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REVIEW ARTICLE

Assessing athlete readiness using physical, physiological, and perceptual markers: A systematic review and meta-analysis

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ABSTRACT

This systematic review and meta-analysis evaluated the validity of tests / markers of athletic readiness to predict physical performance in elite team and individual sport athletes. Ovid MEDLINE, Embase, Emcare, Scopus and SPORT Discus databases were searched from inception until 15 March 2023. Included articles examined physiological and psychological tests / markers of athletic readiness prior to a physical performance measure. 165 studies were included in the systematic review and 27 studies included in the meta-analysis. 20 markers / tests of athletic readiness were identified, of which five were meta-analysed. Countermovement jump (CMJ) jump height had a large correlation with improved 10m sprint speed / time (r = 0.69; *p* = .00), but not maximal velocity (r = 0.46; *p* = .57). Non-significant correlations were observed for peak power (r = 0.13; *p* = .87) and jump height (r = 0.70; *p* = .17) from squat jump, and 10m sprint speed / time. CMJ jump height (r = 0.38; *p* = .41) and salivary cortisol (r = -0.01; *p* = .99) did not correlate with total distance. Sub-maximal exercise heart rate (r = -0.65; *p* = .47) and heart rate variability (r = 0.66; *p* = .31) did not correlate with Yo-Yo Intermittent Recovery Test 1 performance. No correlation was observed between blood C-reactive protein and competition load (r = 0.33; *p* = .89). CMJ jump height can predict sprint and acceleration qualities in elite athletes. The validity of the other readiness tests / markers meta-analysed warrants further investigation.

Keywords: Elite athletes, Athlete readiness, Physical performance, Athlete monitoring.

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INTRODUCTION

The demands and nature of modern day professional sport has caused an increase in not only the physiological demands on athletes but psychological stress from commercial obligations, sponsors, media, education and family (Ryan et al., 2020). Therefore, it is of critical importance performance coaches have a comprehensive understanding of the competing demands on their athletes, their fatigue and recovery status, and ultimately their "*readiness*" to perform in training and competition (Ryan et al., 2020). Athlete monitoring is now standard practice in professional sport (Taylor et al., 2012), with the information collected used to inform performance staff of an athlete's injury risk and readiness to perform (Taylor et al., 2012; Thorpe et al., 2017). The primary goal of athlete monitoring systems is to monitor training load and the athletes' responses to training and competition stress to inform decision making on recovery and availability for subsequent training and competition (Bourdon et al., 2017). Importantly, an intricate understanding of the stress on athletes is fundamental to the subtle manipulation of training load to maximise favourable and functional adaptations to maximise performance (Impellizzeri et al., 2019).

Often the difficulties with monitoring team sport athletes in particular, is the individual variability between athletes in their response to modifiable (health, sleep and training status) and non-modifiable (genetics, weather, and pressure and expectation from media and supporters) factors (Impellizzeri et al., 2019). Indeed, the prescription of the identical training load for one athlete may evoke a completely different internal, psychophysiological response in other athletes from the same team (Bouchard et al., 2011; Mann et al., 2014; Smith, 2003).

With improvements in technologies used to monitor athletes, the current practice in professional sport is to assess athlete readiness for training and competition, and tolerance to training load, at the individual level. Typically, this is comprised of neuromuscular assessments including countermovement jump (CMJ) and squat jump (SJ) (Cormack et al., 2013), fitness tests (i.e., Yo-Yo Intermittent Recovery Test 1 (Yo-Yo IR1)) (Veugelers et al., 2016), and autonomic nervous system assessment using heart rate parameters (i.e., heart rate variability (HRV) and heart rate recovery (HRR) (Plews, Laursen, Stanley, et al., 2013). More invasive measures such as testing biological markers are also commonly used, with inflammatory markers such as creatine kinase (CK) suggested to be a valid and reliable indicator of fatigue in team sport athletes (Hecksteden et al., 2016; Nédélec et al., 2012). Furthermore, whilst the importance of physiological recovery is fundamental to athlete readiness for training and competition, there is well-established literature supporting the use of psychological markers of training status to monitor individual athlete response (Borresen & Lambert, 2009; Raglin, 2001). These psychological recovery markers, commonly assessed through a range of psychological wellness questionnaires (Saw et al., 2015), provide an athlete's individual perception of readiness and comprise a critical component of the recovery-fatigue monitoring process (Kellmann et al., 2018; Saw et al., 2016).

Previous studies that have established changes in readiness tests and markers, particularly HRV, suggest a stronger correlation with measures of performance as opposed to other isolated measures (Bellenger et al., 2016; Plews, Laursen, Kilding, et al., 2013). Importantly, a distinguishing feature of the current review was the investigation of tests and markers of readiness in the context of gold standard measures of athletic performance using correlation analysis. Furthermore, despite the volume of studies which, in isolation, have investigated the use of various tests and markers of athletic readiness as an indicative measure of performance, no study has conducted a holistic investigation and analysis of the various readiness tests and markers used to assess fitness and fatigue in elite team and individual sport athletes.

Given the rise in the reliance and application of these markers and tests for practitioners in sport and exercise science, the aim of this review was to identify the most valid tests and measures of athletic readiness to predict physical performance in elite athletes.

MATERIAL AND METHODS

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement for improved reporting of systematic reviews (Moher et al., 2009).

Literature search

A systematic search of the literature was conducted on 3 November 2021 in the following databases: Ovid MEDLINE, Embase, Emcare, SPORT Discus and Scopus. Database update alerts were monitored until 15 March 2023 for any additional studies that met the inclusion criteria. Database searches were complemented with pearling of reference lists for relevant studies which satisfied the inclusion criteria.

Title, abstract and keyword searches were conducted in the aforementioned databases using the following search strategy (see Supplementary Table 1 for the master search strategy) developed in MEDLINE and Emcare, which was revised and amended for the remaining databases:

1. Elite athletes

AND

2. Tests and / or markers of athletic readiness

AND

3. Physical measures of athletic performance

Eligibility criteria

To be eligible for inclusion in this review, study participants must have been elite, professional able-bodied athletes of any gender competing in team or individual sports. Study participants were considered to have met the inclusion criteria if they satisfied tiers four and five of the classification frameworks developed by McKay et al. (McKay et al., 2022), with the exception of NCAA and elite junior or underage athletes who were excluded as they were not considered professional for the purpose of this review. Studies needed to assess more than one participant using a relevant test and marker of athletic readiness, prior to a subsequent measure of athletic performance. Only studies which analysed participants using a test and marker of readiness in a rested or sub-maximal state were included, due to the disruption of physiological homeostasis following near, or maximal physical exertion (Bellenger et al., 2016). Studies which investigated markers and tests of readiness in the context of other interventions which disrupted a homeostatic state (i.e., caffeine ingestion or heat exposure) were eligible for inclusion provided a placebo / control group's data could be extracted independently of the intervention group, and there was no cross-over of participants to control and / or intervention groups during the study. Studies' intervention period could not exceed 12 months or one season. Studies measuring HRR were only included if heart rate was measured following sub-maximal exercise, in line with previously established sub-maximal heart rate assessment protocols (Buchheit et al., 2009). Studies using session rating of perceived exertion (sRPE) as a performance measure were only included if the subjective measure of load was calculated from a competition or match setting. Studies which analysed sport-specific readiness and performance (i.e., 7-stroke max and repeated sprint ability) tests were not eligible for inclusion as their application was not generalisable, as were unpublished, non-English, or qualitative studies.

Studies were eligible for inclusion in the meta-analysis if the relationship between the marker and test of performance readiness and the subsequent performance measure were analysed using Pearson product-moment correlation coefficient or Spearman's rank correlation coefficient. To improve the generalisability of the findings, studies were only meta-analysed if three or more studies analysed an identical, standardised readiness test and marker in the context of an analogous performance outcome. Where necessary, the direction of relationships was transformed to a positive value to indicate an improvement or decrement in performance. For example, the time to complete a time trial and the average speed in a time trial provide different directions. Therefore, studies included in the meta-analysis were amended to ensure consistency in the direction of the reported relationship between analogous readiness markers and tests, study designs, and performance outcomes.

Studies analysing sub-maximal exercise heart rate were eligible for inclusion if exercise heart rate was measured following a period of at least three minutes of sub-maximal exercise intensity, so a steady state heart rate was established (Buchheit, 2014; Cerretelli & Di Prampero, 1971). For HRV, meta-analyses were only conducted on studies which reported indices of standard deviation of instantaneous beat-to-beat R–R interval variability from Poincare plots (SD1), root-mean-square difference of successive normal R–R intervals from time-domain analysis (RMSSD) and high frequency power (HFP) as measures of pure parasympathetic modulation based on the findings and recommendations of Bellenger et al. (Bellenger et al., 2016).

Study selection
Studies identified in the systematic search were exported into a reference management software program (Endnote version X8.2, Thomson Reuters, 2012). All articles were subsequently imported into Covidence (Covidence Systematic Review Software, Veritas Health Innovation, 2013) where all duplicates were removed. Studies were initially assessed for eligibility by title and abstract screening against the eligibility criteria in Covidence, where irrelevant studies were excluded. The remaining studies were assessed for full-text eligibility using the eligibility criteria. Screening was conducted independently by two investigations (SJJ and GKB), with conflicts resolved by consensus.

Data extraction was conducted by the lead author (SJJ) and confirmed by a second investigator (GKB). The following information was obtained from the included studies: publication details (year, author(s), country), participant characteristics, study design (longitudinal (pre-post test(s) and marker(s) of readiness) or cross-sectional), results (athletic readiness test(s) / marker(s), performance measure(s)), duration of time between the fatiguing exposure and test of readiness and performance, and the relationship between the readiness test and performance measure (acute (<48 hours) or chronic (>48 hours)), based on the passage of time between the assessment of the readiness test and / or marker and the subsequent performance measure.

