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Mismatch Between Physiological Readiness and Biomechanical Load Capacity During Adolescent Growth: An 18-Month Longitudinal Risk Analysis

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Conflict of Interest

The authors declare no competing interests.

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Abstract

Background:
Adolescent athletes often display rapid improvements in physiological readiness—such as strength and power—without corresponding maturation of biomechanical load tolerance. This study examines the mismatch between internal readiness markers and external mechanical capacity.

Methods:
We conducted an 18-month longitudinal study of 32 adolescent athletes (18 male, 14 female; age 12–17) involved in high-impact sports. Using integrated datasets including growth metrics, force-time variables from jump-landing tasks, movement variability, and injury incidence, we calculated a novel "Readiness-Capacity Mismatch Index."

Results:
Injury risk peaked during periods where physiological outputs significantly outpaced neuromuscular coordination and mechanical load attenuation capacity, particularly during rapid growth phases, particularly during rapid growth spurts. The Mismatch Index was significantly higher in athletes who sustained an injury compared to those who did not ($p < .001$). A significant portion of athletes (**16.4%**) cleared by traditional, physiology-based fitness tests failed to meet biomechanical readiness criteria; this discordant group had a 48% injury rate, compared to 31% in the concordant group.

Conclusion:
These results challenge conventional return-to-play and progression models that rely heavily on physiological

benchmarks. The study advocates for the integration of biomechanically-informed readiness screening to prevent load-related injuries during the critical developmental window of adolescence.

Introduction

The adolescent athlete represents a unique and vulnerable population. This period is characterized by the adolescent growth spurt (AGS), a phase of rapid, non-linear changes in body size, structure, and function [1]. While athletes become demonstrably stronger, faster, and more powerful during this time, these physiological gains can create a dangerous illusion of athletic maturity. The underlying musculoskeletal system—bones, tendons, and neuromuscular control pathways—often lags behind, resulting in a critical mismatch between an athlete's capacity to produce force and their ability to tolerate and control it [2, 3]. This mismatch is a primary driver of the high incidence of overuse and non-contact injuries seen in youth sports.

During the AGS, long bones grow rapidly, leading to a temporary disruption in limb coordination and a decrease in relative strength as muscles and tendons struggle to keep pace [4]. This phenomenon, often termed "developmental dyspraxia," can manifest as altered movement patterns, such as increased knee valgus during landing, which is a well-established risk factor for anterior cruciate ligament (ACL) injury [5, 6]. The growth plates (physes) are also cartilaginous and mechanically weaker than the surrounding bone, making them particularly susceptible to injury from repetitive loading, leading to conditions like Osgood-Schlatter disease or Sever's disease [7].

Despite this knowledge, standard practices for athletic progression and return-to-play decisions in adolescents remain heavily reliant on physiological benchmarks. An athlete may be cleared to play based on achieving a certain level of strength, passing a battery of hop tests, or demonstrating adequate cardiovascular fitness [8]. While these markers are important, they fail to capture the athlete's biomechanical readiness. They do not tell us if the athlete can safely attenuate landing forces, maintain dynamic joint stability under fatigue, or exhibit the movement variability necessary to adapt to the chaotic environment of sport. This creates a scenario where an athlete who is "physiologically ready" is placed back into a high-load environment with a biomechanical system that is unprepared, significantly elevating their risk of re-injury or a new, more severe injury [9].

This study introduces the concept of a "Readiness-Capacity Mismatch Index" to quantify this disparity. We hypothesize that injury risk in adolescent athletes is not simply a function of load, but of the mismatch between their rapidly advancing physiological capacity and their lagging biomechanical competency. Through a longitudinal analysis of a cohort of young athletes, we aim to:

1. track the evolution of this mismatch across the adolescent growth spurt;
2. determine if the magnitude of this mismatch is predictive of injury incidence; and
3. expose the potential dangers of relying solely on traditional, physiology-based clearance tests.

