Relationships between resting heart rate, heart rate variability and sleep characteristics among female collegiate cross-country athletes

By: Yasuki Sekiguchi, William M. Adams, Courteney L. Benjamin, Ryan M. Curtis, Gabrielle E.W. Giersch, and Douglas J. Casa

Sekiguchi Y, Adams WM, Benjamin CL, Curtis RM, Giersch GEW, Casa DJ. Relationships between resting heart rate, heart rate variability and sleep characteristics among female collegiate cross-country athletes. *Journal of Sleep Research*. 2019;28(6):e12836

Abstract:

Even though sleep has been shown to be influenced by athletes' training status, the association with resting heart rate and heart rate variability remains unclear. The purpose of this study was to compare the changes in and relationships between resting heart rate, heart rate variability and sleep characteristics across a female collegiate cross-country season. Ten NCAA Division I collegiate female cross-country athletes (mean ± *SD*; age, 19 ± 1 year; height, 167.6 ± 7.6 cm; body mass, 57.7 ± 10.2 kg; VO_{2max}, 53.3 ± 5.9 ml kg^{-1} min^{-1}) participated in this study. Resting heart rate, heart rate variability and the percentage of time in slow wave sleep were captured using a wrist-worn multisensor sleep device throughout the 2016 competitive cross-country season (12 weeks). Linear mixed-effects models and magnitude-based inferences were used to assess differences between each week. Pearson product moment correlations were used to investigate relationships between variables. Resting heart rate at the end of the season, specifically during weeks 10–12 (mean ± *SE*; week 10, 48 ± 2; week 11, 48 ± 3; week 12, 48 ± 3), showed a practically meaningful increase compared to the beginning of the season, weeks 2–4 (week 2, 44 ± 2; week 3, 45 ± 2; week 4, 44 ± 2). Higher resting heart rate ($r = 0.55$) and lower heart rate variability ($r = -0.62$) were largely associated with an increase in percentage of time spent in slow wave sleep. These data suggest that when physiological state was impaired, meaning the physiological restorative demand was higher, the percentage of time in slow wave sleep was increased to ensure recovery. Thus, it is important to implement sleep hygiene strategies to promote adequate slow wave sleep when the body needs physiological restoration.

Keywords: actigraphy | autonomic nervous system | physiological restoration

Article:

1 INTRODUCTION

Appropriate training and recovery, shown to be associated with a high functional state of fitness and minimal levels of fatigue, facilitate the ability of individuals to have a high work capacity followed by expedient recovery (Smith, 2003). Inadequate recovery following excessive training can induce prolonged fatigue, maladaptation and injury (Soligard et al., 2016). Sleep is a critical factor ensuring appropriate recovery from training (Fullagar et al., 2015), with previous literature demonstrating that a lack of sleep can negatively affect metabolic, immunological and restorative physiological processes (Samuels, 2009). Therefore, both sleep quantity and quality are associated with competitive success for athletes (Watson, 2017).

Many factors affect sleep, such as an increase in core temperature 5–6 hr prior to sleep, dehydration (Horne & Horne, 1983), the timing of sleep (Samuels, 2009), the timing of exercise (Costa et al., 2019), athletic competition occurring during the evening and night-time hours (Carriço et al., 2018), exercise intensity and volume (Oda & Shirakawa, 2014; Wall, Mattacola, Swanik, & Levenstein, 2003) and physiological demand of recovery (Driver & Taylor, 2000). The effects of endurance exercise on sleep quantity and quality demonstrate a decreased time spent in rapid eye movement sleep (REM) (Driver & Taylor, 2000). Furthermore, acute exercise has been shown to promote increases in total sleep time and time spent in slow wave sleep (SWS) (Driver & Taylor, 2000). This is critical for athlete's recovery as growth hormone release, protein synthesis and mobilization of free fatty acids are induced during SWS (Sassin et al., 1969; Weitzman, 1976). Other evidence has indicated that the percentage of time spent in slow wave sleep (%SWS) increased when athletes performed high-intensity training and decreased during the tapering period (Taylor, Rogers, & Driver, 1997). Also, a larger portion of SWS could reflect higher need for recovery in elite male and female athletes (Knufinke et al., 2018), further supporting the restorative effects of sleep during time periods consisting of a greater physical demand.

