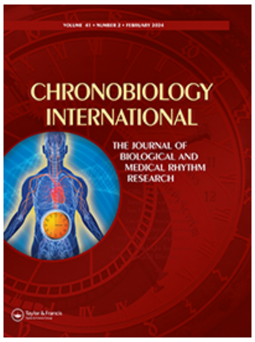

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Sleep architecture of elite soccer players surrounding match days as measured by WHOOP straps

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ABSTRACT

This study aimed to quantify and compare sleep architecture before and after home and away matches in elite soccer players from the English Premier League. Across two seasons, 6 male players (age 28 ± 5 y; body mass 85.1 ± 9.5 kg; height 1.86 ± 0.09 m) wore WHOOP straps to monitor sleep across 13 matches that kicked off before 17:00 h. For each, sleep was recorded the night before (MD_{-1}), after (MD) and following the match (MD_{+1}). Across these 3 days total sleep time (TST), sleep efficiency (SE), sleep disturbances, wake time, light sleep, deep sleep, REM sleep, sleep and wake onsets, alongside external load, were compared. TST was reduced after MD versus MD_{+1} (392.9 ± 76.4 vs 459.1 ± 66.7 min, $p = 0.003$) but no differences existed in any other sleep variables between days ($p > 0.05$). TST did not differ after home (386.9 ± 75.7 min) vs. away matches (401.0 ± 78.3 min) ($p = 0.475$), nor did other sleep variables ($p > 0.05$). GPS-derived external load peaked on MD ($p < 0.05$). In conclusion, despite reduced TST on MD, sleep architecture was unaffected after matches played before 17:00 h, suggesting sleep quality was not significantly compromised.

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Sleep; sleep architecture; soccer; competition; training load; match location

Introduction

Sleep is essential for overall health and well-being. The National Sleep Foundation (NSF) recommends 8–10 h sleep for 14–17 year olds, and 7–9 h for those over 18 years old (Hirshkowitz et al. 2015). Several studies suggest that athletes have impaired sleep (Randell et al. 2021) compared to the general population (Leeder et al. 2012), often not achieving the recommended hours of sleep required per night (Randell et al. 2021; Richmond et al. 2007; Sargent et al. 2014; Watson et al. 2015). In addition, sleep quality, measured subjectively with surveys or objectively with actigraphy, may be worse in athletes; indeed, Leeder et al. (2012) found that sleep efficiency (SE) was lower, and sleep onset latency (SOL) longer, in Olympic athletes compared to age-matched non-athletes. Conversely, Whitworth-Turner et al. (2018) reported longer sleep duration in youth soccer players than controls, suggesting differences in sleep quantity between sports and age groups. However, the consensus from a recent systematic review by Vlahoyiannis et al. (2021) was that sleep duration and SE, especially in junior athletes (~80%), was markedly lower in athletes than recommended levels (7.2 ± 1.1 h and 86.3 ± 6.8%). Where sleep quality may be worse in athletes, the consequences of sleep loss might be greater than in the general population as it may adversely affect growth, tissue repair, and physical and mental performance, which are vital for their sport (Davenne 2009).

The consequences of poor sleep quality and reduced sleep quantity are still being elucidated in elite athletes but may include impaired physical performance similar to that which occurs with total or partial sleep deprivation (Morselli et al. 2010; Mougin et al. 2001). These impairments include effects on cognitive performance (Huber et al. 2004; Killgore 2010) and altered psychological status (Hrozanova et al. 2021). Post-exercise recovery responses may also be negatively affected as changes in hormonal patterns increase protein degradation, compromising muscle protein synthesis (Dáttilo et al. 2020). Elevated levels of creatine kinase (Russell et al. 2015), commonly associated with muscle damage, and muscle soreness (Nédélec et al. 2014) exist following matches in elite soccer players, and glycogen levels in individual muscle fibres are depleted after soccer matches (Krustrup et al. 2006). Restoration of muscle glycogen and repair of damaged tissue are physiological functions reliant on good quantity and quality of sleep (Dattilo et al. 2011; Mohr et al. 2022). Weakened or damaged tissue is more susceptible to injury (Almekinders and Gilbert 1986) and accordingly, lower sleep durations in adolescent athletes