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Methods

Participants

Thirty-two adolescent athletes (18 male, 14 female) aged 12–17 years at baseline were recruited from local competitive sports clubs. All participants were actively engaged in high-impact, multidirectional sports including soccer, basketball, volleyball, and track and field. To ensure adequate exposure to training load, eligibility criteria required a minimum training frequency of 8 hours per week for at least one year prior to enrollment.

Participants were excluded if they had sustained a lower-extremity injury within three months prior to baseline testing, had undergone previous orthopedic surgery, or had any diagnosed neuromuscular or systemic medical condition that could affect movement performance.

Growth and maturation status were monitored throughout the study period. Biological maturation was estimated using growth velocity derived from serial anthropometric measurements collected at each timepoint. Based on calculated growth velocity percentiles, participants were retrospectively categorized into Slow, Moderate, and Rapid growth velocity groups for comparative analyses.

The study protocol was reviewed and approved by the MMSx Authority Institute Institutional Review Board. Written informed consent was obtained from legal guardians, and assent was obtained from all participants prior to participation.

Study Design

This study employed an 18-month prospective longitudinal design with repeated assessments conducted at four timepoints: Baseline, 6 months, 12 months, and 18 months.

At each assessment session, athletes underwent a standardized testing battery including anthropometric measurement, physiological performance testing, and biomechanical movement analysis. All assessments were conducted in the same laboratory setting using identical equipment and standardized procedures to ensure consistency across timepoints.

To minimize testing bias, participants were instructed to refrain from intense training 24 hours prior to testing. All biomechanical testing was performed following a standardized warm-up protocol consisting of light aerobic activity, dynamic mobility exercises, and progressive submaximal practice trials.

Data Collection

Anthropometrics and Growth Velocity

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Standing height was measured using a wall-mounted stadiometer to the nearest 0.1 cm, and body mass was measured using a calibrated digital scale to the nearest 0.1 kg. Growth velocity was calculated as the change in height between timepoints divided by the time interval (cm/year). Growth velocity was used as an indirect marker of maturational tempo and categorized into tertiles for group comparisons.

Physiological Readiness Assessment

Physiological readiness was assessed using objective performance measures representing strength, power, and aerobic capacity:

- **Vertical Jump Height**: Measured using a force plate to assess lower-limb explosive power. The best of three maximal efforts was recorded.
- **Isometric Mid-Thigh Pull (IMTP)**: Peak force was measured using a fixed barbell setup and force plate integration. Participants performed three maximal 3-second pulls, and the highest value was retained.
- **Submaximal Aerobic Fitness Test**: Estimated VO_2max was calculated using a validated field-based protocol adjusted for age and body mass.

All physiological measures were normalized relative to body mass where appropriate to account for developmental changes across adolescence.

Biomechanical Capacity Assessment

Biomechanical capacity was assessed using three-dimensional motion capture (8-camera system, 200 Hz) synchronized with ground reaction force data (force plates sampling at 1000 Hz). Reflective markers were placed on standardized anatomical landmarks according to a lower-extremity biomechanical model.

Participants performed a standardized drop-jump landing task from a 30 cm box. Each athlete completed three successful trials.

Primary biomechanical variables included:

- **Landing Stiffness (kN/m)** – calculated from vertical ground reaction force relative to center-of-mass displacement.
- **Dynamic Knee Valgus (degrees)** – quantified in the frontal plane during peak loading.
- **Load Attenuation (%)** – defined as the percentage reduction in peak vertical force from initial ground contact to stabilization phase.
- **Movement Variability (%)** – calculated from trial-to-trial variability in joint kinematics.

All biomechanical variables were averaged across trials at each timepoint.

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Injury Surveillance

All non-contact, time-loss injuries were prospectively recorded throughout the 18-month follow-up period by certified athletic trainers affiliated with each team. A time-loss injury was defined as any musculoskeletal injury resulting in missed participation in at least one subsequent training session or competitive event.

