

# Wearable-Monitored External Workload (GPS/GNSS/IMU) and Lower-Limb Muscle Injuries in Football: A Systematic Review and Exploratory Data Synthesis

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## Abstract

Lower-limb muscle injuries are common in football and are often linked to fluctuations in training load. Global Positioning System/Global Navigation Satellite System (GPS/GNSS) and Inertial Measurement Unit (IMU) based monitoring of external workload is now routine, yet evidence for its association with injury risk remains inconsistent. This review aimed to synthesize current evidence on the relationship between GPS/IMU-derived workload variables and lower-limb muscle injuries in football players. Following PRISMA guidelines, we searched PubMed and Scopus to September 2025. Eligible studies involved football players at any competitive level, reported GPS/IMU-based workload metrics, and included muscle-injury outcomes. Study quality was assessed with the Newcastle–Ottawa Scale. Twelve studies met the inclusion criteria for qualitative synthesis; however, only four studies provided extractable statistical data for quantitative pooling. These four studies contributed 21 independent effect-size comparisons, analysed as odds ratios (ORs) or relative risks (RRs). Workload definitions and thresholds varied substantially across studies—particularly speed zones, sprint metrics, and ACWR calculations—limiting direct comparability. The exploratory quantitative analysis of OR-based studies showed no significant association between high workload and injury risk (pooled OR=1.33, 95% CI 0.85–2.07;  $p=0.21$ ;  $I^2=93\%$ ). In contrast, the RR-based analysis indicated a significant association, with high workloads more than doubling injury risk (pooled RR=2.33, 95% CI 1.65–3.30;  $p<0.00001$ ;  $I^2=0\%$ ). Given the small number of extractable studies and substantial heterogeneity in workload definitions, these findings should be interpreted as exploratory rather than confirmatory. GPS/IMU-monitored external workload may be associated with muscle-injury risk, but the direction and magnitude depend on analytic approach and how “high workload” is operationalized. Larger, multi-club prospective studies with standardized workload definitions are needed to strengthen the evidence base.

**Keywords:** external workload, football, GPS monitoring, IMU monitoring, muscle injury, systematic review, meta-analysis

## Introduction

Lower-limb muscle injuries are among the most prevalent health problems in football (soccer) (Ferdinand et al., 2025; Nilsson et al., 2023; Nobari et al., 2021, 2022). They reduce on-field performance and cause short- and long-term absences, which affects team continuity and results (Fanchini et al., 2018; Windt et al., 2018). The high incidence of muscle injuries makes this issue a significant concern in sports medicine and athlete performance management.

One factor believed to contribute to injuries is training load. The physical load from training and competition, referred to as training load, is defined as ‘the cumulative stress placed on an individual from multiple training sessions and matches over a given period of time’ (Zumeta-Olaskoaga et al., 2025). Training load is generally a result of training intensity and duration, and research shows that an increase in training load is associated with an increase in the frequency and severity of injuries (Georgiadis et al., 2024; Sumartiningsih et al., 2022). Excessive, disproportionate, or poorly managed training load can increase the risk of lower-limb muscle injuries (Carling et al., 2018; Windt et al., 2017; Windt & Gabbett, 2017). Therefore, monitoring and managing training load is crucial in preventing injuries and optimizing player performance.

Recent technological advances have enabled routine monitoring of athlete-performance indicators. In professional football, Local Positioning Systems (LPS), GNSS/ GPS) and IMU are used to quantify external load. LPS and GPS are used to measure distance traveled at various speed zones (e.g. high-speed running distance or HSRD), or the number of speed changes, (e.g. acceleration (ACC). Meanwhile, IMUs capture movement dynamics and estimate the mechanical load imposed during training and matches. These systems are now standard for real-time external-load monitoring and support day-to-day training decisions (Colby et al., 2014; de Dios-Álvarez et al., 2023; Piłka et al., 2023; Saberisani et al., 2025). The data collected includes distance, speed, sprints, acceleration-deceleration, and power output.

In practice, several key variables are used to evaluate external load, including total distance, high-speed running, sprint distance, number of accelerations-decelerations, and the acute: chronic workload ratio (ACWR) (Buchheit et al., 2021; Clemente et al., 2021; Colby et al., 2014; Fousekis et al., 2025; Georgiadis et al., 2024). These variables characterize the intensity and distribution of training load, which may be associated with injury risk.

However, the operational definitions of these workload metrics vary widely across studies (Buchheit et al., 2021; Windt et al., 2018; Windt & Gabbett, 2017). Speed thresholds for high-speed running and sprinting differ considerably between teams and tracking systems, and ACWR is calculated using multiple non-equivalent formulas. Similarly, accelerations, decelerations, and sprint variables are inconsistently defined across the literature (Buchheit et al., 2021; Windt et al., 2018; Windt & Gabbett, 2017). This lack of standardization has created substantial heterogeneity in how “training load” is conceptualized and measured, contributing to inconsistent findings regarding its association with injury risk.

However, no systematic review or meta-analysis has

specifically focused on the association between GPS/GNSS/IMU-derived exercise load variables and lower-limb muscle injuries in football players. This gap is significant because, although monitoring technology is now standard in professional practice, the scientific evidence supporting its use in injury prevention remains limited and fragmented. This study aims to systematically synthesize observational findings on the relationship between GPS-based training load variables and the risk of lower-limb muscle injuries in football players. The results are expected to provide a more comprehensive scientific understanding and offer practical insights for coaches, medical staff, and performance managers in developing injury prevention strategies informed by training load monitoring technologies.

Given the substantial variability in workload definitions and analytic approaches across studies, a systematic synthesis is needed to clarify the current evidence and assess the extent to which meaningful conclusions can be drawn.