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are associated with increased injury risk (Milewski et al. 2014). The same has been seen in a soccer case study by Nédélec et al. (2019), where the athlete in question had reduced sleep quality compared to baseline in the week and night prior to injury. In subjective studies, Fullagar et al. (2016) showed that players obtained less sleep following night matches, and this was associated with lower perceived recovery. Given these important roles of sleep for general health and athletic performance, there is growing interest in the sleep patterns of elite athletes.

Sleep quality in soccer players has been examined both subjectively with surveys (Fullagar et al. 2016; Thorpe et al. 2015), and objectively with actigraphy (Carriço et al. 2018; Fowler et al. 2014, 2015; Fullagar et al. 2016; Nédélec et al. 2019). These studies have suggested various situational match factors that can affect sleep. For example, night matches (Carriço et al. 2018; Fullagar et al. 2016; Nédélec et al. 2019) and travel (P. Fowler et al. 2015; Fullagar et al. 2016) both reduce total sleep time (TST). Away matches (Carriço et al. 2018) and match losses (Fessi and Moalla 2018) can also negatively affect sleep in elite soccer players, as can caffeine consumption (Drake et al. 2013). The physiological demands of soccer, which is greatest on match-day, may also influence TST (Lastella et al. 2022; Shearer et al. 2015). However, external load is unlikely the only factor that could influence sleep; indeed, other psychological factors surrounding match days, including media, social or family commitments, could also influence post-match sleep.

Despite growing interest, there is currently limited research on the sleep patterns of elite soccer players, such as those playing in both the English Premier League (EPL) and Europe's top competition, the Union of European Football Association Champions League (UCL). Competing in both these competitions necessitates that multiple matches are played per week for large parts of the season, putting extra importance on expeditious recovery. There is also a requirement to travel further, across time zones, and more frequently than teams playing in domestic competitions alone. Lastella et al. (2019) investigated players in the Asian Champions League, showing disrupted sleep following games and compromised sleep when they were required to travel during an intense fixture schedule. The negative effects of travel and away matches on sleep quality and quantity are well documented (Fowler et al. 2014, 2017; Fullagar et al. 2016) but further research is needed to understand the sleep patterns of soccer players who compete in the EPL and UCL, and subsequently establish if interventions to optimise sleep are needed.

Actigraphy and subjective questionnaires are the most common methods used for sleep monitoring in elite athletes. However, a limitation of these methods is that neither measure sleep architecture; specifically, rapid eye movement sleep (REM), which is integral to emotion regulation, memory, and learning (Miller and Gehrman 2019), and non-rapid eye movement (NREM) sleep (light and deep sleep), which is integral for many restorative homeostatic physiological processes (Imeri and Opp 2009). Following training and match days, increased deep sleep might be expected to increase in order to reduce the sleep pressure accumulated from completing more activity (Borbély and Achermann 1999), hence aiding the required recovery. New technologies are now available that can measure sleep architecture without the need for polysomnography, which is expensive, time-consuming, and not feasible for regular use in elite populations. Recent studies have shown that the WHOOP strap, a wearable device that uses heart rate, beat-to-beat intervals and accelerometery to determine sleep time, wake time and three sleep stages (light, deep/slow wave and REM), is a reasonable method for estimating sleep architecture compared to the gold standard polysomnography, and is comparable to research-grade wearables (Miller et al. 2020, 2021). Thus, the WHOOP could be a useful tool for characterising sleep architecture in athletes, where polysomnography is unsuitable.

