Title: Real World Fatigue Testing in Professional Rugby Union: A Systematic Review and Meta-Analysis

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Running Header: Real World Fatigue Testing in Professional Rugby Union

Abstract

Background: Professional rugby union is a high-intensity contact sport with position specific high training and match volumes across a season that may lead to periods of fatigue if above a typically experienced threshold. This study assesses the influence of match-play and/or training on fatigue levels in rugby union players.

Objective: To perform a systematic review and meta-analysis of measures used to assess fatigue status in male professional rugby union players.

Methods: Using electronic databases (PubMed, SPORTDiscus, Web of Science, Cochrane Library, EMBASE, and MEDLINE), a systematic review of fatigue testing in rugby union was conducted on 1) neuromuscular, 2) subjective self-report, 3) biochemical and 4) heart rate derived measures.

Results: Thirty-seven articles were included in this systematic review, of which 14 were further included in a meta-analyses. The results of the meta-analysis revealed small, yet not significant, decreases in countermovement jump height immediately after (ES = -0.29; 95% CIs = -0.64 to 0.06), 24 hours (ES = -0.43; 95% CIs = -3.99 to 3.21), and 48 hours (ES = -0.22; 95% CIs = -0.47 to 0.02) after exposure to rugby union match-play or training. Reported wellness (ES = -0.33; 95% CIs = -1.70 to 1.04) and tiredness (ES = -0.14; 95% CIs = -1.30 to 1.03) declined over a period of a few weeks (however, the results were not-statistically significant), meanwhile muscle soreness increased (ES = 0.91; 95% CIs = 0.06 to 1.75) within the 96 hours after the exposure to rugby union match-play or training. Finally, while cortisol concentrations (ES = 1.87; 95% CIs = -1.54 to 5.29) increased, testosterone declined (ES = -1.54; 95% CIs = -7.16 to 4.08) within the 24 hours after the exposure. However, these results were not-statistically significant.

Conclusions: Subjective measures of muscle soreness can be used to assess fatigue after match play and training in rugby union players. Within and between-study variability for countermovement jump height, biochemical markers and heart-rate derived measures means the utility (practical application) of these measures to assess fatigue in professional rugby union players after matches and training is unclear.

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Key findings/implications of the paper:

- Results indicate acceptable utility for measures of subjective soreness when assessing the influence of match-play and/or training in professional rugby union

- High inter-individual variability for assessing the influence of match-play and/or training in professional rugby union was evident in countermovement jump, biochemical markers and heart-rate derived measures
- Practitioners are advised to assess individual training response to match-play and/or training in professional rugby union to better guide training prescription and optimise player readiness

1. **Background**

Fatigue experienced by rugby players after match play or training is complex, task-specific and can be defined as a self-reported disabling symptom derived from the interdependent attributes of performance and perceived fatiguability [1,2]. Performance fatigability is a decline in an objective measure of performance over time [1] that is typically characterized by immediate (i.e., hours) and prolonged (i.e., days) reductions in muscle contractile function and muscle activation after training or match play (for examples see: West et al., 2014a [3]; Roe et al., 2017 [4]; Brustio et al., 2020 [5]). Contributing factors to performance fatigability after rugby activity might include alterations due to substrate depletion [6], inhibition [7], and muscle damage [3]. Perceived fatiguability refers to changes in the sensations that regulate the integrity of the individual, influenced by disruptions in their homeostasis and psychological state from baseline after match play or training. Rates of change from baseline in one or several modulating factors such as core temperature [8,9], hydration status [10], motivation [11], and pain [12] are likely to influence a player's perceived fatigability [1]. It should also be noted that many of the factors that influence performance and perceived fatiguability might interact between the two domains. For example, increases in muscle soreness after a match could regulate an individual's capacity to generate the necessary voluntary activation to produce force during a countermovement jump. Overall, fatigue *per se* depends upon the changes in these two attributes and will be relative to demands imposed on the performer during training or match play and their individual capacities (i.e., task- and individual-specific).

Fatigue (i.e., changes in performance and perceived fatigability) observed after rugby union match play and training might be attributable to many factors, all of which will be dependent on the demands imposed upon the player during the activity. For example, physical loads such as distance covered, the number and intensity of collisions (while contesting possession in attacking or defensive situations), sprinting (including acceleration), jumping and decelerations and changes of direction [13-15] will all influence factors modulating performance and perceived fatigability. Similarly, environmental conditions [16], cognitive loads [17] and other contextual factors might all contribute to player fatigue. Accordingly, the influence of individual player match and/or training demands should be considered within programme planning to avoid negatively impacting team success and increasing injury risk [2]. Due to the large volumes of both training and match-play activity throughout a playing season, professional rugby union players can also become

periodically fatigued and subsequently underperform if such fatigue is not managed well [18,19]. Such fatigue is known to be transient and when well-managed, typically dissipates before the next competition or training session [20]. Meanwhile, unexplained underperformance over a longitudinal period symbolises reduced readiness to perform optimally [18], with long-lasting fatigue (i.e. > 5 days) associated with sub optimal recovery.

Many objective and subjective tools exist to the influence of match-play and training. These tools largely comprise neuromuscular function (e.g., countermovement jumps [CMJ]), subjective self-report measures (e.g., well-being questionnaires), biochemical measures from blood, saliva, or urine (e.g., creatine kinase), and heart rate derived measures (e.g., heart rate variability) and are often used in combination given that the locus of post-match fatigue is multifaceted (see above). Disturbances in restoration of performance are reported up to 60 hours after professional rugby union match-play [21,22], with muscle soreness, self-reported perceived fatigue, disrupted sleep and reductions in muscle function (CMJ peak power output) reported to last until 60 hours after a professional rugby union match [3]. Aben et al. [23] showed that rugby union match-play was responsible for a decrease in CMJ power (~31%), a 4-5 fold increase in creatine kinase, and negative disturbances to mood 30 minutes post-match. However, peak power during a CMJ is a poor indicator of jump performance [24-27] where alterations in strategy (e.g., countermovement depth) can increase jump height by increasing time for force production, and therefore propulsive impulse, while power may decrease (power = work / time). Furthermore, some authors [28,29] have incorrectly reported jump height as a proxy for peak power, or calculated power based on jump height, resulting in misleading data [28,30,31], questioning the validity or monitoring CMJ power. A 'gold standard' assessment of neuromuscular fatigue would incorporate a tool such as twitch interpolation, which while sensitive, is laboratory based and impractical in team sport settings due to the time requirements [32].

Other measures such as power during cycle ergometry and bench press power tests, self-report well-being and heart rate derived measures have been used to assess fatigue in rugby union [33-36], yet to date, no detailed systematic review has been conducted to assess the application of such measures specifically in rugby union. The complex combinations of positional movement demands in professional rugby union, means the dilution of fatigue to one single measure that represents the perturbations after the intense combative nature of rugby union match-play and training is difficult. Given that there is no consensus on a

single or criterion measure of real-world fatigue for use in applied practice, practitioners often lack confidence in those measurements used to assess a player [36]. Therefore, the aims of this paper were (1) to conduct a systematic review of the literature pertaining to the measures used to assess fatigue status of professional rugby union players, and (2) to conduct a meta-analysis of the between-study heterogeneity in the changes in the neuromuscular, biochemical, self-reported, and heart rate-derived measures associated with monitoring fatigue in professional rugby players. In addition, this review sought to provide recommendations about the efficacy and utility (e.g., practical application of this measure in real world settings) of tools to monitor rugby union player fatigue status after match play and training, based on the quality of the retrieved research.

2. **Methods**

2.1 Focus of the Review

Assessment of the chronic fatigue that is experienced in the hours post rugby union match-play is the specific targeted for this review (and not specific physiological acute fatigue that is more commonly experienced during rugby union matches [7,37]). The intention of this review and meta-analysis is to help guide practitioners working in 'real world' professional rugby union settings on fatigue testing that can be regularly implemented in applied, therefore questioning many laboratory-based tests (e.g., twitch interpolation, electrocardiogram) and maximal testing (e.g., cycle ergometers, isometric testing) due to their time consuming and invasive nature. As such, this systematic review and meta-analysis of monitoring measures is split into four sections focusing on 1) neuromuscular, 2) subjective self-reports, 3) biochemical and 4) heart rate derived. Lastly, this review assesses rugby union performance testing and not those taken from other team sports, as the positional differences and match demands associated with rugby union are likely to influence the fatigue response. Despite the monitoring of objective internal (e.g., heart rate or biochemically derived) and external (e.g., jump height derived) measures to assess chronic fatigue being commonplace in professional rugby union, scientific support that confirms the validity of these identified measures does not exist.

