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Review Article

Functional Asymmetries in Youth Soccer Players: A Systematic Review of Assessment Technologies and Artificial Intelligence Applications

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Abstract

Background. Functional asymmetries in youth soccer players represent an important biomechanical and neuromuscular phenomenon, acting both as adaptive mechanisms and as potential risk factors for injury. However, existing evidence remains fragmented regarding the effectiveness of technological and artificial intelligence (AI)–based approaches for their assessment across different populations.

Purpose. This systematic review aimed to synthesize current methodologies and applications of technological tools and artificial intelligence used to assess functional asymmetries in youth soccer players.

Methods. The review was conducted in accordance with PRISMA guidelines. A total of 418 records were identified through searches in Scopus, Web of Science, and PubMed, of which 28 studies met the inclusion criteria. Methodological quality was evaluated using standardized assessment tools. The included studies examined wearable technologies, biomechanical assessment systems, and AI-based analytical models for asymmetry detection and interpretation.

Results. AI-based models demonstrated moderate predictive accuracy for injury risk, with reported values up to AUC = 0.70. Wearable inertial measurement units showed high ecological validity for on-field assessment of functional asymmetries. However, substantial heterogeneity was observed across studies in terms of asymmetry thresholds, outcome definitions, and analytical procedures, limiting cross-study comparability. A key finding was that strength asymmetries exceeding 15% were significantly associated with increased injury risk ($p < 0.05$), while such asymmetries did not consistently impair sprint performance, indicating context-dependent functional effects.

Conclusions. The findings indicate that technological and AI-based approaches provide valuable tools for assessing functional asymmetries in youth soccer players, particularly when applied in ecologically valid settings. The integration of explainable AI with multimodal biomechanical data appears to be a promising direction for personalized monitoring and intervention strategies. Future research should prioritize standardized methodological reporting, harmonized asymmetry thresholds, and longitudinal study designs to improve comparability and clinical translatability of findings.
Keywords: functional asymmetry, youth soccer, artificial intelligence, injury prediction, wearable sensors.

Introduction

During adolescence, corticospinal plasticity and neuromuscular differentiation create asymmetrical recruitment patterns that consolidate through repeated motor experiences, influencing both torque capacity and proprioceptive recalibration (Ballmann et al., 2021). Contemporary evidence highlights tendon stiffness modulation, fascicle reorganization, and stretch-shortening cycle efficiency as primary mediators of laterality, with divergent energy system contributions modulating metabolic flexibility between limbs (Falces-Prieto et al., 2021). Such divergences interact with proprioceptive weighting strategies, producing interlimb variability during high-intensity actions such as cutting or striking. This complex interplay between structural, neurological, and metabolic factors underscores why asymmetries manifest differently across individuals and contexts. Recent theoretical frameworks describe asymmetry not merely as a deficit but as an adaptive manifestation of ecological dynamics, reflecting functional solutions to sport-specific constraints (Sullivan et al., 2021). This paradigm shift from a purely deficit-based to an adaptation-focused perspective necessitates more nuanced assessment and interpretation strategies. Nonetheless, prospective cohort evidence confirms that magnitudes surpassing 10–15% correlate with elevated musculoskeletal injury risk, emphasizing their dual status as adaptive markers and pathological indicators (Edouard et al., 2024). From a developmental perspective, the timing of peak height velocity strongly conditions asymmetry trajectories, underscoring the necessity for maturation-sensitive interpretation (Solleveld et al., 2022). The adolescent growth spurt represents a critical window where asymmetries may either consolidate or resolve, depending on training load and intervention strategies. Empirical data from multiple geographies reinforce the global relevance of asymmetry, with consistent associations identified across European, South American, and Middle Eastern academies (Moreno-Villanueva et al., 2025). This ecological validity expands the conceptualization of asymmetries beyond Eurocentric contexts, confirming their role as universal markers of adolescent adaptation. However, cultural differences in training methodologies, playing surfaces, and competition structures may influence how asymmetries develop and manifest across different populations. Advances in monitoring technologies now enable their precise quantification across morphological, neuromuscular, and kinematic domains, thereby consolidating asymmetry as a multidimensional construct within contemporary sports science (Jiang et al., 2023). This theoretical anchor legitimizes asymmetry profiling as an indispensable element for understanding developmental motor control, performance optimization, and injury mitigation in youth soccer (Ben Rakaa, Lourenço, et al., 2025). Despite this recognition, significant methodological challenges persist in standardizing assessment protocols and establishing universally applicable thresholds.

The methodological landscape of asymmetry research demonstrates substantial heterogeneity, constraining interpretability and translational impact (França et al., 2023). Isokinetic dynamometry remains the reference standard for torque quantification, but ecological limitations, resource intensity, and scheduling barriers restrict large-scale youth application (Vargas et al., 2020). Comparisons of bilateral versus unilateral countermovement jump assessments reveal divergent reliability properties, with bilateral tasks offering stronger longitudinal stability, although interpretive thresholds remain inconsistent (Fain et al., 2021). Functional tests, such as the Y-Balance, exhibit variable predictive accuracy, particularly in non-Western youth cohorts, highlighting cultural and developmental moderators of screening validity (Johnson et al., 2023). These inconsistencies in test selection, administration, and interpretation undermine the development of evidence-based guidelines for practitioners. Recent advances in wearable inertial measurement units allow for session-embedded asymmetry monitoring during change-of-direction or soccer-specific drills, enhancing ecological validity (Jiang et al., 2023). However, device calibration, placement variability, and task standardization challenge reliability, demanding rigorous validation protocols (Kadlec et al., 2023). Analytical heterogeneity further complicates prevalence estimates, as divergent formulas for limb symmetry indices produce substantial discrepancies in individual classification (Ascenzi et al., 2022). Without consensus on calculation methods and reporting standards, cross-study comparisons remain problematic and meta-analytical approaches limited. Artificial intelligence applications mark a methodological frontier, offering nonlinear modeling of high-dimensional datasets to predict injury susceptibility (Oliver et al., 2020). Exploratory studies report moderate predictive accuracy, but calibration instability, sparse datasets, and overfitting risks limit generalizability (Čular et al., 2023). The integration of domain knowledge with data-driven approaches appears essential for developing clinically useful AI tools. Cross-cultural investigations from South America and North Africa stress the importance of contextualized approaches when applying machine learning models to youth sport (Čular et al., 2023). The relevance of this domain extends to athlete development, where valid, reliable, and scalable methodologies are essential for personalized training, targeted injury prevention, and longitudinal monitoring (Din et al., 2025). Integration of multimodal technologies with explainable AI offers an unprecedented opportunity to reconcile precision with ecological applicability, ensuring translational value for practitioners and safeguarding developmental health (Brouki et al., 2025). This systematic review therefore aims to critically evaluate the convergence of traditional assessment methods with emerging AI technologies in youth soccer asymmetry research.

Empirical evidence from recent observational and interventional studies underscores the prevalence of asymmetries across morphological, neuromuscular, and functional domains in youth soccer (Fain et al., 2021). Interlimb discrepancies in strength and jump metrics often exceed injury-risk thresholds, yet associations with sprint and agility outcomes remain inconsistent, reflecting compensatory neuromuscular strategies (Fain et al., 2021). This performance-asymmetry paradox suggests that athletes may develop effective compensation mechanisms that mask underlying imbalances during specific tasks.Longitudinal data confirm mid-adolescence as a sensitive period where hamstring asymmetries peak, reinforcing the need for maturation-adjusted protocols (Moreno-Villanueva et al., 2025). This proximal-distal interdependence highlights the importance of assessing asymmetries beyond the lower limbs alone. Proximal asymmetries in trunk control additionally propagate distal discrepancies, underscoring integrated conditioning approaches (Moreno-Villanueva et al., 2025). Meta-analyses reveal that targeted unilateral or bilateral training interventions reduce asymmetry magnitudes with small-to-moderate effect sizes, validating progressive overload strategies in academy settings (Bettariga et al., 2022). However, morphological asymmetries derived from imaging technologies exhibit limited predictive power for injury outcomes, cautioning against structural metrics as standalone indicators (Vaillancourt et al., 2024).The dissociation between structural and functional asymmetries necessitates multimodal assessment approaches that capture both anatomical and neuromuscular dimensions. Ecological replications from Turkey, Brazil, and North Africa corroborate the injury–asymmetry nexus, substantiating global applicability across developmental environments (Edouard et al., 2024; Moreno-Villanueva et al., 2025). Despite promising findings, evidence synthesis reveals enduring methodological limitations: small sample sizes, cross-sectional dominance, and inconsistent asymmetry reporting preclude robust causal inferences (França et al., 2023). Moreover, AI-driven injury prediction models remain underdeveloped, characterized by fragile calibration and limited external validation (Xia et al., 2021). These methodological shortcomings collectively constrain the evidence base and hinder the development of clinically actionable insights.These shortcomings underscore the urgency of establishing harmonized thresholds, multi-academic longitudinal datasets, and tailored, inclusive machine learning frameworks (Ben Rakaa, Bassiri, et al., 2025b, 2025a; Ben Rakaa, Lourenço, et al., 2025). The present systematic review directly addresses these challenges by critically synthesizing studies on functional asymmetries in youth soccer between 2015 and 2025, with particular focus on three key domains: assessment technologies, AI applications, and practical implementation frameworks. The present systematic review directly addresses these challenges by critically synthesizing studies on functional asymmetries in youth soccer between 2015 and 2025. By integrating technological innovations with AI-based analytics, the objective is to advance methodological precision, contextual relevance, and applied utility1, thereby supporting evidence-informed interventions in athlete development and injury prevention (Bouzid et al., 2025). Specifically, this review aims to: (1) evaluate the methodological quality of current assessment approaches; (2) synthesize evidence on AI/ML applications for asymmetry analysis and injury prediction; and (3) propose standardized frameworks for asymmetry monitoring and intervention in youth soccer academies.

