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Bilateral Musculoskeletal Asymmetry and Injury Characteristics Among Competitive Track-and-Field Athletes: A Cross-Sectional Analysis

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ABSTRACT: **Background**: Musculoskeletal asymmetry of the body bilaterally is commonly used in studies involving athletes where asymmetries in flexibility and range of motion of joints and functional movements can indicate movement restrictions and can possibly affect injury outcomes. Nevertheless, there could be discrepancies in asymmetry between tests and athletic populations. In the present study, bilateral asymmetry was examined with selected musculoskeletal and functional assessments and injury patterns in track-and-field athletes.

Methods: A cross-sectional study was conducted on 100 competitive track-and-field athletes (58 males, 42 females; mean age 20.22 ± 2.93 years). Anthropometric characteristics such as height, body mass and body mass index (BMI) were measured. Bilateral assessments consisted of the Active Knee Extension (AKE) test, the Active Dynamic Leg Length/ADLT assessment, the Thomas test, hip external rotation (Hip ER), hip internal rotation (Hip IR) and the Lower Quarter Y-Balance Test (LQYBT). Bilateral asymmetry was quantified as an asymmetry index based on the absolute right–left difference relative to the larger absolute side value. Descriptive and comparative statistical analyzes were also performed on injury status, anatomical location, onset, mechanism, severity, diagnosis, training/competition context and time lost.

Results: The athletes' mean values for height, body mass and BMI were 171.17 ± 8.19 cm, 68.35 ± 16.07 kg, and 23.13 ± 4.12 kg/m², respectively. The greatest bilateral asymmetry mean values in the athletes were found in ADLT (13.50 ± 11.63%), the Thomas test (12.00 ± 15.47%), hip external rotation (7.93 ± 11.66%), hip internal rotation (6.93 ± 10.02%), LQYBT (3.98 ± 3.44%), and AKE (1.65 ± 3.18%), respectively. Injured athletes accounted for 68%. In the injured group, the most frequently involved anatomic areas were knee (16.2%), lower leg (14.7%), hip/groin (13.2%), and shoulder (13.2%).

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Acute injuries constituted 33 cases (48.5%) and overuse injuries 30 cases (44.1%), while 63 of 68 injured athletes had non-contact injuries. The most common diagnoses were muscle injuries (33.8%), tendons (19.1%) and ligaments (16.2%). The mean number of days lost after injury was 50.21 ± 76.15 days, with the median value being 21 days. Comparing results between groups, AKE asymmetry was significantly greater in injured than non-injured athletes (2.07% vs. 0.74%, p = 0.011), while hip external rotation asymmetry was significantly lower (5.09% vs. 13.98%, p = 0.003).

Conclusion: Track-and-field competitors have been found to possess significant variation in their levels of bilateral asymmetry in the various musculoskeletal and functional tests, with ADLT and Thomas test possessing highest levels of asymmetry on an average. High incidence of injuries was noted, with majority of injuries being non-contact injuries and significant variations in time loss. Differences in the levels of bilateral asymmetry between injured and non-injured individuals show that bilateral asymmetry cannot be used as an universal indicator of injury risk.

1. INTRODUCTION

Athletics, which is also known as track-and-field, comprises a variety of running, jumping, throwing, and combined disciplines that impose considerable and very specific demands on the musculoskeletal system. According to the discipline, athletes are subject to high-force production at high rates, acceleration and deceleration, repeated running, explosive take-off, impact forces, fast stretch-shortening cycle actions, and discipline-specific movements. This set of mechanical and physiological stress factors may lead to injuries both immediately (acute injuries) and after some time (gradual-onset injuries). Current scientific evidence obtained through a large-scale systematic review and meta-analysis proved the prevalence of musculoskeletal injuries in athletics disciplines, with the thigh, lower leg, foot, and ankle being among the most affected anatomical locations and muscles being the main tissue type affected (Edouard et al., 2026). In addition, the wide range of musculoskeletal injuries sustained by athletes in athletics is associated with the specific loading conditions inherent in each discipline. One factor that recently receives a lot of attention in sports science and medicine is bilateral musculoskeletal asymmetry, i.e., an inequality between the characteristics of the right and left sides of the human body. Some degree of inter-limb variation is expected among healthy athletes and may arise from limb dominance, sport-specific movement strategies, training history, previous injury, anatomical characteristics, and differences in neuromuscular coordination. Nevertheless, substantial asymmetry in flexibility, joint range of motion, strength, or functional performance has traditionally been considered potentially relevant to athletic performance and injury assessment (Bishop et al., 2018). Inter-limb asymmetries have been identified across a wide range of physical qualities and sporting tasks; however, their functional significance appears to depend strongly on the specific physical characteristic being assessed and the demands of the sporting activity. The interpretation of bilateral asymmetry is therefore complex. Different assessment procedures measure different dimensions of musculoskeletal and functional capacity and may consequently produce markedly different asymmetry profiles within the same athlete. For example, an athlete may demonstrate relatively symmetrical knee-extension mobility while simultaneously exhibiting greater side-to-side differences in hip rotation or dynamic postural control. Such differences emphasize that asymmetry should not necessarily be regarded as a single global characteristic of an athlete. Rather, it may represent a multidimensional phenomenon that varies according to the assessment modality, movement task, athlete characteristics, sport-specific demands, and previous exposure to injury or training (Bishop et al., 2018). The proposed relationship between bilateral asymmetry and sports injury is particularly complex. Although greater inter-limb differences have been hypothesized to contribute to injury through altered biomechanics, compensatory movement strategies, and uneven distribution of mechanical loading, empirical evidence has not consistently demonstrated a direct or universal relationship. A systematic review by Hobara et al. and subsequent investigations have emphasized that the presence and magnitude of asymmetry may vary considerably between athletes and physical qualities. More specifically, a systematic review examining lower-limb asymmetry and injury reported only moderate-to-low quality evidence supporting functional asymmetry as a general risk factor for sports injury, with substantial methodological heterogeneity among the included studies (Cuthbert et al., 2021). Similarly, a systematic review restricted to prospective cohort studies found highly inconsistent associations between inter-limb differences in lower-limb functional performance and subsequent sports injury (Moura et al., 2022). These findings suggest that asymmetry should not be interpreted as an independent or universal predictor of injury. The multifactorial nature of sports

