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REVIEW

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Acute to chronic workload ratio (ACWR) for predicting sports injury risk: a systematic review and meta-analysis

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Abstract

Background This study aimed to comprehensively and quantitatively evaluate the effectiveness of single-arm acute to chronic workload ratio (ACWR) in predicting sports injuries through an evidence-based approach and to provide references for injury prevention, physical training and training load management.

Methods Cohort studies on ACWR were retrieved from PubMed, Web of Science, ScienceDirect, CNKI, and Wanfang, covering the period from the inception of the databases to February 15, 2025. The quality of the included literature was evaluated using the Newcastle-Ottawa Scale (NOS), and a meta-analysis was conducted using Stata (version18.0).

Results A total of 22 single-arm cohort studies reporting injury incidence by ACWR category were included. Methodological quality assessment identified 16 high-quality (≥ 7 points) and 6 moderate-quality (4–6 points) indicating an overall high quality of the included research. The results of the Meta subgroup analysis showed that the injury incidence in tissue structures was 79% (95% CI [0.67; 0.89]), the injury incidence in the legs was 73% (95% CI [0.57; 0.86]). Additionally, the injury incidence in soccer players was 75% (95% CI [0.61; 0.87]), the injury incidence due to external loading was 64% (95% CI [0.53; 0.74]), or the injury incidence involving both internal and external loads was 69% (95% CI [0.45; 0.89]), and the injury incidence for individuals over the age of 25 was 73% (95% CI [0.50; 0.91]), whereas the injury incidence was minimized when the interval was kept at 0.8–1.3, with an injury incidence of 56% (95% CI [0.14; 0.94]).

Conclusion Although ACWR is associated with sports injury risk and may be useful in injury prevention strategies, it is necessary to use it with caution as a tool for measuring workload. Due to the heterogeneity between studies, potential publication bias, or differences in ACWR calculation methods, these factors may affect the research results. Therefore, future research should be clearer about its practical applicability. Systematic review registration: PROSPERO CRD42024615589.

Keywords Acute to chronic workload ratio, ACWR, Sports injury, Injury prevention, Injury prediction

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Introduction

The phenomenon of polarization in modern competitive sports demands that athletes endure greater training and competition loads. Both excessive and insufficient training loads can increase the risk of injury. The former is due to an increment of weekly load exceeding 1250 arbitrary units (AU) in football players [1], while the latter is because insufficient training load prevents athletes from meeting the demands of a large number of acceleration and deceleration loads during competitions [2]. To deeply explore the influence of factors such as training workload, competition workload, physical adaptation status and fatigue level on the prediction of athletic performance, various theoretical models have been developed in the field of sports science. Among them, the Fitness-Fatigue two-factor model proposed by Banister in 1982 [3], this model suggests that athletic performance was the result of a dynamic equilibrium between the two opposing effects of adaptive improvement (physical fitness gain) and fatigue accumulation (physical energy depletion). As the demand for precise load monitoring and injury prevention in competitive sports continues to grow, subsequent studies have continuously deepened and expanded this framework. For instance, researchers such as Hulin proposed the concept of Acute to Chronic Workload Ratio (ACWR) innovatively in 2014, defined as the ratio of 1-week acute workload to 4-week chronic workload, and applied it to cricket for the first time [4]. However, it was necessary to emphasize that there are differences in the calculation methods of the ACWR (such as the Rolling Average, RA, and the Exponentially Weighted Moving Average, EWMA), and the differences in the two calculation methods may directly affect the final calculation result of ACWR [5, 6]. and literature searches have found that many studies have applied ACWR to sports such as football, rugby, and tennis, assessing training load and exploring potential associations with injury occurrence for athletes using ACWR.

Literature search revealed that current research mainly focused on discussing the optimal range of ACWR or the application of calculation formulas. While most citations support ACWR's utility, studies with null or contradictory findings (e.g., Fanchini et al., 2018; Suarez-Arrones et al., 2020) should be acknowledged to reflect ongoing debate [7, 8]. Regarding the controversy over training workload measurement indicators (such as session-RPE versus GPS-derived data) [5], some studies, based on systematic reviews, suggested that different workload management tools can be used to calculate ACWR [9, 10]. However, they have not resolved issues such as determining the optimal ACWR for individuals [7], and distinguishing the relationship between load and injury severity [11]. Additionally, there was a lack of research on the moderating variables between the use of ACWR for intervention and injury prediction effects, such as gender, age, sport differences, and injury sites [12, 13]. Most empirical studies on ACWR adopted a combination of prospective and retrospective research paradigms, and their data sources were in line with the research nature of this study. Therefore, based on high-quality literature, this study conducted a meta-analysis on the sample size and the injury cases of the included studies to clarify the practical feasibility of ACWR's application, aiming to provide valuable reference for the prevention of sports injuries.

Materials and methods

This systematic review and meta-analysis was first registered on the PROSPERO website in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines (PROSPERO ID: CRD42024615589) [14].

Search strategy

Literature searches were conducted in databases such as PubMed, Web of Science, ScienceDirect, CNKI, and Wanfang. The search period covered from the establishment of the databases until February 15, 2025, and the search strategy combined subject headings and free-text terms. The literature search formula in the ScienceDirect database was (acute: chronic workload ratio and ACWR), and the literature searches in PubMed, Web of Science, CNKI, Wan fang were ("acute: chronic" OR "acute chronic" OR "acute: chronic workload" OR "acute chronic workload" OR "acute: chronic workload ratio" OR "workload ratio" OR "cumulative load" OR "training load" OR "training volume" OR "ACWR") AND ("injury" OR "contact" OR "non-contact" OR "time loss"). And additional search of grey literature was performed. The two authors conducted a literature search following the PRISMA 2020-compliant flow diagram and then screened the title/abstract and full text independently, as well as utilized EndNote X9 [Clarivate analytics, 2018] to deduplicate the literature, and consulted the third author to resolve disagreements.

Selection criteria

Inclusion criteria: (1) Cohort study (prospective and retrospective cohort); (2) At least one sports event included; (3) The training plan should include either internal load or external load (e.g., internal = session-RPE; external = total distance, accelerations, and so on); (4) The experimental subjects are athletes.

Exclusion criteria: (1) Review articles; (2) Conference proceedings, books, or dissertations; (3) Studies with unavailable full text of missing data; (4) Studies that do not explicitly address the relationship between injury and training (studies where injury was only a secondary descriptive outcome).

Data extraction

In this study, all the eligible research data were independently extracted by two reviewers and recorded it in the predetermined form in the Excel table, and the third author was responsible for verifying the extracted data to ensure the consistency among the included literature. The extracted relevant data contained in the articles: study (authors and year), participants (sex, age, athlete type), study type (research type and data collection period), measurement indicators (internal workload or external workload), sample size, injury cases, injury conditions (injured area).

Methodological quality assessment

In this study, when combining the research results, it was necessary to avoid bias in the research outcomes due to the low quality of the literature. Therefore, it was necessary to conduct a quality evaluation of the literature. This review adopted the tool recognized by the Cochrane Collaboration for evaluating non-randomized cohort studies [15], the Newcastle-Ottawa Scale (NOS) [16], to conduct quality assessment on the included literature. The content evaluated by NOS includes: selection of research subjects (4 items), comparability of study cohorts (1 item), and result evaluation (3 items), and the score range is (0–4), (0–2), and (0–3), with a maximum score of 9. A score of ≥ 7 indicates high quality, a score of 4–6 indicates medium quality, and a score of < 4 indicates low quality literature. Additionally, in the process of literature inclusion and evaluation for this study, it was independently completed by two authors. In case of any disagreement, the opinion of the third author would be sought to ensure the accuracy of the research results.