Methods

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review protocol was registered on the PROSPERO platform prior to the initiation of the selection process (registration number: CRD420241125443).

Working Definitions

To ensure conceptual clarity and methodological consistency throughout this systematic review, the following operational definitions were adopted:

Functional Asymmetry

Functional asymmetry refers to any measurable difference between homologous limbs in strength, power, kinematic, or neuromuscular performance during sport-specific or standardized tasks. In this review, asymmetry is considered functional when it arises from training-induced adaptations, maturation effects, or biomechanical constraints, rather than from structural pathology or injury.

Inter-limb and Intra-limb Asymmetry

Inter-limb asymmetry denotes discrepancies between the dominant and non-dominant limbs in quantitative parameters such as torque, force, or jump height. Intra-limb asymmetry reflects imbalance between agonist and antagonist muscle groups within the same limb (e.g., hamstring-to-quadriceps ratio).

Dominant and Non-dominant Limb

The dominant limb was defined as the limb preferentially used for ball manipulation or kicking tasks, while the non-dominant limb refers to the supporting or stabilizing limb. In studies where self-reported dominance was not provided, functional dominance was inferred from the primary limb used during kicking or performance tasks.

Limb Symmetry Index (LSI)

Limb asymmetry was most frequently quantified using the Limb Symmetry Index (LSI), calculated as:

$$LSI = (Dominant–No\text{-}dominant)/ Dominant \times 100$$

or equivalently using contralateral ratios depending on the variable measured. An LSI of 0–10% was interpreted as normal or negligible; 10–15% represented a “monitoring zone,” suggesting elevated injury susceptibility; and >15% was considered clinically significant, warranting corrective intervention.

Asymmetry Thresholds

Consistent with prior evidence, asymmetry magnitudes exceeding 10–15% were considered predictive of increased musculoskeletal injury risk, particularly for lower-limb soft tissue injuries. However, the functional impact of such asymmetries on performance outcomes (e.g., sprint, change of direction, jump height) was treated as context-dependent and moderated by maturation status, task type, and sport-specific demands.

Technological Assessment Modalities

Assessment technologies included isokinetic dynamometry, force platforms, inertial measurement units (IMUs), 3D motion capture, and AI-based video or wearable systems. These tools were classified according to their measurement domain: Kinetic (e.g., torque, impulse, ground reaction force),Kinematic (e.g., joint angles, movement trajectories), and Neuromuscular (e.g., rate of force development, time-to-stabilization).Wearable sensors and AI algorithms were included when they objectively quantified or predicted asymmetry-related outcomes.

Artificial Intelligence (AI) and Machine Learning (ML)

For the purpose of this review, AI/ML applications refer to computational approaches that use data-driven algorithms (e.g., Random Forest, Support Vector Machine, Neural Networks) to identify, classify, or predict asymmetry patterns and their association with injury risk or performance. Only peer-reviewed studies providing explicit methodological descriptions of algorithm design, validation, and feature selection were considered.

Youth Soccer Players

The term youth soccer players encompasses male and female athletes aged ≤19 years, actively participating in structured competitive or academy programs. Maturation status was classified as pre-, mid-, or post-peak height velocity (PHV), where reported, to allow age- and development-sensitive interpretation of asymmetry profiles.

Information Sources

A comprehensive and systematic literature search was performed across three major electronic bibliographic databases: Scopus, Web of Science, and PubMed. These databases were selected for their extensive coverage of peer-reviewed scientific literature in the fields of sports medicine, biomechanics, orthopedics, and physiotherapy. The search covered the period between the creation of each respective database between January 2015 and July 2025. Furthermore, the reference lists of all included studies and relevant review articles were manually screened to identify any potentially omitted publications.

Eligibility Criteria

Eligible studies will investigate youth soccer players—defined as academy or adolescent athletes of any sex who compete in organized, competitive soccer—and will report original data in a peer-reviewed journal. To meet the phenomenon-of-interest requirement, studies must quantify inter-limb functional asymmetry at the individual level, operationalized as between-limb differences in at least one domain: (i) muscular strength (e.g., isokinetic or isometric measures), (ii) kinematics (e.g., joint angles or segmental motion during task execution), (iii) kinetics (e.g., force, impulse, torque), (iv) morphological characteristics (e.g., muscle volume, architecture), or (v) soccer-relevant functional performance (e.g., jump performance, change-of-direction ability, sprinting outcomes). Assessment must be conducted using technological instrumentation (such as isokinetic dynamometry, three-dimensional motion capture, force platforms, or inertial measurement units) or incorporate artificial intelligence/machine-learning methods for the analysis or interpretation of asymmetry outcomes. The context must be exclusively soccer; mixed-sport samples are admissible only when soccer-specific data are extractable. Acceptable study designs include observational (cross-sectional, cohort, case–control) and experimental (randomized controlled or quasi-experimental) designs that provide sufficient methodological detail on the instruments and procedures used to quantify asymmetry, together with the magnitude and/or direction of inter-limb differences.

Studies will be excluded if they focus solely on adult professional players (typically > ~21 years) without separable youth data; if they are not conducted in soccer or present mixed-sport data from which soccer-specific results cannot be isolated; or if they do not quantify inter-limb asymmetry at the individual level (e.g., report only group means without between-limb metrics). Studies relying exclusively on subjective or non-instrumented assessments (e.g., questionnaires alone, manual clinical tests without technological measurement) will be excluded. Finally, we will exclude non-original or non-peer-reviewed works, including narrative or systematic reviews, editorials, conference abstracts, theses, preprints not certified by peer review, and other grey-literature sources (e.g., conference abstracts, theses, preprints) was excluded to ensure that only peer-reviewed and methodologically validated studies were synthesized. Similarly, no-English publications were excluded due to resource constraints and the need for consistent quality assessment across studies. While this may introduce a language bias, it enhances the reproducibility and comparability of the review process.

Search Strategy

The search strategy was specifically designed to identify studies investigating functional asymmetries in youth soccer players, with a particular focus on assessment technologies and artificial intelligence applications. In collaboration with a specialized librarian, a structured Boolean query was constructed by combining relevant keywords and Medical Subject Headings (MeSH) terms. The core concepts utilized were ("soccer player*" OR "football player*" OR "youth soccer" OR "elite youth" OR junior OR adolescent OR "young athlete*")AND(asymmetr* OR "limb dominan*" OR "bilateral deficit" OR "inter-limb" OR "intra-limb" OR "side-to-side difference" OR imbalance)AND("artificial intelligence" OR "machine learning" OR "deep learning" OR "neural network" OR "AI" OR "predictive model" OR "data analytics" OR "wearable technology" OR "inertial measurement unit" OR IMU OR "wearable sensor*" OR "GPS" OR "local positioning system"OR "force plate" OR "force platform" OR "pressure plate" OR "plantar pressure" OR "3D motion capture" OR "kinematic analysis" OR "isokinetic dynamometer" OR "strength assessment")AND("change of direction" OR COD OR decelerat* OR cut* OR pivot* OR jump* OR "drop jump" OR "countermovement jump" OR CMJ OR "sprint" OR "balance" OR "postural control" OR "strength" OR "injury risk" OR "injury prediction") . This syntax was adapted to the specific formats required by Scopus,Web of Science and Pubmed. No restrictions on language were applied.

In compliance with the PRISMA 2020 statement, the search and selection procedures were documented in full to enhance methodological transparency and reproducibility. Numerical consistency in the PRISMA flow diagram (Figure 1) was verified to ensure complete arithmetic accuracy between records identified, screened, excluded, and included. Reasons for full-text exclusions—such as studies not conducted in soccer, lack of inter-limb asymmetry data, mixed-sport samples without extractable soccer-specific results, or exclusion of non-peer-reviewed sources—are now clearly presented in the Supplementary Appendix.