injury provides an important framework for understanding this relationship. Sports injury is influenced by multiple interacting intrinsic and extrinsic factors, including previous injury, physical characteristics, training exposure, workload, movement strategy, tissue capacity, recovery, and environmental conditions (Meeuwisse, 1994). Consequently, an asymmetry identified in an injured athlete cannot automatically be interpreted as a pre-existing injury risk factor. Consequently, an asymmetry identified in an injured athlete cannot automatically be interpreted as a pre-existing injury risk factor. Previous injury, pain, immobilization, altered training exposure, and rehabilitation may themselves lead to changes in muscle function, range of motion, neuromuscular control, and movement strategies, potentially producing or increasing bilateral asymmetry. Thus, asymmetry may function as a consequence, contributor, marker, or adaptation associated with injury rather than representing a simple causal determinant. This distinction is particularly important in observational research involving injured and non-injured athletes. The identification of a significant difference between groups does not necessarily establish temporal precedence or causality. Contemporary sports-injury frameworks emphasize the importance of considering injury as a dynamic and multifactorial process rather than attributing injury to a single isolated characteristic (Meeuwisse, 1994; Bahr et al., 2020). Accordingly, bilateral asymmetry may be more appropriately considered as one component of an athlete's broader physical profile that warrants interpretation alongside anthropometric characteristics, previous injury history, training exposure, event-specific demands, and functional performance. Dynamic balance represents another important component of athletic movement assessment. The Y-Balance Test Lower Quarter (YBT-LQ) has been extensively investigated as a measure of dynamic postural control and lower-extremity neuromuscular function. Evidence indicates that the YBT-LQ demonstrates good-to-high reliability, although performance may differ according to sex, sport, competitive level, and population characteristics (Plisky et al., 2021). Importantly, evidence regarding the ability of reach asymmetry or composite YBT-LQ scores to predict subsequent injury remains inconsistent. Plisky et al. (2021), in a systematic review and meta-analysis of 57 studies, reported substantial heterogeneity among injury-prediction studies and concluded that population-specific considerations should be incorporated when interpreting YBT-LQ performance. Similarly, an independent validation study among collegiate athletes found no significant differences in YBT-LQ performance between athletes who subsequently sustained lower-extremity injuries and those who remained uninjured (Smith et al., 2017). These findings reinforce the importance of avoiding universal asymmetry thresholds and of interpreting dynamic-balance measures within the context of the athlete population and sporting demands. Sex-specific differences may also be relevant when examining bilateral asymmetry. Athletes differ in anthropometric characteristics, neuromuscular function, movement strategies, and sport-specific exposure, and these factors may influence both the magnitude and functional interpretation of asymmetry. Evidence from the YBT-LQ literature, for example, has demonstrated differences in certain reach directions between male and female athletes, further suggesting that assessment outcomes should not necessarily be interpreted using a single population-independent reference value (Plisky et al., 2021). Therefore, examining male and female athletes separately may provide a more informative understanding of the distribution and characteristics of bilateral asymmetry. Track-and-field athletes provide an especially relevant population for investigating these relationships because athletics consists of highly specialized events with substantially different mechanical requirements. Sprinting and hurdling involve high horizontal and vertical forces, rapid acceleration, maximal-velocity running, and repeated high-rate loading. Jumping events require explosive force production, unilateral or bilateral take-off strategies, and controlled landing mechanics, whereas throwing events impose considerable demands on the shoulder, trunk, pelvis, and lower extremities. Distance-running events are characterized by high repetition and cumulative loading over prolonged periods. These event-specific requirements may contribute to distinctive neuromuscular adaptations and bilateral movement patterns. Recent epidemiological evidence further confirms that injury characteristics in athletics vary substantially according to anatomical region and tissue type, highlighting the importance of considering the specific physical demands of the sport when investigating injury-related characteristics (Edouard et al., 2026). The characterization of injury itself also requires methodological consideration. Differences in injury definitions, anatomical classification, onset, severity, mechanism, exposure, and time-loss criteria can substantially influence reported injury patterns and make comparisons between studies difficult. International consensus recommendations emphasize the importance of standardized definitions, systematic classification, consistent recording procedures, and appropriate reporting of injury severity and exposure (Fuller et al., 2006; Bahr et al., 2020). In the context of athletics, therefore, examining injury prevalence together with anatomical location, onset, mechanism, diagnosis, severity, training or competition context, and time lost from participation may provide a more comprehensive description of the injury burden. Despite the widespread application of bilateral assessments in athletic screening, important questions remain regarding how asymmetry is distributed across different musculoskeletal and functional characteristics and whether these differences are associated with injury status. Existing literature indicates that the relationship between asymmetry and injury varies according to the specific test, athlete population, injury

definition, and method used to quantify asymmetry (Cuthbert et al., 2021; Moura et al., 2022). Consequently, simultaneous evaluation of flexibility, lower-limb mobility, hip rotational range of motion, and dynamic functional performance may provide a broader representation of bilateral physical characteristics than reliance on a single assessment.

Furthermore, the recent evidence base indicates that athletic injury prevention is increasingly moving toward multifactorial assessment rather than reliance on isolated screening variables. Exercise-based interventions incorporating strength, neuromuscular training, conditioning, flexibility, and gait-related strategies have demonstrated potential to reduce injury incidence among track-and-field athletes, although considerable heterogeneity remains between studies and event groups (Weerasinghe et al., 2026). This reinforces the need to identify clinically and practically meaningful physical characteristics that can contribute to individualized screening, monitoring, rehabilitation, and injury-management strategies.

Therefore, the present study examined bilateral asymmetry among competitive track-and-field athletes using a battery of musculoskeletal and functional assessments representing knee flexibility, lower-limb mobility, hip rotational mobility, and dynamic functional performance. In addition, the study characterized the prevalence and distribution of sports injuries according to anatomical location, onset, mechanism, diagnosis, severity, training or competition context, and time lost from participation. Anthropometric characteristics and bilateral asymmetry measures were also compared between injured and non-injured athletes to determine whether specific physical characteristics differed according to injury status. By examining multiple dimensions of bilateral function alongside detailed injury characteristics, the study sought to provide a more comprehensive understanding of asymmetry within competitive athletics and to determine whether assessment-specific asymmetry patterns may have practical relevance for athletic screening and injury-management strategies.

1.1 Objectives of the Study

1.The determination of the magnitude and distribution of bilateral asymmetries during the selected musculoskeletal and functional assessments in competitive track-and-field athletes.

2.The comparison of bilateral asymmetry profiles in male and female athletes.

3.The determination of the occurrence and nature of sports-related injuries in the study population.

4.The comparison of anthropometric characteristics and bilateral asymmetry indicators in injured and uninjured athletes.

5.The examination of the relationship between selected bilateral asymmetry indicators and selected injury parameters.