2.2 Search Strategy

A systematic review was conducted following the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) Guidelines [38]. Six electronic databases (PubMed, SPORTDiscus, Web of Science, Cochrane Library, EMBASE, and MEDLINE) were searched up to July 2023. The key terms included in the search strategy were: (rugby union) AND ((test OR (creatine kinase) OR ck OR saliva OR balance OR (heart rate) OR (self-report*) OR neuromuscular OR biochemical OR endocrin* OR hormon*)) AND (fatigue OR performance OR damage), and the following limits were applied in the databases: (i) English language; (ii) peer-reviewed articles; and (iii) access to the full text. No time frame restrictions were applied. The search strategies and the limits used in the different databases are provided in the supplementary material. The reference lists of included articles were also hand-searched to identify additional relevant articles. This review was registered in the PROSPERO (http://crd.york.ac.uk/PROSPERO) database (PROSPERO ID: CRD42020216706).

2.3 Eligibility Criteria

The target population for this systematic review and meta-analysis was male professional rugby union players. Women rugby players were excluded from the study because of the likely influence of sex-related differences in fatigue [39] (suggested to be a product of relative strength [40]) and that professionalization of the women's game is a recent development (i.e., 2019) is localized to a small number of countries. Studies identified through the search strategy were included in this systematic review if they investigated the influence of match-play and/or training in rugby union players and measured fatigue using neuromuscular, biochemical, subjective self-report, and heart rate-derived measures. Studies were also deemed suitable for inclusion in the present study if they employed any type of before-after design (i.e., longitudinal, pre-post, randomised or non-randomised control trial, etc.). If the articles did not meet any of the above-mentioned eligibility criteria, they were excluded from this review during the screening process.

2.4 Screening

The articles yielded by the search strategy were imported into RAYYAN software [41]. After removing duplicates, three authors (AG, CT, and SH) independently evaluated the study titles and abstract according

to the inclusion/exclusion criteria. The full text of the included studies was independently evaluated by three authors and any discrepancies found were discussed until an agreement was reached. If the full text was unavailable, it was requested via email to the study's authors.

2.5 Data Extraction and Narrative Synthesis

Data were extracted into a custom Microsoft Excel spreadsheet. The extracted data included: authors and year of publication, country in which the study was conducted, competitive tier, sample characteristics (size; age, height and mass), type of measurement used (neuromuscular, self-assessment, biochemical, and heart rate derived), and type of intervention. For this systematic review and meta-analysis, the information extracted regarding the sample size and the effect sizes of the five studies that employed a randomised/non-randomised control trial design [35,42-45] was limited to the control group only.

2.6 Study Quality and Risk of Bias Assessments

An adapted version of the Critical Appraisal Skill Programme Checklist for Cohort Studies (CASP) [46] was used to evaluated quality of the studies included in this systematic review and meta-analysis. The original version comprises 12 items. However, two items related to the confounding factors (for example, sensitivity analysis to correct) were removed, since none of the studies included in this review investigated confounding. Moreover, two items were also modified to address the factors associated with fatigues assessment in rugby union (item 3, match or training accurately measured; and item 4, fatigue accurately measured). The quality of the studies was recorded as "yes" if the study addressed the specific questions, a "no" if the study did not report the information asked in the questions, and a "cd" (cannot determine) if the information asked in the question could not be retrieved from the articles. A value of 1 was given to the "yes" and 0 to the "no" and "cd", with a total score ranging from 0 to 10. Cut-off scores to differentiate quality categories were set as follows: poor quality=1–4; moderate quality=5–7; good quality=8-10. Following Büttner et al. (2020)'s recommendations [47], a risk of bias assessment was also performed to enable the readers to better interpret the credibility of the studies' findings and differentiate them from the quality of the study. The Cochrane ROBINS-I tool [48] was used to evaluate the risk of bias of the included studies. This tool contains seven domains that assess the potential bias in follow-up cohort studies. The

responses to each domain were low, moderate, and high, depending on whether the bias was reported in the study. The overall judgement was calculated using the lowest score in the domain. For example, if a study scored 'low' in six domains and 'moderate' in one domain, the overall judgement was 'moderate'. Two authors assessed the study quality and the risk of bias, and any discrepancies were resolved through discussion.

2.7 Meta-analytic approach.

Meta-analysis was employed to quantitatively summarise the evidence. Studies that reported sufficient data, namely means and standard deviations from which the effect sizes could be calculated or actual effect sizes (e.g., Cohen's *d*, Cohen's f^2), were included in the meta-analytic synthesis. Considering that the reported measurements were gathered in different time points (before, 24 hours, 48 hours, and 72 hours after the match, fatigue over the course of several weeks) and given the subsequently disparate nature of the data, to provide a more robust synthesis of the estimates, the effect sizes reported by the articles were converted into Cohen's *d*. Using the pooled standard deviation, and the standard error of the Cohen's *d* was calculated using Hedges' formulas and suggestions on measurement of standardised effect size [49]. If a study reported the before- and after-exposure means and the standard deviations the effect size *d* was calculated using Cohen's formula [50]. Data were pooled using the "metagen" package in R Studio for precalculated continuous effect size data [51,52], and following IntHout et al. (2014)'s recommendations [53], a random effects model based on the Hartung–Knapp–Sidik–Jonkman adjustment was employed. This method has shown robust estimates of between-study variance when the number of studies included in the meta-analysis and the sample sizes are small and when there is evidence of substantial between-study heterogeneity. To calculate the variance across the studies (Tau^2) and the confidence interval, the DerSimonian-Laird estimator and the Jackson method were respectively employed [54]. In addition to the Tau^2, the heterogeneity of the data was also interpreted using the I^2, and according to the Cochrane Handbook for Systematic reviews [54], the following scale of interpretation was used: 0% to 40% = might not be important; 30% to 60% may represent moderate heterogeneity; 50% to 90% = may represent substantial heterogeneity; and 75% to 100% = considerable heterogeneity. Finally, the following scale of magnitudes was used to evaluate the sizes of these standardised pooled effects: < 0.2 = trivial; 0.20–

0.49 = small; 0.50–0.80 = moderate; and > 0.80 = large [50].

3. **Results**

3.1 Studies Selected

A total of 2,198 articles were retrieved from the search strategy, of which 1,039 were removed as duplicates. The titles and abstracts of the remaining 1,159 articles were independently screened by three researchers and a further 1,101 articles were excluded from this systematic review because they did not meet the eligibility criteria. The full text of the remaining 58 articles was further screened, and 22 articles were excluded for the following reasons: wrong population (n=11), wrong outcome measured (n=6), wrong study design (n=4), and wrong intervention administered (n=1). Finally, a total of 37 articles were included in this systematic review. However, appropriate data was only reported in 17 studies, which were therefore deemed suitable for inclusion in the meta-analytic synthesis, as shown in Fig. 1.