A completed PRISMA 2020 Checklist has been included as Supplementary Appendix 1, allowing independent verification of reporting completeness. Additionally, the full database search strings, including Boolean operators, filters, and final search dates, are provided below to facilitate replication of the search process:

Scopus (last search: July 30, 2025): ("soccer player*" OR "football player*" OR "youth soccer" OR "elite youth" OR "junior" OR "adolescent" OR "young athlete*") AND (asymmetr* OR "limb dominan*" OR "bilateral deficit" OR "inter-limb" OR "side-to-side difference" OR imbalance) AND ("artificial intelligence" OR "machine learning" OR "wearable technology" OR IMU OR "force plate" OR "3D motion capture" OR "isokinetic dynamometer") AND ("change of direction" OR COD OR "jump*" OR "sprint" OR "balance" OR "injury risk"). Filters applied: peer-reviewed journal articles only; publication period January 2015 – July 2025; no language restrictions.

Web of Science (last search: July 30, 2025): Same Boolean logic adapted to "Topic Search (TS)" fields; limited to peer-reviewed journal articles.

PubMed (last search: July 30, 2025): ("soccer"[MeSH Terms] OR "football"[Title/Abstract]) AND (asymmetry OR "limb dominance" OR "bilateral deficit") AND ("artificial intelligence" OR "machine learning" OR "wearable sensor" OR "force plate") AND ("youth" OR "adolescent" OR "academy"). Filters applied: Humans; Journal Article; 2015–2025.

The study selection process was conducted by two independent reviewers (W.B. and O.B.R.). After duplicate removal, both reviewers screened the titles and abstracts of all retrieved records against the eligibility criteria. The full texts of potentially relevant studies were then assessed independently by the same two reviewers. At both stages, any discrepancies regarding the inclusion or exclusion of a study were resolved through discussion until a consensus was reached. If a consensus could not be reached, a third senior reviewer (M.B.) was consulted to make the final decision. No automation tools were used for the study selection process.

Data Extraction and Management

A standardized data extraction form was developed a priori and piloted by the research team. Data from the included studies were extracted independently by two reviewers (Y.B. and A.C.). Any disagreements in the extracted data were resolved by consensus or, if necessary, by arbitration from a third reviewer (A.E.). The following data were extracted: Study characteristics: first author, publication year, country, study design, sample size. Participant characteristics: sex, age, biological maturity status (e.g., Peak Height Velocity - PHV), competitive level (e.g., elite, sub-elite, recreational), and training experience. Asymmetry-related data: type of asymmetry (e.g., strength, kinematic, kinetic), assessment technology used (e.g., isokinetic dynamometer, force plate, IMU), AI model used (if applicable), variables measured (e.g., peak torque, jump height, joint angles), and the magnitude/direction of asymmetry. Key outcomes: primary findings related to asymmetry, injury risk, and performance. Other variables: source of funding and conflicts of interest, as reported. In cases of missing or ambiguous data, the study was not excluded, but the specific missing variable was noted and excluded from the relevant analysis. Authors of the primary studies were not contacted for missing data, as the review was designed to synthesize only the information available in the published reports.

Assessment of Study Methodology

The methodological quality of each included study was independently assessed by two reviewers using validated tools appropriate for the respective study designs (e.g., the Newcastle-Ottawa Scale for cohort and case-control studies, and a modified tool for cross-sectional studies). The domains examined included selection of study groups, their comparability, and the ascertainment of both exposure and outcome. Any discrepancies were resolved through consensus. The results of this appraisal are presented in Table 1, providing a transparent overview of the robustness of the evidence; this assessment was not used as an exclusion criterion.

Asymmetry Metrics and Thresholds

To ensure consistency in terminology, the following abbreviations are used throughout this review: Artificial Intelligence and Machine Learning (AI/ML), Inertial Measurement Unit (IMU), and Limb Symmetry Index (LSI). The magnitude of inter-limb asymmetry was quantified using various metrics across the included studies. The most prevalent method was the Limb Symmetry Index (LSI), typically calculated using the following formula:

$$\text{LSI (\%)} = \left(\frac{\text{Value of Non-Dominant Limb}}{\text{Value of Dominant Limb}}\right) \times 100$$

Alternative common formulae for asymmetry percentage (Asym%) include:

$$\text{Asym\%} = \left(\frac{|\,\text{Dominant Limb} - \text{Non-Dominant Limb}\,|}{\text{Max(Dominant Limb, Non-Dominant Limb)}}\right) \times 100$$

or

$$\text{Asym\%} = \left(\frac{|\,\text{Dominant Limb} - \text{Non-Dominant Limb}\,|}{(\text{Dominant Limb} + \text{Non-Dominant Limb})/2}\right) \times 100$$

For the context of this review, asymmetries exceeding the 10–15% threshold were considered clinically significant. This range is widely cited in the literature, where: Asymmetries below 10% are often considered normal or negligible in youth athletic populations. Asymmetries between 10% and 15% are viewed as a "grey zone," potentially indicating elevated injury risk or a need for monitoring. Asymmetries exceeding 15% are consistently associated with a significantly increased risk of musculoskeletal injury and are typically targeted for corrective intervention. It is important to note that the interpretation of these thresholds can be context-dependent, varying by the specific test (e.g., strength, jump), the variable measured (e.g., peak force, impulse), and the individual's maturation status.

Results

The study selection (Figure 1) identified 418 articles via Scopus (n=205), Web of Science (n=201), and PubMed (n=12). After removing 89 duplicates, 329 abstracts were reviewed. 290 were excluded, leading to the evaluation of 37 full texts. 8 articles were excluded according to predefined criteria (3 not focused on soccer, 3 without individual asymmetry data, and 1 grey literature), resulting in 28 included studies. This PRISMA methodology ensures the rigor and reproducibility of the systematic review.

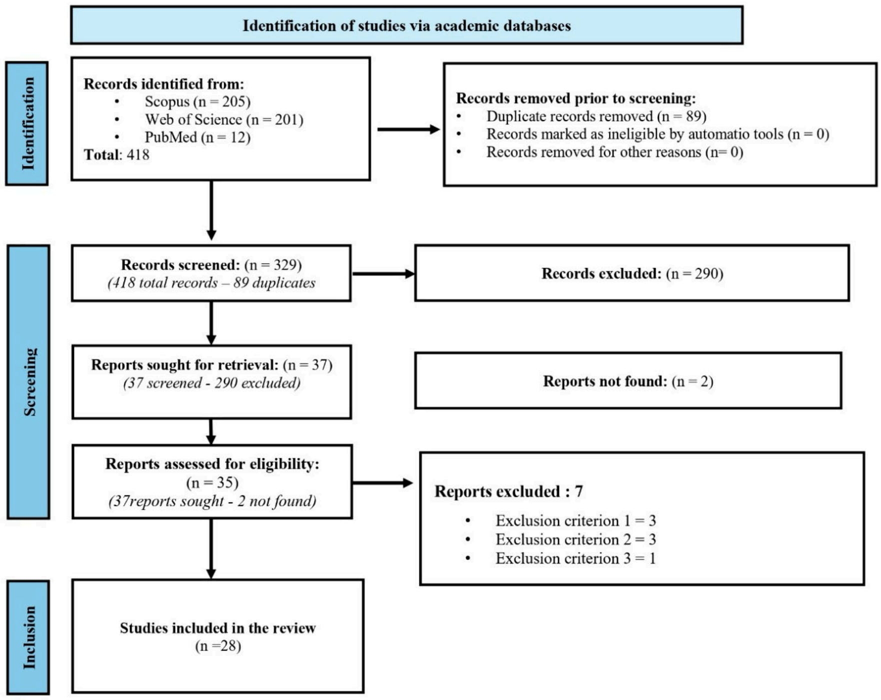

Fig. 1. Flowchart of the systematic review

The following section presents the results of the study, based on the data collected and analyzed.

Synthesis of AI/ML Studies

Among the 28 included studies, two primary investigations focused specifically on the development and validation of AI/ML models for predicting injury risk in youth soccer players. The quantitative characteristics of these models are summarized in Table 3. The study by (Robles-Palazón et al., 2023) utilized an ensemble of models, with the best performance achieved by a Random Forest algorithm. In contrast, (Oliver et al., 2020) compared a single ML model against traditional logistic regression, demonstrating the superior sensitivity of the ML approach. Both studies relied on internal validation methods, and calibration metrics were not consistently reported, highlighting a common limitation in the current literature.

