

Review Article

Multimodal Training-Load Monitoring in Youth Sport: A Scoping Review of Monitoring Metrics, Individualised Decision-Making, and Implications for Strength and Conditioning

Zhuoyang Li*

Wuhan Sports University, Wuhan 430000, China

*Correspondence: Zhuoyang Li, 15337132224@163.com

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Abstract

Training-load monitoring in youth sport should consider external workload, internal response, athlete state, and developmental context. This scoping review synthesised multimodal monitoring approaches and examined their use in individualised training decisions. PubMed/MEDLINE, Web of Science, and Scopus were searched, and 20 of 78 records met the eligibility criteria. Common measures included training duration, running exposure, sRPE, heart rate, neuromuscular performance, wellness, and sleep. Growth and biological maturity were considered important but were inconsistently integrated. Evidence was concentrated in soccer and male academy team sports, with limited representation of female athletes, individual sports, and resistance training. Monitoring was used mainly to describe workload, readiness, and within-athlete change, while evidence supporting specific training-adjustment protocols remained limited. Multimodal monitoring may inform coach-led decisions when interpreted against individual trends and developmental context. Prospective studies are needed to confirm its effects on training adaptation and athlete health.

Keywords

Training load, Youth athletes, Multimodal monitoring, Biological maturation, Strength and conditioning, Individualised decision-making

1. Introduction

Training load connects prescribed work with fatigue and adaptation. In youth programmes, its meaning changes with growth, maturation, school demands, and competition. Across 59 studies, monitoring had been used in multiple youth sports, but evidence linking load to physical qualities,

injury, or illness was limited or inconsistent (Dudley et al., 2023). A review of elite youth soccer likewise found that injury associations depended on the metric, calculation window, and injury definition (Verstappen et al., 2021). Monitoring is therefore better suited to interpreting individual responses than to stand-alone prediction.

External load describes completed work—duration, distance, high-speed running, accelerations, decelerations, jumps, throws, and resistance-training volume—whereas internal load reflects its physiological or perceptual cost, commonly through heart rate, training impulse, or sRPE. sRPE and heart rate are common youth measures (Dudley et al., 2023); their association is affected by scale, familiarisation, and sport context (Liu et al., 2023). The two domains answer distinct questions and are most informative when interpreted together.

Chronological age is a poor proxy for biological maturation. Changes around peak height velocity alter body size, coordination, strength, and tissue tolerance. Maturity therefore influences the interpretation of youth load, injury risk, and performance (Towlson et al., 2021). Maturity offset, percentage of predicted adult height, and skeletal age estimate different constructs and are not interchangeable (Sullivan et al., 2023). Maturity assessment needs to match the biological construct of interest.

Sensors, force platforms, and questionnaires can combine movement exposure, heart rate, sRPE, jump or isometric performance, self-reported wellness, and recovery context. More data are useful only when each measure has a defined purpose, individual reference range, and feasible action. Rebelo et al. (2026) defined monitoring as decision support and prioritised validity, reliability, feasibility, and decision relevance. The practical value of a measure depends on the decision it can change.

Evidence is concentrated in youth soccer and other team sports, leaving direct strength-and-conditioning applications comparatively sparse. Practitioners must still decide whether results justify modifying resistance-training volume, running exposure, exercise selection, mechanical loading, or recovery. This scoping review aimed to map the measures used for multimodal training-load monitoring in youth sport, examine how growth, maturation, and contextual factors were considered, and evaluate how monitoring information was linked to individualised training decisions. A secondary aim was to consider the implications of the available evidence for youth strength-and-conditioning practice. The concentration of evidence in a limited range of sports constrains generalisation.

2. Review Methods

2.1. Scoping review design and questions

This scoping review was conducted in accordance with JBI guidance and reported following the PRISMA extension for scoping reviews (PRISMA-ScR). The review questions were defined using the Population-Concept-Context framework: the population comprised systematically trained athletes

aged 10-19 years; the concept encompassed repeated multimodal monitoring and its relationship with data interpretation or training decisions; and the context was organised youth sport.

