Sleeping to Perform: Examining Sleep and Exercise in Elite Female Athletes

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Abstract

Sleep plays an essential role in biological functions, and is fundamental for human health and wellbeing. Sleep is also widely recognised as playing an important role in the sporting environment, with an increasing awareness of the importance of sleep in elite athletes. Although sleep research in athletes is increasing, elite athletes are still largely underrepresented in the literature, especially female athletes. Through a series of six studies, this PhD thesis aimed to enhance the understanding of sleep habits of elite athletes, specifically female team sport athletes. The main aim of the thesis was to investigate the sleep habits of elite female team sport athletes in both training and competition environments and also to evaluate interventions to improve sleep and subsequent exercise performance.

Study One assessed the reliability and validity of a linear position transducer device as a performance tool for further studies within the thesis. Study Two subjectively and objectively assessed sleep indices in the night leading up to and the nights following competition over a netball season. Study Three investigated perceived and hormonal stress markers and sleep responses following a match, training and control condition. Study Four assessed difference between the melatonin and sleep responses to training and non-training days. Study Fix, objectively assessed the effect of an acute sleep hygiene education session on sleep indices via wrist-actigraphy. Finally, Study Six, an observational and longitudinal study, examined the influence of match-day napping on various performance and perceptual markers.

In Study One, a linear position transducer (GymAware, Kinetic Performance Technology, Canberra, Australia), was shown to be a reliable tool for measuring countermovement squat jump performance in female athletes, with a mean intraclass correlation of 0.70 for jump height, 0.90 for peak velocity, and 0.91 for mean velocity. It was also shown to have a Pearson correlation of $r = 0.90$ and a typical error of ~2.4 cm when compared to a force plate, however the linear position transducer overestimated jump height by an average of 7.0 ± 2.8 cm.

In Study Two, 10 elite female athletes completed a survey on their perceived sleep duration and quality on three consecutive nights; the night before the game, the night of the game and the night following the game on 15 separate occasions over a netball season. In addition, on two separate occasions, 11 elite female athlete's sleep was monitored via an actigraph device for the three consecutive nights. Results showed the athletes perceived sleep duration was significantly different on the night of the game (6:52 h:m) from the night before a game (8:29 h:m). Similarly, when sleep duration was measured using actigraphy, total sleep time was observed to be significantly lower on the night of a game (6:46 h:m) compared to the night before a game (8:31 h:m). Furthermore, total sleep time remained significantly reduced on the night following the game (7:23 h:m).

Findings from Study Three provide further support for poor sleep in athletes following evening competition and training. Ten elite female netballers' sleep was monitored following a netball competition match (MATCH), a netball match simulation session (TRAIN) and a rest day (CON). Salivary cortisol was collected immediately pre and post session, and at 22:00pm. Total sleep time was significantly reduced following the MATCH (6:03 h:m) compared to TRAIN (8:03 h:m) and CON (8:46 h:m). Sleep efficiency was also significantly reduced by 7.7% following the match compared to the training, with sleep latency significantly increased following the game (50.3 minutes) compared to the rest day. Cortisol levels were significantly higher immediately after the match (0.700 μg/dL) compared to training (0.178 μg/dL) and rest (0.077 μg/dL) and remained significantly elevated at 22:00pm.

Study Four compared salivary melatonin levels and sleep behavior of 10 elite female athletes between a training session and a control session (rest day). Significant reductions ($p < 0.05$) in melatonin levels both pre and at 22:00pm were observed in the training condition (6.2 and 17.6 pg/mL, respectively) compared to the control condition (14.8 and 24.3 pg/mL, respectively).

The 26 female athletes in Study Five performed one week of baseline sleep monitoring (PRE), followed by a sleep hygiene education session, and a further week of sleep monitoring (POST). Total sleep time significantly increased by 22.3

minutes ($p < 0.05$), following a one-hour sleep hygiene education session from the PRE week to the POST week. Furthermore, wake variance and wake episode duration were significantly increased from the PRE week to the POST week.

Lastly, in Study Six, on each match day, 14 female athletes provided information on their durations of naps and perceived energy levels before performing 3 countermovement jumps 3.5 hours prior to the start of the match on 26 occasions, over two netball seasons. One hour following the match, subjective player performance ratings and coaching staff player performance ratings were obtained. Improved jump performance and ratings of netball performance were observed following nap durations of 20 minutes or less on match-day in elite female athletes, when compared to no nap or naps lasting longer than 20 minutes.

In summary, the series of studies in this thesis provides a foundation for understanding sleep in elite female team-sport athletes. Sleep disturbances are prevalent around training and further disturbed around competition environments. These disturbances were also associated with perturbations in different salivary hormones. Furthermore, results show sleep can be acutely improved following a single sleep hygiene education session. And finally, match-day naps of varying duration may have an effect on subsequent match performance, with naps lasting <20 minutes being associated with the most favorable results. The studies provide valuable information on the sleep habits of elite female athletes, which can be used by coaches and practitioners to monitor sleep and establish individualized sleep hygiene protocols. Moreover, the sleep patterns around training and competition should be factored in by practitioners when designing training and recovery programs.

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List of Abbreviations

ANOVA	Analysis of variance
CI	Confidence intervals
CMJ	Countermovement jump
CSAI-2	Competitive state anxiety inventory-2
CV	Coefficient of variance
ELISA	Enzyme linked Immunosorbent assay
FP	Force plate
h	Hours
ICC	Intraclass correlation
kg	Kilograms
LOA	Limits of agreement
LPT	Linear position transducer
NREM	Non-rapid eye movement
Min	Minutes
PSD	Perceived sleep duration
PSG	Polysomnography
PSQ	Perceived sleep quality
PSQI	Pittsburgh sleep quality index
REM	Rapid eye movement
RPE	Rate of perceived exertion
SAS	Self rating anxiety scale
SD	Standard deviation
SE	Sleep efficiency
SL	Sleep latency
SOT	Sleep onset time
SOV	Sleep onset variance
SWS	Slow wave sleep
TEE	Typical error of estimate
TST	Total sleep time
TTB	Total time in bed
ug/dL	Microgram per deciliter

VAS	Visual analogue scale
WE	Wake episodes per night
WED	Wake episode duration
WT	Wake time
WV	Wake variance

CHAPTER ONE

Thesis Overview

Thesis Outline

The main aim of the thesis was to investigate the sleep habits of elite female team sport athletes and the relationship between sleep and exercise (Figure 1). The thesis comprises six experimental studies that aimed to; assess the reliability of the GymAware linear position transducer device in female athletes (Study One, Chapter Three); subjectively and objectively measure sleep indices during a netball season (Study Two, Chapter Four); measure the stress and sleep response between training and competition in elite netball athletes (Study Three, Chapter Five); measure the melatonin and sleep responses following training in elite netballers (Study Four, Chapter Six); assess sleep hygiene education on sleep indices in elite netball athletes (Study Five, Chapter Seven); and examine the influence of match-day napping in elite netballers (Study Six, Chapter Eight).

Study One (Chapter Three) is a standalone research piece to assess whether the linear position transducer was a reliable and valid tool that could be used as a performance measure in Study Six (Chapter Eight). Study Two (Chapter Four) was used to establish how athletes' sleep in the nights leading up to and following competition, with Studies Three and Four (Chapters Five and Six) exploring potential mechanisms that may be associated with sleep during competition and training. Study Five (Chapter Seven) examined an interventional strategy to improve sleep in elite female athletes.

The series of studies within the thesis enhance the current understanding of the variables associated with sleep and subsequent athletic performance. The use of elite athletes as the primary participants for this research has the potential to provide novel findings within the elite sport settings and therefore adds to the knowledge base on sleep as a recovery mechanism to ultimately improve sporting performance.

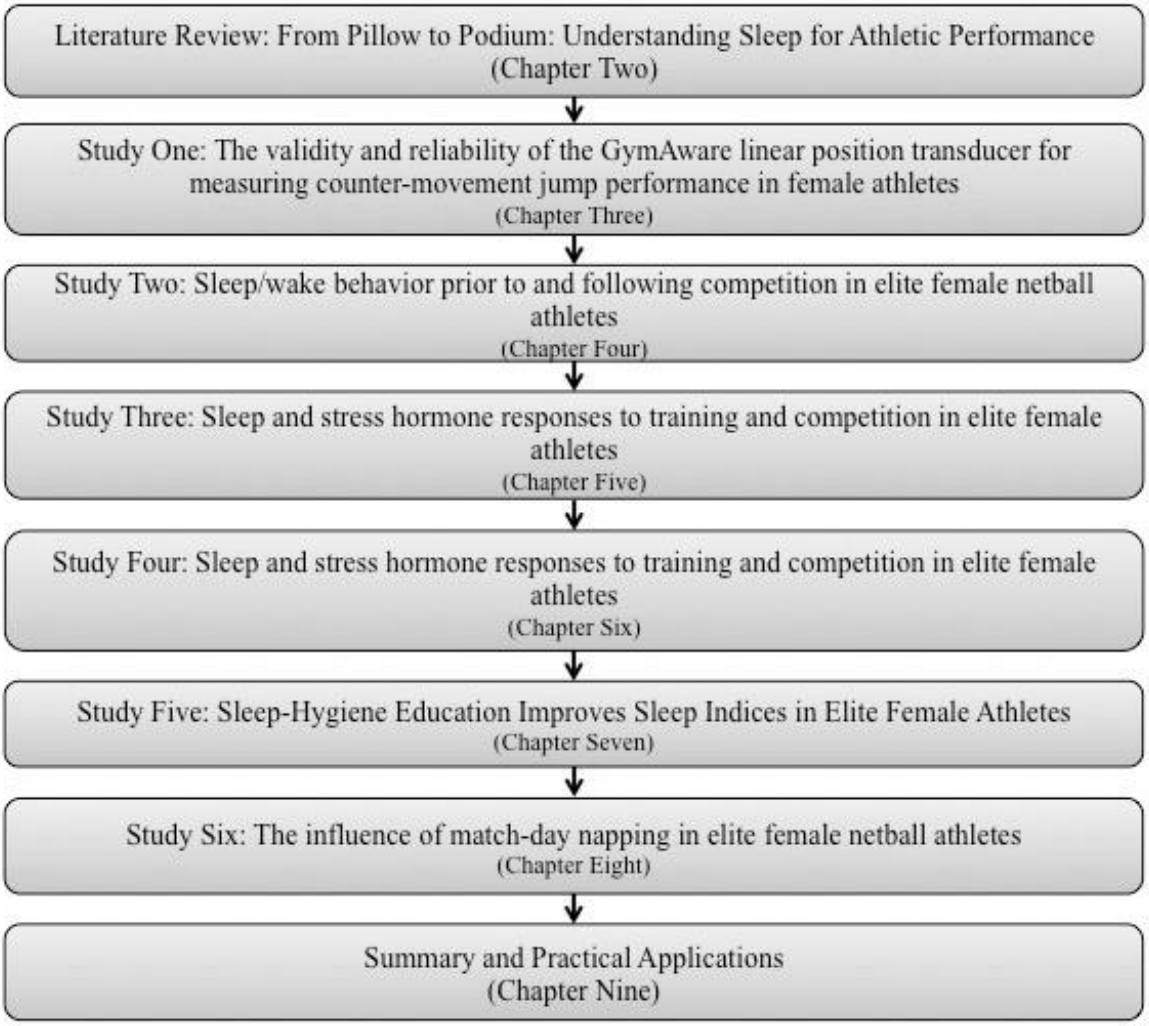

Figure 1 – Schematic of the thesis structure.

Chapter Organization

The thesis comprises a total of nine chapters. Each of the experimental chapters (Three – Eight) are written as standalone chapters that are either published, accepted or under review in journals and incorporate standard paper format (abstract, introduction, methodology, results and discussion) and thus are specific to the aims of that chapter. Chapter Two includes an invited review, which serves the dual purpose of providing a literature review for the overall thesis as well as an individual publication, and therefore, includes references to the other work contained in this thesis. Chapters Two – Eight appear in the same format as required by the individual journals that they were submitted to.

Due to the structure of the thesis, with each chapter submitted as a standalone piece of research work for publication, there is a degree of repetition throughout the thesis. There is a single reference list of citations included at the end of the thesis, for consistency and readability.

Research Outputs Arising from this Doctoral Thesis

Peer Reviewed Journal Publications

Chapter Two

O'Donnell, S., Beaven, C & Driller, M. From pillow to podium: a review on understanding sleep for elite athletes. *Nature and Science of Sleep. (*Published Ahead of Print).