1.2 Research Hypothesis

It was predicted that competitive athletes in track and field would have bilateral asymmetry on a set of physical measures and that the degree of asymmetry would vary according to whether the athlete had a sports injury or not. Furthermore, it was predicted that there would be specific assessment-specific, but not general, associations between the measure of bilateral asymmetry and whether an athlete had an injury or not. Finally, it was hypothesized that bilateral asymmetry would be different in men and women**.**

2. MATERIALS AND METHODS

2.1 Study Design

The research involved conducting a cross-sectional observational study to investigate the bilateral asymmetry of musculoskeletal system and injury characteristics among track-and-field athletes. The analysis was carried out using a dataset that consisted of demographic, anthropometric, bilateral physical test, and sports injury variables. There were 100 competitive athletes in the dataset, including 58 males and 42 females. The main analytical variables included anthropometric variables, six bilateral physical tests, bilateral asymmetry indices, injury status, injury characteristics, and time-loss data. Cross-sectional design was used to find associations between bilateral asymmetry and injury status. Since the analysis involved measurements of asymmetry and injury status within one observational dataset, the results were seen as associations and not as causal associations. It should be noted that this was done due to the fact that there are conflicting studies on associations between interlimb asymmetry and sports injury (Cuthbert et al., 2021; Moura et al., 2022).

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2.2 Participants and Study Population:

A total of 100 track-and-field athletes who competed at an intense level comprised the study sample, comprising 58 men (58.0%) and 42 women (42.0%). The average age of the subjects was 20.22 ± 2.93 years. These were participants from different categories of track-and-field events that include running, jumping, throwing, among others.

Table 1. Participant characteristics

Characteristic	Total (N=100)	Male (n=58)	Female (n=42)
Age, years	20.22 ± 2.93	20.45 ± 3.11	19.90 ± 2.68
Height, cm	171.17 ± 8.19	175.90 ± 5.72	164.63 ± 6.00
Body mass, kg	68.35 ± 16.07	74.72 ± 16.30	59.57 ± 11.39
BMI, kg/m²	23.13 ± 4.12	24.05 ± 4.13	21.86 ± 3.57
Male, n (%)	58 (58.0)	—	—
Female, n (%)	42 (42.0)	—	—

Values are presented as mean ± SD unless otherwise indicated.

The dataset also contained event-specific classifications and detailed injury information. Participant-level identification variables were not used in the statistical analysis.

2.3 Study Variables and Analytical Framework

The study variables were organized into four principal domains:

1. **Participant characteristics** – age, sex, event, height, body mass, and BMI.
2. **Bilateral physical assessments** – AKE, ADLT, Thomas test, Hip ER, Hip IR, and LQYBT.
3. **Bilateral asymmetry** – six corresponding asymmetry indices.
4. **Sports injury characteristics** – injury status, previous injury history, injury count, anatomical location, side, onset, mechanism, severity, diagnosis, session type, training phase, and time lost.

This structure allowed the analysis to examine both the magnitude of asymmetry and its relationship with injury characteristics.

2.4 Bilateral Musculoskeletal and Functional Assessments

The six bilateral assessments included in the present study were the Active Knee Extension (AKE), Active Dynamic Leg Length Test (ADLT), Thomas Test, Hip External Rotation (Hip ER), Hip Internal Rotation (Hip IR), and the Lower-Quarter Y-Balance Test (LQYBT). These assessments assessed lower limb flexibility, mobility, hip joint rotation range of motion, and dynamic postural control. Right- and left-side measures were obtained and then analyzed to determine the bilateral asymmetry index. Multiple tests were conducted because the degree and importance of the asymmetry can differ depending on the type of physical feature and test used (Bishop et al., 2018; Cuthbert et al., 2021; Moura et al., 2022). LQYBT was selected to measure dynamic balance and functional ability. Several studies have reported the validity of LQYBT though the test interpretation differs depending on the athlete population (Plisky et al., 2021).

2.10 Calculation of Bilateral Asymmetry

Bilateral asymmetry was calculated using the following formula:

$$AI(\%) = \frac{|R - L|}{\max(|R|, |L|)} \times 100$$

where:

AI (%) = Bilateral Asymmetry Index, expressed as a percentage

R = Right-side measurement

L = Left-side measurement

(|R-L|) = Absolute difference between right and left measurements

(max (|R|, |L|)) = Maximum absolute value of the right or left measurement

The formula produces a value of **0% when the two sides are identical**, with progressively larger values representing greater relative side-to-side differences.

The following six asymmetry variables were analyzed:

Assessment	Dataset variable	Unit of original measurement	Outcome
Active Knee Extension	AKE(R/L)	Degrees	AKE-AI (%)
Active Dynamic Leg Length	ADLT(R/L)	Cm	ADLT-AI (%)
Thomas Test	Thomas(R/L)	Degrees	Thomas-AI (%)
Hip External Rotation	HipER(R/L)	Degrees	Hip ER-AI (%)
Hip Internal Rotation	HipIR(R/L)	Degrees	Hip IR-AI (%)
Lower-Quarter Y-Balance Test	LQYBT(R/L)	%	LQYBT-AI (%)

The use of a standardized asymmetry index facilitates comparison between assessments expressed in different units. Nevertheless, different asymmetry calculation methods can produce different results; consequently, the selected formula should be clearly reported when interpreting bilateral asymmetry. (Fox J, O'Malley E, Blake C, et al,2023)

2.11 Injury Assessment, Classification, Severity and Time Loss

Injury status was recorded as a binary variable, with 68 athletes (68.0%) classified as injured and 32 (32.0%) as non-injured. For injured athletes, the dataset included previous injury history, injury count, date of first recorded injury, return-to-sport date, total missed days, anatomical location, injured side, injury onset, injury mechanism, maximum severity, diagnosis, diagnostic category, session type, and training phase. Injuries were classified according to anatomical region, injured side (right, left, or bilateral), onset (acute or overuse), mechanism (contact or non-contact), diagnostic category, training or competition setting, and training phase, following established recommendations for standardized sports-injury surveillance and reporting (Fuller et al., 2006; Bahr et al., 2020). The original dataset coding was retained as far as possible to minimize subjective recategorization. Total missed days were used to describe injury-related time loss and severity, consistent with commonly used time-loss approaches in sports-injury epidemiology (Bahr et al., 2020). Because time-loss data may be positively skewed by a small number of severe injuries with prolonged absence, both mean ± SD and median with range were considered where appropriate to provide a more representative description of injury burden (Bahr et al., 2020).