## Methods

### Search strategy

A comprehensive literature search was performed in Scopus and PubMed databases to identify relevant studies examining the association between GPS-monitored workload and lower-limb muscle injuries in football players. The search performed up to September 4, 2025, included no restrictions on publication year, using a combination of controlled vocabulary and free-text terms. Search terms covered sport-related keywords (“soccer,” “football”), monitoring technologies (“GPS,” “GNSS,” “local positioning system,” “wearable tracking”), workload variables (“training load,” “external load,” “acute: chronic workload ratio,” “high-speed running,” “sprint distance,” “acceleration,” “deceleration,” “distance covered”), and injury outcomes (“muscle injury,” “hamstring injury,” “quadriceps injury,” “adductor injury,” “calf injury,” “lower-limb injury,” “time-loss injury,” “injury incidence,” “injury risk,” “injury occurrence”). Eligible study designs were cohort, longitudinal, prospective, observational, and randomized controlled trials. Only peer-reviewed, English-language articles indexed in PubMed and Scopus were eligible. The reference lists of included studies were also screened to identify additional relevant publications not retrieved by the database search.

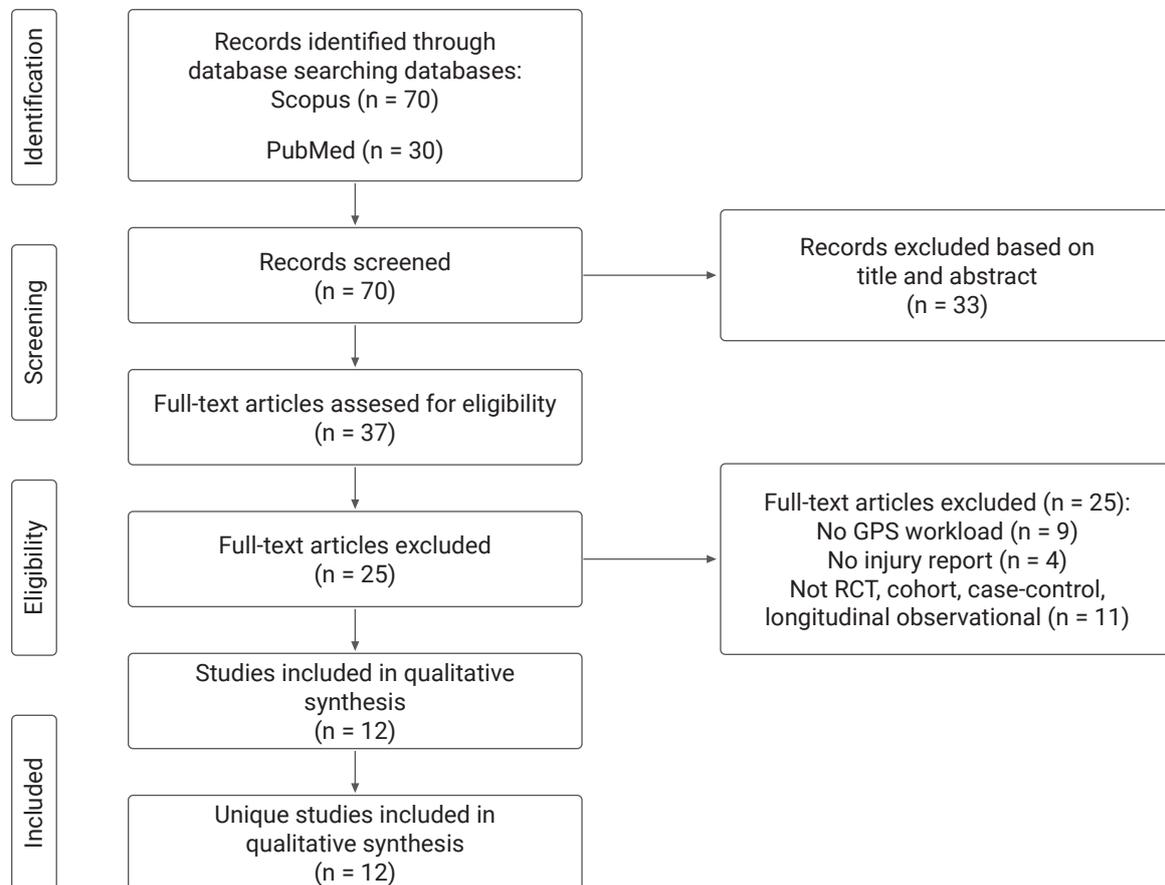
### Study selection and eligibility criteria

The initial search yielded 100 records (Scopus =70; PubMed =30). After removing duplicates, 70 unique articles were screened by title and abstract. Of these, 33 were excluded for not meeting the inclusion criteria (e.g., irrelevant population, GPS not used for workload monitoring, or outcomes unrelated to injury). The full text of 37 articles was assessed for eligibility, and 25 studies were excluded for the following reasons: no GPS workload data (n=9), no injury outcomes reported (n=5), or inappropriate study design (not RCT, cohort, case-control, or longitudinal observational; n=11). Ultimately, 12 articles fulfilled all eligibility criteria and were included in the qualitative synthesis. Of these, four provided sufficient statistical information for quantitative synthesis. Because several studies reported multiple effect sizes (e.g., Malone et

al., 2018: six outcomes; Jaspers et al., 2018: nine outcomes; Nobari et al., 2021: four outcomes; Nobari et al., 2022: two outcomes), the meta-analysis included a total of 21 independent comparisons (15 OR-based and 6 RR-based), which were analysed according to their reported effect measure. The review followed PRISMA guidelines for systematic reviews and meta-analyses, and the protocol was prospectively registered with PROSPERO (CRD420251146818). The PRISMA flow diagram (Figure 1) summarizes the study selection process. When critical statistical information was unavailable, corresponding authors were contacted (up to three times) to request additional data. Studies that remained incomplete were excluded from the quantitative synthesis but were described narratively. The eligibility criteria were defined using the PICOS framework. The population (P) included male and female football players of all competitive levels (professional, semi-professional, academy, and youth). The exposure (I)

was workload variables measured with GPS/IMU technology, including total distance, high-speed running distance, sprint distance, accelerations/decelerations, ACWR, and player load. The comparators (C) included injured versus non-injured players, or groups exposed to different workload levels (e.g., high vs. low workload). The outcomes (O) were lower-limb muscle injuries (hamstring, quadriceps, adductor, calf), measured by incidence, recurrence, and time-loss injuries. Eligible study designs (S) were primary studies such as randomized controlled trials (RCTs), cohort, case-control, and longitudinal observational studies.

