INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue VII July 2026

The Prevalence of Spondylolysis in the Italian Elite Young Athlete

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DOI: https://doi.org/10.51584/IJRIAS.2026.11070179

Received: 03 August 2026; Accepted: 08 August 2026; Published: 19 August 2026

ABSTRACT

Objective: The objective of the current retrospective study was to assess the prevalence of and the association between sports participation and radiographic findings of spondylolysis and isthmic degenerative changes in young elite athletes.

Methods: The radiographic material of the lumbar-sacral spine of 1704 consecutive Olympic athletes was retrospectively analyzed. The athletes included in the study were registered with the Italian National Olympic Committee (CONI) and were selected between January 2008 and December 2018. Participants were aged between 12 and 27 years (mean: 19.50 ± 3.21). Athletes were categorized into five high-prevalence sports (diving, weightlifting, wrestling, gymnastics, track and field) and a baseline control group comprising 12 other sports.

Results: Out of 1704 athletes, 1322 were healthy, while 382 exhibited radiographic abnormalities. Specifically, 103 had isolated spondylolysis, 123 had isolated isthmic degenerative changes, and 156 presented with both conditions. The total prevalence of isthmic spondylolysis was 15.20% (n=259), of which 37.84% (n=98) was associated with spondylolisthesis. The total prevalence of isthmic degenerative alterations was 16.37% (n=279). Spondylolysis prevalence varied significantly across disciplines ($p < 0.001$) : diving (62.63%), weightlifting (36.00%), wrestling (34.78%), gymnastics (31.63%), and track and field (24.80%), compared to 5.06% in the control group. The location of the lesions was the lumbar region in all cases, predominantly L5 (81.85%).

Conclusion: Wrestling, weightlifting, and diving demonstrated a strong independent association with the onset of spondylolysis. Preventive measures are crucial, prioritizing targeted clinical monitoring and reserving diagnostic imaging for symptomatic athletes or those engaging in highly intensive training in high-risk disciplines.

Keywords: Spondylolysis; Elite athletes; Sports biomechanics; Low back pain; Pars interarticularis

INTRODUCTION

Spondylolysis is a condition involving the pars interarticularis of the vertebrae, frequently observed at the L5 and L4 levels (Choi et al., 2022). This defect is bilateral in around 80% of instances and may manifest in multiple levels, leading to isthmic spondylolisthesis, characterized by the forward displacement of the upper vertebrae and the separation of the anterior aspects of the vertebra from its neural arch due to defects in the pars interarticularis (Cassidy et al., 2005) (Nordby et al., 1985) (Figure 1.).

It undergoes into a progression starting from stress reactions in the pre-lytic stage, advancing to acute fractures (spondylolysis), and eventually culminating in chronic fractures. Pars interarticularis defects are often

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anticipated by Nonspecific Adolescent Low Back Pain (NSALBP), exacerbated by extension, or twisting of the spine (Narita et al., 2015).

NSALBP has an averagely high prevalence (Salminen et al., 1999) directly linked to the early diagnosis of spondylolysis and spondylolisthesis. NSALBP is also viewed both as a typical life occurrence in adolescents unrelated to adult low back pain, as well as a potential contributor to later-life low back pain (LBP) risk (Burton et al., 1996). Up to 50% of lower back pain (LBP) in adolescent athletes is associated with posterior element disturbance (PED), primarily located in the lower back segments L4 and L5 (Sundell et al., 2013).

Compared to a non-athlete population with spondylolisthesis, the incidence of lower back pain is, in some studies, overlapping for these two categories. However, for "top-level" athletes, the prevalence of lower back pain was lower (Tawfik et al., 2020) (Gadia et al., 2017) (Berger et al., 2019).

Spondylolysis often develops between the ages of 7 and 10, while it is rare before the age of 5 and beyond 20 years old (Logroscino et al., 2001). The incidence of spondylolysis in the general population ranges from 3% to 11.5%, with a higher incidence observed in young athletes (Toueg et al., 2010). It is also reported that the incidence in adolescent athletes is 2 to 5 times higher than that in non-athletes (Rossi et al., 2001). Despite the prevalence of low back pain is similar between male and female adolescents, males seem to have a higher incidence of spondylolysis (Calvo-Muñoz et al., 2013).