2.2. Literature scope and eligibility criteria

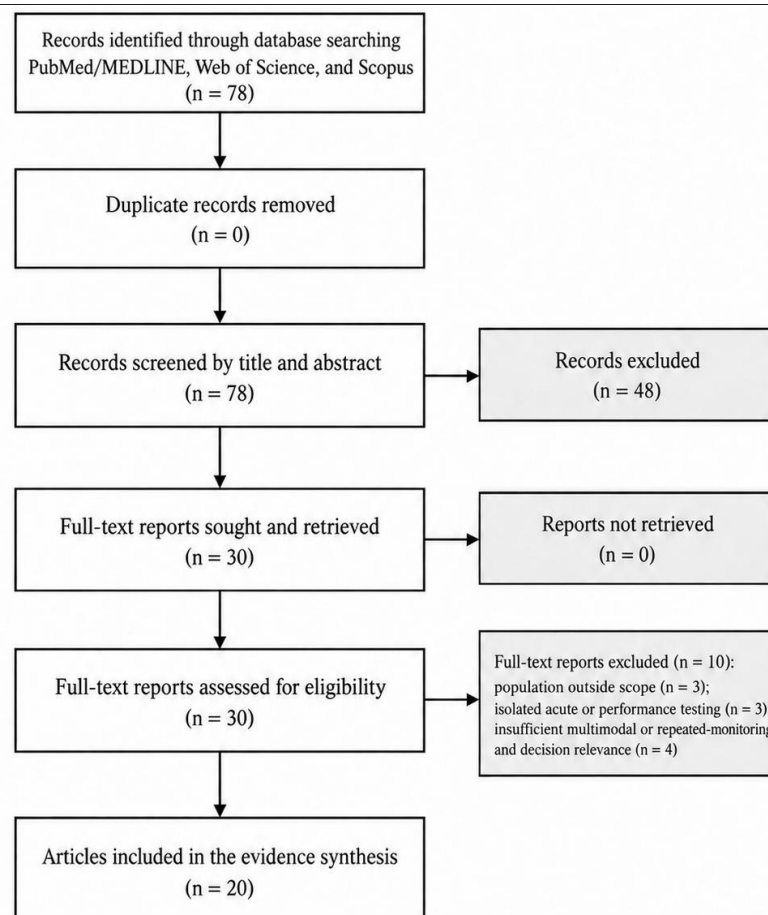
The literature search covered PubMed/MEDLINE, Web of Science, and Scopus for English-language peer-reviewed journal articles published from January 2020 to July 2026. Boolean operators were used to combine population terms (youth, adolescent and academy) with monitoring terms (“training load monitoring,” “training-load monitoring,” and “load monitoring”). The searches covered title, abstract, and keyword fields and were limited by publication period and language. Bibliographic details and DOIs were verified across the retrieved database records.

Eligible articles primarily involved athletes aged 10–19 years who participated in organised competitive programmes and received systematic training. Studies were required to address repeated monitoring of training load, readiness, recovery, growth, or maturation, or the relationship between monitoring information and training decisions. Mixed-age studies were included only when youth data could be extracted separately or the sample was explicitly identified as a youth or academy population. Multimodal monitoring was defined as the inclusion of training-dose measures together with at least one measure of individual response, athlete state, or developmental context. Cross-sectional studies that directly evaluated relevant monitoring tools or practice frameworks were also eligible.

Articles limited to isolated performance testing, a single acute exercise response, general physical activity, device engineering, or non-peer-reviewed material were excluded, as were studies without a direct link to repeated monitoring or training decisions. Before screening, records were checked using DOIs, database accession information, and normalised titles. Of the 78 potentially relevant records screened by title and abstract, 48 were excluded. Thirty full-text articles were assessed for eligibility, of which 10 were excluded: three involved populations outside the review scope, three were limited to isolated acute or performance testing, and four had insufficient relevance to multimodal or repeated monitoring and related decisions. Twenty articles met the predefined eligibility criteria and were included in the evidence synthesis. The selection process is shown in Figure 1.

Figure 1

PRISMA-ScR flow of record identification, screening, eligibility assessment, and inclusion



2.3. Evidence charting and synthesis

Data extracted included source type, sport and study setting, sample characteristics, monitoring period, principal monitoring measures, growth and maturation factors, study outcomes, and links with training decisions. Included articles were grouped into four domains: training dose, individual response, athlete state, and developmental context, and were synthesised narratively. Study design, sample characteristics, measurement properties, and generalisability were considered when interpreting the evidence context and its practical applicability. When reviews overlapped with included primary studies, review findings were used only as contextual evidence and were not counted again.