Although twelve studies met the eligibility criteria and were included in the qualitative synthesis, only four studies provided extractable numerical data (i.e., odds ratios, relative risks, or raw injury counts) suitable for quantitative pooling. The remaining studies lacked compatible effect estimates or reported workload variables using non-comparable formats.



**Figure 1.** Flowchart of study selection

### Definition and categorization of workload variables

Workload variables reported across the included studies were highly heterogeneous in definition, thresholding, and calculation methods. To enable transparent synthesis, we grouped workload metrics into broader conceptual categories based on their physiological and mechanical characteristics. Total distance, high-speed running distance, and sprint distance were classified as “locomotor distance-based metrics.”

Accelerations, decelerations, and change-of-direction actions were categorized as “accelerometry-based metrics.” Acute/chronic workload ratio (ACWR) variables were grouped separately because of their distinct temporal structure and the use of multiple non-equivalent calculation methods (e.g., rolling average vs. EWMA-based models). These categorizations were used to guide narrative comparison and to avoid pooling conceptually incompatible variables within the meta-analysis.

### Study characteristics

Two researchers (YNH and SS) independently extracted data using a predefined form. Variables collected included: study characteristics, population type, GPS/IMU technology, injury definition, sample size, and effect-size values (OR, RR, HR) with 95% CI or raw data. Disagreements were resolved through discussion, and a third reviewer (SR) was consulted when necessary. Inter-rater reliability was calculated (Cohen's  $\kappa$ /ICC). For the NOS quality assessment, inter-rater reliability was good (ICC=0.84, 95% CI).

### Methodological quality assessment

Two authors independently assessed the methodological quality of the included studies using criteria adapted from the Newcastle–Ottawa Scale (NOS) for cohort and observational designs. The assessment focused on three domains: (1) selection of participants and exposure measurement (e.g., clarity of the football population, validity of GPS devices); (2) comparability of groups (e.g., adjustment for potential confounders such as age, playing position, or match exposure); and (3) outcome assessment (e.g., definition of muscle injury, objective confirmation, and adequacy of follow-up). Each study received a risk-of-bias rating (low, moderate, or high). Disagreements were resolved through discussion until consensus was reached. The NOS was chosen because most included studies used observational cohort designs, and the criteria were adapted to the context of sports injuries. Figure 1 shows the PRISMA flow diagram for study selection.

Most studies were rated as having moderate methodological quality, mainly due to limited sample sizes, single-team designs, and lack of adjustment for confounding variables. Nevertheless, all included articles employed prospective or longitudinal injury surveillance and used validated GPS or GNSS devices, supporting the reliability of workload and injury measurements. Any discrepancies in quality ratings between reviewers were resolved through discussion until consensus was reached.

Most studies were rated as of moderate quality, primarily due to small sample sizes, single-team designs, and limited adjustment for potential confounders. Nevertheless, using validated GPS/GNSS devices and standardized injury definitions strengthened the methodological rigor across studies. Inter-rater reliability of NOS ratings was good (ICC=0.84, 95% CI).

### Study outcomes and effect size calculation

The primary outcome was the incidence of lower-limb muscle injuries in football players, including hamstring, quadriceps, adductor, and calf injuries, as well as composite categories of non-contact and overuse muscle injuries. Only studies reporting outcomes according to established consensus definitions (e.g., time-loss or medical-attention criteria) were included. Exposure variables comprised training-load metrics obtained from GPS/GNSS and IMU devices, including total distance, high-speed running distance, sprint distance, accelerations and decelerations, weekly acute workload, four-week rolling-average chronic workload, ACWR, and composite in-

dices such as player load.

For the meta-analysis, studies were eligible if they provided sufficient statistical information (odds ratios [ORs], relative risks [RRs], hazard ratios [HRs]), or raw data permitting conversion to effect sizes). Reported ORs and RRs were extracted directly, and when 95% confidence intervals (CIs) were available, log odds ratios (logOR) and their standard errors (SE) were computed using standard formulas. If only HRs were reported, they were synthesized qualitatively but not pooled. Log odds ratios were calculated as  $\log OR = \ln(OR)$ , while the standard error was derived from the 95% CI using the formula  $SE_{\log OR} = (\ln[\text{upper\_CI}] - \ln[\text{lower\_CI}]) / (2 \times 1.96)$ , and the variance as  $vi = SE_{\log OR}^2$  ( $\ln$  denotes the natural logarithm).

Effect sizes were pooled using a random-effects model to account for between-study heterogeneity. Subgroup analyses were planned to compare non-contact and overuse injuries; however, because of the limited number of studies, these comparisons were interpreted narratively rather than pooled. Heterogeneity was assessed using Cochran's  $Q$  ( $\chi^2$ ),  $\tau^2$ , and  $I^2$ , and publication bias was assessed visually using funnel plots. The quantitative synthesis was performed in Review Manager (RevMan, version 5.4; Cochrane Collaboration, London, UK). RevMan generated forest plots displaying individual study estimates ( $\log(OR)$  or  $\log(RR)$ ), their standard errors and study weights, alongside the pooled effect size with 95% CI, illustrating consistency across studies. Heterogeneity statistics ( $\tau^2$ ,  $\chi^2$ , and  $I^2$ ) and the overall test of effect ( $Z$  statistic and  $p$ -value) were also produced. In accordance with PRISMA guidelines, the forest plots were exported directly from RevMan and incorporated into the Results section.

Because the number of eligible studies was extremely limited ( $n=4$ ), subgroup analysis and meta-regression could not be performed due to insufficient statistical power. Although 15 odds-ratio comparisons were analyzed, these outcomes originated from only two original studies, which further restricted the ability to explore sources of heterogeneity. Consequently, while several training-load indicators suggested an elevated injury risk, the high heterogeneity ( $\tau^2=0.69$ ,  $\chi^2=192.56$ ,  $p<0.00001$ ,  $I^2=93\%$ ) could not be meaningfully investigated, and a random-effects model was applied for all pooled estimates.