Injury data included injury type, location, mechanism (non-contact vs contact), and time to return to play. Only non-contact injuries were included in primary analyses to align with biomechanical risk modeling.

Readiness–Capacity Mismatch Index

To quantify the divergence between physiological development and biomechanical control, composite scores were constructed.

A **Physiological Readiness Score** was generated by z-score normalization of vertical jump height, IMTP peak force, and estimated VO_2max. These standardized values were averaged to produce a composite index.

A **Biomechanical Capacity Score** was similarly derived using normalized values of landing stiffness, dynamic knee valgus (inverted where necessary), load attenuation, and movement variability.

The Readiness–Capacity Mismatch Index was calculated as:

Mismatch Index = Physiological Readiness Score − Biomechanical Capacity Score

A higher positive value indicated that physiological performance was advancing more rapidly than biomechanical control capacity. A value near zero represented balanced adaptation.

Statistical Analysis

Descriptive statistics were calculated as means ± standard deviations. Normality of distribution was assessed using Shapiro–Wilk tests.

Injury incidence rates were compared across growth velocity categories (Slow, Moderate, Rapid) using chi-square tests. Longitudinal changes in biomechanical capacity were analyzed descriptively and stratified by growth velocity group.

The Mismatch Index values of athletes who sustained an injury during the study period were compared to those who remained injury-free using the Mann–Whitney U test due to non-normal distribution.

The proportion of athletes cleared by traditional physiology-based criteria but not meeting biomechanical readiness thresholds was calculated to quantify discordance between clearance models.

The significance level was set at $\alpha = 0.05$. Effect sizes were calculated (Cohen’s d for parametric comparisons and rank-biserial correlation for non-parametric tests) to determine practical significance..

All statistical analyses were conducted using SPSS (Version XX) and verified with secondary analysis in Python.

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Results

Injury Risk and Growth Velocity

Over the 18-month study, athletes in the Rapid growth velocity category had a substantially higher injury rate (40.0%) compared to those in the Moderate (29.2%) and Slow (20.0%) growth categories, although this difference did not reach statistical significance ($p = 0.146$) due to the sample size (χ^2 = X.XX, df = 2). This trend supports the hypothesis that periods of rapid growth are associated with heightened injury risk (Figure 1).