Monitoring resting heat rate (RHR) and heart rate variability (HRV), which are regulated by autonomic activation of the sympathetic and parasympathetic pathways, is a noninvasive method and has been successfully used to indicate acute fatigue and responses to physical demand (Achten & Jeukendrup, 2003). RHR and HRV have been used to adjust training loads and identify positive and negative adaptations to aerobic training (Buchheit, 2014; Plews, Laursen, Kilding, & Buchheit, 2013). For example, HRV in female endurance athletes decreased following overtraining, which was associated with a decrease in maximal aerobic power (Uusitalo, Uusitalo, & Rusko, 2000). Furthermore, increased maximal aerobic speed in a 10-km running test after 9 weeks of a training intervention was associated with decreased RHR and increased HRV (Plews et al., 2013). Thus, RHR and HRV as heart rate-derived markers of the autonomic nervous system have demonstrated responsiveness to an athlete's training, fatigue and recovery in endurance athletes. In addition to this, the other study has indicated supramaximal exercise affected cardiac autonomic functions in women more than in men (Mendonca et al., 2010), suggesting the importance of examining RHR and HRV in female athletes.

Even though sleep quantity and quality have been shown to be influenced by an athlete's training status, the association with heart rate-derived markers of the autonomic nervous system still remains unclear. Furthermore, although evidence suggests that autonomic function as measured by HRV and RHR is altered in female athletes following overtraining or supramaximal exercise, there is no evidence examining how a collegiate cross-country season affects autonomic function in collegiate female student athletes. Therefore, the purpose of this study was to examine the changes in RHR, HRV and sleep characteristics across weeks and investigate the relationships of these variables throughout a female cross-country competitive season.

2 MATERIALS AND METHODS

2.1 Participants

Ten NCAA Division I female collegiate cross-country athletes (mean ± *SD*; age, 19 ± 1 years; height, 167.6 ± 7.6 cm; body mass, 57.7 ± 10.2 kg; VO_{2max}, 53.3 ± 5.9 ml kg^{-1} min^{-1}) participated in this study, which took place during the 2016 NCAA women's cross-country season. Following an explanation of study procedures, which was approved by the Institutional Review Board at University of Connecticut, participants provided written and informed consent to participate in this study.

2.2 Procedures

Data were collected from the first week of the preseason and until the end of the competitive season (84 days over the 12 weeks). Participants were familiarised with the use and proper fitting of athlete tracking and sleep devices prior to the season and instructed to wear the sleep and recovery devices for all hours of the day outside of training or competition.

2.3 Sleep and recovery assessment

Because monitoring sleep via reference standard polysomnography (PSG) in the field is not practical, this study utilised a multisensor (tri-axial accelerometer, optical sensor, capacitive touch sensor and ambient temperature sensor) device, sampling at 100 Hz (WHOOP Inc., Boston, MA), to assess RHR, HRV and sleep characteristics for field-based longitudinal monitoring. RHR and HRV were measured during slow wave sleep. A machine learning algorithm was utilised to calculate the probability of sleep stages and each stage was assigned based on the probability of being true. Wrist actigraphy relying on motion detection has been demonstrated to be a useful and valid method to estimate total sleep time and wakefulness after sleep onset in field studies (Marino et al., 2013). Additionally, using a wrist-worn device can achieve a practical degree of sleep staging accuracy and may be more correct for longitudinal monitoring (Beattie et al., 2017).