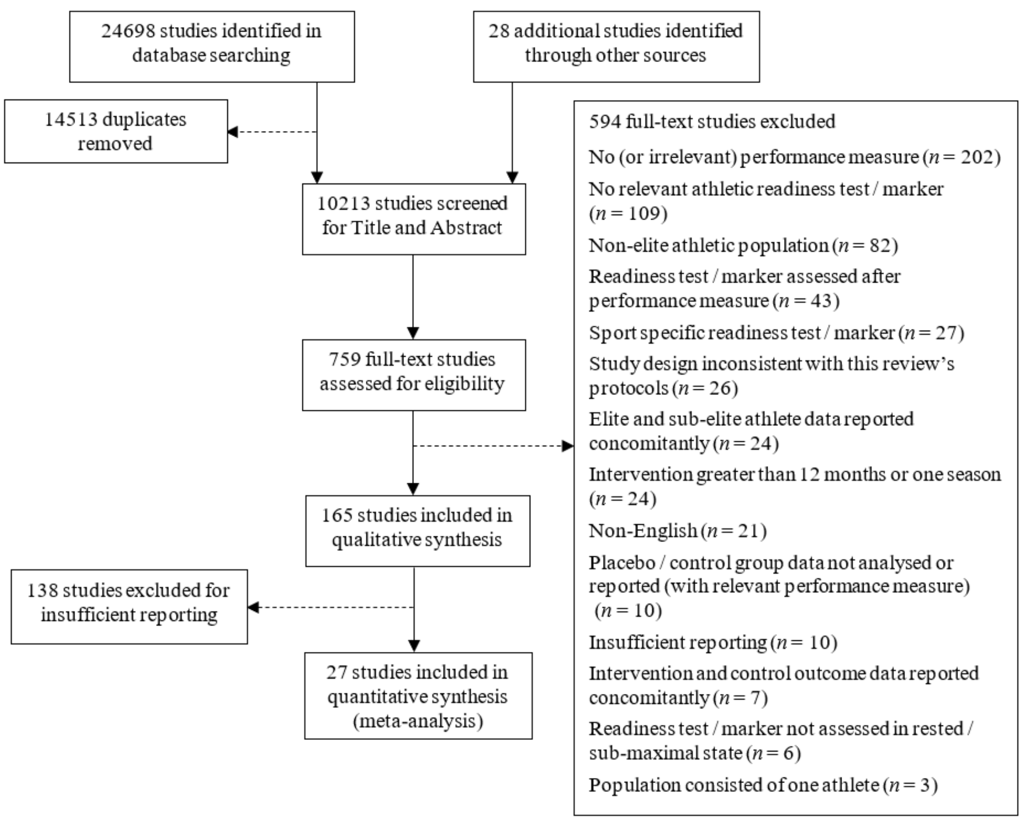
Risk of bias assessment
The Cochrane Collaboration tool was used by the lead author (SJJ) and confirmed by a second investigator (GKB) to assess risk of bias (Higgins et al., 2011). The tool was used to assess selection, performance, detection, attrition and reporting bias from the studies identified from the systematic search.

Statistical analysis

Random effects meta-analyses were performed in Stata 16.1 (College Station, Texas) to assess the relationship between homogenous markers and tests of performance readiness, and performance measures. All correlation coefficient data from the included studies were normally distributed using the Fisher Z-Transformation to calculate the standard error, before being transferred back into Pearson product-moment correlation coefficients for reporting and presentation. Data were presented as Pearson product-moment correlation coefficient (r) ± 95% confidence interval (CI) with statistical significance set at $p < .05$. Qualitative interpretations of the correlation coefficients were applied based on the following framework: 0.00-0.09, trivial; 0.10-0.29, small; 0.30-0.49, moderate; 0.50-0.69, large; 0.70-0.89, very large; 0.90-1.00, nearly perfect (Hopkins, 2000). The presence of statistical heterogeneity was determined by the I^2 statistic and interpreted using the framework developed by Higgins et al. (Higgins et al., 2019).

Meta-analyses were conducted on indices of the following markers and tests of performance readiness: CMJ, biomarkers, SJ, sub-maximal exercise heart rate, and HRV which were sub-grouped into acute (<48 hours) and chronic (>48 hours). These markers were further grouped into cross-sectional and / or longitudinal study designs for analysis, as well as whether the performance measure(s) assessed the marker and test of readiness in a training or competition setting. Identical markers and tests of readiness were eligible to be analysed with different performance measures provided the performance measures assessed different psychophysiological qualities. To ensure uniformity in the analyses and reporting, and where appropriate to do so, data were presented with a positive correlation.

RESULTS



Note. n number of studies.

Figure 1. Literature search flow chart.

The initial search identified 24698 studies, with 28 studies identified through other sources. Once 14513 studies were removed as duplicates, a further 9454 studies were identified as irrelevant by title and abstract screening. 759 studies were reviewed by full text for inclusion. A summary of the search, including the number of studies included in the qualitative synthesis and meta-analysis, is shown in Figure 1. A summary of the 165 studies included in the qualitative synthesis is provided in Table 1.

Table 1. Summary of studies included in the qualitative synthesis.

Study	*n*	Athletes	Study design	Readiness marker(s) / test(s)	Performance measure context	Relationship
Costa et al., 2022	M: 11	Beach Soccer	Longitudinal	Wellness Questionnaire (HI)	Training	Acute
Gaviglio & Cook, 2014	M: 22	Rugby Union	Longitudinal	Biomarker (salivary T, T:C)	Competition	Acute
Loturco et al., 2018	M: 9 F: 7	Athletics	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Training	Acute
Balthazar et al., 2012	M: 8	Triathlon	Cross-sectional	Biomarker (salivary T, C)	Competition	Acute
Morris et al., 2022	M: 14	ARF	Cross-sectional	CMJ (PCF, PEF, eccentric time, concentric time, FT, eccentric: concentric time, PEP, PCP, peak eccentric velocity, peak concentric velocity, jump height, peak eccentric RFD, peak concentric RFD)	Training	Acute
McLellan et al., 2010	M: 17	Rugby League	Longitudinal	Biomarker (blood CK, and salivary T, C)	Competition	Chronic
Crewther et al., 2012	M: 64	Rugby Union	Cross-sectional	Biomarker (salivary T)	Training	Acute
Gaviglio et al., 2014	M: 22	Rugby Union	Longitudinal	Biomarker (salivary T, C, T:C)	Competition	Acute
Loturco et al., 2014	M: 9 F: 10	Karate	Cross-sectional	CMJ (jump height) Squat Jump (jump height, relative mean propulsive power)	Training	Acute
Webster et al., 2022	M: 15	Cricket	Cross-sectional	CMJ (jump height)	Competition	Chronic
Henderson et al., 2019	M: 20	Rugby Sevens	Longitudinal	Wellness Questionnaire (soreness, sleep, stress, fatigue, recovery) Groin Squeeze Assessment (0^0)	Competition	Chronic
Le Panse et al., 2010	M: 13 F:13	Powerlifting	Cross-sectional	Biomarker (salivary T, C, DHEA)	Competition	Acute
Loturco, Pereira, et al., 2015	M: 14	Athletics	Cross-sectional	CMJ (jump height) Squat Jump (jump height) Horizontal Jump	Competition	Chronic
Knöpfli et al., 2001	M: 4 F: 5	Cross-country skiing	Longitudinal	Biomarker (dopamine, epinephrine, norepinephrine)	Competition	Acute
Krustrup et al., 2003	M: 17	Soccer	Longitudinal	Biomarker (blood lactate, plasma K+)	Training	Acute
Staunton et al., 2017	F: 12	Basketball	Longitudinal	Sleep (time, efficiency)	Competition	Acute

Hansen et al., 2019	M: 12	Gymnastics	Cross-sectional	CMJ (jump height, peak power) Drop Jump (jump height)	Competition	Acute
McMahon et al., 2021	M: 15	Hockey	Longitudinal	Biomarker (CK) Wellness Questionnaire (soreness)	Competition	Chronic
Loturco, D'Angelo, et al., 2015	M: 13 F: 9	Athletics	Cross-sectional	CMJ (jump height, peak force) Squat Jump (jump height, peak force) Horizontal Jump (distance (m))	Training	Acute
Pojskic et al., 2018	M: 38	Basketball	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Training	Chronic
Secomb, Farley, et al., 2015	M: 18	Surfing	Cross-sectional	CMJ (peak force, peak velocity, jump height, stiffness) Squat Jump (peak force, peak velocity, jump height) IMTP (peak force, relative force)	Training and Competition	Acute
Nakamura et al., 2020	M: 11	Futsal	Longitudinal	HRV (RMSSD)	Training	Acute
Hooper et al., 1993	M: 5 F: 8	Swimming	Longitudinal	Biomarker (blood cortisol, epinephrine, norepinephrine)	Training	Acute
Thorpe et al., 2015	M: 10	Soccer	Longitudinal	Wellness Questionnaire (fatigue, sleep, soreness) CMJ (jump height) HRV (lnRMSSD) HRR	Training	Acute
Turner et al., 2015	M: 17	Rugby Union	Cross-sectional	CMJ (jump height)	Training	Chronic
Rabbani et al., 2018	M: 14	Soccer	Longitudinal	Sub-maximal exercise HR HRR	Training	Chronic
Colyer et al., 2017	M: 8 F: 5	Skeleton	Longitudinal	CMJ (max centre of mass displacement, peak power, mean power, RFD)	Training	Acute
Lombard et al., 2021	M: 23	Hockey	Longitudinal	CMJ (jump height)	Competition	Chronic
Peñailillo et al., 2015	M: 9	Soccer	Longitudinal	Biomarker (salivary T, C, IgA)	Competition	Acute
Selmi, Levitt, et al., 2022	M: 16	Soccer	Longitudinal	Wellness Questionnaire (physical freshness)	Training	Acute
Hills & Rogerson, 2018	M: 37	Rugby Union	Longitudinal	Wellness Questionnaire	Training	Acute
Loures et al., 2014	M: 21 F: 7	Kayaking (K1)	Longitudinal	Biomarker (blood lactate)	Competition	Acute
Balsalobre-Fernández et al., 2014	M: 12 F: 3	Athletics	Longitudinal	CMJ (jump height) Biomarker (salivary C)	Training	Acute
Spiteri et al., 2014	F: 12	Basketball	Cross-sectional	CMJ (jump height) IMTP (peak force)	Training	Acute
Stojanovic et al., 2012	M: 24	Basketball	Cross-sectional	CMJ (jump height)	Training	Acute

Maior et al., 2018	M: 20	Soccer	Longitudinal	Biomarker (blood CK)	Competition	Acute
Saidi et al., 2022	M: 14	Soccer	Longitudinal	Biomarker (blood CRP, CK, creatinine) CMJ (jump height) Squat Jump (jump height) Wellness Questionnaire (HI)	Training and Competition	Acute and Chronic
Shearer et al., 2015	M: 12	Rugby Union	Cross-sectional	Wellness Questionnaire (BAM)	Training	Acute
Malone et al., 2017	M: 22	Gaelic Football	Longitudinal	HRV (lnSD1) HRR Sub-maximal exercise HR	Training	Acute
Gastin et al., 2013	M: 27	ARF	Longitudinal	Wellness Questionnaire (general muscle strain, hamstring strain, quadriceps strain, stress)	Competition	Acute
R. Gathercole et al., 2015	F: 12	Rugby Sevens	Longitudinal	CMJ (RFD, time to peak power, time to peak force, velocity at peak power, peak displacement, flight time, FT:CT) Wellness Questionnaire (HI)	Training	Acute
Requena et al., 2014	M: 25	Soccer	Longitudinal	CMJ (flight time, velocity at take-off) Drop Jump (flight time, contact time, velocity at take-off)	Training	Acute
Silva et al., 2014	M: 14	Soccer	Longitudinal	CMJ (jump height) Biomarker (blood C, T:C, antioxidant, gluthione peroxidase, superoxide dismutase gluthione peroxidase ratio)	Competition	Chronic
Guilhem et al., 2015	M: 9 F: 15	Athletics	Longitudinal	Wellness Questionnaire (POMS) Biomarker (salivary T, C, AA, IgA, chromogranin A, and blood CK)	Training	Chronic
Díaz Gómez et al., 2013	M: 8 F: 3	Swimming	Longitudinal	Biomarker (salivary AA, chromogranin, nitrate, and blood adrenaline, noradrenaline, dopamine)	Training	Chronic
Hulin et al., 2019	M: 32	Rugby League	Longitudinal	Sub-maximal exercise HR	Training	Acute
Calleja-Gonzalez & Terrados, 2014	M: 8	Basketball	Longitudinal	Biomarker (blood T, C, T:C, CK)	Competition	Chronic
Clarke et al., 2015	F: 12	Rugby Sevens	Longitudinal	Biomarker (blood CK)	Competition	Acute
Moncef et al., 2012	M: 40	Handball	Cross-sectional	CMJ (jump height) Squat Jump (jump height) Vertical Jump (jump height)	Training	Chronic

