ISSN 2703—240X

# The Journal of Sport & Exercise Science™

SESNZ™
SPORT & EXERCISE SCIENCE
— NEW ZEALAND —

SEΩNZ
SPORT & EXERCISE SCIENCE
NEW ZEALAND

*The Journal of Sport and Exercise Science, Vol. 8, Issue 2, 1-20 (2024)*

www.jses.net

**JSES**
**ISSN: 2703-240X**

# The association of sleep with subjective wellbeing and performance in female athletes: A systematic review

Andrew McGeever[1*], Niamh Mallon[1,2], Georgie Bruinvels[2,3,4], Charles R. Pedlar[2,3,4], Rónán Doherty[1], Ken A. van Someren[1]

[1]*Sports Lab Northwest, Atlantic Technological University, Ireland*
[2]*Orreco Ltd., Ireland*
[3]*Faculty of Sport, Allied Health and Performance Sciences, St Mary's University, UK*
[4]*Institute of Sport, Exercise and Health, University College London, UK*

ARTICLE INFO
*Received: 29.04.2024*
*Accepted: 22.07.2024*
*Online: 29.11.2024*

*Keywords:*
*Female athlete*
*Sleep*
*Performance*

ABSTRACT

*Sleep and athletic performance have been investigated in previous research, showing sleep to be important for cognitive function, mood, and recovery. Inferior sleep has been reported in female athletes compared to male athletes; however, no systematic reviews have examined the association of sleep with performance and subjective wellbeing in female athletes. Three electronic databases (SPORTDiscus, PubMed, and Web of Science) were searched with no date restrictions in June 2024. Studies contained primary data and examined any association between sleep and performance in female athletes over the age of 18 years, with their level of competition described. Performance and subjective wellbeing were categorised as sport-specific performance; cognitive performance; physical performance, readiness, and availability; and mood and subjective wellbeing. From 2565 records, 38 studies remained for review. Most studies examined physical performance, readiness, and availability, whereas cognitive performance was the least studied aspect of performance. The majority of studies included in this review supported the general conclusion that positive sleep outcomes were associated with positive performance and subjective wellbeing outcomes (89% of sport-specific performance; 50% of cognitive performance; 38% of physical performance, readiness, and availability; and 21% of mood and subjective wellbeing studies), while negative sleep outcomes were associated with negative performance and subjective wellbeing outcomes (50% of cognitive; 33% of physical, readiness, and availability; and 50% of mood and subjective wellbeing studies) in female athletes. Only 2 studies were of high-quality according to a modified version of the Newcastle-Ottawa Scale, indicating a lack of high-quality evidence in the reviewed literature. Lack of control for sleep, athletic population, and menstrual characteristics were particularly apparent. This review highlights lower sleep duration and/or quality being detrimental to sport-specific performance; cognitive performance; physical performance, readiness, and availability; and mood and subjective wellbeing of female athletes. However, more high-quality research is needed to describe sufficiently the relationship between sleep and performance in female athletes.*

## 1. Introduction

Sleep is a fundamental aspect of human health, performance, and recovery (Consensus Conference Panel, 2015). The quantity, quality and timing of sleep obtained has implications on numerous physiological processes including immunity, hormone function, the cardiovascular system, and cognitive performance alongside psychological processes such as learning, mood, memory, and

---

*Corresponding Author: Andrew McGeever, Sports Lab Northwest, Atlantic Technological University, Ireland, Andrew.mcgeever@research.atu.ie

attention (Consensus Conference Panel, 2015). Sleep and its implications for performance are of particular importance to athletes, with quantity and quality of sleep being one of the most important factors in recovery and overall health among elite athletes (Vitale et al., 2019). Sleep and athletic performance have been linked, with total sleep deprivation for one night (30 hours awake) being associated with decreased average distance travelled by male recreational runners in a 30min treadmill test (Oliver et al., 2009), as well as lower average sprint times, decreased strength and muscle activation during isometric force testing, and reduced muscle glycogen concentrations in male athletes also (Skein et al., 2011). Studies have shown that obtaining less than 7 hours sleep is associated with decreases in cognitive performance in tests of memory, alertness, decision making and reaction time (Fullagar et al., 2015).

International experts have stated that the prevalence of sleep inadequacy is high among elite athletic populations who often experience disruptive training and competition schedules that may limit sleep opportunity (Walsh et al., 2021). Athletes obtaining less sleep than non-athletes have been reported in mixed-sex cohorts with Olympic athletes obtaining between 6.5 hours – 6.8 hours of sleep per night (Leeder et al., 2012), which is below the 7 hours – 9 hours of sleep recommended for adults (Hirshkowitz et al., 2015). When examining a range of sports with mixed cohorts, Sargent et al. (2014) also found that early morning training sessions reduced the total sleep time of athletes and increased pre-training fatigue levels. Sleep disturbances are common in athletic cohorts prior to competition, which could impact athletic performance (Gupta et al., 2017).

Female athletes may be at a greater risk of lower sleep quality and quantity than male athletes. Kawasaki et al. (2020) found that female athletes had significantly higher incidence of lower sleep quality (48.8% of females and 31.4% of males, $p < 0.001$) as measured by the Pittsburgh Sleep Quality Index (PSQI), and greater daytime sleepiness (54.3% of females and 43.0% of males, $p = 0.025$) as measured by the Epworth Sleepiness Scale (ESS), than male athletes. While in Australian Rules Football (Australian Football League [AFL] and Australian Football League Women's [AFLW]), AFLW (female) athletes had less total sleep time, and lower sleep efficiency than AFL (male) athletes when measured using wrist actigraphy (Roberts et al., 2021).

There is evidence to show that the menstrual cycle (MC) can have an impact on the sleep of non-athletic females (Baker & Driver, 2004), with self-reported disturbances during premenstrual and menstrual periods, as well as problems sleeping occurring in those with premenstrual syndrome or polycystic ovary syndrome (Baker & Lee, 2018). Greater menstrual abnormality was reported in female athletes with poor sleep quality than in those who had better sleep quality (Kawasaki et al., 2020), while sleep disturbances and changes in sleep quality were reported by 19.5% and 20.4% of recreational female athletes (Michelekaki et al., 2023). There has also been a strong positive association between scores on the Menstrual Symptom index (indicating severity of symptoms experienced) and both PSQI scores (indicating poor sleep quality) and the Athlete Sleep Behaviour Questionnaire (ASBQ; indicating poor sleep behavior; Kullik et al., 2024). This is indicative of a potential bidirectional relationship between sleep and MC characteristics. MC symptoms such as anxiety, cramps, headaches, and depression are associated with disturbed sleep (Van Reen & Kiesner, 2016). Body temperature changes associated with the MC can also have an influence on sleep. The normal decrease in body temperature while sleeping can be blunted during the luteal phase of the MC due to the thermogenic action of progesterone (Baker & Lee, 2018) which counteracts the hypothermic effect of melatonin during the night when temperature is supposed to fall (Manber & Armitage, 1999). Aside from physiological differences, there are also societal differences that may have an impact on the quantity and quality of sleep available to be obtained by female athletes. Teece et al. (2023) suggested that differences in sleep duration between male and female rugby union athletes may be caused by the impact of training schedules due to differences in professionalism. In female sports, salaries are often less than those of male athletes, leading female athletes to have to work in part-time jobs, which pushes training times to either early morning or late at night. In this study, female athletes also showed higher rates of using sleep medication and reported having more thoughts about both sport-related and non-sport-related matters while in bed when compared with male athletes (Teece et al., 2023). Sleep disruption that may be experienced by female athletes could leave them at an increased risk of detrimental impacts to their health and performance.

Although the impact of sleep on the athlete, and the habitual sleep of athletes in general has been studied, little is known about the impact of sleep on the performance of female athletes. With the known associations between sleep and female physiology, as well as the known prevalence of sleep disturbance and inadequacy in athletic populations, there is a need to further understand the sleep of female athletic populations and how it may or may not impact performance. There are no systematic reviews examining the association between sleep and performance in female athletes. Therefore, the aim of this study is to provide a systematic review of the existing literature examining the association between sleep and performance parameters in female athletes; namely, sport-specific performance; cognitive performance; physical performance, readiness, and availability; and mood and subjective wellbeing.

## 2. Methods

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) and registered with PROSPERO (CRD42022297974).

### *2.1. Search strategy and terms*

Three electronic databases, SPORTDiscus, PubMed, and Web of Science were systematically searched with no date restrictions in June 2024. The sleep measurement search terms outlined with 'OR' were sleep, sleepiness, sleep loss, and sleep deprivation; the sex search terms outlined with 'OR' were female, and women; and the athletic population search terms outlined with 'OR' were athlete, athletic, elite, and sport; the performance parameter search terms outlined with 'OR' were performance, cognition, cognitive, mood, availability, and wellbeing. The performance parameter search terms were deemed to be suitable by the reviewers to encapsulate all aspects of sports performance under relatively broad performance parameters, to allow for the search strategy to capture as many studies as possible examining the association between sleep and any measure of performance in female athletes. The search term keywords were combined with ‘AND’ and searched in ‘All Fields’. Reference lists of included articles were manually searched to ensure that all related texts were captured.

### *2.2. Eligibility criteria and selection process*

The retrieved records’ eligibility was assessed based on title and abstract to determine the relevance of the articles found in the initial search. Duplicate and irrelevant articles were excluded also based on title and abstract. Full-text articles were screened if information from title and abstract was unclear. Articles deemed eligible for full-text review were screened against the following inclusion criteria: (i) the study reported primary data and was published in a peer-reviewed journal as a full-text article in the English language; (ii) the study participants were described as elite or expert athletes or athletes competing at sub-elite (collegiate/national); (iii) the study examined sleep by use of polysomnography, actigraphy, sleep diaries and/or questionnaires; (iv) the study described the impact of sleep on performance from a cognitive, physical, wellbeing or skill-based perspective; and (v) the study included data for female athletes separately reported when study used mixed-sex cohorts. Studies were excluded if: (i) the participants were adolescents (< 18 years old); (ii) male and female results were not separated in the case of mixed-sex cohorts; (iii) no performance variable was investigated; (iv) the population was not athletic; (v) the study was in athletes who had sustained a concussion; (vi) here was the presence of a clinical condition which could have impacted sleep quality. The process of study selection following PRISMA guidelines is shown in Figure 1.

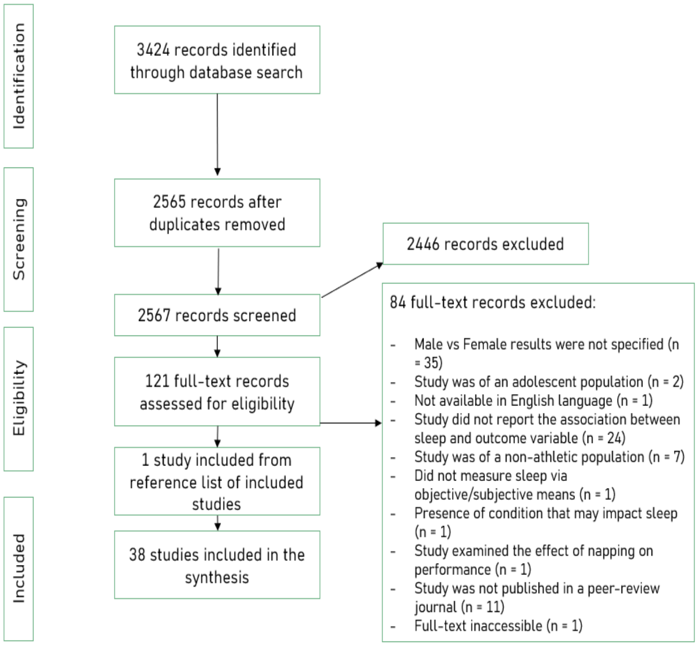

Figure 1: PRISMA Flow Diagram.

### *2.3. Data extraction and quality appraisal*

The competitive level of athletes was examined using a modified taxonomy of Swann et al. (2015), presented in Table 1, in which participants are ranked on a continuum and categorised as semi-elite, competitive-elite, successful elite, and world-class elite to address the varying levels of competition reported in studies of athletic populations. With the application of the full taxonomy limited by participant description in the selected studies, a modified version of this tool was utilised, which has been used in previous systematic reviews of both mixed-sex athlete cohorts (Gupta et al., 2017) and female athlete sleep (Miles et al., 2022). Participants of the selected studies could be categorised as either competitive elite or semi-elite only. Competitive elite cohorts were those with a score greater than or equal to eight in the modified taxonomy. Semi-elite cohorts were those that obtained a score less than eight.

Quality of the studies was evaluated using the modified Newcastle-Ottawa Scale (NOS), a quality assessment instrument that has been previously used in studies of sleep in mixed-sex and female cohorts (Gupta et al., 2017; Miles et al., 2022). Breakdown of the scoring in the NOS is provided in Table 2. Quality of the selected studies was independently scored via the adapted NOS by two reviewers and checked for agreement. In the event of disagreement, the matter was discussed by the two reviewers, and if needed, a third reviewer was brought in for a consensus agreement.

### *2.4. Characterisation of included studies*

The principal characteristics of the included studies are presented in Table 3. These include study design, duration, and performance measure. Performance measure was categorised as sport-specific performance; cognitive performance; physical performance, readiness, and availability; and mood and subjective wellbeing. The four performance categories mentioned were chosen as a method of incorporating all aspects of sports performance. Sport-specific performance incorporated any result relating to the athletes’ performance in outcomes directly related to their sport (i.e., ranking, placing in competition, performance in statistics unique to their sport). Raysmith et al. (2019) stated that for athletes at the highest level of sport, performance at the key competitions is the ‘outstanding measure for success’. Cognitive performance included any outcome measures that could be examined when measuring cognition, such as reaction time and decision making (Brito et al., 2022). Physical performance, readiness, and availability included any muscular performance (e.g., strength, power, speed) outcome, alongside any outcome which may inform the practitioner on the readiness and availability of the athlete (e.g., training load, fatigue, presence of illness). Mood and subjective wellbeing included any mood variable that may have been examined in athletic cohorts (i.e., stress, depression, tension, vigour, motivation, etc.).

Study cohorts were characterised by the percentage of female participants, age and competitive level quantified by the modified taxonomy of Swann et al. (2015). Whether or not a study reported or controlled for menstrual cycle phase was included in the study characterisation since phases of the menstrual cycle have been shown to have an impact on sleep (Van Reen & Kiesner, 2016).

Table 1: Modified competitive level taxonomy for selected studies.

| | Within sport | | | Between sport | | Statistics | |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | | |
| | Standard of performance | Success at level | Experience at level | Competitiveness in country | Global competitiveness of sport | Scores (out of 16) | Competitive elite (> 8) |
| Akazawa et al., 2019 | 1 | NR | NR | 1 | 4 | 2.5 | 0 |
| Barreira et al., 2024 | 4 | NR | NR | 4 | 4 | 16 | 1 |
| Benjamin et al., 2020 | 1 | NR | NR | 3 | 4 | 3.5 | 0 |
| Coombes & Badenhorst, 2024 | 3 | NR | NR | 1 | 4 | 7.5 | 0 |
| Costa et al., 2021 | 4 | NR | NR | 4 | 4 | 16 | 1 |
| Costa et al., 2019 | 3 | NR | NR | 4 | 4 | 12 | 1 |
| Crouch et al., 2021 | 1 | NR | NR | 1 | 1 | 1 | 0 |
| Doeven et al., 2019 | 4 | NR | NR | 1 | 2 | 6 | 0 |
| Dumortier et al., 2018 | 4 | NR | NR | 2 | 4 | 12 | 1 |
| Fernandes et al., 2021 | 3 | NR | NR | 4 | 4 | 12 | 1 |
| Foster et al., 2023 | 1 | NR | NR | 1 | 4 | 2.5 | 0 |
| Grace et al., 2023 | 1 | NR | NR | 2 | 4 | 3 | 0 |
| Haroldsdottir et al., 2021 | 1 | NR | NR | 1 | 4 | 2.5 | 0 |
| Horgan et al., 2021 | 3 | NR | NR | 2 | 1 | 4.5 | 0 |
| Juliff et al., 2018 | 3 | NR | NR | 2 | 1 | 4.5 | 0 |
| Kawasaki et al., 2020 | 1 | NR | NR | 1 | 1 | 1 | 0 |
| Kilic et al., 2021 | 3 | NR | NR | 3 | 4 | 10.5 | 1 |
| Knufinke et al., 2018 | 4 | NR | 4 | 2 | 4 | 12 | 1 |
| Koikawa et al., 2016 | 1 | NR | NR | 3 | 4 | 3.5 | 0 |
| Long et al., 2024 | 1 | NR | NR | 2 | 4 | 3 | 0 |
| Merrigan et al., 2024 | 1 | 2 | NR | 3 | 4 | 3.5 | 0 |
| Mielgo-Ayuso et al., 2017 | 3 | NR | NR | 1 | 4 | 7.5 | 0 |
| Moen et al., 2021 | 4 | NR | NR | 4 | 4 | 16 | 1 |
| O’Donnell et al., 2018a | 4 | 2 | NR | 3 | 1 | 8 | 0 |
| Ressman et al., 2024 | 3 | NR | NR | 3 | 4 | 10.5 | 1 |
| Reyner & Horne, 2013 | 1 | NR | NR | 2 | 4 | 8 | 0 |
| Roberts et al., 2022 | 1 | NR | 2 | 1 | 1 | 1 | 0 |
| Romyn et al., 2016 | 2 | NR | NR | 3 | 4 | 7 | 0 |
| Roy et al., 2019 | 1 | NR | NR | 1 | 4 | 2.5 | 0 |
| Sekiguchi et al., 2019 | 1 | NR | NR | 2 | 1 | 2 | 0 |
| Senbel et al., 2022 | 1 | NR | NR | 4 | 4 | 4 | 0 |
| Silva & Paiva, 2016 | 4 | NR | 4 | 1 | 3 | 8 | 0 |
| Silva & Paiva, 2019a | 4 | NR | 4 | 1 | 3 | 8 | 0 |
| Silva & Paiva, 2019b | 4 | NR | 4 | 1 | 3 | 8 | 0 |
| Staunton et al., 2017 | 3 | NR | NR | 3 | 4 | 10.5 | 1 |
| Taheri & Irandoust, 2020 | 1 | NR | NR | 3 | 3 | 3 | 0 |
| Tsukahara et al., 2022 | 3 | NR | NR | 1 | 4 | 7.5 | 0 |
| Ungureanu et al., 2021 | 3 | NR | NR | 2 | 4 | 9 | 1 |
| Mean | 2.39 | NA | NA | 2.18 | 3.29 | 6.83 | 11/38 |
| SD | 1.28 | NA | NA | 1.10 | 1.17 | 4.32 | NA |

*Notes:* Modified equation = {A × [(D + E)/2)]}; a score > 8 is judged to be a study that has recruited ‘competitive elite’ athletes (see Swann et al., 2015); NR, not reported; NA, not applicable; SD, standard deviation.

Table 2: Modified Newcastle-Ottawa Scale quality appraisal of selected studies.

| | Selection[a] | | | | | Comparability[a] | | | Outcome[b] | | | Statistics | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Representativeness of the sample | *n* | Non-respondents | Ascertainment of the exposure[b] (sleep) | Sub-total | Control for most important factor (sleep) | Control for other factors (competitive standard) | Sub-total | Assessment of outcome | Statistical test | Sub-total | Total (out of 10) | High (> 7) | Mod-high (5–7) | Low (< 5) |
| Akazawa et al., 2019 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 1 | 3 | 4 | 0 | 0 | 1 |
| Barreira et al., 2024 | 1 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 2 | 1 | 3 | 5 | 0 | 1 | 0 |
| Benjamin et al., 2020 | 1 | 1 | 1 | 1 | 4 | 0 | 0 | 0 | 1 | 1 | 2 | 6 | 0 | 1 | 0 |
| Coombes & Badenhorst, 2024 | 1 | 0 | 1 | 1 | 3 | 0 | 0 | 0 | 1 | 1 | 2 | 5 | 0 | 1 | 0 |
| Costa et al., 2021 | 1 | 0 | 1 | 1 | 3 | 0 | 0 | 0 | 2 | 1 | 3 | 6 | 0 | 1 | 0 |
| Costa et al., 2019 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 2 | 1 | 3 | 4 | 0 | 1 | 0 |
| Crouch et al., 2021 | 1 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 0 | 0 | 1 |
| Doeven et al., 2019 | 1 | 0 | 1 | 2 | 4 | 0 | 0 | 0 | 1 | 1 | 2 | 6 | 0 | 1 | 0 |
| Dumortier et al., 2018 | 0 | 0 | 0 | 2 | 2 | 1 | 0 | 1 | 1 | 1 | 2 | 5 | 0 | 1 | 0 |
| Fernandes et al., 2021 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 0 | 0 | 1 |
| Foster et al., 2023 | 1 | 1 | 1 | 1 | 4 | 0 | 0 | 0 | 1 | 1 | 2 | 6 | 0 | 1 | 0 |
| Grace et al., 2023 | 1 | 1 | 1 | 0 | 3 | 0 | 0 | 0 | 1 | 1 | 2 | 5 | 0 | 1 | 0 |
| Haroldsdottir et al., 2021 | 1 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 0 | 0 | 1 |
| Horgan et al., 2021 | 1 | 1 | 1 | 1 | 4 | 0 | 0 | 0 | 1 | 1 | 2 | 6 | 0 | 1 | 0 |
| Juliff et al., 2018 | 1 | 1 | 0 | 1 | 3 | 1 | 0 | 1 | 2 | 1 | 3 | 7 | 0 | 1 | 0 |
| Kawasaki et al., 2020 | 0 | 1 | 1 | 1 | 3 | 0 | 0 | 0 | 1 | 1 | 2 | 5 | 0 | 1 | 0 |
| Kilic et al., 2021 | 1 | 1 | 1 | 2 | 5 | 0 | 1 | 1 | 1 | 1 | 2 | 8 | 1 | 0 | 0 |
| Knufinke et al., 2018 | 0 | 1 | 0 | 2 | 3 | 0 | 0 | 0 | 2 | 1 | 3 | 6 | 0 | 1 | 0 |
| Koikawa et al., 2016 | 0 | 1 | 1 | 1 | 3 | 0 | 0 | 0 | 1 | 1 | 2 | 5 | 0 | 1 | 0 |
| Long et al., 2024 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 0 | 0 | 1 |
| Merrigan et al., 2024 | 1 | 0 | 0 | 2 | 3 | 0 | 0 | 0 | 2 | 1 | 3 | 6 | 0 | 1 | 0 |
| Mielgo-Ayuso et al., 2017 | 1 | 1 | 0 | 2 | 4 | 0 | 0 | 0 | 1 | 1 | 2 | 6 | 0 | 1 | 0 |
| Moen et al., 2021 | 0 | 0 | 1 | 2 | 3 | 0 | 0 | 0 | 2 | 1 | 3 | 6 | 0 | 1 | 0 |
| O’Donnell et al., 2018a | 1 | 0 | 0 | 2 | 3 | 1 | 0 | 1 | 2 | 1 | 3 | 7 | 0 | 1 | 0 |
| Ressman et al., 2024 | 1 | 1 | 1 | 1 | 4 | 0 | 1 | 1 | 2 | 1 | 3 | 8 | 1 | 0 | 0 |
| Reyner & Horne, 2013 | 0 | 0 | 0 | 2 | 2 | 1 | 0 | 1 | 2 | 1 | 3 | 6 | 0 | 1 | 0 |
| Roberts et al., 2022 | 0 | 0 | 1 | 2 | 3 | 0 | 0 | 0 | 2 | 1 | 3 | 6 | 0 | 1 | 0 |
| Romyn et al., 2016 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 2 | 1 | 3 | 5 | 0 | 1 | 0 |
| Roy et al., 2019 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 2 | 3 | 0 | 0 | 1 |
| Sekiguchi et al., 2019 | 1 | 0 | 0 | 2 | 3 | 0 | 0 | 0 | 2 | 1 | 3 | 6 | 0 | 1 | 0 |
| Senbel et al., 2022 | 1 | 0 | 1 | 2 | 4 | 0 | 0 | 0 | 2 | 1 | 3 | 7 | 0 | 1 | 0 |
| Silva & Paiva, 2016 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 0 | 0 | 1 |
| Silva & Paiva, 2019a | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 1 | 3 | 4 | 0 | 0 | 1 |
| Silva & Paiva, 2019b | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 2 | 1 | 3 | 5 | 0 | 1 | 0 |
| Staunton et al., 2017 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 1 | 3 | 4 | 0 | 0 | 1 |
| Taheri & Irandoust, 2020 | 0 | 0 | 1 | 1 | 2 | 0 | 0 | 0 | 2 | 1 | 3 | 5 | 0 | 1 | 0 |
| Tsukahara et al., 2022 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 1 | 2 | 5 | 0 | 1 | 0 |
| Ungureanu et al., 2021 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 2 | 3 | 0 | 0 | 1 |
| Mean | 0.47 | 0.45 | 0.42 | 1.26 | 2.61 | 0.11 | 0.05 | 0.16 | 1.47 | 1.00 | 2.50 | 5.24 | 2 | 26 | 10 |
| SD | 0.50 | 0.50 | 0.49 | 0.59 | 1.06 | 0.31 | 0.22 | 0.36 | 0.50 | 0.00 | 0.50 | 1.31 | NA | NA | NA |

*Notes:* [s]subscale items rated 0–1; [b]subscale items rated 0–2; NA, not applicable; SD, standard deviation; The NOS is scored by allocation of a point for each criterion that is met in each section of: 1. Selection (maximum 5 points); 2. Comparability (maximum 2 points); and 3. Outcome (maximum 3 points). Each section has sub-sections that can be worth either 1 or 2 points depending on the criterion being questioned. The total score out of a possible 10 points determines whether the study is of high (> 7), moderate (5–7) or low (< 5) quality.