To date, no studies have used non-invasive devices that allow the measurement of sleep architecture in elite soccer players. There are also no studies in elite athletes using the WHOOP strap. Thus, the main aim of this study was to quantify the sleep patterns and architecture of elite soccer players from a squad competing in the EPL and UCL surrounding a match-day. A secondary aim was to examine the influence of match location (home vs. away) on these variables. We also measured external load on these match days to determine if there were any differences before and after matches, and thus whether these may explain any differences in sleep on these days. We hypothesized that sleep duration and architecture would be negatively affected by match days and compromised further after away compared to home matches. We also hypothesized that external load would be greatest on match days.

Methods

Participants

Six elite male outfield soccer players (age 28 ± 5 y; body mass 85.1 ± 9.5 kg; height 1.86 ± 0.09 m) competing in both the EPL and UCL provided written informed consent to take part in this research. Players not involved in the relevant match day squad, or who had < 2 matches worth of sleep data available, were excluded from analysis. All the data used in this research are routinely collected by the Club. Ethical approval was granted by the Loughborough University Ethics Committee.

Experimental procedures

Player's sleep was monitored over two competitive seasons (2021–2022 and 2022–2023). Sleep was recorded on the night before the match (MD_{-1}), on the night following match-day (MD) and the night after (MD_{+1}) (3 days in total). Monitoring was restricted to these 3 days to avoid overlap between matches caused by frequent ≤ 2 or 3-day recovery periods between matches. For consistency, matches with kick off (KO) times after 17:00 were also excluded, leaving 13 matches available for analysis. KO times were restricted as late returns from evening matches decreases sleep quantity, due to less opportunity to sleep. The KO times included in the study were 12:30, 15:00, 16:00 and 16:30. As such, 156 data points were analysed with 52 player-match combinations, across the 6 players. Of these, 10 examples were included where the player was not involved in the match as either a starting player or as a substitute. For these data points, if no post-match running was performed, GPS variables were set at 0. From the 13 matches analysed, 7 were played at home and 6 away. It is worth noting that, for the matches observed in this study, all MD_{-1} nights were spent in a hotel. The average distance travelled for the away games was 170 km (±134 km), calculated as the most direct path between respective football stadia. All matches analysed were domestic fixtures.

Sleep collection and analysis

The athletes sleep patterns were monitored using a wrist-band WHOOP device (Generation 4.0 hardware, Generation 4.0 algorithm, CB Rank, Greater Boston, New England, USA), which combines heart rate, beat to beat intervals and accelerometery to determine sleep stages effectively (Berryhill et al. 2020). The players wore the WHOOP straps continuously throughout both the daytime (including water-based activity) and night-time, allowing automatic detection (WHOOP AUTO) of sleep onset. The straps were worn on their wrist, immediately superior to the bony prominence at the head of the ulna, as per WHOOP guidance. Players self-selected which wrist to wear the monitor on. Once paired with the athlete's smartphone via the WHOOP application, the data were automatically downloaded and uploaded to the Cloud following wake onset, assuming connection to an internet signal. The complete dataset was then exported to Microsoft Excel for analysis.

The measures analysed in the current study were TST, SE, frequency of sleep disturbances, light (N1 and N2) and deep (N3) sleep, which are NREM stages, REM sleep, wake time, sleep onset, and wake onset. Light, deep, and REM sleep were analysed as a percentage of total sleep time. The three sleep stages (light, deep and REM), and measures of wake and TST, from the WHOOP strap, were analysed as they have moderate to good validity and reliability when compared to the gold standard method, polysomnography (Miller et al. 2020). SOL was not analysed due to the inaccuracies associated with automatic detection when getting into bed is not recorded or inputted (Miller et al. 2021), since the WHOOP strap cannot independently determine when a person gets in to bed. Naps were not included in the analysis due to similar difficulties with automatic detection and the minimum duration set by WHOOP automatically. Definitions for each sleep variable measured are displayed in Table 1. Sleep onset and wake onset are noted as HH:MM:SS in results and thereafter.