Chapter Three

O'Donnell, S., Tavares, F., McMaster, D & Driller, M. (2017). The validity and reliability of the GymAware linear position transducer for measuring counter-movement jump performance in female athletes. *Measurement in Physical Education and Exercise Science.* 22(1) 101-107.

Chapter Four

O'Donnell, S., Beaven, C & Driller M. (2018). Sleep/wake behavior prior to and following competition in elite female netball athletes. *Sports Science for Health.* (Published Ahead of Print).

Chapter Five

O'Donnell, S., Jacobson, G., Bird, S & Driller M. (2018). Sleep and stress hormone responses to training and competition in elite female athletes. *European Journal of Sports Science.* 18(5) 611-618.

Chapter Six

O'Donnell, S., Beaven, C., Jacobson, G., Bird, S & Driller M. Melatonin and sleep responses following exercise in elite female athletes. Under review in *Clocks & Sleep* as a Short Communication.

Chapter Seven

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

Chapter Eight

O'Donnell, S., Beaven, C & Driller, M. The influence of match-day napping in elite female netball athletes. *International Journal of Sports Physiology and Performance.* (In Press).

Appendix B

Driller, M., McQuillan, J & **O'Donnell, S**. (2016). Inter-device reliability of an automatic-scoring actigraph for measuring sleep in healthy adults. *Sleep Science.* 9(3).

Appendix C

Driller, M., Tavares, F & **O'Donnell, S**. (2017). What wrist should you wear your actigraphy device on? Analysis of dominant vs. non-dominant wrist actigraphy for measuring sleep in healthy adults. *Sleep Science.* 10(3).

Appendix D

Driller, M., Tavares, F., McMaster, D & **O'Donnell, S**. (2017). Assessing a smartphone application to measure countermovement jumps in recreational athletes. *International Journal of Sports Science & Coaching*. (Published Ahead of Print).

Conference Presentations Arising from this Thesis

O'Donnell, S., Jacobson, G., Bird, S & Driller M. Sleep and stress hormones in training and competition in elite female athletes. Proceedings of the Sport and Exercise Science New Zealand Conference, Cambridge, New Zealand. 2016. (Oral Presentation).

O'Donnell, S., Tavares, F., McMaster, D & Driller, M. The validity and reliability of the GymAware linear position transducer for measuring counter-movement jump performance in female athletes. Proceedings of the Sport and Exercise Science New Zealand Conference, Cambridge, New Zealand. 2016. (Poster Presentation).

O'Donnell, S., Jacobson, G., Bird, S & Driller M. Sleep and stress hormones in training and competition in elite female athletes. Proceedings of the ICHPTS 2017: 19th International Conference on High-Performance Training for Sports, Zurich, Switzerland. 2017. (Oral Presentation). * Winner of the best presentation award.

O'Donnell, S., Beaven, C., Driller, M. Match-day napping on perceived energy and performance in elite female athletes. Proceedings of the Sport and Exercise Science New Zealand Conference, Cambridge, New Zealand. 2017. (Oral Presentation).

CHAPTER TWO

Literature Review – From Pillow to Podium: A Review on Understanding Sleep for Elite Athletes

O'Donnell, S., Beaven, C & Driller, M. From pillow to podium: understanding sleep for elite athletic performance. Invited review - *Nature and Science of Sleep*. (Published Ahead of Print).

Abstract

Sleep is considered vital to human health and wellbeing, and is critical to physiological and cognitive functioning. Elite athletes experience high training and competition demands, and are often exposed to various factors, situations and environments that can cause sleep impairments. Previous research has shown that athletes commonly experience sleep loss in the lead up to and following competition, which could have significant impacts on their preparation, performance and recovery. In particular, the results from previous research show significant reductions in total sleep time (~1:40 h:m), and significant increases in sleep latency (~45 minutes) following evening competition. It is anecdotally known that there is a prevalence of napping in both the training and competition setting in athletes, however research on the effect of napping on physiology and performance is limited. In contrast, research on strategies and interventions to improve sleep are increasing in the athletic population, with sleep hygiene education resulting in significant improvements in sleep indices. This review investigates the physiological importance of sleep in athletes, the prevalence of sleep disturbances and the potential mechanisms causing sleep disturbances, the role of sleep for cognitive functioning, current measures to monitor athletes' sleep, the role of napping and different intervention strategies to improve sleep. Given the high training and competition loads athletes experience, it is pertinent that further research and knowledge of the interaction between athletes' sleep and performance is gained.

Introduction

As the training requirements for elite athletes increase, the role of adequate recovery becomes an integral component of improving athletic performance between training sessions and competition (Argus, Driller, Ebert, Martin, & Halson, 2013; Coffey, Leveritt, & Gill, 2004). The challenge that faces coaches and sport scientists working with elite athletes is to ensure that the intense level of training required to optimize performance does not cause maladaptation, injury, over-reaching and/or overtraining (Leeder, Glaister, Pizzoferro, Dawson, & Pedlar, 2012). Therefore, in order for athletes to train and compete on a daily and weekly basis, adequate recovery plays a vital role.

Sleep has been recognised as an essential component in athlete preparation and it is suggested to be one of the most effective recovery strategies available to athletes (Halson, 2013; Juliff, Halson, & Peiffer, 2015), although it is an area often neglected by athletes themselves (Venter, 2012). There is growing evidence to show the effects of competition on elite athletes' sleep; however the direct cause of these effects and to what extent these effects have is yet to be determined. Furthermore, in the athletic setting, there is a paucity of data regarding the utilization of napping, the interaction of different hormonal markers and their relationship to sleep quality and quantity. Therefore, the purpose of this review is to provide a background on the theoretical basis regarding the importance of sleep and its role in recovery and athletic performance. A secondary aim of the review is to evaluate the research literature regarding physiological and performance effects related to sleep, and interventions to improve sleep.

Measuring Sleep in Athletes

Several methods have been used to measure sleep in the general population such as, polysomnography, partial polysomnography (Kosmadopoulos, Sargent, Darwent, Zhou, & Roach, 2014), ballistocardiography (Mack, Mack, & Patrie, 2009), ambulatory polysomnography (McCall, Erwin, Edinger, Krystal, & Marsh, 1992), actigraphy, sleep diaries and logs and sleep questionnaires. While all of these methods are common sleep measures for various sleep research, they may not always be practical in the athlete setting. Measuring sleep in the athletic population is often

performed through two commonly used objective measures are polysomnography and actigraphy, and subjective measures include sleep questionnaires, sleep logs and diaries.

Polysomnography

Polysomnography is considered the 'gold standard' to objectively assess sleep in athletes (Halson, 2014; Roky, Herrera, & Ahmed, 2012). Body functions are measured through scalp and skin surface electrode recordings. The electrodes monitor brain activity (electroencephalogram), eye movements (electrooculogram), muscle activity (electromyogram) and cardiac activity (electrocardiogram) (Halson, 2014). As well as measuring sleep indices, polysomnography allows for the different stages of sleep to be determined. Polysomnography is the primary method used to diagnose and evaluate treatment of sleep disorders and provides the most comprehensive measurement of sleep behavior (Kushida et al., 2005), against which all other measures of sleep should be validated.

Unfortunately, this method for measuring sleep is not often practical in a sport environment due to the sleep laboratory setting, and the requirement of a specialized trained practitioner running the testing. It is a more intrusive measuring system and is not reflective of the 'real world' setting that researchers experience with elite athletes to gain ecologically valid results (see Table 1).

Actigraphy

Another commonly used method to objectively assess sleep is through the use of an actigraphy device. Actigraphy is based on small wristwatch devices that monitor movements over extended periods of time, usually in 1-minute data segments. The raw activity scores are translated to sleep-wake scores based on computerized scoring algorithms (Ancoli-Israel et al., 2003; Driller, McQuillan, & O'Donnell, 2016; Halson, 2014; Sadeh, 2011). Actigraphs are used to measure different sleep indices including: total sleep time, sleep efficiency, number of wake episodes, wake after sleep onset, sleep latency, bed time, and wake time. The validation of actigraphy devices has been investigated in relation to polysomnography (Dunican et al., 2017; Kushida et al., 2001; Sadeh, Hauri, Kripke, & Lavie, 1995). A review article for comparisons between polysomnography and actigraphy by Ancoli-Israel et al (2003)

showed 91 to 93% overall agreement in healthy adults ages 20 to 30 years (Ancoli-Israel et al., 2003). A recent study by Dunican et al (2017) reported that an actigraph device is suitable for determining sleep onset, sleep duration, and wake time. However, caution should be taken when interpreting sleep latency, sleep efficiency, and wake episodes after sleep onset (Dunican et al., 2017). The movement, or lack of movement, that occurs during sleep can be mistaken for either wake or sleep, which in turn may over or underestimate sleep indices. Sleep monitoring through actigraphy devices is a practical method in athletes. Numerous research studies indicate that actigraphy is an acceptable method to use in the assessment of sleep and has been generally accepted in the literature (Driller et al., 2016). It is non-invasive to the individuals, relatively inexpensive, and is more applicable to 'normal' sleeping environments.

Sleep Questionnaires and Diaries

Sleep logs and diaries have been widely used to evaluate both sleep quality and quantity (Caia et al., 2017), to give a participant's perception of bed and wake times and quality of their sleep. Caia et al (2017) investigated self-perceived sleep in comparison to sleep estimated via actigraphy in 63 professional male ruby league athletes. From the 641 nights of sleep monitoring, results showed a very large, positive (r = 0.85) correlation between self-perceived sleep duration and actual sleep duration measured via the actigraph device. A mean bias showed perceived sleep was over estimated by an average of 19.8 minutes (Caia et al., 2017). Therefore, the use of subjective measures to monitor sleep duration are acceptable when objective monitoring cannot be used. Furthermore, using sleep questionnaires and diaries in combination with actigraphy where possible may increase the accuracy of the sleep data (Sadeh, 2011).

The Pittsburg Sleep Quality Index (PSQI) (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989) and the Epworth Sleepiness Scale (ESS) (Johns, 1991) have been widely used in sleep research, including the sport setting. Two recent athlete-specific sleep questionnaires have recently been developed, that are more reflective to the environment and factors that athletes encounter in regards to their sleep (Driller, Mah, & Halson, 2018; Samuels, James, Lawson, & Meeuwisse, 2015). Samuels and colleagues (2015) developed the Athlete Sleep Screening Questionnaire (ASSQ),

which is a 15-item questionnaire with 6 main areas; Total Sleep Time, Insomnia, Sleep Quality, Chronotype, Sleep Disordered Breathing and Travel Disturbances. The ASSQ acts as a clinical tool with thresholds that indicate sleeping disorders. Driller et al (2018) developed the Athlete Sleep Behavior Questionnaire (ASBQ), consisting of an 18-item questionnaire to be used by practitioners and researchers when working with elite athletes. In contrast to the ASSQ, the ASBQ is more of a practical tool used by coaches and practitioners to identify maladaptive sleep hygiene behaviors rather than sleep disorders. Results showed significant differences between athletes (n = 242) and non-athlete (n = 322) groups for the ASBQ global score.

Physiology of Sleep

The human body is fundamentally based upon rhythmicity, with circadian rhythms observed in the majority of human physiological variables (Thun, Bjorvatn, Flo, Harris, & Pallesen, 2015; Venter, 2012). One of the fundamental rhythms characterized by the 24-hour day-night cycle is the sleep-wakefulness cycle, which is of significant importance to human circadian rhythms (Reilly & Edwards, 2007; Smith, Guilleminault, & Efron, 1997; Souissi et al., 2008). In a review article by Halson (2014) sleep was defined as a reversible behavioral state in which an individual is perceptually disengaged from and unresponsive to the environment. The sleep-wakefulness cycle enables the body to recover from prior states of wakefulness allowing an individual to awaken feeling alert (Davenne, 2009).

A number of hormonal responses take place in the lead up to and during sleep. One important hormone relating to athletic recovery is growth hormone. Growth hormone is necessary for body restoration, and plays an important role in muscle growth and repair (Davenne, 2009; Halson, 2008; Shapiro, Bortz, Mitchell, Bartel, & Jooste, 1981). Muscle growth, repair and bone building are vital for recovery following strenuous trainings and competitions that athletes experience. It has been reported that 95% of the daily production of growth hormone is released from the pituitary gland in the endocrine system during non-rapid eye movement (NREM) sleep stage three (Venter, 2012), therefore, NREM sleep is considered the time in which the body actively repairs and restores itself (Davenne, 2009; Roky et al., 2012; Weitzman, 1976).