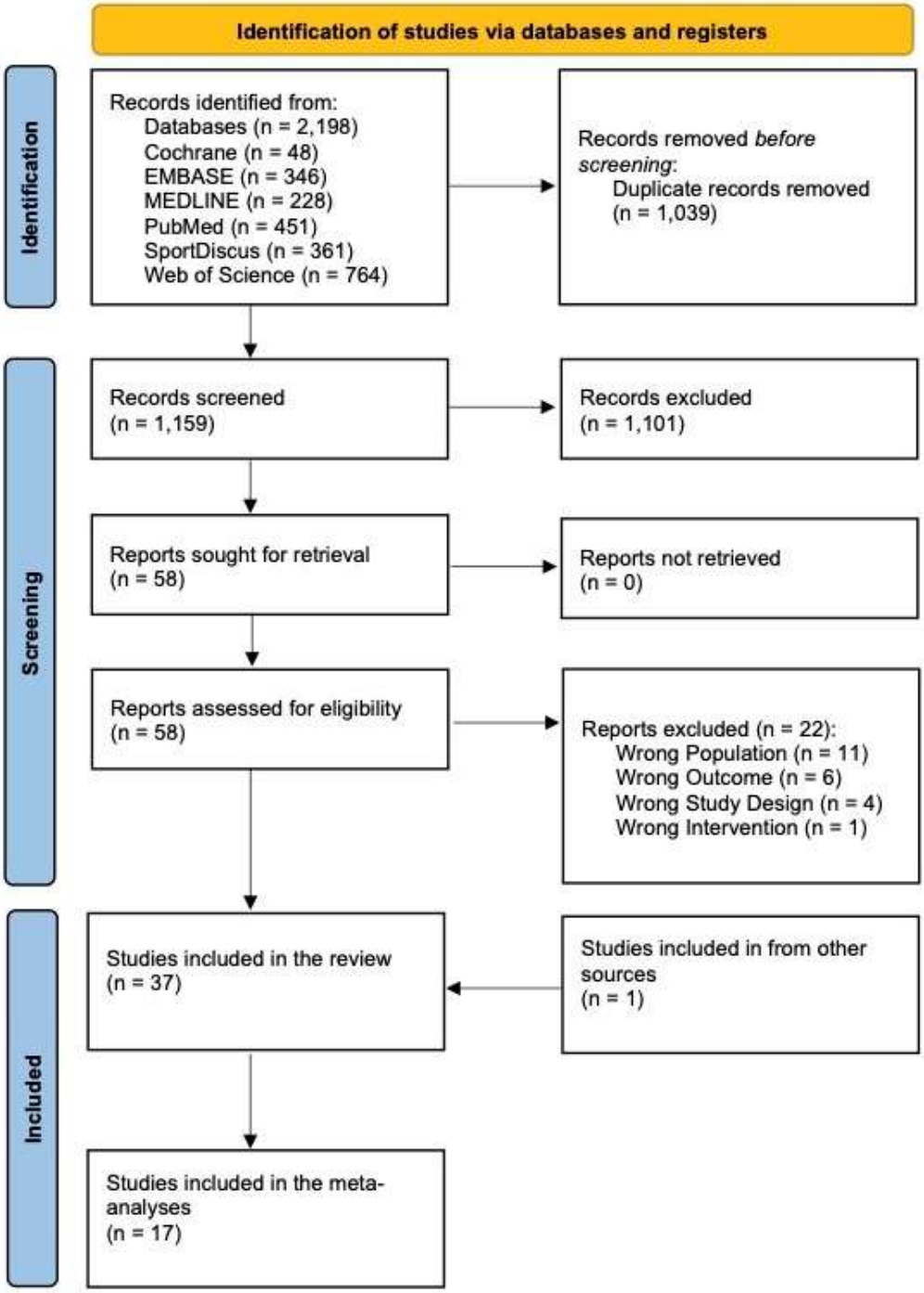


Fig. 1. *PRISMA flow chart of the studies included in the systematic review and meta-analysis.*

3.2 Characteristics of Included Studies

Characteristics of the included studies are displayed in Table 1. The studies included in this systematic review were published between 2008 and 2022 and assessed the fatigue experienced in the hours post-match

or training (thereinafter, the exposure). As per Table 1, data were collected in different data points depending on the nature of the study design; however, the most common timeframe to was immediately before and after the exposure or after 24 to 72 hours after the exposure. At the time of the literature search, the sample of rugby union players in all but one study [44] selected for the review were considered to be in Tier 1 of the *World Rugby* national team classification system. Fifteen studies were longitudinal, 12 used a pre- and post-exposure design, and five studies used a randomised controlled trial. Finally, five studies used a longitudinal pre- post-exposure design. Most of the studies were conducted in the UK (46%, n = 17) [3,21,33-35,43,55-65]. Five studies [66-70] were conducted in Australia, eight in New Zealand [42,45,71-76], three in Ireland [77-79], two in France [80,81], and one in Brazil [44]. A final study included data of players playing both in New Zealand and Australia [82].

Table 1: Characteristics of studies included in the systematic review

Study	Country	Tier	N	Design	Stimulus	Age	Height	Weight	Type of measure			
									NM	SR	BH	HR
Argus et al. (2009) [82]	AUS/NZ	1	32	Longitudinal	Training and match-play	24.4 ± 2.7	184.7 ± 6.2	104.0 ± 11.2	✓	✓	✓	
Black et al. (2018) [42]	NZ	1	20	Longitudinal	Training	22.0 ± 5.8	/	/	✓	✓	✓	
Brown et al. (2020) [43]	UK	1	45	RCT	Training	24 ± 6	1.8 ± 0.08	86.1 ± 15.9	✓	✓	✓	
Crewther et al. (2013) [64]	UK	1	19	Pre-post	Match-play	25.8 ± 4.2	1.89 ± 0.10	101.6 ± 13.3			✓	
Crewther et al. (2020) [65]	UK	1	36	Pre-post	Match-play	27.7 ± 3.3	1.88 ± 0.09	102.3 ± 13.0		✓	✓	
Cunniffe et al. (2010) [21]	UK	1	10	Pre-post	Match-play	26.4 ± 0.7	186.5 ± 2.5	103.1 ± 3.9			✓	
Dubois et al. (2017) [81]	FRA	1	8	Longitudinal	Training and match-play	25.8 ± 4.2	88.4 ± 3.1	NA	✓		✓	
Dubois et al. (2020) [80]	FRA	1	14	Longitudinal	Training and match-play	26.9 ± 1.9	185 ± 7.9	97.6 ± 13.2	✓	✓	✓	
Gaviglio & Cook (2014) [63]	UK	1	22	Longitudinal	Training	27.8 ± 4.0	1.87 ± 0.08	103.4 ± 11.6			✓	
Grainger et al. (2019a) [35]	UK	1	18	RCT	Training	25.4 ± 4.0	188.3 ± 6.0	99.8 ± 10.6	✓			
Grainger et al. (2019b) [33]	UK	1	22	Longitudinal	Training	25 ± 5	186 ± 6	99 ± 13	✓	✓		
Grainger et al. (2022) [34]	UK	1	13	Longitudinal	Training	27 ± 4	183.2 ± 4.9	100.5 ± 12.7		✓		✓
Hills & Rogerson (2018) [62]	UK	1	37	Longitudinal	Training and match-play	25.9 ± 4.1	186.1 ± 8.5	103.8 ± 13.7	✓	✓		
Hudson et al. (2020) [86]	UK	1	22	Longitudinal	Training and match-play	25.7 ± 4.1	/	106.4 ± 12.6			✓	
Hudson et al. (2021) [61]	UK	1	7	RCT	Training and match-play	22.0 ± 2.7	/	102.5 ± 13.7			✓	
Jones et al. (2014) [59]	UK	1	28	Longitudinal pre-post	Training and match-play	25.1 ± 3.1	/	102.9 ± 7.9			✓	
Kennedy & Drake (2018) [78]	IRE	1	17	Pre-post	Training	19.5 ± 2.3	182.2 ± 6.5	94.3 ± 12.2	✓			
Lindsay et al. (2016) [75]	NZ	1	25	Pre-post	Match-play	26.0 ± 3.5	1.86 ± 0.07	104.5 ± 9.3			✓	
Lindsay et al. (2015a) [71]	NZ	1	37	Longitudinal pre-post	Match-play	24.2 ± 2.9	1.87 ± 0.06	103.3 ± 11.6			✓	
Lindsay et al. (2015b) [72]	NZ	1	24	Longitudinal pre-post	Training and match-play	26.1 ± 3.0	1.89 ± 0.04	106.0 ± 6.9			✓	