2.4. Levels of training-load information: from single measures to multimodal integration

Training-load monitoring information can be organised into three levels. At the first level, single-domain measures describe either completed work or its internal cost. External variables include duration, distance, high-speed running, lifted mass, and repetitions, whereas internal measures include heart rate, training impulse, and sRPE. GPS/GNSS interpretation requires consistent variable definitions, thresholds, sampling, and devices (Havanecz et al., 2026). sRPE and heart rate are widely

used in youth sport, but their relationship varies with the scale and sporting context (Dudley et al., 2023; Liu et al., 2023). Single-domain measures answer specific questions, while integrated measures clarify how exposure, response, and readiness interact.

At the second level, load measures are paired with indicators of athlete state. Jump performance, isometric force, movement velocity, fatigue, soreness, stress, mood, and sleep are used to examine whether readiness changes around training. A longitudinal study of youth long-jump athletes showed that neuromuscular readiness and perceptual fatigue can follow different patterns (Franceschi et al., 2020), while sleep-related information added context for interpreting pre-session state (Suppiah et al., 2022). These pairings extend load description, and their interpretation is strengthened by incorporating growth, maturity, and non-sport demands.

At the third level, cross-domain integration combines measures that answer different questions. Lechner et al. (2023) collected running, heart rate, heart-rate variability, RPE, and muscle-status data in youth soccer; the measures were related but not equivalent. Palmer et al. (2023) likewise found partly distinct patterns in load, neuromuscular state, and perceived recovery in youth basketball. Multimodal monitoring combines training dose with at least one measure of response or state and requires interpretation within developmental context. Multimodal monitoring therefore integrates measures from distinct functional domains and assigns each measure a specific interpretive role.

A focused set of measures should be selected according to the decision of interest, reliability, feasibility, and relevance to action. Rebelo et al. (2026) prioritised a small decision-specific set interpreted against within-athlete observations. In youth programmes, these observations also need to account for growth, training age, injury history, and relevant non-sport demands.

2.5. A proposed multidimensional framework for monitoring training load in youth sport

The analytical framework comprises four dimensions: training dose, individual response, athlete state, and developmental context. Measures are grouped by timing and primary interpretive function, allowing variables collected by the same device to serve distinct analytical purposes. Heart rate recorded during a session estimates internal response, whereas resting heart rate collected before training may contribute to an assessment of athlete state.

Rebelo et al. (2026) organised athlete monitoring around training load, athlete state, and training response. For youth sport, this framework distinguishes planned and completed training dose, individual response, and pre-session athlete state, while treating growth, maturation, and developmental context as continuous moderators of interpretation.

Training dose describes what the athlete completed. Relevant strength-and-conditioning measures include sets, repetitions, relative intensity, volume load, and movement velocity in resistance training,

together with duration, distance, high-speed running, sprinting, accelerations, decelerations, jumps, and throws in field or court conditioning. These measures connect prescription with delivery. Findings on load and injury in youth sport show that an external-load value can carry different implications across sports and calculation windows (Verstappen et al., 2021; Sniffen et al., 2022). Its interpretation depends on both sport and calculation window.

Individual response represents the immediate cost of the completed training load. Heart rate, training impulse, sRPE, and differentiated RPE are typical measures. Comparing them with external load can reveal a departure from the athlete's usual dose-response relationship. A familiar workload accompanied by an unusually high sRPE, for example, warrants checking recovery, health, environmental conditions, and non-sport stress. A departure supported by the recent trend or corroborating information may warrant training adjustment (Rebelo et al., 2026). Training adjustment is therefore based on repeated trends, corroborating information, and contextual review.