Silva & Paiva, 2016	F: 67	Rhythmic Gymnastics	Longitudinal	Sleep (duration) Wellness Questionnaire (SCAT-A, PSQI, ESS)	Competition	Not reported
Bonifazi et al., 2000	M: 8	Swimming	Longitudinal	Biomarker (blood C)	Competition	Chronic
Doeven et al., 2019	F: 12	Rugby Sevens	Cross-sectional	Wellness Questionnaire (fatigue, soreness)	Competition	Acute
Bok & Jukić, 2019	M: 11	Soccer	Longitudinal	Biomarker (blood CK)	Competition	Acute
Emmonds et al., 2019	F: 10	Soccer	Cross-sectional	CMJ (jump height, RFD) Squat Jump (jump height, RFD) Drop Jump (jump height)	Training	Acute
Atlaoui et al., 2006	M: 9 F: 5	Swimming	Longitudinal	Biomarker (urinary adrenaline, adrenaline:noradrenaline ratio)	Competition	Chronic
Chamari et al., 2003	M: 9 F: 1	Windsurfing	Longitudinal	Heart rate reserve	Competition	Acute
Hunkin et al., 2014	M: 29	ARF	Longitudinal	Biomarker (blood CK)	Competition	Acute
Selmi et al., 2021	M: 20	Soccer	Longitudinal	Wellness Questionnaire (HI)	Training	Acute
Enes et al., 2021	M: 23	Soccer	Cross-sectional	CMJ (jump height) Sit and Reach Test	Training	Chronic
Mielgo-Ayuso et al., 2017	F: 40	Volleyball	Cross-sectional	Biomarker (blood T, ACTH, C, free T, T:C, free T:C) Wellness Questionnaire (SCAT, STAI, CSAI 2-7, OSQ, GHQ, Psychological Characteristics Related to Sport Performance Questionnaire)	Training	Acute
Messias et al., 2018	M: 10	Kayaking (K1, C1, C2)	Cross-sectional	Wellness Questionnaire (POMS, SCAT, PSQI, ESS)	Training	Acute
Mäestu et al. 2005	M: 11	Rowing	Longitudinal	Biomarker (blood T, C)	Training	Chronic
Haller et al., 2019	M: 26	Soccer	Longitudinal	Biomarker (blood cell-free DNA) Wellness Questionnaire (VAS)	Training and Competition	Acute
Cullen et al., 2021	M: 37	Gaelic Football	Longitudinal	Wellness Questionnaire (mood, sleep (quality and duration), energy, soreness, nutrition, stress, health)	Training and Competition	Acute
Saidi et al., 2019	M: 18	Soccer	Longitudinal	Squat Jump (jump height)	Training	Chronic
Lum & Joseph, 2020	M: 18 F: 6	Floorball	Longitudinal	CMJ (jump height)	Training	Acute
Nunes et al., 2011	F: 12	Basketball	Longitudinal	Biomarker (salivary T)	Training	Chronic
McEwan et al., 2020	M: 12	Cricket	Longitudinal	Wellness Questionnaire (Core-CSD)	Competition	Acute

Solana-Tramunt et al., 2019	F: 12	Synchronised Swimming	Longitudinal	HRV (lnRMSSD)	Training	Acute
Purge et al., 2006	M: 11	Rowing	Longitudinal	Biomarker (blood T, C)	Training	Chronic
Costa et al., 2019	F: 20	Soccer	Longitudinal	HRV (lnRMSSD) Sleep (time, efficiency)	Training and Competition	Acute
Tiernan et al., 2020	M: 19	Rugby Union	Longitudinal	Biomarker (salivary C)	Training	Chronic
Rodríguez-Fernández et al., 2021	M: 14	Basketball	Cross-sectional	CMJ (jump height)	Training	Chronic
Hauer et al., 2020	M: 12	Lacrosse	Longitudinal	Wellness Questionnaire (TQR, SRSS) HRV (RMSSD)	Competition	Acute
Costa et al., 2021	F: 34	Soccer	Longitudinal	HRV (lnRMSSD, lnHFP) Sleep (duration, efficiency)	Training and Competition	Acute
Iizuka et al., 2020	M: 4 F: 4	Badminton	Longitudinal	HRV (RMSSD, HFP)	Training	Acute
Bouaziz et al., 2016	M: 16	Rugby Sevens	Longitudinal	Biomarker (urinary C, cortisone, cortisol: cortisone ratio, adrenaline, adrenaline:noradrenaline ratio)	Training	Chronic
Cormack et al., 2008	M: 22	ARF	Longitudinal	CMJ (FT:CT) Biomarker (salivary T, C, T:C)	Competition	Acute and Chronic
Crewther et al., 2009	M: 24	Rugby Union	Cross-sectional	Biomarker (salivary T, C, T:C)	Training	Acute
Russell et al., 2021	F: 9	Netball	Longitudinal	Biomarker (salivary C, AA) Wellness Questionnaire (SRSS)	Competition	Acute and Chronic
Morales et al., 2019	F: 10	Soccer	Longitudinal	Wellness Questionnaire (RESTQ-Sport) HRV (RMSSD, HFP)	Training	Acute and Chronic
Crewther et al., 2020	M: 29	Rugby Union	Longitudinal	Biomarker (salivary C) Wellness Questionnaire	Competition	Acute
Moalla et al., 2016	M: 14	Soccer	Longitudinal	Wellness Questionnaire (HI)	Training and Competition	Acute
Watanabe et al., 2019	F: 57	Baseball	Cross-sectional	CMJ (jump height) Vertical Jump (jump height)	Competition	Chronic
Coppalle et al., 2019	M: 26	Soccer	Longitudinal	Biomarker (blood LDH, CK, CRP)	Competition and Training	Chronic
Bosco et al., 1996	M: 32	Soccer	Cross-sectional	CMJ (jump height) Biomarker (blood T, C)	Training	Acute
Ingebrigtsen et al., 2014	M: 34	Soccer	Cross-sectional	Sub-maximal exercise HR	Training	Acute
West et al., 2011)	M: 39	Rugby League	Cross-sectional	CMJ (jump height) IMTP (peak force, RFD, force 110 ms)	Training	Acute
Secomb, Lundgren, et al., 2015)	M: 15	Surfing	Cross-sectional	CMJ (jump height, peak force) Squat Jump (jump height, peak force) IMTP (peak force)	Training	Acute

Boraczyński et al., 2020	M: 25	Soccer	Cross-sectional	CMJ (jump height, peak power)	Training	Acute and Chronic
Cunningham et al., 2018	M: 15	Rugby Union	Cross-sectional	CMJ (jump height, peak power) IMTP (peak force, force at 250 ms) Drop Jump (jump height, RSI)	Competition	Chronic
Cook & Beaven, 2013	F: 12	Netball	Longitudinal	Biomarker (salivary T)	Training	Acute
Bishop et al., 2003	F: 14	Hockey	Longitudinal	Biomarker (blood lactate, hydrogen ion, hypoxanthine)	Training	Acute
Teece et al., 2021	M: 29	Rugby Union	Longitudinal	Wellness Questionnaire (HI) Sleep (total, efficiency, latency, wake episodes)	Training	Acute
Stepinski et al., 2020	F: 18	Soccer	Longitudinal	CMJ (peak power)	Training	Acute
de Freitas et al., 2015	M: 11	Futsal	Longitudinal	HRV (lnRMSSD) Sub-maximal exercise HR HRR	Training	Acute
Peacock et al., 2018	M: 8	Martial Arts	Longitudinal	Sleep (time, latency, efficiency, onset variances)	Training	Acute
Wisløff et al., 2004	M: 17	Soccer	Cross-sectional	CMJ (jump height)	Training	Acute and Chronic
Lim et al., 2021	M: 261 F: 79	Basketball	Cross-sectional	Wellness Questionnaire (PSQI)	Training	Acute
Dumortier et al., 2018	F: 7	Artistic Gymnastics	Longitudinal	Sleep (time)	Competition	Acute
Cunningham et al., 2016	M: 20	Rugby Union	Cross-sectional	CMJ (jump height) Drop Jump (contact time, RSI)	Training	Acute
Berriel et al., 2020	M: 13	Volleyball	Longitudinal	Wellness Questionnaire (RESTQ-Sport)	Training	Acute
Smart et al., 2008	M: 23	Rugby Union	Longitudinal	Biomarker (blood CK)	Competition	Acute
Ravé et al., 2020	M: 14	Soccer	Longitudinal	HRV (RMSSD)	Competition	Acute
Landolsi et al., 2014	M: 23	Shot Put	Cross-sectional	CMJ (jump height)	Training	Chronic
Brown et al., 2021	M: 21	Hockey	Cross-sectional	Biomarker (salivary C, DHEA, C:DHEA)	Competition	Acute
João R Silva et al., 2013	M: 13	Soccer	Longitudinal	CMJ (FT:CT)	Competition	Chronic
Carlsson et al., 2012	M: 12	Cross-Country Skiing	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Competition	Chronic
Young et al., 2011	M: 23	ARF	Cross-sectional	CMJ (jump height, peak force, peak velocity, peak power)	Training	Acute
Silva et al., 2021	M: 24	Soccer	Longitudinal	CMJ (jump height)	Training and Competition	Acute and Chronic