The objective of this retrospective observational analysis is to contribute to the literature by assessing the prevalence and the association between specific sports disciplines and the onset of isthmic alterations in a population of young athletes. Due to the retrospective nature of the study, causality cannot be definitively established; therefore, the aim is to evaluate the statistical association between specific athletic gestures (e.g., repeated hyperextension, rotation, vertical impact) and the occurrence of radiographic findings. By comparing high-prevalence disciplines against a baseline control group of athletes from other sports, this study seeks to provide robust epidemiological data to better highlight which athletes are more at risk, informing injury prevention and screening protocols.

Figure 1: Oblique radiograph of the lumbar spine showing the spondylolysis of L5 vertebrae.

MATERIAL AND METHODS

Study Design and Participants

In our study, we retrospectively analyzed the radiographic material of the lumbosacral spine from 1704 athletes registered with the Italian National Olympic Committee (CONI), selected between January 2008 and December 2018, searching for isthmic degenerative changes, spondylolysis, or spondylolisthesis. Participants were aged between 12 and 27 years old (overall mean age: 19.50 ± 3.21 years) and were selected from a wide range of 17 different sports. To conduct a comparative analysis, the cohort was stratified into five main sports with known biomechanical stress on the lumbar spine (diving, weightlifting, wrestling, gymnastics, and track and field) and a control macro-group ("Other 12 Sports") serving as a baseline for elite athletic exposure. This baseline control group comprised athletes practicing archery, basketball, cycling, equestrian sports, fencing, football, handball, martial arts, rowing, sailing, table tennis, and volleyball.

Radiographic Assessment

The radiological study included a postero-anterior teleradiograph of the spine, a lateral radiograph of the lumbar spine in the standing position, and oblique projections of the lumbar spine at 25° to 40°. Based on standard radiographic signs, patients were categorized using the following diagnostic criteria:

1. **Spondylolysis** was defined by the direct visualization of cortical discontinuity or a radiolucent cleft through the pars interarticularis, classically identified as the "Scottie dog collar" sign on oblique views.

2. **Isthmic degenerative changes (stress reactions)** were defined by the presence of pars interarticularis sclerosis, elongation, or focal contour bulging in the absence of a complete fracture line, often accompanied by early signs of disc space narrowing at the affected level.

3. **Spondylolisthesis** was defined as the anterior translation of a lumbar vertebra relative to the caudal segment, visually graded on the standing lateral radiograph according to the Meyerding classification.

To ensure diagnostic accuracy, all 1704 radiographic images were independently assessed by two specialized orthopedic spine surgeons (M.M. and N.S.). In instances of diagnostic uncertainty or disagreement between the two primary readers, a third senior orthopedic surgeon was consulted to review the images and establish a final consensus. A formal inter-rater reliability index (e.g., Cohen’s Kappa) was not calculated, as all discrepancies were resolved through this consensus panel approach. The clinical objectivity of the sample was not significant, with patients being either totally asymptomatic or presenting with very mild, non-specific lower back pain. In no case was it possible to establish the presence of a single violent trauma in the participant’s medical history.

Statistical Analysis

Demographic characteristics, including sex and age distribution, were extracted and categorized based on the presence of isolated or combined radiographic findings. Continuous variables (age) were analyzed using a One-Way ANOVA test to compare means across multiple groups. Categorical variables (sex, sport discipline) were evaluated using the Chi-square test. To estimate the risk associated with each sport while adjusting for potential confounders (age and sex), a multivariable logistic regression model was employed, calculating both Crude and Adjusted Odds Ratios (aOR) with 95% Confidence Intervals (CI). A p-value of <0.05 was considered statistically significant.

RESULTS

Demographic Characteristics and Clinical Overlap

Out of the 1704 athletes examined, 1322 (77.58%) presented normal radiographic findings, while 382 (22.42%) exhibited pathological alterations of the pars interarticularis. A significant clinical overlap was observed: 103 athletes had isolated isthmic spondylolysis, 123 had isolated isthmic degenerative changes, and 156 presented with both conditions concurrently. Consequently, the total number of patients with isthmic degenerative changes was 279 (16.37% of the total cohort), while the total number of patients with isthmic spondylolysis was 259 (15.20%). Among the 259 athletes with spondylolysis, 98 cases (37.84%) were associated with

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spondylolisthesis.