Exercise is a physiological stressor, activating the hormonal systems, namely (the hypothalamic) corticotropin-releasing hormone, (the anterior pituitary) adrenocorticotropic hormone, and adrenal glucocorticoids (Gatti & De Palo, 2011). Two of the main hormones often studied in relation to physical activity are cortisol and testosterone. Cortisol is a steroid hormone, produced and released in the adrenal gland (Lippi et al., 2009). It plays a central role in the physiological and behavioral response to physical activity, as well as important metabolic functions and regulation of the immune system (Gatti & De Palo, 2011; Lippi et al., 2009). Testosterone is also a steroid hormone, and is associated with physiological responses to exercise, specifically contributing in muscular hypertrophy following resistance training (Cook & Beaven, 2013). The balance and timing of anabolic (testosterone) and catabolic (cortisol) hormones are considered essential to muscle adaptation, specifically muscle growth (Beaven, Gill, & Cook, 2008; Hansen, Kvorning, & Sjøaard, 2001). It has been reported that cortisol and testosterone are affected following sleep deprivation, with an increase secretion of cortisol and changes in the pattern of rhythmic secretion of testosterone (Dattilo et al., 2011), which can effect the anabolic and catabolic balance (see Figure 2). Furthermore, stress is a characteristic aspect of sports competition, regarded as a psychophysiological process, affecting athletes both cognitively and physiologically (Filaire, Sagnol, Ferrand, Maso, & Lac, 2001). It should also be acknowledged that hormonal profiles might be different in athletes and non-athletes, this could be at both rest or in response to exercise (Bloom, Johnson, Park, Rennie, & Sulaiman, 1976).

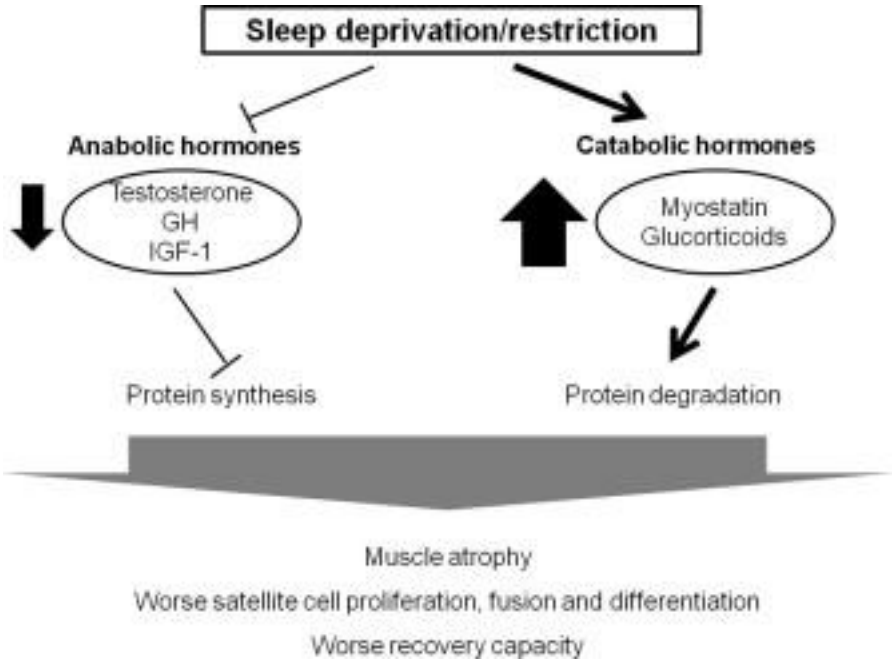

Figure 2 - Effect of sleep debt on skeletal muscle metabolism (Dattilo et al., 2011).

Although previous studies have assessed the effect of sporting competition on sleep (Fullagar, Skorski, Duffield, Julian, et al., 2016; Juliff, Halson, Hebert, Forsyth, & Peiffer, 2017; Sargent & Roach, 2016; Shearer, Jones, Kilduff, & Cook, 2015), few studies have examined the possible mechanisms contributing to poor sleep during competition. Research from our laboratory examined the stress response and subsequent sleep response following an evening netball match and netball simulated match during training in 10 elite female netball athletes. Results showed significantly higher ($p < 0.05$) levels of cortisol immediately post and at 22:00pm following the match compared to the training session (0.700 and 0.165 μg/dL, respectively). Subsequent significant reductions in total sleep time and sleep efficiency were observed following the match (6:03 h:m and 74.4%, respectively) compared to training (8:01 h:m and 82.1%, respectively) (O'Donnell, Bird, Jacobson, & Driller, 2018). Similarly, Juliff, Peiffer and Halson (2017) investigated the physiological mechanisms for impaired sleep. A total of 12 elite female netball athletes had their sleep monitored through actigraphy, along with psychometric and physiological variables measured between a game day and rest day. Results showed a significant ($p < 0.05$) reduction in both sleep duration and sleep efficiency following the game day compared to rest day. Additionally, cortisol levels were significantly higher

immediately post-game and one hour post-game compared to a rest day. A decrease in sleep efficiency was strongly associated (r = -0.611) with an increase in hyperarousal scores (Juliff, Peiffer, & Halson, 2017). Furthermore, a study by Swinburne et al (2018) examined the effect of a sleep extension period on sleep, performance, immunity and stress in rugby players. Results indicated improved sleep indices, beneficial changes in cortisol expression and reaction time performance (Swinbourne, Miller, Smart, Dulson, & Gill, 2018).

Previous reviews into the literature on sleep and stress responses, have indicated this relationship to be complex, with many contributing factors. (Balbo, Leproult, & Van Cauter, 2010; Van Cauter, Spiegel, Tasali, & Leproult, 2008) A study by Omisade et al (2010) examined the levels of cortisol and leptin (hormone associated with feelings of satiety) in 15 young women following acute sleep restriction of a 3 hour total sleep period. The results showed that morning cortisol levels were significantly increased following the sleep restriction period compared to baseline. Moreover, levels of cortisol following the sleep restriction period took significantly longer to decline over the day than baseline measures. Morning leptin levels showed a significant increase in sleep restriction from baseline (Omisade, Buxton, & Rusak, 2010). The results from this study indicate one night of sleep restriction disturbs cortisol levels, which could have an effect on subsequent sleep patterns (Leproult, Copinschi, Buxton, & Van Cauter, 1997), and metabolic function (Knutson, Spiegel, Penev, & Van Cauter, 2007; Taheri, Lin, Austin, Young, & Mignot, 2004).

Exercise may also heavily influence the role of melatonin biorhythms, as previous research has shown the secretion of melatonin levels to be suppressed following exercise (Escames et al., 2012; Monteleone, Maj, Fusco, Orazzo, & Kemali, 1990). It is thought that physical exercise may induce circadian system synchronization, therefore modifying melatonin levels. Melatonin is a hormone that is synchronized from environmental cues, contributing to the initiation of sleep in the circadian system (Escames et al., 2012). Previous research investigating melatonin and exercise has reported conflicting results, with both increases and decreases in melatonin levels observed following exercise (Escames et al., 2012). A study by Buxton et al (1997) assessed the melatonin response following differing intensity and durations of nocturnal exercise in eight moderately trained males. Results reported a phase delay

of plasma melatonin secretion following both a three hour low intensity exercise session (63 min) and a one hour high intensity exercise session (55 minutes) compared to a baseline non-exercising condition (Buxton et al., 1997). It has been summarized in Escames et al (2012) review, that the consequence of exercise on melatonin rhythms varies depending on intensity of lighting, the proximity of exercise to the onset or decline of the circadian production of melatonin, the length and intensity of the exercise, and the time of day.

Table 1 - Studies examining modalities for sleep monitoring in athletes.

References	Subjects (*n*)	Fitness Status	Sleep monitoring modes	Results[#]
Caia et al	63	Professional rugby league athletes	Perceived sleep duration vs. actigraphy device	*Very large*, positive correlation (r = 0.85)
Driller et al	11	Healthy adults	Inter-device reliability of an actigraph device	NS *High* to *very high* ICC (0.80 to >0.90)
Driller et al	13	Healthy adults	Actigraph device between dominant vs. non-dominant wrist	NS *High* to *very high* correlations (r =0.76 to >0.90)
Driller et al	564	Athletes (242) Non-athletes (322)	Athlete Sleep Behavior Questionnaire vs. Pittsburg Sleep Quality Index, Sleep Hygiene Index, and Epworth Sleepiness Scale	*Moderate* to *large* correlations (r = 0.38 to 0.69) between Questionnaire to the 3 other questionnaires ICC retest 7 days (0.87) for the Athlete Sleep Behavior Questionnaire
Samuels et al	58	Highly trained	Athlete Sleep Screening Questionnaire vs. Pittsburg Sleep Quality Index	*High* test-retest correlations (r = 0.90) for Athlete Sleep Screening Questionnaire
Sargent et al	16	Highly trained endurance cyclists	Polysomnography vs. activity monitors	Good agreement (81-90%)

NS non significant, *ICC* intraclass coefficient correlation, *SL* sleep latency, *TST* total sleep time, *SE* sleep efficiency, *WASO* wake after sleep onset

Sleep and Cognitive Performance in Athletic Populations

In regards to cognitive function, REM sleep has a vital role in restorative benefits for cognition (Belenky et al., 2003; Hobson, 2005). Similar EEG activity patterns have been observed between REM sleep and wake periods (Stickgold, 2005). It has been proposed that the high neural activity during REM sleep is associated with memory consolidation and learning of motor skills (Davenne, 2009; Halson, 2008; Stickgold, 2005; Venter, 2012). The quantity and quality of sleep the night following a memory task have been positively correlated to the extent of recall and retention the next day (Zerouali, Jemel, & Godbout, 2010). Elite athletes experience high levels of cognitive requirements in their sports, and the demand for ongoing motor learning and cognitive process is high (Fullagar, Skorski, et al., 2015).

Several studies have investigated the effect of sleep deprivation, both partial and total, on cognitive performance. A significant amount of evidence suggests that sleep deprivation adversely affects cognitive performance (Mograss, Guillem, Brazzini-Poisson, & Godbout, 2009). A study by Taheri & Arabameri (2012) looked at the effect of sleep deprivation on choice reaction time and anaerobic power of college athletes. The cognitive measure in the study showed a significant delay in reaction time reported from baseline to post sleep deprivation (244 milliseconds pre sleep deprivation, 282 milliseconds post sleep deprivation) (Taheri & Arabameri, 2012). A study by Edwards and Waterhouse (2009) assessed the effects of partial sleep deprivation in the accuracy and consistency of throwing darts in 60 participants, with results showing decreases in alertness and accuracy (Edwards & Waterhouse, 2009). Furthermore, Reyner and Horne (2013) examined the effect of sleep restriction on the serving accuracy of tennis players, with results indicating significant impairments in serving accuracy following the sleep restriction period (Reyner & Horne, 2013) (Table 2). A study by Ben Cheikh et al (2017) examined the effect of one night sleep deprivation on selective attention and isometric force in karate athletes, with results indicating significant differences following the one night sleep deprivation period in the activation processes of selective attention and maximal isometric strength (Ben Cheikh, Latiri, Dogui, & Ben Saad, 2017).

Although it is unlikely that athletes will experience sleep deprivation to the extent used in the previous studies, an athlete's sleep can still be disrupted for a number of reasons, which can impact their cognitive performance. In team sports, the ability to make fast and accurate decisions is just as important as executing skills efficiently during a match (Lastella, Roach, Halson, & Sargent, 2015). Therefore, the role of sleep in the sleep-wake cycle is fundamental for both the physical and cognitive repair and recovery of an individual. It is clear that the disruption of the sleep-wake cycle can have significant effects on both mental and physical performance in various settings (Souissi et al., 2008).

Table 2 - Studies examining sleep interventions on cognitive performance in athletes.

References	Subjects (*n*)	Fitness Status	Sleep Intervention	Performance Outcome	Results[#]
Edwards and Waterhouse	60[a]	Dart players	4h delayed bed time	Dart throwing accuracy	↓[#]
				Alertness	↓[#]
Jarraya et al	12[a]	Handball goalkeepers	Partial SD 4-5 h sleep obtained	Reaction time	↓[#]
				Stroop test	↓[#]
Mah et al	11[a]	College basketball athletes	Sleep extension 2h	Reaction time	↑[#]
Reyner and Horne	16[a]	Performance tennis players	2-2.5h delayed bed time	Tennis serving accuracy	↓[#]
Scott et al	6[a]	Recreational athletes	Total SD 30h	Reaction time	↓[#]
Taheri and Arabameri	18[a]	Trained college students	Total SD 24h	Choice reaction time	↓[#]

SD sleep deprivation, ↑ = improvement and ↓ = decline
[#] statistically significant ($p < 0.05$)
[a] single-subject design

Sleep and Sports Performance

Elite athletes are facing more intensive physical training loads, competition loads, and high levels of mental stress on a regular basis (Lastella, Roach, Halson, Martin, et al., 2015; Sargent, Lastella, Halson, & Roach, 2014; Tuomilehto et al., 2016) resulting in several factors that could have an influence on sleep disturbances. These may include scheduling of competition (Fullagar, Skorski, Duffield, & Meyer, 2016), increased psychological stress, 'social' requirements, a disruption from light and noise (Fullagar, Duffield, et al., 2015; Romyn, Robey, Dimmock, Halson, & Peeling, 2015), and increased muscle pain and tension following training and competition (Halson, 2014). Increased core temperature following training and competition (Chennaoui, Arnal, Sauvet, & Léger, 2014; Oda & Shirakawa, 2014), may also potentially disrupt the thermo-physiological cascade that initiates sleep (Kräuchi, 2007; Nédélec, Halson, Abaidia, Ahmaidi, & Dupont, 2015).