Loturco et al., 2019	M & F: 61	Athletics, Soccer, Rugby Sevens, Bobsled	Cross-sectional	CMJ (jump height) Squat jump (jump height)	Training	Acute
Jürimäe et al., 2006	M: 11	Rowing	Longitudinal	Biomarker (T, C, insulin, GH)	Training	Chronic
Casanova et al., 2020	F: 18	Soccer	Longitudinal	Biomarker (salivary C, T, T:C)	Competition	Acute and Chronic
Crewther, Potts, et al., 2018	M: 24	Rugby Union	Longitudinal	Biomarker (T, C)	Competition	Chronic
Boullosa et al., 2013	M: 8	Soccer	Longitudinal	HRV (CV RMSSD, RMSSD, SD1)	Training	Acute
Mancha-Triguero et al., 2021	F: 10	Basketball	Cross-sectional	Abalakov Test (time, height, impulse) Multi-Jump Test (average time)	Competition	Chronic
Rowell et al., 2018	M: 23	Soccer	Longitudinal	CMJ (FT:CT) Biomarker (salivary C, T, T:C)	Competition	Acute
Chrismas et al., 2019	M: 16	Soccer	Longitudinal	HRV (lnRMSSD)	Training	Acute
Araújo et al., 2019	M: 16 F: 16	Soccer	Cross-sectional	Sub-maximal exercise HR	Training	Acute
Ganzevles et al., 2017	M: 5 F: 8	Swimming	Longitudinal	HRR	Training	Acute
Dubois et al., 2020	M: 14	Rugby Union	Longitudinal	Biomarker (blood CK, CRP, T, T:C, RBC, lymphocytes, insulin growth factor, alanine, aspartate aminotransferase) CMJ (jump height) Wellness Questionnaire (RESTQ-Sport)	Training and Competition	Acute and Chronic
Elloumi et al., 2012	M: 16	Rugby Sevens	Longitudinal	Wellness Questionnaire (fatigue)	Training	Acute
Ihsan et al., 2017	M: 12	Hockey	Longitudinal	Wellness Questionnaire (fatigue, soreness, mood, sleep)	Competition	Acute
Northeast et al., 2019	M: 26	Soccer	Cross-sectional	CMJ (jump height, peak power, unilateral asymmetry score) IMTP (peak force, RFD, force at 100 ms) Drop Jump (contact time, jump height, stiffness, RSI)	Training	Acute
Vervoorn et al., 1992	F: 6	Rowing	Longitudinal	Biomarker (blood C, T, free T, free T:C)	Training	Acute
Siart et al., 2017	M: 8 F: 10	Athletics	Longitudinal	Biomarker (salivary T, C)	Competition	Acute
Malone, Mendes, et al., 2018	M: 30	Soccer	Longitudinal	Biomarker (blood CK) CMJ (jump height)	Training	Acute
Oliveira et al., 2020	M: 24	Soccer	Longitudinal	Wellness Questionnaire (HI)	Competition	Acute

Marcote-Pequeño et al., 2019	F: 19	Soccer	Cross-sectional	Squat Jump (jump height)	Training	Acute
Shalfawi et al., 2011	M: 33	Basketball	Cross-sectional	CMJ (jump height, peak power) Squat Jump (jump height, peak power)	Training	Acute
Rago et al., 2021	M: 15	Soccer	Longitudinal	Biomarker (blood T, C, T:C, CK, ferritin, iron, RBC, haemoglobin, haematocrit)	Training	Chronic
Beattie et al., 2021	M: 18	Soccer	Longitudinal	Biomarker (blood CK) CMJ (jump height, FT:CT, CT, FT, peak power, max force, take-off velocity, mean power, mean force)	Competition	Acute
Bootes, 2017	M: 8	Rowing	Longitudinal	CMJ (peak force, mean power, take-off peak force, peak power, eccentric / concentric duration) Squat Jump (peak power, concentric mean force)	Training	Acute
Mangine et al., 2014	M: 12	Basketball	Cross-sectional	Visual Reaction Time Motor Reaction Time Physical Reaction Time Variable Region Choice Reaction	Competition	Chronic
Malone, Owen, et al., 2018	M: 48	Soccer	Longitudinal	Wellness Questionnaire (soreness, sleep, fatigue, stress, energy)	Training	Acute
Troester et al., 2019	M: 27	Rugby Union	Longitudinal	CMJ (jump height, eccentric RFD)	Training	Acute
Díaz et al., 2013	M: 13	Swimming	Cross-sectional and Longitudinal	Biomarker (salivary C)	Competition	Acute
Buchheit et al., 2013	M: 18	ARF	Longitudinal	Biomarker (salivary C) Wellness Questionnaire (fatigue, sleep, soreness, stress, mood) Sub-maximal exercise HR	Training	Acute
Clemente et al., 2018	M: 13	Volleyball	Cross-sectional	Wellness Questionnaire (HI)	Training	Chronic
Crewther et al., 2013	M: 13	Rugby League	Longitudinal	Biomarker (salivary free T, free C)	Competition	Chronic
Springham et al., 2022	M: 18	Soccer	Longitudinal	Biomarker (salivary T, C, T:C)	Training and Competition	Chronic
Redman et al., 2021	M: 14	Rugby League	Cross-sectional	CMJ (jump height, concentric impulse, peak force, peak power)	Training	Chronic
Gonçalves et al., 2021	F: 22	Soccer	Cross-sectional	CMJ (jump height) Squat Jump (jump height) Hip / Groin Adduction and Abduction Test	Competition	Chronic
Saidi et al., 2020	M: 16	Soccer	Longitudinal	Biomarker (blood T, C, T:C)	Training	Acute

				Wellness Questionnaire (POMS)		
Merati et al., 2015	M: 13	Swimming	Cross-sectional	HRV (SD1, HFP)	Competition	Chronic
Veugelers et al., 2016	M: 38	ARF	Cross-sectional	HRR Sub-maximal exercise HR	Training	Acute
Rago et al., 2020	M: 17	Soccer	Longitudinal	Sub-maximal exercise HR	Training and Competition	Chronic
Rodríguez-Marroyo et al., 2017	M: 15	Cycling	Longitudinal	Sub-maximal exercise HR	Training	Acute
Ryan et al., 2021	M: 37	ARF	Longitudinal	Wellness Questionnaire (soreness, sleep, fatigue, stress, motivation) Hip / Groin Adduction and Abduction Test	Competition	Acute and Chronic
Scott et al., 2022	M: 19	Rugby League	Longitudinal	Sub-maximal exercise HR HRR	Training	Acute and Chronic
Berriel et al., 2021	M: 13	Volleyball	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Competition	Chronic
Stanković et al., 2022	F: 16	Soccer	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Training	Acute
Glassbrook et al., 2022	M: 16	Rugby League	Cross-sectional	CMJ (peak power, peak force)	Competition	Chronic
Selmi, Ouergui, et al., 2022	M: 15	Soccer	Longitudinal	Wellness Questionnaire (HI)	Training	Chronic
Silva et al., 2022	M: 25	Soccer	Longitudinal	Biomarker (CRP, albumin, haemoglobin, HDL, lymphocytes, RBC, basophils, eosinophil, potassium)	Training	Acute
Lu et al., 2022	M: 13 F: 10	Shooting	Longitudinal	Wellness Questionnaire (PSQI, POMS, CSAI-2)	Competition	Acute
Dobbin et al., 2020	M: 21 F: 20	Touch Football	Longitudinal	CMJ (jump height, peak power, peak force) Wellness Questionnaire (fatigue, mood, soreness, sleep, stress)	Competition	Acute
Lalor et al., 2020	M: 38	ARF	Longitudinal	Sleep (wake bouts, wake time, efficiency, latency)	Training	Acute
Salhi et al., 2022	M: 22	Soccer	Longitudinal	CMJ (jump height)	Training	Acute
Lourenço et al., 2023	M: 32	Soccer	Longitudinal	Wellness questionnaire (HI)	Training	Acute
Eastburn et al., 2022	M: 34	ARF	Longitudinal	Wellness questionnaire (sleep, fatigue, soreness, stress, mood)	Competition	Chronic
Barreira et al., 2022	F: 16	Soccer	Longitudinal	Sleep (efficiency, duration)	Training	Acute
Crewther, Hamilton, et al., 2018	F: 23	Hockey	Longitudinal	Biomarker (salivary T)	Competition	Acute
Rebelo et al., 2023	M:15	Volleyball	Longitudinal	CMJ (jump height, peak power)	Training	Acute

				Wellness questionnaire (fatigue, recovery, stress, soreness, sleep)		
Haksever et al., 2022	F: 39	Handball	Cross-sectional	Hip abduction test	Training	Acute

Note. AA alpha-amylase, *ACTH* adrenocorticotropic hormone, *ARF* Australian Rules Football, *BAM* Brief Assessment of Mood Questionnaire, *C:DHEA* cortisol to dehydroepiandrosterone ratio, *CK* creatine kinase, *CMJ* countermovement jump, *C* cortisol, *Core-CSD* Core Consensus Sleep Diary, *CRP* C-reactive protein, *CSAI 2-7* Competitive State Anxiety Inventory (2-7), *CT* contraction time, *CV RMSSD* coefficient of variation of root-mean-square difference of successive normal R–R intervals from time-domain analysis, *DHEA* dehydroepiandrosterone, *ESS* Epworth Sleepiness Scale, *F* female, *FT* flight time, *FT:CT* flight time to contact time ratio, *GH* growth hormone, *GHQ* General Health Questionnaire, *HDL* high-density lipoprotein, *HFP* high-frequency power, *HI* Hooper Index, *HR* heart rate, *HRR* heart rate recovery, *HRV* heart rate variability, *IgA* immunoglobulin A, *IMTP* isometric mid-thigh pull, *K+* potassium, *LDH* lactate dehydrogenase, *LDL* low-density lipoprotein, *lnHF* logarithmic high frequency power, *lnRMSSD* log-transformed root-mean-square difference of successive normal R–R intervals from time-domain analysis, *lnSD1* log-transformed standard deviation of instantaneous beat-to-beat R–R interval variability from Poincare plots, *M* male, *ms* milliseconds, *n* sample size, *OSQ* Oviedo Sleep Questionnaire, *PCF* peak concentric force, *PCP* peak concentric power, *PEF* peak eccentric force, *PEP* peak eccentric power, *POMS* Profile of Mood States Questionnaire, *PSQI* Pittsburgh Sleep Quality Index, *RBC* red blood cells, *RESTQ-Sport* Recovery-Stress Questionnaire-Sport, *RFD* rate of force development, *RMSSD* root-mean-square difference of successive normal R–R intervals from time-domain analysis, *RSI* reactive strength index, *SCAT-A* Sport Competition Anxiety Test from A, *SD1* standard deviation of instantaneous beat-to-beat R–R interval variability from Poincare plots, *SFMS* French Society for Sport Medicine Questionnaire, *SRSS* Short Recovery and Stress Scale for Sports, *STAI* State-Trait Anxiety Inventory, *T* testosterone, *T:C* testosterone cortisol ratio, *TQR* Total Quality Recovery Questionnaire, *VAS* Visual Analogue Scale, *WBC* white blood cells.