2.14 Statistical Analysis

Descriptive statistics were obtained for all study variables. Continuous variables were described as mean ± SD, where median and range were additionally provided when required, while categorical variables were described in terms of frequency and percentage. The main continuous variables were six bilateral asymmetry indices. Group comparisons were made for gender (male and female athletes) and injury (injured and non-injured athletes) groups; where possible, sub-group analyses were performed. Normality of continuous variables was examined first to choose the right statistical method. For normally distributed variables, independent-samples t-test was used, and for non-normally distributed variables, Mann–Whitney U test was chosen. For comparison of categorical variables, the chi-square test or Fisher's exact test were applied. The effect sizes

were calculated wherever appropriate along with p values using Cohen's d in case of parametric analysis and respective rank-based effect sizes in case of non-parametric analysis. Relationships between bilateral asymmetry indices and the continuous outcome variables that reflected the injuries, including the total number of missed days were analyzed by means of Pearson's or Spearman's correlation coefficient depending on the data distribution. Whenever sample size and frequencies of events were sufficient, the relationships between the selected asymmetry indices and the injury status were evaluated by means of logistic regression analysis adjusted for possible confounding factors, including age, gender, and body mass index (BMI). Regression analysis findings are reported as odds ratio (OR) with 95% confidence interval (CI) and p-value. Because there are 100 athletes and 68 injured people in the sample, the number of predictors in regression models is limited in order to prevent overfitting (Peduzzi et al., 1996). Two-sided $p < 0.05$ was regarded as statistically significant. Multiple testing correction was performed if necessary (Bender & Lange, 2001).

2.16 Ethical Considerations

Institutional approval was provided by the Institutional Ethical Committee (IEC), Punjabi University, Patiala, Punjab, India (Approval No. 15/11/IEC/PUP/2023, Date: 17 Aug. 2023) for the research conducted. The research protocol titled "A Study to Determine Association of Pre-Season Musculoskeletal Screening with Sports Injuries in National-Level Track and Field Athletes" was evaluated by the committee during its meeting held on 12-13 June 2023. The research was carried out in line with the approved research protocol and ethical principles of research involving human participants. Informed consent and other relevant aspects of the research need to be reported as per the original research protocol.

2.17 Methodological Framework

The overall analytical pathway is presented in **Figure 1**.

The framework begins with participant characteristics, proceeds through bilateral physical assessment and calculation of asymmetry indices, and then integrates injury classification and statistical comparison. This structure permits assessment of both the distribution of asymmetry and its relationship with injury status.

Figure 1. Analytical framework of the study

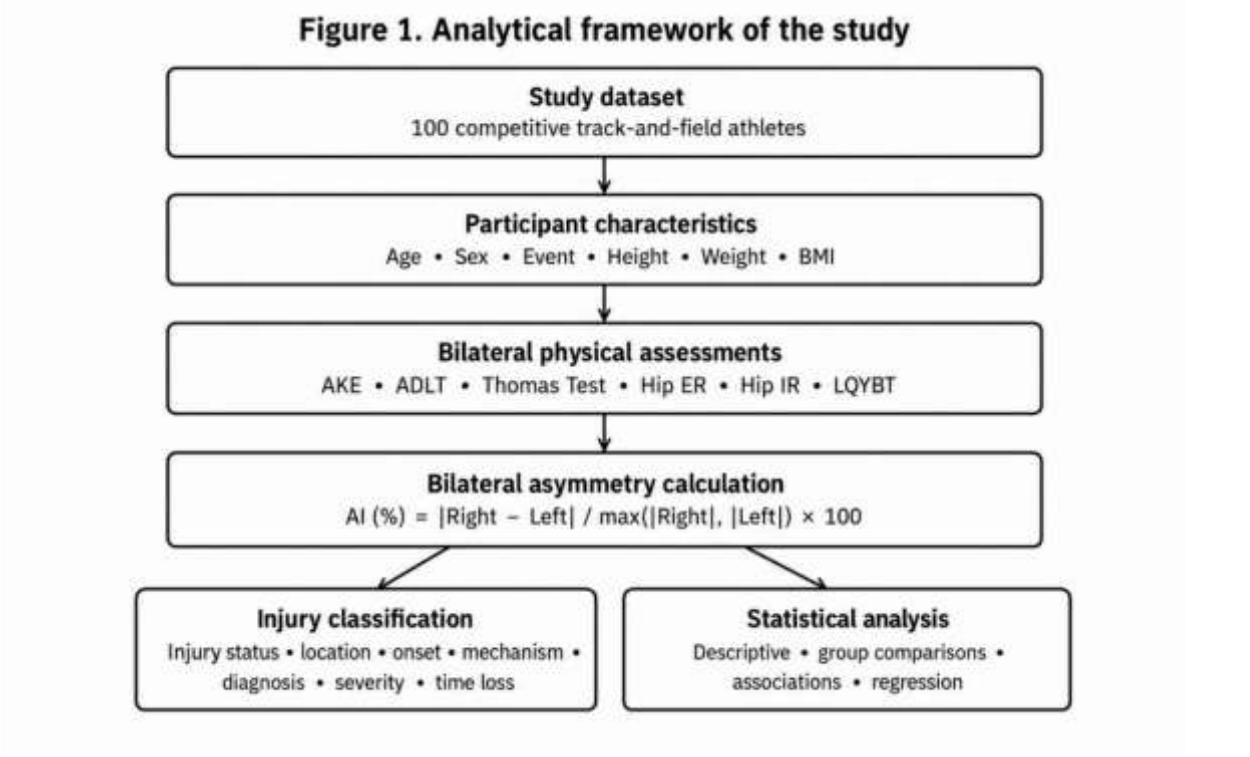


Figure legend: Study analytical framework showing the progression from participant characteristics and bilateral physical assessments to asymmetry-index calculation, injury classification, and statistical analysis.

2.18 Primary Variables

Table 2. Primary variables and analytical role

Domain	Variables	Type	Primary analytical purpose
Demographic	Age, sex, age group	Continuous/categorical	Participant description and covariates
Sport	Event, event group	Categorical	Population characterization
Anthropometry	Height, body mass, BMI	Continuous	Participant characteristics/covariates
Knee mobility	AKE-AI	Continuous	Bilateral asymmetry
Lower-limb mobility	ADLT-AI	Continuous	Bilateral asymmetry
Hip flexibility	Thomas-AI	Continuous	Bilateral asymmetry
Hip mobility	Hip ER-AI, Hip IR-AI	Continuous	Bilateral asymmetry
Dynamic balance	LQYBT-AI	Continuous	Functional asymmetry
Injury status	Injury	Binary	Primary injury outcome
Injury history	Previous injury history, injury count	Categorical/count	Injury profile
Injury characteristics	Location, side, onset, mechanism	Categorical	Injury epidemiology
Injury severity	Maximum severity	Ordinal/categorical	Injury burden
Time loss	Total missed days	Continuous	Injury severity/time-loss outcome
Context	Session type, training phase	Categorical	Injury circumstances

2.19 Methodological Considerations

Two methodological considerations are important when interpreting the findings of the present study. First, bilateral asymmetry should not automatically be considered pathological or interpreted as a direct predictor of sports injury. Previous research has demonstrated substantial heterogeneity in the association between inter-limb asymmetry and injury, with differences in assessment methods, participant characteristics, injury definitions, and asymmetry calculations influencing the reported findings (Bishop et al., 2018; Cuthbert et al., 2021; Moura et al., 2022). Second, functional assessments such as the Lower-Quarter Y-Balance Test (YBT-LQ) should be interpreted according to the characteristics of the population being assessed, as performance may vary with sex, sport, and competitive level, while the evidence supporting universal injury-risk thresholds remains inconsistent (Plisky et al., 2021). Therefore, the present study focuses primarily on describing assessment-specific bilateral asymmetry patterns and their associations with injury status, rather than establishing universal injury-risk thresholds or causal relationships.