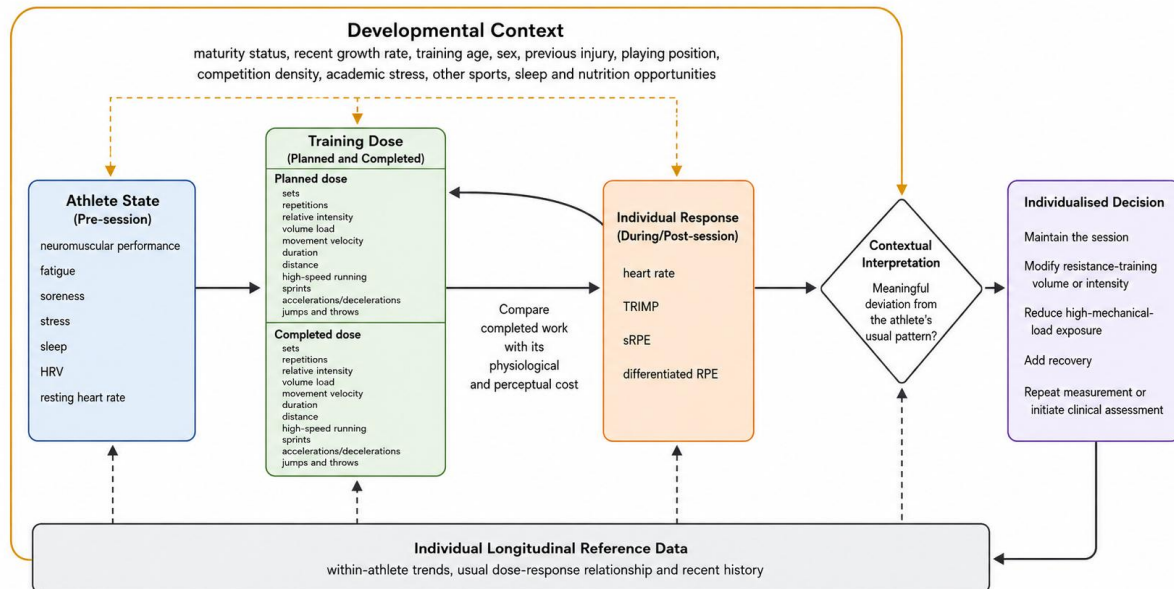
Athlete state concerns readiness for the planned session. Neuromuscular performance, perceived fatigue, soreness, stress, prior-night sleep, heart-rate variability, and resting heart rate may contribute to this assessment. Objective performance and subjective wellness do not always change in parallel in youth basketball (Palmer et al., 2023). A discrepancy between domains is a reason to discuss, repeat, or contextualise the measurement before changing the session; agreement across several measures provides stronger grounds for a proportionate adjustment.

Developmental context modifies the interpretation of dose, response, and state. It includes maturity status, recent growth rate, training age, sex, previous injury, playing position, competition density, academic stress, participation in other sports, and habitual opportunities for sleep and nutrition. Chronological age alone does not represent tissue tolerance or the development of physical capacity (Towlson et al., 2021; Sullivan et al., 2023). A survey of UK soccer academies found broad recognition of maturation in load management but substantial variation in assessment and adjustment procedures (Salter et al., 2021). Within the framework, developmental context functions as a continuous moderator of training dose, individual response, and athlete state.

As shown in Figure 2, the four dimensions form a proposed conceptual decision framework. Pre-session state informs interpretation of the planned dose; the completed dose is compared with the resulting internal response; and developmental context moderates both comparisons. Current observations are then evaluated against the athlete's longitudinal reference data. The decision may be to maintain the session, reduce high-mechanical-load exposure, modify resistance-training volume or intensity, add recovery, repeat a measurement, or initiate clinical assessment. Jayanthi et al. (2022) similarly proposed that load progression in specialised youth athletes varies with maturity, training experience, movement capacity, and injury susceptibility. The framework provides a structure for sport-specific, maturity-sensitive, and monitoring-system-specific interpretation.

Figure 2

Proposed conceptual framework developed by the authors from the evidence map for multimodal monitoring and individualised decision-making in youth sport



3. Results: Evidence Mapping of Multimodal Training-Load Monitoring in Youth Sport

3.1. Study characteristics and evidence distribution

The evidence map comprised 20 articles: 10 primary empirical reports and 10 reviews, evidence syntheses, or conceptual sources. The primary reports consisted of eight athlete studies, one academy-practice survey, and one Delphi study. Nine articles concerned soccer, two basketball, eight mixed, general, or team-sport settings, and one long jump. All eight primary athlete studies were observational. Three athlete studies recruited male-only samples, two included both sexes, and three did not clearly report sex; none recruited an exclusively female sample. Two athlete studies directly assessed biological maturity. For multi-study reviews and conceptual sources, Table 1 reports the evidence base rather than a single participant sample.