Discussion

This systematic review, based on the analysis of 28 studies, highlights the considerable evolution of methods for evaluating functional asymmetries in young soccer players, driven by emerging technologies and artificial intelligence. All of the studies converge on one conclusion: instrumented approaches, whether involving motion capture, isokinetic dynamometry, force platforms, inertial measurement units (IMU), or machine learning algorithms, allow for the quantification of inter-limb imbalances with unprecedented precision, sensitivity, and predictive value. As demonstrated by (Robles-Palazón et al., 2023), models of automated learning incorporating six asymmetric variables — notably valgus, force of landing and internal rotation of the hip — achieve a rate of precision of 70% in predicting the likelihood of injury. This approach provides an economically advantageous alternative to the use of bulky batteries for testing purposes. Furthermore, it is necessary to conside, As indicated by (Oliver et al., 2020), the application of machine learning algorithms to asymétries resulting from single-leg countermovement jump does not enhance the sensitivity of injury prediction (55.6% compared to 15.2% for the logistical regression model). A multitude of studies, including those by (Barbalho et al., 2021) and (Read et al., 2016), have underscored the significance of a multi-test approach. The asymmetries detected in a particular jump (e.g., the squat jump [SJ], the countermovement jump [CMJ], or the drop jump [DJ]) vary according to the task, thereby substantiating the necessity of a comprehensive evaluation encompassing diverse modalities. The proliferation of portable tools signifies a pivotal juncture within this domain. Indeed, the research conducted by (Di Paolo et al., 2021) and (Izzo et al., 2022) has demonstrated the significance of inertial sensors in the longitudinal monitoring of asymétries throughout the season. These investigations have facilitated the identification of fluctuations associated with the load of training, thereby providing novel insights into the analysis of sporting performance. In addition, non-marker-based motion capture systems, such as those employed by (Nakahira et al., 2022), have been shown to detect subtle cinematic asymmetries, including a valgus knee rotation of 8 to 10° in the dominant lower extremity, which is imperceptible to the naked eye. As demonstrated in the studies conducted by (Zeleznik et al., 2025) and (Vargas

Table 1. Summary of Included Studies on Asymmetry in Athletes

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Robles-Palazón et al., 2023)	Predicting injury risk using machine learning in male youth soccer players	Spain	Age: U11-U19; PHV: Mixed; Level: Non-elite; Sex: Male	Bilateral asymmetry (ROM, landing, force)	Support Vector Machine (SMO), Random Forest, Ensemble (UBAG), SHAP	Anthropometry, ROM, jump, sprint, agility, y-balance, injury	Asymmetry Index (%); Threshold: >15% for injury risk	Not reported	Moderate
(Bonetti et al., 2017)	Isokinetic performance of knee extensors and flexors in adolescent male soccer athletes	Brazil	Age: U17; PHV: Not specified; Level: Not specified; Sex: Male	Strength asymmetry (knee extensors/flexors)	Isokinetic dynamometer (Biodex System 4); No AI	Peak torque; flexor/ extensor ratio; bilateral asymmetry	LSI (%); Threshold: Not specified	Not reported	Moderate
(Vargas et al., 2020)	Knee isokinetic muscle strength and balance ratio in female soccer players of different age groups: a cross-sectional study	Brazil	Age: U13-PRO; PHV: Not specified; Level: Mixed; Sex: Female	Age-related asymmetry; dominant vs. non-dominant	Isokinetic dynamometry (System 4 Biodex); no AI	Peak torque; average power; conventional & functional ratios; contralateral deficit	LSI (%); Threshold: Not specified	Not reported	High
(Jones et al., 2021)	Field-based lower limb strength tests provide insight into sprint and change of direction ability in academy footballers	Uk/nl/no	Age: 10-18 yrs; PHV: Mixed; Level: Academy; Sex: Male	Between-limb imbalances in hip/ groin strength	Nordbord (hamstring), ForceFrame (hip strength), CMJ platform; No AI	Sprint times (5-20 m); change of direction (505 test); CMJ impulse; hip ADD/ABD; Nordic hamstring strength	Asymmetry Index (%); Threshold: >10% for imbalance	Nordbord: ICC = 0.85-0.95; ForceFrame: ICC = 0.88-0.93	High
(Di Paolo et al., 2021)	Poor motor coordination elicits altered lower limb biomechanics in young football (soccer) players: implications for injury prevention through wearable sensors	Italy	Age: ~10 yrs; PHV: Pre-PHV; Level: Juvenile; Sex: Male	Motor coordination-related asymmetry	Wearable inertial sensors (Xsens MVN); No AI	Joint angles (hip, knee, ankle); accelerations; asymmetry indices	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Przysucha et al., 2024)	Postural sway characteristics in static balance control of youth female soccer players	Canada	Age: 11-13 yrs; PHV: Pre-PHV; Level: Not specified; Sex: Female	Dominant vs. non-dominant leg balance	Force platform (AMTI®); No AI	Center of pressure sway, path length, velocity, AP sway	Inter-limb difference in CoP metrics; Threshold: Not specified	ICC for path length = 0.89	Moderate

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Zeleznik et al., 2025)	Relation of dominant leg use with functional symmetries in young football players of different age groups	Slovenia	Age: U12-U19; PHV: Mixed; Level: Not specified; Sex: Male	Dominant leg use vs. bilateral function	Video analysis; radar gun; photocells; dual-force plate; No AI	Ball speed, dribbling with change of direction, CMJ power	Asymmetry Index (%); Threshold: Not specified	Not reported	High
(Silva et al., 2022)	Relationships of final velocity at 30-15 intermittent fitness test and anaerobic speed reserve with body composition, sprinting, change-of-direction and vertical jumping performances: a cross-sectional study in youth soccer players	Portugal	Age: U14-U19; PHV: Mixed; Level: Not specified; Sex: Male	Functional performance asymmetries (sprint, COD, jump)	Field tests: CMJ, sprints, COD test, 30-15 IFT; No AI	Anthropometry, CMJ, sprint, COD, VIFT, ASR	Asymmetry Index (%); Threshold: Not specified	Not reported	High
(Barbalho et al., 2021)	Assessing interlimb jump asymmetry in young soccer players: the my jump 2 app	Uk	Age: U17; PHV: Not specified; Level: Elite; Sex: Male	Interlimb asymmetry (SJ, CMJ, DJ)	Dual force plates; No AI	Jump height, peak force, concentric impulse, power	Asymmetry Index = [(Dominant - Non-dominant)/ Dominant] × 100; Threshold: Not specified	Not reported	Moderate
(Read et al., 2016)	Consistency of field-based measures of neuromuscular control using force-plate diagnostics in elite male youth soccer players	Uk	Age: Pre/post-PHV; PHV: Pre/post-PHV; Level: Elite; Sex: Male	Neuromuscular asymmetry (landing forces, stability)	Force plates; No AI	pVGRF, time-to-stabilization, asymmetry indices	Asymmetry Index (%); Threshold: Not specified	ICC for pVGRF = 0.78-0.94; CV = 4.1-11.3%	High

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Bromley et al., 2021)	Effects of a competitive soccer match on jump performance and interlimb asymmetities in elite academy soccer players	Uk	Age: Not specified; PHV: Not specified; Level: Elite Academy; Sex: Male	Interlimb asymmetry under fatigue	Force platform; No AI	Eccentric/concentric impulse, peak force, landing metrics, asymmetry indices	Asymmetry Index (%); Threshold: >10% considered meaningful	Not reported	High
(Vasileiou et al., 2024)	Effects of an 8-week in-season explosive power training program on neuromuscular performance and lower-limb asymmetries in young male soccer players	Greece	Age: 13-15 yrs; PHV: Not specified; Level: Not specified; Sex: Male	Interlimb asymmetry (jumping, COD)	OptoJump system, sprint timing gates; No AI	CMJ, SLCMJ, 10-20 m sprint, 505 COD test	Asymmetry Index (%); Threshold: >10% targeted for reduction	Not reported	High
(Daneshjoo et al., 2015)	Analysis of jumping-landing manoeuvers after different speed performances in soccer players	Iran/ malaysia	Age: Collegiate; PHV: Adult; Level: Collegiate; Sex: Male	Bilateral asymmetry (kinematic/ kinetic)	Vicon motion capture; Kistler force plates; No AI	Knee angles, valgus moment, GRF	Inter-limb differences; Threshold: Not specified	Not reported	Moderate
(Bahenský et al., 2020)	Power, muscle, and take-off asymmetry in young soccer players	Czech republic	Age: U16-U19; PHV: Not specified; Level: Not specified; Sex: Male	Dominant vs. non-dominant limb; muscle mass vs. force	Force plate; Wingate anaerobic test; Tanita BC418 body comp.; No AI	Muscle mass distribution, take-off force, anaerobic power	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Michailidis et al., 2025)	Correlation of the asymmetry index from the single-leg countermovement jump with the asymmetry index from isokinetic strength in elite youth football players	Greece	Age: ~15 yrs; PHV: Not specified; Level: Elite; Sex: Male	Functional vs. isokinetic asymmetry indices	Chronojump leap mat; Cybex dynamometer; No AI	SLCMJ height, quadriceps/ hamstring isokinetic torque	Asymmetry Index (%); Threshold: Not specified	Not reported	High