Statistical analysis

In this study, Stata (version18.0) statistical software was used for forest plotting, meta-regression analysis, subgroup analysis, sensitivity analysis, funnel plots drawing, and Begg's rank correlation test and Egger's regression test for publication bias. The literature included were all single-arm cohort studies, and the outcome indicators were all dichotomous variables, so the effect value (ES) and 95% CI were chosen as the effect scales for the combined effect sizes. The I^2 statistic and Q-test were used to test the heterogeneity of the included study, if $P < 0.05$ and I^2 >50% indicates greater heterogeneity, a random effects model will be used, and vice versa, a fixed effects model will be used, and if I^2 >75%, meta-regression analysis, subgroup analysis, and sensitivity analysis will be required to explore the source of heterogeneity. In this study, the funnel plot method, Begg's rank correlation test and Egger's regression test will be used to detect publication bias and draw a schematic diagram for assessment, and publication bias is considered to exist if the *P*-value of Begg and Egger test is < 0.05. All analyzed results in the study were tested using two-sided test and were considered statistically different with $P < 0.05$.

Results

Included studies

The specific search process is shown in Fig. 1. By searching WOS ($n = 1634$), PubMed ($n = 872$), ScienceDirect ($n = 116$) and other databases ($n = 441$), a total of 3063 pieces of literature were retrieved 969 pieces of duplicate literature were deleted by using EndNote (version 21.5), and 1707 records were excluded after title and abstract screening. Meanwhile, 23 studies were traced back to the literature, and finally after careful reading, 22 studies were decided to be included.

Literature characteristics

A total of twenty-two studies were included (Table 1), among them, twenty-one studies had injury records, and one literature was not recorded. A total of 921 participants were included, with 657 reported injuries, accounting for approximately 71.34% of the sample. Most of the injuries were tissue and structure injuries, mainly in terms of muscular tissues, with a total of seventeen studies, followed by injuries to the lower extremities of the legs with a total of fourteen studies, and two literatures had no record of the injuries. in terms of gender, two studies used both male and female subjects, and one literature was not detailed records, last were all male, the remaining studies involved only male athletes. The period of data collection included seven studies focused on the period before the official games, and fifteen studies during the official games, and the sports involved were seventeen studies of soccer, two studies of tennis and rugby respectively, one study of hockey, and the literature on soccer direction included in this research accounted for about 81% of the total literature, meanwhile, seventeen studies were prospective cohort studies, and the other five studies were retrospective cohort studies.

Effects of ACWR on sports injuries

Meta-analysis results

The result of the analysis is shown in Fig. 2. In this research, a forest plot was drawn based on the number of sample size and injury cases, and the forest plot showed the results of the ACWR in different ratios for the prediction of sports injuries, the heterogeneity was determined by the Q-test, where $P < 0.1$ was considered significant. A total of twenty-two studies were included in this research, and the results showed a high degree of heterogeneity among studies, so the random effects model

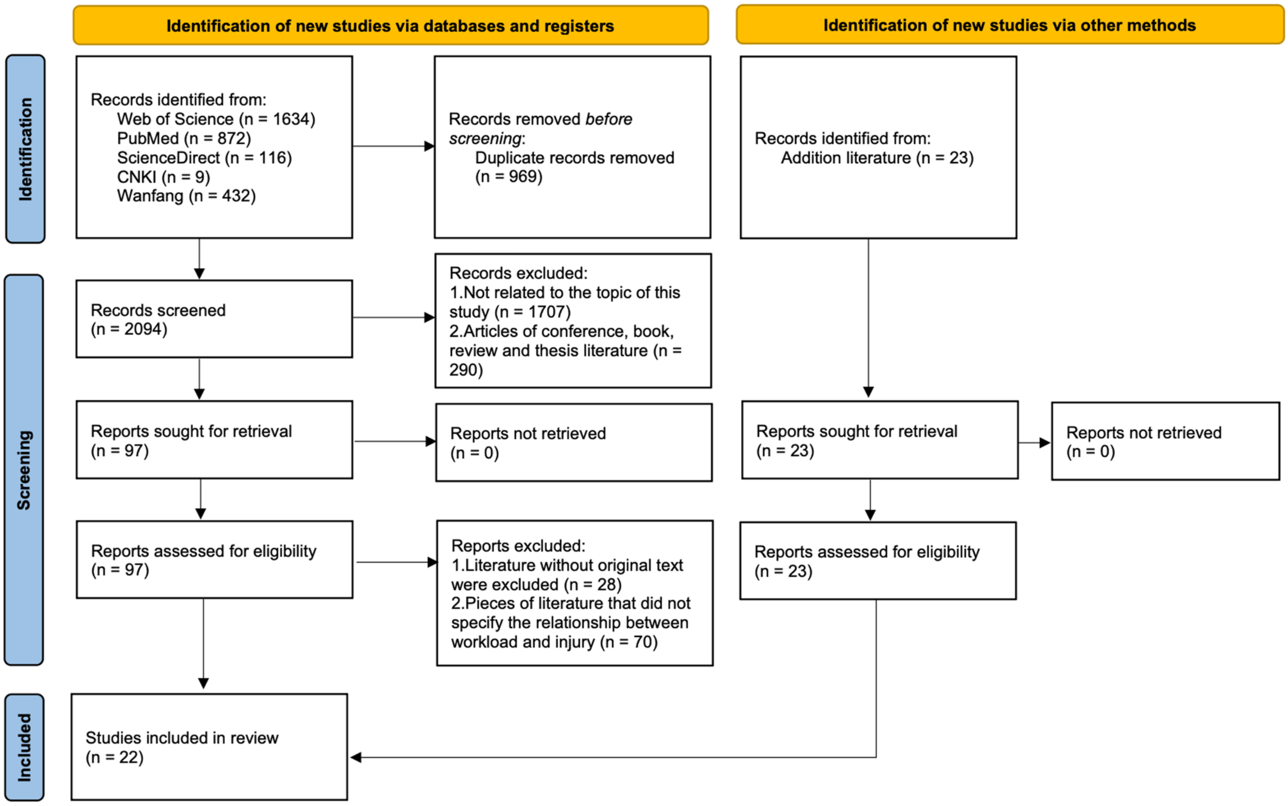

Fig. 1 PRISMA 2020 flow diagram for updated systematic reviews which included searches of databases, registers and other sources

was used to combine them, resulting in a statistically significant combined effect size (ES = 0.72, 95% CI [0.60; 0.82]; Z = 14.47, $P < 0.01$), indicating a positive association between ACWR and injury occurrence, the results of the heterogeneity test showed statistically significant differences between the studies ($P < 0.05$).

Relationship between ACWR and different sites of injury

This research conducted a combined analysis of two or more studies with the same injury site. When I^2 >50, the random effects model was employed, and the results of the analysis are shown in Table 2. The subgroup analysis showed that there was no significant difference in the head. Instead, the significant differences were concentrated in the tissue structure (ES = 0.79, 95% CI [0.67; 0.89]), legs (ES = 0.73, 95% CI [0.57; 0.86]), upper limbs (ES = 0.83, 95% CI [0.65; 0.96]), abdomen (ES = 0.64, 95% CI [0.28; 0.94]), buttocks (ES = 0.89, 95% CI [0.62; 1.00]), back (ES = 0.82, 95% CI [0.72; 0.90]), trunk (ES = 0.83, 95% CI [0.69; 0.93]), and bones (ES = 0.86, 95% CI [0.73; 0.96]), and all of them were statistically significant ($P < 0.05$), However, face and neck injuries were not analyzed because only recorded facial injuries [12] and another recorded neck injury [26] in the outcome indicators.