3. RESULTS

3.1 Participant Characteristics

The study included **100 competitive track-and-field athletes**, comprising 58 males (58.0%) and 42 females (42.0%). The overall mean age was **20.22 ± 2.93 years**. Mean height, body mass, and BMI were **171.17 ± 8.19 cm, 68.35 ± 16.07 kg, and 23.13 ± 4.12 kg/m²**, respectively. Male athletes were taller and heavier than female athletes. Mean height was 175.90 ± 5.72

cm in males compared with 164.63 ± 6.00 cm in females, while mean body mass was 73.46 ± 16.30 kg and 61.28 ± 11.39 kg, respectively. BMI did not differ significantly between sexes.

Table 3. Participant characteristics according to sex

Variable	Total (N=100)	Male (n=58)	Female (n=42)	p-value*
Age (years)	20.22 ± 2.93	20.45 ± 3.11	19.90 ± 2.68	0.351
Height (cm)	171.17 ± 8.19	175.90 ± 5.72	164.63 ± 6.00	<0.001
Body mass (kg)	68.35 ± 16.07	73.46 ± 16.30	61.28 ± 11.39	<0.001
BMI (kg/m²)	23.13 ± 4.12	23.59 ± 4.13	22.49 ± 4.07	0.186

P-values are from independent-samples comparisons; values <0.05 were considered statistically significant.

The largest event groups were **throws (34%)**, **jumps (23%)**, and **sprints/hurdles (22%)**, followed by middle/long-distance events (11%) and multi-events (3%). The remaining observations represented individual event classifications recorded in the raw dataset.

3.2 Overall Bilateral Asymmetry Profile

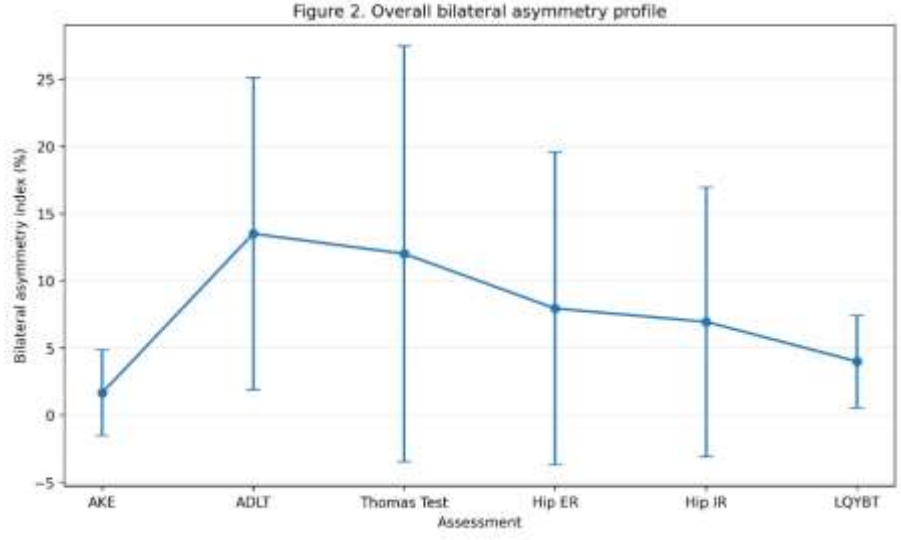
Bilateral asymmetry varied considerably according to the assessment used. The greatest mean asymmetry was observed for **ADLT (13.50 ± 11.63%)**, followed by the **Thomas Test (12.00 ± 15.47%)**, **Hip ER (7.93 ± 11.66%)**, **Hip IR (6.93 ± 10.02%)**, and **LQYBT (3.98 ± 3.44%)**. The smallest asymmetry was observed for **AKE (1.65 ± 3.18%)**.

Table 4. Overall bilateral asymmetry indices

Assessment	n	Mean ± SD (%)	Median (%)	Minimum–Maximum (%)
AKE-AI	100	1.65 ± 3.18	0.00	0.00–16.13
ADLT-AI	100	13.50 ± 11.63	10.71	0.00–60.00
Thomas-AI	100	12.00 ± 15.47	7.69	0.00–50.00
Hip ER-AI	100	7.93 ± 11.66	4.88	0.00–50.00
Hip IR-AI	100	6.93 ± 10.02	4.26	0.00–40.00
LQYBT-AI	98	3.98 ± 3.44	3.33	0.00–17.94

The results demonstrate that bilateral asymmetry was **assessment-specific**, with substantially greater variability in ADLT, Thomas Test, and hip-rotation measures than in AKE and LQYBT.

Figure 2. Overall bilateral asymmetry profile



3.3 Sex-Specific Differences in Bilateral Asymmetry

Male athletes demonstrated greater mean AKE asymmetry than female athletes (**2.17 ± 3.82% vs. 0.93 ± 1.82%**). In contrast, female athletes showed greater LQYBT asymmetry (**5.15 ± 3.97% vs. 3.13 ± 2.78%**). The sex difference was statistically significant for **AKE asymmetry (p = 0.033)** using the independent-samples comparison and for **LQYBT asymmetry (p = 0.008)**. The remaining asymmetry measures did not demonstrate statistically significant sex differences.

Table 5. Bilateral asymmetry according to sex

Asymmetry measure	Male (n=58) Mean ± SD	Female (n=42) Mean ± SD	p-value
AKE-AI (%)	2.17 ± 3.82	0.93 ± 1.82	0.033
ADLT-AI (%)	14.16 ± 12.36	12.58 ± 10.56	0.490
Thomas-AI (%)	10.83 ± 15.15	13.63 ± 15.85	0.382
Hip ER-AI (%)	7.81 ± 11.59	8.10 ± 11.87	0.905
Hip IR-AI (%)	6.44 ± 9.53	7.62 ± 10.67	0.568
LQYBT-AI (%)	3.13 ± 2.78	5.15 ± 3.97	0.008

These findings indicate that sex-related differences were **not consistent across all assessments**, further supporting an assessment-specific interpretation of bilateral asymmetry.