### Secondary analysis

Secondary analyses were performed to evaluate the robustness of the pooled effects. Publication bias was assessed visually using funnel plots; however, because fewer than ten studies were included in the meta-analysis, the interpretation of any asymmetry was limited. Sensitivity analyses (e.g., leave-one-out procedures) and formal statistical tests (e.g., Egger's regression test, prediction intervals) were initially planned but not performed due to the small number of eligible studies. Therefore, the results of the secondary analyses should be interpreted with caution. All analyses used Review Manager (RevMan, version 5.4; Cochrane Collaboration, London, UK).

Because the included studies reported effect estimates using different statistical measures (i.e., odds ratios and relative risks), pooling was performed separately for OR-based

and RR-based outcomes. Converting OR to RR was avoided because the required baseline-risk assumptions could not be satisfied given the heterogeneity across studies. Therefore, two independent meta-analyses were conducted, and their findings were interpreted with caution due to the limited number of available studies. Because the number of included studies was limited (n=4), subgroup analysis and meta-regression could not be performed due to insufficient statistical power. Consequently, heterogeneity was addressed using a random-effects model for all meta-analytic calculations.

## Results

The initial database search identified 100 records (Scopus, n=70; PubMed, n=30). After deduplication, 70 unique records remained for screening. Following title and abstract screening, 33 records were excluded, leaving 37 full-text articles for eligibility assessment. Of these, 25 were excluded due

to lack of GPS/GNSS-derived workload data (n=9), absence of injury outcomes (n=5), or ineligible study design (n=11). Consequently, 12 studies met all inclusion criteria and were included in the qualitative synthesis and methodological quality assessment (Figure 1). Because several studies reported multiple effect sizes (e.g., Malone et al., 2018: six; Jaspers et al., 2018: nine; Nobari et al., 2021: four; Nobari et al., 2022: two), the meta-analysis was based on 21 independent comparisons (15 OR-based, 6 RR-based). The studies varied in sample size, competitive level, and exposure measures, but all met the eligibility criteria and provided sufficient statistical information for pooling. The methodological quality of these 12 studies was appraised using the Newcastle–Ottawa Scale (NOS). Overall, the studies demonstrated acceptable quality, with scores ranging from 5 to 8. Based on the ratings, five studies were categorized as low risk of bias, six as moderate, and one as high. Details of the assessment are presented in Table 2.

**Table 1.** Study characteristics

Authors (Year)	Country	Population	Load Variables	Injury Outcomes	Key Results	Meta-analysis Eligibility
Morgans et al. (2025)	England	30 EPL players	Sprint distance	Hamstring injury	Players who sustained injuries had higher sprint distance in the week prior to injury (p = 0.038).	Insufficient data
Zumeta-Olaskoaga et al. (2025)	Spain	36 LaLiga players	Cumulative distance, avg. speed	Non-contact injuries	Cumulative workload from the last seven sessions was associated with increased injury risk.	Not compatible
Soler et al. (2025)	Spain	41 LaLiga players	TD, HMLD, Acc/Dec	Calf injuries	Greater total distance and high metabolic load distance in the week before injury were significantly associated with calf injuries.	Not compatible
Marshall et al. (2024)	Germany	23 Bundesliga players	HMLD, ACWR, CW	Non-contact injuries	Chronic workload was the strongest predictor of injury compared to acute workload or ACWR.	Narrative only
González et al. (2024)	Spain	24 FC Barcelona Women	Player load + omics	Non-contact injuries	Combining player load with genetic and metabolomic data improved injury risk prediction compared to workload alone.	Narrative only
Herazo-Sánchez et al. (2024)	Colombia	31 pro players	TD, HIRd, sprints	Hamstring injuries	No significant associations were found between external workload and hamstring injuries.	Narrative only
Nilsson et al. (2023)	Sweden	56 youth elite players	Internal & external load	Trauma & overuse injuries	Sudden increases in training load were associated with higher injury risk, while regular sprinting appeared to have a protective effect.	Narrative only

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**Table 1.** Study characteristics

Authors (Year)	Country	Population	Load Variables	Injury Outcomes	Key Results	Meta-analysis Eligibility
Martins et al. (2023)	Portugal	33 Liga players	TD, HSR, ACC, DEC	Lower-limb injuries	Higher total distance, high-speed running, accelerations, and decelerations in the four weeks before injury were linked to increased risk.	Narrative only
Nobari et al. (2022)	Iran	21 pro players	ACWR, 1-AW	Non-contact injuries	Weeks with high ACWR or acute workload variation were associated with higher risk of non-contact injuries (OR/RR significant).	Included (RR)
Nobari et al. (2021)	Iran	21 pro players	TD, HSD, SPD, RS	Non-contact injuries	High sprint-related loads (total distance, high-speed distance, sprint distance) significantly increased the risk of non-contact injuries (OR/RR significant).	Included (RR)
Jaspers et al. (2018)	Turkey	30 pro players	TD, HSR, s-RPE	Overuse injuries	Greater total distance and higher session-RPE were significant predictors of overuse injuries (OR significant).	Included (OR)
Malone et al. (2018)	Europe	37 elite players	HSR, sprinting, chronic load	Lower-limb injuries	Excessive high-speed running and sprinting loads increased injury risk, while good aerobic fitness and chronic high load had protective effects.	Included (OR)

Abbreviations: TD-total distance; HMLD-high metabolic load distance; Acc/Dec-accelerations/decelerations; ACWR-acute:chronic workload ratio; CW-chronic workload; HIRd-high-intensity running distance; HSR-high-speed running; ACC-accelerations; DEC-decelerations; 1-AW-one-week acute workload; HSD-high-speed distance; SPD-sprint distance; RS-repeated sprint; s-RPE-session rating of perceived exertion. Studies labeled as "Not compatible" or "Insufficient data" were excluded from the quantitative synthesis because they did not provide the minimum numerical information required for effect-size calculation.