2.4 Measurements

Sleep was recorded in 30-s epochs. The probability of sleep stage class was calculated by a machine learning algorithm, and then each epoch subsequently was assigned to the class with the highest calculated probability of being the true class. Measures of RHR and HRV were evaluated during the last slow wave cycle of sleep, which was shown to be the best recording condition because of a high level of environmental and respiratory standardization (Achten & Jeukendrup, 2003; Buchheit, Simon, Piquard, Ehrhart, & Brandenberger, 2004). Pulse-rate variability via photoplethysmography (PPG) recordings at the wrist has been demonstrated to be a valid method for measurement of R-R intervals via electrocardiogram whilst at rest (Bolanos, Nazeran, & Haltiwanger, 2006; Lu, Yang, Taylor, & Stein, 2009; Pinheiro et al., 2016).

Metrics captured included: RHR, HRV (square root of the mean sum of the squared differences between R-R intervals), total time spent sleeping, time in bed, time spent in the various sleep phases, including the percentage of time spent in light sleep, %SWS, the percentage of time spent in rapid eye movement sleep (%REM), the percentage of wake time, time spent in light sleep, time spent in SWS, time spent in REM, wake time, sleep efficiency, and sleep consistency. Sleep consistency captures changes in the timing of sleep on a day-to-day timescale and calculates the percentage probability of an individual being in the same state (asleep versus awake), and is similar to the sleep regularity index (SRI) introduced by Phillips et al. (2017). The SRI is defined as the percent probability of an individual being in the same state (asleep versus awake) at any two time-points 24 hr apart and it is then scaled such that a maximal score of 100 is given to two 24-hr periods in which the clock times of sleep episodes are identical (Phillips et al., 2017). The difference between sleep consistency and the SRI is that sleep consistency captures the percent probability of an individual being in the same state at any four time-points 24 hr apart.

2.5 Statistical analysis

Data were reported as mean ± *SE*. The mean of each variable across each week was calculated to determine weekly averages per individual participant (weeks 1–12) (Plews et al., 2013).Pearson product moment correlations were used to calculate the relationships between RHR, HRV, total time spent sleeping, the percentage of time spent in light sleep, %SWS, %REM, sleep efficiency and sleep consistency. Correlation coefficient thresholds were set at 0.1, 0.3, 0.5, 0.7 and 0.9, depicting small, moderate, large, very large and extremely large associations, respectively (Hopkins, Marshall, Batterham, & Hanin, 2009). Linear mixed-effect models were used to assess differences between each week with all variables. A random intercept was set for each participant in all mixed-model analyses. For all fixed factors, pairwise differences were assessed post hoc with an adjustment for multiple comparisons of the Bonferroni test. Cohen's effect size (ES) was calculated for each difference and ES was used for magnitude analysis, as described by Batterham and Hopkins, to calculate practical importance. ES was identified at the following thresholds: <0.2 = trivial, 0.2–0.6 = small, 0.7–1.1 = moderate, 1.2–2.0 = large and >2.0 = very large (Batterham & Hopkins, 2006). Differences were considered practically important and substantial when there was >75% likelihood of exceeding the smallest important ES value (0.2) and classifications were set at: 25%–75%, “possibly”; 75%–94%, “likely”; 95%–99%, “very likely”; >99%, “almost certainly”. Alpha level was set at $\alpha < 0.05$. These statistical analyses were performed using SPSS (v.24. IBM Corporation, Armonk, NY).

3 RESULTS

Table 1 displays changes in RHR, HRV, total time spent sleeping, time in bed, sleep consistency and sleep efficiency between weeks over the competitive season. RHR at the end of the season (weeks 10–12) was higher than at the beginning of the season (weeks 2–4). Also, HRV in week 11 was lower than in weeks 1, 2, 4, 5, 6, 7, 8, 9 and 10. There were practically important differences between weeks found for RHR and sleep consistency. Table 2 demonstrates changes in sleep phases over a competitive season. Practically important differences were found for SWS and %SWS between weeks 2 and 3.