Table 1

Characteristics, monitoring domains, and decision relevance of the 20 included articles

Source	Setting and design	Sample and monitoring period	Monitoring domains and context	Main outcome and decision relevance
Dudley et al. 2023	Multiple countries; mixed sports; Systematic review and best-	59 studies; competitive athletes aged 10-19; mixed sports	sRPE, duration, resistance volume, distance and other load measures; Maturation	Physical qualities, injury and illness; Evidence synthesis

	evidence synthesis	and sexes; Search to Mar 2022	considered as a moderator	
Verstappen et al. 2021	Multiple countries; soccer; Systematic review and best-evidence synthesis	5 prospective studies; male elite youth soccer, 12-21 y; Load windows of 1-4 weeks	Internal and external cumulative load; Male academy soccer context	Injury associations; Group-level synthesis
Liu et al. 2023	Multiple countries; mixed sports; Meta-analysis	16 studies; adolescent athletes; mixed sports; Search to 2022	sRPE compared with heart-rate measures; Age and sport context	Criterion-related validity
Towilson et al. 2021	Multiple countries; soccer; Narrative review	Youth soccer; no pooled participant sample	Training load, performance and injury; PHV, predicted adult height and skeletal maturation	Maturity-sensitive interpretation; Practice guidance
Sullivan et al. 2023	Multiple countries; soccer; Narrative systematic review	15 studies; 4,707 male academy soccer players, 8-18 y; Cross-sectional and longitudinal studies	Maturity-assessment methods; Adult-height, PHV and skeletal-age methods	Agreement and reliability of methods; Method-selection guidance
Rebelo et al. 2026	Multiple countries; general sport; Narrative review and conceptual framework	Athletes generally; not youth-specific; Repeated monitoring framework	Training load, response, state, readiness and sleep; Contextual stressors	General monitoring framework; Athlete-specific thresholds proposed
Havanecz et al. 2026	Multiple countries; soccer; Narrative review	34 studies; male youth soccer; Studies published 2012-2025	GPS distance, speed, acceleration and deceleration; Position, training format and season phase	Variable definitions and comparability
Franceschi et al. 2020	Italy; long jump; Longitudinal case study	2 elite U18 long jumpers; 1 female and 1 male; 16.0-16.5 y; 16 weeks	Training time, sprint, jump and weights volume; jump tests; wellness; No direct maturity measure	Individual readiness and fatigue trends; Individual-level analysis
Suppiah et al. 2022	Singapore; mixed sports; Cross-sectional prediction study	115 elite youth athletes; age and sex not clearly reported; Single questionnaire assessment	Training exposure, sleep and hygiene questionnaire variables; Sleep environment and behaviour	Sleep-quality prediction; Individual classification tool
Lechner et al. 2023	Germany; soccer; Observational longitudinal study	9 male U17 academy soccer players; 16 y; 6	GPS, heart rate, HRV, RPE and muscle status; School and youth	Load-response associations; individual response

		weeks	academy context	patterns
Palmer et al. 2023	Australia; basketball; Exploratory longitudinal study	14 youth basketball players; 5 male and 9 female; 15.1 +/- 1.0 y; 10 weeks	HR, IMU, wellness, activity, CMJ and IMTP; Youth basketball setting	Accumulated-load and readiness trends; Repeated athlete data; coaching intent reported
Sniffen et al. 2022	Multiple countries; team sports; Systematic review	11 studies; youth team-sport athletes younger than 18 y; Search covered 2010-Apr 2021	Cumulative internal and external load; Youth team-sport context	Load-injury associations; Evidence synthesis
Salter et al. 2021	United Kingdom; soccer; Cross-sectional academy survey	49 staff respondents; 38 male academies and 11 female talent clubs; Single online survey	Training-load and maturity-monitoring practices; Maturity methods and academy resources	Current practice variation; Reported practice
Jayanthi et al. 2022	Multiple countries; mixed sports; Clinical review and developmental model	Sport-specialised youth athletes; no pooled participant sample	Workload progression and capacity; Maturity, specialisation, injury history and movement capacity	Developmental training model; Conceptual decision pathway
Evans et al. 2022	United Kingdom; soccer; Repeated observational study	16 elite youth soccer players; 18 +/- 1 y; sex not clearly reported; Competitive season; 36 fixtures	GPS/accelerometry, CMJ and wellness; Competitive schedule	Postmatch fatigue and subsequent match output; Repeated group analysis
Mason et al. 2025	Ireland; team sports; Cross-sectional questionnaire study	51 elite adolescent team-sport athletes; 15.67 +/- 1.61 y; sex not clearly reported; Single questionnaire battery	Sleep, recovery and nutrition questionnaires; Sport and recovery behaviours	Recovery characteristics and associations
Salter et al. 2024	United Kingdom; soccer; Longitudinal observational study	55 male academy soccer players; 14.5 +/- 1.2 y; Competitive season	Differential RPE, CMJ, RSI and leg stiffness; Percentage of predicted adult height	Maturity-related load and neuromuscular response; Repeated group analysis; prescription implications suggested
Arede et al. 2022	Portugal; basketball; Training-camp observational	29 male U16 national basketball players; 16.0 +/- 0.4 y; 2-week	sRPE-derived load, monotony and strain; APHV, maturity offset and maturity timing	Training load and later selection; Group analysis