External load collection

External load measures were monitored on all training and match days. Global Position Systems (GPS) units were used to capture external load at 10 Hz for training (Apex Units, StatSports, Newry, N. Ireland) and video tracking was used for matches (Second Spectrum, Los Angeles, USA & Hawkeye, Basingstoke, England). Previously calculated conversion factors were applied to the match data to make it compatible and comparable with GPS data. The variables analysed were total distance (TD), high-speed distance (over 5.5 m/s; HSD), sprint distance (over 7 m/s; SD), accelerations over 3 m/s/s (ACC) and decelerations over 3 m/s/s (DEC). Definitions for all GPS metrics are noted in Table 1.

Data analysis

The sleep measures from the observed nights were compared using linear mixed models (LMM). Normal distribution of data was assessed by inspecting histograms and Q-Q plots of the residuals. For each linear mixed model, the sleep parameter was selected as the dependent variable, and day type (MD_{-1}, MD, MD_{+1}) as the independent variable. Player ID was selected as a random variable, and day type as a fixed factor, with both random intercepts and random slopes assigned for each player. Any post-hoc tests for significant differences were carried out using Holm-Bonferroni

Table 1. Definition of each sleep and external load metric measured.

Term, abbreviation	Definition
TST (mins)	Time spent asleep determined from sleep onset to wake onset, minus any wake time.
Sleep disturbances (No.)	Episodes of wakefulness lasting less than 4 minutes.
SE (%)	Percentage of time spent asleep between sleep onset and wake onset.
REM sleep (%)	Percentage of TST spent in REM sleep, between the start and end of sleep.
Deep sleep (%)	Percentage of TST spent in deep sleep, between the start and end of sleep.
Light sleep (%)	Percentage of TST spent in light sleep, between the start and end of sleep.
Wake time (%)	Percentage of time spent awake between sleep onset and wake onset, between the onset and end of sleep.
Sleep onset (hh:mm:ss)	Time of initial onset of sleep.
Wake onset (hh:mm:ss)	Time of final awakening.
TD (m)	Total distance covered in training/game.
HSD (m)	Distance covered in training/game over threshold of 5.5 m/s.
SD (m)	Distance covered in training/game over threshold of 7 m/s.
ACC (No.)	Accelerations registering over threshold of 3 m/s/s.
DEC (No.)	Decelerations registering over threshold of 3 m/s/s.

TST, total sleep time; SE, sleep efficiency; REM, rapid eye movement; TD, total distance; HSD, high speed distance; SD, sprint distance; ACC, accelerations; DEC, decelerations.

adjustments. This analysis was repeated for home vs. away matches, for the single night after the match (MD), where the sleep marker was selected as the dependent variable, and match location as the independent variable. Player ID was set as a random variable and match location as a fixed factor, with random intercepts and random slopes for each player. There were minor deviations in normality for sleep efficiency, % awake, TD, HSD, SD, ACC, and DEC. These data were log transformed but this did not alter the distribution; therefore, LMM analysis was conducted with the raw data as there was no suitable equivalent non-parametric test. As the deviations were only minor, this approach was considered the most appropriate, given the applied outcomes in our study and the fact that LMM are widely considered robust against minor deviations in normal distribution (Schielzeth et al. 2020). All analyses were completed in Jamovi (The Jamovi project (2022). *Jamovi* (Version 2.3) [Computer Software]. Retrieved from https://www.jamovi.org). Effect sizes were included for all pairwise comparisons; Hedges' g was used due to the small sample size (Grissom and Kim 2005), and the following thresholds were set for small, medium and large effects, respectively; 0.2, 0.5 and 0.8 (Hedges and Olkin 1985). 95% confidence intervals are provided for *post-hoc* pairwise comparisons; these are the unadjusted values. Statistical significance was set at $p < 0.05$.