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Izzo et al., 2022)	Symmetry and performance index evaluation in a youth football group using the latest generation imu	Italy	Age: U11-12; PHV: Pre-PHV; Level: Not specified; Sex: Male	Lateral imbalance during COD	Inertial sensors (K-Sport IMU); No AI	Training load, average strength, imbalance index	Imbalance Index; Threshold: Not specified	Not reported	Moderate
(Bishop et al., 2021)	Intra-and inter-limb strength asymmetry in soccer: a comparison of professional and under-18 players	Uk & italy	Age: Pro & U18; PHV: Adult & Adolescent; Level: Professional & Academy; Sex: Male	Inter-limb & intra-limb (quadriceps/ hamstrings)	Isokinetic dynamometer (Cybex Norm); No AI	Knee extensor/flexor torque, H:Q ratios, asymmetry indices	LSI (%); Threshold: >10-15% for inter-limb asymmetry	Not reported	High
(Contreras-Díaz et al., 2023)	Dynamometric strength profile of hip muscles in youth soccer players	Chile & spain	Age: U17; PHV: Not specified; Level: Not specified; Sex: Male	Bilateral asymmetry (hip abductors, adductors, flexors, extensors)	Functional electromechanical dynamometer (FEMD); No AI	Concentric/ eccentric hip torque, unilateral ratios, bilateral balance	LSI (%); Threshold: <10% considered normal	Not reported	High
(Rosa et al., 2022)	Knee and hip agonist-antagonist relationship in male under-19 soccer players	Portugal & colombia	Age: U19; PHV: Late adolescent; Level: Not specified; Sex: Male	Agonist-antagonist & bilateral asymmetry	Isokinetic dynamometer (Biodex); isometric dynamometer (Smart Groin Trainer); No AI	Knee flex/extension, hip add/abduction, functional ratios	LSI (%); Threshold: Not specified	Not reported	Moderate
(Sannicandro et al., 2023)	Jumps and lower limb strength asymmetry in young soccer players: differences between sand and conventional surfaces	Italy	Age: U17; PHV: Not specified; Level: Not specified; Sex: Male	Inter-limb asymmetry (jumping tasks)	Jump tests on sand vs grass (Hop, Side Hop, Broad Jump); No AI	Jump height, asymmetry %, performance deficits	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Michailidis et al., 2020)	Association between jump asymmetry and reduced performance in the change of direction tests of youth soccer players	Greece	Age: U10 & U15; PHV: Pre-PHV & Mid-PHV; Level: Not specified; Sex: Male	Inter-limb asymmetry (jump tests)	SLCMJ, SLLJ, SLTJ, 505 COD, Arrowhead test; No AI	Jump distances, COD times, asymmetry indices	Asymmetry Index (%); Threshold: >10% for performance impact	Not reported	Moderate

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Nakahira et al., 2022)	Kinematic differences between the dominant and nondominant legs during a single-leg drop vertical jump in female soccer players	Japan	Age: 15-22 yrs; PHV: Post-PHV; Level: Not specified; Sex: Female	Kinematic asymmetry (dominant vs nondominant)	AI-based video motion capture (VMocap), Video motion capture with AI-based markerless tracking (OpenPose)	Knee valgus, flexion, hip flexion, inclination angles	Inter-limb angular differences; Threshold: Not specified	Not reported	High
(Ince & Tortu, 2025)	Association between intra and inter-limb strength asymmetry with sprint kinematics and force-velocity profile in youth team athletes	Türkiye	Age: Youth; PHV: Not specified; Level: Mixed; Sex: Mixed (34 soccer)	Inter- & intra-limb asymmetry	Isokinetic dynamometer (Cybex HUMAC Norm); OptoJump; No AI	Sprint times, step length/velocity, F-V profile, strength asymmetry	LSI (%); Threshold: >15% for critical asymmetry	Not reported	High
(Trecroci et al., 2020)	Agreement between dribble and change of direction deficits to assess directional asymmetry in young elite football players	Italy	Age: Youth; PHV: Not specified; Level: Elite; Sex: Male	Directional asymmetry (dribble vs COD deficit)	Timing gates (Witty Microgate); No AI	Sprint time, COD deficit, dribble deficit, asymmetry index	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Ferreira et al., 2018)	Impact of competitive level and age on the strength and asymmetry of young soccer players	Brazil	Age: U15-U20; PHV: Mixed; Level: Mixed; Sex: Male	Bilateral asymmetry (force, impulse, power)	Dual force plates (PLA3-1D-7KN/ JBAZb); No AI	Jump height, peak force, impulse, peak power, asymmetry indices	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Atkins et al., 2016)	The presence of bilateral imbalance of the lower limbs in elite youth soccer players of different ages	Uk	Age: U13-U17; PHV: Mixed; Level: Elite; Sex: Male	Bilateral imbalance (ground reaction forces, DS test)	Twin force plates (Globus Ergo); No AI	Peak GRF, deep squat scores, asymmetry across age groups	Asymmetry Index (%); Threshold: Not specified	Not reported	High
(Oliver et al., 2020)	Using machine learning to improve our understanding of injury risk and prediction in elite male youth football players	Uk, spain, qatar	Age: U10-U18; PHV: Mixed; Level: Elite; Sex: Male	Neuromuscular asymmetry (SLCMJ, SLHD, 75%Hop, Y-balance)	Force plates, Y-balance kit, tuck jump video; Machine Learning	Asymmetry indices, jump kinetics, knee valgus, injury incidence	Asymmetry Index (%); Threshold: >15% for injury risk	Not reported	High

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Trecroci et al., 2020)	Agreement between dribble and change of direction deficits to assess directional asymmetry in young elite football players	Italy	Age: Youth; PHV: Not specified; Level: Elite; Sex: Male	Same as Trecroci (dribble vs COD)	Timing gates; No AI	Sprint time, COD deficit, dribble deficit, asymmetry index	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate

Rom. Range Of Motion, Cmj. Countermovement Jump, Sj. Squat Jump, Dj. Drop Jump, Slcmj. Single-Leg Countermovement Jump, Sllj. Single-Leg Long Jump, Sltj. Single-Leg Triple Jump, Slhd. Single-Leg Hop For Distance, Cod. Change Of Direction, Ift (30–15 Ift). 30–15 Intermittent Fitness Test, Vift. Final Velocity At The 30–15 Intermittent Fitness Test, Asr. Anaerobic Speed Reserve, Grf/Pvgrf. Ground Reaction Force/Peak Vertical Ground Reaction Force, Add/Abd. Hip Adduction/Abduction, H:Q Ratio. Hamstring-To-Quadriceps Strength Ratio, F–V Profile. Force–Velocity Profile, Imu. Inertial Measurement Unit, Ai. Artificial Intelligence, Svm (Smo). Support Vector Machine (Sequential Minimal Optimization), Rf. Random Forest, Ubag. Uniform Bootstrap Aggregating Ensemble, Shap. Shapley Additive Explanations, Cod. Change Of Direction, Ds Test. Deep Squat Test.

Table 2. Study Objectives, Methodologies, Adaptations, and Key Findings

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Robles-Palazón et al., 2023)	Build ML models predicting LE-ST injuries	Prospective cohort; 260 youth; preseason battery; 135 predictors; ML vs CV	Use 6-feature screen if asymmetry >15% (valgus, landing force asymmetry, BMI, FPPA, hip IR, ankle ROM)	Best ML model AUC 0.70; moderate predictive power	Compact, low-cost screen predicts injuries moderately well	Extends ML injury models to non-elite youth
(Bonetti et al., 2017)	Assess contralateral and flexor–extensor strength in adolescent soccer players across positions	Cross-sectional, isokinetic dynamometry (4 velocities)	Pre-season testing for imbalance detection; target athletes with asymmetry >10% (based on peak torque)	Only minor asymmetry at 60°/s in flexors (<10%); no positional differences	Adolescent soccer did not induce large knee asymmetries	Provides baseline isokinetic data for youth; highlights timing for preventive training
(Vargas et al., 2020)	Compare strength, power, and balance ratios across female age groups	Cross-sectional, isokinetic dynamometry	Group comparisons U13–PRO; monitor athletes with H:Q ratios <0.6	Strength improves after U13 and again post-U17; ratios remain stable but below normative levels	Balance ratios in females remain suboptimal, raising injury risk	Establishes normative female profiles; emphasizes developmental thresholds
(Jones et al., 2021)	Relate field-based strength measures to sprint & COD in academy footballers	Multicenter field study; CMJ, Nordbord, ForceFrame, sprints	Age-controlled regression & PCA; target athletes with strength asymmetry >10%	Running ability predicted by CMJ impulse, Nordic hamstring strength, hip adduction	Strength qualities underpin sprint/ COD; hip and hamstring strength critical	Demonstrates utility of scalable, field-based tests for academies

Table 2 (continued)