Table 3: Characteristics of included studies.

| | Sport | Female (*n*) | Female (%) | Female age (years) | Study design | Study duration | Performance measure | “Eliteness” of sample | Control for MC Phase/Regularity /HC use | Quality assessment score (adapted NOS 0–10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Akazawa et al., 2019 | Volleyball | 12 | 100 | 20.0 ± 0.3 | Cross-sectional | 1 day | Cognitive | Semi | No | Low (4) |
| Barreira et al., 2024 | Soccer | 16 | 100 | 25.4 ± 3.6 | Observational | 7 days | Physical, readiness, and availability | Competitive | No | Moderate (5) |
| Benjamin et al., 2020 | Soccer | 120 | 52 | 20.0 ± 1.0 | Observational | 3 competitive seasons | Mood and subjective wellbeing | Semi | No | Moderate (6) |
| Coombes & Badenhorst, 2024 | Soccer | 22 | 100 | 20.8 ± 3.5 | Cross-sectional | 1 data collection session | Physical, readiness, and availability | Semi | Menstrual status recorded via LEAF-Q | Moderate (5) |
| Costa et al., 2021 | Soccer | 20 | 100 | 25.2 ± 3.1 | Observational | 9 days | Physical, readiness, and availability | Competitive | No | Moderate (6) |
| Costa et al., 2019 | Soccer | 34 | 100 | 20.6 ± 2.3 | Observational | 14 days | Physical, readiness, and availability | Competitive | No | Low (4) |
| Crouch et al., 2021 | Lacrosse | 27 | 100 | 18.7 ± 0.9 | Observational | 13 weeks | Physical, readiness, and availability | Semi | No | Low (4) |
| Doeven et al., 2019 | Rugby (7s) | 12 | 100 | 25.3 ± 4.1 | Observational | 7 days | Physical, readiness, and availability | Semi | No | Moderate (6) |
| Dumortier et al., 2018 | Gymnastics | 7 | 100 | 20.9 ± 2.8 | Observational | 14 weeks | Sport-specific | Competitive | No | Moderate (5) |
| Fernandes et al., 2021 | Soccer | 19 | 100 | 24.1 ± 2.7 | Observational | 10 weeks | Physical, readiness, and availability; mood and subjective wellbeing | Semi | No | Low (2) |
| Foster et al., 2023 | Volleyball | 67 | 100 | NR | Observational | 5 competitive seasons | Physical, readiness, and availability; mood and subjective wellbeing | Semi | No | Moderate (6) |
| Grace et al., 2023 | Lacrosse | 32 | 100 | NR | Observational | 1 competitive season | Sport-specific | Semi | No | Moderate (5) |
| Haroldsdottir et al., 2021 | Volleyball | 17 | 100 | 19.6 ± 1.0 | Observational | 9 months | Physical, readiness, and availability; mood and subjective wellbeing | Semi | No | Low (4) |
| Horgan et al., 2021 | Netball | 536 | 100 | 18.8 ± 4.6 | Retrospective cohort | 4 years | Physical, readiness, and availability | Semi | No | Moderate (6) |
| Juliff et al., 2018 | Netball | 42 | 100 | 19.2 ± 1.0 | Observational | 18 days | Sport-specific | Semi | No | Moderate (7) |
| Kawasaki et al., 2020 | Multiple | 215 | 51 | 19.0 ± 3.5;<br>20.3 ± 4.4 | Cross-sectional | 1 data collection session | Mood and subjective wellbeing | Semi | Yes | Moderate (5) |
| Kilic et al., 2021 | Australian Football | 132 | 36 | 22.8 ± 4.0 | Cross-sectional | 3 months | Physical, readiness, and availability; mood and subjective wellbeing | Competitive | No | High (8) |
| Knufinke et al., 2018 | Multiple | 56 | 57 | NR | Observational | 10 days | Physical, readiness, and availability | Competitive | No | Moderate (6) |
| Koikawa et al., 2016 | Soccer | 30 | 32 | 19.8 ± 1.2 | Cross-sectional | 1 day | Mood and subjective wellbeing | Semi | No | Moderate (5) |

*Continued*

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Long et al., 2024 | Soccer | 30 | 100 | NR | Observational | 1 competitive season | Physical, readiness, and availability; mood and subjective wellbeing | Semi | No | Low (4) |
| Merrigan et al., 2024 | Ice Hockey | 25 | 100 | 20.7 ± 1.6 | Retrospective | 1 competitive season | Physical, readiness, and availability | Semi | No | Moderate (6) |
| Mielgo-Ayuso et al., 2017 | Volleyball | 40 | 100 | 27.0 ± 4.0 | Cross-sectional | 1 day | Physical, readiness, and availability | Semi | Yes | Moderate (6) |
| Moen et al., 2021 | Soccer | 29 | 100 | 25.9 ± 4.1 | Observational | 124 days | Physical, readiness, and availability | Competitive | No | Moderate (6) |
| O'Donnell et al., 2018a | Netball | 10 | 100 | 23.0 ± 6.0 | Observational | 7 days | Mood and subjective wellbeing | Semi | No | Moderate (7) |
| Ressman et al., 2024 | Soccer | 254 | 100 | 22 (No SD) | Cross-sectional | 1 day | Physical, readiness, and availability | Competitive | No | High (8) |
| Reyner & Horne, 2013 | Tennis | 8 | 50 | 18–22 years | Experimental | 4 days | Sport-specific | Semi | No | Moderate (6) |
| Roberts et al., 2022 | Ultra-Marathon | 18 | 50 | 38.0 ± 7.0 | Observational | 3 consecutive days | Physical, readiness, and availability; mood and subjective wellbeing | Semi | No | Moderate (6) |
| Romyn et al., 2016 | Netball | 8 | 100 | 19.6 ± 1.5 | Observational | 14 total days | Mood and subjective wellbeing | Semi | No | Moderate (5) |
| Roy et al., 2019 | Volleyball | 15 | 100 | NR | Observational | 54 days | Physical, readiness, and availability; mood and subjective wellbeing | Semi | No | Low (3) |
| Sekiguchi et al., 2019 | Athletics | 10 | 100 | 19.0 ± 1.0 | Observational | 12 weeks | Physical, readiness, and availability | Semi | No | Moderate (6) |
| Senbel et al. [53] | Basketball | 16 | 100 | NR | Observational | 25 weeks | Sport-specific | Semi | No | Moderate (7) |
| Silva & Paiva, 2016 | Gymnastics | 67 | 100 | 18.7 ± 2.9 | Cross-sectional | 1 data collection session | Sport-specific | Semi | No | Low (4) |
| Silva & Paiva, 2019a | Gymnastics | 67 | 100 | 18.7 ± 2.9 | Cross-sectional | 1 data collection session | Mood and subjective wellbeing | Semi | No | Moderate (5) |
| Silva & Paiva, 2019b | Gymnastics | 67 | 100 | 18.7 ± 2.9 | Cross-sectional | 1 data collection session | Mood and subjective wellbeing; sport-specific | Semi | Identified delayed menarche and menstrual irregularities | Low (4) |
| Staunton et al., 2017 | Basketball | 17 | 100 | NR | Observational | 30 weeks (16 in one season, 14 in one season) | Sport-specific | Competitive | No | Low (4) |
| Taheri & Irandoust, 2020 | Volleyball | 21 | 100 | 23.6 ± 2.9 | Experimental | 2 days | Cognitive | Semi | No | Moderate (5) |
| Tshukahara et al., 2022 | Athletics | 77 | 100 | NR | Cross-sectional | 1 testing session | Sport-specific | Semi | No | Moderate (5) |
| Ungureanu et al., 2021 | Volleyball | 10 | 100 | 23.0 ± 4.0 | Observational | 16 weeks | Physical, readiness, and availability | Competitive | No | Low (3) |

Notes: SD, standard deviation; HC, hormonal contraception; MC, menstrual cycle; NR, not reported.

## 3. Results

The database search returned 2565 records. Following a title and abstract screening, one hundred and twenty-one studies remained for full-text eligibility assessment. Following the application of inclusion and exclusion criteria, thirty-eight studies were included in the synthesis.

### *3.1. Quality appraisal*

The quality of the selected studies was moderate to low, with twenty-six studies (68%) scoring between 5 – 7 (moderate quality) and ten studies (26%) scoring < 5 (low quality). Only two studies scored > 7 (high quality).

Due to many of the studies being observational in design, there was a lack of control for both sleep quality and/or quantity (only five studies included this control) and competitive standard (one study included this control). The full quality appraisal using the modified Newcastle-Ottawa Scale is presented in Table 2.

### *3.2. Characteristics of included studies*

In the selected studies, thirty-one of the thirty-eight studies examined females exclusively, with the seven remaining studies containing mixed-sex sample with a mean of 46.9% female. The mean number of female athletes in the samples of included studies was $n = 58$ (range: 7 – 536).

Most studies were observational in design, with only two experimental studies included. Studies were conducted across fourteen different sports and two multi-sport cohorts, with soccer and volleyball being the most examined sports. Study durations varied, some studies were as short as one day in duration, while others spanned between three months and five competitive seasons.

Only two of the included studies reported menstrual cycle phase/regularity and/or hormonal contraceptive use, one study reported menstrual status, while one other study identified delayed menarche and menstrual irregularities. A full description of study characteristics is presented in Table 3.

### *3.3. Association between sleep and sport-specific performance*

Results from included studies in this category of performance are presented in Table 4. In studies examining sport-specific performance, two studies recorded sleep through objective measures (wrist actigraphy) while the five remaining studies used subjective sleep measurement (Epworth Sleepiness Scale; Pittsburgh Sleep Quality Index; Sleep log/diary). The study durations ranged from one data collection session to two competitive seasons of monitoring. Five studies were of moderate quality with the remaining two studies being of low quality. Competitive level of the athletes in the studies sample was semi-elite in seven studies and competitive elite in two studies. The average sample size of the studies examining sleep and sport-specific performance was $n = 30$ (range: 7 – 67).

Performance outcomes measures included: coach ratings; championship/competition rankings; mean apparatus score (gymnastics); team win/loss record; serving accuracy (tennis); game statistics; injury reports; and competition scores (gymnastics). Associations between improved sleep indices and positive performance outcomes were moderate to strong in general. Superior competition ranking had significant associations with sleep duration ($r = -0.680$, $p < 0.01$; $r = 0.339$, $p = 0.005$) over both an 18-day monitoring period as well as cross-sectional data (Juliff et al., 2018; Silva & Paiva, 2016), while inferior competition ranking was associated with increased sleepiness (ESS score; $r = -0.454$, $p < 0.001$), and increased sleep disturbance (PSQI score; $r = -0.242$, $p = 0.042$; Silva & Paiva, 2016). The strongest association between sleep and sport-specific performance was found to be between increased total sleep time and mean apparatus score ($r = 0.771$) and world championship ranking ($r = -0.771$) in gymnasts over 14 weeks of data collection (Dumortier et al., 2017), however these associations were not significant.

### *3.4. Association between sleep and cognitive performance*

Results from included studies in this category are also presented in Table 4. Cognitive performance was the least examined performance parameter in this review. In the two studies examining cognitive performance, two types of actigraphy were used to monitor sleep (mattress-based actigraphy; wrist actigraphy). The quality of these studies was moderate and low. Study duration was relatively short, having a one- and two-day testing period respectively. Average sample size was $n = 12$ with all the participants in the studies being female.

One study involved partial sleep deprivation to examine the impact of acute sleep loss on performance using the Vienna system test (Taheri & Irandoust, 2020), where participants slept for 3 hours the night before testing. This study saw significantly impaired reaction time ($p = 0.004$), accuracy rate ($p = 0.001$) median cognitive reaction ($p = 0.001$), median motor time ($p = 0.01$), processing speed ($p = 0.001$) and selective attention ($p = 0.001$) in a sleep deprivation group compared to a sleep deprivation group who completed an exercise bout upon waking before testing (both slept 3 hours). Reaction time (via Stroop task) during heavy exercise was found to improve in a superior sleep quality group ($p < 0.05$; Akazawa et al., 2019). Improved sleep efficiency was also associated with improved reaction time during heavy exercise compared to less strenuous exercise ($r = -0.680$, $p < 0.05$).

### *3.5. Association between sleep and physical performance, readiness, and availability*

Results from included studies in this category can be found in Table 5. A total of twenty-one studies reported on the association between sleep and the physical performance, readiness, and availability of female athletes. Methods of objective sleep measurement included wrist actigraphy (Barreira et al., 2022; Costa et al., 2019; Costa et al., 2021; Knufinke et al., 2018; Roberts et al., 2022; Sekiguchi et al., 2019), a non-contact smart sleep monitor (Moen et al., 2021), a commercially available wearable (Merrigan et al., 2024) and partial polysomnography (Knufinke et al., 2018). Sleep was measured subjectively using wellness questionnaires (Costa et al., 2021; Crouch et al., 2021), Hooper Index (Fernandes et al., 2021; Roy et al., 2019; Ungureanu et al., 2021), sleep diaries (Barreira et al., 2022; Haroldsdottir et al., 2021; Horgan et al., 2021) and questionnaires

Table 4: Results from studies examining the association between sleep and sport-specific performance and cognitive performance in female athletes.

| | Sleep Measurement | Performance Measurement | Results |
|---|---|---|---|
| Dumortier et al., 2018 | Sleep log | Trainer rating; WC ranking; mean apparatus score | TST trended to association with ↑ gymnastics mean apparatus score ($r = 0.771$, $p = 0.072$) and gymnastics WC ranking ($r = -0.771$, $p = 0.072$). |
| Grace et al., 2023 | Subjective wellness survey | Team win/loss record | 60% of losses occurred with low sleep quality.<br>60% of wins occurred with high sleep quality.<br>(Not significant: $p = 0.527$). |
| Juliff et al., 2018 | Sleep diary; ESS; Wrist actigraphy | Finishing place in netball competition | ↑ sleep duration associated with higher finishing place ($r = -0.68$, $p < 0.01$).<br>Top 2 teams had ↑ TIB ($p < 0.001$), ↑ sleep duration ($p < 0.001$), ↑ subjective sleep rating ($p = 0.008$) compared to bottom 2 teams. |
| Reyner & Horne, 2013 | Wrist actigraphy | Set target box within the tennis service area | Significant association between sleep condition (normal vs restricted) and number of hits inside the service box ($F = 38.7$, df:1,28; $p < 0.001$).<br>Result the same for both men and women (no significant relative difference in effect of sleep reduction on serving accuracy). |
| Senbel et al., 2022 | Wrist accelerometery | Game statistics; injury reports | Sleep need, sleep debt hours and weekly sleep duration were ranked in the top 10 features affecting game performance (5th, 8th, and 9th respectively). |
| Silva & Paiva, 2016 | ESS; PSQI; sleep/wake times | Overall performance ranking from published general competition results | ↑ sleep duration associated with superior performance ranking ($r = 0.339$, $p = 0.005$).<br>↑ sleepiness (ESS score) associated with inferior performance ranking ($r = -0.454$, $p < 0.001$)<br>↑ sleep disturbance (PSQI score) associated with inferior performance ranking ($r = -0.242$, $p = 0.042$). |
| Silva & Paiva, 2019a | ESS; PSQI; sleep/wake times | Overall performance ranking from published general competition results | Lowest performances (OR = 1.25, 95% CI [0.76, 2.06]) and sleep duration <8h30m on weekdays (OR = 1.93, 95% CI [1.48, 2.50]) identified as risk factors for reduced sleep quality. |
| Staunton et al., 2017 | Wrist actigraphy | Basketball Efficiency Statistic | Association between TST and basketball efficiency statistic for individual players ranged from moderate negative to strong positive; a significant association for one player only ($r = 0.60$, $p = 0.025$). No association between SE and basketball efficiency statistic. |
| Tsukahara et al., 2022 | Customised training load and recovery questionnaire | IAAF competition scores | Number of sleep hours was not associated with IAAF score in the whole group or in the Japanese athlete sub-group.<br>For American athlete sub-group, ↑ number of sleep hours per day associated with inferior performance ($r = -0.43$, $p < 0.05$). |
| Akazawa et al., 2019 | Non-wearable, mattress-based actigraphy | Stroop test | In the difficult task RT was unchanged in lesser sleep quality group; RT improved in better sleep quality group during heavy exercise intensity ($p < 0.05$).<br>↑ SE associated with improved RT during heavy intensity exercise compared to light intensity exercise and rest ($r = -0.680$, $p < 0.05$). |
| Taheri & Irandoust, 2020 | Wrist actigraphy; partial sleep deprivation group | Vienna system test: movement detection time; visual pursuit test, cognitrone test | Impaired RT ($p = 0.004$), accuracy rate ($p = 0.001$), median cognitive reaction ($p = 0.001$), median motor time ($p = 0.005$), processing speed ($p = 0.001$), and selective attention ($p = 0.001$) in those with PSD compared those with PSD with exercise upon waking before testing. |

Notes*:* ESS = Epworth Sleepiness Scale; IAAF = International Association of Athletics Federation; IC = confidence interval; OR = odds ratio; PSD = partial sleep deprivation; PSQI = Pittsburgh Sleep Quality Index; RT = reaction time; SE = sleep efficiency; TST = total sleep time; WC = world championship.