We did not perform an *a priori* power analysis for this study, because the limited number of players in the squad meant our sample size was inherently constrained. We instead performed a sensitivity power analysis to estimate the smallest effect size we could observe given our sample size of 6 (GPower 3.1.9.2, Dusseldorf, Germany). In a within-subject design, at 80% power, and an alpha of 0.05, we could only detect large (statistically significant) effects between the 3 time-points (η_p^2: 0.56). We acknowledge that the small sample size is a limitation of this research and limits our ability to detect small effects. However, we have, where possible, followed the recent guidance on how to optimise data analysis on small samples in football (Hecksteden et al. 2022); specifically, given the exclusivity of the participants, at the data collection stage we collected data at multiple time-points and each participant was their own matched control and, at the analysis stage, we used LMM, to allow for random individual variation around the fixed effects (e.g. match day). Indeed, whilst most previous studies in soccer players have only analysed data collected from one match or training week (Fowler et al. 2015; Fullagar et al. 2016), our observations are based on several different matches and training weeks, increasing the robustness of our findings. We would also like to highlight that this is the first data to examine sleep architecture, with these methods, in soccer players at this level, and therefore the data and effect sizes not only provide new insights into sleep in this setting, but they can also be used in a future meta-analysis.

Results

Sleep

The players went to sleep at 00:15:16 ± 01:00:16 on MD_{-1}, 00:47:21 ± 01:27:31 on MD and 23:45:36 ± 01:07:21 on MD_{+1}. The players woke at 08:53:47 ± 00:40:45 after MD_{-1}, 08:14:18 ± 01:05:23 after MD and 08:33:15 ± 01:04:11 after MD_{+1}. Sleep data separated by day are presented in Table 2. There was a significant effect of day type on TST; post-hoc tests revealed that TST on MD was lower than on MD_{+1} ($p = 0.003$, 95% CI, −100 to −29, $g = 0.92$ (large)), with no difference between MD_{-1} and MD ($p = 0.051$, 95% CI, 11 to 114, $g = 0.85$ (large)) or MD_{-1} and MD_{+1} ($p = 0.938$, 95%, CI −63 to 59, $g = 0.07$ (none)). However, there were no significant

Table 2. Sleep variables in professional soccer players across three nights; before matches, after matches and nights following the day after matches.

	Day			
Variable Nights#	MD_{-1} 52	MD 52	MD_{+1} 52	*p*-value
TST (mins)	454.3 ± 66.7	392.9 ± 76.4	459.1 ± 66.7	0.003*
Sleep efficiency (%)	87.8 ± 7.2	88.4 ± 7.0	88.0 ± 8.7	0.844
Sleep disturbances	12.4 ± 4.2	11.7 ± 3.5	13.8 ± 4.6	0.212
% REM sleep	26.7 ± 8.8	25.5 ± 7.7	23.7 ± 9.1	0.366
% Deep sleep	23.2 ± 4.7	22.1 ± 5.7	23.0 ± 4.7	0.541
% Light sleep	50.0 ± 9.6	52.4 ± 7.7	53.3 ± 9.1	0.442
% Awake	14.7 ± 10.0	13.9 ± 12.7	15.3 ± 15.1	0.771

Data are mean ± standard deviation. *indicates significant differences between match day types ($p < 0.05$). TST, total sleep time; REM, rapid eye movement; MD, match-day; MD_{-1}, day before match-day; MD_{+1}, day after match day. #Number of nights used for analysis.

Table 3. Sleep variables in professional soccer players following match play with different match locations.