Table 1. Resting heart rate , heart rate variability, total time spent sleeping, time in bed, sleep consistency and sleep efficiency throughout a competitive season

Week	RHR (bmp)	HRV (ms)	Total time spent sleeping (hr)	Time in bed (hr)	Sleep consistency (%)	Sleep efficiency (%)
1	46 ± 2	4.2 ± 0.2	6.7 ± 0.2	7.6 ± 0.2	91 ± 1***$^{\uparrow 11}$	88 ± 0
2	44 ± 2*$^{*\downarrow 10,***\downarrow 11,**\downarrow 12}$	4.3 ± 0.1	6.6 ± 0.2	7.5 ± 0.2	91 ± 1***$^{\uparrow 11}$	89 ± 0
3	45 ± 2*$^{\downarrow 10,**\downarrow 11,*\downarrow 12}$	4.2 ± 0.2	7.0 ± 0.1	8.0 ± 0.2	87 ± 2	89 ± 0
4	44 ± 2*$^{*\downarrow 10,**\downarrow 12}$	4.2 ± 0.2	6.8 ± 0.3	7.8 ± 0.3	89 ± 2**$^{\uparrow 11}$	88 ± 0
5	46 ± 2	4.2 ± 0.2	7.2 ± 0.4	8.1 ± 0.4	88 ± 2**$^{\uparrow 11}$	90 ± 0
6	47 ± 2	4.2 ± 0.2	6.9 ± 0.1	7.8 ± 0.1	88 ± 2**$^{\uparrow 11}$	90 ± 0
7	46 ± 2	4.3 ± 0.2	6.9 ± 0.2	7.8 ± 0.2	89 ± 17**$^{\uparrow 11}$	89 ± 0
8	45 ± 2	4.4 ± 0.2	6.8 ± 0.4	7.8 ± 0.3	91 ± 2***$^{\uparrow 11}$	88 ± 0
9	45 ± 2	4.3 ± 0.1	6.7 ± 0.4	7.6 ± 0.4	89 ± 2*$^{\uparrow 11}$	89 ± 0
10	48 ± 2	4.2 ± 0.2	6.9 ± 0.3	7.8 ± 0.8	88 ± 2**$^{\uparrow 11}$	89 ± 0
11	48 ± 3	4.3 ± 0.2	7.1 ± 0.2	8.1 ± 0.3	81 ± 3	92 ± 0
12	48 ± 3	4.3 ± 0.2	7.0 ± 0.3	8.0 ± 0.3	87 ± 2	87 ± 0

RHR, resting heart rate; HRV, heart rate variability; Ln rMSSD, square root of the mean sum of the squared differences between R-R intervals.
(^{10,11,12}) = practically important difference compared with the respective week. (*) = "likely" to be different. (**) = "very likely" to be different. (***) = "most likely" to be different. ($^{\uparrow}$) = the direction of the difference is positive. ($^{\downarrow}$) = the direction of the difference is negative.

Table 2. Sleep characteristics throughout a female collegiate cross-country season