Lindsay et al. (2015c) [22]	NZ	1	37	Pre-post	Match-play	26.0 ± 3.6	1.86 ± 0.08	104.5 ± 9.4			✓
Lindsay et al. (2017) [74]	NZ	1	13	Pre-post	Match-play	26.0 ± 3.5	1.86 ± 0.07	104.5 ± 9.3			✓
Lonergan et al. (2018) [58]	UK	1	14	Pre-post	Training and match-play	23	186	104	✓		
Nicholls et al. (2009) [57]	UK	1	16	Longitudinal	Training and match-play	19.3 ± 1.0	/	/		✓	
Nunes et al. (2019) [44]	BRA	3	22	RCT	Training and match-play	25.2 ± 3.6	182.2 ± 6.3	96.8 ± 16.8	✓	✓	✓
Serpell et al. (2019) [83]	AUS	1	19	Longitudinal	Training	26.4 ± 3.9	186.0 ± 9.4	104.1 ± 13.4		✓	✓
Shearer, Kilduff et al. (2015a) [56]	UK	1	12	Longitudinal pre-post	Match-play	24.4 ± 2.9	NA	103.9 ± 12.2		✓	✓
Shearer, Jones et al. (2015b) [55]	UK	1	28	Pre-post	Match-play	24.9 ± 4.35	NA	NA		✓	
Smart et al. (2008) [76]	NZ	1	23	Longitudinal pre-post	Match-play	25 ± 3	184 ± 9	99.2 ± 10.1			✓
Tavares et al. (2018) [45]	NZ	1	23	RCT	Training	/	/	/	✓	✓	
Tiernan et al. (2019a) [77]	IRE	1	19	Longitudinal	Training and match-play	19.7 ± 1.1	184.5 ± 7.7	96.2 ± 12.5	✓	✓	
Tiernan et al. (2019b) [79]	IRE	1	19	Longitudinal	Training and match-play	19.7 ± 1.1	184.5 ± 7.7	96.2 ± 12.5			✓
Troester & Duffield (2019a) [67]	AUS	1	27	Longitudinal	Training and match-play	26 ± 3	190 ± 8	107 ± 18	✓		
Troester et al. (2019b) [69]	AUS	1	22	Longitudinal	Training and match-play	26 ± 3	189 ± 6	106 ± 14	✓		
Troester (2019) [66]	AUS	1	27	Pre-post	Training and match-play	24 ± 4	187 ± 7	104 ± 12	✓		
Troester & Duffield (2022) [68]	AUS	1	22	Pre-post	Training and match-play	26 ± 3	190 ± 8	107 ± 18	✓		
West et al. (2014) [3]	UK	1	14	Pre-post	Training and match-play	24.9 ± 4.4	1.85 ± 0.10	105.2 ± 12.3	✓	✓	✓

N = sample size; NM = neuromuscular measures (countermovement jump, squat jump, drop jump); SR = athlete self-reported measures (soreness, tiredness, sleep quality and duration); BI = bio-hormonal measures (cortisol, testosterone); HR = heart rate-derived measures (fitness tests, resting metabolic rate); RCT = randomised controlled trial.

3.3 Quality of the Studies

Table 2 shows a comparison between the study quality and the study risk of bias using the CASP Checklist for Cohort Studies and the ROBINS-I tool. Thirty-six of the studies included in this systematic review and meta-analysis showed good quality in the methodological approach (the studies' scores ranged from 8 to 10, except for one study that scored 4 out of a maximum of 10 points), and 26 studies reported a low potential risk of bias. However, 11 studies showed either a moderate (10) or high (1) risk of bias. A breakdown of the study quality checklist and the risk of bias tool is provided in the Supplementary Tables 1 and 2. The most common bias was due to missing data, namely, studies omitting participants from the analyses due to numerous reasons (injuries, not enough training accomplished, etc.).

Table 2. Summary of the study quality and the potential risk of bias of the studies included in the systematic review, using the CASP Cohort checklist and the ROBINS-I tool respectively.

	Study Quality (CASP Cohort Study checklist)		**Risk of Bias (Cochrane ROBINS-I tool)**
Study	**Summary Score**	**Quality Category**	**Overall risk of bias judgement**
Argus et al. (2009) [82]	10	Good quality	Moderate risk
Black et al. (2018) [42]	9	Good quality	Low risk
Brown et al. (2020) [43]	10	Good quality	Moderate risk
Crewther et al. (2013) [64]	8	Good quality	Moderate risk
Crewther et al. (2020) [65]	9	Good quality	Moderate risk
Cunniffe et al. (2010) [21]	9	Good quality	Moderate risk
Dubois et al. (2017) [81]	9	Good quality	Low risk
Dubois et al. (2020) [80]	10	Good quality	Low risk
Gaviglio & Cook (2014) [63]	9	Good quality	Low risk
Grainger et al. (2019a) [35]	9	Good quality	Low risk
Grainger et al. (2019b) [33]	10	Good quality	Low risk
Grainger et al. (2022) [34]	9	Good quality	Low risk
Hills & Rogerson (2018) [62]	9	Good quality	Low risk
Hudson et al. (2020) [86]	9	Good quality	Low risk
Hudson et al. (2021) [61]	4	Poor quality	High risk
Jones et al. (2014) [59]	9	Good quality	Moderate risk
Kennedy & Drake (2018) [78]	10	Good quality	Low risk

Lindsay et al. (2016) [75]	8	Good quality	Moderate risk
Lindsay et al. (2015a) [71]	8	Good quality	Moderate risk
Lindsay et al. (2015b) [72]	9	Good quality	Moderate risk
Lindsay et al. (2015c) [22]	10	Good quality	Moderate risk
Lindsay et al. (2017) [74]	10	Good quality	Moderate risk
Lonergan et al. (2018) [58]	9	Good quality	Low risk
Nicholls et al. (2009) [57]	9	Good quality	Moderate risk
Nunes et al. (2019) [44]	9	Good quality	Moderate risk
Serpell et al. (2019) [83]	9	Good quality	Low risk
Shearer, Kilduff et al. (2015a) [56]	9	Good quality	Low risk
Shearer, Jones et al. (2015b) [55]	9	Good quality	Low risk
Smart et al. (2008) [76]	10	Good quality	Moderate risk
Tavares et al. (2018) [45]	10	Good quality	Moderate risk
Tiernan et al. (2019a) [77]	10	Good quality	Low risk
Tiernan et al. (2019b) [79]	10	Good quality	Low risk
Troester & Duffield (2019a) [67]	9	Good quality	Low risk
Troester et al. (2019b) [69]	10	Good quality	Low risk
Troester (2019) [66]	10	Good quality	Low risk
Troester & Duffield (2022) [68]	9	Good quality	Low risk
West et al. (2014) [3]	8	Good quality	Moderate risk

Cut-off scores to differentiate quality categories: poor quality=1–4; moderate quality=5–7; good quality=8-10.
Overall Judgement for the risk of bias were equal to the lowest score performed in the seven dimensions.

3.4 Meta-analyses

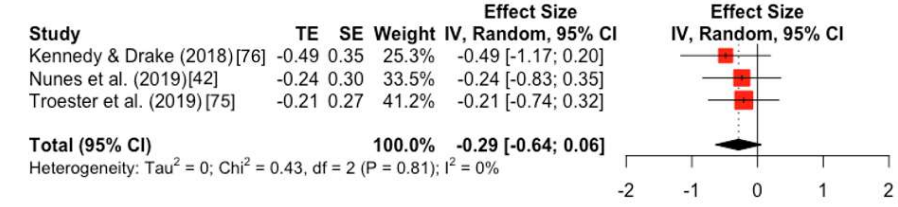
Of the 37 studies included in this systematic review, only 17 reported sufficient data to be included in a meta-analysis [21,33-35,43-45,56,57,62,64,69,71,78,80,82,83]. The raw data used for the meta-analyses is reported in Supplementary Table 3. Only one study [34] assessed athletes' fatigue using heart rate derived measures; as such, a meta-analytic approach was not possible.

3.5 Neuromuscular measures

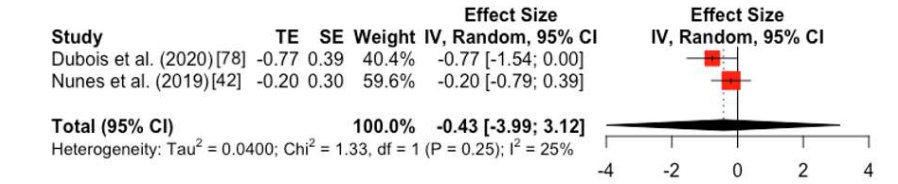
Five studies were eligible for inclusion in the meta-analysis investigating the differences in the muscle function after a match or a training session [35,44,69,78,80]. Each of the five studies used CMJ to

indirectly assess fatigue. Only studies that reported the changes in the jump height (the most consistently reported variable) were included in the meta-analysis, as jump height is the primary outcome, and the other variables are not predictors of jump performance [31]. This approach was necessary to provide a robust and consistent analysis of the overall effect. A small but non-significant decrease in CMJ height was observed immediately after exposure (ES = -0.29; 95% CIs = -0.64 to 0.06; t = -3.56; $p = 0.07$). Heterogeneity in the data was absent, indicating consistency in the results of the studies, as demonstrated by $I^2 = 0\%$ and the between-study standard deviation $Tau = 0$ (Fig. 2a). A small yet non-significant decrease in CMJ height was observed (ES = -0.43; 95% CIs = -3.99 to 3.21; t = -1.54; $p = 0.37$) 24 hours after exposure. The $I^2 = 25\%$ and the $Tau = 0.04$ indicate that heterogeneity in the data might not be important and the results of the studies are consistent (Fig. 2b). Finally, a small non-significant decrease in CMJ height (ES = -0.22; 95% CIs = -0.47 to 0.02; t = -3.93; $p = 0.06$) was also observed 48 hours after exposure. These changes in jump height (a small negative effect, yet non-significant) appear to be consistent for each individual study and the results of the meta-analysis. As shown by $I^2 = 0\%$ and the between-study standard deviation $Tau = 0$, heterogeneity in the data was absent, showing consistency in the results of the studies (Fig. 2c).