	Game location			
Variable Nights#	Home 30	Away 22	*p*-values	Hedges *g*
TST (mins)	386.9 ± 75.7	401.0 ± 78.3	0.475	0.02
Sleep efficiency (%)	88.4 ± 8.1	88.4 ± 5.2	0.820	0.00
Sleep disturbances	11.7 ± 3.3	11.6 ± 3.9	0.702	−0.03
% REM sleep	24.1 ± 8.0	27.4 ± 6.9	0.121	0.43
% Deep sleep	22.2 ± 6.2	22.0 ± 5.1	0.944	−0.03
% Light sleep	53.7 ± 8.3	50.6 ± 6.5	0.148	−0.04
% Awake	14.6 ± 15.5	13.1 ± 7.6	0.746	−0.12

Data are mean ± standard deviation. TST, total sleep time; REM, rapid eye movement. #Number of nights used for analysis.

between-day differences for any of the other sleep metrics (Table 2).

The players went to sleep at 00:41:13 ± 01:20:00 following home matches and at 00:55:43 ± 01:38:09 following away matches. The players woke at 08:02:01 ± 01:04:18 on MD + 1 following home matches and at 08:31:03 ± 01:04:32 following away matches. There were no significant differences in the sleep variables between home and away matches (Table 3).

External load

Results for external load measures are displayed in Table 4. There were significant differences for all external load measures, with large (g > 0.80) effects between day types for all significant post-hoc comparisons except between MD_{-1} and MD for ACC, which showed a medium difference (g = 0.69) as reported below. Post-hoc tests revealed TD was significantly different between MD_{-1} and MD ($p = 0.008$, 95% CI, −6439 to −1515, $g = 1.26$), MD and MD_{+1} ($p = 0.003$, 95% CI, 3877 to 9408, $g = 2.10$), and the two training days, MD_{-1} and MD_{+1} ($p < 0.001$, 95% CI, 1352 to 3979, $g = 2.16$). HSD was significantly different between MD_{-1} and MD ($p = 0.008$, 95% CI, −747 to −275, $g = 1.89$), MD and MD_{+1} ($p = 0.008$, 95% CI, 292 to 842, $g = 2.09$), but not between MD_{-1} and MD_{+1} ($p = 0.165$, 95% CI, −52 to 164, $g = 0.78$). SD was significantly different between MD_{-1} and MD ($p = 0.033$, 95% CI, −229 to −49, $g = 1.54$), MD and MD_{+1} ($p = 0.033$, 95% CI, 47 to 250, $g = 1.64$), but not MD_{-1} and MD_{+1} ($p = 0.360$, 95% CI −20 to 40, $g = 0.45$). ACC were significantly between MD_{-1} and MD ($p = 0.040$, 95% CI, −36 to 0, $g = 0.69$), MD and MD_{+1} ($p = 0.015$, 95% CI, 19 to 68, $g = 1.50$), and between MD_{-1} and MD_{+1} ($p = 0.015$, 95% CI, 10 to 41, $g = 1.27$), and DEC were also significantly different between MD_{-1} and MD ($p = 0.017$, 95%, CI −58 to −15, $g = 1.37$), MD and MD_{+1} ($p = 0.014$, 95% CI, 24 to 74, $g = 1.73$), and MD_{-1} and MD_{+1} ($p = 0.017$, 95% CI, 0 to 25, $g = 0.82$).

Table 4. GPS variables in professional soccer players across three days.

	Day			
Variable Nights#	MD_{-1} 52	MD 52	MD_{+1} 52	p-values
TD (m)	3279.8 ± 810.4	6783.4 ± 3804.0	690.8 ± 1475.3	<0.001*
HSD (m)	72.8 ± 63.2	545.7 ± 344.9	24.4 ± 59.3	0.002*
SD (m)	12.0 ± 16.9	134.3 ± 110.0	4.4 ± 16.8	0.013*
ACC (No.)	33.1 ± 13.6	49.2 ± 29.6	9.1 ± 22.6	0.007*
DEC (No.)	18.7 ± 10.5	50.9 ± 31.3	7.0 ± 17.1	0.004*

Data are mean ± standard deviation. *indicates significant differences between match day types. TD, total distance; HSD, high speed distance; SD, sprint distance; ACC, high intensity accelerations; DEC, high intensity decelerations; MD, match-day; MD_{-1}, day before match-day; MD_{+1}, day after match day. #Number of nights used for analysis.