Reason for exclusion

Of the 759 studies for which the full text was reviewed, 594 were excluded from the qualitative synthesis (Figure 1). The two primary reasons for study exclusion were attributable to the failure to identify or analyse a relevant test and / or marker of athletic readiness (n = 109) or analyse a readiness test and / or marker with an appropriate performance measure (n = 202). Several studies analysed data from participants who failed this review's definition of an elite athlete and were excluded (n = 82). Studies which assessed the readiness marker and test following the performance measure (n = 43) were excluded, as were studies which applied a sport-specific test to assess athlete readiness (n = 27). Studies which reported elite and sub-elite athlete data concomitantly were excluded if the data from the elite athletic population could not be extrapolated independently (n = 24). Some studies analysed markers or tests of readiness across more than one season or 12-month period and were excluded (n = 24).

Risk of bias

Selection bias (in the form of random sequence generation and allocation concealment bias) was assessed as unclear or low risk for all included studies due to the nature of the study interventions. All studies were assessed as unclear or low risk of performance and detection bias, as the study designs did not require or address participant blinding.

Risk of attrition bias was assessed as unclear or low for all studies as they either did not address the wholeness of data, failed to report reasons for missing data or excluded participants, or the missing data from excluded participants were unlikely to relate to the true outcome. However, one study was assessed as potentially having a high risk of attrition bias with 26% of the original participants not included in the final analysis (Hooper et al., 1993).

Thirteen studies were assessed at high risk of reporting bias as they either reported only some of the correlations between the marker(s) or test(s) of readiness and the performance measure(s), or only the statistically significant correlations (Berriel et al., 2020; Bok & Jukić, 2019; Cormack et al., 2008; Doeven et al., 2019; R. Gathercole et al., 2015; Guilhem et al., 2015; Jürimäe et al., 2006; Mangine et al., 2014; Merati et al., 2015; Morales et al., 2019; Purge et al., 2006; Russell et al., 2021; Silva et al., 2014).

Participants

The studies included in this review reported on 3564 athletes, of which 2779 were male and 785 females, who submitted to a marker of athletic readiness prior to a subsequent measure of athletic performance. Of these studies, 115 investigated male athletes only, 28 investigated female athletes only, while 22 investigated a mixed sex cohort.

Study outcomes

From the 165 studies included in this review, a total of 20 different markers or tests of athletic readiness were identified across 46 sports (Table 1). The most common readiness markers and tests identified across the included studies were biomarkers (n = 58), CMJ (n = 58), wellness questionnaires (n = 42), SJ (n = 20), HRV (n = 14), sub-maximal exercise heart rate (n = 11), and sleep measures (n = 10).

73 studies implemented a longitudinal study design to assess the readiness measure and performance outcome relationship in an acute setting, 27 in a chronic setting, and 9 in a combined acute and chronic setting. 33 studies analysed the relationship between markers and tests of readiness and performance outcomes using a cross-sectional study design in an acute setting, 19 in a chronic setting, and two in a combined acute and chronic setting. One study used a combined longitudinal and cross-sectional study design to assess the readiness marker, performance outcome relationship in an acute setting, while one study implemented a longitudinal study design but failed to report the strength of the relationship between the performance measure and readiness marker (Silva & Paiva, 2016).

Meta-analysis

Table 1. Summary of acute markers and tests of athletic readiness included in the meta-analysis.

Readiness test / marker		**Performance measure**	**Studies (*n*)**	**Summary Correlation (*r*)**	**95% CI**	**Significance (*p*)**	**Heterogeneity (I^2)**
Cross-sectional studies							
CMJ	*Jump Height*	10 m sprint speed / time	6	0.69	0.47 to 0.83	.00	71.4%
	Peak Power	10 m sprint time	3	0.13	-0.10 to 0.35	.87	0.0%
Squat Jump	*Jump Height*	10 m sprint speed / time	3	0.70	0.48 to 0.84	.17	45.0%
Longitudinal studies							
CMJ	*Jump Height*	Total distance covered	3	0.38	0.12 to 0.59	.41	0.0%
Biomarker	*Salivary Cortisol*	Total distance covered	3	-0.01	-0.33 to 0.32	.99	0.0%
Exercise Heart Rate	*Sub-maximal*	Yo-Yo IR1 distance	3	-0.65	-0.78 to -0.47	.47	0.0%
HRV	*RMSSD + SD1*	Yo-Yo IR1 distance	5	0.66	0.44 to 0.80	.31	14.5%
	RMSSD	Competition load (sRPE)	3	0.10	-0.15 to 0.35	.91	0.0%

Note. CI confidence interval, *CMJ* countermovement jump, *HRV* heart rate variability, I^2 proportion of variance in observed effect due to variance in true effects, *m* metre, *n* sample size, *r* Pearson product-moment correlation coefficient, *RMSSD* root-mean-square difference of successive normal R–R intervals from time-domain analysis, *SD1* standard deviation of instantaneous beat-to-beat R–R interval variability from Poincare plots, *sRPE* session rating of perceived exertion, *Yo-Yo IR1,* Yo-Yo Intermittent Recovery Test Level 1.

From the 27 studies which satisfied the inclusion criteria (Balsalobre-Fernández et al., 2014; Beattie et al., 2021; Boraczyński et al., 2020; Boullosa et al., 2013; Buchheit et al., 2013; Coppalle et al., 2019; Costa et al., 2019; Costa et al., 2021; Cunningham et al., 2016; de Freitas et al., 2015; Dubois et al., 2020; Gonçalves et al., 2021; Hauer et al., 2020; Hulin et al., 2019; Loturco et al., 2018; Loturco, D'Angelo, et al., 2015; Malone et al., 2017; Moncef et al., 2012; Morales et al., 2019; Nakamura et al., 2020; Northeast et al., 2019; Peñailillo et al., 2015; Saidi et al., 2022; Shalfawi et al., 2011; Silva et al., 2021; Webster et al., 2022; Young et al., 2011), five markers and tests of athletic readiness were identified and meta-analysed: CMJ, biomarkers, SJ, sub-maximal exercise heart rate, and HRV. A summary of the acute and chronic, and longitudinal and cross-sectional study correlations of the readiness markers and tests with the relevant performance measures, are outlined in Tables 2 and 3.

Table 2. Summary of chronic markers and tests of athletic readiness included in the meta-analysis.

Readiness test / marker		Performance measure	Studies (*n*)	Summary Correlation (*r*)	95% CI	Significance (*p*)	Heterogeneity (I^2)
Cross-sectional studies							
CMJ	*Jump Height*	Maximal velocity	3	0.46	0.25 to 0.62	.57	0.0%
Longitudinal studies							
Biomarker	*Blood CRP*	Competition load (sRPE)	3	0.33	-0.04 to 0.56	.89	0.0%

Note. CI confidence interval, CMJ countermovement jump, CRP C-reactive protein, HRV heart rate variability, I^2 proportion of variance in observed effect due to variance in true effects, n sample size, r Pearson product-moment correlation coefficient, sRPE session rating of perceived exertion.

Countermovement jump

Figure 2 shows the association between various indices of CMJ and athletic performance. Acute, cross-sectional assessment revealed a large, statistically significant correlation between CMJ jump height and faster 10 m sprint speed and time (r = 0.69; p = .00), which was affected by substantial statistical heterogeneity (I^2 = 71%). A small, non-significant correlation existed between CMJ peak power and 10 m sprint time (r = 0.13; p = .87). Acute and longitudinal assessment of CMJ jump height found a non-significant, moderate association with total distance covered (r = 0.38; p = .41). Chronic, and cross-sectional CMJ jump height had a moderate, non-significant correlation with maximal speed (r = 0.46; p = .57).

Biomarkers

An acute, longitudinal assessment of salivary cortisol revealed a statistically non-significant, negative, and trivial association with total distance (Figure 3; r = -0.01; p = .99). When assessed over a chronic timeframe, blood C-reactive protein (CRP) exhibited a moderate but non-significant correlation with competition load quantified by sRPE (Figure 3; r = 0.33; p = .89).

Squat jump

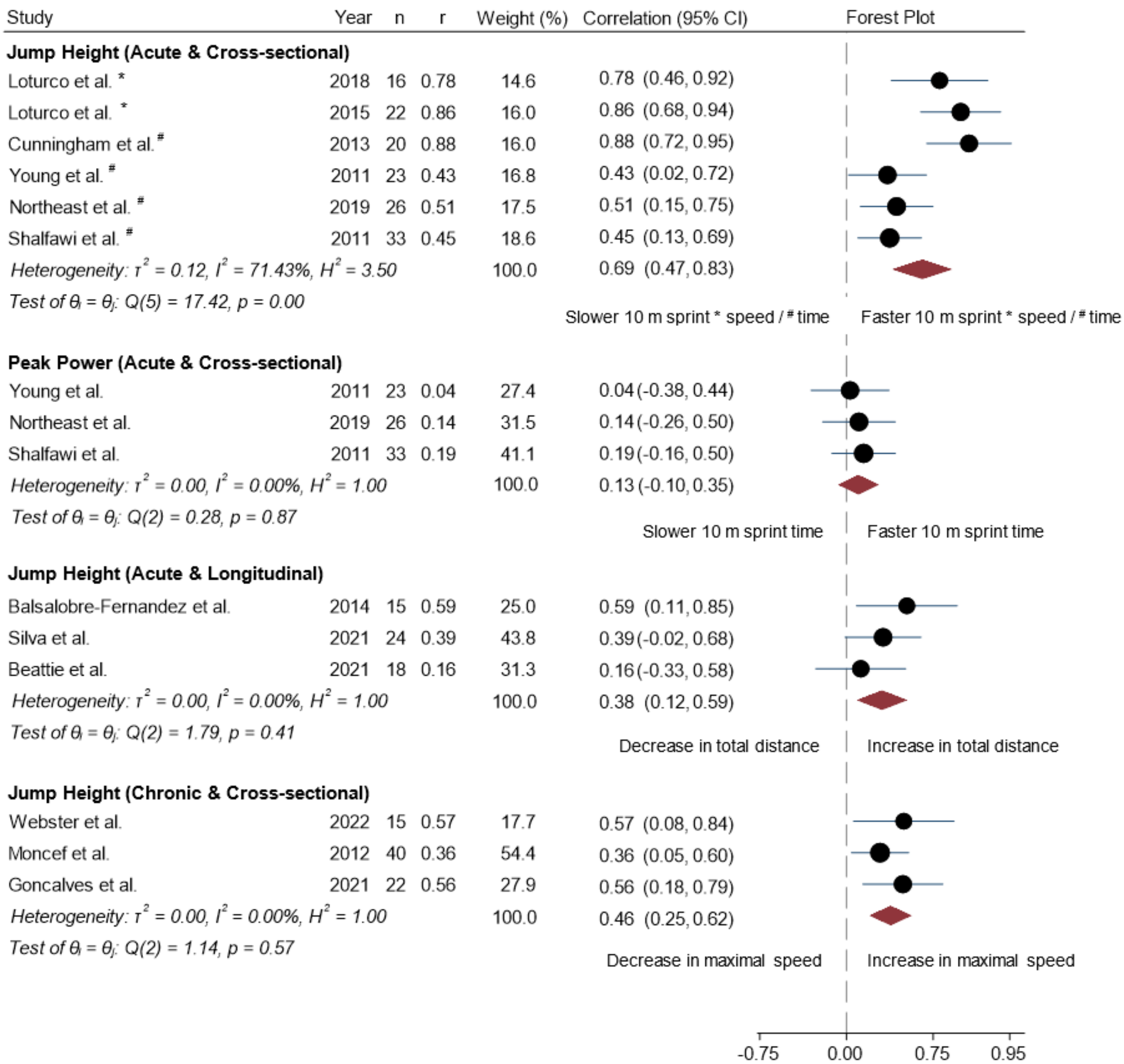
Cross-sectional and acute assessment of jump height from SJ provided a very large, but statistically non-significant correlation with 10 m sprint speed and time (Figure 4; r = 0.70; p = .17), which was affected by moderate statistical heterogeneity (I^2 = 45%).