2a



2b



2c

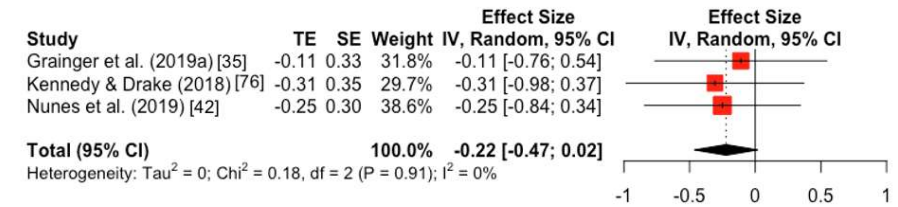


Fig. 2. Forest Plots of the meta-analysed jump height outcomes. Individual and pooled effect sizes of the changes in jump height: before and immediately after the exposure (2a); before and 24 hours after the exposure (2b); and before and 48 hours after the exposure (2c). The vertical line represents the value zero of the effect size. CI, confidence interval; TE, effect size; SE standard error; IV, inverse variance; df, degrees of freedom. The black diamond represents the pooled meta-analytic effect. The red squares and the associated horizontal lines represent the values and the associated uncertainties for each study's effect size.

3.6 Subjective self-reported measures

Twelve studies reported appropriate data to be included in the meta-analysis [33-35,43-45,56,57,62,80,82,83]. However, two studies [56,80], used validated questionnaires to measure the RESTq (Recovery Rest Questionnaire for Athletes) and the mood disturbance, respectively. As no other studies investigated such outcomes, these two studies were not included in any of the pooled effects. Fig. 3a shows an overall small non-statistically significant negative effect, as illustrated by the large 95% CI for the effect sizes, of exposure on athletes' self-reported wellness over a period of 3 to 13 weeks (ES = -0.33; 95% CIs = -1.70 to 1.04; t = -0.66; $p = 0.54$). Heterogeneity in the data was considerable and indicated inconsistency in the results of the studies, as demonstrated by $I^2 = 87\%$ and the between-study standard deviation *Tau* = 0.810. Fig. 3b shows the pooled effect of the studies that investigated soreness after the exposure. The meta-analytic results revealed a large statistically significant positive effect on soreness among elite rugby players (ES = 0.91; 95% CIs = 0.06 to 1.75; t = 2.97; $p = 0.041$) over the 96 hours after the exposure. However, the I^2 and *Tau* values indicate substantial heterogeneity across the studies, indicating low consistency in the results of the studies ($I^2 = 70\%$; *Tau* = 0.53). Finally, only two studies assessed athletes' tiredness over several weeks. The forest plot in Fig. 3c shows a trivial non-statistically significant negative effect of exposure on athletes' self-reported tiredness (ES = -0.14; 95% CIs = -1.30 to 1.03; t = -1.48; $p = 0.38$). The absence of heterogeneity in the data (*Tau* = 0; $I^2 = 0\%$) shows consistency in the results of the studies.

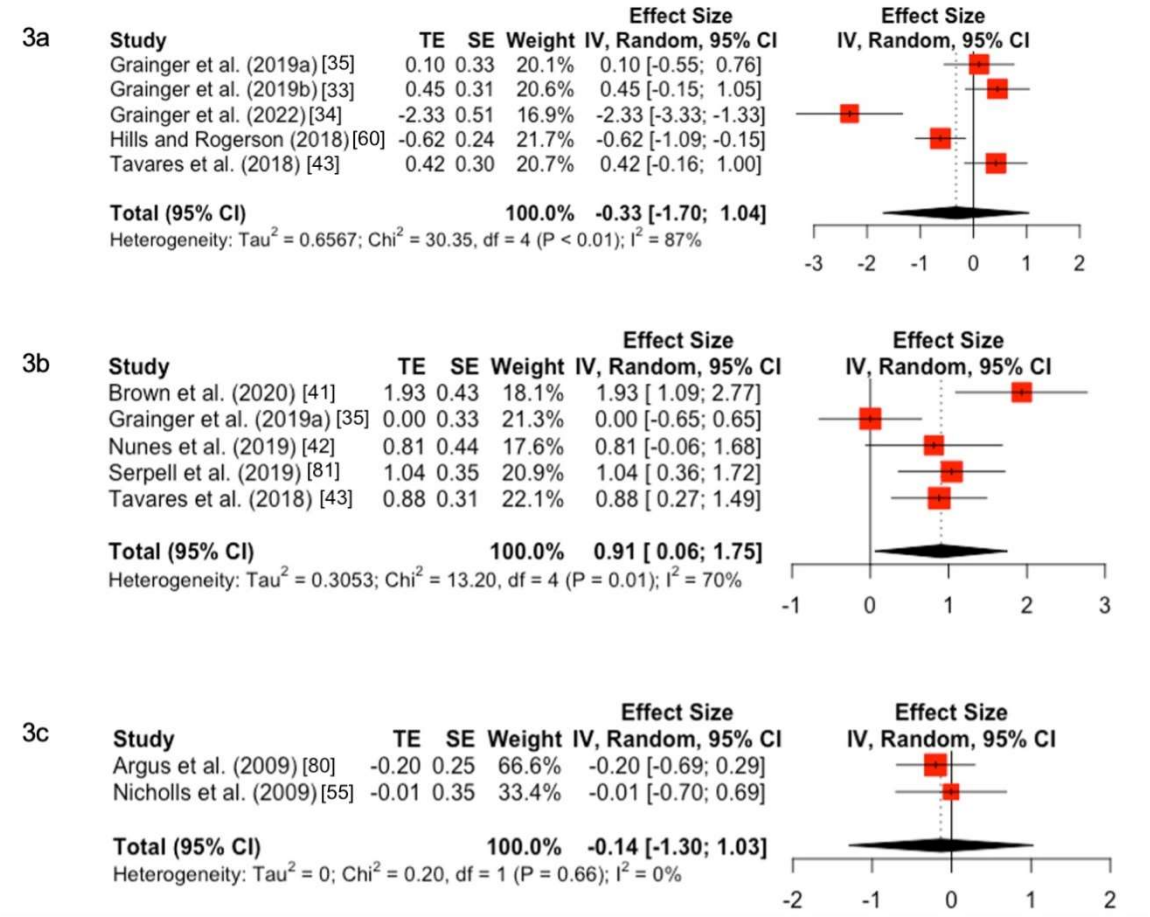


Fig. 3. Forest Plots of the meta-analysed self-reported outcomes. Individual and pooled effect sizes of the wellness (3a) measured over a period of 3 to 13 weeks; soreness (3b) measured over a period of 24 to 96 hours after the exposure; and tiredness (3c) among participants measured over a period of a season. The vertical line represents the value zero of the effect size. CI, confidence interval; TE, effect size; SE standard error; IV, inverse variance; df, degrees of freedom. The black diamond represents the pooled meta-analytic mean. The red squares and the associated horizontal lines represent the values and the associated uncertainties for each study's effect size.

3.7 Biochemical measures

Only four studies reported sufficient data using biochemical markers to assess fatigue (i.e., cortisol, and testosterone, whereas not enough data were reported to meta-analyse the changes in the creatine kinase concentrations) [21,56,64,71]. Fig. 4a shows a large non-statistically significant increase in cortisol concentration (ES = 1.87; 95% CIs = -1.54 to 5.29; t = 1.75; $p = 0.18$) within the 42 hours after the exposure, whereas Fig. 4b shows a large non-statistically significant decrease in players' testosterone

concentration (ES = -1.54; 95% CIs = -7.16 to 4.08; t = -1.18; p = 0.36) over the 24 hours after the exposure. In both meta-analyses, however, there was considerable heterogeneity, as demonstrated by the inconsistency in the results of the studies (I^2 = 91% and I^2 = 92% respectively), and the between-study standard deviation (*Tau* = 1.612 and *Tau* = 2.5500 respectively).