Discussion

The primary aim of this study was to quantify sleep architecture before and after match-days in a group of elite soccer players competing in the EPL and UCL. The main findings were that players slept less on MD compared to MD_{+1}, but there was no difference in sleep architecture or any other sleep variables. The players also slept less on MD compared to MD_{-1} but the difference was not statistically significant. Sleep was unaffected by match location.

The NSF suggests that young adults and adults should obtain at least 7 h (420 min) sleep per night (Hirshkowitz et al. 2015). The soccer players in the current study slept on average 435 min across the 3 days monitored, but only 393 min following MD; this meant the soccer players did not meet the recommended 7 h on MD. These durations are in line with sleep patterns previously reported in soccer players; for example, in Carriço et al. (2018), soccer players from the Portuguese top division averaged 396 min of sleep on training days and 349 min following match days. Similarly, Nédélec et al. (2019) found lower TST on match days when compared to training days in Ligue 1 soccer players also playing in the UCL. In Fullagar et al. (2016), soccer players from the Bundesliga (Germany) and Eredivisie (the Netherlands) slept markedly less the night following evening (KO after 18:00 h) matches (~343 min) versus day (concluded before 18:00 h) matches (~500 min). Sleep was not measured after matches with later KO times, but based on these previous findings, TST may have been even lower after evening matches, due to later arrival at home and closer proximity of physical and psychological stimulation to bedtime. More research is warranted on the impact of day vs. evening KO times on sleep quality, especially sleep architecture.

The later sleep onset on MD most likely reduced TST compared with MD_{+1}. Later bedtimes (>00:00 h), were also reported by Nédélec et al. (2019) and Carriço et al. (2018) on training days in elite soccer players. There are several possible reasons why players may sleep later on MD. One explanation is that exposure to bright light at football stadia, which suppresses melatonin and hence influences circadian rhythm (Cajochen, 2007), could have delayed the onset of sleepiness following matches. Other factors known to affect sleep quantity and/or quality such as caffeine intake (Drake et al. 2013) and psychological or physical arousal (Gupta et al, 2017) could also explain the later sleep onset. Lower TST following matches could negatively affect subsequent physical performance (Walsh et al, 2021), via reduced restoration of muscle glycogen (Mohr et al. 2022) and/or impaired regeneration of damaged muscle tissue (Dattilo et al. 2011). Thus, strategies to promote sleep following matches may be warranted, especially during periods of fixture congestion where injury rates are higher (Dellal et al. 2015).

Despite differences in TST, we found no difference in sleep architecture between days. Deep sleep and REM sleep have important implications for muscular recovery (Léger et al. 2018), memory consolidation (Diekelmann and Born 2010) and cognitive function (Léger et al. 2018); all likely important for optimisation of soccer performance in training and matches. To the best of our knowledge, this is the first study to compare sleep architecture across different days in elite adult soccer players, so direct comparison to previous studies is not possible. However, the average deep sleep percentage of ~ 29% across the three days is above the 16–20% recommended by the National Sleep Foundation (Ohayon et al. 2017). Sargent et al. (2013) used polysomnography to measure sleep quality in elite young soccer players and reported that, at baseline, ~23% of the night was spent in REM sleep and ~ 27% in deep sleep, broadly comparable to the present study. Besides this, Brand et al. (2010) found long-term changes in brain activity and higher sleep quality following vigorous training regimes of young soccer players when compared to controls. More acutely, it has previously been shown that deep sleep increases following strenuous activity (Shapiro et al, 1981), but no increase was found in the present study despite higher external load on MD across all parameters. Similarly, Knufinke et al. (2018), found no effect of training load on sleep architecture in elite athletes, including soccer players. Although exercise can delay the onset of REM sleep and reduce total REM sleep in elite athletes (Netzer et al. 2001), the longer duration between match completion and sleep onset in the current study could have prevented any marked disruption to REM sleep (Youngstedt et al. 1997). Homeostatic recovery appeared not to be fully compromised following the higher external load on MD, with no difference in deep sleep between days despite expectations (Borbély and Achermann 1999; Borbély et al. 2016). This is an interesting and novel finding, as previous studies in soccer players have not included measures of sleep architecture (Carriço et al. 2018; Nédélec et al. 2019). It is also important to note that staying in a hotel on MD_{-1} seemingly had no effect on sleep architecture or TST.