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Di Paolo et al., 2021)	Examine motor coordination's effect on biomechanics with wearables	On-field drill with inertial sensors (MVJ, ladder, COD)	Harre test to classify coordination; target poorly coordinated athletes (bottom 25%)	Poorly coordinated group showed stiffer hips, knee valgus, and limb asymmetry (>15% in joint angles)	Motor coordination strongly influences biomechanics and injury risk	Innovative integration of motor skills & wearable biomechanics
(Przysucha et al., 2024)	Characterize static balance sway in youth female soccer players	Force platform analysis of bi/unipedal stance	Within-subject repeated trials; monitor athletes with CoP sway >2x standard deviation	Dominant leg exhibited greater sway and faster oscillations	Postural asymmetry likely linked to muscular dominance	First study on COP asymmetry in young females; practical balance insights
(Zeleznik et al., 2025)	Determine links between dominant leg use and functional asymmetries	Large sample, match video analysis, radar, force plate	Ball touches quantified; motor tasks measured; target athletes with >70% dominant leg use	High dominant-leg use correlated with asymmetry in ball speed and CMJ power (U15, U17)	Repetitive dominant leg use promotes functional asymmetry	Strong evidence that training biases reinforce asymmetry; urges bilateral development
(Silva et al., 2022)	To examine associations between 30–15 IFT velocity and anaerobic speed reserve with body composition, sprinting, COD, and jump performance	Cross-sectional design with 124 male soccer players (14–19 yrs)	Applied field-based running and neuromuscular tests; used Pearson correlations for variable associations	VIFT highly correlated with body mass, height, CMJ, sprinting, COD (r=0.7-0.8). ASR showed weaker correlations (r=0.3-0.4)	VIFT is strongly associated with multiple fitness capacities; ASR appears independent	Introduces ASR as an independent marker, useful for locomotor profiling
(Barbalho et al., 2021)	To compare magnitude and direction of inter-limb asymmetry across SJ, CMJ, and DJ	18 elite U17 female players performed unilateral jumps on force platforms	Used multiple jump tests to detect inter-limb differences; applied Kappa coefficients to assess direction consistency	Asymmetry magnitude task-specific; concentric impulse asymmetry greater in SJ (15-20%). Direction inconsistent across tests (κ=0.3)	Single test insufficient for full asymmetry profiling; direction valuable for monitoring	Demonstrates that asymmetry assessment must be multi-test and multi-variable
(Read et al., 2016b)	To evaluate reliability of field-based neuromuscular control measures	51 male players (pre- and post-PHV) performed jumps on force plates. Test-retest across two weeks	Applied repeated measures with ICC and CV for reliability analysis; use tests with ICC>0.75	Acceptable reliability for pVGRF (ICC=0.78-0.94) and asymmetry during single-leg tests; higher variability in drop jumps	Single-leg CMJ and hop provide more reliable assessment than DVJ	Offers evidence-based guidance for injury screening protocols
(Bromley et al., 2021a)	To investigate effects of a competitive match on jump performance and asymmetry	14 elite academy players; unilateral CMJs pre-, post-, 24h, 48h, 72h post-match	Time-course monitoring of fatigue and asymmetry; target athletes with post-match asymmetry increase >10%	Significant decrements in jump metrics (except height). Asymmetries increased sharply post-match (+8-12%), recovering by 48h	Inter-limb asymmetries are sensitive indicators of post-match fatigue	Provides practical monitoring insights for recovery management

Table 2 (continued)

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Vasileiou et al., 2024)	To test effects of explosive power training on performance and asymmetries	35 youth male players (13–15 yrs), randomized into experimental and control groups	Intervention with plyometric and explosive COD drills; target athletes with asymmetry >10% (SLCMJ)	Significant improvements in sprint, jump, COD performance ($p<.05$, $d=0.8$); asymmetry reduced slightly (3-5%)	Explosive power training enhances performance and reduces asymmetry	Adds causal evidence that targeted training mitigates asymmetries
(Daneshjoo et al., 2015)	To examine biomechanical effects of sprinting on jumping-landing	23 collegiate male players; four conditions with motion capture + force plates	Comparison of kinematics/kinetics across different run-up speeds	Sprint-preceded jumps increased knee valgus moment (15-20%) and reduced knee flexion (10-15%)	High-speed running before landing elevates knee injury risk	Highlights mechanism linking sprint-to-jump actions to injury risk
(Bahenský et al., 2020)	To investigate relationships between muscle mass, strength, and take-off asymmetry	65 U16–U19 male players; force plate jumps, Wingate test, body composition	Correlational analysis of dominant vs. non-dominant leg performance	Muscle mass correlated with power output ($r=0.6$) but not take-off force. Asymmetry decreased with training duration	Training reduces performance differences between limbs	Provides insight on how training minimizes asymmetry
(Michailidis et al., 2025)	To assess correlation between SLCMJ and isokinetic strength asymmetry	63 academy players; SLCMJ with leap mat + isokinetic dynamometer	Compared asymmetry indices across functional and laboratory tests	Small positive correlation with quadriceps ($r=0.3$); negative with hamstrings at 60°/s ($r=-0.4$); regression explained 20.6% variance	SLCMJ asymmetry cannot replace isokinetic testing	Evidence on limited interchangeability of field vs. lab assessments
(Izzo et al., 2022)	To evaluate symmetry using inertial sensors (IMU)	104 players (11.7 yrs); preseason and postseason tests with IMU during COD	Longitudinal preseason-to-postseason comparison; monitor athletes with imbalance >15%	Mixed results: ~71% decreased training load, ~50% improved strength, ~56% increased imbalance	Symmetry indices fluctuate across the season; IMUs allow precise monitoring	Demonstrates feasibility of wearable IMU for longitudinal tracking
(Bishop et al., 2021)	Compare intra- and inter-limb strength asymmetry in professional vs U18	Cross-sectional; 100 players; isokinetic knee dynamometry	Use asymmetry profiling to guide interventions; target U18 with asymmetry >15%	Pro players showed lower inter-limb asymmetry (8%) than U18 (12-15%); intra-limb ratios more stable	Professional training reduces asymmetry, whereas U18s show higher imbalance	Demonstrates maturation and training level affect asymmetry

Table 2 (continued)

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Contreras-Díaz et al., 2023)	Profile concentric/eccentric hip muscle strength	Cross-sectional; 37 U17 male players; FEMD dynamometer	Monitor hip ADD/ABD ratios and correct imbalances with targeted training if asymmetry >10%	Hip extensors produced higher torque; bilateral differences <10%; ratios stable across sides	Hip strength balance is preserved, but screening remains useful	Provides normative hip strength values for youth players
(Rosa et al., 2022)	Evaluate agonist-antagonist and bilateral strength relationships	23 U19 male players; isokinetic knee test + isometric groin test	Include hip ADD:ABD and H:Q ratios in screening; target athletes with ratios outside 0.8-1.2 range	Significant bilateral differences in knee torque (10-12%); no significant ADD:ABD imbalance	Inter-limb asymmetry exists in knee but not hip; functional ratios within safe range	First to combine knee and hip joint asymmetries
(Sannicandro et al., 2023)	Compare jump performance and asymmetry on sand vs grass	20 youth players; hop, side hop, broad jump on two surfaces	Use sand training to stress explosive ability; monitor athletes with asymmetry increase >20% on sand	All jump heights reduced on sand (15-20%); asymmetry % increased (up to +41%) compared to grass	Sand increases neuromuscular demand and asymmetry	Novel evidence on surface-specific asymmetry
(Michailidis et al., 2020)	Assess relation between jump asymmetry and COD performance	42 players (U10 & U15); multiple jump and COD tests	Individualize training if >10% asymmetry detected	U10: SLTJ asymmetry predicted slower Arrowhead COD (r=0.6); U15: SLCMJ asymmetry predicted slower 505 COD (r=0.55)	Asymmetry type and test influence COD performance differently by age	Identifies age- and test-specific asymmetry-performance links
(Nakahira et al., 2022)	Analyze kinematic differences between dominant vs nondominant legs	64 female players (15–22 yrs); single-leg DVJ; AI-based motion capture	Focus preventive training on nondominant leg valgus control if angle difference >5°	Nondominant leg showed greater knee valgus angle at landing (8-10° difference)	Knee valgus asymmetry may predispose to ACL risk in females	Innovative AI motion capture highlights dominance-related injury risk
(Ince & tortu, 2025)	Examine strength asymmetry in relation to sprint kinematics and F-V profile	74 youth athletes (34 soccer); isokinetic strength, OptoJump sprint tests	Screen athletes with asymmetry >15% and apply sprint-specific strength training	Weak–moderate correlations between asymmetry and sprint kinetics (r=0.3-0.4); outliers showed >40% asymmetry	Most youth athletes below critical threshold; asymmetry impacts sprint efficiency	First to link isokinetic asymmetry with full sprint F-V profiling in youth
(Trecroci et al., 2020a)	To assess agreement between dribble and COD asymmetry	Cross-sectional, 16 elite youth footballers tested in sprint, COD, dribble tasks	Field-based battery with repeated maximal efforts; use task-specific thresholds	Poor agreement between dribble and COD asymmetry (κ=-0.159); dribble deficit significantly higher (12% vs 8%)	Asymmetry is task-specific; cannot be used interchangeably	Provides evidence that assessment must be task-specific

Table 2 (continued)