Sources of heterogeneity

Meta-regression analysis, subgroup analysis, and sensitivity analysis were necessary when heterogeneity exceeds 50% (I^2 >50%). In this research, substantial heterogeneity was observed, so we conducted meta-regression and subgroup analyses to explore potential contributing factors. Six indicators were selected based on the study data, study type, measurement indicators, measurement period, age range, sport programs and specific intervals, and a one-way meta-regression analysis was conducted for these indicators. Meta-regression analysis showed that no statistically significant effects for study type ($P = 0.673$), sport program ($P = 0.292$), measurement indicator ($P = 0.755$), age range ($P = 0.705$), measurement period ($P = 0.589$), or specific interval ($P = 0.319$) (all $P > 0.05$). The results of the one-way meta- regression analysis showed that none of these six factors had a significant moderating effect on the effect size. This might indicate that the current effect size was relatively stable for these factors, or that the true effect is too small to be detected, and the specific results are shown in Table 3. Although these statistical factors did not significantly explain the heterogeneity, the high I^2 values likely reflect clinical diversity, such as variations in population characteristics (such as athlete fitness level, sport-specific demands), differences in ACWR calculation methods,

Table 1 Basic characteristics of the literature included in this study ($n = 22$)

Author, year	Participants	Study type	Sports	Measurement indicators	Sample size	Injury cases	Injured condition
Ehrmann et al., 2016 [2]	M, 25.7 ± 5.1, Professional Athletes	Retrospective study, In-season	Soccer	ETL: TD、HIR、VHIR、MS、PL	19	11	(1), (4)
Malone et al., 2017 [17]	M, 24 ± 3, Elite Athletes	Prospective study, Pre-season	Soccer	ITL; ETL: VHSD、sRPE	37	37	(12)
Malone et al., 2017 [18]	M, 25.3 ± 3.1, Elite Athletes	Prospective study, In-season	Soccer	ITL: sRPE; ETL: IAC	48	48	(1), (12)
Malone et al., 2017 [19]	M, 24.2 ± 2.9, Elite Athletes	Prospective study, In-season	Soccer	ITL: sRPE	37	37	(1), (3), (5), (7), (12)
Murray et al., 2017 [20]	M, 23 ± 4, Elite Athletes	Prospective study, In-season	Soccer	ETL: TD、LSD、MSD、HSD、VHSD、PL	59	40	(1)
Murray et al., 2017 [5]	M, 23.5 ± 4.4, Elite Athletes	Prospective study, In-season	Soccer	ETL: TD、LSD、MSD、HSD、VHSD、PL	59	40	(1), (12)
Lu et al., 2017 [21]	M, 26.4 ± 5.1, Professional Athletes	Prospective study, In-season	Soccer	ITL: sRPE; ETL: TD、LSD、HSD、VHSD、MS、PL	45	39	(12)
Esmaeili et al., 2018 [22]	M, 22.9 ± 3.9, Elite Athletes	Prospective study, In-season	Soccer	ITL: sRPE; ETL: TD、HIR、PL	55	33	(1), (12)
Murray et al., 2018 [23]	M, 22 ± 3, Elite Athletes	Prospective study, In-season	Soccer	ETL: TD、LSD、MSD、HSD、VHSD	45	31	(1), (4), (12)
McCall et al., 2018 [24]	M, 26.6 ± 4.7, Professional Athletes	Prospective study, In-season	Soccer	ITL: sRPE; ETL	33	7	(12)
McCall et al., 2018 [25]	M, 25.1 ± 4.9, Elite Athletes	Prospective study, In-season	Soccer	ITL: sRPE	171	129	(12)
Sampson et al., 2018 [26]	M, 20.7 ± 1.5, Student Athletes	Retrospective study, Pre-season	Soccer	ITL、ETL	52	46	(1), (2), (6), (9), (12)
Cummins et al., 2019 [27]	M, Professional Athletes	Retrospective study, Pre-season	Rugby	ETL: TD、RD、HSD、VHSD、ACC、DEC、PL	48	36	(12)
Arazi et al., 2020 [28]	M, 17.1 ± 0.7, semi, Professional Athletes	Prospective study, Pre-season	Soccer	ITL: sRPE; ET	22	15	(1), (2), (5), (12)
Suarez-Arrones et al., 2020 [8]	18.6 ± 0.8, Professional Athletes	Prospective study, Pre-season	Soccer	ITL: sRPE; ETL: TD、MSD、HSD、VHSD、SD	15	2	(1), (4)
Myers et al., 2020 [29]	M15, F16, Student Athletes	Prospective study, Pre-season	Tennis	ITL: sRPE; ETL	26	17	(1), (2), (5), (6), (10), (12)
Moreno-Pérez et al., 2021 [12]	M F, 17.2 ± 1.1, Student Athletes	Prospective study, Pre-season	Tennis	ITL: sRPE; ETL	15	15	(1), (2), (4), (5), (7), (8), (10), (11), (12)
Veiga et al., 2021 [30]	M, 19, 24, Elite Athletes	Prospective study, In-season	Hockey	ITL: sRPE、SSWS; ETL	14	0	*N*
Tiernan et al., 2022 [13]	M, 23.4 ± 4.8, Elite Athletes	Prospective study, In-season	Soccer	ITL: sRPE	15	15	(12)
Bakal et al., 2023 [31]	M, 20.2 ± 1.1, Elite Athletes	Retrospective study, In-season	Soccer	ETL: TD、HSD、ACC、MS、PL	23	16	(1), (11), (12)
Fousekis et al., 2023 [32]	M, 21.1 ± 0.6, Professional Athletes	Prospective study, In-season	Soccer	ETL: TD、ACC、DEC	35	9	(1), (12)
Iwasaki et al., 2024 [33]	M, 27.5 ± 3.1, Elite Athletes	Retrospective study, In-season	Rugby	ETL: TD、HSD	48	34	*N*

NOTE: M = male; F = female; ITL = internal loads; ETL = external loads; sRPE = session-Rating of Perceived Exertion: RPE×training duration; IAC = interval aerobic capacity; TD = total distance; LSD = low-speed distance; MSD = moderate-speed distance; HSD = high-speed distance; VHSD = very high-speed distance; RD = related distance; MS = moderate speed; SD = sprint distance; HIR = high-intensity running; LIR = low-intensity running; PL = player load; ACC = accelerates; DEC = decelerations; SSWS = specific subjective wellness scores: fatigue, sleep quality, general muscle soreness, mood and stress level; injured condition: (1): lower limbs; (2): upper limbs; (3): hands; (4): abdomen; (5): buttocks; (6): back; (7): head; (8): face; (9): neck; (10): trunk; (11): bones; (12): tissue structures