A study by Leeder et al (2012) examined the sleep duration and quality of 46 elite athletes participating at a national level in a range of sports. Results from the study showed that, although not statistically significant, athletes sleep duration was less than the control group (6:55 h:m and 7:11 h:m, respectively). Results showed a significant difference between the athletes and control, for both sleep latency (18.2 minutes and 5.0 minutes, respectively) and sleep efficiency (80.6% and 88.7%, respectively) (Leeder et al., 2012). Furthermore, the study by Lastella et al (2015) investigated the sleep/wake behavior of 124 elite athletes from individual and team sports. The results from the study reported that on average athletes from individual sports obtained 6:30 h:m of sleep per night and athletes from team sports obtained 7:0 h:m of sleep per night. Moreover, it was reported that athletes from individual sports had a higher napping frequency than athletes from a team sport (Lastella, Roach, Halson, & Sargent, 2015). A study by Hoshikawa et al (2018) investigated the sleep of 817 Japanese athletes, with results showing a mean time in bed of 7:29 h:min, and 229 (28%) athletes showing a PSQI global score above the clinical criteria for poor sleep quality (Hoshikawa, Uchida, & Hirano, 2018). Similarly, a study by Mah et al (2018) examined the sleep of 628 collegiate student-athletes, with results showing 42.4%

of athletes experiencing poor sleep quality, and 39.1% of athletes regularly obtaining less than 7 hours of sleep per night (Mah, Kezirian, Marcello, & Dement, 2018).

Another important area important for future research is how sleep is affected by athletic competition (Fullagar, Skorski, Duffield, Julian, et al., 2016; Juliff, Halson, Hebert, Forsyth, & Peiffer, 2017; O'Donnell, Beaven, & Driller, 2018b; Sargent & Roach, 2016; Shearer, Jones, Kilduff, & Cook, 2015), considering the increased demand in competition scheduling as more sports transition into the professional era. Research from our laboratory, assessed the sleep/wake behavior prior to, on the night of and following competition in 11 elite female netball athletes. The results showed total sleep time was significantly reduced on the night of competition (6:46 h:m), compared to the night prior to competition (8:31 h:m) and remained significantly reduced on the night following competition (7:23 h:m). A significant difference was observed for sleep onset time between all three nights, with an average sleep onset time of 23:57 on the night of competition (O'Donnell, Beaven, & Driller, 2018b). A study by Shearer et al (2015) assessed the sleep of 28 male rugby union players following a game and a reference night, with results showing a significant reduction in sleep following the game (6:02 h:m) compared to the reference night (7:04 h:m). Similarly, both Fullagar et a (2016) and Sargent and Roach (2016) reported significant reductions in sleep on the night following competition in 16 elite male football athletes and 22 male Australian rules football athletes (5:43 h:m and 5:18 h:m, respectively). Furthermore, a study by Juliff et al (2017) investigated sleep patterns of 42 female netball athletes across a six-day competition. The results reported that athletes' sleep was reduced by 29 min following the night games compared to the afternoon games. Interestingly, a strong correlation (r = -0.68) indicated longer sleep durations throughout the competition were associated with a higher tournament finishing place. These studies demonstrated that both male and female athletes are experiencing impaired sleep following competition, therefore suitable interventions may need to be used to alleviate these issues (Table 3). It has also been shown that changes to the training environment also affect athletes' sleep habits. Pitchford et al (2016) investigated the effect of a change in training environment from an eight day home to camp period in 19 Australian rules

football players, with results indicating the camp environment compromised sleep quality compared to the home environment (Pitchford et al., 2016).

Given the significant changes to athlete's sleep habits around competition periods, understanding factors that could contribute to these is important. One such factor is the use of caffeine as a stimulus on competition days. A study by Dunican et al (2018) evaluated caffeine use in 20 elite rugby union players in a Super Rugby competition game and its relationship to post-game sleep. Results showed a significant increase in salivary caffeine levels post game to pre game (2.35 μg/mL), which may have contributed to the reduced sleep duration observed on the night of competition (Dunican et al., 2018).

The majority of sleep research has evaluated the effect of sleep deprivation (partial and total) and the accumulation of sleep debt on cognitive function, mood levels, daytime sleepiness, and physical performances (Mah, Mah, Kezirian, & Dement, 2011). Few previous studies have examined the role of sleep extension, and the subsequent benefits. A study by Mah et al (2011) investigated the effect of sleep extension on the athletic performance of 11 college basketball players. The total sleep time duration of the athletes showed a significant improvement by 110 minutes from baseline to the sleep extension period. In regards to athletic performance, all three variables (282 feet sprint, free throws out of 10 and three-point field goals out of 15) significantly improved following the sleep extension period. The mean reaction time performed morning and evening significantly imrpoved over the sleep extension period. Daytime sleepiness and mood levels resulted in a significant improvement following the sleep extension period.

An important area for future research that is often overlooked is the relationship between sports injuries and both sleep quality and quantity. As sleep deprivation has been shown to reduce reaction time, cognitive function and affect mood, it is proposed that this could be associated with an increase risk of sporting injuries (Milewski et al., 2014). A recent study by Milewski et al (2014) investigated chronic lack of sleep and the subsequent association with increased sports injuries in 112 adolescent athletes over a 21-month period. Of the 112 participants, 64

athletes (57%) sustained a total of 205 injuries over the course of monitoring. Relative risk of injury by Poisson regression showed that the strongest predictor of injury was < 8 hours sleep per night. The results reported that 65% of athletes who reported sleeping < 8 hours of sleep per night experienced an injury over the 21 months of monitoring. It was also reported that athletes who slept on average < 8 hours per night had 1.7 times greater risk of being injured than the athletes who obtained ≥ 8 hours of sleep per night.

Elite athletes experience disturbance to their sleep from a variety of variables as illustrated in the previous research. The improvements shown in performance, reaction time, injury risk, and mood following a sleep extension intervention provide a strong rationale for future research targeting sleep hygiene to enhance athletic performance.

Table 3 - Studies examining sleep and exercise in athletes.

References	Subjects (*n*)	Sport and fitness status	Protocol	Results[#] TST	SE	SL
Juliff et al	42[a]	Netball National	Evening competition vs. afternoon competition	↓[#]	NR	NR
Fullagar et al	16[a]	Football Elite	Evening competition vs. day training	↓[#]	NR	↓[#]
Lastella et al	21[a]	Endurance Cyclists Elite	Competition vs. baseline	↓[#]	NS	NS
Oda and Shirakawa	12[a]	Healthy adults	High intensity evening exercise vs. non exercise	↓[#]	↓[#]	↓[#]
O'Donnell et al	11[a]	Netball Elite	Evening competition vs. night prior	↓[#]	NS	NS
			vs. night following	↓[#]	NS	NS
O'Donnell et al	10[a]	Netball Elite	Evening game vs. evening training	↓[#]	↓[#]	NS
			vs. control	↓[#]	↓[#]	↓[#]
Richmond et al	10[a]	Australian Football League Elite	Evening games vs. baseline Home	↓[#]	NS	NS
			Away	↓[#]	NS	NS
Sargent and Roach	22[a]	Australian Football League Elite	Evening game vs. day game	↓[#]	NS	NS
Shearer et al	28[a]	Rugby Union National	Evening home game vs. reference night	↓[#]	NS	NS

NS non significant, *NR* not reported, *TST* total sleep time, *SE* sleep efficiency, *SL* sleep latency, ↑ = improvement and ↓ = decline
[#] statistically significant ($p < 0.05$)
[a] single-subject design

Napping and Sports Performance

Napping has been reported by Petit, Mougin & Bourdin (2014) as a behavioral measure to alleviate sleep debt, with the afternoon being the most frequent time that napping occurs; likely due to the dip in circadian alertness (Waterhouse, Atkinson, Edwards, & Reilly, 2007). It has been highlighted in previous research, in particular by Davies et al (2010) and Petit et al (2014), that there are two 'ideal' time durations of a nap. The nap duration of less than 20 minutes is considered optimal to avoid waking up during slow-wave sleep (deep sleep) (Petit, Mougin, & Bourdin, 2014). Alternatively, 90 minutes is also considered optimal as this allows a complete sleep cycle (NREM and REM) to occur, reducing the effects of sleep inertia (Davies, Graham, & Chow, 2010). Although limited, previous research (Lastella, Roach, Halson, & Sargent, 2015; Sargent, Halson, & Roach, 2014; Thornton et al., 2016) has reported on the prevalence of daytime naps in the athletic training setting. According to Lastella et al (2015), team sport athletes nap frequency was 11% over a seven night period, with a mean duration of 0:59 ± 1:02 h:min (Lastella, Roach, Halson, & Sargent, 2015). Additionally, Thornton et al (2016) reported of the 31 professional male rugby league athletes, 83% choose to nap during a two-week training camp, with an average 6.3 naps each (Thornton et al., 2016).

A study by Waterhouse et al (2007) investigated the effect of a lunchtime nap following a partial (4 hours) sleep deprivation, in 10 healthy male participants. Results from the study reported a significant improvement in both the 2 m ($p = 0.03$) and 20 m sprint following the 30-minute nap condition compared to a no nap condition. Research from our laboratory assessed the effect of match-day napping on perceptual and performance indices in 14 elite female athletes throughout two competitive netball seasons. The results reported a significant increase in peak jump velocity from a counter-movement squat jump following a nap of a 20-minute or less nap compared to no nap. Further, coach performance ratings of player performance during competitive matches were significantly higher following a 20-minute or less nap compared to athletes that had not napped (O'Donnell, Beaven, & Driller, 2018a).

Furthermore, a study by Davies et al (2010) investigated the sleep quality of a nap following a morning endurance training session in six trained male athletes. The participants completed a standardized 90-minute endurance training session in the morning followed by a 90-minute nap at either one hour or two hours post training session. Their results indicated that a nap at 11.30am as opposed to 10.30am showed a significantly greater amount of slow-wave sleep (13.7 minutes vs 6.9 minutes). As mentioned previously, the slow wave recuperative sleep may be essential for the release of growth hormone, and aid in the physiological recovery of an athlete.

To our knowledge, our study (O'Donnell, Beaven, et al., 2018a) is the only study that examines the effective of a pre-competition nap on subsequent performance in elite athletes, although anecdotal evidence suggests that napping occurs on the day of competition. It is hypothesized that sleep behavior, in particular reduced sleep, on the night prior to competition may be a reason that athletes utilize pre competition naps prior to their performance to alleviate the sleep debt from the previous night. According to Lastella, Lovell & Sargent (2014) 68% of athletes in their study reported experiencing poorer than normal sleep on the night prior to competition, resulting in a total sleep time of 5 hours 51 minutes on average (Lastella, Lovell, & Sargent, 2014). Furthermore, a recent study by Juliff et al (2015) reported 64% of the 283 elite athletes sampled indicated they had slept worse than usual in the night(s) prior to an important competition, with 42.1% reporting an increase in daytime sleepiness as a consequence for sleep disruption (Juliff et al., 2015).

Sleep Hygiene Education and Sports Performance

Sleep hygiene is described as practicing behaviors that facilitate sleep and avoiding behaviors that interfere with sleep (Halson, 2014; Lacks & Rotert, 1986; Mastin, Bryson, & Corwyn, 2006). Sleep hygiene education has been used as a tool to educate individuals on the fundamental aspects of sleep and practical applications to improve sleep quality and quantity. Sleep hygiene education may include aspects of lifestyle and behavior as well as environmental factors that

influence sleep such as light, noise and temperature (Kakinuma et al., 2010; Nishinoue et al., 2012; Sousa, Araujo, & Azevedo, 2007).