	study	monitoring within a 5-week camp		
Parry et al. 2024	Multiple countries; mixed sports; Scoping review	30 studies; elite youth pathways; mixed sports and sexes; Studies published since 2000	Growth, maturation and injury evidence; Growth rate and maturity status/timing	Injury incidence and burden; Evidence map
Sullivan et al. 2024	United Kingdom; soccer; Three- round Delphi study	9 youth-soccer academy practitioners; Three Delphi rounds	Maturity-data collection and prevention practices; Percentage predicted adult height and growth period	Expert consensus; Consensus guidance

3.2. Classification and applied use of monitoring indicators

The included evidence was concentrated in academy team sports: nine of the 20 articles concerned soccer and two concerned basketball. The remaining articles addressed long jump, mixed-sport samples, general youth sport, or team-sport settings. All eight primary athlete studies were observational and mainly covered competitive seasons, training camps, or preparatory periods. None recruited an exclusively female sample. Resistance-training variables were discussed as relevant to practice but were seldom examined as the central exposure. Multimodal data collection was more common than direct evaluation of monitoring-guided decisions.

Training-dose indicators described the work completed. Dudley et al. (2023) and Havanecz et al. (2026) identified duration, total and high-speed running distance, sprinting, accelerations, decelerations, and inertial-sensor outputs as commonly used measures in youth team sports. Lechner et al. (2023) and Palmer et al. (2023) further illustrated how external-load and physiological measures can be combined to characterise completed training exposure. Sets, repetitions, relative intensity, volume load, and movement velocity were identified as relevant to strength and conditioning, but they were seldom the central exposure variables in the included youth studies. The available evidence therefore applies more directly to field- and court-based conditioning than to the regulation of resistance-training dose.

Internal-response indicators were dominated by sRPE, differential RPE, heart rate, and heart-rate-derived training load. These measures estimated the cost of a completed session and were interpreted separately from the external work. Liu et al. (2023) supported the criterion-related validity of sRPE in adolescent athletes while showing that scale and sporting context affect interpretation. Lechner et al. (2023) found associations between external and internal variables during youth soccer preparation, but those associations varied by metric. The two domains were related but not interchangeable.

Athlete-state monitoring included countermovement-jump performance, isometric force, perceived fatigue, soreness, stress, energy, mood, and sleep. Longitudinal studies in youth long jump

and basketball showed that neuromuscular and perceptual measures could follow different time courses (Franceschi et al., 2020; Palmer et al., 2023). Evans et al. (2022) also reported distinct seasonal response patterns for self-reported wellness and countermovement-jump measures. Sleep and nutrition studies extended interpretation from immediate fatigue to the conditions under which recovery occurred (Suppiah et al., 2022; Mason et al., 2025). These measures therefore retained distinct temporal and functional information.

Across the primary studies, measures were mainly used to characterise exposure, compare periods or groups, and examine associations between workload and response. Formal individual reference ranges and prespecified action thresholds were uncommon. Device definitions and processing also varied, particularly for positioning-derived measures (Havanecz et al., 2026). The literature therefore focused more on multimodal data collection than on its use in subsequent training decisions.

3.3. Consideration of growth, maturation, and contextual factors in the included studies

Growth and maturation were prominent in reviews and developmental models but were handled inconsistently in primary monitoring studies. Some articles reported only chronological age, whereas others estimated maturity offset, percentage of predicted adult height, or maturity timing. These methods represent different biological constructs and carry different errors (Sullivan et al., 2023). Repeated measurement of growth rate across a season was uncommon, even though a single estimate may become outdated during rapid development.