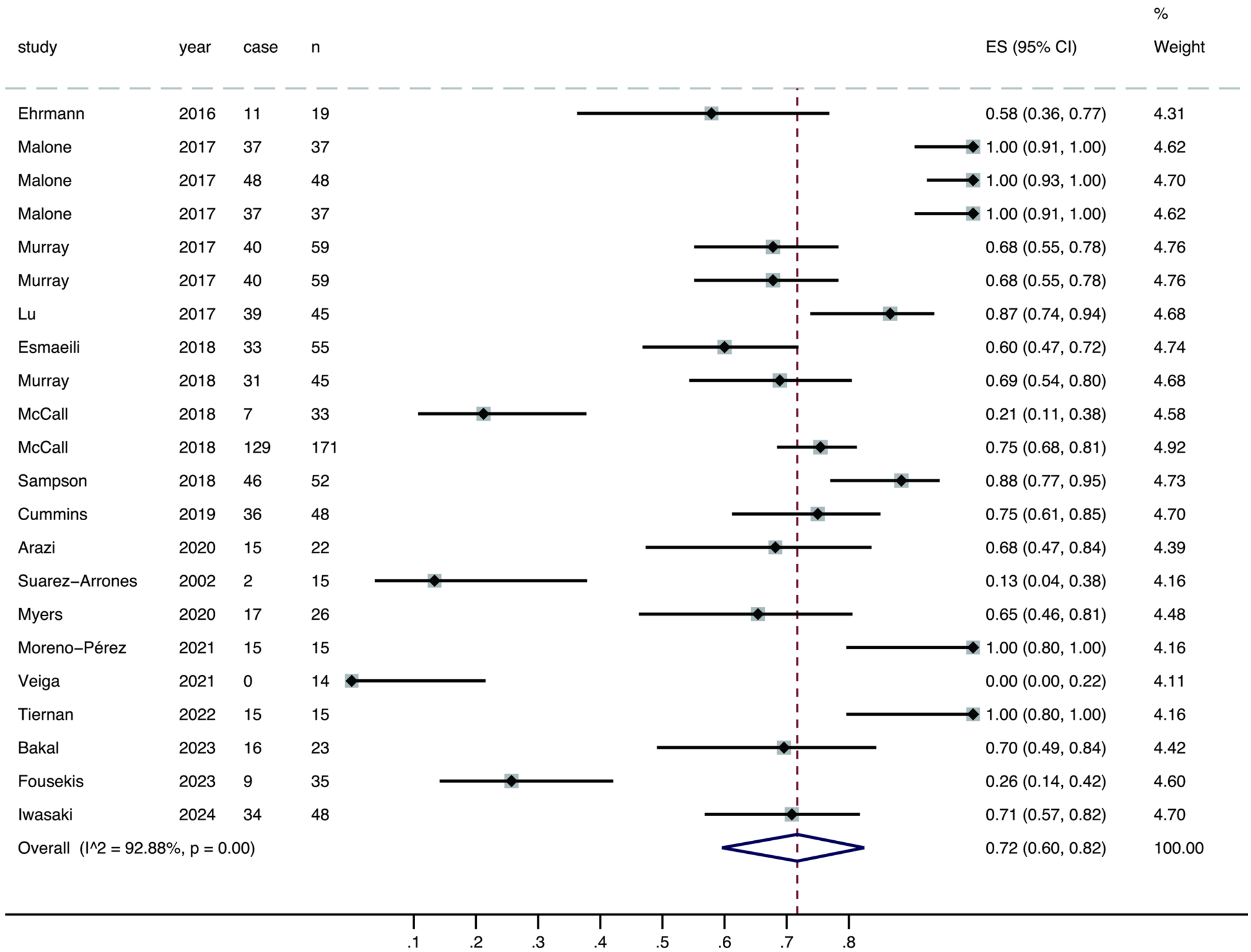

Fig. 2 Overall forest plot for inclusion in the literature. NOTE: ES > 0 indicates a positive association between higher ACWR and injury occurrence

Table 2 Specific results of meta-analysis for different sites of injury

Variables	No. of studies	Heterogeneity		Effect model	Meta-analysis		
		I^2	*P*		ES (95%CI)	Z	*P*
Tissue structures	17	92.5%	< 0.01	Random	0.79 (0.67, 0.89)	14.85	< 0.01
Lower limbs	14	92.0%	< 0.01	Random	0.73 (0.57, 0.86)	11.68	< 0.01
Upper limbs	4	78.7%	< 0.01	Random	0.83 (0.65, 0.96)	9.82	< 0.01
Abdomen	4	91.2%	< 0.01	Random	0.64 (0.28, 0.94)	4.46	< 0.01
Buttocks	4	89.5%	< 0.01	Random	0.89 (0.62, 1.00)	7.09	< 0.01
Back	2	80.0%	< 0.03	Random	0.82 (0.72, 0.90)	18.42	< 0.01
Head	2	0.0%	> 0.05	Fixed	1.00 (0.97, 1.00)	19.94	< 0.01
Trunk	2	91.2%	< 0.01	Random	0.83 (0.69, 0.93)	13.10	< 0.01
Bones	2	88.0%	< 0.01	Random	0.86 (0.73, 0.96)	13.09	< 0.01

Table 3 Specific results of one-way meta-regression analysis for each effect size

Effect indicator	β-regression coefficient	Standard error	T-value	*P*>| t |	95%CI
Literature types	-0.0582	0.1357	-0.43	0.673	-0.3410, 0.2249
Sport programs	-0.0822	0.0760	-1.08	0.292	-0.2407, 0.0763
Measurement indicators	0.0196	0.0622	0.32	0.755	-0.1100, 0.1493
Age range	-0.0353	0.0918	-0.38	0.705	-0.2274, 0.1569
Measurement period	-0.0668	0.1217	-0.55	0.589	-0.3207, 0.1871
Specific intervals	0.1109	0.1063	1.04	0.319	-0.1230, 0.3448

injury definition criteria, and contextual factors like training environment and competition level. These clinical and methodological variations may contribute substantially to the observed heterogeneity, even if not captured by the examined moderators.

Subgroup analysis again indicated high heterogeneity (I^2 >50% for all subgroups), leading to the use of random effects models (Table 4). All study types showed significant effects ($P<0.05$), with a smaller gap between retrospective cohort studies (ES = 0.75, 95% CI [0.64; 0.84]) and prospective cohort studies (ES = 0.71, 95% CI [0.55; 0.85]) suggesting that both have an impact on predicting sports injuries. In terms of sports, no injuries were recorded in hockey [29], however, soccer (ES = 0.75, 95% CI [0.61; 0.87]) had a greater impact on injuries, followed by tennis (ES = 0.83, 95% CI [0.69; 0.93]) and both were statistically significant ($P<0.05$). The probability of injury caused by the measure using only internal workloads (ES = 0.95, 95% CI [0.70; 1.00]) was greater than when using only external workloads (ES = 0.64, 95% CI [0.53; 0.74]) or when both internal and external workloads were included (ES = 0.69, 95% CI [0.45; 0.89]) was large and all were statistically significant ($P<0.05$). At the age level of the subjects, after 25 years (ES = 0.73, 95% CI [0.50; 0.91]) and between 20 and 25 years (ES = 0.72, 95% CI [0.53; 0.88]) were more prone to injury than before 20 years (ES = 0.66, 95% CI [0.28; 0.95]), and all were statistically significant ($P<0.05$). The data measurement intervals were all statistically significant ($P<0.05$), with data collection in the pre-season (ES = 0.76, 95% CI [0.56; 0.92]) having a greater impact on injuries than in-season (ES = 0.69, 95% CI [0.53; 0.83]). In terms of specific intervals, it was clearly observed that the 0.8–1.3 (ES = 0.56, 95% CI [0.14; 0.94]) interval had a lower probability of injury than < 0.8 (ES = 0.74, 95% CI [0.68; 0.80]) and > 1.3 (ES = 0.77, 95% CI [0.58; 0.92]).

Literature publication bias

The funnel plot (Fig. 3) showed that a few data points at the edges, but the overall distribution remains symmetric. Further statistical tests, including Begg's test (*P = 0.351*) and Egger's test (*P = 0.254*), confirmed the absence of significant publication bias. These findings indicated that no significant publication bias was detected; however, this does not exclude the possibility of bias (Figs. 4 and 5).

Sensitivity analysis

Sensitivity analysis was conducted on the twenty-two studies included in this research by excluding individual studies one by one, and the random effect model was chosen for the effect model, which showed that no significant changes were found in the combined results, indicating the stability of the results (Fig. 6).

Risk of bias and NOS

The specific evaluation process is shown in Table 5, among them, there are sixteen high-quality studies, and six medium-quality ones. The average NOS score for the included studies was 6.9, indicating a good overall methodological quality. However, some studies had limitations in the Comparability section, which may affect the precise estimation of the effect.

Table 4 Specific results of subgroup analysis for each effect size

Effect indicator	No. of studies	Heterogeneity		Subgroup	Meta-analysis		
		I^2	*P*		ES (95%CI)	Z	*P*
Literature types	22	92.9%	< 0.01	Retrospective	0.75(0.64, 0.84)	16.59	< 0.01
				Prospective	0.71(0.55, 0.85)	11.27	< 0.01
Sport programs	22	92.9%	< 0.01	Soccer	0.75(0.61, 0.87)	12.63	< 0.01
				Rugby	0.67(0.58, 0.76)	18.96	< 0.01
				Tennis	0.83(0.69, 0.93)	13.10	< 0.01
				Hockey	0.00(0.00, 0.22)	0.00	> 0.01
Measurement indicators	22	92.9%	< 0.01	Internal Loads	0.95(0.70, 1.00)	7.20	< 0.01
				External loads	0.64(0.53, 0.74)	15.58	< 0.01
				All	0.69(0.45, 0.89)	7.19	< 0.01
Age range	21	93.2%	< 0.01	< 20	0.66(0.28, 0.95)	4.35	< 0.01
				20–25	0.72(0.53, 0.88)	9.21	< 0.01
				> 25	0.73(0.50, 0.91)	7.91	< 0.01
Measurement period	22	92.9%	< 0.01	Pre-season	0.76(0.56, 0.92)	8.89	< 0.01
				In-season	0.69(0.53, 0.83)	11.13	< 0.01
Specific intervals	13	94.2%	< 0.01	< 0.8	0.74(0.68, 0.80)	28.72	< 0.01
				0.8–1.3	0.56(0.14, 0.94)	3.31	< 0.01
				> 1.3	0.77(0.58, 0.92)	9.42	< 0.01