Week	Sleep time spent in light sleep (hr)	The percentage of sleep time spent in light sleep (%)	SWS (hr)	%SWS (%)	REM (hr)	%REM (%)	Wake time (hr)	The percentage of wake time (%)
1	4.4 ± 0.3	57 ± 2	1.2 ± 0.2	15 ± 2	1.1 ± 0.1	15 ± 2	0.9 ± 0.1	12 ± 1
2	4.8 ± 0.3	64 ± 3	0.8 ± 0.1*$^{\downarrow 3}$	11 ± 2*$^{\downarrow 3}$	1.0 ± 0.2	13 ± 2	0.9 ± 0.1	13 ± 1
3	4.5 ± 0.3	57 ± 4	1.5 ± 0.3	19 ± 3	1.0 ± 0.2	13 ± 3	1.0 ± 0.1	12 ± 2
4	4.4 ± 0.3	57 ± 3	1.1 ± 0.2	14 ± 2	1.3 ± 0.2	16 ± 2	1.0 ± 0.1	13 ± 2
5	5.0 ± 0.3	62 ± 2	1.0 ± 0.3	12 ± 3	1.2 ± 0.2	15 ± 2	0.9 ± 0.1	11 ± 1
6	4.5 ± 0.2	57 ± 3	1.2 ± 0.2	15 ± 3	1.3 ± 0.2	16 ± 3	0.9 ± 0.1	11 ± 1
7	4.6 ± 0.2	59 ± 3	1.0 ± 0.2	13 ± 3	1.3 ± 0.2	17 ± 2	0.9 ± 0.1	11 ± 1
8	4.9 ± 0.3	63 ± 3	0.9 ± 0.2	11 ± 2	1.0 ± 0.2	12 ± 2	1.0 ± 0.1	14 ± 2
9	4.7 ± 0.2	62 ± 2	0.9 ± 0.2	11 ± 2	1.2 ± 0.2	15 ± 2	0.9 ± 0.1	12 ± 1
10	4.5 ± 1.2	57 ± 3	1.0 ± 0.7	13 ± 3	1.4 ± 0.6	18 ± 2	0.9 ± 0.2	12 ± 3
11	4.7 ± 0.3	58 ± 3	1.3 ± 0.4	16 ± 4	1.1 ± 0.4	14 ± 5	1.0 ± 0.2	12 ± 2
12	4.7 ± 0.3	58 ± 2	1.2 ± 0.2	15 ± 3	1.2 ± 0.2	14 ± 2	1.0 ± 0.1	14 ± 1

SWS, slow wave sleep; REM, rapid eye movement sleep.
(^{3}) = practically important difference compared with the respective week. (*) = "likely" to be different. ($^{\downarrow}$) = the direction of the difference is positive.

Relationships between RHR, HRV, total time spent sleeping, time in bed, the percentage of time spent in light sleep, %SWS, %REM, the percentage of wake time, time spent in light sleep, SWS, REM, wake time, sleep consistency and sleep efficiency are depicted in Table 3. Higher RHR was largely associated with increased %SWS and largely related to decreased percentage of time spent in light sleep ($p < 0.05$). Figure 1 shows the very similar fluctuations in RHR and

%SWS throughout a competitive season. Higher RHR had a moderate relationship with lower sleep consistency ($p < 0.05$), which indicated a decrease in the percent probability of an individual being in the same state at any four time-points 24 hr apart was associated with higher RHR. A decrease in HRV was largely associated with increased %SWS and largely related to decreased percentage of time spent in light sleep ($p < 0.05$). However, RHR ($p = 0.35$), HRV ($p = 0.18$) and %SWS ($p = 0.14$) were not associated with total time spent sleeping, and HRV ($p = 0.07$) and %SWS ($p = 0.65$) were not related to sleep consistency.

Table 3. Relationships between resting heart rate and heart rate variability and sleep characteristics

r	**RHR**	**HRV**
Total time spent sleeping	0.09	−0.13
Time in bed	0.09	−0.09
Percentage of sleep time spent in light sleep	−0.65[a]	0.54[a]
%SWS	0.55[a]	−0.62[a]
%REM	0.20[a]	−0.05
Percentage of wake time	−0.01	0.13
Sleep time spent in light sleep	−0.47[a]	0.38[a]
SWS	0.54[a]	−0.61[a]
REM	0.21[a]	−0.06
Wake time	0.00	0.13
Sleep consistency	−0.41[a]	0.18
Sleep efficiency	−0.01	−0.08

RHR, resting heart rate; HRV, heart rate variability; SWS, slow wave sleep; REM, rapid eye movement.

[a] Significant ($p < 0.05$) relationship between variables using Pearson product moment correlations.