**Table 2.** Quality assessment of included studies – Newcastle–Ottawa Scale (NOS)

Author/Year	Selection	Comparability	Outcome	Total	Risk of Bias
Morgans et al. (2025)	3	1	2	6	Moderate
Zumeta-Olaskoaga et al. (2025)	4	1	2	7	Moderate
Soler et al. (2025)	3	1	2	6	Moderate
Marshall et al. (2024)	3	2	2	7	Low
González et al. (2024)	3	1	3	7	Low
Herazo-Sánchez et al. (2024)	2	1	2	5	High
Nilsson et al. (2023)	3	1	2	6	Moderate
Martins et al. (2023)	3	1	2	6	Moderate
Nobari et al. (2022)	4	2	2	8	Low

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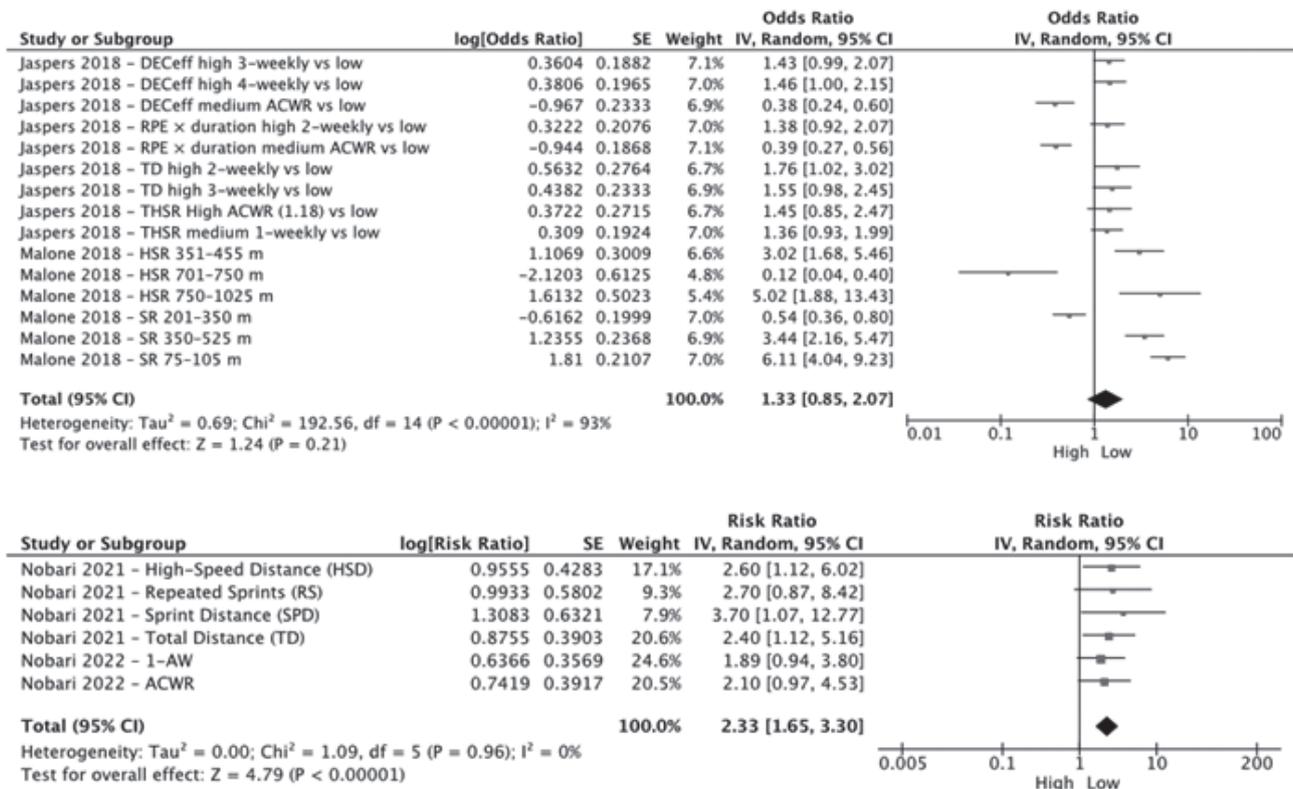
**Table 2.** Quality assessment of included studies – Newcastle–Ottawa Scale (NOS)

Author/Year	Selection	Comparability	Outcome	Total	Risk of Bias
Nobari et al. (2021)	4	2	2	8	Low
Jaspers et al. (2018)	3	1	3	7	Low
Malone et al. (2018)	3	1	2	6	Moderate

Because the extractable studies used different effect-size metrics (OR vs. RR), two independent meta-analyses were performed. OR-based and RR-based results were therefore interpreted separately to avoid combining conceptually incompatible estimates. A meta-analysis of studies reporting odds ratios (ORs) (Jaspers et al., 2018; Malone et al., 2018) showed no significant association between high training load and increased risk of lower-limb muscle injury (pooled OR=1.33; 95% CI [0.85–2.07],  $p=0.21$ ). Study-specific estimates between studies varied widely (OR ranged from 0.12 to 6.11), reflecting differences in workload definition such as sprint distance, high-speed running, session-RPE, and total distance. Heterogeneity between studies was very high ( $Tau^2=0.69$ ,  $Chi^2$  192.56,  $p$  0.00001,  $I^2=93%$ ), indicating inconsistency in study results. Thus, although some training load indicators showed an increased risk of injury, the combined effect did

not reach statistical significance. It should also be noted that despite the relatively large number of outcomes analyzed (15 OR-based comparisons), these were derived from only two original studies. This limited study base reduces the robustness of the findings and increases the risk of bias, warranting cautious interpretation.

In contrast, studies reporting risk ratios (RRs) (Nobari et al., 2021, 2022) indicated a consistent and robust association between higher workload and injury risk (pooled RR =2.33; 95% CI [1.65–3.30],  $p<0.00001$ ;  $I^2=0%$ ; Figure 2b). These findings suggest that athletes exposed to higher workloads have more than double the risk of injury compared with those with lower exposure. Risk estimates also appeared higher for non-contact injuries than for overuse injuries based on individual study results. However, no formal subgroup pooling was conducted due to the small number of studies.

**Figure 2a.** Forest plot of OR-based studies (upper figure);**Figure 2b.** Forest plot of RR-based studies (lower figure)

The contrast between the non-significant OR-based analysis and the significant RR-based analysis likely reflects differences in workload definitions, thresholding practices, and injury-risk modelling across studies.