Age and Sex Distribution

Statistical analysis revealed a highly significant relationship between demographic variables and the severity of the radiographic findings. The mean age progressively and significantly decreased as the clinical picture worsened ($p < 0.001$): healthy controls had a mean age of 19.83 ± 3.13 years, those with a single condition averaged approximately 18.7 ± 3.2 years, and athletes presenting with both conditions were the youngest (17.87 ± 3.27 years). Similarly, sex distribution showed a strong, non-random disparity ($p < 0.001$). While females comprised the majority of the healthy control group (59.76%), the male-to-female ratio inverted and drastically increased in pathological cohorts. Males accounted for 67.96% of isolated spondylolysis cases, 82.11% of isolated isthmic alterations, and 92.95% (145 males vs. 11 females) of the patients affected by both conditions simultaneously.

Baseline Characteristics	Total Cohort (N = 1704)	Healthy Controls (N = 1322)	Isolated Spondylolysis (N = 103)	Isolated Isthmic Alt. (N = 123)	Both Conditions (N = 156)	P value
Age (years), mean ± SD	19,50 ± 3,21	19,83 ± 3,13	18,82 ± 3,22	18,65 ± 3,13	17,87 ± 3,27	p < 0.001
Sex, n (%)						p < 0.001
- Male	848 (49,77%)	532 (40,24%)	70 (67,96%)	101 (82,11%)	145 (92,95%)	
- Female	856 (50,23%)	790 (59,76%)	33 (32,04%)	22 (17,89%)	11 (7,05%)	
Sport Discipline, n (%)						p < 0.001
- Diving	99 (5,81%)	8 (0,61%)	10 (9,71%)	29 (23,58%)	52 (33,33%)	
- Weightlifting	100 (5,87%)	47 (3,56%)	8 (7,77%)	17 (13,82%)	28 (17,95%)	
- Wrestling	115 (6,75%)	61 (4,61%)	9 (8,74%)	14 (11,38%)	31 (19,87%)	
- Gymnastics	98 (5,75%)	51 (3,86%)	11 (10,68%)	16 (13,01%)	20 (12,82%)	
- Track and Field	125 (7,35%)	78 (5,90%)	15 (14,56%)	16 (13,01%)	16 (10,26%)	
- Other 12 Sports	1167 (68,47%)	1077 (81,47%)	50 (48,54%)	31 (25,20%)	9 (5,77%)	

Prevalence and Risk by Sport Discipline

The prevalence of spondylolysis varied significantly depending on the sport discipline ($p < 0.001$). In the control group (Other 12 Sports, N=1167), the baseline prevalence of spondylolysis was 5.06% (95% CI: 3.94% - 6.47%). In contrast, higher prevalences were observed in the selected disciplines: Track and field (24.80%; 95% CI: 18.06% - 33.05%), Gymnastics (31.63%; 95% CI: 23.27% - 41.38%), Wrestling (34.78%; 95% CI: 26.70% - 43.85%), Weightlifting (36.00%; 95% CI: 27.27% - 45.76%), and Diving (62.63%; 95% CI: 52.79% - 71.52%).

Multivariable logistic regression confirmed that these five sports are strong, independent risk factors for spondylolysis, even when adjusted for the confounding effects of age and sex. Compared to the control group (Reference OR = 1.00), the Adjusted Odds Ratios (aOR) were 7.26 for Track and field, 8.85 for Gymnastics, 14.27 for Wrestling, 15.74 for Weightlifting, and 56.63 for Diving (all $p < 0.001$).

Sport Discipline	Total Athletes (N)	Spondylolysis Cases, n (%)	95% CI for Prevalence	Crude OR (95% CI)	Adjusted OR* (95% CI)	p-value
Other 12 Sports	1167	59 (5.06%)	3.94% – 6.47%	1.00 (Reference)	1.00 (Reference)	-
Track and Field	125	31 (24.80%)	18.06% – 33.05%	6.19 (3.82–10.04)	7.26 (4.28–12.31)	p < 0.001
Gymnastics	98	31 (31.63%)	23.27% – 41.38%	8.69 (5.27–14.32)	8.85 (4.78–16.39)	p < 0.001
Wrestling	115	40 (34.78%)	26.70% – 43.85%	10.02 (6.29–15.94)	14.27 (8.41–24.19)	p < 0.001
Weightlifting	100	36 (36.00%)	27.27% – 45.76%	10.56 (6.50–17.16)	15.74 (9.02–27.48)	p < 0.001
Diving	99	62 (62.63%)	52.79% – 71.52%	31.47 (19.39–51.06)	56.63 (29.92–107.20)	p < 0.001
* Adjusted Odds Ratio (aOR) computed via multivariable logistic regression, adjusted for age and sex.						