The primary studies that assessed maturation illustrated its interpretive role. Salter et al. (2024) reported maturity-related differences in perceived training load and neuromuscular performance during an academy soccer season. In national youth basketball, maturity timing was associated with the training-load profile during an intensive camp (Arede et al., 2022). Reviews of youth pathways also indicated that injury patterns varied with growth and maturity stage, although the direction and magnitude depended on sport, injury type, and assessment method (Towlson et al., 2021; Parry et al., 2024). These findings highlight biological maturity as an important contextual factor when interpreting training load and neuromuscular responses in youth athletes.

Contextual monitoring was narrower. Sleep quantity and quality, perceived recovery, soreness, stress, and nutrition were represented (Suppiah et al., 2022; Mason et al., 2025), but school workload, examination periods, travel, participation in other sports, and family constraints were rarely integrated with session-level data. Sex-specific interpretation was also limited: three primary athlete studies were male-only, two included both sexes, and three did not report sex clearly; none recruited an exclusively female sample. Where maturity was considered, reporting methods and timing varied, limiting cross-

study comparison.

3.4. Use of monitoring data to inform individualised training decisions

Individualised decision-making requires repeated information to be interpreted against an athlete's usual response and connected to a possible change in training or recovery. Most primary studies used group summaries and associations, even when data had been collected at the individual level. Repeated measures were common, but formal individual reference ranges and prespecified action thresholds were rare.

Several studies provided evidence relevant to individualised interpretation. Franceschi et al. (2020) used longitudinal training, jump, and fatigue profiles to examine within-athlete change in elite youth long jumpers. Palmer et al. (2023) showed that daily load, wellness, and periodic neuromuscular tests supplied non-redundant information in youth basketball. In youth soccer, pre-match wellness and countermovement-jump results served different interpretive functions (Evans et al., 2022). Suppiah et al. (2022) translated predictors of sleep quality into a tool intended to support practitioner decisions. Together, these studies show how longitudinal load, wellness, sleep, and neuromuscular measures can provide complementary information for individualised interpretation.

Reviews, conceptual frameworks, and practitioner studies described how monitoring information may inform training decisions. Jayanthi et al. (2022) recommended adjusting progression for maturity, training history, movement capacity, and injury susceptibility. Salter et al. (2021) and Sullivan et al. (2024) reported variation in how academy practitioners assess these factors and translate them into practice. Overall, the available evidence positions structured monitoring as support for coaching and clinical judgement, with decisions informed by individual trends and training context.

4. Discussion

4.1. Integrating multimodal indicators for individualised training decision-making

Across the evidence map, training dose, internal response, athlete state, and developmental context provided complementary information. Maturation and recovery conditions altered the meaning of a workload, yet they were not consistently incorporated into longitudinal monitoring. The framework distinguishes completed training dose, individual response, and pre-session athlete state while treating developmental context as a continuing moderator in youth sport, consistent with the general athlete-monitoring framework described by Rebelo et al. (2026). A central practical question is how multiple measurements should be combined to inform and evaluate an individual training decision.

Integration begins with the planned training dose. The completed dose establishes what occurred;

internal load indicates its cost; state measures show whether readiness changed; and developmental context explains why the same dose may carry different implications across athletes. These layers are interpreted against a stable within-athlete reference that reflects differences in maturity, training age, and exposure history (Jayanthi et al., 2022). The relevant comparison is each athlete's recent pattern under broadly comparable conditions. Periods of rapid growth can alter body size, coordination, and tissue loading within a season (Towlson et al., 2021; Parry et al., 2024). This makes repeated observation particularly important during accelerated development.

Interpretation can begin by comparing planned with completed exposure and the internal response with the athlete's usual response to similar work (Franceschi et al., 2020; Palmer et al., 2023). Evans et al. (2022) further showed that wellness and neuromuscular state provide complementary information for this assessment. High external load accompanied by an expected internal response and stable state generally supports continuation of the plan. A familiar external dose accompanied by unusually high exertion, impaired wellness, and reduced neuromuscular performance provides stronger grounds for a temporary reduction in volume or mechanical demand. Depending on the training aim, this may involve reducing high-speed running or plyometric contacts, changing exercise selection, or retaining intensity while reducing resistance-training volume. If the indicators conflict, the appropriate response may be to repeat the test, check data quality, and speak with the athlete before changing the programme.