The use of education on sleep hygiene has been proven to improve sleep quality and quantity in previous research, within different populations and contexts (Gebhart, Erlacher, & Schredl, 2011; Kakinuma et al., 2010; Nishinoue et al., 2012; Sousa et al., 2007). However, sleep hygiene interventions and education research has only been a recent development in the athletic setting. A study by Fullagar et al (2016) investigated the effect of an acute sleep hygiene strategy following an evening soccer match in 20 male athletes. The sleep hygiene strategy involved temperature and light controlled rooms, with restricted technological device use prior to lights out, and was implemented following the athletes' post match routines. Results reported that the athletes' total sleep time was significantly greater (1:39 h:min) following the sleep hygiene strategy group when compared to a no sleep hygiene strategy group (Fullagar, Skorski, Duffield, & Meyer, 2016). Similarly, research from our laboratory examined the effect of a one-hour sleep hygiene education session in 26 elite female netball athletes from a baseline week to a post week. The results show a significant increase in total sleep time of 22.3 minutes in the week following the sleep hygiene education session compared to baseline (O'Donnell & Driller, 2017).

A study by Duffield et al (2014) evaluated the effect of a mixed recovery intervention, including sleep hygiene recommendations in 8 professional male tennis players. Similarly to Fullagar and colleagues (2016) protocol, restricted electronic stimulants was implemented 30 minutes prior to lights out, and the athletes slept in a temperature-controlled rooms. The authors reported increased time in bed and minutes spent asleep following the sleep hygiene condition, combined with the other recovery interventions, compared to the control condition (Duffield, Murphy, Kellett, & Reid, 2014). Furthermore, Van Ryswyk et al (2017) investigated the effect of a six-week sleep hygiene optimization program in 25 male football athletes. The athletes were provided with a one-hour sleep hygiene education session at the start of the study period. Feedback and progress was provided to the athletes once per week for the six-week period, with a follow up mid-program education session. The results from Van Ryswyk et al (2017) also

demonstrated significant increases in total sleep time and sleep efficiency at the conclusion of the six-week sleep hygiene education intervention compared to baseline values (Van Ryswyk et al., 2017).

The mentioned studies (Duffield et al., 2014; Fullagar, Skorski, Duffield, & Meyer, 2016; O'Donnell & Driller, 2017; Van Ryswyk et al., 2017) show a positive relationship with sleep indices and the use of sleep hygiene intervention and education sessions, highlighting the importance of sleep hygiene in the athletic population for both team and individual sport athletes (Table 4).

Table 4 - Studies examining strategies to improve sleep indices in athletes.

References	Subjects (*n*)	Sport and fitness status	Sleep Intervention	Measures	Results[#]
Duffield et al	8[a]	Tennis Professional	Sleep hygiene recommendations	TST SE (%) SL	*Large* effect (*d* = 2.60) ↑ NS *Moderate* effect (*d* = 0.90) ↑ NS *Small* effect (*d* = 0.23) ↑ NS
Fullagar et al	20[a]	Football Highly trained	Sleep hygiene strategy	TST SE (%) SL	↑[#] NS NS
Mah et al	11[a]	Basketball Trained	Sleep extension (2h)	Sprint Free throws Three-point goals	↑[#] ↑[#] ↑[#]
O'Donnell and Driller	26[a]	Netball Elite	Sleep hygiene education session	TST SE (%) SL	*Small* effect (*d* = 0.39) ↑[#] *Small* effect (*d* = 0.26) ↑ NS *Small* effect (*d* = -0.27)↑ NS
Tuomilehto et al	40[a]	Ice Hockey Professional	Sleep counseling	Perceived sleep quality	83% reported benefit ↑[#]
Van Ryswsk et al	25[a]	Football Trained	Education session	Perceived TST SE (%)	 ↑[#] ↑[#]

NS non significant, *TST* total sleep time, *SE* sleep efficiency, *SL* sleep latency, ↑ = improvement and ↓ = decline
[#] statistically significant ($p < 0.05$)
[a] single-subject design

Conclusion

The current review highlights the relationship between sleep and athletes and the multiple factors that may influence athletes' sleep behavior. The relationship between sleep and varying hormonal markers is increasing in the current literature; however further research is required to better understand how these interact to impact on athletic performance. Studies focusing on sleep loss and cognitive performance have shown cognitive functions to decrease, which could have a detrimental effect on sports that require high levels of cognitive functioning. A range of factors also combine to negatively influence sleep in athletes, with an increased incidence of sleep impairments occurring around competition. The area of napping and athletic performance remains underrepresented in the current literature; which given the anecdotal prevalence of napping in athletes, is an area that requires more in-depth investigation. Sleep hygiene interventions have generated positive results in improving sleep indices in previous research, offering a practical tool for coaching staff and practitioners to use. Furthermore, sleep extension protocols, nutritional interventions and the implementation of meditation and relaxation strategies may also be implemented by coaching staff and practitioners to assist with sleep in athletes. The current review highlights the importance for the need to investigate sleep in the elite athlete population. Given that sleep provides a number of both psychological and physiological important functions that facilitate the recovery process (Nédélec et al., 2015), a greater understanding of strategies to improve sleep, is central to future research in elite athletes.

CHAPTER THREE

The Validity and Reliability of the GymAware Linear Position Transducer for Measuring Counter-Movement Jump Performance in Female Athletes

O'Donnell, S., Tavares, F., McMaster, D & Driller, M. (2017). The validity and reliability of the GymAware linear position transducer for measuring counter-movement jump performance in female athletes. *Measurement in Physical Education and Exercise Science.* 22(1) 101-107.

Abstract

The current study aimed to assess the validity and test-retest reliability of a linear position transducer (LPT) when compared to a force plate (FP) through a countermovement jump (CMJ) in female participants. Twenty-seven female recreational athletes (19 ± 2yrs) performed three CMJ's simultaneously using the LPT and FP for validity. In addition, eleven elite female athletes (23 ± 6yrs) performed three CMJ's with the LPT on three separate days for test-retest reliability. Pearson correlations for jump height between the devices were at a high level (r = 0.90), with the LPT overestimating jump height by 7.0 ± 2.8cm. The reliability measured by the LPT resulted in a mean ICC of 0.70 for jump height, 0.90 for peak velocity and 0.91 for mean velocity. The LPT was reliable for measuring CMJ's in elite female athletes, however, caution should be taken for one-off jump measures as it may over-estimate jump height.

Introduction

Explosive neuromuscular capability is crucial to sport performance, therefore the ability to accurately measure this capability is increasingly important for athlete monitoring and training progress (Glatthorn et al., 2011; Leard et al., 2007; Stojanovic, Ristic, McMaster, & Milanovic, 2016). In the athletic setting, neuromuscular capabilities are often measured and monitored through various types of vertical jumps, including drop-jumps, counter-movement jumps and squat jumps (Cronin, Hing, & McNair, 2004; Garnacho-Castano, Lopez-Lastra, & Mate-Munoz, 2015; Lombard, Reid, Pearson, & Lambert, 2017). The counter-movement jump is commonly performed within sport specific training and competition (i.e. basketball, volleyball, and netball); whereas the drop jump and squat jump are rarely performed within the sporting environment (Struzik, Pietraszewski, & Zawadzki, 2014; Thomas et al., 2017; Wagner, Tilp, Von Duvillard, & Muller, 2009). Therefore, the counter-movement is arguably the most relevant vertical jump movement pattern to sport performance. It is also important to ensure that the instruments used to measure vertical jump performance (i.e. impulse, force, velocity and jump height) are valid and reliable, ensuring data derived is accurate for the practitioner.

Numerous instruments are used to measure changes in vertical jump performance, including: force plates (FP), video analysis, contact mats, wireless accelerometers, and linear position transducers (LPT) (Aragon, 2000; Casartelli, Muller, & Maffiuletti, 2010; Cormie, Deane, & McBride, 2007; Cronin et al., 2004; Glatthorn et al., 2011; Hansen, Cronin, & Newton, 2011a; Hopkins, Schabort, & Hawley, 2001; Markovic, Dizdar, Jukic, & Cardinale, 2004). However, the different technologies used and various methods of calculations for jump height can provide varying results (Aragon, 2000). FPs are considered the ‘gold standard’ to assess jump performance (Glatthorn et al., 2011), although the cost associated and the accessibility to FP technology can make them impractical to use in the general sport setting outside a laboratory. However, technology to measure athletic performance is constantly evolving and becoming more portable, practical and cost effective, leading to the emergence and development of new forms of devices to measure kinetic and kinematic information similar to what a FP provides. A LPT, which is a portable and practical tool, measures the

displacement of an object using optical encoding technology, through a change in the position of a tethered cable, converting this into metric variables (Hansen et al., 2011a; Harris, Cronin, Taylor, Boris, & Sheppard, 2010). From the displacement data, jump height, and velocity (i.e. differentiation of displacement-time curve) are calculated. A further advantage of LPT technology is that the device can be attached to various implements (e.g. dowel and barbell) and athletes (via a waist belt).

Previous research has attempted to validate the use of LPTs to measure jumping performance in male populations (Crewther et al., 2011; Cronin et al., 2004; Hansen et al., 2011a; Hansen, Cronin, & Newton, 2011b; Taylor, Cronin, Gill, Chapman, & Sheppard, 2010). These studies reported high reliability for peak force (CV = 2.9 – 5.5%; ICC = 0.88 – 0.98), peak velocity (CV = 2.6 - 3.7%; ICC = 0.89) and jump height (CV = 7.0 – 7.7%) during loaded and unloaded vertical jumps. Although force and velocity between the FP and LPT are correlated (r = 0.67 - 0.88), there are inherent differences in these outputs that must be considered when selecting the appropriate system to measure jump performance (Crewther et al., 2011; Hansen et al., 2011a, 2011b).

As evident above, studies assessing the validity and reliability of jump performance tests are male-dominant and currently lacking the inclusion of female athlete participants. The under-representation of female participants in the research highlights a gap in the current literature (Costello, Bieuzen, & Bleakley, 2014), alongside the need to validate new technology to measure counter-movement jump performance. Therefore, the purpose of the current study was to assess the reliability and validity of a LPT to measure peak velocity and jump height, when compared to a FP in recreational and elite female athletes.

Methods

Participants

A total of 38 female participants volunteered to take part in the current study. This included 27 recreational athletes (mean age = 19.4 ± 2.2 years; mean body mass = 67.7 ± 10.2 kg) in part one of the study, and 11 elite athletes (mean age =

23 ± 6 years; mean body mass = 79.8 ± 8.9 kg) in part two of the study. Prior to inclusion, all participants were informed about the study including potential risks and benefits and were required to give written consent. This study was given ethical clearance by the institution's Human Research Ethics Committee. All 38 female participants recruited for the study completed the entirety of the study, with no data excluded from analyses. All testing took place in a temperature-controlled laboratory.

Participants were recruited through a university sport-science class for part one, and for part two, participants were recruited through the region's elite netball team. All participants were required to perform a minimum of three exercise training sessions per week for their chosen sport. To be eligible for the study, all participants were required to be free from lower-limb injuries that may have affected their ability to perform counter-movement jumps.

Figure 3 – Set up of the test session. Linear position transducer attached to a waist harness on top a force platform.

Design

Part One - Validity

Participants were asked to perform three counter-movement jumps (CMJs) on the FP (Dual-Axis Force Platform, Pasco®, California, USA). At the same time, participants were attached to the LPT (GymAware, Kinetic Performance Technology, Canberra, Australia) via a waist belt (Figure 3). Jump height measurements were simultaneously recorded by both devices for analysis of validity.

Part Two - Reliability

Athletes completed three CMJs with the LPT attached to the athlete via a waist belt on three separate days to assess the test-retest reliability of the LPT. Participants performed the three counter-movement jumps at the same time of day (15:30) to control for diurnal variation. All trials were separated by 48 hours, and the testing took place during a light-training, non-competition week of the netball season. Each testing day was preceded by a rest day when no training occurred.

Protocol

The protocol for the counter-movement jump assessment was identical for parts one and two of the study. On arrival to the testing session, participants completed a standardized warm-up prior to performing the counter-movement jumps including: hip external and internal rotations, leg swings, single leg Romanian deadlifts, bodyweight squats, dynamic lunges, and three submaximal CMJs. Following the warm-up, participants were required to perform three counter-movement jumps on the FP (part one), with the LPT (part one and two) attached to the athlete via a waist belt. The waist belt was positioned to sit just above the iliac crests of participants, with the same researcher applying the waist belt for each participant on each occasion, to ensure a similar fit each time. Participants started in an upright position, with hands on their hips, using a self-selected depth for the squat phase and keeping their legs straight during the flight phase of the jump (Driller, Tavares, McMaster, & O'Donnell, 2017). A rest interval of 20 seconds was given between each jump.