Table 5: Results from studies examining the association between sleep and physical performance, readiness, and availability in female athletes.

| | Sleep Measurement | Performance Measurement | Results |
|---|---|---|---|
| Barreira et al., 2024 | Wrist actigraphy; Sleep diary | GPS; Subjective wellbeing | ↑ perceived fatigue associated with ↓ TST and SE ($r = -0.33$, FDR-adjusted $p = 0.04$). |
| Coombes & Badenhorst, 2024 | ASSQ | LEAF-Q | Significant difference in mean SDS between players at risk of LEA (7.8 ± 3.9AU) and players not at risk of LEA (5.4 ± 1.4AU) ($p = 0.18$).<br>Those who had moderate and/or severe clinical sleep problems were 1.7 times more likely to be identified as being at risk of LEA.<br>No significant relationship between SDS score and risk of LEA. |
| Costa et al., 2021 | Wrist actigraphy; Hooper Index | s-RPE; GPS for running variables; total distance during matches and training | ↑ sleep duration associated with ↓ training impulse ($r = -0.25$, $p < 0.001$), and ↓ s-RPE ($r = -0.43$, $p < 0.001$).<br>↑ sleep efficiency associated with ↓ training impulse ($r = -0.20$, $p = 0.004$); and ↓ s-RPE ($r = -0.17$, $p = 0.02$). |
| Costa et al., 2019 | Wrist actigraphy | s-RPE; Training impulse | No association between training and match load parameters and TST, SE and lnRMSSD. |
| Crouch et al., 2021 | Daily wellness scores | s-RPE; External training load variables (GPS) | ↑ subjective sleep quality associated with ↑ distance covered (parameter estimate change = 303.8m, $p = 0.019$), ↑ high intensity distance (parameter estimate change = 64.2m, $p = 0.015$) and ↑ athlete load (parameter estimate change = 5.7AU, $p = 0.015$). |
| Doeven et al., 2019 | Wellbeing questionnaire | s-RPE; questionnaire for fatigue and muscle soreness; Total Quality of Recovery scale of 6-20; training load via GPS; CMJ | No association between self-reported sleep quality and training load. |
| Fernandes et al., 2021 | Hooper index | s-RPE; internal training load (CR-10 scale) | No association between sleep and stress, fatigue, DOMS, training monotony, training strain and ACWR. |
| Foster et al., 2023 | Metrifit athlete monitoring application | Metrifit athlete monitoring application | ↑ sleep quality associated with ↑ energy ($r = 0.387$, $p < 0.001$).<br>↑ sleep duration associated with ↑ energy ($r = 0.218$, $p < 0.001$).<br>(Larger numbers on Likert scale indicate positive effect, hence positive correlation with stress). |
| Haroldsdottir et al., 2021 | Likert scale 1-5 for sleep quality; subjective sleep duration | Injury onset; internal training load self-report | ↑ sleep quality and duration associated with ↓ fatigue ($r = 0.52$, $p < 0.001$; $r = 0.17$, $p < 0.001$) and ↓ soreness ($r = 0.22$, $p < 0.001$; $r = 0.07$, $p < 0.001$).<br>Sleep quality (OR = 0.49, $p < 0.001$) and prior night sleep duration (OR 0.69, $p = 0.001$) predicted in-season injury. |
| Horgan et al., 2021 | AIS Athlete Management System: 1- Likert scale for sleep quality; TST to nearest half hour | Internal training load: s-RPE; monotony; strain; acute and chronic training load; ACWR.<br>Injury and illness incidence | Sleep duration, fatigue and sleep quality explained 19.3% of the variance in risk for injury and illness.<br>Significant effects for bidirectional changes in sleep duration (OR = 1.02 ± 0.04, p < 0.001; AR = 0.57 ± 0.11) and sleep quality (OR = 1.03 ± 0.09, p < 0.001; AR = 0.97 ± 0.18) in the 7-day period prior to an injury as well as bidirectional changes in sleep quality (OR = 1.00 ± 0.03, p < 0.01; AR = 0.94 ± 0.08) in the 28-day period prior to an injury event. Significant effects for - sleep duration (OR = 1.03 ± 0.03, p < 0.001; AR = 2.08 ± 0.84) and ¯ sleep quality (OR = 0.95 ± 0.12, p <0.001; AR = 1.89 ± 0.98) in the 7-day period prior to an illness event and for - sleep duration (OR = 1.01 ± 0.02, p < 0.001; AR = 1.70 ± 0.29) and for ¯ sleep quality (OR = 0.99 ± 0.04, p < 0.001; AR = 1.79 ± 0.17) in the 28-day period prior to an illness event. Significant effects were also found for the 7-day following an illness event for ¯ sleep duration (OR = 0.99 ± 0.03, p < 0.001; AR = 1.12 ± 0.25) and sleep quality (OR = 1.00 ± 0.05, p < 0.001; AR = 1.30 ± 0.02), as well as the 28-day period following an illness event for ¯ sleep duration (OR = 1.00 ± 0.01, p < 0.001; AR = 1.41 ± 0.27). |

*Continued*

| | | | |
|---|---|---|---|
| Kilic et al., 2021 | Sleep disturbance via Athlete Sleep Screening Questionnaire | Injury incidence | Sleep disturbance associated with injury in previous 6 months (OR = 2.65; 95% CI [1.20, 5.85]). |
| Knufinke et al., 2018 | Wrist actigraphy and wireless one-channel EEG sensor | Self-reported training load (1-10 scale) | Gender is a significant predictor of TIB (B = -13.12, CI [-22.55, -3.69], $p = 0.01$), TST (B = -15.34, CI [-24.10, -6.57], $p = 0.003$), and SE (B = -0.74, CI [-1.36, -0.12], $p = 0.02$) (B = small point estimate).<br>No association between training load and sleep variables. |
| Long et al., 2024 | Self-report via mobile app for duration and quality | GPS; self-reported wellness via mobile app (1-10 scale) | Significant interaction of day by sleep duration, indicating the effect of sleep duration on soreness differs depending on the day ($\beta = -0.0032$, $p = 0.040$).<br>Sleep duration significantly predicted soreness ($\beta = 0.18$, $p = 0.010$).<br>Day ($\beta = 0.0036$, $p < 0.001$), load ($\beta = -0.14$, $p = 0.004$), RPE ($\beta = 0.15$, $p = 0.002$), mental fatigue ($\beta = -0.15$, $p < 0.001$), and sleep quality ($\beta = 0.34$, $p < 0.001$) had a significant effect on sleep duration. |
| Merrigan et al., 2024 | Consumer wearable (ring) | GPS monitoring system | ↓ TRIMP(Intercept = 7.43 ± 0.09; Estimate = -0.13 ± 0.02), duration (I = 7.43 ± 0.10; E = -0.13 ± 0.02), total distance (I = 7.43 ± 0.10; E = -0.12 ± 0.02), time > 80% HRmax (I = 7.43 ± 0.09; E = -0.09 ± 0.02), time < 80% HRmax (I = 7.43 ± 0.10; E = -0.13 ± 0.02), and average HR(%) (I = 7.43 ± 0.10; E = -0.04 ± 0.02) were associated with ↓ sleep duration.<br>There were also associations between all workload metrics and Sleep Score and Readiness Score. |
| Mielgo-Ayuso et al., 2017 | Oviedo Sleep Questionnaire | Vertical jump; spike jump; 2x18m sprint (speed); 9-3-6-3-9m agility test; crunch test; overhead med ball throw | ↓ OSQ score (better sleep) associated with ↑ vertical jump ($r = -0.32$, $p < 0.05$).<br>↓ OSQ score (better sleep) associated with ↑ spike jump ($r = -0.33$, $p < 0.05$).<br>↓ scores on sleep subscale of the OSQ (better sleep) associated with ↑ crunch test score ($r = -0.38$, $p < 0.05$).<br>↓ scores on insomnia subscale of the OSQ (better sleep) associated with ↑ vertical jump ($r = -0.37$, $p < 0.05$) and spike jump ($r = -0.36$, $p < 0.05$). |
| Moen et al., 2021 | Actigraphy via Somnofy sleep monitor | Perceived fatigue on 1-10 scale via smartphone application | ↑ in perceived fatigue associated with ↑ SWS (1.2 ± 0.6 min, $p = 0.007$) and ↓ TIB (3.6 ± 1.8 min, $p = 0.038$).<br>↑ REM sleep duration associated with ↓ perceived fatigue (0.21 ± 0.08 AU, $p = 0.008$).<br>↑ NREM respiration associated with ↑ perceived fatigue (0.27 ± 0.09 AU, $p = 0.002$). |
| Ressman et al., 2024 | PSQI | SLS test | No significant association between PSQI score and SLS. 51% of poor sleepers (PSQI score ≥ 6) failed the SLS compared to 42% of good sleepers (PSQI score ≤ 5) on their non-dominant leg ($p = 0.18$). 71% of poor sleepers failed the SLS compared to 68% of good sleepers on their dominant leg ($p = 0.45$). |
| Roberts et al., 2022 | Wrist actigraphy | Short recovery and stress scale | ↑ sleep duration associated with ↑ recovery (b = 0.004 AU for every unit increase in sleep duration, $p = 0.048$). |
| Roy et al., 2019 | Hooper Questionnaire | Internal training load and fatigue | ↓ sleep quality associated with ↑ sRPE ($r = 0.098$, $p < 0.05$), ↑ HS ($r = 0.689$, $p < 0.01$), ↑ fatigue ($r = 0.390$, $p < 0.01$), ↑ muscle soreness ($r = 0.215$, $p < 0.01$). |
| Sekiguchi et al., 2019 | Wrist actigraphy | RHR; HRV | ↑ RHR associated with ↓ % time spent in light sleep ($r = -0.65$, $p < 0.05$), ↑ %SWS ($r = 0.55$, $p < 0.05$), ↑ %REM ($r = 0.20$, $p < 0.05$), ↓ sleep time spent in light sleep ($r = -0.47$, $p < 0.05$), ↑ SWS ($r = 0.54$, $p < 0.05$), ↑ REM ($r = 0.21$, $p < 0.05$), ↓ sleep consistency ($r = -0.41$, $p < 0.05$).<br>↑ HRV associated with ↑ % time spent in light sleep ($r = 0.54$, $p < 0.05$), ↓ %SWS ($r = -0.62$, $p < 0.05$), ↑ sleep time spent in light sleep ($r = 0.38$, $p < 0.05$), ↓ SWS ($r = -0.61$, $p < 0.05$). |
| Ungureanu et al., 2021 | Hooper Index | sRPE; No. of jumps recorded via video | Sleep quality not associated with previous day sRPE or no. of jumps recorded in volleyball players. |

*Notes:* ACWR = acute chronic workload ratio; AIS = Australian Institute of Sport; AR = absolute risk; ASSQ = Athlete Sleep Screening Questionnaire; AU = arbitrary unit; bpm = beats per minute; CI = confidence interval; CMJ = countermovement jump; CR-10 = category ratio-10; DOMS = delayed onset muscle soreness; E = estimate; EEG = electroencephalography; EMG = electromyography; EOG = electrooculography; ES = effect size; GPS = Global Positioning System; HR = heart rate; I = intercept; LEAF-Q = Low Energy Availability in Female Athletes Questionnaire; lnRMSSD = log-transformed root mean square of successive R-R intervals; NREM = non-rapid eye movement; OR = odds ratio; OSQ = Oviedo Sleep Questionnaire; PSQI = Pittsburgh Sleep Quality Index; RAT = Reactive Agility Test; REM = rapid eye movement; RPE = rate of perceived exertion; R-1 = from start line to the first gate; SDS = sleep difficulty score; SE = sleep efficiency; SLS = single leg squat; s-RPE = Session Rate of Perceived Exertion; SWS = slow wave sleep; TIB = time in bed; TST = total sleep time; YoYo IRT = YoYo Intermittent Recovery Test; b = beta value indicating the change in outcome variable for each one-unit increase in the predictor variable.

(Coombes & Badenhorst, 2024; Kilic et al., 2021; Mielgo-Ayuso et al., 2017; Ressman et al., 2024), analogue scales (Haroldsdottir et al., 2021; Horgan et al., 2021), and athlete monitoring applications (Foster et al., 2023; Long et al., 2024). Two of these studies were of high quality, seven were of low quality and fifteen were of moderate quality. Eight of the twenty-one studies contained a competitive-elite sample. The average sample size of these studies was $n = 66$ (range: 7 – 536).

Multiple studies examined the association between sleep indices and readiness to train/compete in female athletes. Increases in subjective fatigue were associated with decreases in total sleep time over a 7-day monitoring period ($r = -0.33$, FDR-adjusted $p = 0.04$) (Barreira et al., 2022) and increases in SWS (1.2 ± 0.6 min, $p = 0.007$), time in bed (3.6 ± 1.8 min, $p = 0.038$) and non-rapid eye movement (NREM) respiration (0.27 ± 0.09 AU, $p = 0.002$) over 124 observation days (Moen et al., 2021), while decreases in subjective fatigue were associated with increased rapid eye movement (REM) sleep duration (0.21 ± 0.08 AU, $p = 0.008$) (Moen et al., 2021), and increases in sleep quality and duration ($r = 0.52$, $p < 0.001$; $r = 0.17$, $p < 0.001$) over a 9-month period (Haroldsdottir et al., 2021). Increases in sleep quality and duration were also associated with increased energy ($r = 0.387$, $p < 0.001$; ($r = 0.218$, $p < 0.001$) (Foster et al., 2023) and decreased soreness (Haroldsdottir et al., 2021), with increased sleep duration also being associated with increased recovery (b = 0.004 AU for every unit increase in sleep duration, $p = 0.048$) (Roberts et al., 2022). Mean sleep difficulty scores via the Athlete Sleep Screening Questionnaire (ASSQ) in female athletes at risk of low energy availability (7.8 ± 3.9AU) were significantly higher than sleep difficulty scores in female athletes not at risk of low energy availability (5.4 ± 1.4AU) via the Low Energy Availability in Female Athletes Questionnaire (LEAF-Q) ($p = 0.018$) (Coombes & Badenhorst, 2024). There were also associations between decreased sleep quality and illness (Horgan et al., 2021) and injury (Haroldsdottir et al., 2021; Horgan et al., 2021; Kilic et al., 2021) in female athletes over 3 months, 9 months, and a full competitive season. There were clear associations observed between increased resting heart rate and decreases in percentage of time spent in light sleep ($r = -0.65$, $p < 0.05$), increases in percentage of time spent in slow wave sleep ($r = 0.55$, $p < 0.05$), increased percentage time spent in REM sleep ($r = 0.20$, $p < 0.05$), increased total slow wave sleep ($r = 0.54$, $p < 0.05$) and REM sleep ($r = 0.21$, $p < 0.05$), as well as decreased sleep consistency ($r = -0.41$, $p < 0.05$) over an 84-day period (Sekiguchi et al., 2019). Conversely, increases in heart rate variability (HRV) were associated with increases in percentage time spent in light sleep ($r = 0.54$, $p < 0.05$), and total time spent in light sleep ($r = 0.38$, $p < 0.05$), as well as decreases in percentage time spent in slow wave sleep ($r = -0.62$, $p < 0.05$) and total time spent in slow wave sleep ($r = -0.61$, $p < 0.05$) (Sekiguchi et al., 2019).

Sleep was associated with training intensity in female athletes. Increased sleep duration and sleep efficiency was associated with decreased training impulse ($r = -0.25$, $p < 0.001$; $r = -0.20$, $p = 0.004$), and decreased sleep quality was associated with session rating of perceived exertion (s-RPE) ($r = 0.098$, $p < 0.05$) over a 54-day period (Roy et al., 2019). Increased sleep duration and sleep efficiency was also associated with decreased s-RPE ($r = -0.43$, $p < 0.001$; ($r = -0.17$, $p = 0.02$) (Costa et al., 2021). Greater subjective sleep quality in female athletes was associated with greater distances covered (parameter estimate change = 303.8m, $p = 0.019$), greater high-intensity distance covered (parameter estimate change = 64.2m, $p = 0.015$), and athlete load (parameter estimate change = 5.7AU, $p = 0.015$) over a 13-week monitoring period (Crouch et al., 2021). RPE ($\beta = 0.15$, $p = 0.002$), load ($\beta = -0.14$, $p = 0.004$) and mental fatigue ($\beta = -0.15$, $p < 0.001$) all had a significant effect on sleep duration following a training session in female collegiate soccer athletes (Long et al., 2024). Increases in workload metrics (via GPS) were associated with decreases in sleep duration, Sleep Score and Readiness Score (via commercially available wearable), average HRV was negatively associated with increases in training impulse (TRIMP), time > 80% HRmax, and average HR (%) (Merrigan et al., 2024). Decreases in Oviedo Sleep Questionnaire (OSQ) scores were associated with increased vertical jump ($r = -0.32$, $p < 0.05$), spike jump ($r = -0.33$, $p < 0.05$), and crunch test score ($r = -0.38$, $p < 0.05$) (Mielgo-Ayuso et al., 2017). However, some studies found no association between sleep and physical performance outcomes in female athletes (Costa et al., 2019; Doeven et al., 2019; Fernandes et al., 2021; Knufinke et al., 2018; Ressman et al., 2024).

### *3.6. Association between sleep and mood and subjective wellbeing*

Results from included studies in this category can be found in Table 6. In total, fourteen studies examined this association, with eight being of moderate quality, five of low quality, and one high quality study. One of the studies contained a competitive elite sample, with the remaining twelve studies containing semi-elite samples. The average sample size of these studies was $n = 110$ (range: 8 – 536). Five of the studies contained mixed-sex cohorts, while nine had all female cohorts. Sleep measurements used within this category included: sleep questionnaires (PSQI; ESS; ASSQ; Benjamin et al., 2020; Kawasaki et al., 2020; Silva & Paiva, 2019a; Silva & Paiva 2019b); Hooper Index/Questionnaire (Fernandes et al., 2021; Roy et al., 2019); subjective sleep quality (Foster et al., 2023; Haroldsdottir et al., 2021; Long et al., 2024); wrist actigraphy (O'Donnell et al., 2018a; Roberts et al., 2022; Romyn et al., 2016); and sleep diaries (Romyn et al., 2016).

Sleep duration and quality were significantly associated with stress in multiple studies ranging from 1 day of data collection to a full competitive season in duration, showing that improved sleep indices correlated with lower levels of stress (Foster et al., 2023; Haroldsdottir et al., 2021; Roy et al., 2019) as well as precompetitive stress (Silva & Paiva, 2019b) in female athletes. Increased PSQI scores were associated with increased tension; depression; anger; fatigue; confusion; and total mood disturbance over 3 competitive seasons of monitoring (Benjamin et al., 2020); as well as decreased physical functioning, general health perception, vitality, social functioning, and mental health, alongside increases in role limitations due to physical and emotional problems in a cross-sectional study (Kawasaki et al., 2020). However, one study found no association between sleep and mood variables over a 3-month period (Kilic et al., 2021).

## 4. Discussion

This systematic review targeted studies that examined the association between sleep and performance parameters in female athletes; namely, sport-specific performance; cognitive performance; physical performance, readiness, and availability;

Table 6: Results from studies examining the association between sleep and mood and subjective wellbeing in female athletes.

| | Sleep Measurement | Performance Measurement | Results |
|---|---|---|---|
| Benjamin et al., 2020 | PSQI | Profile of Mood States; Sports Anxiety Scale-2 | ↓ sleep quality associated with ↑ tension ($p < 0.001$), depression ($p < 0.001$), anger ($p < 0.001$), fatigue ($p < 0.001$), confusion ($p < 0.001$), total mood disturbance ($p < 0.001$); ↓ vigour ($p = 0.08$, not significant).<br>Decreased sleep quality associated with greater tension and anger in females compared to males ($p = 0.040$, $p = 0.010$, respectively). |
| Fernandes et al., 2021 | Hooper Index | Internal training load (CR-10 scale) | Moderate, non-significant association between ↑ sleep and ↑ stress ($r = 0.412$, $p > 0.05$). |
| Foster et al., 2023 | Metrifit athlete monitoring application | Metrifit athlete monitoring application | ↑ sleep quality associated with ↑ energy ($r = 0.387$, $p < 0.001$) and ↑ stress ($r = 0.255$, $p < 0.001$).<br>↑ sleep duration associated with ↑ energy ($r = 0.218$, $p < 0.001$) and ↑ stress ($r = 0.179$, $p < 0.001$).<br>(Larger numbers on Likert scale indicate positive effect, hence positive correlation with stress). |
| Haroldsdottir et al., 2021 | Likert scale 1-5 for sleep quality; sleep duration recorded via Metrifit app | Internal training load | ↑ sleep quality and duration associated with ↓ stress ($r = 0.26$ and $r = 0.08$, $p < 0.001$) and mood ($r = 0.40$ and $r = 0.06$, $p < 0.001$). |
| Kawasaki et al., 2020 | PSQI; ESS | Short form-8 | ↓ sleep quality associated with ↓ physical functioning, ↑ role limitations due to physical problems, ↓ general health perception, ↓ vitality, ↓ social functioning, ↑ role limitations due to emotional problems, and ↓ mental health. |
| Kilic et al., 2021 | Athlete Sleep Screening Questionnaire | Athlete Psychological Strain Questionnaire (APSQ) and Kessler-10 (K-10); Anxiety - General Anxiety Disorder-7 (GAD-7); Depression - PHQ-9 | No association between sleep disturbance and anxiety. |
| Koikawa et al., 2016 | PSQI; ESS | Short form-8 | Univariate analysis: low social functioning and mental health scores associated with female gender (OR = 2.92, $p = 0.020$; OR = 2.68, $p = 0.030$) and longer sleep duration (OR = 0.59, $p <= 0.020$; OR = 0.55, $p = 0.018$). Non-significant association with greater PSQI scores. |
| Long et al., 2024 | Self-report via mobile app for duration and quality | GPS; self-reported wellness via mobile app (1-10 scale) | Mood and mental stress did not have a significant effect on sleep duration ($p > 0.05$). |
| O’Donnell et al., 2018a | Wrist actigraphy | Perceived stress | ↓ sleep quality and duration following match compared night before game ($p < 0.05$). |
| Roberts et al., 2022 | Wrist actigraphy | Short recovery and stress scale (SRSS) | Sleep duration ↓ for every unit increase in emotional balance for model 3 (b = -28.7 min, $p = 0.02$) and model 5 (b = -31.3 min, $p = 0.01$) and negative emotional state for model 3 (b = -25.4 min, $p < 0.001$) and model 5 (b = -20.7 min, $p < 0.001$).<br>In model 9, WASO ↓ for every one unit increase in negative emotional state ($p = 0.049$) and ↑ for every unit increase in overall stress ($p = 0.02$). |
| Romyn et al., 2016 | Wrist actigraphy; Sleep diary | Tension/anxiety subscale of the Profile of Mood States | ↑ Perceived sleep quality associated with ↓ state anxiety ($r = -0.82$, $p < 0.05$) |
| Roy et al., 2019 | Hooper Questionnaire | Internal training load and fatigue | ↓ sleep quality associated with ↑ stress ($r = 0.383$, $p < 0.01$). |
| Silva & Paiva, 2019a | ESS; PSQI; bed and wake time of weekdays and weekend days | Sport Competition Anxiety Test form A (SCAT-A) | ≥ 24 SCAT-A score (95%IC 1.27 to 2.95, $p = 0.004$) associated with abnormal daytime sleepiness.<br>Reduced sleep duration observed in gymnasts with abnormal daytime sleepiness, reduced sleep quality and precompetitive anxiety, however no significant differences shown ($p > 0.05$). |
| Silva & Paiva, 2019b | ESS; PSQI; bed and wake time of weekdays and weekend days | Sport Competition Anxiety Test form A (SCAT-A) | ↑ sleep disturbance associated with ↓ sleep quality ($p = 0.014$) and ↑ precompetitive stress ($p < 0.01$).<br>↓ sleep quality associated with ↑ precompetitive stress ($p = 0.010$). |

*Notes: APSQ* = Athlete Psychological Strain Questionnaire; CSAI-2 = Competitive State Anxiety Inventory-2; GAD-7 = General Anxiety Disorder 7; IC = confidence interval; K-10 = Kessler-10; PCSP = Psychological Characteristics Related to Sport Performance; PHQ-9 = Patient Health Questionnaire 9; PHQ-15 = Patient Health Questionnaire 15; PSQI = Pittsburgh Sleep Quality Index; QOL = Quality of Life Questionnaire; SCAT = Sport Competition Anxiety Test; SCAT-A = Sport Competition Anxiety Test form - A; SF-8 = Short form-8; STAI = State-Trait Anxiety Inventory; WASO = wake after sleep onset; b = beta value indicating the change in outcome variable for each one-unit increase in the predictor variable.

and mood and subjective wellbeing. Thirty-eight studies met the inclusion criteria and were included in the review. Greater sleep quality and quantity was associated with improvements in a range of performance and subjective wellbeing outcomes examined in this review, with lesser sleep quality and quantity being associated with negative outcomes in both performance and subjective wellbeing outcomes. Making concentrated efforts to allow athletes to obtain more optimal sleep could be advantageous in aiding athletes to achieve their desired performance outcomes.