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Ferreira et al., 2018)	To compare strength and asymmetry across age and club levels	151 youth players, 3 age groups, 2 competitive levels; CMJ on dual force plates	Standardized vertical jumps; monitor athletes in first-division with asymmetry >15%	No age effect; first-division players had higher force and asymmetry (12-18% vs 8-12%)	Competitive level affects both strength and asymmetry more than age	Demonstrates competitive level as determinant of asymmetry
(Atkins et al., 2016)	To analyze bilateral imbalance in youth players of different ages	105 elite youth players (U13–U17); deep squat with twin force plates	Functional movement screening; focus interventions during peak asymmetry years (14-16 yrs)	Significant bilateral GRF differences except in U13 and U17; greatest asymmetry in 14-16 yrs (15-20%)	Asymmetry peaks in mid-adolescence, declines later	Highlights adolescence as «trigger point» for asymmetry
(Oliver et al., 2020)	To test if machine learning improves injury risk prediction	355 players, preseason screen; injury tracked 10 months	Combined regression and ML with asymmetry cut-offs >15% (SLCMJ)	ML model identified multiple interacting factors; improved sensitivity (55.6%) vs logistic regression (15.2%)	ML improved sensitivity vs logistic regression	Introduces AI as superior approach for multifactorial injury risk
(Trecroci et al., 2020)	To replicate asymmetry agreement assessment in COD vs dribble	16 elite footballers, sprint, COD, dribble tests	Field testing with timing gates; confirm task-specificity	Same outcome: poor agreement, task-specific asymmetry	Task-specificity confirmed	Reinforces reliability of asymmetry indices across tasks

Ml. Machine Learning, Le-St. Lower-Extremity Soft-Tissue, Cv. Cross-Validation, Bmi. Body Mass Index, Fppa. Frontal Plane Projection Angle, Ir. Internal Rotation, Rom. Range Of Motion, Auc. Area Under The Curve, U13–Pro. Under-13 To Professional, Pca. Principal Component Analysis, Cmj. Countermovement Jump, Cod. Change Of Direction, Icc. Intraclass Correlation Coefficient, Cv (In Reliability Context). Coefficient Of Variation, Phv. Peak Height Velocity, Pvgrf. Peak Vertical Ground Reaction Force, Dvj. Drop Vertical Jump, Slcmj. Single-Leg Countermovement Jump, Sj. Squat Jump, Dj. Drop Jump, Cop. Center Of Pressure, Femd. Functional Electromechanical Dynamometer, Add/Abd. Hip Adduction/Abduction, H:Q Ratio. Hamstring-To-Quadriceps Ratio, F–V Profile. Force–Velocity Profile, Imu. Inertial Measurement Unit, Ai. Artificial Intelligence, Acl. Anterior Cruciate Ligament, K. Kappa Coefficient.

Table 3. Risk of Bias Assessment Table Newcastle–Ottawa Scale (NOS)

Author(s) and Year	Study Type	Selection (4)	Comparability (2)	Outcome / Exposure (3)	Total Score /9	Subjective Evaluation
(Robles-Palazón et al., 2023)	Prospective cohort	3	1	2	6	Moderate
(Bonetti et al., 2017)	Cross-sectional	3	1	2	6	Moderate
(Vargas et al., 2020)	Cross-sectional	4	2	2	8	High
(Jones et al., 2021)	Multicenter cross-sectional	4	2	2	8	High
(Di paolo et al., 2021)	Cross-sectional	3	1	2	6	Moderate
(Przysucha et al., 2024)	Cross-sectional	3	1	2	6	Moderate
(Zeleznik et al., 2025)	Cross-sectional	4	2	2	8	High
(Silva et al., 2022)	Cross-sectional	4	2	2	8	High
(Barbalho et al., 2021)	Cross-sectional	3	1	2	6	Moderate
(Read et al., 2016b)	Cross-sectional	4	2	2	8	High
(Bromley et al., 2021a)	Experimental	4	2	2	8	High
(Vasileiou et al., 2024)	Experimental	4	2	2	8	High
(Daneshjoo et al., 2015)	Cross-sectional	3	1	2	6	Moderate
(Bahenský et al., 2020)	Cross-sectional	3	1	2	6	Moderate
(Michailidis et al., 2025)	Cross-sectional	4	2	2	8	High
(Izzo et al., 2022)	Longitudinal	3	1	2	6	Moderate
(Bishop et al., 2021)	Comparative cross-sectional	4	2	2	8	High
(Contreras-díaz et al., 2023)	Cross-sectional	4	2	2	8	High
(Rosa et al., 2022)	Cross-sectional	3	1	2	6	Moderate
(Sannicandro et al., 2023)	Cross-sectional	3	1	2	6	Moderate
(Michailidis et al., 2020)	Cross-sectional	3	1	2	6	Moderate
(Nakahira et al., 2022)	Cross-sectional (AI-based)	4	2	2	8	High
(Ince & tortu, 2025)	Cross-sectional	4	2	2	8	High
(Trecroci et al., 2020)	Cross-sectional	3	1	2	6	Moderate
(Ferreira et al., 2018)	Cross-sectional	3	1	2	6	Moderate
(Atkins et al., 2016)	Cross-sectional	4	2	2	8	High
(Oliver et al., 2020)	Prospective cohort	4	2	2	8	High
(Trecroci et al., 2020)	Cross-sectional	3	1	2	6	Moderate

Table 4. Quantitative Summary of AI/ML Studies for Injury Risk Prediction

Author(s) & Year	AI/ML Model(s) Used	Key Predictive Features	AUC (95% CI)	Calibration Metrics	Type of Validation
(Robles-Palazón et al., 2023)	Support Vector Machine (SMO), Random Forest, Uniform Bootstrap Aggregating Ensemble (UBAG). Best Model: Random Forest.	Knee valgus, landing force asymmetry, BMI, Frontal Plane Projection Angle (FPPA), hip internal rotation, ankle range of motion.	AUC: 0.70 (95% CI not reported)	Not reported.	Internal: Cross-validation.
(Oliver et al., 2020b)	Machine Learning Model (specific algorithm not specified). Comparison: Traditional Logistic Regression.	Single-leg countermovement jump (SLCMJ) asymmetry, knee valgus, anthropometry.	AUC for ML model not explicitly reported. The model identified multiple interacting risk factors.	Not reported.	Internal: Model performance was assessed on the dataset used for training.

Legend: AUC, Area Under the Curve; CI, Confidence Interval; BMI, Body Mass Index; FPPA, Frontal Plane Projection Angle; SLCMJ, Single-Leg Countermovement Jump.

Table 5. Evidence-to-Practice Framework for Managing Functional Asymmetries in Youth Soccer

Test/Technology	LSI Threshold	Outcomes/Risks	Practical Action
Isokinetic Dynamometry (Knee Flexors/Extensors)	>10-15% (Strength Deficit)	Significantly increased risk of hamstring strains & ACL injuries (OR: 1.8-2.5)	Implement targeted unilateral strengthening (Nordic hamstrings, single-leg RDLs); re-test every 4-6 weeks.
Force Plates (CMJ, SLCMJ, Drop Jump)	>10-15% (Peak Force, Impulse)	Moderate association with non-contact LBI; inconsistent link to sprint performance.	Use as primary monitoring tool; if asymmetry >15%, integrate plyometric and ballistic training with emphasis on deficient limb.
Wearable IMUs (COD, Soccer Drills)	>10% (Kinematic Asymmetry)	Elevated biomechanical injury risk during high-intensity maneuvers; valuable for ecological validity.	Adjust technical coaching cues based on real-time data; modify training load and incorporate sport-specific balance drills.
Field-Based Strength Tests (Nordbord, ForceFrame)	>10% (Bilateral Deficit)	Strong predictor of sprint and COD performance deficits; moderate injury risk correlation.	Prescribe hip- and hamstring-focused strengthening; monitor as part of regular fitness testing.
AI/ML Predictive Models (Multi-factor Analysis)	N/A (Risk Stratification)	Moderate predictive accuracy for LE injury (AUC up to 0.70); identifies complex risk interactions.	Utilize for pre-season screening to flag high-risk athletes; guide allocation of preventive resources; requires clinical interpretation.

LSI: Limb Symmetry Index; CMJ: Countermovement Jump; SLCMJ: Single-Leg CMJ; COD: Change of Direction; IMU: Inertial Measurement Unit; LBI: Lower Body Injury; OR: Odds Ratio; AUC: Area Under the Curve; LE: Lower Extremity; RDL: Romanian Deadlift

et al., 2020), the asymmetrical practice, specifically the utilization of a single upper limb to exceed 70% of the total body's movement, has been found to exacerbate imbalances in power and coordination, As posited by (Vasileiou et al., 2024), empirical evidence has been demonstrated that targeted pliometric training can result in a reduction of these disparities by 3 to 5 percent. As indicated by other contributions, such as those by (Sannicandro et al., 2023) , the context of execution exerts a significant influence on the expression of asymétries. The surface of training, the competitive level, and the developmental stage (14–16 years of age, according to (Atkins et al., 2016) have been shown to modulate these expressions. Recent literature (Ince & Tortu, 2025; Michailidis et al., 2020); (Rosa et al., 2022; Contreras-Díaz et al., 2023) suggests that the concurrent incorporation of cinematic, neuromuscular, and biomecahnic assessments facilitates the acquisition of customized, asymmetric profiles, thereby enabling precise preventive interventions. The collective analysis of these results substantiates the notion that the amalgamation of portable technologies, artificial intelligence, and sophisticated analytical models engenders a profound transformation in the evaluation of functional asymmetries. This integration bestows a comprehensive, dynamic, and clinically actionable perspective, thereby marking a significant advancement in the field.