3.4 Injury Prevalence

Of the 100 athletes, **68 (68.0%) were classified as injured**, while 32 (32.0%) were classified as non-injured. Thus, approximately two-thirds of the study population had an injury recorded in the dataset.

Table 6. Injury prevalence

Injury status	n	%
Injured	68	68.0
Non-injured	32	32.0
Total	**100**	**100.0**

3.5 Comparison Between Injured and Non-Injured Athletes

Injured athletes were slightly older and taller than non-injured athletes. Mean age was **20.66 ± 2.90 years** among injured athletes compared with **19.28 ± 2.87 years** among non-injured athletes.

The most notable differences in bilateral asymmetry were observed for **AKE and Hip ER**.

AKE asymmetry was significantly greater in injured athletes (**2.07 ± 3.57%**) than in non-injured athletes (**0.74 ± 1.87%; p = 0.011**). In contrast, Hip ER asymmetry was significantly lower among injured athletes (**5.09 ± 7.91%**) than among non-injured athletes (**13.98 ± 15.80%; p = 0.003**).

No statistically significant differences were observed for ADLT, Thomas Test, Hip IR, or LQYBT asymmetry.

Table 7. Comparison of anthropometric and asymmetry variables according to injury status

Variable	Injured (n=68) Mean ± SD	Non-injured (n=32) Mean ± SD	p-value
Age (years)	20.66 ± 2.90	19.28 ± 2.87	0.020

Variable	Injured (n=68) Mean ± SD	Non-injured (n=32) Mean ± SD	p-value
Height (cm)	172.30 ± 8.09	168.76 ± 8.05	0.040
Body mass (kg)	68.79 ± 16.68	67.41 ± 14.80	0.662
BMI (kg/m²)	22.94 ± 4.19	23.54 ± 3.96	0.470
AKE-AI (%)	**2.07 ± 3.57**	**0.74 ± 1.87**	**0.011**
ADLT-AI (%)	13.94 ± 12.12	12.55 ± 10.58	0.539
Thomas-AI (%)	11.23 ± 14.45	13.64 ± 17.40	0.468
Hip ER-AI (%)	**5.09 ± 7.91**	**13.98 ± 15.80**	**0.003**
Hip IR-AI (%)	5.39 ± 7.65	10.22 ± 13.29	0.066
LQYBT-AI (%)	4.07 ± 3.50	3.78 ± 3.33	0.700

Interpretation: The two statistically significant findings moved in opposite directions. Injured athletes had **greater AKE asymmetry but lower Hip ER asymmetry**. Therefore, the data do **not** support the interpretation that greater bilateral asymmetry across all tests is uniformly associated with injury.

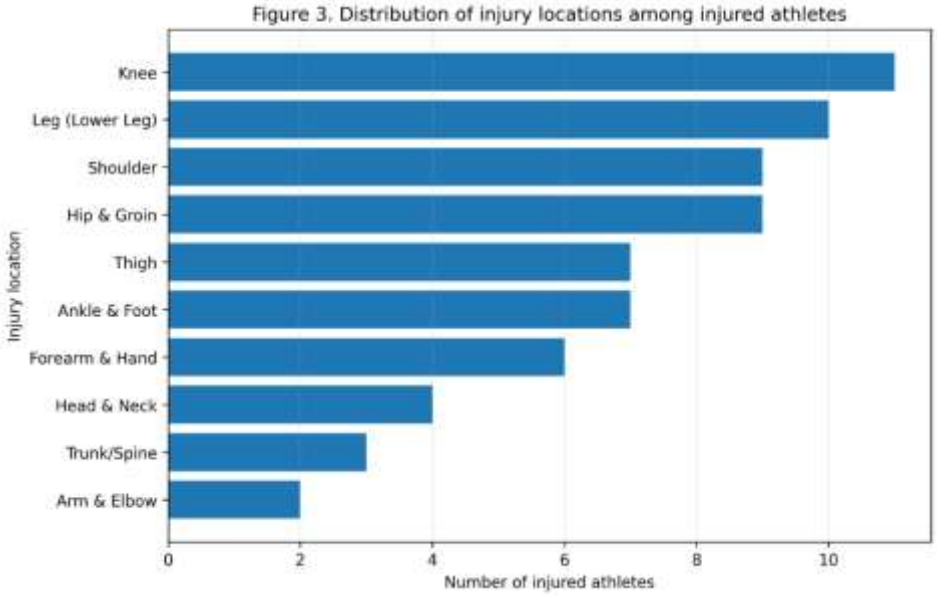
3.6 Anatomical Distribution of Injuries

Among the 68 injured athletes, the **knee was the most frequently affected anatomical region (11 cases; 16.2%)**, followed by the lower leg (10; 14.7%), hip and groin (9; 13.2%), and shoulder (9; 13.2%). Ankle and foot injuries and thigh injuries each accounted for 7 cases (10.3%).

Table 8. Anatomical distribution of injuries

Injury location	n	%
Knee	11	16.2
Leg (Lower Leg)	10	14.7
Hip & Groin	9	13.2
Shoulder	9	13.2
Ankle & Foot	7	10.3
Thigh	7	10.3
Forearm & Hand	6	8.8
Head & Neck	4	5.9
Trunk/Spine	3	4.4
Arm & Elbow	2	2.9
Total	**68**	**100.0**

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3.7 Injury Side, Onset, and Mechanism

Of the 68 injured athletes, **28 (41.2%) sustained right-sided injuries**, 27 (39.7%) sustained left-sided injuries, and 13 (19.1%) sustained bilateral injuries. Regarding injury onset, **33 injuries (48.5%) were acute**, 30 (44.1%) were classified as overuse, and 5 (7.4%) had an unclear onset.The majority of injuries were **non-contact injuries (63; 92.6%)**, whereas only 2 (2.9%) were contact injuries and 3 (4.4%) had an unclear mechanism.

Table 9. Injury onset, side, and mechanism

Characteristic	Category	N	%
Injured side	Right	28	41.2
	Left	27	39.7
	Bilateral	13	19.1
Onset	Acute	33	48.5
	Overuse	30	44.1
	Unclear	5	7.4
Mechanism	Non-contact	63	92.6
	Contact	2	2.9
	Unclear	3	4.4

3.8 Injury Severity and Diagnostic Characteristics

The recorded injury severity was relatively evenly distributed across the three severity categories. **Severe injuries accounted for 25 cases (36.8%)**, followed by mild injuries (22; 32.4%) and moderate injuries (21; 30.9%). With respect to diagnosis, **muscle injuries were the most common diagnostic category (23; 33.8%)**, followed by tendon injuries (13; 19.1%), ligament injuries (11; 16.2%), and bone/stress injuries (10; 14.7%).

