OVERUSE INJURIES IN ADOLESCENT ATHLETES: TRAINING LOAD MODELS, RISK MECHANISMS, AND PREVENTION STRATEGIES

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Abstract: Overuse injuries are a major concern in adolescent athletes due to high training volumes, early sport specialization, and ongoing musculoskeletal development. Unlike acute injuries, overuse injuries result from repetitive submaximal loading without adequate recovery, leading to progressive tissue microdamage. This review synthesizes current evidence on training load models, underlying injury mechanisms, and prevention strategies in youth athletes. Key conceptual frameworks including the acute:chronic workload ratio (ACWR), cumulative load theory, and fitness–fatigue model are critically examined. Furthermore, biological, biomechanical, and psychosocial mechanisms contributing to overuse injury development are discussed. Finally, evidence-based prevention strategies including load monitoring, neuromuscular training, and periodization approaches are evaluated. Current evidence suggests that overuse injury risk is multifactorial and cannot be explained by training load alone. Instead, injury emergence results from dynamic interactions between external load, internal capacity, and individual developmental factors. Practical implications emphasize individualized load management and integrated monitoring systems.

Key words： Adolescent athletes; Overuse injury; Training load; ACWR; Injury prevention; Sports medicine

1 Introduction

1.1 Epidemiological Burden and Clinical Significance

Overuse injuries constitute a substantial and growing proportion of sports-related morbidity in adolescent athletes, frequently accounting for a higher injury burden than acute traumatic events in endurance-, running-, and jumping-based sports. Unlike acute injuries, overuse conditions emerge insidiously through repetitive submaximal loading that exceeds the adaptive capacity of developing musculoskeletal tissues. Recent epidemiological evidence suggests that approximately one-third to one-half of all youth sports injuries may be classified as overuse-related, underscoring their clinical and public health relevance [1,2].

1.2 Developmental Vulnerability in Adolescent Athletes

Adolescence represents a period of rapid biological transition characterized by skeletal growth, hormonal modulation, and neuromuscular reorganization. During peak growth velocity, transient imbalances between bone elongation and soft tissue adaptation can increase mechanical strain at musculoskeletal insertion sites.

Consequently, growth-related structures such as apophyseal and epiphyseal regions exhibit heightened susceptibility to repetitive loading stress. This developmental vulnerability is further amplified in athletes exposed to high training volumes or early sport specialization [3,4].

1.3 Conceptual Rationale and Aim of the Review

In recent years, training load has been proposed as a central construct for understanding and managing injury risk in sport. However, the empirical validity of load–injury relationships remains debated due to methodological heterogeneity and inconsistent findings across studies. Rather than functioning as a deterministic predictor, training load should be conceptualized as one component within a broader multifactorial injury system incorporating biological maturation, neuromuscular control, and psychosocial stressors. Accordingly, this systematic review synthesizes current evidence on training load models, mechanistic pathways of overuse injury, and evidence-based prevention strategies in adolescent athletic populations.

2 Mechanisms of Overuse Injuries

2.1 Tissue Adaptation Failure and Microdamage Accumulation

The pathogenesis of overuse injuries is primarily driven by an imbalance between tissue loading and recovery capacity. Repetitive mechanical stress induces microscopic structural damage within bone, tendon, and muscle tissues. Under physiological conditions, these microinjuries trigger adaptive remodeling; however, when recovery is insufficient, cumulative microdamage progressively exceeds repair capacity, ultimately resulting in tissue failure along a continuum from functional overload to structural breakdown [5].

2.2 Growth-Related Biomechanical Constraints

During adolescence, rapid longitudinal bone growth alters musculoskeletal geometry and temporarily reduces the functional capacity of muscle–tendon units to absorb mechanical load. This mismatch contributes to increased strain at tendon-bone interfaces and is implicated in common youth overuse conditions such as Osgood–Schlatter disease and calcaneal apophysitis. In addition, reduced neuromuscular coordination during growth spurts may further compromise movement efficiency and load distribution [3,4].

2.3 Movement Dysfunction and Neuromuscular Fatigue

Biomechanical inefficiencies, including altered landing mechanics, dynamic valgus collapse, and inter-limb asymmetries, are strongly associated with localized tissue overload. These maladaptive movement patterns are exacerbated under fatigue conditions, where diminished neuromuscular control reduces joint stability and increases aberrant loading patterns during repetitive athletic tasks [6].

2.4 Psychophysiological Modulators

In addition to mechanical factors, psychosocial stress and inadequate recovery represent important modulators of injury risk. Elevated psychological stress, sleep disruption, and insufficient recovery behaviors may impair tissue repair processes and alter perceived exertion, thereby indirectly increasing susceptibility to overuse injury [7].