The LPT manufacturers software (GymAware Lite v2.10, GymAware, Kinetic Performance Technology, Canberra, Australia) was connected to an iPad 3 (Apple Inc., USA) via a Bluetooth connection. The transducer was placed next to the FP and was attached to a magnetic weight plate. The LPT was calibrated prior to every individual participant performing the jumps; the LPT was 'zeroed' whilst the tether was fully retracted. Jump height from the LPT was determined based on change in displacement from the starting position (zero displacement = standing erect with feet shoulder-width apart) to peak positive displacement (maximum jump height). Jump height was calculated from the FP using customized software (WeightRoom, High Performance Sport New Zealand-Goldmine, Auckland, New Zealand). Jump height from the FP was determined based on flight time (time between takeoff, ground reaction force < 5% body weight and landing, ground reaction force > 5% body weight). Velocity from the LPT was calculated (velocity = displacement/time), with peak velocity being the highest value during the jump. Mean velocity is calculated from the average of all data points obtained throughout the jump. The highest mean velocity of the three jumps was retained for analysis.

Statistical Analysis

All data are presented as mean ± SD, unless stated otherwise. Comparison of the LPT with the FP was achieved using paired t-tests ($P < 0.05$), Pearson product-moment correlation analysis (r), 95% limits of agreement (LOA), mean bias and typical error of estimate (TEE). While correlation analyses indicate the degree to which two variables are associated, they do not necessarily indicate the extent to which values agree or disagree (Altman & Bland, 1983; Atkinson & Nevill, 1998; Hopkins, 2015). Therefore the Bland-Altman technique was used to display levels of agreement analysis. The TEE and mean bias between methods was determined using an excel spreadsheet (Hopkins, 2015) with the TEE expressed both in raw units and as a percentage. The magnitude of correlation between the LPT and the FP was assessed using the following thresholds: 0.00-0.19, *very weak*; 0.20-0.39, *weak*; 0.40-0.59, *moderate*; 0.60-0.79, *strong;* and 0.80-1.0, *very strong* (Evans, 1996). Criterion validity thresholds were as follows: TEE of less than or equal to 5%, r of equal to or greater than 0.90 and a *P-value* of greater than 0.05.

Inter-day test-retest reliability data were analyzed using an Excel spreadsheet for reliability (Hopkins, 2015). TEE and overall reliability of the LPT is presented as a coefficient of variation percentage (CV%) and as an absolute value (cm) along with ICCs and 90% confidence intervals (90% CI). The variable used for validity was jump height (cm), and the variables used for reliability were jump height (cm), peak velocity ($m.s^{-1}$) and mean velocity ($m.s^{-1}$). As reported previously (Hopkins et al., 2001; Markwick, Bird, Tufano, Seitz, & Haff, 2015) a test-retest CV of less than 8% has been deemed as acceptable.

Results

All 38 participants were confirmed eligible to participate in the current study, and completed the entirety of the study with no missing data points.

Part One - Validity

Pearson correlation coefficients for jump height were *very strong* (r = 0.90, Figure 4), with a TEE of 2.4 cm (11.8%). These results were associated with a mean bias of 7.0 ± 2.8 cm, with the LPT significantly (p = < *0.01)* overestimating jump height in comparison to the FP (Table 5). Figure 5 highlights the mean bias and 95% limits of agreement (1.5 – 12.5 cm) between the two methods for jump height.

Part Two - Reliability

The test-retest values of the LPT for jump height, peak velocity, and mean velocity over the three testing days are presented in Table 6. The within-participant test-retest reliability of the LPT in elite female athletes across three trials for the jumps measured by the LPT resulted in ICC's of 0.70, 0.90 and 0.91 for jump height, peak velocity and mean velocity, respectively (Table 7). The mean CVs for jump height, peak velocity and mean velocity were 6.2%, 4.7% and 6.7%, respectively. The highest reliability for all three jump variables occurred between tests two and three, with CV's of 5.7%, 4.6% and 5.2% for jump height, peak velocity and mean velocity, respectively. The mean TEE in raw units for jump height, peak velocity and mean velocity were 0.02 m, 0.132 $m.s^{-1}$ and 0.070 $m.s^{-1}$, respectively (Table 7).

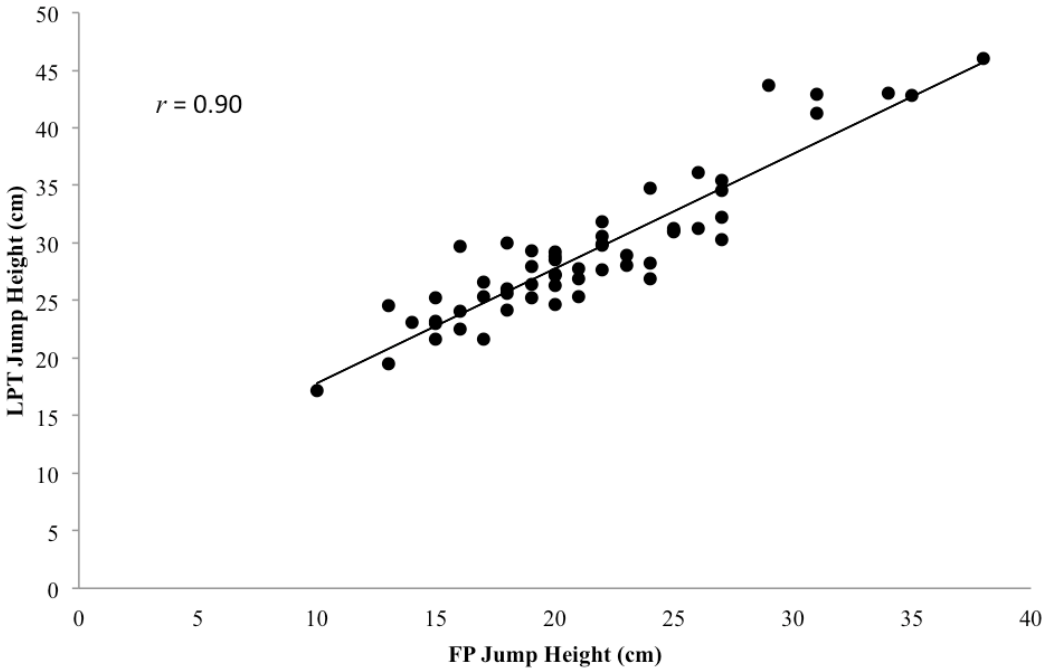

Figure 4 – Relationship between the force plate and linear position transducer-derived jump height (cm).

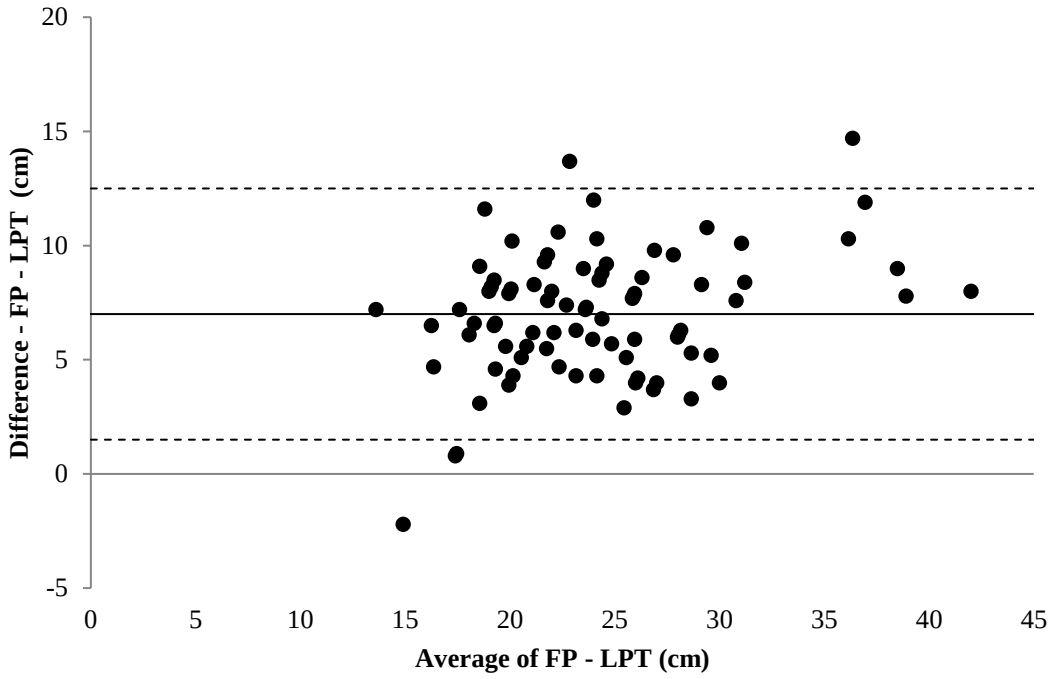

Figure 5 – The level of agreement plots (Bland-Altman) showing 95% limits of agreement (represented as dashed lines) between the force plate (FP) and linear position transducer (LPT) for jump height (cm). Solid black line represents the mean bias between methods.

Table 5 - Comparison of the force plate and linear position transducer (LPT) for jump height (cm), showing the mean bias, the range of mean difference (±2SD), typical error of estimate (TEE – raw and %), the Pearson's moment correlation (*r*) and P-Value between the two methods. 2SD = two standard deviations. 90% CI = 90% confidence interval.

	Force Plate (Mean ± SD)	LPT GymAware (Mean ± SD)	Mean bias raw (Mean ± SD)	Range of mean difference (±2SD)	TEE (raw) (90% CI)	TEE (%) (90% CI)	Correlation (*r*) (90% CI)	P-Value
Jump Height (cm)	20.7 ± 0.1	27.7 ± 0.1	7.0 ± 2.8	(1.5-12.5)	2.4 (2.1-2.7)	11.8 (10.1-14.1)	0.90 (0.86-0.93) *very strong*	< 0.01

Table 6 - Test-retest values of the linear position transducer over the three testing days for jump height (cm), peak velocity ($m.s^{-1}$) and mean velocity ($m.s^{-1}$). All data shown as mean ± SD.

Jump measure	Day 1	Day 2	Day 3	Average
Jump height (cm)	34.4 ± 3.8	34.1 ± 2.6	33.7 ± 3.8	34.1 ± 3.4
Peak velocity ($m.s^{-1}$)	2.97 ± 0.38	2.88 ± 0.39	3.03 ± 0.35	2.96 ± 0.37
Mean velocity ($m.s^{-1}$)	1.71 ± 0.27	1.64 ± 0.30	1.65 ± 0.32	1.67 ± 0.30

Table 7 - Mean within-woman intraclass correlation (ICC), typical error of estimate (TEE) and coefficient of variation (CV%) for three trials in elite female athletes. All data shown as mean (90% confidence interval). The subscript value in the first column is the comparison between trial days; 2–1 (trial day 2 to trial day 1) and 3–2 (trial day 3 to trial day 2).

	Jump Height (cm)	Peak Velocity ($m.s^{-1}$)	Mean Velocity ($m.s^{-1}$)
ICC_{2-1}	0.59 (0.13-0.84)	0.90 (0.73-0.97)	0.86 (0.63-0.95)
ICC_{3-2}	0.72 (0.34-0.90)	0.91 (0.74-0.97)	0.96 (O.89-0.99)
Mean ICC	0.70 (0.40-0.88)	0.90 (0.77-0.96)	0.91 (0.80-0.97)
TEE_{2-1}	2.2 (0.2-0.3)	0.135 (0.100-0.216)	0.120 (0.089-0.192)
TEE_{3-2}	1.9 (0.1-0.3)	0.128 (0.094-0.203)	0.070 (0.052-0.112)
Mean TEE	2.0 (0.2-0.3)	0.132 (0.104-0.193)	0.099 (0.078-0.145)
$CV\%_{2-1}$	6.6 (4.8-10.7)	4.9 (3.6-7.8)	8.0 (5.8-13.0)
$CV\%_{3-2}$	5.7 (4.2-9.3)	4.6 (3.4-7.4)	5.2 (3.8-8.3)
Mean CV%	6.2 (4.8-9.2)	4.7 (3.7-7.0)	6.7 (5.2-10.0)

Discussion

The findings from the study suggest that the LPT significantly overestimates jump height when compared to the 'gold standard' force plate (mean bias = 7.0 ± 2.8 cm, 33.8%). Other studies have also reported LPTs to overestimate vertical jump performance (i.e. peak force by 11% and peak velocity by 30%) in comparison to FP technology (Hansen et al., 2011a, 2011b). Despite this overestimation, the relationship between the two devices was *very strong* (*r* = 0.90) and was also associated with a low typical error of estimate (2.4 cm). While the validity of the LPT for measuring jump height may be questionable, the reliability of the LPT for measuring counter-movement jump performance in elite female athletes was acceptable (CV = 6%, Table 7). This information suggests that FP and LPT should not be used interchangeably to measure or monitor changes in vertical jump performance. However, the LPT may be used a practical tool for coaches aiming to monitor jump performance changes over time. When monitoring changes in performance, it is essential that the tool being used has sufficient reliability to precisely measure small fluctuations in performance.

