgery. Sports Health: A Multidisciplinary Approach. 2016;8(4):331–335. DOI: https://doi.org/10.1177/1941738116634685

32. Dziegciarczyk A, Wiater Z, Włodarczyk A, Swoboda K, Brankowska K, Kuryłek M, Dziegciarczyk A, Banyś F, Polakowska A, Pyzik A, Jakubowska M. Scoliosis in young

athletes: influence of gymnastic training and screening strategies. Qual Sport. 2026;55:71120. DOI: https://doi.org/10.12775/qs.2026.55.71120

33. Oszczędłowski P, Niewęgłowski K, Madoń B, Nowaczek J, Giermasiński A. Impact of physical activity on incidence of osteoporotic fractures - a review. J Educ Health Sport. 2021;11(9):196–207. DOI: https://doi.org/10.12775/jehs.2021.11.09.025