A visual assessment of funnel plots was limited because fewer than ten studies were included. For RR-based analyses (Figure 3b), the plot appeared relatively symmetrical, suggesting low potential for publication bias and reasonable consistency across studies. In contrast, the OR-based funnel plot

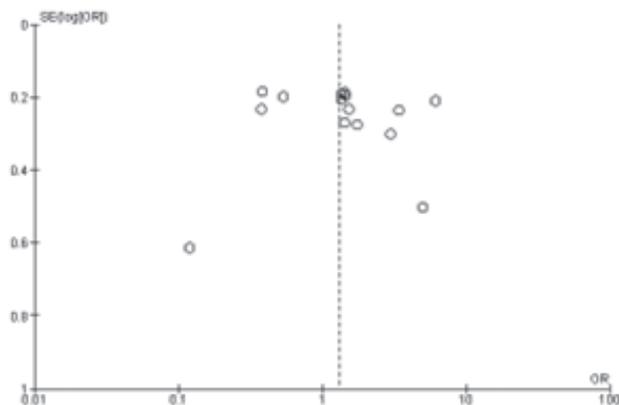


Figure 3a. Funnel plot OR

(Figure 3a) appeared asymmetrical, which may reflect high between-study heterogeneity and possible publication bias. Such asymmetry can arise when smaller studies with significant findings are more likely to be published than those with non-significant results, thereby distorting the pooled effect. Given the small evidence base (<10 studies), these patterns should be interpreted cautiously and do not constitute strong evidence of publication bias.

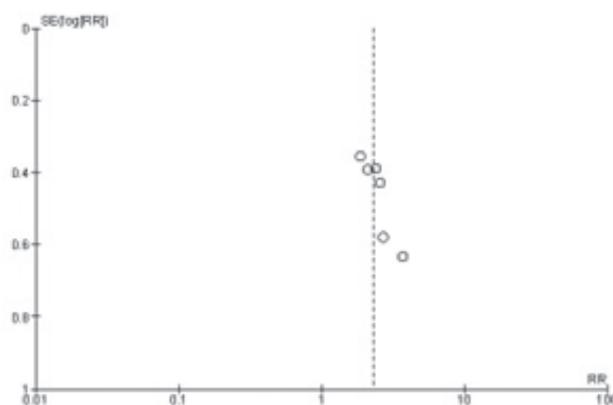


Figure 3b. Funnel plot RR

## Discussion

The results of this study indicate that the association between GPS/GNSS- and IMU-derived training load variables and the incidence of lower-limb muscle injuries in football players remains inconsistent. Analysis based on odds ratios (ORs) obtained from the studies by Malone et al. (2018) and Jaspers et al. (2018) showed no significant association between high training load and increased risk of injury (pooled OR=1.33; 95% CI [0.85–2.07]), and exhibited very high heterogeneity. Conversely, analysis using risk ratios (RR) from studies by Nobari et al. (2021, 2022) showed a strong and consistent relationship, where exposure to high loads was associated with more than double the risk of injury (pooled RR =2.33; 95% CI [1.65–3.30]), as well as low heterogeneity. These differing findings warrant cautious interpretation, given the small evidence base, variation in workload definitions, and differences in statistical approaches.

A major challenge in synthesizing the current evidence is the substantial heterogeneity in how external workload is defined and operationalized across studies. Speed thresholds for high-speed running and sprinting vary widely between teams and tracking systems, accelerometry-based variables lack standardized cut-offs, and ACWR is calculated using multiple non-equivalent approaches (e.g., rolling averages vs. EWMA models). These inconsistencies limit the comparability of workload metrics and likely contribute to the divergent findings observed between studies.

The inconsistency between OR and RR based results likely reflects differences in how definitions and selection of workload indicators in each study. For example, Malone et al. (2018) emphasized high-speed running (HSR) and sprinting with various distance cut-off ranges, while Jaspers

et al. (2018) focused on total distance and session-RPE. By contrast, Nobari et al. (2021, 2022) used acute workload, chronic workload, and ACWR, placing greater emphasis on weekly workload fluctuations. Certain variables, such as HSR, high-distance sprinting, and ACWR >1.5, are consistently reported with an increased risk of muscle injury (Malone et al., 2018; Nobari et al., 2021).

Conversely, moderate workload and good physical capacity can be protective. For example, higher aerobic capacity has been associated with reduced injury susceptibility in players with high training loads (Malone et al., 2018).

Physiologically, this can be explained through the concept of muscle fatigue and the accumulation of microtrauma from repeated exposure to sprints, accelerations, and decelerations. Exposure to excessive loads without adequate recovery can reduce the muscles' capacity to absorb external forces, increasing the risk of tissue damage (Carling et al., 2018; Colby et al., 2014). Conversely, when increased loads are applied gradually in accordance with the player's capacity, physiological adaptations can occur, reducing injury risk (Windt & Gabbett, 2017). Taken together, this indicates that the relationship between training load and injury is nonlinear and depends on the balance among external load, physical capacity, and recovery quality.

The findings in this review are consistent with prior work showing that load spikes—sudden increases in training load are important predictors of injury in football players. For example, Colby et al. (2014) found that abrupt increases in GPS-monitored running load correlated with a higher risk of injury in elite players.

A similar finding was reported by Windt et al. (2018), who noted that the relationship between training load and

injury is nonlinear, but rather influenced by the balance between load exposure and individual adaptive capacity. Carling et al. (2018) further observed that accumulating high loads in a short period may lead to neuromuscular fatigue and increased muscle damage, thereby increasing the risk of injury if not balanced with adequate recovery. Thus, although GPS-monitored training load can indicate risk, the relationship is not necessarily linear; it depends on the interaction among load intensity, distribution, and players' physiological capacity to tolerate load.

In practice, monitoring training load with GPS can serve as a warning system for coaches and medical teams by detecting load spikes that may increase injury risk. This information enables rapid adjustments to the training plan to keep load within a player's tolerance. Load management should prioritize preventing spikes and implementing progressive increases aligned with individual physical capacity. Indices such as ACWR can help monitor the balance between acute and chronic load, but they should not be used in isolation. Individual factors—such as age, playing position, and injury history—must also be considered to make prevention strategies more effective and to personalize training programs.