Quality assessment of the included studies found that many of the studies were of moderate quality (71%), with the remaining studies being of low quality (26%) apart from one high quality study. Studies were not excluded from this review based on quality rating or study design, to allow for maximal number of studies examining the association between sleep and female athletes to be included. Studies were of moderate and low quality largely due to some studies not monitoring sleep objectively alongside subjective measurement, as well as lack of control for both sleep and level of competition of the participants, resulting in lower scores on the modified NOS. These findings show a need for more high-quality research to be conducted in this area. Gupta et al. (2017) also reported on the limited quality of the majority investigating sleep in elite athletes, finding the quality of studies examining characteristics of sleep among elite athletes was low in 62% of studies. Similarly, Miles et al. (2022) reported 82% of studies examining the sleep of female athletes were of moderate study quality.

Methodological guidelines have been outlined in recent publications to improve research in sport and exercise science with female participants (Elliott-Sale et al., 2021); for example, recording hormonal contraceptive use or whether the participants were naturally and regularly menstruating or amenorrhoeic. Three of the studies in this review examined aspects of the menstrual cycle (MC) including regularity, phase and hormonal contraceptive use, as well as delayed menarche. Symptoms of the MC such as mood changes and anxiety could be related to sleep disruption or loss in exercising females (Bruinvels et al., 2021). There have also been reported alterations to sleep architecture with the cyclic fluctuations of oestrogen and progesterone throughout the MC, as well as sleep disturbances related to fluctuating body temperature as a result of the menstrual cycle (Baker & Lee, 2018). Future studies should consider the MC phases and symptoms, hormonal contraceptive use and other factors related to the MC.

Classification of competition level showed that 74% of the studies were conducted using semi-elite cohorts, with the remaining studies using competitive elite cohorts. This is a lower level of competition than in studies reviewed by Gupta et al. (2017), where 54% of the studies were judged to have recruited competitive elite athletes. This could be due to the inclusion of male participants in these studies. Inclusion of male athletes in sleep and performance research could allow for larger sample sizes given that there may be increased opportunity to recruit professional athletes in a wide range of sports to participate. Future research in sleep and performance of female athletes should be conducted in high-level (competitive elite) cohorts if possible. Further research in this area will allow practitioners to better understand the associations between sleep and performance in elite female athletic cohorts and will inform evidence-based sleep intervention. Studies found varying associations between sleep, performance, and subjective wellbeing. Percentages of studies in each category showing various associations can be found outlined through this section of the review.

### *4.1. Association between sleep and sport-specific performance*

Eight out of the nine (89%) studies investigating sleep and sport-specific performance found that improved sleep indices were associated with improved or superior sport-specific performance outcomes for female athletes. While one study found contrasting findings showing that number of sleep hours per day was negatively associated with performance. The most examined performance outcome was in competition scores and rankings for both team and individual sports. Four of the studies in this area examined sleep objectively through wrist actigraphy; however, only one of these four studies also employed sleep diaries. Sleep diaries are useful for both the subjective measure of sleep from the participant but also to confirm approximate sleep and wake times, as well as if naps take place. Other sleep measurements included wellness surveys, as well as validated sleep questionnaires in the ESS and PSQI.

Six studies showed that sleep duration and quality had a positive effect on the performance of the athletes (Dumortier et al., 2018; Grace et al., 2023; Juliff et al., 2018; Reyner & Horne, 2013; Silva & Paiva, 2016; Staunton et al., 2017), with one finding that lower performances were often associated with poor sleep quality (Silva & Paiva, 2019b). Juliff et al. (2018) found that top performing teams in netball competition had higher sleep duration, time in bed and subjective sleep rating than those who were placed at the bottom of the competition rankings. Netball athletes have been reported to obtain more sleep on the night before a game compared to the night of a game (O'Donnell et al., 2018b). This could be an attempt by athletes to obtain more sleep before competition, but care needs to be taken to ensure athletes obtain adequate sleep to elicit sufficient recovery from competition, which may be of particular importance at major international tournaments where competition schedules can be condensed. Senbel et al. (2022) identified that sleep need, sleep debt hours and weekly sleep duration were ranked in the top ten features affecting performance in collegiate basketball players, with positive correlations for each variable and player efficiency. However, Tsukahara et al. (2022) reported that number of sleep hours per day was associated with lower International Association of Athletics Federation (IAAF) scores in track and field athletes. This contrasting finding, with increased sleep hours associated with decreased performance, provides rationale for further research in female athletic cohorts' sleep and sport-specific performance. It should be noted that within applied research of elite athletic cohorts, confounding variables (e.g. nutrition, injury, travel) are common and could have an impact on the performance of an athlete in competition.

Collectively, the evidence demonstrates that sleep has a clear positive association with improved sport-specific performance outcomes in female athletes. This shows that sleep not only can have an impact on the key performance indicators associated with sporting performance, but differences in sleep duration and quality can have a direct impact on actual competition outcomes and scores for athletes.

### *4.2. Association between sleep and cognitive performance*

Only two studies in this review examined the relationship between sleep and cognitive performance. One of the studies showed a positive association between sleep and performance outcomes, with the other showing that negative sleep outcomes are associated with negative performance outcomes. Akazawa et al. (2019) examined the impacts of sleep quality on cognitive performance, finding that reaction time in the Stroop Test was faster in the better sleep quality group during high-intensity exercise compared to the lesser sleep quality group. Taheri and Irandoust (2020) utilised interventions in the form of partial sleep deprivation (athletes slept for 3h), finding performance measures to be impaired in the sleep deprivation group but not in the group that completed exercise prior to the cognitive assessment on the morning post-sleep deprivation. Both studies showed the positive effect of increased sleep quality and duration on performance. The results from Taheri and Irandoust (2020) are similar to previous findings showing acute physical exercise improves cognitive performance in a mixed-sex cohort of college-aged students (Chang et al., 2014). This provides evidence that exercise can be a combatant to the negative effects of sleep loss on athletic populations. In a review of sleep hygiene and optimal recovery in athletes, Vitale et al. (2019) concluded that focus should be placed on obtaining more sleep rather than prioritising training time, however the findings of Taheri and Irandoust (2020) may offer a possible alternative if optimal sleep durations cannot be achieved due to circumstances often faced in elite sport, such as travel and competition/training schedule.

### *4.3. Association between sleep and physical performance, readiness, and availability*

An interesting finding in relation to female athlete sleep is that although females have been shown to have objectively better sleep quality (less time awake during the night and higher sleep efficiency) than their male counterparts (Leeder et al., 2012), they report worse sleep quality when measured subjectively (Schaal et al., 2011). These findings are in line with the reported paradox in female sleep, where females tend to report inferior subjective sleep compared to males, while obtaining superior objective sleep (Hrozanova et al., 2021). For this reason, this review was not confined to just objective measures of sleep and included subjective measures also.

Only one study in this systematic review was rated as high quality using the adapted NOS used in the quality appraisal of studies examining this aspect of performance (Kilic et al., 2021). This study examined injury in the previous six months and sleep disturbances, finding that the two were associated with one another. However, all other studies of sleep and the association with physical performance, readiness, and availability were of moderate or low quality.

Of the twenty-one studies in this category, eight (38%) found positive associations between sleep improved sleep and performance, seven (33%) found negative associations between impaired sleep and performance, while six (29%) found no association between sleep outcomes and performance. When investigating the relationship between sleep and readiness and availability, this review found varying effects of sleep relating to external and internal training load variables (e.g., total distance covered, training impulse, s-RPE, fatigue). Perceived fatigue in female athletes was associated with less sleep, particularly less REM sleep hours (Moen et al., 2021) as well as lower total sleep time and sleep efficiency (Barreira et al., 2022). Fatigue was increased with decreases in sleep quality (Roy et al., 2019), which was also associated with increases in s-RPE, and muscle soreness. Workload metrics such as TRIMP, total distance, training duration, and time spent in HR of greater than and less than 80% of max HR, were all associated with lesser sleep duration (Merrigan et al., 2024). Care must be taken when managing the objective and subjective workload of athletes when attempting to achieve more optimal sleep. Both perceived fatigue and increases in workload metrics have been shown to have a significant impact on the following night's sleep (Long et al., 2024; Merrigan et al., 2024). This could be of particular importance when preparing for competition or attempting to both train and compete at a high level in a condensed competition schedule.

Poorer sleep quality was identified as a predictor of illness both seven and twenty-eight days prior to an illness event by Horgan et al. (2021), which is similar to findings in male athletes where poorer sleep quality and less sleep duration was associated with greater odds of illness in both the short term and long term (Fitzgerald et al., 2019). It was also reported that athletes at risk of low energy availability (LEA) had significantly higher sleep difficulty scores via the ASSQ than those who were not at risk of LEA (Coombes et al., 2024). Increasing sleep opportunity in female athletic cohorts could lead to decreases in perceived fatigue and improvements of the athlete’s feeling of readiness to compete or train on any given day. This also may lead to improvements in availability and decrease time missed through illness. The importance of sleep for optimal readiness and performance provides rationale for good sleep hygiene strategies in this cohort. Improved sleep hygiene through education seminars has been shown to increase time in bed and therefore sleep opportunity in professional rugby league athletes, by eliciting earlier sleep times and later wake times (Caia et al., 2018). Driller et al. (2019) found that sleep efficiency, sleep latency, sleep onset variance were improved from pre- to post-intervention of sleep education sessions in male cricket athletes, while O’Donnell et al. (2017) reported a significant increase in total sleep time in elite female athletes following a one-hour sleep hygiene education session.

Mielgo-Ayuso et al. (2017) examined the impact of sleep on jump performance, measuring sleep through the OSQ to determine the impact of sleep on vertical and spike jump performance. This study identified a positive influence of sleep on jump performance in the form of vertical and spike jump score improvements. In a study of male cyclists, Mah et al. (2019) found that maximal vertical jump decreased following sleep restriction. Athletes’ sleep was decreased from 7 hours to 4 hours, with significant detrimental effects being shown for both maximal vertical jump as well as slower psychomotor vigilance task response time. With these results linking sleep and jumping performance in athletes, those competing in sport where jump performance is a key performance indicator should take measures to attempt to optimise athlete sleep.

In other research of sleep and physical performance, it has also been shown in male cycling time trials that performance is hindered in those who had their sleep restricted compared to performance with normal sleep and compared to those who have had extended sleep (Roberts et al., 2019), with performance deteriorating as the number of days of sleep restriction increased. Performance in this study was unaffected by one night of sleep restriction but began to deteriorate over subsequent days. This is an indication of the problems faced by athletes who experience sleep loss on a consistent basis. These athletes may be more at risk of negative implications on their performance over time than those who experience only one night of disturbed sleep. This finding should encourage the analysis of sleep and performance over a more prolonged period.

### *4.4. Association between sleep and mood and subjective wellbeing*

Psychological mood and subjective wellbeing of athletes is important for training and competition, with emotions experienced before and during sports competition influencing sports performance (Lane et al., 2012). The selected studies in this review that examine the relationship between sleep and subjective wellbeing in female athletes support the conclusion that disrupted sleep or less sleep is correlated with greater mood disturbances in stress, anger, depression, confusion, and tension. Three of the studies (21%) found that positive sleep outcomes were associated with positive mood and subjective wellbeing outcomes while seven studies (50%) found negative sleep outcomes to be associated with negative mood and subjective wellbeing outcomes. Two studies (14.5%) found no association between sleep and mood and subjective wellbeing variables, while two studies (14.5%) found contrasting findings indicating that increases in sleep outcomes were associated with negative mood and subjective wellbeing outcomes. This finding supports the current literature surrounding sleep quality and mood. In a mixed cohort, confusion, fatigue, and tension have been shown to be detrimental to sleep quality, while vigour has been shown to reduce the likelihood of poor sleep (Andrade et al., 2019). All mood and subjective wellbeing variables were measured subjectively. In the case of stress, there is opportunity for objective measurement through a method such as examining salivary cortisol (Bozovic et al., 2013), which may yield different results to that of perceived stress in athletes.

Subjective wellbeing and sleep can impact each other, in that less sleep can increase the severity of negative mood variables (such as confusion, tension, fatigue), and these variables can have a negative impact on sleep. An example of this is increased pre-competition stress in athletes, especially before and during important competitions. Silva and Paiva (2016) found that increased sleep disturbance was associated with increases in precompetitive stress, which is similar to previous findings in elite male and female German athletes (Erlacher et al., 2011). Negative mood variables such as fatigue and tension were both significantly negatively correlated with pre-competitive sleep quality and total sleep time in a mixed cohort of athletes (Lastella et al., 2014).

### *4.5. Limitations*

The present review did not exclude studies based on methodological quality, allowing for studies that scored low in quality appraisal to be included in the review. This was deemed a necessary limitation, as the research examining the sleep and performance of female athletes and athletes in general is relatively scarce and generally low in quality. Excluding studies based on quality would have left very few studies remaining to be included in this review. The aim of this systematic review was to review all the evidence and literature that met the inclusion criteria and was not limited to only high-quality research. This review included only articles published in the English language in peer-reviewed journals.

## Conclusion

Relatively few studies have reported the effects of sleep on performance in female athletes. The studies included in this review support the conclusion that lower sleep duration and quality are associated with negative performance and subjective wellbeing outcomes in female athletes, while greater sleep duration and quality are associated with positive performance and subjective wellbeing outcomes. Superior sleep duration and quality has repeatedly been reported to be associated with superior performance in female athletes from various sports, with associations shown with sport-specific performance; cognitive performance; physical performance, readiness and availability; and mood and subjective wellbeing. Some of the strongest associations between sleep and outcome variables were with respect to finishing place in competition or competition ranking, and the association of decreased sleep with increased levels of fatigue. Given the association of sleep with subjective wellbeing and performance, efforts should be made by both athletes and their support staff to optimise sleep where possible. Optimal sleep hygiene practices and planning of training times to allow for maximal sleep opportunity could be of benefit in this regard.

However, within the included studies there is a lack of methodological consistency, where studies examine both sleep and performance parameters through a variety of methods. Collectively, there is very limited high-quality research in sleep and performance in female athletes. An emerging theme from this review is the lack of consideration of the MC in studies examining the sleep and performance of female athletes, with only three included studies doing so. Future research of the sleep and performance of female athletes, and any research including female athletes, should include the monitoring of the MC, MC symptoms, and/or hormonal contraception use to improve methodological quality of the research.

## Conflict of Interest

The authors declare no conflict of interests.

## References

Akazawa, N., Kobayashi, N., Nakamura, Y., Kumagai, H., Choi, Y., & Maeda, S. (2019). Effect of sleep efficiency on salivary metabolite profile and cognitive function during exercise in volleyball athletes. *European Journal of Applied Physiology*, *119*(10), 2215–2223. https://doi.org/10.1007/s00421-019-04205-7

Andrade, A., Bevilacqua, G., Casagrande, P., Brandt, R., & Reis Coimbra, D. (2018). Sleep quality associated with mood in elite athletes. *The Physician and Sports Medicine*, *47*(3), 312–317. https://doi.org/10.1080/00913847.2018.1553467

Baker, F. C., & Driver, H. S. (2004). Self-reported sleep across the menstrual cycle in young, healthy women. *Journal of Psychosomatic Research*, *56*(2), 239–243. https://doi.org/10.1016/S0022-3999(03)00067-9

Baker, F. C., & Lee, K. A. (2018). Menstrual cycle effects on sleep. *Sleep Medicine Clinics*, *13*(3), 283–294. https://doi.org/10.1016/j.jsmc.2018.04.002

Barreira, J., Brito, J., Costa, J. A., & Figueiredo, P. (2024). Sleep duration is associated with overnight changes in perceived fatigue in elite women soccer players. *Science & Medicine in Football*, *8*(2), 145–152. https://doi.org/10.1080/24733938.2022.2163511

Benjamin, C. L., Curtis, R. M., Huggins, R. A., Sekiguchi, Y., Jain, R. K., McFadden, B. A., & Casa, D. J. (2020). Sleep Dysfunction and Mood in Collegiate Soccer Athletes. *Sports Health*, *12*(3), 234–240. https://doi.org/10.1177/1941738120916735

Bozovic, D., Racic, M., & Ivkovic, N. (2013). Salivary cortisol levels as a biological marker of stress reaction. *Medical Archives (Sarajevo, Bosnia and Herzegovina)*, *67*(5), 374–377. https://doi.org/10.5455/medarh.2013.67.374-377

Brito, M. A., Fernandes, J. R., Esteves, N. S., Müller, V. T., Alexandria, D. B., Pérez, D. I. V., Slimani, M., Brito, C. J., Bragazzi, N. L., & Miarka, B. (2022). The effect of neurofeedback on the reaction time and cognitive performance of athletes: A systematic review and meta-analysis. *Frontiers in Human Neuroscience*, *16*, 1–12. https://doi.org/10.3389/fnhum.2022.868450

Bruinvels, G., Goldsmith, E., Blagrove, R., Simpkin, A., Lewis, N., Morton, K., Suppiah, A., Rogers, J. P., Ackerman, K. E., Newell, J., & Pedlar, C. (2021). Prevalence and frequency of menstrual cycle symptoms are associated with availability to train and compete: A study of 6812 exercising women recruited using the Strava exercise app. *British Journal of Sports Medicine*, *55*(8), 438–443. https://doi.org/10.1136/bjsports-2020-102792

Caia, J., Scott, T. J., Halson, S. L., & Kelly, V. G. (2018). The influence of sleep hygiene education on sleep in professional rugby league athletes. *Sleep Health*, *4*(4), 364–368. https://doi.org/10.1016/j.sleh.2018.05.002

Chang, Y.-K., Chi, L., Etnier, J. L., Wang, C.-C., Chu, C.-H., & Zhou, C. (2014). Effect of acute aerobic exercise on cognitive performance: Role of cardiovascular fitness. *Psychology of Sport and Exercise*, *15*(5), 464–470. https://doi.org/10.1016/j.psychsport.2014.04.007

Consensus Conference Panel, Watson, N. F., Badr, M. S., Belenky, G., Bliwise, D. L., Buxton, O. M., Buysse, D., Dinges, D. F., Gangwisch, J., Grandner, M. A., Kushida, C., Malhotra, R. K., Martin, J. L., Patel, S. R., Quan, S. F., & Tasali, E. (2015). Joint consensus statement of the American Academy of Sleep Medicine and Sleep Research Society on the recommended amount of sleep for a healthy adult: Methodology and discussion. *Sleep*, *38*(8), 1161–1183. https://doi.org/10.5665/sleep.4886

Coombes, I., & Badenhorst, C. (2024). Risk of low energy availability in New Zealand National Team and U20 Female Football Representatives. *Women in Sport and Physical Activity Journal*, *32*, 1-8. https://doi.org/10.1123/wspaj.2023-0041

Costa, J. A., Figueiredo, P., Nakamura, F. Y., Rebelo, A., & Brito, J. (2021). Monitoring individual sleep and nocturnal heart rate variability indices: The impact of training and match schedule and load in high-level female soccer players. *Frontiers in Physiology*, *12*, 1-10. https://doi.org/10.3389/fphys.2021.678462

Costa, J., Figueiredo, P., Nakamura, F., Rago, V., Rebelo, A., & Brito, J. (2019). Intra-individual variability of sleep and nocturnal cardiac autonomic activity in elite female soccer players during an international tournament. PLoS One, 14(9), 1-19. https://doi.org/10.1371/journal.pone.0218635

Crouch, A. K., Jiroutek, M. R., Snarr, R. L., & Bunn, J. A. (2021). Relationship between pre-training wellness scores and internal and external training loads in a Division I women's lacrosse team. *Journal of Sports Sciences*, *39*(9), 1070–1076. https://doi.org/10.1080/02640414.2020.1857106

Doeven, S. H., Brink, M. S., Huijgen, B. C. H., de Jong, J., & Lemmink, K. A. P. M. (2019). High match load's relation to decreased well-being during an Elite Women's Rugby Sevens Tournament. *International Journal of Sports Physiology and Performance*, *14*(8), 1036–1042. https://doi.org/10.1123/ijspp.2018-0516

Driller, M. W., Lastella, M., & Sharp, A. P. (2019). Individualized sleep education improves subjective and objective sleep indices in elite cricket athletes: A pilot study. *Journal of Sports Sciences*, *37*(17), 2121–2125. https://doi.org/10.1080/02640414.2019.1616900

Dumortier, J., Mariman, A., Boone, J., Delesie, L., Tobback, E., Vogelaers, D., & Bourgois, J. G. (2018). Sleep, training load and performance in elite female gymnasts. *European Journal of Sport Science*, *18*(2), 151–161. https://doi.org/10.1080/17461391.2017.1389992

Elliott-Sale, K. J., Minahan, C. L., de Jonge, X. A. K. J., Ackerman, K. E., Sipilä, S., Constantini, N. W., Lebrun, C. M., & Hackney, A. C. (2021). Methodological Considerations for Studies in Sport and Exercise Science with Women as Participants: A Working Guide for Standards of Practice for Research on Women. *Sports Medicine (Auckland, N.Z.)*, *51*(5), 843–861. https://doi.org/10.1007/s40279-021-01435-8

Erlacher, D., Ehrlenspiel, F., Adegbesan, O. A., & El-Din, H. G. (2011). Sleep habits in German athletes before important competitions or games. *Journal of Sports Sciences*, *29*(8), 859–866. https://doi.org/10.1080/02640414.2011.565782

Fernandes, R., Brito, J. P., Vieira, L. H. P., Martins, A. D., Clemente, F. M., Nobari, H., Reis, V. M., & Oliveira, R. (2021). In-Season Internal Load and Wellness Variations in Professional Women Soccer Players: Comparisons between Playing Positions and Status. *International Journal of Environmental Research and Public Health*, *18*(23), 12817. https://doi.org/10.3390/ijerph182312817

Fitzgerald, D., Beckmans, C., Joyce, D., & Mills, K. (2019). The influence of sleep and training load on illness in nationally competitive male Australian Football athletes: A cohort study over one season. *Journal of Science and Medicine in Sport*, *22*(2), 130–134. https://doi.org/10.1016/j.jsams.2018.06.011

Foster, E., Schumann, C., & Bunn, J. A. (2023). Sleep, energy, and stress in collegiate female volleyball athletes. *TRENDS in Sport Sciences*, *30*(3). https://tss.awf.poznan.pl/Sleep-Energy-and-Stress-in-Collegiate-Female-Volleyball-Athletes,169475,0,2.html

Fullagar, H. H. K., Skorski, S., Duffield, R., Hammes, D., Coutts, A. J., & Meyer, T. (2015). Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Medicine (Auckland, N.Z.)*, *45*(2), 161–186. https://doi.org/10.1007/s40279-014-0260-0

Gupta, L., Morgan, K., & Gilchrist, S. (2017). Does elite sport degrade sleep quality? A systematic review. *Sports Medicine*, *47*(7), 1317–1333. https://doi.org/10.1007/s40279-016-0650-6