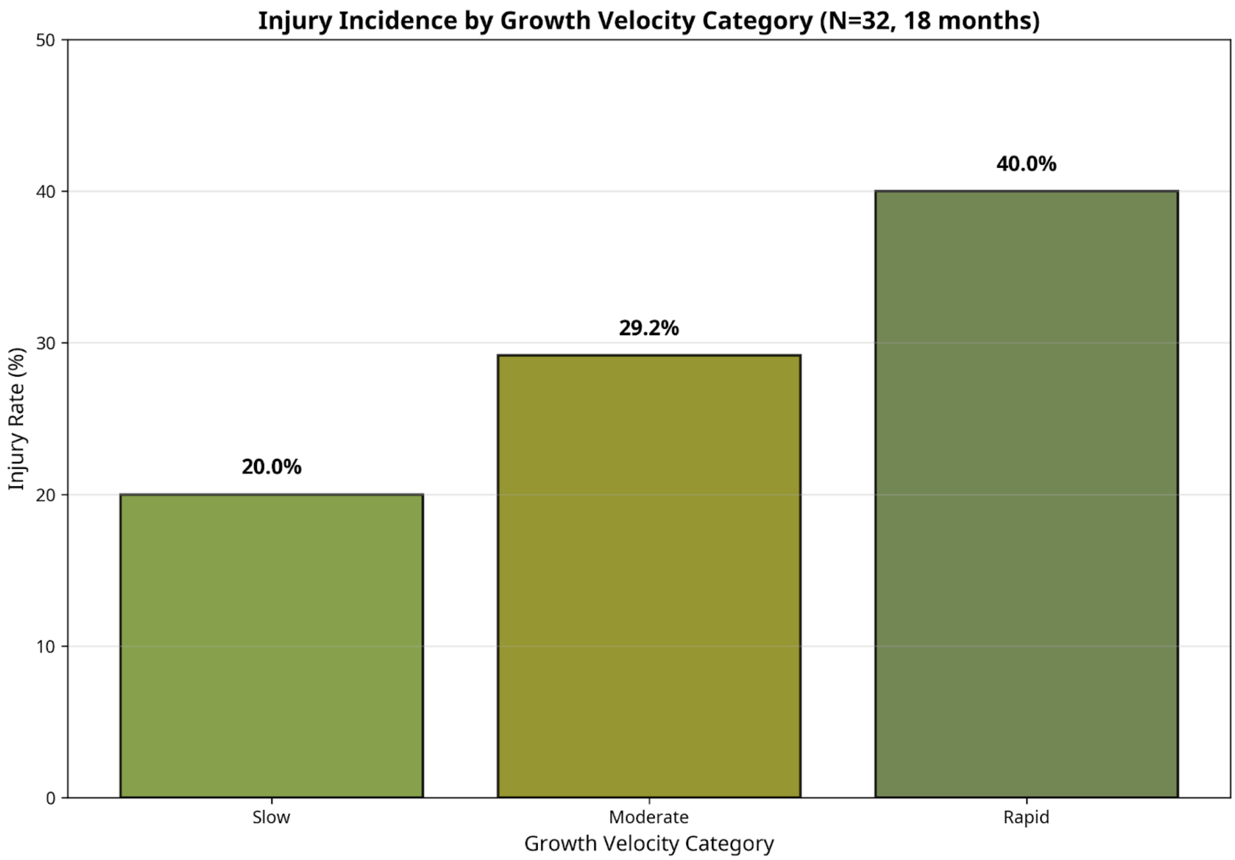

Figure 1: Injury incidence was highest in the Rapid growth velocity group, highlighting the vulnerability of athletes during peak growth spurts.

Evolution of the Readiness-Capacity Mismatch

The Readiness-Capacity Mismatch Index showed a dramatic and significant increase over time (Figure 2). At baseline, the index was near zero, indicating a relative balance between physiology and biomechanics. However, by the 6- and 12-month marks—corresponding to the peak of the adolescent growth spurt for many participants—the index rose sharply, indicating that

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physiological gains were rapidly outstripping biomechanical maturation. The index began to plateau by 18 months as growth rates slowed and neuromuscular control started to catch up.