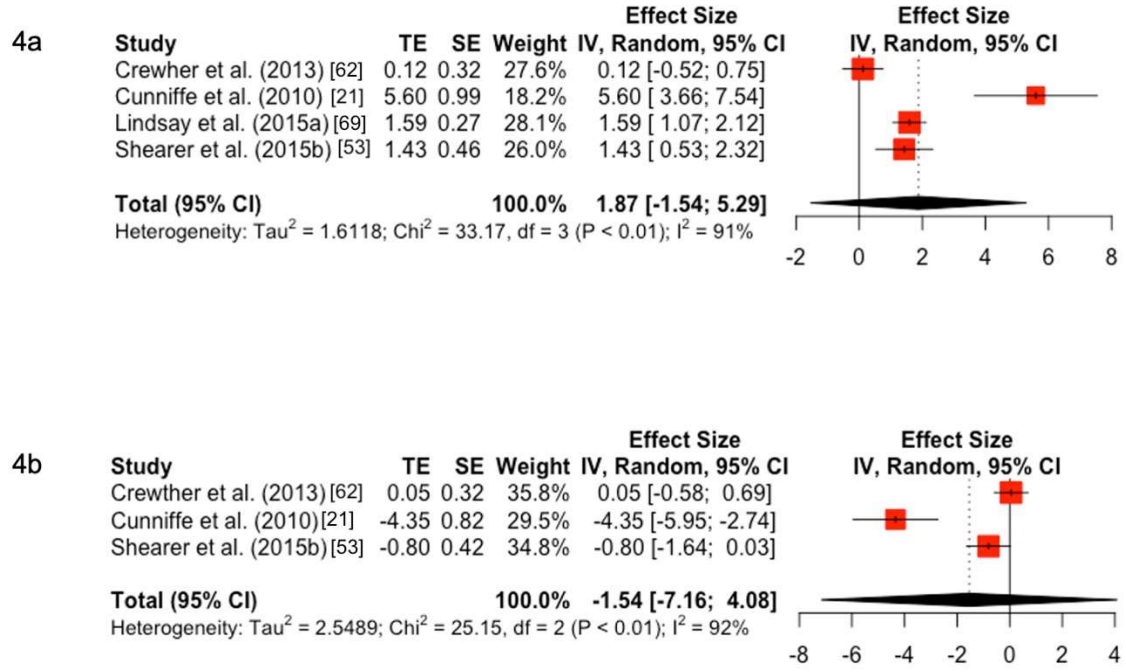


Fig. 4. Forest Plots of the meta-analysed biochemical outcomes. Individual and pooled effect sizes for the changes in cortisol (4a) within the 24 hours after the exposure; and testosterone (4b) concentrations among participants within 24 hours after the exposure. The vertical line represents the value zero of the effect size. CI, confidence interval; TE, effect size; SE standard error; IV, inverse variance; df, degrees of freedom. The black diamond represents the pooled meta-analytic mean. The red squares and the associated horizontal lines represent the values and the associated uncertainties for each study's effect size.

3.8 Narrative synthesis of the studies

3.8.1 Neuromuscular measures

Alongside the articles included in the meta-analysis, seven more studies included CMJ values [3,12,33,42,43,58,62], but they did not provide adequate data to be included in the meta-analytic synthesis. For example, Grainger et al. [33] did report jump height, yet the values available were not suitable for

inclusion, as data were gathered over a period of 11 weeks (four times per week) and did not align within any of the timepoints considered for the meta-analyses. Three studies not included in the meta-analysis reported postural control from a single leg landing action [66-68], and one study assessed fatigue measuring the adductor squeeze via sphygmomanometer during pre-season [77]. CMJ height (calculated via flight time) measured via *Optojump* (Microgate, Bolzano, Italy) was used for the two of the studies included in the meta-analysis [34,80], force plates were used in three [44,69,78]. Despite testing equipment varying, this does not influence the results as the same protocol was implemented at all individual study timepoints. The differences in jump height sensitivity values are perhaps due to study methods; for example, three studies were conducted in season [34,44,80] and two in pre-season [69,78].

Alongside these different phases of collection, differences in training loads typically encountered in preseason periods [33,70,78] and the varying match demands reported to occur at professional rugby union match-play [13,14,84,85] perhaps further explain the lack of jump height consistency and sensitivity to fatigue. Grainger et al. [33] assessed fatigue across an 11-week pre-season period that encompassed varying training phases aiming to assess the change in upper and lower body neuromuscular fatigue over three distinct pre-season training blocks. It is therefore not surprising that this study reported CMJ values that may have been positively impacted by the training intervention or negatively impacted by the chronic fatigue that distinct pre-season training blocks create [19,33].

Of those not included in the meta-analysis, linear position transducer was used for one of the studies [62], with four others using force plates [3,12,42,58]. Peak velocity, time to peak velocity and phase duration were reported by Hills and Rogerson [62], with CMJ peak velocity significantly ($p = 0.02$) reduced from baseline over the twelve-week assessment period, with an overall decrease of -3.52% (Cis: -6.22 to -0.81%; 95% confidence interval), therefore indicating accumulation of fatigue and incomplete recovery between match weeks. Such peak velocity and phase duration information are likely to inform practitioners more about fatigue rugby players are experiencing post-match or training session, with further analysis and implementation of this detailed below.

3.8.2. Self-Reported measures

From the selected articles included in the meta-analysis, five reported wellness [33-35,45,62], six reported soreness [35,43-45,83] and two reported tiredness [57,82]. Of those not included in the meta-analysis (as they did not provide enough data for analysis), all four used a multivariate questionnaire to measure fatigue, with three of these assessing fatigue post-match in season [3,34,65] and one assessing fatigue post-match pre-season [77]. Assessing fatigue across 11-week match microcycles, Grainger et al. [34] reported significant differences between match day and 24 hours post-match in multiple self-report wellness measures (Readiness $p = 0.18$; ES = -2.33, 95%CI -1.54 - 3.13; Energy $p = 0.02$; ES = -2.24, 95%CI -1.44 – 3.03; Soreness $p = <0.001$; ES = -2.42, 95%CI -1.63 - 3.23). Meanwhile, West et al. [3] reported self-report mood disturbance increased at 12 hours ($p = 0.031$) before returning to baseline at 36 and 60 hours post-match.

3.8.3 Biochemical measures

From the four selected articles included in the meta-analysis, two used saliva [56,64], one used blood only [21], and one used urine and saliva to indirectly assess fatigue [71], with all of these assessing fatigue post-match during competition phases of a season. Of those not included in the meta-analysis (as they did not provide enough data for analysis), eight used saliva, three used blood and three used urine to indirectly assess fatigue, with two of these studies assessing fatigue after training [63,77,81] and the remaining others all collected post-match. Three articles not included in the meta-analysis (as they did not provide enough data for analysis) assessed testosterone, four assessed cortisol and one the testosterone to cortisol [T/C] ratio, one assessed creatine kinase, two saliva IgA and one assessed creatine kinase, testosterone, cortisol and T/C ratio. One study not in the meta-analysis focused upon resting metabolic rate [86], while another study focused on metabolic perturbations [87]. Meanwhile, one study [74] assessed cardiovascular stress response to match-play (via NTpro BNP a substrate from the heart), with one study [72] assessing catabolic response to match-play (assessed via neopterin).

3.8.4 Heart rate derived measures

Only one study investigated fatigue using heart rate derived measures [34]. Across a match week microcycle, it was reported that time-domain heart rate variability measures are sensitive to match day load

when assessed via Omegawave® Ltd (Espoo, Finland) technology. Specifically, these were between match day and 24 hours post-match for Root Mean Square of Successive Differences (RMSSD) (p = 0.04, ES = -0.66, 95%CI -0.11 - 1.20), Standard Deviation of the NN intervals (SDNN) (p = 0.04, ES = -0.66, 95%CI -0.12 - 1.20) and Total Power (p = 0.05, ES = -0.65, 95%CI -0.11 - 1.20). SDSD assesses the standard deviation of differences between adjacent normal to normal cardio interval. RMSSD is the square root of the sum of differences of a sequential series of cardio intervals, reflecting parasympathetic activity (measured in milliseconds). Total power is the variance of all normal-to-normal intervals in frequency range of 0 to 0.4 Hz (measured in milliseconds squared).