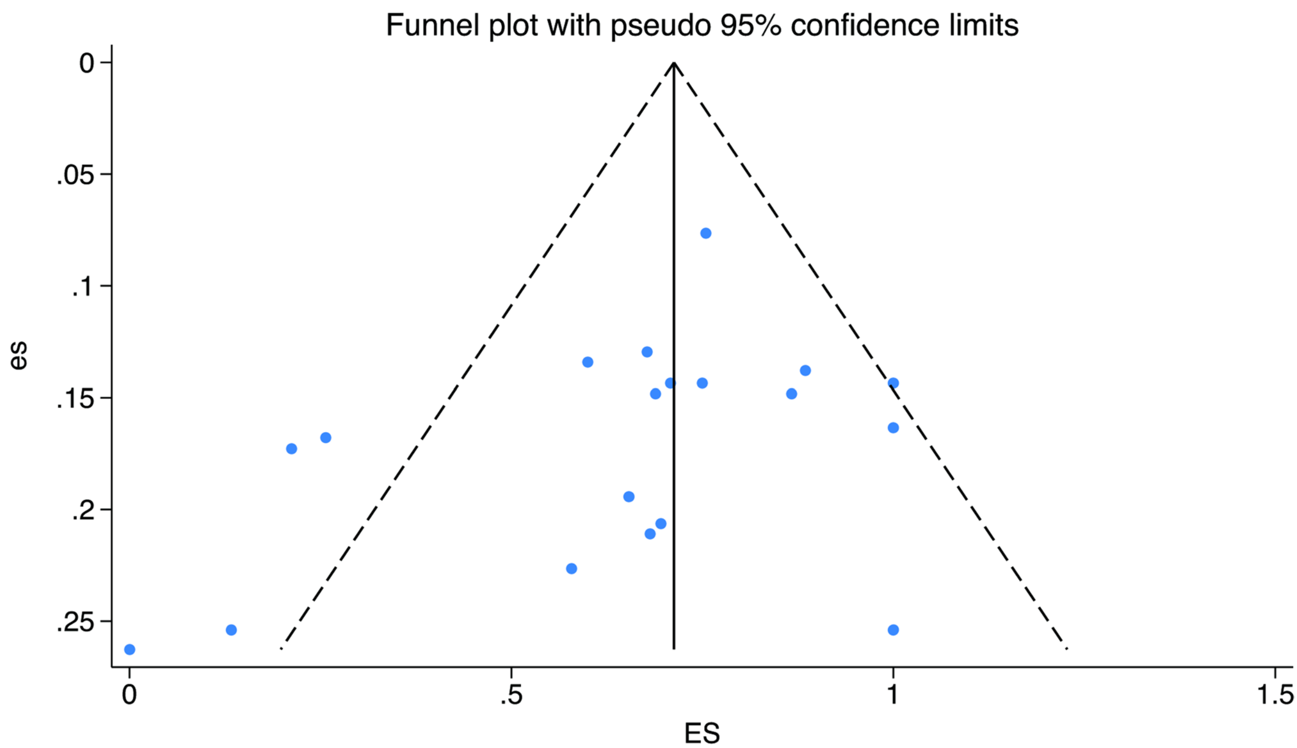

Fig. 3 Overall funnel plot of the included literature

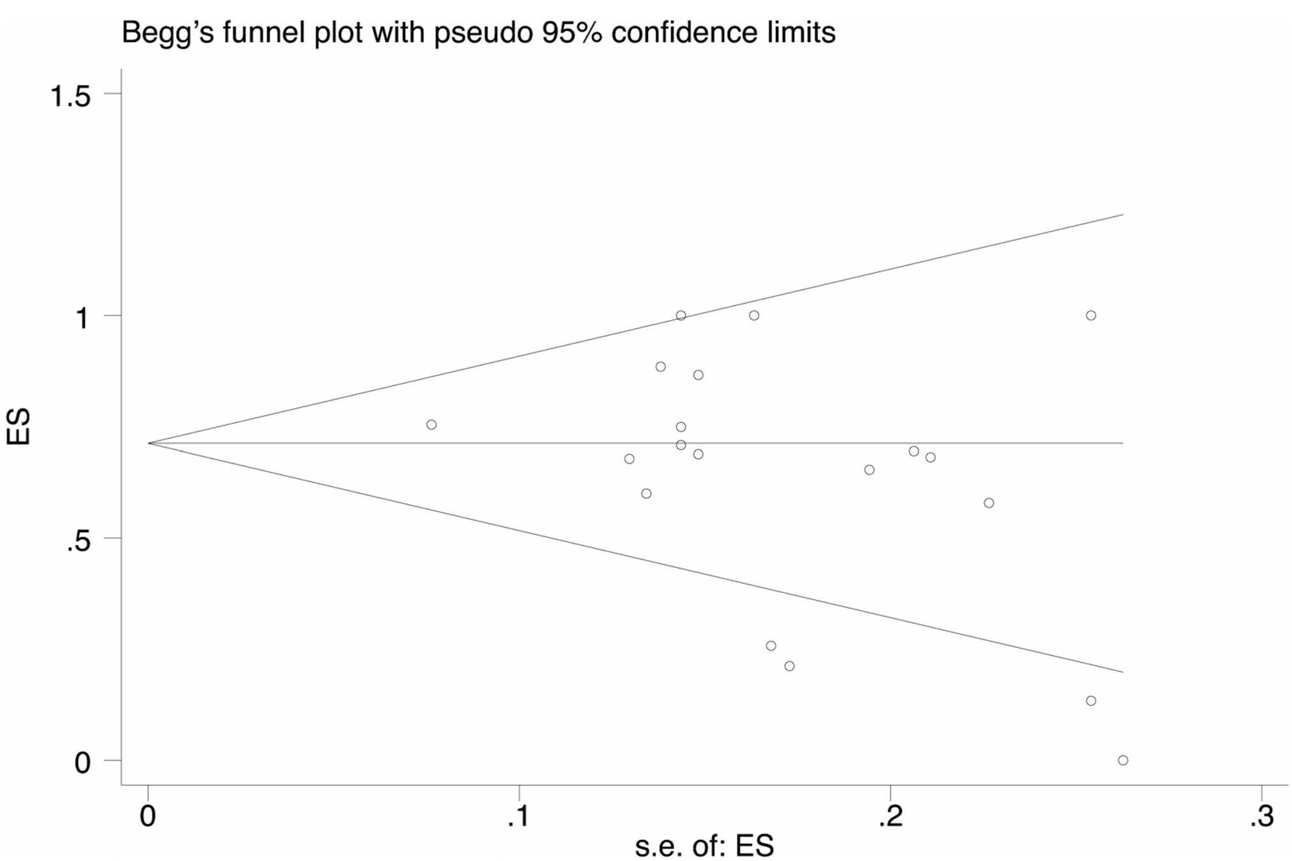

Fig. 4 Begg's test plot of the included literature

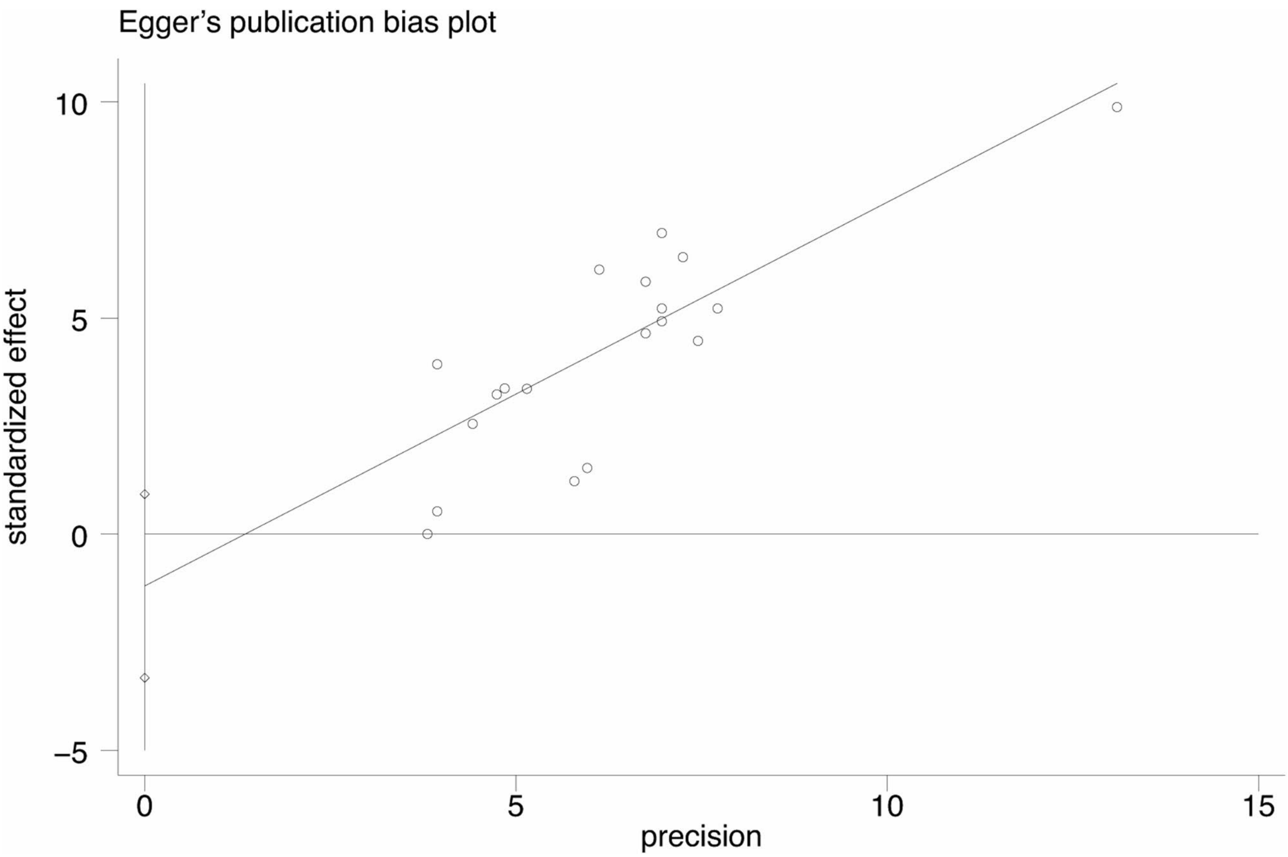

Fig. 5 Egger's test plot of the included literature

Discussion

Summary of main findings

At the injured condition, the results of meta-analysis showed that sports injuries occurred mostly in the tissue structure part such as: tendon, hamstring, popliteus muscle, lower limb parts and so on, the incidences was 79% and 73% respectively, and the types were mainly contact and non-contact injuries, however, there is no clear definition of contact injuries at present, and the related research is relatively limited [34], so this study focuses on exploring the effect of ACWR on non-contact injuries.

In terms of sports, this study included seventeen studies on soccer, two on tennis and rugby, and one hockey. These sports are characterized by high physical intensity and frequent movements such as sprinting, abrupt stops, and rapid turns, demanding high levels of endurance, speed, strength, and flexibility. Subgroup analysis indicated that an ACWR range of 0.8–1.3 represented a low-risk zone for sports injuries, it may help prevent injuries in soccer players [13, 18, 24, 28, 32], and this range has also been associated with reduced injury risk in cricket [4], tennis [29], and rugby [35]. In contrast, an ACWR exceeding 1.5 has been associated with a higher injury risk, this may increase the risk of injury in cricket [4], and tennis [29], when the ACWR > 2, there will be a 17% risk of injury for the rugby in the current week, and still be 12% risk in the following week [35], and may also cause injuries to football players [20]. However, the effect of training load on injury varies among individuals. While many studies have shown that an ACWR > 1.5 may increase injury risk, but some studies have reported cases where uninjured soccer players repeatedly exceeded this threshold during training [8], which might be related to their good tolerance capacity [36, 37]. Thus, many studies have confirmed that maintaining ACWR in the range of 0.8–1.3 may reduce the risk of injury, and most of them have noted that exceeding this range in one week may lead to an increased risk of injury in the following week.

In terms of workload type, this study analyzed eleven studies assessing both internal and external workloads, eight studies focusing solely on external workloads, and three studies using only internal workloads. Injury incidence varied depending on the measurement method used. Studies that measured internal workloads alone reported the highest injury incidence (ES = 0.95, 95% CI: 0.70-1.00). In contrast, studies combining internal and external workloads reported an injury incidence of 69%, while those using only external workloads had the lowest injury incidence. External workload represents an athlete's physical performance during training and is