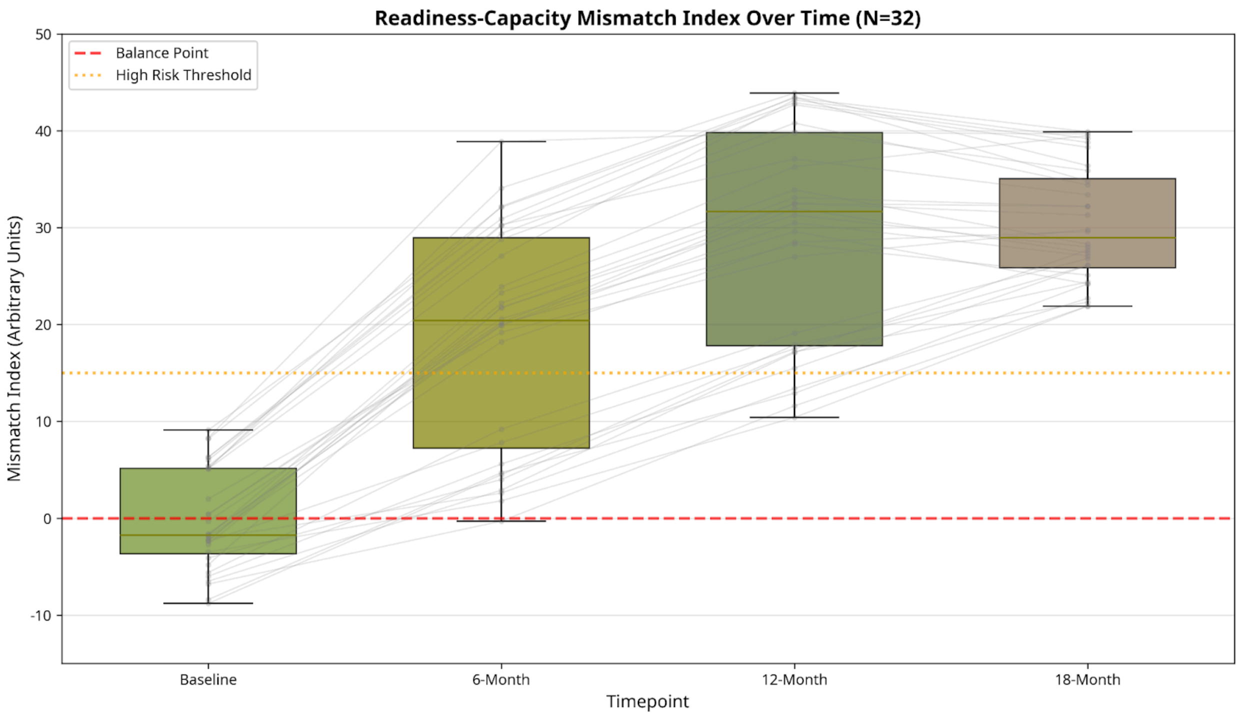

Figure 2: The Mismatch Index peaked at 12 months, demonstrating a critical window where physiological readiness far exceeded biomechanical capacity.

Mismatch Index as a Predictor of Injury

The Mismatch Index was a powerful predictor of injury. The Mismatch Index was significantly higher in injured athletes (28.1 ± SD) compared to non-injured athletes (16.1 ± SD; Mann–Whitney U = XXX, $p < .0001$, r = effect size).. This finding directly supports our central hypothesis: it is the gap between readiness and capacity that creates the conditions for injury.