Contrary to Carriço et al. (2018) findings, where players from the Portuguese top division had higher TST following away matches, match location did not affect sleep in the present study. Interestingly, Carriço et al. (2018) suggested that the lower TST found following home matches could be due to more social opportunities than after away matches. By contrast, in elite Australian rules football, a reduced TST was reported following away matches (Sargent et al. 2022), where travel requirements partly dictate a later bedtime, especially after later KOs. Sargent et al. (2022) also found a significant difference in TST between Australian football matches that KO in the day vs. night; indeed, 40 min less sleep was reported after evening games. Akin to the present study, Fowler et al. (2014) found no differences in measures of sleep quality between home and away matches in Australian top division soccer players. The earlier KO time of the matches in the current study could mean that match location had less of an impact on sleep quality. Thus, any travel requirements following away matches that start before 17:00 h may not impair sleep to the same extent as after night matches.

In the present study, external load was greater on match days than on training days. The differences in load in the current study are due to the comparatively higher physical demands of soccer match play versus training (Bangsbo et al. 2006). Stevens et al. (2017) showed MD_{-1} loads in Eredivisie soccer players were only 35% relative to match requirements (100%) for TD, 15% for HSD and 39% for ACC. In the current study, the lowest external load was on MD_{+1}, where the training focus was on recovery for those who played substantial minutes in the match. While it cannot be excluded that the greater external load on MD influenced TST, there are limited data suggesting training load significantly influences sleep quality in soccer players. De Beéck et al. (2019) showed no predictive potential of external or internal load measured for perceived sleep quality, and Thorpe et al. (2016) showed no association between training load and sleep quality in elite soccer players. It is important to note in the present study that although the lower TST coincided with higher external load, there were also 10 cases where the players did not play and therefore had no external load. It could be argued that a large part of the lower TST was more related to the aforementioned effects of physiological and psychological arousal, caffeine intake and other stimuli, than load. Future studies with larger sample sizes should compare sleep habits in match day squad players who do and don't play in matches, to determine if reduced MD TST is significantly related to training load.

This study has several limitations to acknowledge. Firstly, the sample size is low, partly due to the limited number of players available in a squad (~25), but also due to low compliance rates with the WHOOP straps from individual players. As such, the data should be interpreted cautiously, pending further, larger scale studies. We were unable to monitor the intake of substances that could influence sleep, such as caffeine or sleeping medication, and were also unable to manually input when participants went to bed, instead relying on the automatic sleep detection of the WHOOP strap. Another limitation is that the algorithm to detect sleep architecture with the WHOOP strap is the propriety of information that is not publicly available. Despite these limitations, this is the first study to report sleep architecture with a WHOOP strap on male elite soccer players and therefore provides new insights into the sleep physiology of these players. Therefore, these findings will be of interest to sport science practitioners working in elite team-sports.

In conclusion, although players slept less after match days than training days, sleep architecture was unaffected. In particular, deep sleep and REM sleep were unchanged following matches suggesting that, despite reduced TST, recovery may not be fully compromised. The lower sleep duration was caused by later sleep onset, which could be a result of physical, social, nutritional, or psychological factors. By targeting the schedule on the morning following MD, teams may allow for sleep extension and greater TST. Match location also had no effect on sleep, possibly because all KO times were before 17:00; future research is needed into sleep after evening and night matches.

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