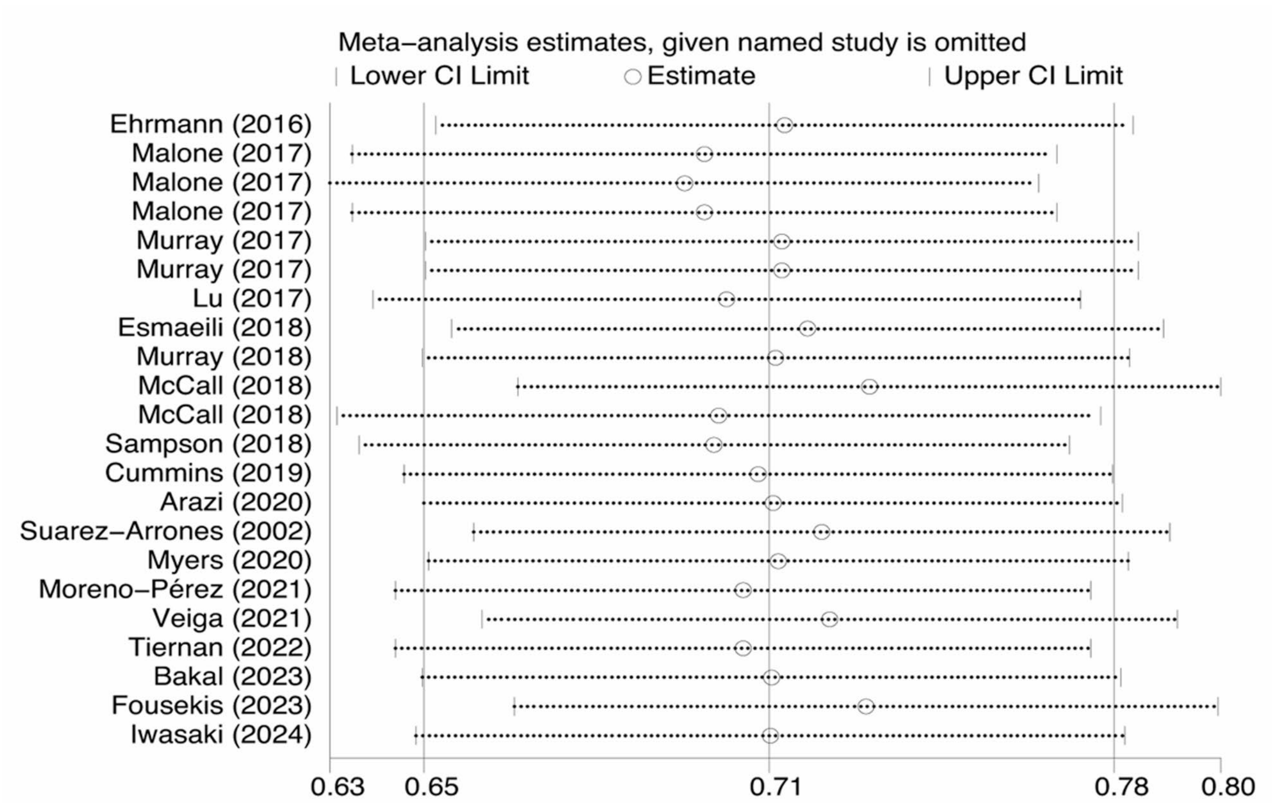

Fig. 6 Sensitivity analysis plot of the included literature

Table 5 Quality of included studies as assessed on the NOS

Authors, year	NOS scores				
	Selection	Comparison	Outcome	Total	Literature quality
Ehrmann et al., 2016 [2]	2	1	3	6	Moderate
Malone et al., 2017 [17]	3	1	3	7	High
Malone et al., 2017 [18]	3	2	3	8	High
Malone et al., 2017 [19]	3	1	3	7	High
Murray et al., 2017 [20]	2	1	3	6	Moderate
Murray et al., 2017 [5]	2	2	3	7	High
Lu et al., 2017 [21]	3	1	2	6	Moderate
Esmaeili et al., 2018 [22]	3	1	3	7	High
Murray et al., 2018 [23]	2	2	3	7	High
McCall et al., 2018 [24]	3	1	3	7	High
McCall et al., 2018 [25]	3	2	2	7	High
Sampson et al., 2018 [26]	2	1	3	6	Moderate
Cummins et al., 2019 [27]	2	2	3	7	High
Arazi et al., 2020 [28]	3	2	3	8	High
Suarez-Arrones et al., 2020 [8]	3	1	3	7	High
Myers et al., 2020 [29]	3	1	3	7	High
Moreno-Pérez et al., 2021 [12]	3	1	3	7	High
Veiga et al., 2021 [30]	3	1	3	7	High
Tiernan et al., 2022 [13]	3	1	3	7	High
Bakal et al., 2023 [31]	2	1	3	6	Moderate
Fousekis et al., 2023 [32]	2	2	3	7	High
Iwasaki et al., 2024 [33]	2	1	3	6	Moderate
Median	2.6	1.4	2.9	6.9	——

commonly measured by speed, acceleration, running distance, and similar parameters. In contrast, internal workload reflects an athlete's physiological and psychological response to training loads. Commonly used indicators include session-RPE, heart rate, blood lactate levels, and oxygen consumption. Internal workload is an important indicator of athletes' gradual adaptation to the increase of external workload. In this study, the internal workload measurements were made using only session-RPE, which is a more subjective method, while the external workload measurements were commonly performed with GPS devices.

In terms of sports experience, four studies included participants younger than 20 years old, eleven studies focused on athletes aged 20–25 years, and six studies included athletes over 25 years old. The analysis revealed a significant increase in injury incidence among athletes older than 20 years, with an overall incidence of approximately 72%. This trend may be attributed to age-related changes in skeletal muscle, including a decline in muscle mass and a reduction in both the size and quantity of muscle fibers [38], and if muscle fiber degeneration do begin around the age of 25, this might explain why the increased risk of hamstring injuries in high-intensity sports such as soccer [39, 40], even subtle changes in these muscle groups can significantly impact injury susceptibility [41, 42]. Studies have shown that athletes with over 7 years of professional experience may have a higher risk of injury than those with 3–6 years of experience. This might be related to the fact that the body's ability to adapt to training stimuli and fatigue recovery gradually weakens with age and professional experience [22]. However, athletes with only one year of sports experience have the highest risk of injury, the reason for this might be related to the fact that these athletes train and compete without exposure to elite-level training loads [19], which requires coaches to be cautious when assigning training workloads to athletes with less sports experience. In cases where necessary, they should provide transitional training workloads for these athletes, allowing them to gradually adapt to the training intensity of elite athletes.

Interpretation and comparison with previous studies

When looking at injury causes, due to the differences in the special characteristics of different sports, the sites of sports injuries are also different, for example, in soccer, the lower limb quadriceps muscle strength is larger [43], while the hamstring muscle strength and the lack of core strength are the main causative factors of non-contact injuries in soccer players, the twisting and stopping actions in tennis will increase the risk of injuries to the knee joint anatomical structures [44], and in the rugby sport, the knee and ankle joints are often in a twisted state, which in turn leads to a significant increase in the incidence of knee and ankle injuries [45]. In addition, the history of injuries present in the lower limbs is more likely to result in secondary injuries than other parts of the body under the same loading conditions [22]. At the same time, the relationship between training workloads and non-contact injuries has also attracted much attention, with studies pointed out that acute workload changes over > 9% [13] or > 1000 AU [19] per-week will increase the risk of non-contact injuries, prolonged participation in sports that require sustained muscular contraction increases the likelihood of muscle strains [8], and it should be noted that interruptions in training due to injury may trigger decreases in fitness, strength, and neuromuscular control, which may further increase the risk of future injury [46].

Secondly, the high density of scheduling in different sports was a major contributing factor, with hundreds of major tournaments played each year in soccer and tennis, while rugby and hockey also play up to 70 or 80 matches per year. In soccer, for example, European professional teams played 50–80 matches in a 40- week season, often two matches per-week, and some teams even completed as many as three matches in a one-week microcircuit [47], but if more than one match is played per-week, athletes need at least 96 h of recovery time to avoid re-injury [48], however, the high-density schedule superimposed on the psychological pressure, climatic adaptations and other factors, leading to excessive physical and mental fatigue, further weakening their decision, making, coordination, and confrontation abilities during competition, and putting them at high risk of injury.

Among the metrics of external workload, the higher the total distance, the higher the risk of injury, when the ACWR for total distance = 1.76 [46], or remains within the range of 0.88–1.11 [49], and may more likely to result in an injury in the following week when the ACWR > 2.0 [20]. In terms of high-speed running distance (> 20 km/h), ACWR > 1.18 leads to an increased risk of injury [49], while ACWR > 2.0 may lead to a high likelihood of injury in the following week [20], and a significant increase in the risk of non-contact injuries was seen when high acute and low chronic workloads coexist, whereas no significant risk of injury was seen when combining high acute and high chronic workloads coexist [46]. These three studies have shown that a low ACWR may be able to avoid the risk of damage. In terms of the number of accelerations, the risk of contact injury was greatest when ACWR = 1.77 [49], or ACWR > 2.0 and chronic loading < 1731 repetitions [50], whereas when ACWR > 2.0 may lead to a further increase in the risk of non-contact injuries [50], and both studies suggested that a rapid increase in accelerations under acute workloads will lead to an increased risk of injury, especially under low chronic workloads situations. In terms of the number of decelerations, the risk of injury was lowest when the ACWR was in the 0.86–1.12 [49].

Implications for practice and future research

In order to reduce the incidence of injury, some studies suggested that the maximum speed training intensity of athletes should reach above 95% during training [17], or higher levels of training loads should be maintained over a long period of time [46]. In addition, maintaining stable ACWR, avoiding abrupt changes in acute workloads, and sustaining high chronic training loads may be associated with reduced injury incidence. At the same time, by strengthening the strength of the lower limb muscles and the stability of the core, it may further reduce non-contact injuries caused by the imbalance of ACWR. Otherwise, since too short a rest period may cause soft tissue injuries, so the intervals between training need to be planned, together with the necessary physical fitness exercises, studies have shown that the probability of injury in athletes with higher strength qualities was lower than that of ordinary athletes [22], for example, in soccer sport, which might be related to allows athletes to avoid injuries such as shoveling of the ball with similar movements during the game. At the same time, strength qualities can act as a modifier of sports injuries, and athletes with higher strength qualities were better able to tolerate larger variations in weekly training loads (550–1000 AU) [46].