Sub-Maximal Exercise Heart Rate

Acute and longitudinal assessment of sub-maximal exercise heart rate revealed a negative and large, but statistically non-significant, correlation with Yo-Yo IR1 distance (Figure 5; r = -0.65; p = .47).

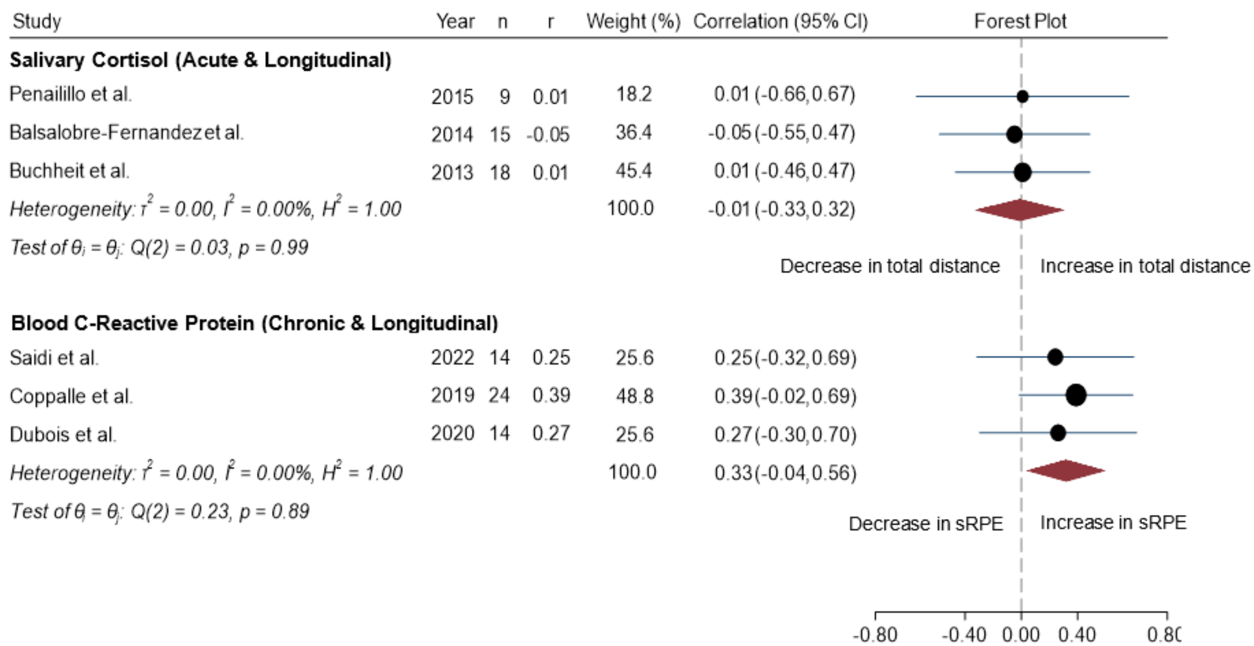
Heart Rate Variability

Figure 6 provides the correlation of acute and longitudinal assessment of RMSSD and SD1 indices of HRV and subsequent athletic performance. Pooled RMSSD and SD1 exhibited a large, but statistically non-significant, correlation with Yo-Yo IR1 distance (*r* = 0.66; *p* = .31), while a small, non-significant correlation was found between RMSSD and competition sRPE load (*r* = 0.10; *p* = .91).



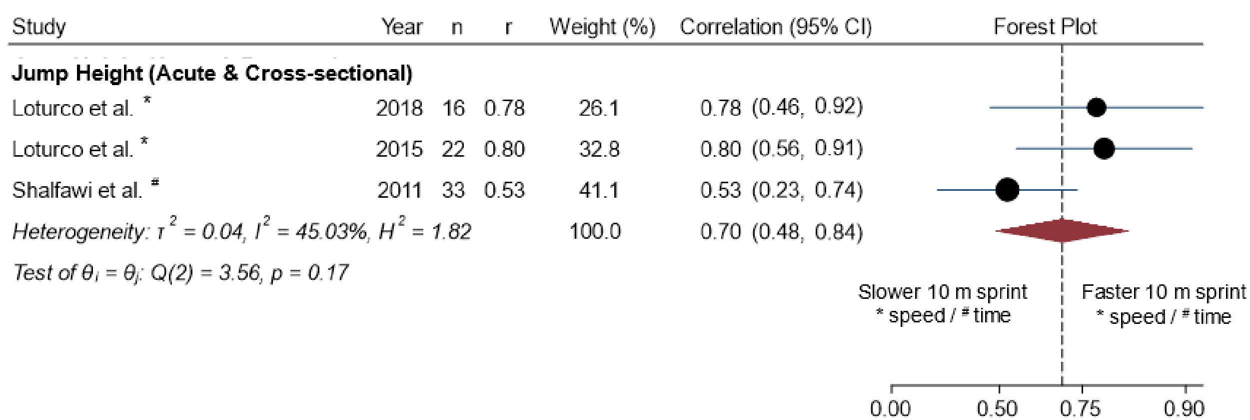
Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient.

Figure 2. Correlation of CMJ indices (using static arm position) and athletic performance measures.



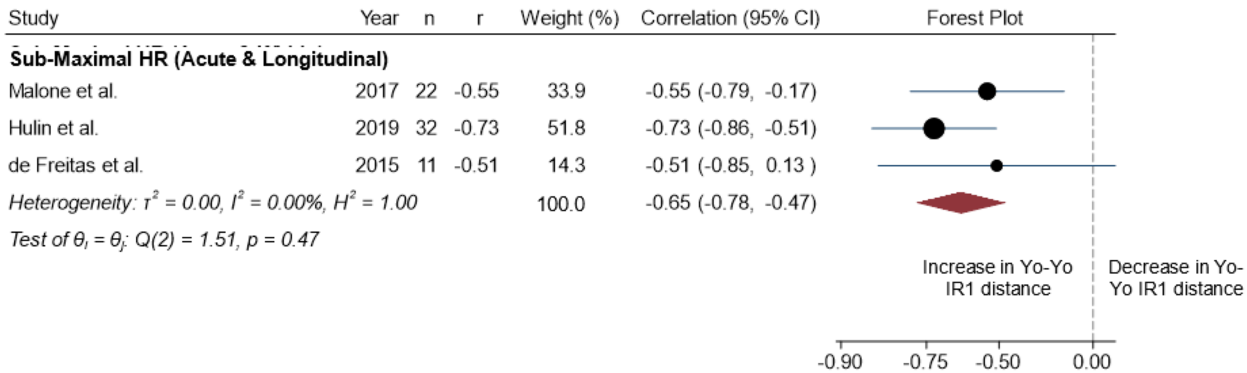
Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient, sRPE session rating of perceived exertion derived from competition.

Figure 3. Correlation of salivary cortisol and blood C-reactive protein biomarkers and athletic performance measures.



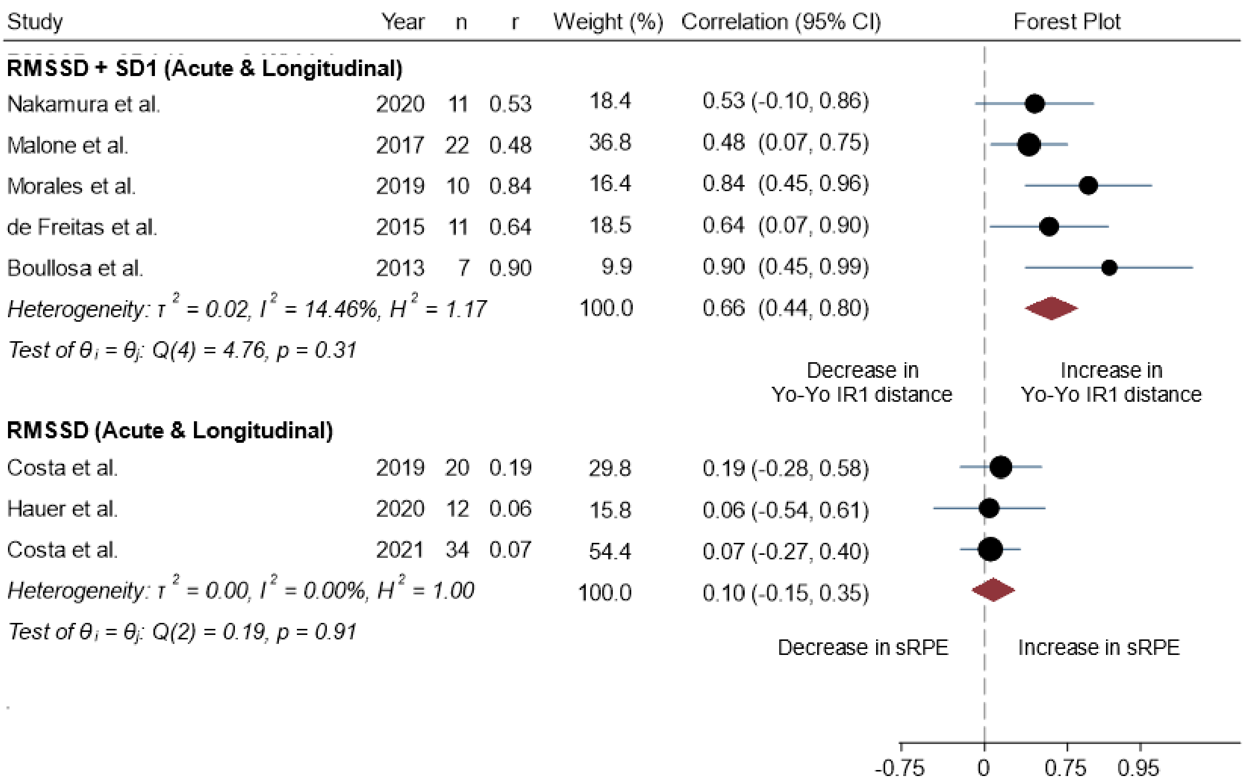
Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient.