4. Discussion

The aim of this systematic review was to synthesise the common measures used to assess fatigue in male professional rugby union players. This systematic review provides a novel meta-analytic approach that estimated changes in neuromuscular, biochemical and self-reported fatigue after the exposure to match-play or training. From the relevant studies that met the inclusion criteria our data reveal acceptable consistency in the use of subjective soreness measures to assess fatigue after rugby activity in male professional players. However, the efficacy of CMJ height, biochemical markers, and heart-rate derived measures is unclear. In the best-case scenario, this is indicative of high variation in individual responses to training and match exposure, yet the worst-case scenario is that this reflects measures with a high degree of 'noise'.

4.1 Jump measures to assess fatigue

Findings from our meta-analyses indicate that CMJ height demonstrates high individual variability (based on the large 95%CI values) when used to evaluate fatigue (Fig. 2), with the pooled effect showing an overall small effect of exposure (either from a match or training stimulus). The 95% confidence intervals suggest some professional rugby union in some studies players demonstrate a decreased jump height post-match, with varied individual athlete responses being apparent (Fig. 2). Results do not, however, offer clear direction of CMJ sensitivity inter-individual match demands variation and future application to assess fatigue in professional rugby union players. Considering the inconsistency of these findings, use of force plates to assess jump measures as a determinant of fatigue is advised for implementation in applied rugby

union settings, as these will permit calculation of additional jump variables which may be more sensitive to fatigue [24-27]. As reported by Hills and Rogerson [62], additional information such as CMJ phase duration (collected via a force plate) is recommended as this may allow for greater understanding of underlying contributing factors to the jump response, via identification of players that may have, for example, altered their jump strategy [24-27]. Our observations are re-affirmed by the very large association between wellness and CMJ displacement (r = 0.80, 95% CIs = 0.72-0.86), and the strong negative correlation between wellness changes and CMJ duration (r = -0.62, 95% CIs = -0.49 - -0.72) during the competitive phase of a professional rugby union season [62].

Alongside the finding that CMJ presents unclear efficacy and high individual variability, it is worth noting that the specific measures used to assess CMJ also needs consideration [25]. Participants might increase countermovement displacement to increase time to apply force to maintain impulse [25]. Variability in the match demands for each player driven by positional differences, is most likely to cause the high variability reported in our results and therefore should be considered in future research. Practitioners should avoid the sole use of jump height as measure of fatigue and instead consider metrics such as time to take-off, countermovement displacement / depth, or the components of propulsive impulse (propulsion phase duration and mean propulsive force), as such metrics and a temporal phase analysis can provide greater insight into the jump strategy employed and the associated fatigue [45]. Practitioners should also consider if body mass has decreased post-match [88], which might enable players to maintain jump height when compared to pre-match values.

Despite some studies included in this review reporting peak power, we advise practitioners to avoid using this metric given its poor reliability [89-91]. Lastly, in other team sport settings, other forms of jumps (drop jumps, unilateral jumps and balance tests) [69] have been used to assess fatigue. Drop jumps involve muscle actions that are associated with some aspects of rugby union match-play (such as fast stretch shortening cycle actions like changes of direction) and therefore might contribute to fatigue [13]. However, practitioners should note that the use of drop jumps is limited as the height from which athletes' drop varies between sessions due to the procedures or drop jump strategy employed [92].

Despite the high individual variability reported for CMJ height as an assessment of fatigue, we support its continued use for fatigue assessment in professional rugby union settings. However, CMJ data should be interpreted on an individual athlete basis and acted upon accordingly. The use of CMJ to assess fatigue is not a concern, but simply reporting jump height without other key strategy variables is. Practitioners are therefore advised to administer a consistent and standardized testing protocol that includes consideration of the player's jump strategy. For example, calculation of propulsive phase duration and propulsive mean force, with considerations for post-match changes in body mass, will indicate if jump height has changed due to a change in jump strategy, or a decrease in the athletes' mass [93]. The relative ease of implementation of CMJ testing, its inexpensive nature and the previously reported reduced neuromuscular fatigue (assessed using CMJ) for up to 48 hours after a rugby union match-play [3,6] mean it still has worth if applied on an individual case basis.

4.2 Biochemical markers to assess fatigue

Although biochemical markers provide more objective measures of homeostatic disturbances and previous rugby union research exists which assesses the time-course of changes in biochemical markers in rugby union [3,82,94], our data (see in Fig. 4) suggests these measures possess high heterogeneity for biochemical markers used to assess fatigue. Poor reliability and large intra-individual differences associated with biochemical testing (Tables 1 and 2) support previous work that indicates variable reliability and validity of such measures [73,95] that can perhaps be explained by individual responses or between-study heterogeneity. Common issues that are known to affect the reliability of biochemical testing include: ambient temperature, hydration status, diet, glycogen content, previous exercise, circadian rhythm and sampling procedures [96]. Practically, issues with measurements error for biochemical markers might render these problematic when used over a longitudinal period. Similarly, the expense associated with current biochemical testing, the expertise needed to perform such tests, slow feedback and the practical challenges of testing large number of players would make them unrealistic for assessment in many rugby union teams. The current lack of rapid feedback involved within such biochemical testing procedures makes their use impractical, therefore practitioners should proceed with caution when implementing such measures.

4.3 Subjective self-reporting of well-being to assess fatigue

Present results indicate a small and a moderate effect on fatigue by self-reported measures of wellness and tiredness, respectively (Fig. 3.), meaning the utility of such measures and testing protocol employed is unclear. In the best-case scenario, this is indicative of high individual responses to training exposure. In the worst-case scenario, this is indicative of very 'noisy' measurement. When monitoring fatigue after training in professional rugby union players, lower body muscle soreness provides important information for strength and conditioning coaches [12]. Further support for the use of muscle soreness as a sensitive measure of fatigue has been previously reported [97,98], with evidence showing muscle soreness lasting for longer than decreases in CMJ height and biochemical markers in professional rugby league players (lasting up to 48 hours post-match in some studies) and the influence of impacts incurred during match-play negatively influencing muscle soreness. In professional rugby union, muscle soreness is also reported to take greater than 48 h to recover post-match [12,35], with present results offering similar support for the use of muscle soreness to assess fatigue post-match. Likely reasons for the muscle soreness differences reported in studies could be explained by the match demands and the individual responses to these demands, with blunt force trauma from impacts perhaps explaining individual variability [13].

4.4 Heart rate variability

Recent technological developments have enabled objective 'real-time' physiological feedback from training and competition, allowing evaluation of fatigue [99]. However, there is currently limited scientific field-based application of these technologies in elite rugby union settings. One such field-based technological development has been the application of HRV assessment tools, which characterise fluctuations in autonomic control [100], regulated by innervations from the sympathetic and parasympathetic branches of the autonomic nervous system [101]. In the time-domain, lower HRV signals are an indicator of insufficient adaptability to stressors, suggesting compromised health or a state of chronic fatigue [100]. Heart rate variability is affected by the balance of sympathetic and parasympathetic tone, which appears to be perturbed after rugby competition [102,103]. In rugby league [104], daily time domain measures of HRV during a competitive playing season demonstrated a shift in cardiac autonomic balance towards lower HRV on match day, lasting for 1-2 days post-match. Conversely, Grainger et al. (2022) [34] reported HRV

to be dysregulated post-match, but recovered in the 24 hours after the match. The lack of sensitivity in comparison to a self-report wellness measure questions its value and therefore requires further investigation.

RMSSD is one of many time-domain HRV measures, which assesses the variability of vagus-mediated differences between neighboring RR intervals (time between QRS complexes) [100]. Similarly, the standard deviation of successive RR interval differences (namely SDSD and SDNN) can be used to assess autonomic balance [98]. Specifically, for professional rugby union, Grainger et al. (2022) [34] reported time-domain measures (SDNN, SDSD and RMSSD) being sensitive to match day load yet recovering during the micro-cycle. Frequency-domain measures typically show two patterns of oscillation, separated into low frequency (LF; 0.04-0.15 Hz) and high frequency (HF; 0.15-0.4 Hz), which can be used to evaluate parasympathetic and sympathetic regulation. A combination of time- and frequency-domain measures have been used to monitor signs of non-functional overreaching among combat athletes, where distinct changes in HRV were reported alongside increased training load [105]. Whilst single measures of autonomic function might not consistently respond to training stress across individuals [101], a combination of time- and frequency-domain HRV indices (i.e., RMSSD, SDNN, LF, LF) might appropriately account for physical and psycho-emotional stressors [98,105].