Table 10. Injury severity and diagnosis

Characteristic	Category	n	%
Severity	Mild	22	32.4
	Moderate	21	30.9
	Severe	25	36.8
Diagnosis	Muscle injuries	23	33.8
	Tendon injuries	13	19.1
	Ligament injuries	11	16.2
	Bone/Stress injuries	10	14.7
	Joint/Cartilage/Meniscus	5	7.4
	Contusion/Miscellaneous	4	5.9
	Post-operative	2	2.9

3.9 Training and Competition Context

Of the injured athletes, **36 (52.9%) were injured during training**, while **32 (47.1%) were injured during competition**. Similarly, 36 injuries (52.9%) occurred during the **preparatory phase**, while 32 (47.1%) occurred during the **competitive phase**.

Table 11. Injury context

Variable	Category	n	%
Session type	Training	36	52.9
	Competition	32	47.1
Phase of training	Preparatory	36	52.9
	Competitive	32	47.1

3.10 Time Loss Following Injury

Time-loss data demonstrated substantial variability among injured athletes. The mean number of missed days was **50.21 ± 76.15 days**, while the median was **21 days**. The interquartile range was 7–41.25 days, with a minimum of 1 day and a maximum of 300 days. The marked difference between the mean and median indicates a **right-skewed distribution**, suggesting that a relatively small number of athletes experienced substantially prolonged periods away from participation.

Table 12. Time-loss characteristics among injured athletes

Measure	Value
n	68
Mean missed days	50.21

Measure	Value
SD	76.15
Median	21
25th percentile	7
75th percentile	41.25
Minimum	1
Maximum	300

3.11 Principal Findings

The present study demonstrated substantial assessment-specific variation in bilateral asymmetry among competitive track-and-field athletes, with the highest mean asymmetry observed for the ADLT and Thomas Test, whereas AKE showed the lowest average asymmetry, indicating comparatively greater bilateral similarity. Sex-specific differences were also observed, with male athletes demonstrating greater AKE asymmetry and female athletes showing greater LQYBT asymmetry. Overall, 68% of the athletes were classified as injured, with the knee representing the most frequently affected anatomical region, followed by the lower leg, hip/groin, and shoulder. Most injuries were non-contact in nature (92.6%), while acute and overuse injuries occurred at broadly comparable frequencies, and muscle injuries represented the most common diagnostic category. Comparisons according to injury status revealed that injured athletes had significantly greater AKE asymmetry but significantly lower Hip ER asymmetry than non-injured athletes. Injury-related time loss showed considerable variability, with a median of 21 days and a mean of approximately 50 days, indicating substantial variation in injury burden within the study population. The most interesting finding for the eventual discussion is not simply that asymmetry was associated with injury. Rather, the relationship was measure-specific and directionally inconsistent: AKE asymmetry was higher among injured athletes, while Hip ER asymmetry was lower. This is scientifically important because it argues against treating a generic "higher asymmetry = higher injury risk" model as universally applicable to these athletes.

4. DISCUSSION

The present study investigated bilateral asymmetry across selected lower-limb mobility, hip rotation, and dynamic balance assessments and examined its association with injury status among competitive track-and-field athletes. The findings demonstrated considerable assessment-specific variation in bilateral asymmetry, with the highest mean asymmetry observed for the Active Dynamic Leg Length Test (ADLT; 13.50 ± 11.63%) and Thomas Test (12.00 ± 15.47%), while Active Knee Extension (AKE) showed the lowest asymmetry (1.65 ± 3.18%). This variation suggests that bilateral asymmetry is not a single, uniform characteristic but may differ according to the physical quality, assessment method, and athlete characteristics (Bishop et al., 2018; Bishop et al., 2019). The relatively greater asymmetry observed in ADLT and the Thomas Test may reflect greater individual variation in lower-limb mobility and hip-related flexibility, whereas the low AKE asymmetry indicates greater bilateral similarity in active knee-extension mobility. However, the relatively large standard deviations observed for several assessments demonstrate considerable inter-individual variability, which is consistent with previous research showing that the magnitude of inter-limb asymmetry can vary substantially between tests and populations (Bishop et al., 2018; Cuthbert et al., 2021).

An important finding was that the assessments demonstrating the greatest overall asymmetry did not necessarily show the strongest relationship with injury status. Although ADLT and the Thomas Test demonstrated the highest mean asymmetry, neither differed significantly between injured and non-injured athletes. In contrast, AKE demonstrated the lowest overall asymmetry but was significantly greater among injured athletes (2.07 ± 3.57% vs. 0.74 ± 1.87%; $p = 0.011$). This finding indicates that the magnitude of asymmetry alone may not determine its relevance to injury. Previous systematic reviews have similarly reported inconsistent associations between inter-limb asymmetry and sports injury, with findings influenced by assessment procedures, participant characteristics, injury definitions, and asymmetry calculations (Cuthbert et al., 2021; Moura et al., 2022). The present findings therefore support an assessment-specific interpretation rather than the assumption that greater asymmetry universally represents greater injury risk.

Significant sex-related differences were observed for AKE and Lower-Quarter Y-Balance Test (LQYBT) asymmetry. Male athletes demonstrated greater AKE asymmetry than females (2.17 ± 3.82% vs. 0.93 ± 1.82%; p = 0.033), whereas females demonstrated greater LQYBT asymmetry than males (5.15 ± 3.97% vs. 3.13 ± 2.78%; p = 0.008). No significant sex differences were observed for ADLT, Thomas Test, Hip External Rotation (Hip ER), or Hip Internal Rotation (Hip IR). The contrasting direction of these findings suggests that sex-related differences may depend on the specific physical characteristic assessed rather than reflecting a generalized tendency for greater asymmetry in either sex. Previous studies have demonstrated that sex, sport, competitive level, and individual characteristics can influence dynamic balance and functional performance (Gribble et al., 2012; Plisky et al., 2021). Although the LQYBT has demonstrated good reliability, its performance and interpretation may vary across populations; therefore, the greater LQYBT asymmetry observed among female athletes should not automatically be interpreted as evidence of greater injury susceptibility (Plisky et al., 2021).

The present study also demonstrated a substantial injury burden, with **68 of 100 athletes (68.0%) classified as injured**. The knee was the most frequently affected anatomical region (16.2%), followed by the lower leg (14.7%), hip/groin (13.2%), and shoulder (13.2%), while muscle injuries represented the most common diagnostic category (33.8%), followed by tendon (19.1%) and ligament injuries (16.2%). The high proportion of non-contact injuries was also notable, with 92.6% of injuries classified as non-contact. This pattern is plausible given the characteristics of track-and-field, where athletes are frequently exposed to repetitive mechanical loading, acceleration, deceleration, high-force take-offs and landings, and event-specific training demands. Recent epidemiological evidence has demonstrated a substantial burden of musculoskeletal injury across athletics and considerable variation according to event and anatomical region (Edouard et al., 2026). Consistent injury surveillance and standardized injury definitions are therefore important for meaningful comparison between athletic populations (Bahr et al., 2020).