Figure 4. Correlation of squat jump height (with hands on hips) and 10 m sprint speed and time.



Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient, Sub-Maximal HR, Sub-Maximal Exercise Heart Rate, Yo-Yo IR1, Yo-Yo Intermittent Recovery Test Level 1.

Figure 5. Correlation of sub-maximal exercise heart rate and yo-yo IR1 distance.



Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient, sRPE session rating of perceived exertion derived from competition, Yo-Yo IR1 Yo-Yo Intermittent Recovery Test Level 1.

Figure 6. Correlation of heart rate variability indices RMSSD and SD1, and athletic performance measures.

DISCUSSION

This systematic literature review explored the relationship between tests and markers of athletic readiness and subsequent performance in elite athletes. To the knowledge of the authors, no review has provided a combined, holistic assessment of the psychological and physiological readiness markers and tests to assess training status in elite team and individual sport athletes, while using correlation analysis to assess athletic performance (to best evaluate the sensitivity of the readiness measures). The 165 studies included in this review identified 20 markers and tests of athletic readiness, of which five measures were meta-analysed across 27 studies. The most common measures of athletic readiness were biomarkers, CMJ and wellness questionnaires. The most significant finding from this review was the validation of jump height from CMJ (without arm swing) to predict explosive leg muscle function, expressed as acceleration and speed qualities, in elite athletes. The five markers and tests of readiness included in the meta-analysis are discussed independently below.

Countermovement jump

This review found a large, positive correlation between an acute and cross-sectional assessment of jump height from CMJ (without arm swing) and superior 10 m sprint speed and time (Figure 2), which may have been impacted by substantial statistical heterogeneity. Interestingly, an increase in jump height when assessed in different contexts (i.e., chronic and cross-sectional, and acute and longitudinal designs), did not correlate to greater maximal speed or total distance in training and competition (Figure 2). Similarly, the acute and cross-sectional assessment of peak power from CMJ did not correlate with 10 m sprint time (Figure 2).

As a monitoring tool for leg muscle function, the CMJ remains the most utilised vertical jump test for practitioners to provide a practical measure of neuromuscular fatigue and recovery time from training and competition demands (Alba-Jiménez et al., 2022). As a measure of physical performance, the CMJ provides an assessment of the explosive qualities of the leg muscles (Young et al., 2011). Whilst modern technologies assessing CMJ provide numerous variables of interest, jump height is still the most commonly assessed variable (Taylor et al., 2012), which is in keeping with the findings of this review (Table 1). Yet standardisation of the CMJ is influenced by a number of factors including the depth of countermovement, use of arm swing, as well as the number and frequency of jumps used for analysis (Alba-Jiménez et al., 2022). However, comparison of the "*highest*" and "*average*" CMJ results found the use of an "*average*", in comparison to the "*best*" jump, to be more sensitive in identifying fatigue or the positive effects of supercompensation (Claudino et al., 2017).

Whilst the studies meta-analysed in this review were controlled for the use (or not) of arm swing, the depth of countermovement and varying number and frequency of jumps used in the analysis could not be controlled. These methodological variances may explain the substantial statistical heterogeneity found for jump height, and potentially the non-significant findings found for all CMJ variables other than jump height. Interestingly, acute and longitudinal, and chronic and cross-sectional, assessment of CMJ jump height was not correlated with increases in total distance and maximal speed respectively (Figure 2). These findings potentially suggest jump height is sensitive to various study designs, as well as assessment in the context of different physical performance measures.

In keeping with the significant finding from this review, previous studies with an identical study design also found statistically significant correlations between jump height from CMJ as a predictor of various speed and power qualities in elite soccer (Bosco et al., 1996), rugby league (West et al., 2011), athletics (Loturco et al., 2019), and surfing (Secomb, Lundgren, et al., 2015) athletes. Interestingly, a number of studies which implemented an identical acute and cross-sectional study design to this review, found a statistically significant correlation between CMJ jump height and 5 m sprint time (Boraczyński et al., 2020), 20 m sprint time (Northeast et al., 2019; Shalfawi et al., 2011), and 40 m sprint time (Shalfawi et al., 2011), but not for peak power. These previous findings are in keeping with the results from this review and supports the notion of a potential inverse relationship between jump height and peak power from CMJ, as a predictor of acceleration and power qualities in elite athletes.

Whilst this review validates the acute, cross-sectional assessment of jump height from CMJ (without arm swing) to predict acceleration and power qualities in elite athletes, caution should be used in the application of other CMJ variables and study designs to predict similar athletic qualities. In particular, the use of peak power from CMJ to predict 10 m sprint time, as well as the application of acute and longitudinal, and chronic and cross-sectional assessments of jump height to predict total distance and maximal speed, respectively.

Biomarkers

Despite finding biomarkers to be the most extensively investigated readiness measure in elite athletes (Table 1), neither of the biomarkers meta-analysed in this review were found to have a significant relationship with their respective performance measure. Specifically, a longitudinal assessment of acute, salivary cortisol and chronic, blood derived CRP, were not correlated with subsequent distance covered or competition load quantified by sRPE, respectively (Figure 3).

Cortisol is one of the most commonly used biochemical stress hormones to evaluate athlete response to recovery, workload, and training and competition stress (Edwards et al., 2018a). Whilst previous studies have established an association between salivary cortisol and subsequent competition performance variables in netball (Russell et al., 2021), triathlon (Balthazar et al., 2012), rugby union (Crewther, Potts, et al., 2018), soccer (Springham et al., 2022) and athletics (Balsalobre-Fernández et al., 2014; Siart et al., 2017), the application of cortisol as a marker to ascertain a change in performance remains ambiguous (Greenham et al., 2018). Similarly, and in keeping with the findings from this review, the majority of research in ARF (Buchheit et al., 2013; Cormack et al., 2008), soccer (Casanova et al., 2020; Peñailillo et al., 2015), rugby league (Crewther et al., 2013; McLellan et al., 2010), rugby union (Crewther et al., 2009; Gaviglio et al., 2014; Tiernan et al., 2020), track and field (Balsalobre-Fernández et al., 2014; Guilhem et al., 2015), swimming (Díaz et al., 2013), hockey (Brown et al., 2021), and powerlifting (Le Panse et al., 2010) athletes, found no association between salivary cortisol and various measures of athletic performance.

It has been postulated salivary cortisol is not sensitive to total volume and lower intensity performance measures (i.e., total distance) in professional soccer (Peñailillo et al., 2015), offering a potential explanation for the non-significant correlation found in this review. This suggests the use of salivary cortisol may be best utilised as a readiness marker to predict higher intensity performance measures which evoke a greater stress response. Whilst this relationship requires further investigation to be validated, this hypothesis is supported by studies in elite netball (Russell et al., 2021) and soccer (Springham et al., 2022) athletes which found pre-competition salivary cortisol to be significantly, positively associated with subsequent "*higher intensity*" change of direction and high-speed running measures, respectively.

A consequence of intense training and competition stress commonly induces an inflammatory response in the body, often presenting as swelling and muscle soreness, and results in decreased muscle function and the leakage of muscle protein such as CRP (Chatzinikolaou et al., 2010; Hirose et al., 2004). Given its link to acute inflammation, CRP is considered an important measure to provide information regarding the severity of the trauma or injury precipitating the inflammatory processes (Coppalle et al., 2019; Joao R Silva et al., 2013). Yet the validity of pre-training or competition CRP as an indicator of performance in elite athletes has not been widely investigated outside of soccer and rugby union, with few significant correlations between blood CRP and ensuing athletic performance (Coppalle et al., 2019; Dubois et al., 2020; Saidi et al., 2022; Silva et al., 2022).

The non-significant correlation found in this review between blood CRP and chronic, competition load is potentially explained by the passage of time between the assessment of CRP relative to the competition load.

It has been established that CRP returns to baseline levels in elite team-sport athletes within two days following competition (37 hours) (Souglis et al., 2015). Therefore, unless the recovery period between the preceding competition / training stimulus and the subsequent activity is appropriate (i.e., less than 37 hours), then it is conceivable a pre-competition measure of CRP has no relationship to competition load. Whilst future research should look to investigate this relationship further, practitioners should apply caution when using CRP as a marker of readiness more generally, but particularly in circumstances when the duration of recovery between training or competition is insufficient to allow the homeostatic restoration of inflammation (less than 37 hours).

Squat jump

This review highlights the relative lack of research in the application of squat jump variables to homogenous performance measures. Whilst 20 studies evaluated squat jump variables in the context of a subsequent measure of athletic performance (Table 1), only three studies assessed jump height from squat jump using an analogous study design and performance measure. These studies were meta-analysed using a standardised, acute, and cross-sectional squat jump protocol, in which participants kept their hands on their hips throughout the jump. Despite the level of standardisation, no significant correlation was observed between jump height and 10 m sprint speed and time (Figure 4).

This finding provides mixed support for previous studies assessing the relationship between jump height from SJ and subsequent athletic performance. The current finding complements an existing body of literature which found no association between SJ jump height and various training and competition performance outcomes in elite karate (Loturco et al., 2014), basketball (Pojskic et al., 2018), surfing (Secomb, Farley, et al., 2015), soccer (Gonçalves et al., 2021; Saidi et al., 2020; Saidi et al., 2022; Saidi et al., 2019; Stanković et al., 2022), cross-country skiing (Carlsson et al., 2012), and track and field (Loturco et al., 2019) athletes. Conversely, studies have found a positive correlation between jump height from squat jump and performance outcomes in elite track and field (Loturco, Pereira, et al., 2015; Loturco et al., 2019), basketball (Pojskic et al., 2018), handball (Moncef et al., 2012), soccer (Emmonds et al., 2019; Gonçalves et al., 2021; Marcote-Pequeño et al., 2019; Stanković et al., 2022), surfing (Secomb, Lundgren, et al., 2015), and volleyball (Berriel et al., 2021) athletes. Clearly, the current finding contributes to the ambiguity around the sensitivity of SJ jump height to predict athletic performance, whilst also inadvertently supporting the suggestion alternate SJ variables of mean force, mean power and relative mean power should be preferred, as they exhibit acceptable reliability and sensitivity (Edwards et al., 2018b).

Interestingly, the current finding is also in contrast with an earlier finding of this review for CMJ jump height, despite an identical, standardised testing protocol and performance measure. Whilst both findings were affected by statistical heterogeneity, the contrasting findings are possibly explained by several other factors. Firstly, the use of different technologies to measure jump height (i.e., contact mat or force platform), as well as the sensitivity of the inherent physiological and biomechanical differences of each jump (Van Hooren & Zolotarjova, 2017), particularly the performance enhancing effect of the stretch-shortening cycle from the countermovement (McGuigan et al., 2006). Further, the smaller sample of studies used to meta-analyse the association between jump height from SJ and the performance outcome, is also a likely contributing factor.