Location of the Lesions and Progression

All cases (100%) of degenerative changes and spondylolysis were localized in the isthmic lumbar region. The most prevalent level affected by spondylolysis (n=212, 81.85%) was L5. Spondylolysis was bilateral in 226 cases (87.26%), of which 9 cases (3.47%) were both double and simultaneously bilateral, and unilateral in 33 cases (12.74%). Double localizations occurred predominantly in athletes engaged in sports with a preferential hyperextension and unilateral torsional involvement.

DISCUSSION

Summary

According to the results of our analysis, wrestling, weightlifting, and diving have been labelled as sports carrying a higher risk for the onset of spondylolysis, boasting a prevalence between 34.78% and 62.43%. Artistic gymnastics and track and field demonstrated a comparatively lower prevalence than the highest-risk sports, yet they still maintain a clinically and statistically significant risk compared to the baseline athletic population.

State of the art

As early as 1976, Jackson et al. documented, in a group of 100 young gymnasts, an incidence of injuries to the pars interarticularis four times higher than that of white women and twice as high as in a male population of the same age (Jackson et al., 1976). A higher incidence of injury to the pars interarticularis was found in those, both males and females, engaging in activities such as karate, football, gymnastics, hurdle racing, pole vaulting, and high jump (Jackson et al., 1976). In 1982, Ichikawa et al. identified a high percentage of spondylolisthesis (26%) in athletes involved in football, weightlifting, and judo (Ichikawa et al., 1982). In 1984, Caldarone, in a study conducted at the Institute of Sports Medicine in Rome, highlighted that 16.71% of athletes (239 positive cases out of 1430 examined) belonging to various sports disciplines showed morphological-structural alterations of the isthmus, spondylolysis and spondylolisthesis (Caldarone, 1984). In 1985, Ottolenghi et al. found a higher incidence of spondylolysis in athletes engaged in gymnastics and sailing compared to control groups, probably caused by micro-multiple traumas. (Ottolenghi et al., 1985). In 1986, McCarrol et al. conducted a prospective study on 145 college football players throughout their sports careers, reporting that the incidence of spondylolysis (15.2%) is higher than in a normal population. Spondylolysis appeared during adolescence and was associated with physically demanding athletic activities (McCarrol et al., 1986). In 1992, a review of the radiographic archive material at the Institute of Sports Science of C.O.N.I. (from 1962 to 1988), examining 3132 X-rays of the lumbosacral spine performed on high-level athletes complaining of varying intensity, duration, and frequency of lumbar discomfort, showed a total of 390 cases of isthmic spondylolysis, corresponding to an incidence of 12.45% (Dragoni et al., 1992). In 1995, in a study by Morita T. et al., it was highlighted that out of 381 individuals with spondylolysis aged between 6-18 years old, 376 were engaged in high-level sports (Morita et al., 1995).

It has been observed, therefore, that when each sport is considered separately, the literature indicates very significantly higher values of defects in the pars interarticularis and spondylolysis, with certain sports showing a higher percentage compared to others (Tawfik et al., 2020). As early as 2001, Rossi and Dragoni highlighted varying prevalences of spondylolysis and spondylolisthesis among symptomatic athletes in different sports, with a prevalence of 40% in diving, 25% in wrestling, 22% in weightlifting, 17% in gymnastics, and 16% in judo (Rossi et al., 2001). Similarly, in 2004, Lim M. et al. highlighted different prevalences of spondylolysis in specific sports, with a prevalence of 83% in diving, 45% in weightlifting, 38% in multidisciplinary gymnastics, 33% in wrestling, 27% in throwing sports, 25% in high jump, and 24% in football (Lim et al., 2004). Recently in 2020, the prevalence of pars interarticularis defects was observed to be highest in the following sports: diving (35.38%), cricket (31.97%), baseball/softball (26.91%), rugby (22.22%), weightlifting (19.49%), sailing (17.18%), table tennis (15.63%), and wrestling (14.74%) (Tawfik et al., 2020).