Notwithstanding these laudable advances in methodology, the limitations of conventional approaches remain conspicuous. Although field tests and standardized protocols are accessible and have been disseminated extensively, they exhibit inherent limitations. These limitations include their limited sensitivity, subjective nature, and inability to accurately replicate the multifaceted demands of football. The research conducted by (Bonetti et al., 2017) and (Bishop et al., 2021) utilizes dynamometric isocentricity, a method that had previously been regarded as the gold standard, and demonstrates that these assessments effectively isolate the movement of the joints without accounting for the actual dynamic characteristics of the activity under investigation. Additionally, the 505 test of direction change, as employed by (Jones et al., 2021), obscures the distinction between genuine asymétries of force and variables associated with coordination and motor strategy. Conversely, traditional postural assessments are characterized by their lack of reliability. As evidenced by (Daneshjoo et al., 2015) the intraclass correlation coefficient (ICC) value obtained with a force plate platform exceeded the ICC values reported in clinical balance tests. Furthermore, as demonstrated by (Bromley et al., 2021), fatigue significantly alters asymétries (with a 60% increase after a match), underscoring the variable and situational nature of these metrics. Contemporary instruments, including inertial sensors and dual-platform systems (Di Paolo et al., 2021; (Barbalho et al., 2021), have been developed to address these limitations by capturing global kinematic parameters and temporal variations in functional symmetry. These observations thus necessitate a clear transition between the evaluation of a single moment and the ongoing observation of a process, taking into account its context and ecological validity.

In the final analysis, the relationship between asymetry and the potential for injury remains the paramount clinical impetus for these innovations. The collected data demonstrate that, upon exceeding a critical threshold (typically >10–15%), asymétries emerge as quantifiable predictive factors for musculoskeletal injury. As posited by (Robles-

Palazón et al., 2023) and (Oliver et al., 2020c), a deficit exceeding 15% during unipodal jumps has been demonstrated to engender a heightened risk of injury, particularly during periods of fatigue neuromuscular function (Bromley et al., 2021). These imbalances impact not only performance but also joint stability and neuromuscular control. (Jones et al., 2021) found that an asymetry of greater than 10% in the superior hip adduction resulted in a decrease in the rate of change of direction. Conversely, (Michailidis et al., 2025) observed that asymétries measured in vivo did not always result in laboratory-measured strength deficits, emphasizing the necessity of a multifactorial approach. Furthermore, the findings of (Vasileiou et al., 2024) and (Bahenský et al., 2020) suggest that training regimens involving high-intensity or high-volume exercises, as well as extended periods of practice, may contribute to the mitigation of inter-membrane discrepancies, thereby promoting preventative measures. The preponderance of evidence suggests a consensus: an integrated evaluation approach, integrating artificial intelligence, biomecânica, and longitudinal monitoring, is imperative for the early identification of risk-implicated asymmetries, the development of customized interventions, and the promotion of a healthy athletic development in young football players.

Implications for Practice, Policy, and Research

Practice Implications:

Implement regular asymmetry monitoring using combined field tests (CMJ, SLCMJ) and wearable sensors during soccer-specific drills, Apply the 10–15% LSI threshold for intervention prioritization, with individualized correction programs focusing on unilateral strength training, Develop maturation-adjusted training protocols that account for PHV-related asymmetry fluctuations ,Integrate multi-joint assessment approaches addressing proximal-to-distal imbalance propagation.

Policy Implications:

Sports federations should establish standardized asymmetry assessment protocols across youth academies, Incorporate asymmetry profiling into periodic health examination protocols for young athletes, Develop clear guidelines for return-to-play decision making based on asymmetry thresholds, Allocate resources for technological infrastructure supporting ecological monitoring in youth sports programs.

Research Implications:

Prioritize longitudinal studies tracking asymmetry development throughout adolescent maturation, Establish consensus on standardized LSI calculation methods and reporting standards, Develop validated AI models with cross-cultural applicability for injury prediction, Investigate cost-effectiveness of different technological approaches for widespread implementation, Explore integrative biomarker approaches combining neuromuscular, metabolic, and psychological determinants of asymmetry.

Decision Pathway When LSI >10–15%

ASSESSMENT PHASE, Conduct Multimodal Evaluation: Strength: Isokinetic dynamometry/field-based tests, Movement: Wearable sensors/video analysis, Function: Sport-specific drills, History: Injury record/training load.

INTERPRETATION PHASE: Contextualize Findings Using: Maturation status (pre-/mid-/post-PHV), Playing position demands, Competitive level,Training phase (in-season/off-season).

INTERVENTION PHASE: Implement Targeted Strategies:Unilateral strength training (deficit limb focus), Bilateral coordination exercises, Sport-specific technique correction, Load management adjustments, Proprioceptive training.

MONITORING PHASE, Track Progress Through: Regular re-assessment (4–6 week intervals), Field-based tests with established reliability (ICC > 0.8), Sport-specific performance metrics, Symptom response monitoring

OUTCOME DECISION: LSI <10%: Maintain preventive exercises, LSI 10–15%: Continue targeted intervention, LSI >15%: Enhance intervention intensity/frequency

No Progress: Refer for specialist consultation

This pathway emphasizes that single assessments provide limited value—trend analysis over time is essential for effective management. Integration of quantitative data with qualitative coaching observation ensures comprehensive athlete care.

Conclusion

This systematic review establishes that functional asymmetries exceeding the 10-15% threshold represent a significant injury risk factor in youth soccer players, while their impact on athletic performance remains variable and context-dependent. Technological advances, particularly wearable inertial sensors and explainable AI, offer promising avenues for ecological and personalized monitoring. Decision-making pathway for practice: For any Limb Symmetry Index (LSI) >10-15%: Assess through a multimodal approach combining field tests, biomechanical analysis, and medical history review, interpret within context considering maturation status, playing position, and competitive level, Intervene via targeted unilateral strengthening and proprioceptive training. Monitor progression through serial standardized testing over time, The rigorous validation of AI models and standardization of assessment methodologies represent crucial next steps for transforming asymmetry evaluation into a reliable tool for performance optimization and injury prevention.

Ethics Approval

Ethical approval was not required for this study, as it is a systematic review based exclusively on previously published and publicly available data.

Informed Consent

Not applicable.

Data Availability Statement

All data analyzed in this study are derived from published sources cited in the reference list. No new datasets were generated.

AI Transparency Statement

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Conflict of Interest

The authors declare no conflicts of interest.

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Функціональні асиметрії у юних футболістів: систематичний огляд технологій оцінювання та застосування штучного інтелекту

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 23 с., 5 табл., 1 рис., 49 джерел.

Обґрунтування. Функціональні асиметрії у юних футболістів є важливою біомеханічною та нейром’язовою проблемою, оскільки вони можуть виступати як адаптивні характеристики, так і чинники підвищеного ризику травм. Водночас наявні наукові дані залишаються фрагментованими щодо ефективності застосування технологічних засобів і інструментів штучного інтелекту (ШІ) для кількісної оцінки та інтерпретації таких асиметрій у різних вибірках спортсменів.

Мета. Метою систематичного огляду було узагальнення методологічних підходів і напрямів застосування технологічних та ШІ-орієнтованих інструментів для оцінювання функціональних асиметрій у юних футболістів.

Методи. Огляд виконано відповідно до рекомендацій PRISMA. Пошук літератури здійснювали в базах даних Scopus, Web of Science та PubMed, у результаті чого було ідентифіковано 418 публікацій, з яких 28 відповідали критеріям включення. Методологічну якість відібраних досліджень оцінювали з використанням стандартизованих інструментів. Проаналізовано застосування носимих технологій, біомеханічних систем оцінювання та моделей штучного інтелекту для виявлення й інтерпретації функціональних асиметрій.

Результати. Моделі штучного інтелекту продемонстрували помірну прогностичну точність щодо ризику травм (AUC до 0,70). Носимі інерціальні вимірювальні пристрої характеризувалися високою екологічною валідністю під час оцінювання асиметрій у польових умовах. Водночас виявлено значну міждослідницьку гетерогенність порогових значень асиметрії та аналітичних протоколів, що обмежує можливості міждослідного порівняння результатів. Ключовим результатом стало те, що силові асиметрії понад 15 % були статистично значуще пов’язані з підвищеним ризиком травм ($p < 0{,}05$), однак не супроводжувалися стабільним зниженням показників спринтерської працездатності, що вказує на контекстозалежний характер їх впливу.

Висновки. Отримані результати свідчать, що технологічні та ШІ-орієнтовані підходи є перспективними інструментами для оцінювання функціональних асиметрій у юних футболістів, особливо за умов їх використання в екологічно валідному середовищі. Інтеграція пояснюваного штучного інтелекту з мультимодальними підходами до оцінювання розглядається як перспективний напрям для розроблення персоналізованих програм моніторингу та втручань. Подальші дослідження мають бути спрямовані на стандартизацію методологічної звітності, гармонізацію порогових значень асиметрії та впровадження лонгітюдних дизайнів з метою підвищення клінічної й практичної трансляційності результатів.

Ключові слова: функціональна асиметрія, юнацький футбол, штучний інтелект, прогнозування травматизму, носимі сенсори.

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