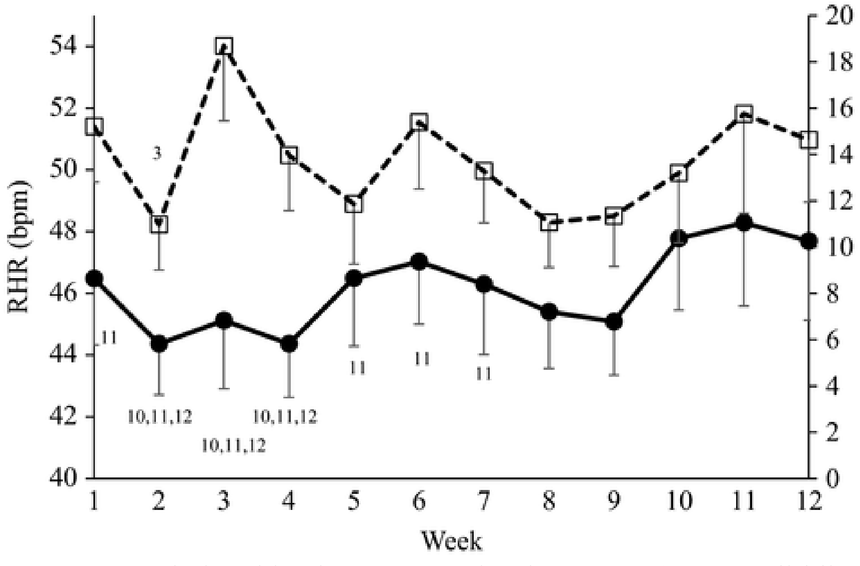

Figure 1. Relationships between resting heart rate (RHR; solid line) and the percentage of time spent in slow wave sleep (%SWS; dotted line) throughout a collegiate cross-country season. (^{3,10,11,12}) = practically important difference compared with the respective week. Week 1 and the first 2 days in week 2 were the preseason. The rest of the weeks were in the season. A conference championship was at the end of week 11 and a regional championship was at the end of week 12

4 DISCUSSION

This study monitored RHR, HRV, total time spent sleeping, time in bed, sleep phases, sleep efficiency and sleep consistency throughout a female competitive cross-country season to examine the changes across weeks and demonstrate relationships between these variables. This investigation showed an elevation of RHR at the end of the season (weeks 10–12) compared to the beginning of the season (weeks 2–4). Furthermore, higher RHR was associated with increased %SWS and decreased sleep consistency. Also, lower HRV was associated with increased %SWS, but not with sleep consistency. RHR, HRV, %SWS and sleep consistency were not associated with total time spent sleeping. To our knowledge, this is the first investigation of relationships between RHR, HRV and sleep characteristics during a female collegiate cross-country season.

4.1 RHR across a female collegiate cross-country season

In Table 1 and Figure 1, RHR at the end of the season, weeks 10–12, showed a practically meaningful increase compared to the beginning of the season, weeks 2–4. These results suggest heart rate-derived markers of autonomic nervous system function were impaired at the end of the season compared with the beginning of season. Athletes in the current study showed signs of accumulated fatigue and under-recovery at the end of season, as indicted by an increase in RHR, which has been shown to be sensitive to both positive and negative adaptations to aerobic training and provide information on acute and chronic fatigue (Buchheit, 2014; Jeukendrup, Hesselink, Snyder, Kuipers, & Keizer, 1992). Additionally, accumulated psychological stress resulting from the competitive season could have an impact on heart rate-derived markers of the autonomic nervous system (Fatisson, Oswald, & Lalonde, 2016). Managing accumulated physiological and psychological stress throughout a season is critical for athletes to achieve optimal results in the target races. Rest and recovery are particularly important before competitions (Smith, 2003). Thus, tracking RHR across a competitive season could allow coaches and sport scientists to monitor heart rate-derived markers of autonomic nervous system status, which may be used to achieve appropriate training and recovery.