Chen et al. [106] noted that parasympathetic reactivation occurred at a slower rate amongst competitive weightlifters than was seen for endurance athletes [107] further commenting that this discrepancy is probably due to weightlifting being a sport that involves more muscle trauma than endurance sport. Morales et al. [108] noted that, in judo, difficulty arises when attempting to quantify training load because of the characteristics of the sport. The same difficulties are apparent in rugby union, where opponents, volume of contact training completed, and intensity of matches all add to the questionable quantification of the training load completed. Some aspects of a rugby player's training week are easier to quantify, such as strength and conditioning sessions, yet contact sessions would not represent the whole training week prescribed to the player with the associated effect this can have upon HRV. Morales et al. [108], therefore, recommended further analysis of HRV and training load responses in sports such as wrestling, rugby and other contact sports. It is expected that as rugby specific technological advances are developed, the focus of fatigue measures will continue to investigate the use of heart rate derived measures will likely continue, as unlike jump testing and maximal and submaximal performance tests for example, heart rate derived

measures present a true representation of internal load and therefore may be of more practical interest to practitioners.

4.5 Heart rate recovery

Heart rate recovery (HRR) measures the rate at which heart rate declines at the cessation of exercise, with support for HRR guided training programs presented by Buchheit et al. [109], who noted HRR to be more sensitive to training induced changes than HRV indices. No research assessing HRR in elite rugby union exists. Previous studies in team sports settings utilising HRR have produced contrasting results [110-114], mainly due to the wide variation in baseline fitness of athletes measured and exercise protocols used. Support for HRR does, however, exist [115] where HRR showed an increase in fitness correlating ($p = 0.016$) with 2km time trial results improving in elite Australian Rules football players. This research by Cornforth et al. [115] supports the views of previous researchers [112,116] that training load influences HRR.

4.6 Meaningful change

Informed decisions on the meaningfulness of any change in a measure of fatigue depends on the reliability of that measure. Arbitrary cut-off points (e.g., change of 5%) for different measurements to identify a fatigued condition should be avoided by practitioners because this might fall within the range of typical variation for some measurements (e.g., jump measurements ~1-6%; Roe et al. [117]), but not others (e.g., CK; 26.1%; Roe et al. [118]). Practitioners might interpret whether a change is meaningful using reliability and inter-day variability of the measure (typical error) for everyone by taking repeated measures of the parameter and calculating the (SD/sqrt2). Practitioners can then interpret a true change in a recovery parameter if the change is greater than the typical error for that measurement. The magnitude of the change in that parameter can then be decided using modified standardized effects, i.e., multiplying the standard deviation of the athletes' scores by 0.2. Note that when determining the meaningfulness of self-reported measures of fatigue, this approach is not possible when scores are only free to change by increments of 1. In these instances, practitioners might combine self-report measures with other measures of fatigue (e.g.,

CMJ) to determine the fatigue status of a rugby player.

4.7 Future research directions

Large variances in individual player responses are noted with our analysis, with these differences likely due to the individual demands experienced during match-play. It is also worth considering that fatigue from elite rugby union matches and training will likely to be position specific, with the causes of these mechanisms evident considering the varying blunt force trauma, distances covered, accelerations and decelerations encountered during matches and training [3,14,18,59]. Positions that complete a large volume of accelerations and decelerations during match-play, should perhaps have their fatigue assessed by force at zero velocity, as this measure is likely to offer good repeatability and appears useful for inferring changes in movement strategy during the eccentric phase [24-27]. However, evidence presented by Twist et al. [119] reported an inverse relationship between contacts and impaired CMJ flight time, indicating that players that are involved in more contacts experience more loading on the lower limb musculature. Meanwhile, it is worth considering that many cognitive factors exist that might contribute to perceived fatiguability as well as performance fatiguability [57,120-125]. Future research is therefore required to confirm individual responses upon specific measures of fatigue and the influence of match and training demands.

Despite these large variances in individual responses and inconclusive evidence presented within our findings to support their worth, use of sub maximal neuromuscular testing (such as CMJ), self-report well-being, biochemical markers and heart rate derived measures will likely continue to be regularly used in applied rugby settings [23,126]. We recommend that future analysis of CMJ data to assess fatigue after a match considers more insightful metrics such as time to take off, phase duration, propulsive impulse and its components (mean propulsive force and propulsion phase duration) or countermovement displacement, as such information will inform practitioners more about the jump strategy employed and the resultant influence fatigue may have had upon this jump strategy. We also recommend the use of drop jumps to measure fatigue, where fall height is calculated and not assumed as box height [127].

Practitioners are advised to consider fatigue to be a multifaceted process [1,128], meaning recovery from rugby union match play should target factors that have contributed to both performance and perceived

fatigiability. This notion is supported by Rattray et al. (2015) [129] who proposed that modern post-exercise recovery strategies should focus on both peripherally- and central-orientated mechanisms. When considering the high cognitive load (a multi-dimensional construct representing the load that performing a task imposes on the learner's cognitive system) experienced by rugby union players, the need to assess psychological stressors and attempt to influence a hastening of restoration of performance from a central fatigue viewpoint is paramount [130]. Current methods of assessing neurophysiological measures [computed tomography (CT), magnetic resonance imaging scan (MRIS) and electroencephalography (EEG)] limit its appeal for practitioners in the professional field, due to logistical and budget restrictions. Similarly, fatigue assessment via heart rate measures is well-documented and validated in endurance sports ple [105,131], yet to date methods of assessment in all rugby codes (rugby league, rugby sevens and rugby union, specifically) has been limited [34,102,104] and therefore warrant further investigation. Developing an understanding that post-exercise recovery practices should not solely focus upon peripheral mechanisms of fatigue is key. Further research in recovery strategies that impact perceived fatiguability is needed to understand better current methods that would minimise fatigue and ultimately improve performance [132]. Future recovery intervention planning should therefore consider elements of a rugby player's daily life, including, for example, peer pressure and potential pressure from sponsors. Practitioners working with professional players are advised to look beyond physiological time-course of recovery assessment, and instead include a combined approach of physiological and psychosocial recovery intervention.

4.13 Limitations

This study is not without limitations. That we chose to study only male professional players means these findings are difficult to generalize to other relevant groups, such as amateurs and younger age groups, i.e. academy players. Data used in the studies accepted for analysis were also often non-experimental (i.e., descriptive) and did not include a control group. Therefore, the extent to which these data reflect genuine changes in fatigue markers remains unclear. We were also unable to account for the effect different match loads experience by players when interpreting fatigue responses. For example, players that were interchanged during a match or performed fewer collisions are likely to have experienced different post-match fatigue responses to whole match players or players involve in more collisions. Finally, despite our recommendations for the use of self-report measures, Jeffries et al. (2020) [133] have pointed out that many of the most frequently used athlete-reported outcome measures have not been validated on the population of

interest. Furthermore, where individual items from a previously unvalidated measure are used, these are done without justification or validation. It is also unclear with many of these scales the extent to which the measured item(s) reflect the intended construct (e.g., 'wellbeing', 'wellness') or why this construct is useful when monitoring fatigue status in professional rugby players.

5. Summary

The continued use of self-report assessment of subjective muscle soreness seems the most applicable for regular use in many professional rugby union settings. If using CMJ as a measure of post-match fatigue, practitioners are encouraged to use force plates to assess a variety of previously reported reliable jump metrics (such as time to take-off, propulsive phase durations, propulsive mean force, countermovement displacement / depth along with changes in body mass). This will allow for greater insight into the jump strategy employed, to determine if CMJ height is maintained by a change in jump strategy, or changes in body mass. Practitioners should also consider individual fatigue responses that accounts for task-specificity within match play and training, ensuring the reliability of any chosen metric has been established beforehand. Adopting this approach will offer practitioners meaningful assessment of fatigue status of rugby union players that helps to manage player preparedness for training and competition, while minimizing the risk of fatigue-related injuries.

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