Haraldsdottir, K., Sanfilippo, J., McKay, L., & Watson, A. (2021). Decreased sleep and subjective well-being as independent predictors of injury in female collegiate volleyball players. *Orthopaedic Journal of Sports Medicine*, *9*, 1-7. https://doi.org/10.1177/23259671211029285

Hirshkowitz, M., Whiton, K., Albert, S. M., Alessi, C., Bruni, O., DonCarlos, L., Hazen, N., Herman, J., Adams Hillard, P. J., Katz, E. S., Kheirandish-Gozal, L., Neubauer, D. N., O'Donnell, A. E., Ohayon, M., Peever, J., Rawding, R., Sachdeva, R. C., Setters, B., Vitiello, M. V., & Ware, J. C. (2015). National Sleep Foundation's updated sleep duration recommendations: Final report. *Sleep Health*, *1*(4), 233–243. https://doi.org/10.1016/j.sleh.2015.10.004

Horgan, B. G., Drew, M. K., Halson, S. L., Piromalli, L. E., Drinkwater, E. J., Chapman, D. W., & Haff, G. G. (2021). Impaired recovery is associated with increased injury and illness: A retrospective study of 536 female netball athletes. *Scandinavian Journal of Medicine & Science in Sports*, *31*(3), 691–701. https://doi.org/10.1111/sms.13866

Hrozanova, M., Klöckner, C. A., Sandbakk, Ø., Pallesen, S., & Moen, F. (2021). Sex differences in sleep and influence of the menstrual cycle on women's sleep in junior endurance athletes. *PLoS ONE*, *16*(6), 1-18. https://doi.org/10.1371/journal.pone.0253376

Juliff, L. E., Halson, S. L., Hebert, J. J., Forsyth, P. L., & Peiffer, J. J. (2018). Longer sleep durations are positively associated with finishing place during a national multiday netball competition. *Journal of Strength and Conditioning Research*, *32*(1), 189–194. https://doi.org/10.1519/JSC.0000000000001793

Kawasaki, Y., Kasai, T., Koikawa, N., Hanazato, N., Suda, S., Murata, A., Ozaki, R., Nagai, S., Matsumura, Y., Kaneko, H., Kubo, M., Osawa, A., Nojiri, S., Ogasawara, E., Sakuraba, K., Daida, H., Kitade, M., & Itakura, A. (2019). Sex differences in factors associated with poor subjective sleep quality in athletes. *The Journal of Sports Medicine and Physical Fitness*, *60*(1), 140–151. https://doi.org/10.23736/S0022-4707.19.09875-X

Kilic, Ö., Carmody, S., Upmeijer, J., Kerkhoffs, G. M. M. J., Purcell, R., Rice, S., & Gouttebarge, V. (2021). Prevalence of mental health symptoms among male and female Australian professional footballers. *BMJ Open Sport & Exercise Medicine*, *7*(3), 1-7. https://doi.org/10.1136/bmjsem-2021-001043

Knufinke, M., Nieuwenhuys, A., Geurts, S. A. E., Møst, E. I. S., Maase, K., Moen, M. H., Coenen, A. M. L., & Kompier, M. A. J. (2018). Train hard, sleep well? Perceived training load, sleep quantity and sleep stage distribution in elite level athletes. *Journal of Science and Medicine in Sport*, *21*(4), 427–432. https://doi.org/10.1016/j.jsams.2017.07.003

Koikawa, N., Shimada, S., Suda, S., Murata, A., & Kasai, T. (2016). Sex differences in subjective sleep quality, sleepiness, and health-related quality of life among collegiate soccer players. *Sleep and Biological Rhythms*, *14*(4), 377–386. https://doi.org/10.1007/s41105-016-0068-4

Kullik, L., Stork, M., Kiel, A., Kellmann, M., & Jakowski, S. (2024). The prevalence of menstrual cycle symptoms and their association with mental health and sleep in German exercising women and athletes. *Journal of Science and Medicine in Sport*, *27*(6), 362–367. https://doi.org/10.1016/j.jsams.2024.02.008

Lane, A. M., Beedie, C. J., Jones, M. V., Uphill, M., & Devonport, T. J. (2012). The BASES expert statement on emotion regulation in sport. *Journal of Sports Sciences*, *30*(11), 1189–1195. https://doi.org/10.1080/02640414.2012.693621

Lastella, M., Lovell, G. P., & Sargent, C. (2014). Athletes' precompetitive sleep behaviour and its relationship with subsequent precompetitive mood and performance. *European Journal of Sport Science*, *14*(1), 123–130. https://doi.org/10.1080/17461391.2012.660505

Leeder, J., Glaister, M., Pizzoferro, K., Dawson, J., & Pedlar, C. (2012). Sleep duration and quality in elite athletes measured using wristwatch actigraphy. *Journal of Sports Sciences*, *30*(6), 541–545. https://doi.org/10.1080/02640414.2012.660188

Long, J. W., Brown, D., Farrell, J., Gonzalez, M., & Cheever, K. (2024). Relationship between Workload, Psychological State and Recovery in Female Soccer Athletes. *International Journal of Sports Medicine*, 45(11), 829–836. https://doi.org/10.1055/a-2304-3694

Mah, C. D., Sparks, A. J., Samaan, M. A., Souza, R. B., & Luke, A. (2019). Sleep restriction impairs maximal jump performance and joint coordination in elite athletes. *Journal of Sports Sciences*, *37*(17), 1981–1988. https://doi.org/10.1080/02640414.2019.1612504

Manber, R., & Armitage, R. (1999). Sex, steroids, and sleep: A review. *Sleep*, *22*(5), 540–555.

Merrigan, J. J., Stone, J. D., Kraemer, W. J., Friend, C., Lennon, K., Vatne, E. A., & Hagen, J. A. (2024). Analysis of sleep, nocturnal physiology, and physical demands of NCAA Women's Ice Hockey across a championship season. *Journal of Strength and Conditioning Research*, *38*(4), 694–703. https://doi.org/10.1519/JSC.0000000000004678

Michelekaki, E. A., Michaelides, M., Govindasamy, K., & Parpa, K. (2023). Recreational female athletes' understanding of and perceived impact of the menstrual cycle on physical performance, mood, and sleeping behaviour. *Women*, *3*(3), 445-456. https://doi.org/10.3390/women3030034

Mielgo-Ayuso, J., Zourdos, M. C., Clemente-Suárez, V. J., Calleja-González, J., & Shipherd, A. M. (2017). Can psychological well-being scales and hormone levels be used to predict acute performance of anaerobic training tasks in elite female volleyball players? *Physiology & Behavior*, *180*, 31–38. https://doi.org/10.1016/j.physbeh.2017.08.008

Miles, K. H., Clark, B., Fowler, P. M., Miller, J., & Pumpa, K. L. (2022). What are the sleep characteristics of elite female athletes? A systematic review with meta-analysis. *Biology of Sport*, *39*(3), 751–763. https://doi.org/10.5114/biolsport.2022.108705

Moen, F., Olsen, M., Halmøy, G., & Hrozanova, M. (2021). Variations in elite female soccer players' sleep, and associations with perceived fatigue and soccer games.

*Frontiers in Sports and Active Living*, *3*, 1-11. https://doi.org/10.3389/fspor.2021.694537

O'Donnell, S., Beaven, C., & Driller, M. (2018). Sleep/wake behavior prior to and following competition in elite female netball athletes. *Sport Sciences for Health*, *14*, 1-7. https://doi.org/10.1007/s11332-017-0425-y

O'Donnell, S., Bird, S., Jacobson, G., & Driller, M. (2018). Sleep and stress hormone responses to training and competition in elite female athletes. *European Journal of Sport Science*, *18*(5), 611–618. https://doi.org/10.1080/17461391.2018.1439535

O'Donnell, S., & Driller, M. W. (2017). Sleep-hygiene education improves sleep indices in elite female athletes. *International Journal of Exercise Science*, *10*(4), 522–530.

Oliver, S. J., Costa, R. J. S., Laing, S. J., Bilzon, J. L. J., & Walsh, N. P. (2009). One night of sleep deprivation decreases treadmill endurance performance. *European Journal of Applied Physiology*, *107*(2), 155–161. https://doi.org/10.1007/s00421-009-1103-9

Pacetti-Donelson, V. (2023, November 3). Associations between game outcome, game location, and wellness in Division I Women's Lacrosse athletes. *The Sport Journal*. https://thesportjournal.org/article/associations-between-game-outcome-game-location-and-wellness-in-division-i-womens-lacrosse-athletes/

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, 1–9. https://doi.org/10.1136/bmj.n71

Raysmith, B. P., Jacobsson, J., Drew, M. K., & Timpka, T. (2019). What is performance? A scoping review of performance outcomes as study endpoints in athletics. *Sports*, *7*(3), 1-14. https://doi.org/10.3390/sports7030066

Ressman, J., von Rosen, P., Grooten, W. J. A., & Rasmussen-Barr, E. (2024). Factors associated with the single leg squat test in female soccer players: A cross-sectional study. *BMC Sports Science, Medicine & Rehabilitation*, *16*(1), 1-14. https://doi.org/10.1186/s13102-024-00853-1

Reyner, L. A., & Horne, J. A. (2013). Sleep restriction and serving accuracy in performance tennis players, and effects of caffeine. *Physiology & Behavior*, *120*, 93–96. https://doi.org/10.1016/j.physbeh.2013.07.002

Roberts, S. S. H., Falkenberg, E., Stevens, A., Aisbett, B., Lastella, M., & Condo, D. (2021). The sleep of elite Australian Rules Footballers during preseason: A comparison of men and women. *International Journal of Sports Physiology and Performance*, *16*(5), 641–646. https://doi.org/10.1123/ijspp.2020-0340

Roberts, S. S. H., Main, L. C., Condo, D., Carr, A., Jardine, W., Urwin, C., Convit, L., Rahman, S. S., & Snipe, R. M. J. (2022). Sex differences among endurance athletes in the pre-race relationships between sleep, and perceived stress and recovery. *Journal of Sports Sciences*, *40*(14), 1542–1551. https://doi.org/10.1080/02640414.2022.2091345

Roberts, S. S. H., Teo, W.-P., Aisbett, B., & Warmington, S. A. (2019). Extended sleep maintains endurance performance better than normal or restricted sleep. *Medicine and Science in Sports and Exercise*, *51*(12), 2516–2523. https://doi.org/10.1249/MSS.0000000000002071

Romyn, G., Robey, E., Dimmock, J. A., Halson, S. L., & Peeling, P. (2016). Sleep, anxiety and electronic device use by athletes in the training and competition environments. *European Journal of Sport Science*, *16*(3), 301–308. https://doi.org/10.1080/17461391.2015.1023221

Roy, X., Comtois, A. S., & Sercia, P. (2019). Relationship between daily training loads and perceptions of wellness in Canadian university volleyball athletes. *Journal of Australian Strength and Conditioning*, *27*(7), 8–12.

Sargent, C., Lastella, M., Halson, S. L., & Roach, G. D. (2014). The impact of training schedules on the sleep and fatigue of elite athletes. *Chronobiology International*, *31*(10), 1160–1168. https://doi.org/10.3109/07420528.2014.957306

Schaal, K., Tafflet, M., Nassif, H., Thibault, V., Pichard, C., Alcotte, M., Guillet, T., El Helou, N., Berthelot, G., Simon, S., & Toussaint, J.-F. (2011). Psychological balance in high level athletes: Gender-based differences and sport-specific patterns. *PLoS ONE*, *6*(5), 1-9. https://doi.org/10.1371/journal.pone.0019007

Sekiguchi, Y., Adams, W. M., Benjamin, C. L., Curtis, R. M., Giersch, G. E. W., & Casa, D. J. (2019). Relationships between resting heart rate, heart rate variability and sleep characteristics among female collegiate cross-country athletes. *Journal of Sleep Research*, *28*(6), 1-7. https://doi.org/10.1111/jsr.12836

Senbel, S., Sharma, S., Raval, M., Taber, C., Nolan, J., Artan, N. S., Ezzeddine, D., & Kaya, T. (2022). Impact of sleep and training on game performance and injury in Division-1 Women's Basketball amidst the pandemic. *IEEE Access*, *10*(177), 15516–15527. https://doi.org/10.1109/ACCESS.2022.3145368

Silva, M.-R. G., & Paiva, T. (2016). Poor precompetitive sleep habits, nutrients' deficiencies, inappropriate body composition and athletic performance in elite gymnasts. *European Journal of Sport Science*, *16*(6), 726–735. https://doi.org/10.1080/17461391.2015.1103316

Silva, M.-R., & Paiva, T. (2019a). Risk factors for precompetitive sleep behavior in elite female athletes. *The Journal of Sports Medicine and Physical Fitness*, *59*(4), 708–716. https://doi.org/10.23736/S0022-4707.18.08498-0

Silva, M.-R. G., & Paiva, T. (2019b). Sleep, energy disturbances and pre-competitive stress in female traveller athletes. *Sleep Science*, *12*(4), 279–286. https://doi.org/10.5935/1984-0063.20190093

Skein, M., Duffield, R., Edge, J., Short, M. J., & Mündel, T. (2011). Intermittent-sprint performance and muscle glycogen after 30 h of sleep deprivation. *Medicine and Science in Sports and Exercise*, *43*(7), 1301–1311. https://doi.org/10.1249/MSS.0b013e31820abc5a

Staunton, C., Gordon, B., Custovic, E., Stanger, J., & Kingsley, M. (2017). Sleep patterns and match performance in elite Australian basketball athletes. *Journal of Science and Medicine in Sport*, *20*(8), 786–789. https://doi.org/10.1016/j.jsams.2016.11.016

Swann, C., Moran, A., & Piggott, D. (2015). Defining elite athletes: Issues in the study of expert performance in sport psychology. *Psychology of Sport and Exercise*, *16*, 3–14. https://doi.org/10.1016/j.psychsport.2014.07.004

Taheri, M., & Irandoust, K. (2020). Morning exercise improves cognitive performance decrements induced by partial sleep deprivation in elite athletes. *Biological Rhythm Research*, *51*(4), 644–653. https://doi.org/10.1080/09291016.2019.1576279

Teece, A. R., Beaven, M., Argus, C. K., Gill, N., & Driller, M. W. (2023). Comparing perceived sleep quality, practices, and behaviors of male and female elite Rugby Union athletes with the use of sleep questionnaires. *Sleep Science (Sao Paulo, Brazil)*, *16*(3), e271–e277. https://doi.org/10.1055/s-0043-1772788

Tsukahara, Y., Mason, R. A., & Macznik, A. (2022). Training and physiological characteristics of American and Japanese female track and field athletes. *The Journal of Sports Medicine and Physical Fitness*, *62*(9), 1184–1190. https://doi.org/10.23736/S0022-4707.22.13045-8

Ungureanu, A., Lupo, C., Boccia, G., & Brustio, P. (2021). Internal training load affects day-after-pretraining perceived fatigue in female volleyball players. *International Journal of Sports Physiology and Performance*, *16*(12), 1–7. https://doi.org/10.1123/ijspp.2020-0829

Van Reen, E., & Kiesner, J. (2016). Individual differences in self-reported difficulty sleeping across the menstrual cycle. *Archives of Women's Mental Health*, *19*(4), 599–608. https://doi.org/10.1007/s00737-016-0621-9

Vitale, K. C., Owens, R., Hopkins, S. R., & Malhotra, A. (2019). Sleep hygiene for optimizing recovery in athletes: Review and recommendations. *International Journal of Sports Medicine*, *40*(8), 535–543. https://doi.org/10.1055/a-0905-3103

Walsh, N. P., Halson, S. L., Sargent, C., Roach, G. D., Nédélec, M., Gupta, L., Leeder, J., Fullagar, H. H., Coutts, A. J., Edwards, B. J., Pullinger, S. A., Robertson, C. M., Burniston, J. G., Lastella, M., Meur, Y. L., Hausswirth, C., Bender, A. M., Grandner, M. A., & Samuels, C. H. (2021). Sleep and the athlete: Narrative review and 2021 expert consensus recommendations. *British Journal of Sports Medicine*, *55*(7), 356–368. https://doi.org/10.1136/bjsports-2020-102025

SEΩNZ
SPORT & EXERCISE SCIENCE
NEW ZEALAND

The Journal of Sport and Exercise Science, Vol. 8, Issue 2, 21-25 (2024)

www.jses.net

JSES
ISSN: 2703-240X

# The Tokyo Olympics had no Soul: A swimming cap controversy

Graeme Harris[1], Lindsey Alton[1], Michael J. Hamlin[2], Ashleigh Macdonald[3,4], Peter Olsen[3]*

[1]*Department of Engineering and Architectural Studies, Ara Institute of Canterbury, New Zealand*
[2]*Department of Tourism, Sport and Society, Lincoln University, New Zealand*
[3]*Department of Applied Sciences and Social Practice, Ara Institute of Canterbury, New Zealand*
[4]*Cotswold Mātāhae, New Zealand*

ARTICLE INFO

*Received: 28.05.2024*
*Accepted: 23.08.2024*
*Online: 30.12.2024*

*Keywords:*
*Swim caps*
*Equity*
*Drag*

ABSTRACT

*The Soul swimming cap designed specifically for long hair, afro, and dreadlock hair was banned by the swimming body FINA at the Tokyo Olympics. The ban was due to the cap not following the natural form of the head and the possibility the Soul cap could increase swimming performance. The ban attracted considerable media attention and backlash online centering around inclusivity, equity, and the low participation of minority groups in swimming. Anecdotally, swimmers also indicated the larger Soul cap would potentially decrease swimming performance, and previous research had found wrinkled swim caps produced higher drag. There is no research on the Soul cap, therefore the purpose of this study was to investigate the drag of Soul swimming caps compared to a standard Speedo competition cap. A wind tunnel, set at a speed equivalent to 1.76 m/s in the water, was used to measure the drag on a model head with a long wig (representing a long-haired swimmer) in different cap conditions i.e., Soul caps designed for long hair (small [S-Soul], large [L-Soul], extra-large [XL-Soul]) and a standard Speedo swim cap. The Speedo swim cap produced significantly less ($p$'s < 0.0001) drag compared to all Soul caps (141.54 ± 2.92 g [Speedo] vs. 150.53 ± 4.83 g [S-Soul], 164.54 ± 3.24 g [L-Soul], and 172.87 ± 3.70 [XL-Soul]). Differences in drag were progressively larger with an increase in the size of the Soul swimming caps (8.89 g to 31.33 g, $p$'s < 0.0001). It is likely the differences in cap conditions were due to smoothness of the swim caps, with less wrinkling occurring in the Speedo cap and increased wrinkling in the larger Soul caps. Our findings indicate it is unlikely that a Soul swimming cap would confer a performance advantage relative to a standard Speedo swimming cap.*

## 1. Introduction

The Soul swimming cap designed specifically for thick, long, and curly hair including afros to waist-length dreadlocks was banned at the Tokyo Olympics held in 2021 (soulcap.com). This position aligns with the historical stance of the international swimming body (World Aquatics[1]), which prohibits any technology or device that could help speed, buoyancy and/or resistance during a competition (Morales et al., 2019). However, the ban by FINA attracted considerable media attention and substantial backlash that centered around the inclusivity of minority groups and equity in swimming competitions and swimming as a sport overall (De George, 2021). Some of the criticism may have been warranted, as research on drowning indicates that indigenous and minority groups typically have a substantially higher risk of drowning in the USA, Canada, New Zealand, and Australia (Willcox-Pidgeon, 2020). Therefore, banning a swim cap designed for afros and dreadlocks could be viewed as insensitive given the typically lower participation rates in swimming by minority groups and the greater risk of drowning (Myers, 2017; Willcox-Pidgeon, 2020). The media condemnation prompted a response by FINA who indicated they were reviewing the situation with the ban being based on the caps being unsuitable because they did not follow

---

*Corresponding Author: Peter Olsen, Department of Applied Science and Social Practice, Ara Institute of Canterbury, New Zealand, peter.olsen@ara.ac.nz

the natural form of the head. The response by FINA also indicated that the organisation is committed to ensuring that all athletes have access to appropriate swimwear for competitions, where this swimwear does not confer a competitive advantage (FINA Media Statement, 2021). While the FINA response may be appropriate in terms of equality, it does not consider the equity of minority groups participating in swimming competitions. For example, African Americans represent 12.1% of the total population in the United States (U.S Department of Health and Social Services, 2021) and are considerably under-represented in competitive swimming (1% to 2% of total membership) as indicated in data from USA Swimming (USA Swimming, 2020). Research by Myers et al. (2017) also found a strong inverse relationship between competitive swimming rates and drowning, which was most pronounced among African American males. Anecdotally, it would seem unlikely that a swim cap designed for long hair would create an advantage in competition, and some swimmers indicated that because the Soul Cap is larger, it could be disadvantageous to wear in a race (Brown, 2021).

Although FINA eventually approved the Soul swim cap for competitions on 1 September 2022, approximately one year after the Olympics, the question of whether the swim cap would confer an advantage remains unanswered. In contrast to swimsuit technology, there has been considerably less research on the effect of swim caps on swimming performance (Gatta et al., 2015; Marinho et al., 2011). Marinho et al. (2011) found a swim cap reduced hydrodynamic drag by approximately 15% during gliding in swimming relative to no swim cap in a computational model of a female Olympic swimmer. Further research in swimming pools found a smooth rigid silicone swim cap without seams as worn in competitions caused less passive drag than silicone or Lycra caps with seams (Gatta et al., 2013), and a wrinkled silicone swim cap caused more speed-specific drag than a dimpled or smooth swimming cap when swimmers were towed with their arms alongside the body (Gatta et al., 2015). Consequently, Gatta et al. (2015) indicated a wrinkled swim cap could potentially be detrimental to swimming performance. To the authors knowledge, there has been no research comparing the drag produced by a competitive swim cap and the Soul swimming cap.

## 2. Methods

### 2.1. Procedure

A model head was set up in an open circuit wind tunnel, connected to a load cell (PT Transducers shear beam load cell [3 kg], https://www.ptglobal.com/) where PT transducers adjustable software was used to measure the aerodynamic drag at a fixed, vertical head position (Figure 1A and 1B). The wind speed was set at 10 m/s, equivalent to a Reynolds number of $1.32 \times 10^6$, which is comparable to a 1.98 m swimmer at 1.76 m/s in the water, corresponding to 56.94 s per 100 m (Wei et al., 2014). Therefore, the turbulent regime in the wind tunnel is similar to what would be observed by swimmers in the water. Prior to testing in the wind tunnel, a wig was placed on the model head to represent a swimmer with long hair, and different swimming caps were placed over the top of the head: a standard Speedo swim cap used for competitive swimming (Figure 1A) and Soul caps designed for long hair (small [S-Soul], large [L-Soul], extra-large [XL-Soul]).