4.2 Associations between RHR, HRV and %SWS

Higher RHR and lower HRV were largely associated with increased %SWS (Table 3). Also, Figure 1 showed very similar fluctuations in RHR and %SWS throughout the competitive season; as RHR increased, %SWS was also elevated. SWS is highly associated with body restoration, resulting from increased growth hormone, muscle repair, bone building (Davenne & Davenne, 2009), nervous system recuperation, protein synthesis and mobilizing free fatty acid (Fullagar et al., 2015). It is possible that intense exercise led to an increase in SWS in order to attain appropriate recovery (Shapiro, Bortz, Mitchell, Bartel, & Jooste, 1981). In swimming, SWS was higher at the peak training period (31%) as opposed to the pre-competition period (16%) and SWS has been shown to decrease with reduced physiological demand for recovery (Taylor et al., 1997). RHR and HRV have been responsive to fatigue and recovery in endurance athletes in previous research (Buchheit, 2014). The results in the current study suggest that the athletes needed more recovery, as indicated by higher RHR, lower HRV and increased %SWS, to attain physiological restoration.

4.3 Associations between RHR, HRV and sleep consistency

Higher sleep consistency was moderately associated with lower RHR, but not with total time spent sleeping, HRV and %SWS. Previous research indicated irregular sleepers, measured by SRI, had a lower GPA score than regular sleepers (Phillips et al., 2017). Irregular sleep causes misalignment between circadian rhythms and the sleep–wake cycle (Phillips et al., 2017). This misalignment disturbs energy metabolism, cardiovascular regulation, overall health (Czeisler, 2015) and sleep efficiency (Buxton et al., 2012). Disturbance of circadian rhythms has also been linked to changes in heart rate (Potter et al., 2016). These factors could impair heart rate-derived markers of the autonomic nervous system. However, relationships between RHR, HRV and disturbance of circadian rhythms were not consistent across the research. In the previous research, RHR was not changed (Buxton et al., 2012) or HRV was reduced by misalignment (Potter et al., 2016), which is opposite to the results of the current study. To our knowledge, this is the first investigation to show the relationships between RHR, HRV and sleep consistency in athletes. Even though many factors influence an athlete's heart rate-derived markers of the autonomic nervous system, and more studies are needed, sleep consistency could be one of the factors associated with an athlete's recovery.

4.4 Limitations of the study

Some factors can influence RHR and HRV, such as stress, mood, fatigue and training load, and they were not measured in this study. Also, a menstrual cycle can change sleep; however, this was not examined in this study because this was an observational study (Baker & Driver, 2007), even though it was known that HRV does not change between menstrual cycle phases (Leicht, Hirning, & Allen, 2003). This study had a small sample (#=10) but this is a minimal concern because of the robustness of the data and the statistical analysis performed (linear mixed models). This is why Gelman and Hill are against using a normality test for this type of analysis (Gelman & Hill, 2006). Furthermore, more studies and a larger number of subjects are needed to examine the effect of sleep on RHR and HRV in female athletes.

4.5 Implications

The population of the study was female collegiate athletes and they have to balance sports, academic study and their daily life. Previous studies have not focused on this population, which needs special consideration. Thus, tracking sleep and recovery metrics over the course of a competitive season may assist coaches and sports scientists in making informed decisions regarding training and recovery in female collegiate athletes. Our findings suggest that when heart rate-derived markers of the autonomic nervous system are impaired, which indicates a higher physiological restorative demand, %SWS is increased, possibly to ensure recovery. Thus, it is important for female collegiate athletes to have adequate SWS time when the body needs physiological restoration. For example, implementing sleep hygiene strategies has been shown to be effective in improving sleep in elite female athletes (O'Donnell & Driller, 2017). Finally, increased sleep consistency could be one of the factors that are related to lower RHR, and athletes may need higher sleep consistency to induce better heart rate-derived markers of the autonomic nervous system.

ACKNOWLEDGEMENTS

The authors would like to express their sincere thanks to the athletes and coaching staff for their time and commitment during the study. The authors alone were responsible for the content and writing of this article. They are thankful for the financial support for this research provided by WHOOP Inc.

CONFLICT OF INTEREST

The authors have no conflicts of interest to disclose for the submitted work.

AUTHOR CONTRIBUTION

All authors contributed to data collection, analysis and drafting of the manuscript.

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