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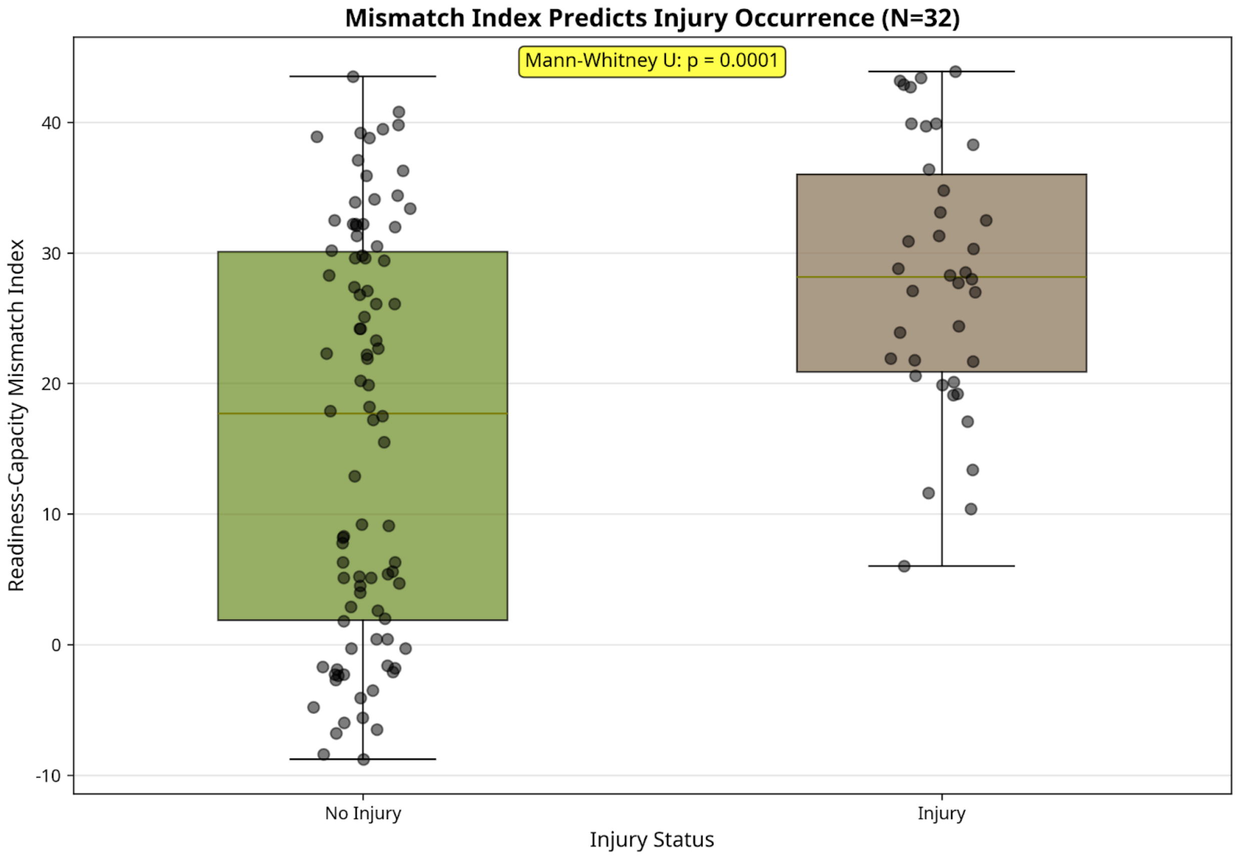

Figure 3: The Mismatch Index was significantly higher in athletes who sustained an injury, confirming its utility as a risk stratification tool.

Discordance in Clearance Protocols

Our analysis revealed a concerning discordance between traditional and biomechanical clearance criteria. Across all timepoints, 16.4% of athletes who were "cleared" based on standard physiological fitness tests failed to meet minimum biomechanical safety thresholds. The injury rate within this discordant group was 47.6%, substantially higher than the 31.2% injury rate in the group that was cleared by both physiological and biomechanical standards.

Finally, Figure 4 illustrates the underlying biomechanical changes. During the growth spurt, athletes in the Rapid growth group showed a transient decline in joint stability and load attenuation, and an increase in movement variability, precisely when their physiological power was increasing. This is the mechanistic signature of the readiness-capacity mismatch.