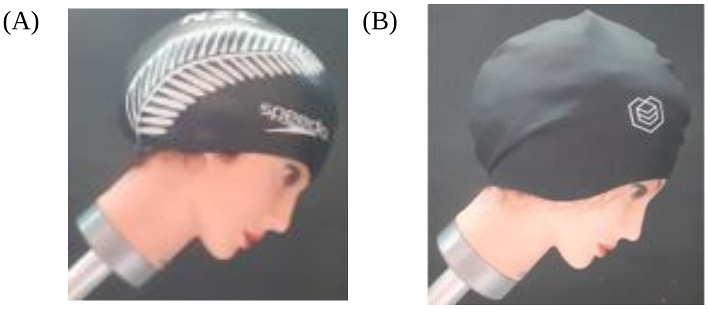

Figure 1: Standard size Speedo swim (A), L-Soul swim cap (B) in the wind tunnel on a model head.

Figure 2 shows the increase in the size of the swim caps in the following order: Speedo, S-Soul, L-Soul, and XL-Soul. Table 1 below shows the height and width of each swim cap. All swimming caps were made from silicone material. Drag data was collected for one trial of 45 s in each swim cap condition. The first 5 s of data were removed from the raw dataset of each trial, to ensure there was consistency in wind speed. The next 400 measurements (approximately 40 s at 10 Hz) of the trial were extracted from each raw data sheet so there was the same number of data points in each condition for comparison. All data was collected in the same test session and the research had institutional ethical approval.

Figure 2: Size of the swim caps (order: Speedo, S-Soul, L-Soul, and XL-Soul).

Table 1: Height and width of the swim caps.

| Swim cap | Base width (mm) | Height (mm) |
|---|---|---|
| Speedo | 185 | 195 |
| S-Soul | 185 | 190 |
| L-Soul | 200 | 255 |
| XL-Soul | 220 | 285 |

---

[1] The Federation Internationale de Natation (FINA [International Federation of Swimming]) became World Aquatics in January 2023.

### *2.2. Statistical Approach*

The data was downloaded from the wind tunnel software (PT transducers adjustable software) into an Excel spreadsheet and transferred to the Statistical Analysis System version 9.4 (SAS Institute; Cary, NC, USA) for further analysis. The data was then visually checked for outliers and inaccurate data by investigating the distribution and probability plots. Means and standard deviation (SD) data were calculated for drag measurements (g) in each condition for the 400 data points using a mixed modelling procedure (Proc Mixed) in the Statistical Analysis System. The differences in drag variables were compared between conditions using a repeated measures analysis. Statistical significance was set at $p < 0.05$.

## 3. Results

The Speedo swim cap produced significantly less ($p < 0.0001$) drag compared to all of the Soul caps (141.54 ± 2.92 g [Speedo] vs. 150.53 ± 4.83 g [S-Soul], 164.54 ± 3.24 g [L-Soul], and 172.87 ± 3.70 [XL-Soul], see Figure 3). Differences in drag were progressively larger with an increase in the size of the Soul swimming caps (8.89 g to 31.33 g, *p's* < 0.0001).

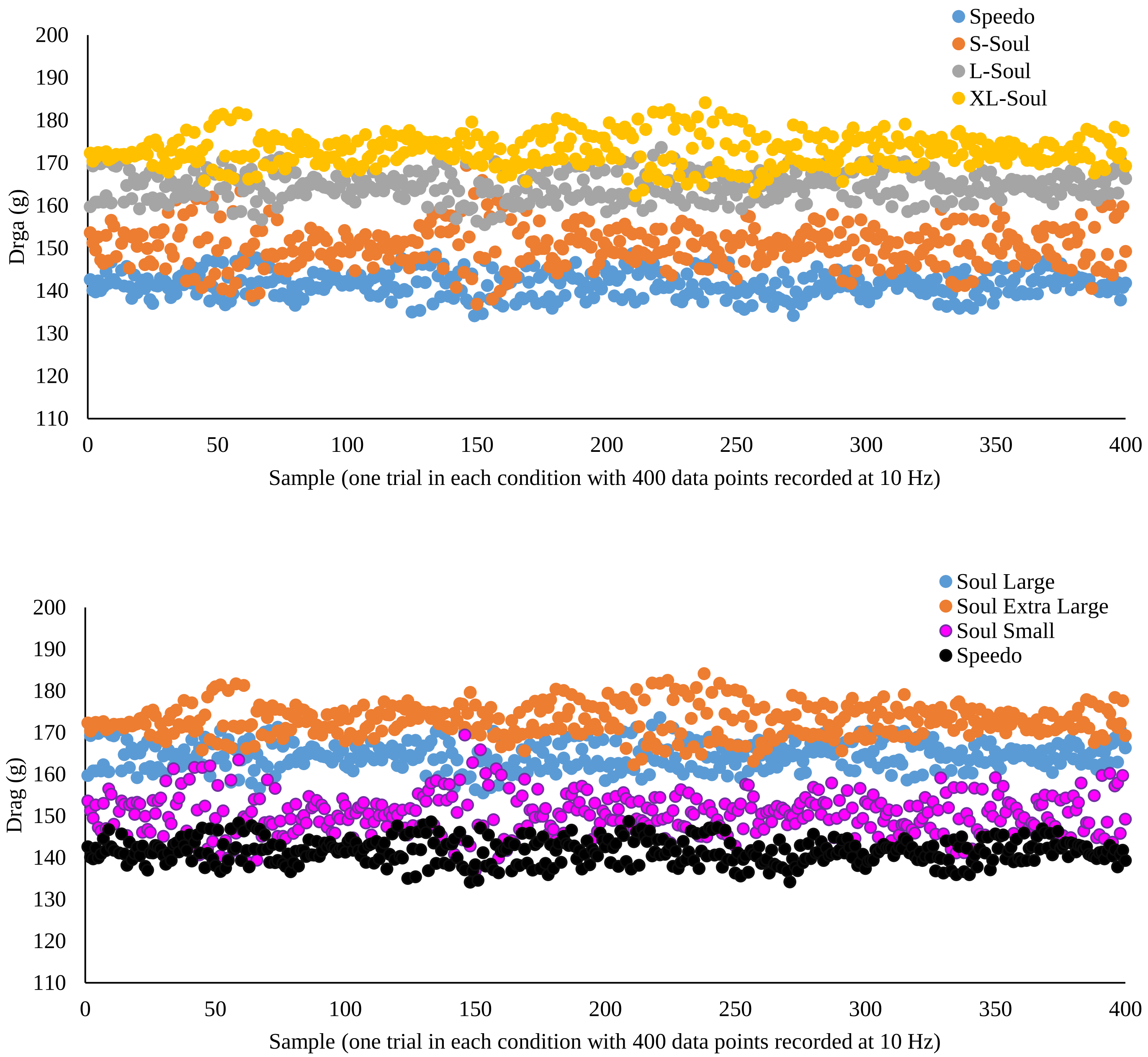

Figure 3: Drag in the Speedo and Soul swimming caps.

## 4. Discussion

The Soul swimming caps (S-Soul, L-Soul, and XL-Soul) were found to have significantly higher drag compared to a standard Speedo swimming cap (6%, 16%, and 22%, respectively) in wind tunnel testing, where airflow had a Reynolds number comparable to that found in competitive swimming. Previous research has also found significant differences between different types of swim caps or wearing no swim caps at all. For example, the greater drag measurements for the larger Soul swim caps (L-Soul and XL-Soul) relative to the Speedo cap are similar to differences observed by Marinho et al. (2011), who found a swim cap reduced hydrodynamic drag by approximately 15% during gliding in swimming relative to no swim cap in a computational model. Whereas the 6% difference between the small Soul cap and the standard Speedo swimming cap is similar to findings by Gatta et al. (2013) where a lower passive drag (~ 6%) was observed in a silicone cap without seams versus a Lycra cap or a classic silicone cap (with seams). Further research by Gatta et al. (2015) also found decreased speed-specific drag (4%) in dimpled or smooth caps compared to a wrinkled silicone swim cap. Gatta et al. (2015) hypothesized that a wrinkled cap could increase total drag because of an increase in frictional drag, which is greater than any possible benefit from a decrease in pressure drag. Anecdotally, the wrinkles observed in the Soul swim caps in our study (e.g., Figure 1B) were more substantial than the standard Speedo cap (Figure 1B), and those illustrated in Gatta et al. (2013; 2015). It is likely the presence of wrinkles in this research contributed to the increase in drag observed between the Soul caps and the Speedo cap. The wrinkles are possibly due to the design of the Soul caps, which are made for swimmers with large voluminous hair (https://soulcap.com/). Consequently, the decreased drag observed in the standard Speedo cap and also the smallest Soul swimming cap, was probably due to a closer adherence of these caps to the model head thereby decreasing the amount of wrinkles relative to the larger Soul swimming caps. Based on their findings, Gatta et al. (2015) suggested that swimmers should ensure there are minimal ripples and a close adherence of a swim cap to the head to reduce drag, as even a small decrease in drag could make a difference due to small winning time margins in elite competitions. Nevertheless, supplementary unpublished research by the authors, which analyzed video footage of three elite women's 200 m backstroke races (i.e., the Rio Olympic final and a semi-final at the London and Tokyo Olympics, $n = 40$ swimmers) found 52.5% of the elite swimmers had a smooth cap surface, while 47.5% had a swim cap with some ripples (Olsen et al., 2024). Therefore, the ripples present in swimming caps in our current study are not uncommon in elite swimming.

The observation of a size effect, with drag progressively increasing in the larger Soul swim caps due to wrinkling and a looser fit is similar to Gatta et al. (2013; 2015) results, despite differences in methodologies i.e., passive towing in a swimming pool vs. a wind tunnel. This may be due to the Reynolds value in our research approximating the turbulent flow experienced during competitive swimming (Wei et al., 2014). An advantage of using a wind tunnel is that it is easier to manipulate head position, drier, and probably a more consistent testing environment compared to a swimming pool setting. Nevertheless, several factors may affect the external validity of our findings. For example, in our study, the swim caps were pulled tightly over the long hair wig on the model head; however, a competitive swimmer with long hair would likely have their hair in a tight bun or similar to ensure a closer adherence to the head, which may create a smoother cap surface. Indeed, our supplementary research indicated all elite female backstroke competitors wore their hair in a low or high bun (87.5% and 12.5%, respectively; Olsen et al., 2024). It was not possible in our current study to place the hair on the wig in a low or high bun. Future research could examine swim cap use in competitions (e.g., the effect of different hairstyles, double capping, and swim cap shape on drag in swimming or wind tunnel settings). The researchers also acknowledge that testing in an aquatic environment may have produced different outcomes than those obtained in a wind tunnel due to the myriad of factors that can affect swimming performance such as training, limb coordination, stroke, and technical skill (Zamparo et al, 2019).

Based on our findings it is unlikely that a Soul swimming cap, especially larger sizes would have created an unfair advantage for swimmers relative to a standard Speedo swim cap at the Tokyo Olympics. The authors further reiterate the recommendations of Gatta et al. (2015), where swimmers should ensure there are minimal ripples and a close adherence of a swim cap to the head. Following these guidelines would more likely decrease drag, with the smaller Soul cap probably producing similar levels of drag as a competitive Speedo swimming cap.

## Conflict of Interest

The authors declare no conflict of interests.

## Acknowledgment

This research was funded by Ara Institute of Canterbury.

## References

Brown, E. (2021, July 04). How a ban on a swim cap galvanized black swimmers. *The New York Times*. www.nytimes.com/2021/07/14/style/olympics-soul-cap-ban-.

De George, M. (2021, July 2). FINA releases statement saying it is 'Reviewing' competition ban on Soul cap. *Swimming World Magazine*. https://www.swimmingworldmagazine.com/news/fina-releases-statement-saying-it-is-reviewing-competition-ban-on-soul-cap/

Gatta, G., Zamparo, P., & Cortesi, M. (2013). Effect of swim sap model on passive drag. *Journal of Strength and Conditioning Research*, *27*(10), 2904–2908.

Gatta, G., Zamparo, P., & & Cortesi, M. (2015). Effect of swim cap surface roughness on passive drag. *Journal of Strength and Conditioning Research, 29*(11), 3253–3259.

Marinho, D. A., Mantha, V. R., Rouboa, A., Vilas-Boas, J. P., Machado, L., Barbosa, T. M., & Silva, A. (2011). The effect of wearing a cap on the swimmer passive drag. *Portuguese Journal of Sport Sciences*, *11* (Supplement 2). 319–322.

Morales, A. T., Tamayo Fajardo, J. A., & González-García, H. (2019). High-speed swimsuits and their historical development in competitive swimming. *Frontiers in*

*Psychology*, *10*, 1–11. https://doi.org/10.3389/fpsyg.2019.02639

Myers, S. L., Cuesta, A., & Lai, Y. (2017). Competitive swimming and racial disparities in drowning. *The Review of Black Political Economy*, *44*(1–2), 77–97. https://doi.org/10.1007/s12114-017-9248-y

Olsen, P., Alton, L., Marshall, H., Macdonald, A., Oo, L., Simcic, A., & Harris, G (2024). The effect of swim cap shape on aerodynamic drag. In J. Smiler, D. Bentley-Gray, J. Drysdall, & J. L. Savage (Eds.), *ITP Symposium 2024 Book of Abstracts* (pp. 201). Te Pūkenga. https://doi.org/10.34074/proc.2412

Soul Cap. (2022, September 1). It’s official: Soul cap is now approved by FINA. *Soul Cap.* https://soulcap.com/blogs/editorial/soul-cap-approved-by-fina.

USA Swimming. (2020). *USA Swimming 2020 Membership Demographics Report.* https://www.usaswimming.org/docs/default-source/governance/governance-lsc-website/membership-demographics/2020-membership-demographics-report.pdf

U.S. Department of Health and Human Services. (2021). U.S. Department of Health and Human Services Office of Minority Health. https://minorityhealth.hhs.gov/blackafrican-american-health

Wei, T., Mark, R., & Hutchison, S. (2014). The fluid dynamics of competitive swimming. *Annual Review of Fluid Mechanics*, *46*, 547–565.

Willcox-Pidgeon, S. M., Franklin, R. C., Leggat, P. A., & Devine, S. (2020). Identifying a gap in drowning prevention: High-risk populations. *Injury Prevention*, *26*(3),279–288.

World Aquatics. (2021, July 2). *FINA Media Statement.* https://www.worldaquatics.com/news/2183443/fina-media-statement

Zamparo, P., Cortesi, M., & Gatta, G (2020). The energy cost of swimming and its determinants. *European Journal of Applied Physiology*, *120*(1), 41–66. https://doi.org/10.1007/s00421-019-04270-y

SPORT & EXERCISE SCIENCE NEW ZEALAND

*The Journal of Sport and Exercise Science, Vol. 8, Issue 2, 26-36 (2024)*

www.jses.net

**JSES**

**ISSN: 2703-240X**

# Electromyographic signals during pullover exercise variants, and relationships between strength and throwing performance

Jad Adrian Washif[1*], Christopher Martyn Beaven[1,2], Kim Hebert-Losier[1,2]

[1]*Sports Performance Division, National Sports Institute of Malaysia (Institut Sukan Negara Malaysia), Malaysia*
[2]*Te Huataki Waiora School of Health, Division of Health, Engineering, Computing and Science, University of Waikato, New Zealand*

ARTICLE INFO

*Received: 13.02.2024*
*Accepted: 13.09.2024*
*Online: 30.12.2024*

*Keywords:*
*Athletics*
*EMG*
*Javelin throw*
*Long muscle length*
*Overhand throw*
*Specific strength*

ABSTRACT

*Developing event-specific strength is necessary for optimising throwing performance. Currently, the movement patterns and transferability of pullover exercise to javelin throw performance are unknown. This study assessed the electromyography (EMG) signals during pullover exercise variants, and examined whether maximum strength related to release velocity and throwing performance. Seven national-level javelin throwers performed four barbell pullover variants (conventional [CONV], straight-arm [STR], bent-arm [BENT], and conventional on an exercise ball [BALL]) at approximately 85% of one-repetition maximum (1-RM) and three repetitions of javelin throw (JAV) while EMG activity was recorded from nine muscles: upper-trapezius; anterior, middle, and posterior-deltoid; triceps brachii; clavicular and sternal portions of pectoralis major; latissimus dorsi; and rectus abdominus. Bench press and back squat 1-RM were also determined. BENT variant peak muscle activation most closely approximated JAV peak muscle activation, especially for posterior deltoid, clavicular, and latissimus dorsi ($p > 0.05$, < 10% vs JAV). Significant correlations were found for CONV, STR, BENT, and half-squat absolute strength with release velocity ($r = 0.77$ to $0.80$), and for BENT relative strength with throwing performance ($r = 0.85$). Training to improve overhand throwing may consider exercises that specifically target the muscles activated during throwing to maximise training transference. Herein, muscle activation during the BENT pullover variant was most similar to JAV, and elicited the greatest muscle activation for most muscles examined. Furthermore, developing maximal strength, particularly by engaging in exercises such as BENT, seems to be crucial for optimising release velocity and throwing performance, potentially leading to a more effective training program.*

## 1. Introduction

The pullover exercise is an integral part of strength and conditioning routines of athletes to develop upper body athleticism. It typically involves lying on a bench or stability ball while holding a weight (external load) with both hands above the chest. From this position, the weight is then lowered in a controlled manner behind the head until the arms are parallel to the ground or slightly below, and then lifted back to the starting position. As this exercise involves a succession of eccentric-concentric muscle actions (Marchetti et al., 2011), it “mimics” upper-body actions seen in several throwing sports. The exercise engages muscles in the chest, back, and arms, and is often used to improve performance in sports involving overhead throwing motions. Apart from the muscle actions, the movement pattern and range of motion involved in this exercise appear relevant for various throwing movement sports, such as the javelin throw. Hence, these particular characteristics of the pullover exercise are

---

[*] Corresponding Author: Jad Adrian Washif, National Sports Institute of Malaysia, Malaysia, jad@isn.gov.my

JSES | https://doi.org/10.36905/jses.2024.02.03

thought to be useful to improve throwing performance and are commonly integrated into resistance training programs of javelin throwers (Chelly et al., 2010; Young, 2001).

Electromyography (EMG) has been used as a method to examine the level of muscle activation during the pullover exercise, with higher activity reported in the pectoralis major compared to the latissimus dorsi muscles (Marchetti et al., 2011). Assessment in this aforementioned study, however, was limited to these two muscle groups. The pullover exercise may also be used to develop various other upper body muscles, including the teres major, pectoralis minor, serratus anterior, triceps brachii, and posterior deltoid (Leavy, 2004). Further, the level of activation of these muscles likely depends on individual technique as well as variants of the pullover exercise.

Specialised training needs to provide stimuli that reflects those of the actual sporting movement and that recruits higher threshold motor units, which is crucial for developing the requisite skills and strength required for an event (Zaras et al., 2013). The pullover exercise may be performed in different techniques (variants) and in both stable and unstable conditions to elicit preferential training effects. Examining pullover variants may therefore provide additional information relating to muscle activation patterns helpful for training prescription and transference to overhand throwing capability. Indeed, implementing appropriate and targeted strength and conditioning exercises (i.e., pullover variants) that mimic activation patterns during the javelin throw may help optimise performance gains in athletes. Furthermore, it is well accepted that even among experienced athletes, technical skills can be improved when implementing specialised strength-training development programs (Bartonietz, 2000). For the pullover exercise, there are a limited number of studies examining EMG activity, which have only addressed certain techniques and variants of the pullover exercise (Borges et al., 2018; Marchetti et al., 2011). Indeed, previous studies focused solely on the "conventional" pullover exercises (Borges et al., 2018; Marchetti et al., 2011), despite variants to this exercise commonly used. This limited focus constrains our understanding and evidence-based implementation of pullover exercise variants, thereby hindering the effective application of the pullover variants for, among others, progressive overload, balanced muscle development, and optimal transference benefits. The most common pullover variants involve slight modifications to the technical execution, such as positioning the elbows straight or bent, as well as incorporating an unstable surface during the pullover exercise.

Likewise, the relationship between pullover performance, release velocity, and throwing ability has not been thoroughly examined. Muscle strength is a component that can affect throwing performance (Zaras et al., 2013) and increasing strength and power of the upper body may improve success in throwing-related sports (Hermassi et al., 2015). Specifically, strength and power, as well as technique and temporal coordination of body segments, are key determinants of throwing release velocity, which is an essential component of performance (Lehmann et al., 2010; Murakami et al., 2006; Ogiolda, 1993; van Muijen et al., 1991). Indeed, 'strength' refers to the capacity of an athlete to handle an external load, usually quantified by the maximum load that can be lifted once (Haff & Triplett, 2015). Understanding the maximum load capabilities in various pullover variants helps in tailoring strength and conditioning programs that meet the specific demands of throwing sports. Previous research suggests that the maximum strength achieved in specific exercise variants can directly influence the power and efficiency of performance movements (Young, 2001). However, there are limited data on the relationship between maximum strength and release velocity in throwing events – including javelin throw – or on the relationship between ability to perform pullover exercise and throwing performance.

Therefore, the purpose of this study was three-fold: (i) to quantify and compare muscle activation of nine upper-body muscles during four variants of pullover exercise and maximum javelin throwing attempts; (ii) to examine the relationship between maximum strength and release velocity; and (iii) to investigate the relationship between maximum external load (strength) lifted and javelin throw performance. Due to kinematic dissimilarities, we hypothesised that each type of pullover exercise would produce different muscle activation levels. We also hypothesised that maximum strength in the BENT pullover variant would correlate to javelin throw performance and release velocity more strongly, due to an arm-straightening motion that mimics throwing action.

## 2. Methods

This cross-sectional study required all participants to perform four pullover exercise variants in a random order: conventional (CONV), straight-arm (STR), bent-arm (BENT), and CONV on an unstable Swiss-ball surface (BALL). Following pullover exercise variants, all participants completed a series of three maximum javelin throws (JAV) using standard equipment for men (800 g) and women (600 g). Surface EMG signals were recorded throughout the movements from the following nine muscles on the throwing-arm side: upper trapezius; anterior, middle, and posterior deltoid; triceps brachii; clavicular (upper) and sternal (middle) portions of pectoralis major; latissimus dorsi; and rectus abdominus. Maximum strength in CONV, STR, BENT, half-squat, and bench press exercises were also established in a separate session to investigate the relationship between maximum strength, release velocity, and javelin throw performance.