3 Training Load Models

3.1 Acute: Chronic Workload Ratio (ACWR)

The ACWR model has been widely adopted in applied sports science to quantify the relationship between recent training load and longer-term load exposure. It is defined as the ratio between short-term (acute) and medium-term (chronic) workload:

$$ACWR = \frac{Acute\ Load}{Chronic\ Load}$$

Conceptually, elevated ratios have been interpreted as periods of insufficient adaptation following rapid load escalation. However, accumulating evidence indicates substantial methodological variability and limited predictive validity across populations and sports contexts. Several systematic reviews have reported inconsistent associations between ACWR and injury outcomes, suggesting that its utility as a standalone risk metric is limited [8,9].

3.2 Cumulative Load Framework

In contrast to ratio-based models, cumulative load approaches emphasize the total accumulated training exposure over time. This framework posits that injury risk is more strongly associated with chronic mechanical stress accumulation than short-term load fluctuations. From a physiological standpoint, cumulative overload reflects progressive failure of tissue remodeling capacity under sustained repetitive loading conditions [10].

3.3 Fitness–Fatigue Interaction Model

The fitness–fatigue model conceptualizes training adaptation as the net outcome of opposing physiological processes: positive adaptations (fitness) and transient performance decrements (fatigue). Injury risk is hypothesized to increase when fatigue dominates adaptive capacity, leading to compromised neuromuscular control and reduced movement efficiency. Compared with ACWR, this model provides a more dynamic representation of training responses [11].

3.4 Limitations and Conceptual Shift

Collectively, current evidence indicates that no single load-derived metric reliably predicts overuse injury risk. Instead, injury emergence should be understood as a nonlinear system behavior arising from interactions between load exposure, individual capacity, and contextual factors. This represents a shift away from reductionist load–injury paradigms toward multivariate risk modeling approaches [12].

4 Prevention Strategies

4.1 Integrated Load Monitoring

Modern load monitoring strategies combine external metrics (e.g., GPS-derived distance, acceleration counts) with internal responses (e.g., session-RPE, heart rate variability). While these tools provide valuable insight into training stress dynamics, their predictive accuracy remains limited when used in isolation. Their primary value lies in facilitating longitudinal trend analysis and early detection of abnormal load fluctuations rather than precise injury prediction [13].

4.2 Neuromuscular Training Interventions

Neuromuscular training programs represent one of the most consistently supported interventions for injury prevention in youth sport. These programs enhance movement control, improve force absorption capacity, and reduce aberrant joint loading patterns during dynamic tasks. Meta-analytic evidence supports their effectiveness in reducing lower extremity overuse injuries, particularly when implemented during early developmental stages [14].

4.3 Load Periodization Principles

Appropriate periodization of training load is essential for optimizing adaptation while minimizing injury risk. Gradual and structured progression of workload facilitates physiological adaptation and reduces exposure to abrupt load spikes that may exceed tissue tolerance thresholds. Individualized periodization strategies are increasingly recommended due to variability in maturation status and training history [15].

4.4 Recovery and Behavioral Factors

Recovery optimization represents a critical but often underemphasized component of injury prevention. Sleep quality, nutritional status, and psychological stress significantly influence physiological recovery processes and neuromuscular function. Evidence suggests that insufficient sleep is associated with increased injury risk in adolescent athletes, likely mediated through impaired neuromuscular recovery and cognitive performance [16].

Conclusion

Overuse injuries in adolescent athletes represent a major challenge in contemporary sports medicine due to their multifactorial etiology and long-term implications for athletic development. This systematic review demonstrates that repetitive mechanical loading alone is insufficient to explain injury occurrence. Instead, overuse injuries emerge from dynamic interactions among training load, biological maturation, neuromuscular control, biomechanical efficiency, and psychosocial stressors. Adolescent athletes are particularly vulnerable because rapid skeletal growth and incomplete musculoskeletal maturation reduce tissue tolerance to repetitive stress. Current evidence further indicates that early sport specialization and excessive year-round training may amplify these vulnerabilities by limiting recovery opportunities and increasing cumulative tissue overload.

The findings of this review also highlight important limitations in current training load models. Although frameworks such as the acute:chronic workload ratio (ACWR), cumulative load models, and fitness–fatigue paradigms provide valuable theoretical insight into athlete adaptation, none consistently demonstrate sufficient predictive accuracy when applied in isolation. Injury development should therefore be conceptualized as a nonlinear and individualized process rather than a direct consequence of elevated workload. Contemporary research increasingly supports integrated monitoring approaches that combine external and internal load metrics with contextual variables including sleep quality, psychological stress, and maturation status. Such multidimensional frameworks may provide a more accurate representation of injury susceptibility in youth athletes than single-variable load measures.

From a practical perspective, effective prevention of overuse injuries requires a comprehensive and individualized athlete management strategy. Gradual load progression, structured periodization, neuromuscular training, and adequate recovery optimization remain central components of evidence-based prevention programs. In addition, coaches, clinicians, and sports organizations should prioritize long-term athlete development over short-term performance outcomes, particularly during critical stages of adolescent growth. Future research should focus on longitudinal and technology-assisted approaches, including wearable monitoring systems and machine learning-based injury prediction models, to improve individualized risk assessment and support safer athletic participation in youth sport populations.

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