In the second place, in daily training, pre-competition workload management typically involved increased training intensity coupled with reduced training volume to optimize adaptation to competition conditions. Nevertheless, excessive training workloads may lead to accumulated fatigue, which can impair peak performance. In addition, some objective conditions such as lack of competition experience [19], poor physical and mental condition of the athletes, and non-adaptation of the equipment worn during the test may be potential factors contributing to athletes' injuries. ACWR may provide a useful reference for training workload adjustments, but it does not fully capture individual variability in physiological responses to training. Certain athletes can sustain higher ACWR values without experiencing increased injury risk, while others may be more susceptible even within the recommended range. Therefore, coaches and athletes also need to adjust the ACWR appropriately according to the event schedule, and at the same time dynamically monitor the athletes' physical and mental states to minimize the occurrence of unnecessary injuries.

However, in terms of the athletes' experience. For athletes with less sports experience or experiencing training team transitions, it is recommended to adapt to the new training workload by adjusting the training program or adopting a gradual transition, while athletes with less sports experience have a weaker ability to adapt to the load, and need to reduce the risk of injuries due to sudden changes in load. For athletes who have been engaged in professional sports for a long time, they usually have a mature training system, strong adaptability to load, good cumulative effect of long-term load, a large base of chronic workload, and a relatively lower risk of injury under the same acute load conditions. However, due to the gradual decline of their physical fitness with age, the arrangement of training load also needs to be scientific and reasonable, because they have undergone long-term high-load training, their adaptation threshold is usually high, and the impact of acute load increase in a short term on the body is relatively small. Therefore, it is crucial to scientifically plan long-term training loads while simultaneously minimizing injury risks.

The calculation of average workload can be categorized into the Rolling Average Model (RA) and the Exponential Weighted Moving Average Model (EWMA). RA calculated the acute workload as the rolling average over 7 days and the chronic workload as the rolling average over 28 days. However, Williams et al. (2017) argued that RA fails to consider the progressive attenuation of adaptation and fatigue. In contrast, EWMA assigned greater weight to recent training loads, allowing for a more accurate representation of the training effect. Therefore, they proposed EWMA which refers to assigning decreasing weights to the completed workloads and larger weights to the most recently completed workloads, calculating the average of the total load under different weights. The specific calculation formula for EWMA on a certain day is $EWMA_{today} = Load_{Today} \times \gamma a + [(1, \gamma a) \times Load_{Yesterday}]$, $\gamma a = 2/(N+1)$, where γa is between 0 and 1, representing the attenuation degree of the load, and N is the time decay constant selected, indicating the time window for chronic and acute workloads [6]. Meanwhile, the calculation of chronic workload also needed to pay attention to the coupling or non- coupling, $\text{chronic workload}_{coupling} = \text{acute workload}/(\text{acute workload} + \text{chronic workload})$, and conversely, $\text{chronic workload}_{non-coupling} = \text{acute workload}/\text{chronic workload}$. Numerous studies have indicated that there is a significant correlation between both RA and EWMA for injury prediction, and although there is no significant difference between RA and EWMA when the ACWR were maintained at a low level interval (<0.49, 0.5–0.99), but EWMA may have a higher sensitivity for predicting injuries when the ACWR are within the high-level range (1.50–1.99, >2.0) [5], and most studies have confirmed that the use of EWMA may be more accurate than RA [22, 27], which may be due to the differences in the formulas of the two, with EWMA giving more weight to the most recently completed workloads, taking into account the timeframe as well as the attenuating nature of acclimatization and fatigue.

In summary, when the ACWR is in the higher range, it will lead to an increased injury risk for the total distance, high-speed running distance and the number of accelerations and decelerations. Therefore, coaches and athletes need to pay attention to the following appropriate ranges when arranging training and competition workloads: total distance ACWR < 0.8, high-speed running distance ACWR < 1.18, and acceleration and deceleration times ACWR to maintain a suitable interval of 0.8–1.3, to avoid a rapid increase in acute workloads. Meanwhile, when calculating the average workload, some studies have pointed out that EWMA may be more accurate than RA when ACWR is in the high-level interval, however, this study supports that only when ACWR is within the range of 0.8–1.3, there might be a lower probability of injury. Therefore, the calculation formula should be applied according to the actual situation. When the ACWR is kept at a low-level, it is recommended to use RA for load calculation [22], which is a simple formula that is less likely to produce a large discrepancy, and when the ACWR is at a high-level, the EWMA is chosen to predict the risk of injury with a higher degree of accuracy [27]. In addition, some studies have pointed out that the time window of seven days acute versus twenty-one days chronic loading is more sensitive to non-contact injury risk [26]. However, there may be contradictions in the current research on the relationship between various measures and ACWR. On the one hand, there are differences in the definition of training load-control of intervals, GPS equipment used, and statistical methods applied in some studies, and on the other hand, the uncertainties that exist in official competitions may have different effects on injury risk, and the session-RPE also cannot accurately distinguish the load of short-term high-intensity exercise from that of long-term low-intensity exercise [25].

Limitations

One limitation of this study lies in the fact that there are some potential factors that may cause the heterogeneity of the results, such as differences in gender, BMI, sport type, injury definition variability, measurement methods (session-RPE vs. GPS), and study quality. Additionally, this study included only articles that explicitly reported impairments, excluding others, which this may have excluded potentially relevant datasets, thus narrowing the evidence base. And this study only includes English-language literature, even if Begg's and Egger's tests did not detect publication bias, small-study effects and selective reporting remain possible. Lastly, although subgroup analyses suggested robust results, residual heterogeneity (I^2 >75% in some analyses) remains unexplained and should be acknowledged as a limitation for interpreting pooled effect sizes.

Conclusion and future research

ACWR shows potential as a workload monitoring approach to assess associations with sports injury risk. Based on high-quality literature, this study draws the following summary conclusions: (1) Among elite athletes, keeping the ACWR in the range of 0.8–1.3 may minimize the chance of incurring sports injuries in soccer, cricket, tennis, and rugby; (2) when choosing training load indexes, it is recommended to use external workload or a combination of internal and external workloads; (3) when calculating the average workload of the ACWR, both the RA and the EWMA showed a positive correlation with the risk of injury, and the EWMA may have a higher sensitivity in predicting injury, and many studies have confirmed that EWMA may be more appropriate than RA, however, when the workload is relatively small, both calculation methods may be appropriate. (4) Reasonable control of ACWR, avoiding rapid changes in acute workload, and maintaining a large long, term training workload, and strengthening the lower limb muscle strength and core stability can further reduce non-contact injuries due to the imbalance of ACWR; (5) For athletes with less experience in sports can be adjusted by adjusting the training program or adopting a gradual transition to adapt to the new training load, at the same time, it is necessary to avoid the sudden change of load, for athletes engaged in professional sports for a long period of time, it is necessary to pay attention to the scientific planning of long-term load; (6) However, we should also note that when the ACWR = 0.8–1.3, the confidence interval range of the combined results is relatively large (95% CI [0.14; 0.94]), thus we cannot definitely state that this interval is necessarily safe, and the reliability of this conclusion is questionable.

At the same time, this study also puts forward some constructive expectations: (1) at the level of sports, most of the literature is more dominated by soccer, and it is recommended to increase the application to other sports (such as endurance and individual sports) to strengthen the effectiveness of ACWR in predicting collective ball sports; (2) in terms of subject selection, most of the study is mainly dominated by males, thus future research should aim at the discussion of ACWR on the gender differences, and specify the need for stratified analyses or sex-specific thresholds; (3) in order to enhance the effectiveness of ACWR in predicting the nature of the ACWR, the optimal interval of the ACWR should be refined more from an experimental perspective, taking longitudinal or intervention studies to test causality; (4) optimize the means of monitoring training loads (such as wearable technology and subjective measures in combination) to further clarify the relationship between loads and injuries; (5) since the lack of analysis of the nature and severity of the previously existing injury sites is a limitation of this study as it may lead to secondary injuries, subsequent researches may also explore this aspect.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Author contributions

Conception and design: WLQ. Administrative support: RL and LC. Provision of study materials or patients: All authors. Collection and assembly of data: All authors. Data analysis and interpretation: WLQ. Manuscript writing: All authors. Final approval of manuscript: All authors.

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Data availability

Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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