### *2.1. Participants*

The entire population of athletes meeting inclusion (at the national training centre) participated in this study. Seven javelin throwers, 5 men (*M* age = 20.2 ± 0.4 years; *M* body mass = 77.6 ± 7.5 kg; *M* stature = 1.77 ± 0.05 m) and 2 women (*M* age = 21.5 ± 3.5 years; *M* body mass = 59.5 ± 7.8 kg; *M* stature = 1.60 ± 0.01 m) (combined *M* age = 20.6 ± 1.6 years; *M* body mass = 72.4 ± 11.2 kg; *M* stature = 1.72 ± 0.09 m), gave their written informed consent to participate in the study after being thoroughly informed regarding the objectives, benefits, and risks of the study. The participants were considered to be moderately trained in regard to throwing performance (World Athletics score = 724 ± 71 points). The throwers reported no history of musculoskeletal injury in the last 3 months. All athletes competed in national-level competitions and had been engaged in resistance training for at least 2 years that incorporated the pullover exercise and all variants under examination. All participants completed a medical history and physical activity questionnaire before participation and were instructed to refrain from any strenuous activities involving the upper body in the 48 hours before data collection. This study adhered to the ethical principles of the World Medical Association (Declaration of Helsinki) and was approved by a Research Ethics Committee.

### *2.2. Procedures*

All throwers attended four sessions within a 10-day period. The first session involved obtaining informed consent signatures, familiarisation to the testing protocol, and collection of baseline anthropometric characteristics. The second session involved incremental loading tests to obtain maximum strength values for CONV, STR, and BENT. The following day, maximum strength for half-squat and bench press were assessed in the third session. A week later, the fourth session was conducted that involved EMG assessment of all pullover variants and the javelin throws. The order of pullover exercises was randomised to balance any effect of fatigue across exercises.

All data were collected within one testing session to avoid repositioning of electrodes between sessions. However, only the second to fifth repetitions (4 repetitions; 1 set) of pullover variants were used (averaged) and analysed to minimise the chances of end-point errors resulting from the improper execution of the initial and final exercise sets.

### *2.2.1. Maximum external load assessment*

The warm-up protocol involved approximately 10-min general dynamic movements, followed by a warm-up specific to the exercise tested using an unloaded pullover bar (i.e., E-Z curl barbell [Figure 1] or Olympic bar for bench press and back squat) for 10 repetitions. The warm-up set for each exercise was done using the same exercise at approximately 50% of the estimated 1 repetition-maximum (1-RM) for approximately 8 repetitions, and at approximately 70% of 1-RM (5 repetitions).

Figure 1: An E-Z curl barbell used for the current study

Next, participants followed a modified National Strength and Conditioning Association testing protocol, performing 3 to 5 sets with progressively increased loads to reach their 1-RM. The testing sequence involved 2 to 3 repetitions at approximately 85% of expected 1-RM, 1 to 2 repetitions at approximately 95% of 1-RM, and then 1 repetition, of which the load was added or reduced by 2.2 to 4.4 kg (for pullover exercises), 4.4 to 9 kg (for bench press), or 9 to 20 kg (for half-squat) to reach 1-RM exactly. The inter-set rest was set to 2 to 4 min, and rest between exercises was approximately 10 min (Haff & Triplett, 2015; Washif & Kok, 2022; Washif et al., 2024). A trained investigator oversaw participants during all performances to ensure safety and correct technique. Both absolute (kg) and relative strength (kg per kg of body mass) were analysed.

### *2.2.2. MVICs and pullover procedures*

Participants performed three maximum voluntary isometric contractions (MVICs) of approximately 7 s (2 s ramped effort, 3 s of max hold, 2 s decrease effort) with 2 min rest interval between contractions prior to pullover variants and javelin throws. An MVIC task was done for each one of the muscles. Three researchers provided manual resistance, adequate stabilisation, and strong verbal encouragement during efforts. The maximum efforts were followed by a 10-min recovery period.

Subsequently, all throwers performed 6 repetitions of each pullover variant (CONV, STR, BENT, and BALL, in random order) using a free-weight curled barbell (named E-Z) against an external load equivalent to 85% of 1-RM (Figure 2).

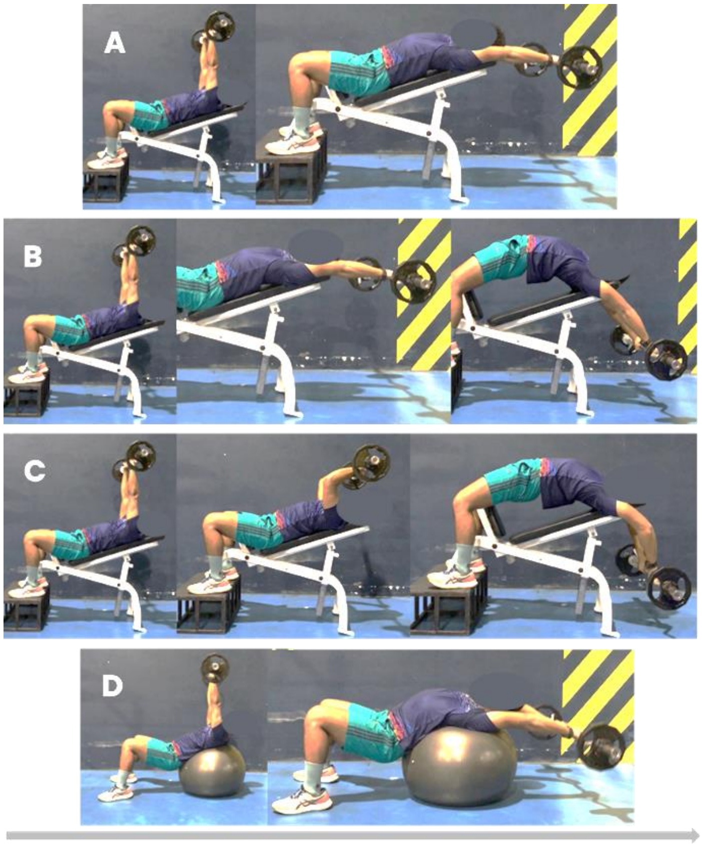

Figure 2: The specific movement pattern of each pullover variant (A = conventional [CONV], B = straight-arm [STR], C = bent-arm [BENT], D = conventional on an exercise ball [BALL]). The standard five-point body contact position technique (head, upper back, and buttocks firmly on the bench with both feet flat on the floor or box) was implemented at the start of each pullover exercise (except for D). However, dependent on exercise, the five-point contact was not always maintained throughout the exercise (e.g., buttocks raised in STR and BENT – third image of B and C). At start of each exercise, the shoulder was in a flexed position so that the arms were perpendicular above the chest. The exercise was initiated through flexion of the shoulders until the forearms were about parallel to the floor or trunk (or optimal elbow-flexion during C). To complete one repetition, the arms needed to return to the initial position through shoulder extension.

A rest of at least 5 min and up to 15 min between each exercise was permitted to allow participants to feel recovered between trials. As we used a sample of national-level javelin throwers, 85% of their 1-RM represents a common training load. Prior to beginning each exercise variant, participants performed a warm-up set of 6 repetitions at 50% of 1-RM to ensure proper execution and re-familiarisation. A detailed description of each variant is provided as supplementary material.

### 2.2.3. Javelin throw

Participants performed three maximal-effort javelin throws using a standard javelin implement with a 5 min rest interval between throws.

*Release velocity and throwing performance.* Release velocity was recorded during the EMG recording session (javelin throw) with the synchronised infrared camera system. The throw in which the highest velocity was attained was maintained for further analysis. This kinematic parameter was taken from a selected time-instant of the delivery phase, called javelin release. The linear velocity was calculated as resultant velocity of the grip of the javelin at the instant of release (i.e., the first frame the implement and hand lost contact). Throwing performance was derived from the most recent competitive event for each athlete that was classified based on the World Athletics scoring table.

### 2.2.4. Electromyography assessment

*Electrodes placement.* Similar to the maximum strength assessment, participants performed a standardised 5-min dynamic warm-up followed by a warm-up specific to the exercises tested using the unloaded pullover bar, allowing re-familiarisation. A 10-min recovery period was given during which time the electrodes were applied to the nine selected muscles on the throwing-arm side. Before electrode placement, the area of the skin where electrodes were to be positioned were shaved, gently abraded with fine sandpaper, and wiped with isopropyl alcohol. The position of electrodes was determined by palpating the pre-selected muscle bellies, while under contraction. A pair of Ag-AgCl pre-gelled electrodes (Noraxon USA Inc., Scottsdale, AZ) of 10 mm in diameter were subsequently placed in parallel on the non-contracted muscle bellies, with an interelectrode distance of 20 mm on each of the specified locations: (a) upper trapezius; (b) anterior deltoid; (c) middle deltoid; (d) posterior deltoid; (e) triceps brachii; (f) pectoralis clavicular portion; (g) pectoralis sternal portion; (h) latissimus dorsi; and (i) rectus abdominus. Double-sided tape and Hypafix® medical tape were used to affix each sensor to the skin and allow freedom of movement during actions. After positioning the electrodes, a quality check was performed to ensure EMG signal validity by requesting individuals to actively contract the muscles under investigation. Skin preparation and electrode positioning followed the recommendations of SENIAM organisation (Hermens et al., 2000) and other scientific sources (see Supplementary Table 2).

*EMG recording procedures.* EMG signals were collected during pullover variants and javelin throws using wireless Noraxon system, MyoMuscle v3.6 (Noraxon USA Inc., Scottsdale, AZ) at a sampling rate of 1500 Hz, which was synchronised with an infrared camera system (100 Hz) that recorded the exercise motion concurrently. EMG signals were recorded during both the concentric (shoulder extension) and eccentric (shoulder flexion) phases of the movement. Signals collected were filtered through a 4th order Butterworth band-pass filter with a pass band of 10 to 500 Hz. EMG data were rectified and smoothed by calculating the root mean square (RMS, μV) using a moving window with a window size of 250 ms, which resulted in smoothing of the data. EMG signals were then normalised to their peak amplitudes collected during a maximum voluntary isometric contraction (see Section 2.2.2.) and expressed a percent of MVIC. All data were stored within the Noraxon software and exported to Excel for further processing.

### 2.3. Data analysis

All data are presented as means and standard deviations. Friedman test was employed to assess the normalised (% MVIC) EMG amplitude data for the nine muscle groups during each exercise: CONV, STR, BENT, BALL, and JAV. Next, Wilcoxon signed-rank post hoc test was implemented where statistically significant differences were detected. The same analyses were conducted for the comparison of maximal loads in strength exercises. The Spearman's rank correlation coefficient was used to determine relationships between maximum strength with release velocity and throwing performance. The magnitudes of correlation coefficients were interpreted as: trivial, $r < 0.10$; small, $r = 0.10$ to 0.29; moderate, $r = 0.30$ to 0.49; large, $r \geq 0.50$ (Cohen, 1988). Furthermore, we computed percentage differences to evaluate relative difference between exercises (pullover vs javelin throw). We also calculated the sum of squared differences to quantify overall variability (difference) in muscle activity between pullover variations and javelin throw, summing the square of the difference in EMG activity between a given pullover variant and javelin throw of each muscle. Analyses were performed in Microsoft Excel 2010 (Microsoft Corp., Redmond, WA, USA) and SPSS Statistics 26 for Windows (SPSS Science, Chicago, IL, USA). Alpha was set at $p \leq 0.05$ for all analyses.

## 3. Results

### 3.1. Muscular strength

The mean absolute and relative 1-RM loads are presented in Table 1. Absolute BENT strength was significantly greater than both absolute CONV ($z = -2.37$, $p = 0.018$; +46% difference) and STR ($z = -2.21$, $p = 0.027$; +18% difference). Similarly, relative BENT strength was significantly greater than both relative CONV ($z = -2.37$, $p = 0.018$; +49% difference) and STR ($z = -2.21$, $p = 0.027$; +19% difference). Additionally, STR strength was significantly greater than CONV for both absolute ($z = -2.37$, $p = 0.018$; +25% difference) and relative ($z = -2.37$, $p = 0.018$; +25% difference) values.

Table 1: Mean ± SD of peak EMG amplitudes (% MVIC) of nine upper body muscles during the conventional (CONV), straight-arm (STR), bent-arm (BENT), unstable (BALL) pullover variants, and javelin throw (JAV).

| | | CONV | STR | BENT | BALL | JAV | χ2(5) | *p* |
|---|---|---|---|---|---|---|---|---|
| Upper trapezius | % MVIC ± SD | 23 ± 4$^{*\dagger}$ | 39 ± 11$^{*\dagger}$ | ***59 ± 6***$^{\dagger}$ | 40 ± 17$^{*\dagger}$ | 64 ± 4$^{*}$ | 19.385 | 0.001 |
| | % to JAV | -41 | -25 | ***-5*** | -24 | | | |
| Anterior deltoid | % MVIC ± SD | 24 ± 3$^{\dagger}$ | 27 ± 20 | **34 ± 13** | 28 ± 12 | 47 ± 15 | 10.382 | 0.034 |
| | % to JAV | -23 | -20 | **-13** | -19 | | | |
| Middle deltoid | % MVIC ± SD | 16 ± 1$^{\dagger}$ | 15 ± 1$^{*\dagger}$ | **23 ± 7**$^{\dagger}$ | 17 ± 5$^{*\dagger}$ | 44 ± 8$^{*}$ | 19.238 | 0.001 |
| | % to JAV | -28 | -29 | **-21** | -27 | | | |
| Posterior deltoid | % MVIC ± SD | 14 ± 4 | 17 ± 8 | **28 ± 16** | 23 ± 10 | 27 ± 21 | 4.311 | 0.366 |
| | % to JAV | -13 | *-10* | ***1*** | *-4* | | | |
| Clavicular | % MVIC ± SD | 76 ± 24 | 72 ± 27 | **84 ± 26** | 54 ± 32 | 91 ± 51 | 4.427 | 0.351 |
| | % to JAV | -15 | -19 | ***-7*** | -37 | | | |
| Sternal | % MVIC ± SD | 76 ± 12 | 74 ± 29 | 77 ± 25 | **65 ± 37** | 63 ± 34 | 2.212 | 0.697 |
| | % to JAV | 13 | 11 | 14 | ***2*** | | | |
| Tricep bracii | % MVIC ± SD | 73 ± 20 | **58 ± 21** | 75 ± 25 | 65 ± 23 | 43 ± 25 | 6.254 | 0.181 |
| | % to JAV | 30 | **15** | 32 | 22 | | | |
| Rectus abdominal | % MVIC ± SD | **71 ± 35** | 107 ± 36 | 84 ± 32 | 99 ± 45 | 46 ± 37 | 8.366 | 0.079 |
| | % to JAV | **25** | 61 | 38 | 53 | | | |
| Latissimus dorsi | % MVIC ± SD | 29 ± 11 | *52 ± 33* | **46 ± 26** | 40 ± 15 | 47 ± 31 | 2.617 | 0.624 |
| | % to JAV | -18 | *5* | ***-1*** | *-7* | | | |

*Notes:* EMG = electromyography; MVIC = maximum voluntary isometric contraction; BALL = CONV on an exercise ball. *Statistically significant difference from the BENT. †Statistically significant difference from the JAV. Muscle activations among pullover variants most closely to JAV are in bold. Muscle activations within 10% of JAV (absolute difference) are in italic.

### *3.2. EMG analysis*

The comparisons of root mean square (RMS) amplitudes (% MVIC) elicited from each muscle examined are summarised in Table 2. Among pullover variants and JAV, no significant differences (*p's* > 0.07) were observed for posterior deltoid, clavicular or sternal portions of pectoralis major, lateral triceps, rectus abdominal, and latissimus dorsi muscles in terms of muscle activation levels.

Table 2: Descriptive values of maximum absolute and relative strength (± SD).

| | CONV | STR | BENT | HS | BP |
|---|---|---|---|---|---|
| Absolute 1-RM (kg) | 30 ±11 | 37 ±13 | 44 ±10 | 129 ±26 | 72 ±18 |
| Relative 1-RM (kg·kg$^{-1}$) | 0.40 ±0.09 | 0.50 ±0.10 | 0.60 ±0.05 | 1.77 ±0.16 | 0.98 ±0.13 |

*Notes:* CONV = conventional pullover, STR = straight-arm pullover, BENT = bent-arm pullover, HS = half-squat, BP = bench press.

*Percent difference between pullover variants and javelin throw.* Furthermore, percent differences indicated that BENT exercise variant most closely approximated the peak muscle activation during JAV in six of the nine muscle groups (67%). Similarly, when the sum of squared differences from the JAV was calculated for the four exercise variants, the BENT variant was the most similar to the javelin throw peak activation pattern, with muscle activations of four muscle groups (upper trapezius, posterior deltoid, clavicular and latissimus dorsi) within 10% of JAV (Table 1). Figure 3 shows the normalised percentage of muscle activations relative to JAV (100% baseline).

*Difference among pullover variants.* Significant differences were found between exercise variants in the muscle activation levels for the upper trapezius ($\chi2(5) = 19.385$; $p = 0.001$), anterior deltoid ($\chi2(5) = 10.382$; $p = 0.034$), and middle deltoid ($\chi2(5) = 19.238$; $p = 0.001$). Post hoc analysis for the upper trapezius revealed that BENT elicited a significantly greater peak muscle activity than CONV ($z = -2.23$, $p = 0.026$), STR ($z = -2.01$, $p = 0.044$), and BALL ($z = - 2.01$, $p = 0.044$), that was closer but significantly less than JAV ($z = -2.05$, $p = 0.040$). Furthermore, JAV was significantly higher than CONV for anterior deltoid activation ($z = -2.20$, $p = 0.028$). For the middle deltoid, BENT induced a relatively higher muscle activity than other pullover variants, and significantly higher against STR ($z = -2.20$, $p = 0.028$).

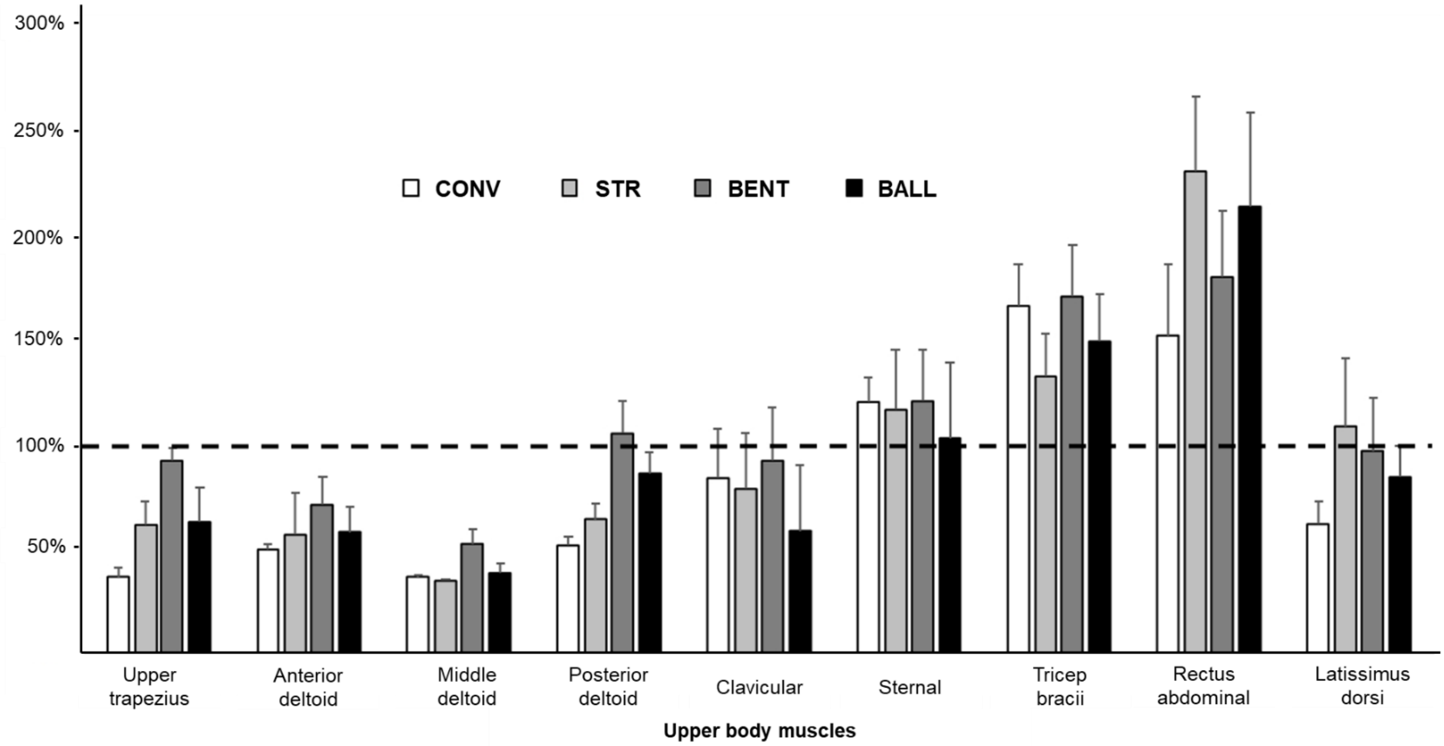

Figure 3: Differences (normalised %) from the javelin throw (100% line) for the four exercises variants. *Notes:* CONV = conventional pullover, STR = straight-arm pullover, BENT = bent-arm pullover, BALL = CONV on an exercise ball.

Moreover, for this muscle, JAV produced a significantly higher muscle activity than the four pullover variants (*p's* < 0.03). Additionally, lower peak activity levels were observed for upper trapezius, anterior deltoid, and middle deltoid relative to JAV (-5 to -21%). Activation of the triceps brachii and rectus abdominus exceeded peak levels observed during JAV (Table 1).

### *3.3. Relationship between maximum strength and javelin throw*

The throwing performance, recorded within official competition was equivalent to 50.40 ± 6.00 m across participants. Table 3 shows the relationship between maximum strength values and release velocity and performance. The absolute CONV, STR, BENT, and half-squat showed significant and very large relationships with release velocity ($r$ = 0.77 to 0.80), with the largest relationship seen for absolute BENT. In contrast, only one large significant relationship was found between relative strength in the BENT variant and throwing performance ($r$ = 0.85).

## 4. Discussion

In our study, muscle activity levels during four variants of pullover exercise as well as maximal-effort javelin throw were examined. Overall, these five exercises yielded no statistically significant difference for posterior deltoid, clavicular or sternal, pectoralis major, lateral triceps, rectus abdominal, and latissimus dorsi muscle activity levels. Further, among exercise variants, the BENT condition most closely mimicked the muscle activity levels observed when performing a javelin throw (6 of 9 muscles), confirming the hypothesis of the current study. Furthermore, muscle activation levels were within 10% of JAV for upper trapezius, posterior deltoid, clavicular, and latissimus dorsi during BENT. Additionally, relative strength during BENT was significantly and largely related to throwing performance; as were absolute strength during CONV, STR, BENT, and half-squat to release velocity. Taken together, muscle activations depended on pullover variants, with BENT producing the greatest muscle activation levels and strongest correlations with throwing performance.