### Limitations

Although this review provides an overview of the association between GPS-based workload variables and lower-limb muscle injuries, several limitations should be considered. Multiple effect sizes were extracted from single studies, which may introduce dependency bias despite representing distinct workload variables. The quantitative evidence base was small: of the twelve eligible studies, only four provided extractable numerical data, contributing a total of 21 outcomes—most of which originated from just two primary studies. This limited evidence base reduces the statistical power and stability of the pooled estimates, restricts the possibility of subgroup or sensitivity analyses, and increases vulnerability to bias. Additionally, definitions of workload variables were not uniform (e.g., speed cut-offs for HSR and sprinting, ACWR formulas), inflating heterogeneity and hindering direct comparisons. Most studies were single-club with small samples, limiting generalizability, and publication bias remains possible.

The contrasting results between the OR-based and RR-based analyses further highlight the influence of methodological and definitional variability. The OR meta-analysis showed no significant association and very high heterogeneity, whereas the RR meta-analysis demonstrated a strong and consistent effect. This discrepancy likely reflects differences in how “high workload” was defined, the injury-risk models employed, and the types of workload metrics emphasized across the included studies. As such, differences in effect size metrics should not be interpreted as contradictory findings, but rather as evidence of non-equivalent exposure definitions.

Despite these limitations, the findings suggest that elevated external workloads—particularly when captured through GPS/GNSS metrics such as high-distance locomotor loads or repeated sprint exposures—may increase the risk of lower-limb muscle injuries. However, given the variability in workload definitions and small number of contributing stud-

ies, practitioners should apply these findings cautiously and prioritize individualized monitoring frameworks rather than rigid workload thresholds.

### Future research

To address these limitations, future research should use multi-club, multi-season designs with larger samples to improve representativeness. Standardizing the definition and measurement of training load—particularly sprint speed cut-offs, HSR, and ACWR—is essential to improve consistency across studies. In addition, integrating external load (GPS) with internal load (e.g., heart rate [HR] and session-RPE), together with individual factors such as fitness level, injury history, and genetic aspects, can provide a more comprehensive picture of injury risk. Looking ahead, machine-learning-based analytical approaches and predictive modelling (Saberisani et al., 2025), could help generate more accurate and applicable models for injury prevention in professional football.

### Conclusion

This systematic review and exploratory quantitative synthesis indicate that GPS-monitored training-load variables are associated with lower-limb muscle-injury risk in football players. However, the available evidence is limited and not entirely consistent. OR-based analyses found no significant association, whereas RR-based analyses showed more than a twofold increase in injury risk among players with high loads. These divergent results suggest that the relationship between training load and injury is nonlinear and influenced by variable definitions, analytical methods, and individual player capacity. GPS monitoring can serve as an early-warning system for coaches and medical teams to manage training load, emphasizing a balance between gradual progression and physical capacity. Nonetheless, the limited number of studies, variations in workload definitions, and small samples highlight the need for further research using multi-club designs, standardized variables, and modern predictive approaches to strengthen the evidence base.

#### Acknowledgments

There are no acknowledgments.

#### Conflict of interest

The authors declare no conflicts of interest.

**Received:** 03 October 2025 | **Accepted:** 08 January 2026 | **Published:** 01 February 2026

### References

- Buchheit, M., Simpson, B. M., Hader, K., & Lacombe, M. (2021). Occurrences of near-to-maximal speed-running bouts in elite soccer: insights for training prescription and injury mitigation. *Science and Medicine in Football*, 5(2), 105–110. <https://doi.org/10.1080/24733938.2020.1802058>
- Carling, C., Lacombe, M., McCall, A., Dupont, G., Le Gall, F., Simpson, B., & Buchheit, M. (2018). Monitoring of Post-match Fatigue in Professional Soccer: Welcome to the Real World. *Sports Medicine*, 48(12), 2695–2702. <https://doi.org/10.1007/s40279-018-0935-z>