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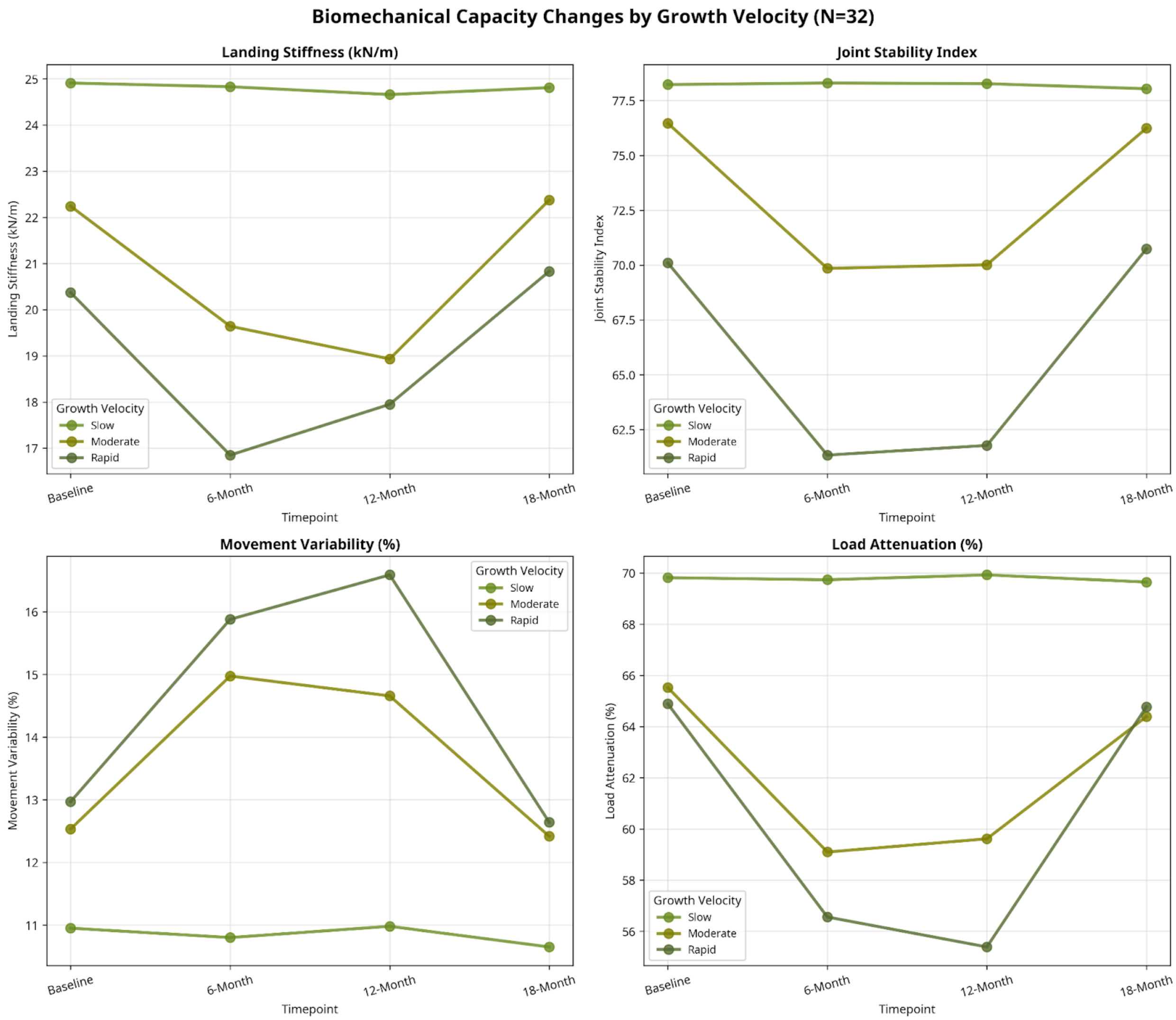

Figure 4: Athletes in the Rapid growth group exhibited a temporary decline in key biomechanical control metrics during the 6- and 12-month periods, coinciding with the peak of their growth spurt.

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Discussion

This 18-month longitudinal investigation provides evidence that injury risk in adolescent athletes may be more accurately understood through the interaction between physiological development and biomechanical control rather than through isolated performance metrics. By quantifying the divergence between physiological readiness and biomechanical capacity using the Readiness–Capacity Mismatch Index, this study demonstrates that periods of accelerated physical development are accompanied by measurable instability in neuromuscular control and impact management.

The most pronounced increase in the Mismatch Index occurred between the 6- and 12-month timepoints, which aligns temporally with expected windows of accelerated growth velocity in mid-adolescence. During this period, athletes demonstrated improvements in power and strength metrics, yet concurrent declines in landing stiffness regulation, joint stability indices, and load attenuation efficiency were observed. These findings support the concept that physiological output may progress more rapidly than structural and neuromotor control systems during maturation.