The results from the current study suggest an acceptable within-woman reliability of the LPT for both peak and mean velocity (ICC = 0.90, and 0.91). A mean CV of less than 8% indicates sufficient reliability (Hopkins et al., 2001). Jump height (CV = 6%), peak (CV = 5%) and mean velocity (CV = 7%) were all deemed reliable based on this threshold. The results of the current study offer support to previous research assessing the reliability and validity of LPTs (Cronin et al., 2004; Youngson, 2010). Youngson (2010) attached three LPTs with a Calibration Rig, reporting low TEE for displacement (0.00m) and velocity (0.01m/s), respectively. A further study by García-Ramos et al. (2016) reported high ICC's and low CV's for peak velocity (0.97 and 3.0%, respectively) from a LPT device. These findings are similar to the current study reporting low error for jump height (TEE = 0.02 m), peak velocity (TEE = 0.132 $m.s^{-1}$) and mean velocity (TEE = 0.070 $m.s^{-1}$), respectively.

Other devices, such as contact mats and vertical jump apparatuses have also been deemed reliable to measure vertical jump performance in female athletes (García-

Ramos et al., 2016; Moir, Shastri, & Connaboy, 2008; Nuzzo, Anning, & Scharfenberg, 2011; Vescovi & Mcguigan, 2008). Vescovi and McGuigan (2008) found contact mats to be *highly* reliable to assess vertical jump performance in a large sample of female athletes (Vescovi & Mcguigan, 2008). Similarly, Moir et al. (2008) found a contact mat to have high intersession reliability (ICC 0.90-0.95) for jump height in female athletes. A further study by, Barnes et al. (2007), found the Vertec was reliable (CV = 7%; ICC = 0.89) for measuring vertical jump height in female volleyball athletes (Barnes et al., 2007). Although the device used to measure jump height differ between the studies, the results from the current study reported similar reliability outcomes in jump performance, which further highlights the ability to use these devices to assess explosive neuromuscular capabilities in female athletes.

Female participants are still largely under-represented in the sport science and biomedical literature (Mazure & Jones, 2015). Costello et al (2014) suggested that under 40% of participants in over 1300 sport and exercise science studies were female. Historically, women have been excluded from research, partially due to the concern that they are more 'physiologically variable' than men (Bruinvels et al., 2016), causing male participants to be viewed as adequate proxies for women in the research. However, it is now known that female participants may actually respond very differently to a range of different treatments in both sport and clinical trials (Costello et al., 2014) due to their physiological and morphological make-up. Given females are increasingly represented among sports participants, sport audiences and media coverage (Capranica et al., 2013), the need for more research studies to include the use of female participants is warranted. Hence, the importance of the current study in assessing the reliability of female athletes for a specific sport performance test. Now that the reliability of the countermovement jump test has been assessed in elite female athletes, future studies can implement this reliability data when analyzing the smallest worthwhile changes to performance in similar elite female athlete populations (e.g. by using CV% results).

One possible limitation of the current study was the attachment of the LPT device via a waist harness. The waist harness was fitted specifically to each individual

participant; however, the variation in movement of the waist harness between participants cannot be discounted. Although not possible in the current study, comparing the reliability of the LPT placement between a waist harness and a bar across the shoulders would be worthwhile for future research. A further limitation of the current study was the small, select nature of the sample that was used, which may compromise the ability to generalize results to other populations.

Conclusion

The results from the current study suggest using a LPT in elite female athletes produces reliable test-retest measures for countermovement jumps over subsequent days for jump height, peak and mean velocity. Although, the LPT showed a *very strong* correlation and low typical error of estimate in relation to the force plate, the LPT overestimated jump height by ~7cm, therefore, these devices should not be used interchangeably to assess vertical jump performance in male or female athletes. The ability to use reliable devices, such as LPT, outside a sport laboratory setting is vital in being able to acquire performance variables in a 'real-time'. In conclusion, it is recommended that the linear position transducer used herein can be used to measure and track vertical jump performance changes in female athletes over time; however, caution is advised when reporting and interpreting jump heights from different measurement systems.

CHAPTER FOUR

Sleep/Wake Behavior Prior to and Following Competition in Elite Female Netball Athletes

O'Donnell, S., Beaven, C & Driller, M. (2018). Sleep/wake behavior prior to and following competition in elite female netball athletes. *Sports Science for Health.* (Published Ahead of Print).

Abstract

Purpose: To determine the sleep routines of elite athletes in the lead up to and following competition. Methods: Ten elite female netballers (mean ± SD; age = 23 ± 6 years) completed a survey on their perceived sleep duration (PSD) and perceived sleep quality (PSQ) on three consecutive nights, the night before the game (G − 1), the night of the game (G), and the night following the game (G + 1) on 15 separate occasions during the in-season competition period. Additionally, the sleep behavior of 11 elite female netballers (mean ± SD; age = 23 ± 4 years) was monitored on two separate occasions using wrist-actigraphy to assess total time in bed (TTB), total sleep time (TST), sleep efficiency (SE), sleep latency (SL), wake episodes per night (WE), sleep onset time (SOT), and wake time (WT) on G − 1, G, and G + 1 nights. Results: There was a significant difference in PSD from G − 1 to G (8:29 to 6:52 h:min, d = − 1.98) and from G to G + 1 (6:52 to 8:09 h:min, d = 1.70). TST was significantly different from G − 1 to G (8:31 to 6:46 h:min, d = − 1.36). At G + 1, TST remained significantly below the G − 1 level (7:23 and 8:31 h:min, respectively, d = − 0.97). SOT was significantly later on the night of the game (23:57), and was also significantly delayed at G + 1 (23:17) compared to G − 1 (22:41). Conclusion: Following an evening netball game, PSD, TST, TTB and SOT are impaired. Additionally, TST and TTB remain impaired on the night following competition.

Introduction

The importance of adequate sleep in providing psychophysiological preparation and recovery in elite athletes is becoming widely recognised in the elite sport setting (Halson, 2013; Leeder et al., 2012). Despite the increased recognition of the importance of sleep, elite athletes often experience reduced sleep quantity compared with non-athletes (Driller, Dixon, & Clark, 2017; Simpson, Gibbs, & Matheson, 2017; Swinbourne, Gill, Vaile, & Smart, 2016; Tuomilehto et al., 2016). Previous research has reported that elite female athletes obtain on average 6:56 h:min of sleep per night (Leeder et al., 2012), and elite athletes from team sports obtain on average 7:00 h:min of sleep per night (Lastella, Roach, Halson, & Sargent, 2015). Elite athletes experience intensive physical training loads and high levels of mental stress on a regular basis (Lastella, Roach, Halson, Martin, et al., 2015; Tuomilehto et al., 2016), resulting in several factors that could contribute to sleep disturbances. These may include increased psychological stress, 'social' requirements, a disruption from light and noise (Fullagar, Duffield, et al., 2015; Romyn et al., 2015), scheduling of competition (Fullagar, Skorski, Duffield, & Meyer, 2016), and increased muscle pain and tension following training and competition (Halson, 2014). Increased core temperature following training and competition (Chennaoui et al., 2014; Oda & Shirakawa, 2014), may also potentially disrupt the thermo-physiological cascade that initiate's sleep (Kräuchi, 2007; Nédélec et al., 2015).

A review of the literature by Chennaoui and collegues (2014), suggest that sleep and exercise influence each other through complex reciprocal interactions, with athletes often mismanaging their sleep. A small number of studies have previously evaluated the effects of competition on the sleep patterns of elite athletes. Sleep was monitored on the night preceding, and the night following, both a day game and a night game in 22 male Australian Rules football athletes (Sargent & Roach, 2016). The results showed substantial differences in sleep variables; in particular sleep duration, on the night following the night game (5:18 h:min) compared to the night following the day game (7:24 h:min $p < 0.008$). Similarly, Shearer et al (2015) reported a reduction in total sleep time in 28 male rugby union players following a game compared to a reference night (6:02 h:min vs. 7:04 h:min, $p < 0.05$).

To our knowledge, perceptual and objective sleep prior to and following netball matches throughout a season in elite female athletes has yet to be evaluated. Furthermore, monitoring the night following competition takes place may give an indication of how the patterns of sleep are altered based on any delayed sleep onset or reduced sleep time following a match. Therefore, the aim of the current study was to evaluate three nights of perceptual sleep; 1) the night before the game (G-1); 2) the night of the game (G), and 3) the night following the game (G+1), across an entire professional netball season in elite female athletes. A secondary aim of the study evaluated three nights of objective sleep on two separate occasions during a professional netball season in elite female netball players; 1) the night before the game (G-1); 2) the night of the game (G), and 3) the night following the game (G+1). In accordance with previous literature, we hypothesize that female athlete's sleep will be impaired on the night preceding, the night of and the night following the game.

Methods

Participants

A total of 21 elite female netball athletes volunteered to participate in the current study. Part One of the study included 10 elite female athletes (mean ± SD; age = 23 ± 6 yrs; body mass = 79.8 ± 8.9 kg) from the same team, and Part Two included 11 elite female athletes (mean ± SD; age = 23 ± 4 yrs; body mass = 76.6 ± 7.9 kg) from the same team. The majority of athletes (n = 18) were from separate teams for Part One and Part Two, with three athletes in both Part One and Two. Athletes were of international representative standard. The study took place during the in-season competition phase of two netball seasons. All participants provided informed written consent before taking part in this study. Ethical approval for the study was obtained through an institutional Human Research Ethics Committee.

Design

Part One – Perceptual Sleep Data

Perceptual sleep data was obtained on three consecutive nights: 1) night before the game (G-1), 2) night of the game (G), and 3) night following the game (G+1) on

15 separate occasions during the in-season period (45 nights in total from each athlete, totaling 450 nights of data collection). The game commenced at 19:30 on the G night. On the morning following G-1, G, and G+1, athletes were sent an electronic survey link (Survey Monkey, Palo Alto Inc. CA, USA) to rate their perceived sleep duration (PSD) and perceived sleep quality (PSQ) from the previous night. Athletes PSD was obtained by stating the time (h:min) they perceived being spent asleep. Athletes PSQ was obtained by providing a 1 to 5 rating (1=very poor, 2=poor, 3=average, 4=good, and 5=very good) on their perceived quality of sleep.

Part Two – Objective Sleep Data

On two separate occasions during the in-season period, 11 athletes wore a wrist actigraph (Readiband, Fatigue Science, Vancouver) over a period of three consecutive days and nights on G-1, G, and G+1 (six days/nights in total from each athlete, totaling 66 nights of monitoring) to monitor and objectively quantify their sleeping patterns on G-1, G and G+1. On both occasions, the evening game started at 19:30 on the G night. The sleep measures obtained from the actigraph are described in Table 1. Athletes were asked to maintain their usual pre- and post-match sleeping habits and general daily activity patterns during all monitoring periods.

The raw activity scores were translated to sleep-wake scores based on computerized scoring algorithms (Sadeh, 2011). The Readiband device has been shown to be reliable in a healthy adult population (Driller et al., 2016; Dunican et al., 2017) and is commonly used in sporting teams as it is more practical and less intrusive compared to polysomnography (PSG) (Dennis, Dawson, Heasman, Rogalski, & Robey, 2016; Shearer, Jones, Kilduff, & Cook, 2015). Athletes were instructed to wear the actigraph on the wrist they felt most comfortable (Driller, Tavares, & O'Donnell, 2017), continuously for the monitoring period, with the exception of time spent during on-court training sessions, during competition, or when in contact with water (e.g. showering or swimming). Sleep indices (Table 8) were quantified via the Fatigue Science software at a sampling rate of 16 Hz.

Table 8 - Definitions of each sleep variable measured through wrist-actigraphy. Adapted from by M. Driller, J. McQuillan, and S. O'Donnell, 2016.