The level of muscle activity profile was dependent on the exercise variants, even though a similar load intensity was used for each pullover variant (i.e., 6 repetitions at 85% 1-RM) during the EMG recording sessions. The variation in execution altered the moment arm and muscle leverage (Hébert-Losier et al., 2012), and according to the concept of mechanical advantage, the BENT technique resulted in a greater amount of lifted load by the throwers. Specifically, during BENT, the load resistance was brought closer to the pivot point or 'fulcrum' via flexions of the elbows and shoulders, providing a shorter lever arm of the external load (Figure 2C). As a result, the absolute lifted load value for BENT in the present study was, on average, 18% and 46% greater than STR and CONV, respectively (see Results). Given that load increases have been shown to increase muscle activation (Pinto et al., 2013), this observation might reflect the load experienced by muscles and not merely the external load being lifted. Importantly, favourable changes in moment arm can lead to reduced muscle loading, allowing more external load to be lifted. Consequently, BENT resulted in a greater muscle activation than other pullover variants.

Table 3: Relationship (*r*) between maximum strength with release velocity and javelin throw performance, *p*-value, and descriptor.

| | CONV | STR | BENT | HS | BP |
|---|---|---|---|---|---|
| Absolute strength | | | | | |
| Release velocity | 0.78 | 0.79 | 0.80 | 0.77 | 0.68 |
| *p*-value | 0.040* | 0.036* | 0.032* | 0.045* | 0.093 |
| Descriptor | Very large | Very large | Very large | Very large | Large |
| Javelin throw performance | 0.59 | 0.63 | 0.66 | 0.45 | 0.21 |
| *p*-value | 0.164 | 0.126 | 0.104 | 0.308 | 0.669 |
| Descriptor | Large | Large | Large | Medium | Small |
| Relative strength | | | | | |
| Release velocity | 0.67 | 0.68 | 0.51 | 0.23 | 0.30 |
| *p*-value | 0.099 | 0.091 | 0.240 | 0.623 | 0.515 |
| Descriptor | Large | Large | Large | Small | Medium |
| Javelin throw performance | 0.55 | 0.65 | 0.85 | 0.18 | -0.17 |
| *p*-value | 0.204 | 0.112 | 0.016* | 0.696 | 0.722 |
| Descriptor | Large | Large | Very Large | Small | Trivial |

*Notes:* CONV = conventional pullover, STR = straight-arm pullover, BENT = bent-arm pullover, HS = half-squat, BP = bench press. *$p < 0.05$.

Regardless of the above, the individual ratio of pullover variants indicate BENT exercise was the closest to JAV, which implies "specificity" in muscle activation among the muscles involved during BENT and JAV actions. Upon close examination, pullovers and javelin throws may exhibit inconsistencies in terms of muscular engagement and techniques. Pullovers involve a bilateral exercise, and a relatively "slow pace" motion of the arms (adducted) towards the midline (Marchetti et al., 2011), whereas JAV is unilateral and involves a forceful movement of the arm away from the midline together with considerable body torsion or rotational movement (Murakami et al., 2006).

To our knowledge, no study has examined the relationships between pullover variants and throwing performance to understand their importance for training and sports performance, which limits comparisons to existing literature. However, both Marchetti and Uchida (2011) and Borges et al. (2018) have reported a higher activation of the pectoralis major when compared to the latissimus dorsi when performing the pullover exercise using lighter loads than those used in the current study. It was noted though that the bench press (68% MVIC) and lateral pulldown (60% MVIC) exercises enabled greater activation of the pectoralis major and latissimus dorsi, respectively, than the pullover (Borges et al., 2018). The present study extends these previous research findings by demonstrating similar results (i.e., greater activations of pectoralis major than latissimus dorsi) across the range of pullover variants examined. Interestingly, the activation levels of the latissimus dorsi in the STR condition (52% MVIC) approached those reported for the lateral pulldown by Borges et al. (2018). It is noteworthy that despite being the same exercise, performance on the unstable surface displayed a relatively greater peak muscle activity than CONV, except for the pectoralis muscles and triceps brachii. This observation agrees with findings that exercises on an unstable surface (e.g., using Swiss ball) either decreases, increases, or does not affect muscle activation levels when performed with some ground contact (de Mey et al., 2014), such as placing both legs on the floor, as done in the present study.

The relatively high activation levels of the pectoralis major (63% and 91% MVIC for sternal and clavicular, respectively) and upper trapezius (64% MVIC) found during JAV demonstrates the importance of these specific muscles during JAV. For each of these muscles, the BENT condition elicited the greatest activations, with 93 to 122% of the peak activity observed during the javelin throw (Figure 3). While we did not examine muscle activity during the bench press, the activation of the pectoralis major during the BENT condition was on average 84% MVIC compared to the 68% reported by Borges et al. (2018). Importantly, our study subsequently performed correlational analyses to examine the relationship between the strength during pullover variants – as a proxy for upper body strength – on release velocity and throwing performance.

We found some strong relationships between absolute and relative strength values with release velocity and throwing performance as shown in Table 3. An overhand exercise like javelin throwing is a complex action involving the whole body that is performed in a synchronised manner to generate a high release velocity and attain a greater throwing distance (van Muijen et al., 1991). Release velocity depends on four fundamental factors: technique, temporal coordination of actions of different body segments, muscular strength, and power of the upper- and lower-body (van Muijen et al., 1991). The best thrower in the current study produced the highest release velocity (23.9 m/s). For perspective during the 2009 World Championships, the average release velocity in men's javelin throw was 28.5 m/s, with the best performers (80+ m) reaching 29.4 m/s (Lehmann, 2010). Previous studies have highlighted the contributions of strength and power for enhanced throwing velocity and performance (e.g., Chelly et al., 201; Granados et al., 2007; Terzis et al., 2003; Terzis et al., 2007; Young, 2006). Our findings in javelin throwers align with an earlier study among professional handball players that reported a relationship between throwing velocity and maximal dynamic strength, peak power, and peak bar velocity during the bench press (Marques et al., 2007).

The present study found a stronger relationship between absolute strength with the release velocity and throwing performance versus relative strength (except BENT, Table 3). These findings suggest that increasing absolute strength levels can be considered as a precursor for the other strength qualities necessary to improve throwing performance (i.e., release velocity). Overall, the clear outcome of the present study is that the correlations between both absolute and relative strength with release velocity and throwing performance are large to very large (Table 3), which implies high levels of strength in the lower-body limbs and in the musculature involved in the pullover variants are important for javelin throwers.

The magnitude of the correlations between the strength exercises with release velocity and throwing performance in the present study suggests a potential dependency on "exercise specificity," which could contribute to better transference to performance (Washif & Kok, 2020). Despite bench press being traditionally considered an important upper-body exercise for throwing performance, our results indicate weaker relationships to throwing metrics compared to pullover variants and the half squat (Table 3). Thus, the outcomes of the present study suggest that pullover variants may be more relevant and similar to throwing performances involving shoulder extension, which contrasts with handball studies that reported the bench press exercise (elbow extension) as most relevant to the overhand throwing (Fleck et al., 1992; Granados et al., 2013). Specifically, the barbell pullover requires flexion (descending) and extension (ascending) of the shoulder, almost imitating an overhand throw movement such as the javelin throw; whereas the bench press exercise requires elbow flexion and shoulder horizontal adduction during the descending phase, and elbow extension and shoulder abduction during the ascending phase. Importantly, the relative strength in the BENT exercise variant was the only variable examined that significantly correlated with actual throwing performance. Overall, while our results suggest exercise specificity may play a role in throwing performance, further research with more targeted interventions is needed to confirm these findings and better understand the nuances of exercise selection and their impact on athletic performance.

Finally, our study presents limitations that should be considered when interpreting the findings. Due to the calibre and requirement of familiarity with the exercise variants, the sample size is relatively small. While this adds to the ecological validity, it does limit the ability to generalise to a larger population. We also acknowledge that collecting EMG data during the javelin throw, although wireless, may have influenced the skill execution. Throwing distance was taken from recent competitions that were competed in a different environment to allow for use of actual competitive throwing performance in the analysis. Even though we conducted separate MVICs for each of the nine muscles, it is also possible that a muscle may not reach maximal contraction during this task, which potentially affects the inter-muscular comparisons. Finally, while relative differences between muscles within the same individual were considered, caution should still be exercised in interpreting absolute EMG values. Furthermore, EMG is unable to directly measure force production, but instead provides insight into muscle activity patterns (Dick et al., 2024). Notably, EMG alone offers limited insight into muscle force or force-sharing strategies during dynamic contractions, as force also depends on biomechanical (e.g., specific tension, force-length, force-velocity) and physiological (e.g., cross-sectional area, fiber length, pennation angle) factors (Dick et al., 2024). The variability of EMG readings can be influenced by factors such as the precise placement of electrodes, skin impedance, and the potential for signal contamination from neighbouring muscles. It is important to note that electrode placement (or relocation) was not an issue in our study because we did not replace electrodes (see 'electrodes placement' section in the Methods). Furthermore, factors like variations in muscle lengths (e.g., exercise techniques), and movement velocity can also influence EMG data. EMG recordings are typically higher in dynamic contractions due to changes in muscle fiber length, differing neural control strategies, and lower recruitment thresholds (Tsai et al., 2014). Dynamic tasks, requiring more complex motor control and coordination, suggest that strong isometric performance may not translate to dynamic tasks if inter-muscular coordination is poor, and vice versa (Van Hooren et al., 2022). Therefore, EMG patterns can vary with muscle contraction types (concentric, eccentric, and isometric) and should be interpreted carefully (Tsai et al., 2014). These considerations are critical for interpreting EMG data accurately and understanding its implications for our findings.

In conclusion, exercise selection is one important variable for attaining athletic training aims and transference to performance. Our results suggest that for enhancing overhand throwing performance like the javelin throw, exercise selection such as the BENT condition is vital due to its similarity in muscle activation levels to actual throwing (JAV). We recommend including additional exercises targeting the upper trapezius and middle deltoid, and emphasising maximum strength development using pullover variants (especially BENT) and half squats. These recommendations are also due to their observed relationships with release velocity and throwing performance. Being bilateral and non-torsional (i.e., without body rotation), application of the pullover variants can form a fundamental basis, complementing other (unilateral and specific) exercises for a more effective training program.

## Conflict of Interest

The authors declare no conflict of interests.

## Acknowledgment

The authors sincerely thank the athletes, coaches (especially coach Mohamad Ali Hamid), and those who helped in the study (including Ms Ngieng Siew Yin), for their participation and contributions.

## References

Bartonietz, K. (2000). Javelin throwing: An approach to performance development. In: V. M. Zatsiorsky (Eds.). *Biomechanics in Sports: Performance enhancement and injury prevention.* Blackwell Science.

Borges, E., Mezencio, B., Pinho, J., Soncin, R., Barbosa, J., Araujo, F., Gianolla, F., Amadio, C., & Serrao, J. (2018). Resistance training acute session: pectoralis major, latissimus dorsi and triceps brachii electromyographic activity. *Journal of Physical Education and Sport, 18*(2), 648–653.

Chelly, M. S., Hermassi, S., & Shephard, R. J. (2010). Relationships between power and strength of the upper and lower limb muscles and throwing velocity in male handball players. *Journal of Strength and Conditioning Research, 24*(6), 1480–1487.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd Ed.). Lawrence Erlbaum.

de Mey, K., Danneels, L., Cagnie, B., Borms, D., T'Jonck, Z., Van Damme, E., & Cools, A. M. (2014). Shoulder muscle activation levels during four closed kinetic chain exercises with and without Redcord slings. *Journal of Strength and Conditioning Research, 28*(6), 1626–1635.

Dick T. J. M., Tucker, K., Hug, F., Besomi, M., van Dieën, J. H., Enoka, R. M., Besier, T., Carson, R. G., Clancy, E. A., Disselhorst-Klug, C., Falla, D., Farina, D., Gandevia, S., Holobar, A., Kiernan, M. C., Lowery, M., McGill, K., Merletti, R., Perreault, E., Rothwell, J. C., Søgaard, K., Wrigley, T., & Hodges, P. W. Consensus for experimental design in electromyography (CEDE) project: Application of EMG to estimate muscle force. *Journal of Electromyography and Kinesiology*, 79, 1–12.

Fleck, S. J., Smith, S. L., Craib, M. W., Denahan, T., Snow, R. E., & Mitchell, M. R. (1992). Upper extremity isokinetic torque and throwing velocity in team handball. *Journal of Applied and Sports Science Research, 6*, 120–124.

Granados, C., Izquierdo, M., Ibañez, J., Bonnabau, H., & Gorostiaga, E. M. (2007). Differences in physical fitness and throwing velocity among elite and amateur female handball players. *International Journal of Sports Medicine, 28*(10), 860–867.

Granados, C., Izquierdo, M., Ibanez, J., Ruesta, M., & Gorostiaga, E. M. (2013). Are there any differences in physical fitness and throwing velocity between national and international elite female handball players? *Journal of Strength and Conditioning Research, 27*, 723–732.

Hébert-Losier, K., Schneiders, A. G., Garcı´a, J. A., Sullivan, S. J., & Simoneau, G. G. (2012). Influence of knee flexion angle and age on triceps surae muscle activity during heel raises. *Journal of Strength and Conditioning Research, 26*(11), 3124–3133.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology, 10*(5), 361–334.

Hermassi, S., van den Tillaar, R., Khlifa, R., Chelly, M. S., & Chamari, K. (2015). Comparison of in-season-specific resistance vs. a regular throwing training program on throwing velocity, anthropometry, and power performance in elite handball players. *Journal of Strength and Conditioning Research, 29*(8), 2105–2114.

Leavy, C. M. (2004). Dumbbell pullover. *Strength and Conditioning Journal, 26*(2), 48–49.

Lehmann, F. (2010). Biomechanical analysis of the javelin throw at the 2009 IAAF World Championships in athletics. *New Studies in Athletics, 25*(3/4),61–77.

Marchetti, P. G., & Uchida, M. C. (2011). Effects of the pullover exercise on the pectoralis major and latissimus dorsi muscles as evaluated by EMG. *Journal of Applied Biomechanics, 27*, 380–384.

Marques, M. C., van den Tilaar, R., Vescovi, J. D., & Gonzalez-Badillo, J. J. (2007). Relationship between throwing velocity, muscle power, and bar velocity during bench press in elite handball players. *International Journal of Sports Physiology and Performance, 2*(4), 414–422.

Murakami, M., Tanabe, S., Ishikawa, M., Isolehto, J., Komi, P. V., & Ito, A. (2006). Biomechanical analysis of the Javelin at the 2005 IAAF World Championships in athletics. *New Studies in Athletics, 21*, 67–80.

Haff, G. G., & Triplett, N. T. (Eds.) (2015). *Essentials of strength training and conditioning* (4th ed.). Human Kinetics.

Ogiolda, P. (1993). The javelin throw and the role of speed in throwing events. *New Studies in Athletics, 8*(3), 7–13.

Pinto, R., Cadore, E., Correa, C., da Silva, B. G. C., Alberton, C. L., Lima, C. S., & de Moraes, A. C. (2013). Relationship between workload and neuromuscular activity in the bench press exercise. *Medicina Sportiva, 17*, 1–6.

Terzis, G., Georgiadis, G., Vassiliadou, E., & Manta, P. (2003). Relationship between shot put performance and triceps brachii fiber type composition and power production. *European Journal of Applied Physiology, 90*(1–2), 10–15.

Terzis, G., Karampatsos, G., & Georgiadis, G. (2007). Neuromuscular control and performance in shot-put athletes. *Journal of Sports Medicine and Physical Fitness 47*(3), 284–290.

Tsai, A. C., Hsieh, T. H., Luh, J. J., Lin, T. T. (2014). A comparison of upper-limb motion pattern recognition using EMG signals during dynamic and isometric muscle contractions. *Biomedical Signal Processing and Control, 11*, 17–26.

van Hooren. B., Kozinc, Ž., Smajla, D., & Šarabon, N. (2022). Isometric single-joint rate of force development shows trivial to small associations with jumping rate of force development, jump height, and propulsive duration. *JSAMS Plus, 1*, 1 – 8.

van Muijen, A. E., Jorisa, H., Kemperb, H. C. G., & van Ingen Schenau, G. J. (1991). Throwing practice with different ball weights: effects on throwing velocity and muscle strength in female handball players. *Sports Medicine, Training and Rehabilitation, 2*(2), 103–113.

Washif, J. A., & Kok, L. Y. (2020). The reactive bounding coefficient as a measure of horizontal reactive strength to evaluate stretch-shortening cycle performance in sprinters. *Journal of Human Kinetics, 21*(73), 45–55.

Washif, J. A., & Kok, L. Y. (2022). Relationships between vertical jump metrics and sprint performance, and qualities that distinguish between faster and slower sprinters. *Journal of Science in Sports and Exercise, 4*, 135–144.

Washif, J. A., Hébert-Losier, K., Gill, N., Zainuddin, M., Nasruddin, S., Zakaria, A. Z., & Beaven, C. M. (2024). Reliability, interrelationships, and minimal detectable changes of strength and power metrics among well-trained Rugby Sevens players. *Biology of Sport 41*(3), 231–241.

Young, M. (2001). Developing event-specific strength for the javelin throw. *Track Coach 13*, 4921–4931.

Young, W. B. (2006). Transfer of strength and power training to sports performance. *International Journal of Sports Physiology and Performance, 1*(2), 74–83.

Zaras, N., Spengos, Z., Methenitis, S., Papadopoulos, C., Karampatsos, G., Georgiadis, G., Stasinaki, A., Manta, P., & Terzis, G. (2013). Effects of strength vs. ballistic-power training on throwing performance. *Journal of Sports Science and Medicine, 12*, 130–137.

## Supplemental material

Supplementary Table 1: Step by step protocols of pullover exercise variants.

| Pullover exercise variant | Step by step protocol |
|---|---|
| Conventional Pullover | *Starting Position*<br>1. Lie down on a (flat or incline) bench ensuring five point contact with the bench or floor.*<br>2. Grasp a barbell (e.g., E-Z curl barbell) with both hands, using pronated grips, with both arms fully extended above your chest. Your grips/palms face internally (~45 degrees) when using E-Z curl barbell.<br>*Descent Phase*<br>1. Inhale as you gradually lower the barbell behind your head, maintaining an unlocked elbows (slightly bend).<br>2. Continue to lower the barbell until you feel a stretch in your chest and shoulders.<br>3. Align your arms so that they are parallel to or slightly below your torso.<br>*Ascent Phase*<br>1. Gradually lift the weight back to the initial position, following the same trajectory during the lowering phase. Exhale at the 'sticking point' (the heaviest part).<br>2. Keep your elbows unlocked throughout the movement.<br>*5-point contacts: (1) back of head, (2) shoulder blades/upper back region, (3) gluteal, (4) right foot, and (5) left foot. |
| Straight-Arm Pullover | *Starting Position*<br>1. Lie down on a (flat or incline) bench ensuring five point contact with the bench or floor.<br>2. Grasp a barbell (e.g., E-Z curl barbell) with both hands, using pronated grips, with both arms fully extended above your chest. Your grips/palms face internally (~45 degrees) when using E-Z curl barbell.<br>*Descent Phase*<br>1. Inhale as you gradually lower the barbell behind your head, maintaining an unlocked elbows (slightly bend).<br>2. Continue to lower the barbell.<br>3. As the barbell reaches a position almost parallel to the torso, raise your glutes and simultaneously lower the barbell further in a controlled manner to maximise the stretch.<br>*Ascent Phase*<br>1. Gradually lift the barbell back to the initial position, simultaneously lowering the gluteus, following the same trajectory during the lowering phase. Exhale at the 'sticking point' (the heaviest part).<br>2. Keep your elbows unlocked throughout the movement. |
| Bent-Arm Pullover | *Starting Position*<br>1. Lie down on a (flat or incline) bench ensuring five point contact with the bench or floor.<br>2. Grasp a barbell (e.g., E-Z curl barbell) with both hands, using pronated grips, with both arms fully extended above your chest. Your grips/palms face internally (~45 degrees) when using E-Z curl barbell.<br>*Descent Phase*<br>1. Inhale as you gradually bend and lower the barbell behind your head.<br>2. As the barbell reaches a position almost parallel to the torso, with elbows bent at approximately 45 degrees, raise your glutes and simultaneously lower the barbell further in a controlled manner to maximize the stretch.<br>3. Keep the elbows bent or extend them slightly to reach further down and further maximise the stretch.<br>*Ascent Phase*<br>1. Gradually lift the barbell back to the initial position, simultaneously lowering the gluteus, following the same trajectory during the lowering phase. Exhale at the 'sticking point' (the heaviest part). |
| Conventional Pullover on an Exercise Ball | Similar to conventional pullover with 3-point contacts (upper back, right foot, and left foot) performed on an exercise ball (or unstable surface) |

Supplementary Table 2: Electrode positions based on SENIAM recommendations (Hermens et al., 2000) available at www.seniam.org, and other sources.

| Electrode positions | Recommendations |
|---|---|
| Upper trapezius | 50% on the line from the acromion to the spine on vertebra C7.[1] |
| Anterior deltoid | One finger width distal and anterior to the acromion.[1] |
| Middle deltoid | The greatest bulge of the muscle (from the acromion to the lateral epicondyle of the elbow).[1] |
| Posterior deltoid | About two finger breaths behind the angle of the acromion.[1] |
| Triceps brachii | 50 % on the line between the posterior crista of the acromion and the olecranon at 2 finger widths medial to the line.[1] |
| Pectoralis clavicular portion | Placed medially along the belly of the clavicular part.[2,3] |
| Pectoralis sternal portion | Placed medially along the imaginary angle bisector (that forms a boundary) of the sternal part.[2,3] |
| Latissimus dorsi | 4 cm below the inferior tip of the scapula, and midway between the spine and lateral edge of the torso; oblique angle (throwing side).[4] |
| Rectus abdominus | 3 cm from the sagittal plane and 5 cm above the umbilicus.[5] |

---

[1] Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology, 10*(5), 361–334.

[2] Król, H., Sobota, G., & Nawrat, A. (2007). Effect of electrode position on EMG recording in pectoralis major. *Journal of Human Kinetics, 17*, 105–111.

[3] Lee, H. M. (2019). Force direction and arm position affect contribution of clavicular and sternal parts of pectoralis major muscle during muscle strength testing. *Journal of Hand Therapy*, *32*(1), 71–79.

[4] Park, S. Y., & Yoo, W. G. (2013). Comparison of exercises inducing maximum voluntary isometric contraction for the latissimus dorsi using surface electromyography. *Journal of Electromyography and Kinesiology*, *23*(5), 1106–1110.

[5] Moraes, A. C., Pinto, R. S., Valamatos, M. J., Valamatos, M. J., Pezarat-Correia, P. L., Okano, A. H., Santos, P. M., & Cabri, J. M. (2009). EMG activation of abdominal muscles in the crunch exercise performed with different external loads. *Physical Therapy in Sport, 10*(2), 57–62.