- Clemente, F., Silva, R., Arslan, E., Aquino, R., Castillo, D., & Mendes, B. (2021). The effects of congested fixture periods on distance-based workload indices: A full-season study in professional soccer players. *Biology of Sport*, 38(1), 37–44. <https://doi.org/10.5114/biolSport.2020.97068>
- Colby, M. J., Dawson, B., Heasman, J., Rogalski, B., & Gabbett, T. J. (2014). Accelerometer and GPS-Derived Running Loads and Injury Risk in Elite Australian Footballers. *Journal of Strength and Conditioning Research*, 28(8), 2244–2252. <https://doi.org/10.1519/JSC.0000000000000362>
- de Dios-Álvarez, V., Suárez-Iglesias, D., Bouzas-Rico, S., Alkain, P., González-Conde, A., & Ayán-Pérez, C. (2023). Relationships between RPE-derived internal training load parameters and GPS-based external training load variables in elite young soccer players. *Research in Sports Medicine*, 31(1), 58–73. <https://doi.org/10.1080/15438627.2021.1937165>
- Fanchini, M., Rampinini, E., Riggio, M., Coutts, A. J., Pecci, C., & McCall, A. (2018). Despite association, the acute:chronic work load ratio does not predict non-contact injury in elite footballers. *Science and Medicine in Football*, 2(2), 108–114. <https://doi.org/10.1080/24733938.2018.1429014>
- Ferdinand, L., Hanief, Y. N., & Manimtim, R. M. (2025). Injury pattern and risk factors in grassroots football: A study of 10-year-old athletes. *Sport, Exercise, and Injury*, 1(1), 27–39. <https://doi.org/10.56003/sei.v1i1.512>
- Fousekis, A., Fousekis, K., Fousekis, G., Gkrilias, P., Michailidis, Y., Mandroukas, A., & Metaxas, T. (2025). Assessment of Injury Risk in Professional Soccer Players: A Long-Term Study. *Applied Sciences*, 15(9), 5039. <https://doi.org/10.3390/app15095039>
- Georgiadis, G., Van Gaal Appelhof, R., Stoop, R., Peters, J., & Essers, J. (2024). Association between External Load and Injury Incidence in Professional and Elite-Youth Football Players. *Physical Education and Sports: Studies and Research*, 3(1), 10–25. <https://doi.org/10.56003/pessr.v3i1.316>
- González, J. R., Caceres, A., Ferrer, E., Balagué-Dobón, L., Escriba-Montagut, X., Sarrat-González, D., ... & Rodas, G. (2024). Predicting Injuries in Elite Female Football Players With Global-Positioning-System and Multiomics Data. *International Journal of Sports Physiology and Performance*, 19(7), 661–669. <https://doi.org/10.1123/ijsp.2023-0184>
- Herazo-Sánchez, R. T., Jiménez-Trujillo, J. O., & González-Palacio, E. V. (2024). Unravelling the Relationship between External Load and the Incidence of Hamstring Injuries in Professional Soccer Players. *Physical Education Theory and Methodology*, 24(2), 224–231. <https://doi.org/10.17309/tmfv.2024.2.05>
- Jaspers, A., Kuyvenhoven, J. P., Staes, F., Frencken, W. G. P., Helsen, W. F., & Brink, M. S. (2018). Examination of the external and internal load indicators' association with overuse injuries in professional soccer players. *Journal of Science and Medicine in Sport*, 21(6), 579–585. <https://doi.org/10.1016/j.jsams.2017.10.005>
- Malone, S., Owen, A., Mendes, B., Hughes, B., Collins, K., & Gabbett, T. J. (2018). High-speed running and sprinting as an injury risk factor in soccer: Can well-developed physical qualities reduce the risk? *Journal of Science and Medicine in Sport*, 21(3), 257–262. <https://doi.org/10.1016/j.jsams.2017.05.016>
- Marshall, R. P., Schulze, S., Droste, J.-N., Riepenhof, H., Delank, K.-S., Kurz, E., & Schwesig, R. (2024). Is the Endurance Standardized ACWRHMLD or the Underlying Acute and Chronic Components Related to Injuries? *Applied Sciences (Switzerland)*, 14(20). <https://doi.org/10.3390/app14209427>
- Martins, F., Marques, A., França, C., Sarmiento, H., Henriques, R., Ihle, A., ... & Gouveia, É. R. (2023). Weekly External Load Performance Effects on Sports Injuries of Male Professional Football Players. *International Journal of Environmental Research and Public Health*, 20(2). <https://doi.org/10.3390/ijerph20021121>
- Morgans, R., Oliveira, R., Ceylan, H. I., Teixeira, J., Ryan, B., Modrić, T., & Moreira, A. (2025). High-intensity running and sprint distance prior to hamstring injury in elite male soccer players. Is there a common theme in over-or under-loading in the weeks preceding hamstring injury? *Journal of Physical Education and Sport*, 25(5), 946–953. <https://doi.org/10.7752/jpes.2025.05103>
- Nilsson, T., Börjesson, M., Lundblad, M., Ivarsson, A., & Fransson, D. (2023). Injury incidence in male elite youth football players is associated with preceding levels and changes in training load. *BMJ Open Sport and Exercise Medicine*, 9(4). <https://doi.org/10.1136/bmjsem-2023-001638>
- Nobari, H., Khalili, S. M., Denche-Zamorano, A. D., Bowman, T. G., & Granacher, U. (2022). Workload is associated with the occurrence of non-contact injuries in professional male soccer players: A pilot study. *Frontiers in Psychology*, 13. <https://doi.org/10.3389/fpsyg.2022.925722>
- Nobari, H., Mainer-Pardos, E., Denche-Zamorano, A. D., Bowman, T. G., Clemente, F. M., & Pérez-Gómez, J. (2021). Sprint variables are associated with the odds ratios of non-contact injuries in professional soccer players. *International Journal of Environmental Research and Public Health*, 18(19). <https://doi.org/10.3390/ijerph181910417>
- Piłka, T., Grzelak, B., Sadurska, A., Górecki, T., & Dyczkowski, K. (2023). Predicting Injuries in Football Based on Data Collected from GPS-Based Wearable Sensors. *Sensors*, 23(3), 1227. <https://doi.org/10.3390/s23031227>
- Saberisani, R., Barati, A. H., Zarei, M., Santos, P., Gorouhi, A., Ardigò, L. P., & Nobari, H. (2025). Prediction of football injuries using GPS-based data in Iranian professional football players: a machine learning approach. *Frontiers in Sports and Active Living*, 7. <https://doi.org/10.3389/fspor.2025.1425180>
- Soler, A., Agulló, F., Hernández-Davó, J., Raya-González, J., Del Coso, J., González-Ródenas, J., & Moreno-Pérez, V. (2025). Influence of the external workload on calf muscle strain injuries in professional football players: a pilot study. *Sports Health*, 17(1), 175–182.
- Sumartiningsih, S., Risdiyanto, A., Yusof, A., Rahayu, S., Handoyo, E., Puspita, M. A., ... & Hanief, Y. N. (2022). The FIFA 11+ for kids warm-up program improved balance and leg muscle strength in children (9–12 years old). *Journal of Physical Education and Sport*, 22(12), 3122–3127.
- Windt, J., Ardern, C. L., Gabbett, T. J., Khan, K. M., Cook, C. E., Sporer, B. C., & Zumbo, B. D. (2018). Getting the most out of intensive longitudinal data: a methodological review of workload–injury studies. *BMJ Open*, 8(10), e022626. <https://doi.org/10.1136/bmjopen-2018-022626>
- Windt, J., & Gabbett, T. J. (2017). How do training and competition workloads relate to injury? The workload–injury aetiology model. *British Journal of Sports Medicine*, 51(5), 428–435. <https://doi.org/10.1136/bjsports-2016-096040>
- Windt, J., Zumbo, B. D., Sporer, B., MacDonald, K., & Gabbett, T. J. (2017). Why do workload spikes cause injuries, and which athletes are at higher risk? Mediators and moderators in workload–injury investigations. *British Journal of Sports Medicine*, 51(13), 993–994. <https://doi.org/10.1136/bjsports-2016-097255>
- Zumeta-Olaskoaga, L., Bender, A., & Lee, D.-J. (2025). Flexible modelling of time-varying exposures and recurrent events to analyse training load effects in team sports injuries. *Journal of the Royal Statistical Society Series C: Applied Statistics*, 74(2), 391–405. <https://doi.org/10.1093/jrsssc/qlae059>