The contrasting relationship between AKE and Hip ER asymmetry and injury status represents one of the most important findings of the study. Injured athletes demonstrated significantly greater AKE asymmetry but significantly lower Hip ER asymmetry than non-injured athletes (5.09 ± 7.91% vs. 13.98 ± 15.80%; p = 0.003). No significant differences were observed for ADLT, Thomas Test, Hip IR, or LQYBT. The greater AKE asymmetry among injured athletes may indicate an association between knee-extension mobility and injury status; however, the cross-sectional design prevents determination of whether this asymmetry preceded the injury or developed following injury. Previous injury, pain, reduced loading, rehabilitation, and compensatory movement strategies may all alter bilateral physical characteristics. Conversely, the lower Hip ER asymmetry among injured athletes challenges the assumption that greater asymmetry is necessarily associated with greater injury occurrence. Similar inconsistent findings have been reported in previous investigations of inter-limb asymmetry and sports injury (Bishop et al., 2018; Cuthbert et al., 2021; Moura et al., 2022). Thus, the present results reinforce the concept that different asymmetry measures may have different functional meanings and should be interpreted according to the specific physical characteristic being assessed.

The findings have practical implications for athletic screening and injury management. Bilateral asymmetry assessments may provide useful information about an athlete's individual movement profile, but they should not be considered independent or universal predictors of injury. Instead, asymmetry should be interpreted alongside other relevant factors, including previous injury, strength, mobility, neuromuscular control, training exposure, workload, recovery, and event-specific demands (Meeuwisse, 1994; Bahr et al., 2020). The LQYBT provides a relevant example because, although it is a reliable measure of dynamic balance, evidence regarding the ability of reach asymmetry to predict subsequent injury remains inconsistent (Plisky et al., 2021). Therefore, the use of a single asymmetry threshold across different assessments may be inappropriate.

Finally, injury-related time loss demonstrated considerable variability, with a mean of **50.21 ± 76.15 days**, a median of **21 days**, an interquartile range of **7–41.25 days**, and a maximum of **300 days**. The difference between the mean and median suggests a positively skewed distribution, probably reflecting a small number of athletes with prolonged absence. Reporting both central tendency and variability is therefore important when describing injury burden, consistent with recommendations for sports-injury surveillance (Bahr et al., 2020). Overall, the findings indicate that bilateral asymmetry among competitive track-and-field athletes is **multidimensional and assessment-specific**. Although AKE asymmetry was significantly greater among injured athletes, Hip ER asymmetry was significantly lower, while the remaining measures showed no significant injury-related differences. These findings challenge the simplistic assumption that greater asymmetry necessarily indicates greater injury risk and support a more comprehensive interpretation in which asymmetry represents one component of an athlete's broader

physical and injury profile. Future prospective studies using longitudinal measurements and event-specific analyses are warranted to determine whether particular asymmetry patterns measured before injury can provide meaningful information regarding subsequent injury occurrence (Bishop et al., 2018; Cuthbert et al., 2021).

5. RECOMMENDATIONS

Based on the findings of the present study, bilateral asymmetry should be incorporated into athletic screening as an **assessment-specific measure rather than a standalone indicator of injury risk**. Coaches, strength and conditioning professionals, physiotherapists, and sports scientists should consider AKE, ADLT, Thomas Test, hip rotation, and LQYBT findings together with previous injury history, strength, mobility, training load, recovery status, and event-specific demands. Particular attention may be given to athletes demonstrating notable AKE asymmetry, while recognizing that the observed association does not establish causation. Regular monitoring may also help practitioners identify meaningful changes in an athlete's individual asymmetry profile over time. Because sex-related differences were observed for AKE and LQYBT, practitioners should consider sex-specific reference values where appropriate rather than applying identical thresholds to all athletes. Future studies should use longitudinal designs to determine whether asymmetry precedes injury or develops as a consequence of injury and should examine event-specific differences among sprinters, jumpers, throwers, and other track-and-field athletes. Larger samples are also recommended to improve statistical power and allow more reliable multivariable analyses.

6. STRENGTHS AND LIMITATIONS

A major strength of the present study was the simultaneous assessment of multiple bilateral musculoskeletal and functional characteristics together with detailed injury information. The study also included both male and female competitive athletes and considered several injury characteristics, including anatomical location, mechanism, onset, diagnosis, severity, and time loss. However, several limitations should be acknowledged. First, the **cross-sectional design** prevents determination of temporal or causal relationships between asymmetry and injury. Second, the sample size was relatively small (**n = 100**), which may limit statistical power, particularly for subgroup and regression analyses. Third, the athletes represented different track-and-field event groups, which may have different physical demands and injury profiles. Fourth, injury information was based on the available dataset and may be influenced by differences in previous injury history and reporting. Finally, the study focused on selected asymmetry measures and did not include other potentially important factors such as muscle strength, training workload, previous injury severity, or detailed biomechanical variables. Therefore, the findings should be interpreted as **observational associations rather than causal evidence**.

7. CONCLUSION

The present study demonstrated that bilateral asymmetry among competitive track-and-field athletes varies considerably according to the assessment used. ADLT and the Thomas Test showed the greatest average asymmetry, whereas AKE demonstrated the lowest. Significant sex-related differences were observed for AKE and LQYBT asymmetry. Injury status was associated with greater AKE asymmetry but lower Hip ER asymmetry, while the remaining asymmetry measures did not differ significantly between injured and non-injured athletes. These findings indicate that bilateral asymmetry should **not be interpreted as a universal marker of injury risk**. Instead, each assessment should be considered within the context of the athlete's characteristics, sport-specific demands, injury history, and overall physical profile. Longitudinal research with larger and event-specific samples is recommended to determine whether particular asymmetry patterns can contribute meaningfully to injury prevention, screening, and rehabilitation.

8. PRACTICAL IMPLICATIONS

From a practical perspective, bilateral testing can provide a simple and useful method for monitoring individual differences between limbs. However, practitioners should avoid using a single asymmetry percentage as a definitive criterion for identifying athletes at high risk of injury. A **multifactorial screening approach**, combining bilateral asymmetry with strength, flexibility, balance, previous injury, workload, and sport-specific performance measures, is likely to provide a more meaningful assessment of athlete readiness and injury-related status. Regular reassessment may also be useful for monitoring changes following training, injury, and rehabilitation.

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