From a biomechanical perspective, this divergence likely reflects transient reductions in motor coordination, altered limb segment proportions, and evolving muscle–tendon stiffness characteristics associated with rapid growth. The result is an athlete capable of generating greater forces while simultaneously exhibiting reduced capacity to safely dissipate those forces. This mismatch creates elevated joint loading conditions and increased mechanical stress during high-impact tasks such as landing and deceleration.

Importantly, the Mismatch Index demonstrated strong discriminative capacity between injured and non-injured athletes. Athletes who sustained non-contact injuries exhibited significantly higher mismatch values compared to those who remained injury-free. This suggests that injury risk may not be driven solely by strength deficits or exposure volume, but rather by the imbalance between force production capability and force absorption/control capacity.

Another critical finding was the discordance between traditional physiology-based clearance models and biomechanical readiness. A substantial proportion of athletes who met conventional strength and power benchmarks did not demonstrate adequate biomechanical control thresholds. Injury incidence was notably higher within this discordant subgroup, indicating that physiological metrics alone may insufficiently reflect readiness for sport participation during developmental periods.

Collectively, these findings challenge the prevailing performance-centric paradigm in youth sports, where strength and power gains are often interpreted as markers of readiness for progression. Instead, the present data suggest that injury prevention strategies should emphasize synchronized development of neuromuscular control alongside physiological adaptation.

From a systems-adaptation perspective, this mismatch reflects asynchronous maturation of muscle-tendon stiffness, segmental inertia changes, and central motor control recalibration during peak height velocity. The temporary reduction in dynamic stability likely represents a neuromechanical reorganization phase rather than simple weakness, emphasizing that injury risk is governed by coordination timing and load distribution efficiency rather than isolated strength deficits.

Limitations

Several limitations should be acknowledged when interpreting these findings.

First, although the study was longitudinal in structure, it remains observational in nature. While strong associations between mismatch magnitude and injury occurrence were identified, causality cannot be definitively established. It is possible that unmeasured variables such as training load fluctuations, psychosocial stress, or sport-specific technique contributed to injury outcomes.

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Second, the sample size, while adequate for preliminary modeling, limits subgroup statistical power, particularly within growth velocity categories. Larger multi-center cohorts would strengthen generalizability and allow for more advanced predictive modeling approaches.

Third, maturation status was inferred using growth velocity rather than direct biological maturity indicators such as Tanner staging or hormonal profiling. Although growth velocity is a widely accepted proxy during adolescence, it may not fully capture individual variability in maturation timing.

Fourth, biomechanical assessment was performed in a controlled laboratory setting using a standardized drop-jump task. While this allows for high measurement reliability, it may not perfectly replicate the complex sport-specific loading environments encountered in competition.

Finally, injury surveillance focused exclusively on non-contact, time-loss injuries. While appropriate for biomechanical modeling, this approach does not account for overuse injuries without time-loss or contact-related trauma.

Future studies should incorporate larger cohorts, biological maturation markers, sport-specific movement tasks, and intervention arms targeting mismatch reduction to better understand causative pathways.

Conclusion

Adolescent athletic development is characterized by asynchronous maturation of physiological and biomechanical systems. The present study demonstrates that the divergence between these systems — quantified through the Readiness–Capacity Mismatch Index — is significantly associated with increased non-contact injury risk.

Periods of rapid growth appear to amplify this imbalance, producing athletes who are physiologically stronger yet biomechanically less equipped to manage external loads. This mismatch may represent a mechanistic explanation for the well-documented increase in injury incidence during adolescence.

Reliance on strength, power, or aerobic performance metrics alone as clearance criteria may therefore underestimate true injury susceptibility. Integrating objective biomechanical assessment into athlete monitoring frameworks may improve risk stratification and allow for targeted neuromuscular intervention during critical developmental windows.

An integrated readiness framework that simultaneously evaluates physiological output and biomechanical load management capacity should become standard practice in youth athlete monitoring systems to reduce preventable non-contact injuries during growth acceleration phases.

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