A composite score should not be interpreted as a direct physiological measure (Rebelo et al., 2026). Summing variables with different units can conceal the reason for a change and may give unreliable measures the same weight as more responsive measures. Lechner et al. (2023) reported that cardiovascular and inertial outputs did not move in parallel in youth soccer. Palmer et al. (2023) and Evans et al. (2022) found that perceptual and neuromuscular measures followed different patterns in youth basketball and soccer. Disagreement between domains can be useful when it prompts a more specific question rather than an automatic adjustment.

Decisions also need to reflect measurement uncertainty. Short-term fluctuations are expected, and neither a high workload nor a low readiness score proves impending injury. Associations between cumulative load and injury in youth sport remained inconsistent (Verstappen et al., 2021; Sniffen et al., 2022). Monitoring may identify atypical patterns for further assessment, while causal interpretation continues to require technical observation, athlete communication, and clinical assessment.

4.2. Implications for youth strength and conditioning practice and future research

For youth strength-and-conditioning practice, the evidence supports a cautious core monitoring system that does not depend on expensive technology. Session duration and sRPE can estimate completed dose and perceived response; a brief wellness check can cover fatigue, soreness, stress, and

prior-night sleep; and serial stature or maturity assessment can inform developmental interpretation. Direct evidence for monitoring resistance-training dose remained limited. New measures are justified only when they are sufficiently reliable, interpretable, and linked to a decision (Rebelo et al., 2026). Collection time should be kept short, and missing entries should be reviewed rather than silently imputed.

Programmes with greater resources can add heart rate, positioning or inertial sensors, and a short neuromuscular test such as a countermovement jump or isometric mid-thigh pull. Technology is matched to the demands of the session. Positioning data may be useful for running exposure, whereas sets, repetitions, relative intensity, and movement velocity are more relevant to resistance training. Consensus on positioning variables and processing remains incomplete (Havanecz et al., 2026), and maturity-assessment methods are not interchangeable (Sullivan et al., 2023). Within-programme consistency is more defensible than comparing unstandardised values with external thresholds.

The evidence base needs prospective studies that test decisions rather than measurements alone. Priority populations include female athletes, individual-sport participants, and youth resistance-training settings, all of which were sparsely represented in the included articles. Future studies should repeat growth and maturity assessments, report device and variable definitions, prespecify action rules, and compare monitoring-guided practice with usual coaching. Outcomes should include adaptation, availability, health, adherence, and implementation burden.

Future monitoring models should explicitly account for missing data, school stress, illness, travel, and measurement error rather than absorb these factors into a single readiness score. Consensus work and academy surveys agree that maturation matters, but show variation in how information is obtained and used (Salter et al., 2021; Sullivan et al., 2024). Shared reporting standards and transparent decision rules would make studies easier to compare and allow practitioners to judge whether a proposed system is feasible in their setting.

4.3. Limitations of the evidence map

The evidence map was restricted to English-language journal articles published from January 2020 to July 2026 and retrieved through PubMed/MEDLINE, Web of Science, and Scopus. Direct comparison was constrained by heterogeneous source types, participant samples, monitoring definitions, device processing, and outcomes. The evidence remained dominated by soccer and male academy settings, with no female-only primary athlete study and limited individual-sport and resistance-training research.

5. Conclusion

Multimodal monitoring in youth sport is most informative when it separates four questions: what

work was completed, how demanding it was for the athlete, whether the athlete's current state changed, and which developmental or contextual factors modify that interpretation. Across the 20 included articles, the literature identified candidate measures for each question and showed how they can contribute distinct information to interpretation. Growth and maturation are therefore best treated as recurring interpretive information throughout monitoring.

Evidence from predominantly male academy team sports supports using a small set of measures to inform coach-led decisions. Decisions to maintain or modify training, or to refer an athlete for further assessment, should consider within-athlete trends, agreement across monitoring domains, data quality, and communication. This monitoring approach provides a practical basis for individualised training and strength-and-conditioning practice in youth sport.

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Author contributions

Zhuoyang Li individually undertook all roles including conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, original draft writing, review & editing, visualization, supervision and project administration for this study, and has read and agreed to the published version of the manuscript.

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Conflict of interest

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Consent to participate

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Consent for publication

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