In the assessment of the association between pathogenetic mechanisms and the development of these defects, many authors have emphasized the cause-and-effect relationship between sports and spondylolysis, documenting the importance of mechanical factors. The majority believed that spondylolysis is probably caused by repeated micro-trauma rather than a single traumatic event (Wiltse et al., 1975) (Micheli et al., 1995). It would be a specific injury of the human species and growth period, due to sector-specific static-dynamic stresses, although multiple factors may be involved in its genesis. When spondylolysis occurs in athletes, it is commonly considered a stress fracture (Jackson et al., 1976) (Cyron et al., 1978) (Rosenberg et al., 1981) (Weiker et al., 1989).

In evaluating the specific movements that cause an increase in stress on the pars interarticularis, two theories have been formulated.

The first focuses on the compression on the articular facets during hyperextension. Specifically, with an associated rotational movement, the stress on the pars interarticularis is further increased (Schulitz et al., 1980). Fractures of the pars interarticularis due to mechanical failure could occur in hyperextension under oscillating loads ranging from 3000 to 12000 newtons. Moreover, with the addition of rotation, contact between the articular facets and laminae could occur even with simple extension (Jacob et al., 1985).

The second theory argues that repeated flexion movements generate unbalanced shear forces, resulting in an increased stress on the pars interarticularis (Farfan et al., 1976) (Schulitz et al., 1980) (Junghanns et al., 1990). Biomechanical studies demonstrated an increase in shear forces on the pars during specific athletic movements, especially in the growing spine, likely associated with the chain of pathological events leading to spondylolisthesis (Troup et al., 1976) (Hutchinson et al., 1999).

A postural theory has also been proposed to assess the sagittal alignment of the spine and pelvis in patients with spondylolysis before the development of a large secondary deformity associated with the progression of spondylolisthesis. It is noted that patients with spondylolysis and low-grade spondylolisthesis show increased pelvic incidence (>55°), increased lumbar lordosis, but less segmental extension between L5 and S1 than in a normal population (Roussouly et al., 2006).

The majority of injuries occur at the L5 level (up to 84.29%), followed by L4 (11.88%), and rarely in other locations (Rossi et al., 2001) (Soler et al., 2000), presumably because the bending moment is maximal on the pars interarticularis of L5, due to sacral inclination.

Based on the recently described pathogenetic biomechanical mechanisms of spondylolysis, research focused on recurrent micro-traumas caused by repetitive hyperextension, flexion, and rotation of the lumbar spine (Bono, 2004). Athletes engaged in sports involving repeated axial loading, hyperextension, direct impact, and twisting are at an increased risk of lumbar spinal injuries and so at an increased risk of spondylolysis and spondylolisthesis (Bono, 2004).

Indeed, among young athletes, recurrent trauma may result in a mechanical stress injury to the pars interarticularis and might be the prevailing source of lower back pain in athletic children and adolescents (Hensinger, 1983). Also, some studies showed that in initially asymptomatic patients, specifically in athletes, spondylolysis appeared after a few years and had a high incidence (up to 50%) (Rossi, 1978). In children and adolescents engaged in organized sports, there is a growing occurrence of spine-related injuries: in particular, those involved in sports that require repetitive hyperextension of the lumbar spine have been proven to be at increased risk (Ladenhauf et al., 2013).

Interpretation of outcomes

The high prevalence of spondylolysis and isthmic changes in certain athlete categories suggests that some sports exhibit a specific predisposition to the development of these lumbar alterations, owing to the types of mechanical movements and specific loading forces associated with each sport.

In diving, the pressure on the head exerted by water contact on these athletes is very similar to that of the trampoline on gymnasts. In a perfect water entry, there are no abnormal stresses at the lumbo-sacral level. In an incorrect water entry, with an exaggerated hyperextension posture, the stress on the pars interarticularis increases.

In weightlifting, in maximum lumbar hyperextension during the "snatch" and "clean and jerk" exercises, there is the maximum stress on the lumbar pars interarticularis.

In wrestling's most classic form, the sudden and rapid hyperextension movement, executed with a final trunk twist, is the main cause of increased stress on the pars interarticularis.

In gymnastics, at-risk movements include hyperextension in "free body," in "vaulting" during hand impact on equipment, on the "beam," on the "parallel bars," and on the "asymmetric bars." In the specific subcategories of artistic and rhythmic gymnastics, the high prevalence is justified by the fact that hyperextension and twisting mechanisms are exacerbated by the vertical impact of the landing from a jump (Tawfik et al., 2020). In rhythmic gymnastics, movements on one leg, with the spine in hyperextension, add additional stress and explain the occurrence of unilateral spondylolysis (Tawfik et al., 2020).