While squat jump assessment more broadly is considered a simple, practical, valid and reliable tool for measuring neuromuscular function (R. J. Gathercole et al., 2015) and explosive power output from the lower limbs (Markovic et al., 2004), the current finding suggests practitioners should exhibit caution when using SJ jump height as a monitoring tool of the lower limbs to predict acceleration and power performance in elite athletes.

Sub-Maximal Exercise Heart Rate

This review found 11 studies which evaluated the use of sub-maximal exercise heart rate to forecast athletic performance (Table 1). Three studies were meta-analysed, which found no association between the acute, longitudinal assessment of sub-maximal exercise heart rate and greater Yo-Yo IR1 performance (Figure 5).

This finding is inconsistent with previous cross-sectional assessments in studies investigating sub-maximal heart rate, which found significant correlations with Yo-Yo IR1 (Ingebrigtsen et al., 2014) and Yo-Yo IR2 performance (Ingebrigtsen et al., 2014; Veugelers et al., 2016). This inconsistency in findings may be attributable to the sensitivity of sub-maximal heart rate assessment to the type of study design (longitudinal or cross-sectional assessment). This explanation would appear consistent with the likelihood of longitudinal assessment of sub-maximal exercise heart rate being accentuated and influenced by day-to-day variability in heart rate and environmental factors (Juul & Jeukendrup, 2003). Previous studies have also found the assessment of other maximal aerobic performance measures such as total competition and training distance, to have small to large correlations with sub-maximal heart rate (Buchheit et al., 2013; Rago et al., 2020). Ultimately, this suggests sub-maximal heart rate may also be sensitive to various measures of athletic performance.

Heart rate assessment at a fixed, sub-maximal intensity is commonly used as an indicator of training status in elite athletic populations and is a valid and reliable tool to assess Yo-Yo IR2 performance in elite Australian rules football players (Veugelers et al., 2016). This review's non-significant finding emphasises the need for practitioners to ensure their sub-maximal exercise heart rate assessment protocol is sensitive to their specific performance outcome. The contrasting finding from this review with previous studies (Ingebrigtsen et al., 2014; Veugelers et al., 2016), cautions the use of a longitudinal assessment of sub-maximal heart rate to predict an elite athlete's capacity to perform intense, intermittent exercise assessed by Yo-Yo IR1 performance (Bangsbo et al., 2008). This adds further support to the existing literature that a cross-sectional assessment of sub-maximal heart should perhaps be preferred as a measure of training status in elite athletes to predict maximal aerobic capacity.

Heart Rate Variability

Of the 14 studies which assessed pre-training and competition HRV, eight studies implementing a longitudinal study design were meta-analysed across two different performance outcomes (Table 1; Figure 6). This review found an acute, pre-training and competition HRV assessment of pooled RMSSD and SD1, and RMSSD measures separately, were not correlated with subsequent Yo-Yo IR1 distance and competition load quantified by sRPE (Figure 6).

The use of HRV assessment as a non-invasive measure of autonomic nervous system status in response to training and competition stress is common practice in elite sport (Plews et al., 2014). The current application and interpretation in the literature of HRV assessment as a readiness marker offers mixed support for the findings of this review, particularly in studies with an acute, longitudinal study design. In support of this review's findings, a previous study in elite male futsal players using a similar performance measure in Yo-Yo IR2 distance, also failed to find a statistically significant correlation with resting HRV (de Freitas et al., 2015). Similarly, other studies assessing the correlation between HRV, and training and match derived physical output data in elite male Gaelic football and female soccer players, were unable to find significant associations (Costa et al., 2019; Malone et al., 2017). However, some studies found statistically significant correlations between resting HRV assessment and physical output data from training (Thorpe et al., 2015) and Cooper 12-minute run test performance (Morales et al., 2019) in elite soccer athletes. It has been suggested such ambiguous findings in the literature may be attributable to methodological inaccuracies due to the large variation in day-to-day HRV measurements (Plews et al., 2014), offering a potential explanation for the contrast in findings between this review and existing research.

The assessment of HRV can be influenced by a myriad of complex environmental, lifestyle, physiological, neuropsychological and non-modifiable (i.e., gender and age) factors (Fatisson et al., 2016). The confounding influences on HRV assessment potentially explains the non-significant findings from this review and highlights the importance of ensuring standardised HRV measurements, despite the inherent difficulties of doing so in a team sport setting. However, the findings from a previous review found vagal-related HRV indices increased in response to positive training adaptations which is suggestive of HRV being a sensitive marker of readiness, albeit in the absence of a standardised performance outcome (Bellenger et al., 2016). Therefore, the application of this review's findings for practitioners cautions the use of resting, pre-training HRV assessment as a sensitive marker of readiness in predicting aerobic capacity in elite athletes, specifically for Yo-Yo IR1 performance and subjective competition load.

Limitations

Evidenced by the volume of studies included in this review and summarised in Table 1, this review is limited by the amount of data which could be extracted from eligible studies, particularly those included in the meta-analysis. The lack of standardisation in the application of markers and tests of athletic readiness, and the outcome correlation, to common and consistent performance measures in the included studies, limited the depth of findings and analysis in this review. However, it is acknowledged the application of markers and tests of readiness to assess athletic performance is largely determined by the contextual physiological and psychological requirements of the sport. As such, the assessment and application of various readiness markers and tests with consistent and standardised performance measures may not be appropriate in practice.

This review acknowledged the methodological differences and variations in the application of various measures of readiness, particularly the assessment of HRV and sub-maximal exercise heart rate (Plews et al., 2014). These inconsistencies potentially limit the generalisability of this review's findings, particularly given the known sensitivities associated with the markers and tests of readiness identified in this review. Whilst the strict standardisation of studies eligible for inclusion in the meta-analysis intended to account for this limitation, this confounder ultimately reduced the number of studies eligible to be meta-analysed.

CONCLUSIONS

This review sought to investigate the validity of tests and markers of athletic readiness to predict subsequent athletic performance in elite athletes. In examining this relationship, 20 athletic readiness markers and tests were identified, with the requisite level of data from five readiness measures meta-analysed. The most common measures employed to assess athletic readiness in elite athletes includes the assessment of biomarkers, CMJ testing and the use of subjective wellness questionnaires.

The most significant finding from this review is the validation of the use of jump height from CMJ (without arm swing) to predict power and acceleration qualities in elite team and individual sport athletes, where explosive leg muscle function is an integral physical requirement of the sport. However, there was no significant relationship between additional measures of readiness, in the form of salivary cortisol and blood CRP biomarkers, SJ, sub-maximal exercise heart rate, indices of HRV, and subsequent athletic performance. It is suggested, when implementing these readiness measures as part of an athlete monitoring system, that practitioners ensure their validity with the relevant performance outcome(s).

It is postulated this review's non-significant findings are explained by the sensitivity of different study designs, the application of different performance measures, and the methodological differences in the assessment of the various tests and markers used to assess athletic readiness. Whilst this review has somewhat contributed to the ambiguity in the literature, and uncovered conflicting findings in the current evidence, the findings highlight the sensitivities of the inter and intra-individual variations between athletes which likely influences the validity of some measures identified in this review. However, further research into, and standardisation of, these markers and tests of readiness is required to ensure their sensitivity and validity to contextualised measures of subsequent athletic performance in elite team and individual sport athletes.

AUTHOR CONTRIBUTIONS

SJJ designed and conceptualised the research question and method of analysis, conducted the systematic search, screened all articles, extracted and analysed the data, and prepared the manuscript. PCB designed and conceptualised the research question and method of analysis, assisted with the analysis and interpretation of data, and substantively revised the manuscript. DJB designed and conceptualised the research question and method of analysis, assisted with the analysis and interpretation of data, and substantively revised the manuscript. GKB screened all articles and confirmed the data extraction and risk of bias assessment of the lead author. CRB designed and conceptualised the research question and method of analysis, assisted with the analysis and interpretation of data, and substantively revised the manuscript. All authors read and approved the final manuscript.

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APPENDIX

Supplementary Table 1. Systematic review master search strategy.

1. Athletes/ and (high perform* or professional* or olympic or Olympian* or competit* or elite) OR ((high perform* or professional* or olympic or Olympian* or competit* or elite) and (sportspe* or sportswo* or sportsm* or athlete* or player*))

AND

2. gait/ OR gait analysis/ OR gait OR Biomarkers/ OR Lactic Acid/ OR Urea/ OR Creatine Kinase/ OR Norepinephrine/ OR Catecholamines/ OR Epinephrine/ OR Cytokines/ OR Immunoglobulin/ OR alpha-Amylases/ OR Glutamine/ OR Testosterone/ OR Hydrocortisone/ OR lymphocyte count/ OR Neutrophils/ OR Hormones/ OR (biomarker* or bio marker* or cortisol hormone* or endocrine* or lactic acid or creatine kinase or CK or urea or norepinephrine or catecholamine* or epinephrine or cytokine* or biological marker* or biochemical marker* or immunoglobulin or IgA or alpha-Amylase* or alpha Amylase* or physiological marker* or immunoendocrine marker* or glutamine or glutamate or physiological measure* or testosterone or hydrocortisone or lymphocyte count* or neutrophil* or hormone*) OR (countermovement jump or counter movement jump or CMJ or vertical jump or run* pattern* or isometric midthigh pull or isometric mid-thigh pull or isometric mid-thigh pull or ISMTP or flight time to contraction time or flight time to contraction ratio or FT:CT or adductor strength assessment or eccentric hamstring strength assessment or adductor strength test or hamstring strength test or hamstring strength assessment or groin squeeze strength test or groin squeeze strength assessment) OR Heart Rate/ OR Sleep/ OR sleep hygiene/ OR (heart rate or heartrate or HR or HRV or HRR or sleep or yo-yo intermittent recovery or yoyo intermittent recovery or submaximal heart rate assessment or sub-maximal heart rate assessment or submaximal heart rate test or sub-maximal heart rate test) OR Reaction Time/ OR ((reaction or response) adj (speed* or tim* or laten*)) OR (choice response or rating of perceived exertion or RPE or perceptual wellness questionnaire* or perceived wellness or recovery stress questionnaire* or recovery cue or athlete burnout questionnaire or athlete distress questionnaire or daily analysis of life demands for athletes) OR Exercise Test/ OR (exercise test* or fitness test*)

AND

3. Fatigue/ OR Muscle Fatigue/ OR fatigue* OR Athletic Performance/ OR Psychomotor Performance/ OR (((athlete* or psychomotor or physical or fitness or competit*) adj2 Perform*) or training status) OR recove* OR Physical Endurance/ OR Endurance Training/ OR Resistance Training/ OR Muscle Strength/ OR (endurance or stamina or overtraining or over training or over reach* or overreach* or prepare* or readiness or endurance training or resistance training or power training or strength training or motor learning training or muscle strength).