Track and field, while presenting a relatively lower crude prevalence of isolated spondylolysis compared to diving or weightlifting, still carries a highly significant independent risk (aOR: 7.26, $p < 0.001$) compared to the baseline athletic population. This strong association reflects the impact of repetitive micro-traumas in specific track and field events (e.g., throwing or jumping disciplines) that subject the immature lumbar spine to extreme loading.

LIMITATIONS

This study presents several limitations. First, the retrospective observational design allows us to identify epidemiological associations but precludes establishing a definitive cause-and-effect relationship between athletic exposure and the onset of spondylolysis. Second, there is an inherent selection bias, as the cohort consisted exclusively of elite CONI registered athletes who underwent specific radiographic evaluation. Finally, the absence of a non-athletic control group limits the ability to compare these findings with the general population, although the inclusion of a baseline cohort of athletes from lower-stress sports provided a valuable internal control for comparative analysis.

IMPLICATIONS OF FINDING

Identifying high-risk sports, as highlighted in this study, underlines the need for strict prevention and targeted monitoring for certain athlete categories. In summary, we may conclude that lower back pain is not always a pronounced criterion in identifying a current spondylolysis condition. It is more useful to rely on a diagnostic assumption based on the knowledge of which sports pose a higher risk for the development of such alterations.

Contrary to literature descriptions, a lower number of spondylolisthesis cases were found in athletes and sports (e.g., diving and gymnastics) where, despite pronounced lordosis, significant muscle constraints were applied, highlighting the importance of integrity and power in maintaining kinematic constraints. Although our retrospective cross-sectional design precludes tracking structural progression over time, the high number of active elite athletes identified with stable isthmic alterations aligns with current literature. This suggests that sports participation itself does not inevitably drive the structural progression into severe spondylolisthesis, while it may provide beneficial muscular core constraints. Therefore, there is no justification for arbitrarily discouraging sports participation in asymptomatic or mildly symptomatic adolescents with spondylolysis, provided rigorous clinical monitoring is maintained.

All lower back pain in athletes should raise suspicion of spondylolysis, and certain sports can be a contributing factor due to excessive and repeated hyperextension and flexion mechanisms. Although spondylolysis may not impair athletic performance initially, it is susceptible to progression in spondylolisthesis in the future (Beutler et al., 2003). It is important to identify in advance the categories of athletes at higher risk to carefully design training programs, especially for younger ones. Specifically, ensuring the proper execution of technical movements to avoid additional overload and improper flexion is crucial. Incorporating individual muscle stretching and strengthening the entire abdominal trunk musculature provides essential support to the lumbar spine.

While prevention is paramount, the recommendation for routine radiographic screening must be carefully weighed against the risks of exposing adolescents and young adults to ionizing radiation. Rather than a blanket radiographic screening, we advise implementing rigorous clinical monitoring in sports medical programs. Diagnostic imaging (preferably utilizing MRI to avoid radiation, or targeted radiographs) should be strictly reserved for athletes presenting with persistent NSALBP or those engaging in highly intensive training loads in high-risk disciplines, ensuring that clinical utility justifies the intervention.

CONCLUSION

In this retrospective analysis, we identified diving, weightlifting, wrestling, gymnastics, and track and field as sports significantly associated with an elevated risk for the onset of spondylolysis compared to a baseline athletic cohort. Fewer spondylolisthesis cases were found in sports with pronounced lordosis but significant muscle constraints, emphasizing the protective role of structural integrity and power. The sport itself does not appear to increase the risk of progression into spondylolisthesis. Preventive measures remain crucial, prioritizing targeted clinical monitoring, core-strengthening protocols, and the judicious use of imaging to minimize radiation exposure while safely managing the young athlete's spinal health.

ETHICAL CONSIDERATIONS

Ethical approval for this retrospective study was obtained prior to data collection. The study was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. Patient data were anonymized to protect personal confidentiality.

DATA AVAILABILITY

The datasets analyzed during the current study are not publicly available due to strict privacy, medical confidentiality, and ethical restrictions concerning the athletes registered with the Italian National Olympic Committee (CONI). However, anonymized data are available from the corresponding author upon reasonable request, subject to permission from the relevant authorities.

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