Sleep Indices	**Units**	**Description**
Total Sleep Time (TST)	Minutes	Total time spent asleep
Sleep Efficiency (SE)	%	Total time in bed divided by total sleep time
Total Time in Bed (TTB)	Minutes	Total time spent in bed
Sleep Latency (SL)	Minutes	Time taken for sleep onset
Wake Episodes per Night (WE)	Number count	Total number of awakenings per night
Sleep Onset Variance (SOV)	Minutes	Sleep onset consistency relative to mean
Wake Variance (WV)	Minutes	Wake time consistency relative to mean
Wake Episode Duration (WED)	Minutes	Mean wake episode duration
Sleep Onset Time (SOT)	Time of day	Time of transition from wakefulness into sleep
Wake Time (WT)	Time of day	Wake up time for the sleep period

Statistical Analysis

Descriptive statistics are reported as means ± standard deviations unless stated otherwise. A Student's paired *t*-test was used to compare time points (night before the game, night of the game, and the night following the game) for all sleep measures using a Statistical Package for Social Science (V. 22.0, SPSS Inc., Chicago, IL), with statistical significance set at $p \leq 0.05$. Scores for all measured variables were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$). Magnitudes of the standardized effects were calculated using Cohen's *d* and interpreted using thresholds of 0.2, 0.6, 1.2 and 2.0 for *small, moderate, large and very large,* respectively (Hopkins, Marshall, Batterham, & Hanin, 2009). An effect size of < 0.2 was considered to be *trivial* and the effect was deemed *unclear* if its 90% confidence interval overlapped the thresholds for *small* positive and negative effects (Hopkins et al., 2009).

Results

Part One – Perceptual Sleep Data

Perceptual sleep data for G-1, G, and G+1 is presented in Table 9 and 10. There were substantial differences in PSD between the G night and both G-1 and G+1 (*d* = -1.98; 90% confidence limits ±0.56 and *d* =1.70; ±0.43, respectively, $p < 0.05$, Tables 9 & 10). There was a significant increase in PSQ rating from G-1 to G of 0.5 (*d* = 0.74; ±0.39, $p < 0.05$, Table 10).

Part Two – Objective Sleep Data

The values for the comparison between G-1, G, and G+1 for the objective sleep variables can be observed in Tables 9 and 10. There were substantial reductions in TST between G-1 and G (-1:51 ± 0:58 h, *d* = -1.36; ±0.47, $p < 0.05$, Table 10) and between G-1 and G+1 (-1:05 ± 0:58 h, *d* = -0.97; ±0.47, $p < 0.05$, Table 10). Substantial reductions were also observed in TTB between G-1 and G, (-1:42 ± 1:21 h, *d* = -1.24; ±0.54, $p < 0.05$, Table 9), and between G-1 and G+1 (-1:29 ± 1:26 h, *d* = -1.08; ±0.57 $p < 0.05$, Table 10).

A significant difference was also observed for SOT between each night ($p < 0.05$, Table 9). There were no significant differences observed in SE and SL for comparison between nights (Table 9). Although not statistically significant, SE showed a meaningful -3.5% decrease from G-1 to G (*d* = -0.50; ±0.52, Table 10).

Table 9 - Mean ± SD values for the measured perceived and objective sleep variables on the night before the game (G-1), night of the game (G), and the night following the game (G+1).

Sleep Indices	Night Before Game (G-1)	Night of Game (G)	Night Following Game (G+1)
Part One **Perceived Sleep Duration (PSD) (h:min)**	8:29 ± 0:44[#]	6:52 ± 0:40	8:09 ± 0:46[#]
Perceived Sleep Quality (PSQ) (1 to 5)	3.7 ± 0.4[#]	3.3 ± 0.6	3.7 ± 0.3
Part Two **Total Sleep Time (TST) (h:min)**	8:31 ± 1:02[#, ^]	6:46 ± 0:47	7:23 ± 0:47
Sleep Efficiency (SE) (%)	82.4 ± 6.4	79.4 ± 6.1	84.1 ± 6.7
Total Time in Bed (TTB) (h:min)	10:07 ± 1:17[#, ^]	8:25 ± 1:07	8:39 ± 1:02
Sleep Latency (SL) (min)	23.4 ± 14.7	21.7 ± 25.6	33.1 ± 16.3
Wake Episodes per Night (WE) (No.)	4.5 ± 2.8[^]	4.0 ± 2.0	2.6 ± 1.6[#]
Sleep Onset Time (SOT) (h:mm)	22:41 ± 0:34[#, ^]	23:57 ± 0:43	23:17 ± 0:57[#]
Wake Time (WT) (h:mm)	07:44 ± 0:52[^]	07:55 ± 0:57	06:40 ± 0:59[#]

[#] significantly different ($p < 0.05$) to G,
[^] significantly different ($p < 0.05$) to G+1.

Table 10 - Mean ± SD data for differences between nights for perceived and objective sleep indices, including effect sizes (*d*) and 90% confidence limits (90%CL) for comparison between conditions.

Sleep Indices	Night Before Game – Night of Game (Effect Size)	Night of Game – Night Following Game (Effect Size)	Night before Game – Night Following Game (Effect Size)
Part One **Perceived Sleep Duration (PSD)** **(h:min)**	-1:42 ± 0:46[#] -1.98 ±0.56 *Large*	1:22 ± 1:00[#] 1.70 ±0.43 *Large*	-0:20 ± 0:50 -0.40 ±0.52 *Small*
Perceived Sleep Quality (PSQ) **(1 to 5)**	-0.5 ± 0.5[#] -0.74 ±0.39 *Moderate*	0.5 ± 0.4 -0.78 ±0.34 *Moderate*	0.0 ± 0.3 -0.07 ±0.48 *Trivial*
Part Two **Total Sleep Time (TST)** **(h:min)**	-1:51 ± 0:58[#] -1.36 ±0.47 *Large*	0:27 ± 0:51 0.52 ±0.54 *Small*	-1:05 ± 0:58[#] -0.97 ±0.47 *Moderate*
Sleep Efficiency (SE) **(%)**	-3.5 ± 6.2 -0.50 ±0.52 *Small*	4.1 ± 9.3 0.62 ±0.81 *Moderate*	1.7 ± 7.7 0.25 ±0.61 *Small*
Total Time in Bed (TTB) **(h:min)**	-1:42 ± 1:21[#] -1.24 ±0.54 *Large*	13:0 ± 1:13 0.18 ±0.55 *Trivial*	-1:29 ± 1:26[#] -1.08 ±0.57 *Moderate*
Sleep Latency (SL) **(min)**	-1.6 ± 19.3 -0.10 ±0.66 *Trivial*	11.4 ± 34.4 0.41 ±0.68 *Small*	9.7 ± 26.0 0.61 ±0.89 *Moderate*
Wake Episodes per Night (WE) **(No.)**	-0.5 ± 2.9 -0.16 ±0.52 *Trivial*	-1.4 ± 1.4[#] -0.64 ±0.36 *Moderate*	-1.9 ± 2.1[#] -0.61 ±0.38 *Moderate*

[#] Significantly different between nights ($p < 0.05$).

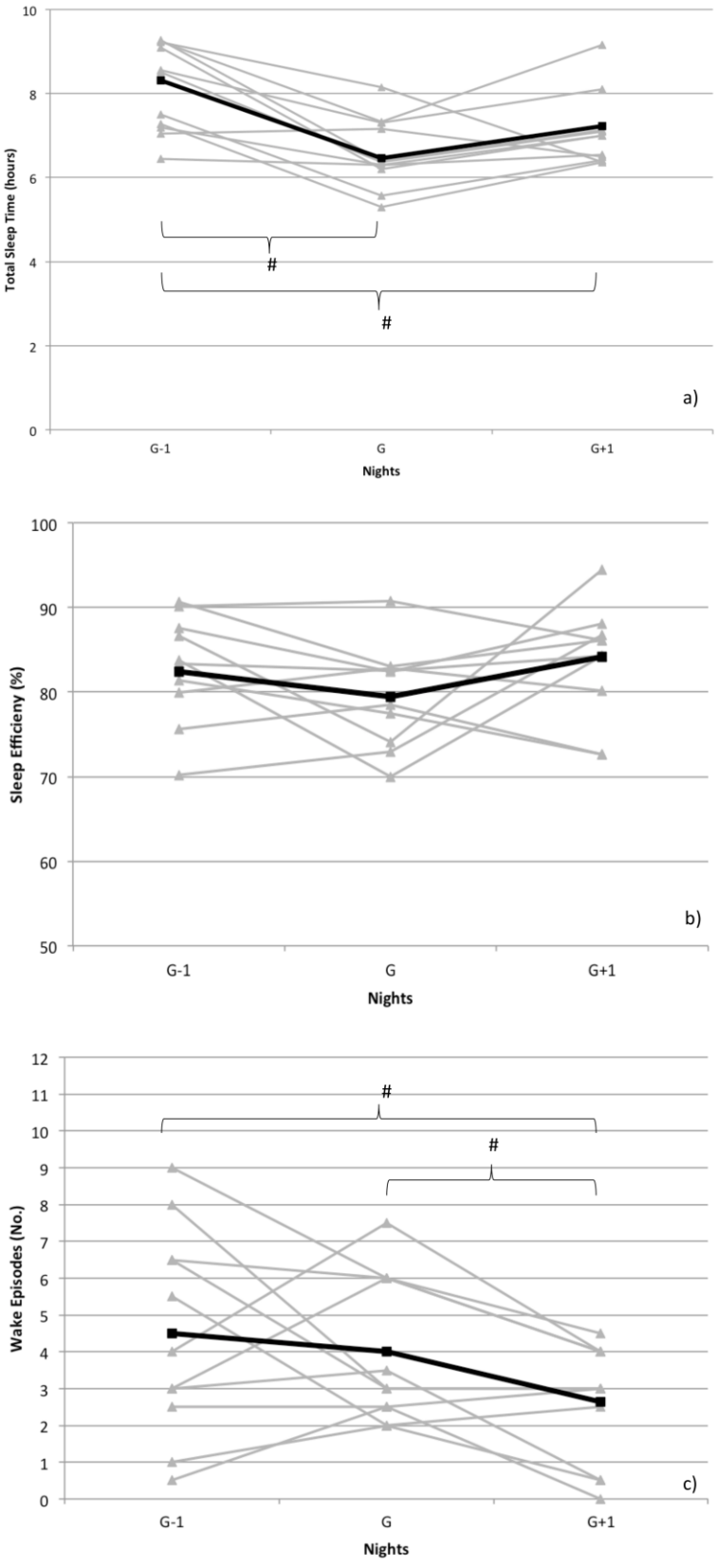

Figure 6 – Mean data from two games for a) Total Sleep Time (hours); b) Sleep Efficiency (%); and c) Wake Episodes (No.) for all participants (n=11) for the night before the game (G-1), night of the game (G), and night following the game (G+1). Thick black line represents group average and grey lines represent each player. # indicates significant difference between nights ($p < 0.05$).

Discussion

This study presents novel sleep data from elite female team sport athletes across a competitive season and demonstrated large sleep impairments as a result of competing at night. The main findings from the current study was that both perceptual and objective measures of sleep times were reduced on the night of the game when compared to the night before by 1:41 and 1:51 h:min, respectively. Additionally, the objective data showed that total sleep time on the night after the game remained significantly reduced by 1:05 h:min compared to the night before the game. These findings provide the first evidence that elite female athletes experience sleep impairments following competition, adding support to the previous research. Therefore, practitioners should ensure that scheduling on the day following games allows for adequate sleep to be achieved.

As reported by Sargent and Roach (2016), sleep duration following a night game was significantly reduced when compared to a day game in 22 male Australian Rules football athletes. The results of the current study are consistent with those found by Sargent and Roach (2016) and similar to a further study by Fullagar et al (2016) in which sleep duration was significantly reduced in 16 elite male football players following a night match. Perceived recovery was also significantly reduced following the night match compared to both the day match and a day training session (Fullagar et al., 2016). Furthermore, a study by Juliff and colleagues (2017) investigated sleep patterns of 42 female netball athletes across a six-day competition. The results reported that athletes' sleep was reduced by 29 min following the night games compared to afternoon games (Juliff, Halson, Hebert, Forsyth, & Peiffer, 2017). Although a similar trend of reduced sleep following competition can be observed between the two studies, the current study reported a much higher reduction in sleep loss (1:51 h:min). The athletes may have been more aware of the importance of sleep and recovery for performance considering they were competing in a compact competition period, compared to the season long competition period of the current study.

The primary cause of the reduced total sleep time and sleep efficiency on the night following the game appears to be associated with a later sleep onset time, which may be related to changes that occur in physiology, psychology, and behavior

following competition (Sargent & Roach, 2016). As previously mentioned, the increases in psychological stress, social requirements, muscle pain and soreness, core temperature, and hormonal levels (Dattilo et al., 2011; Fullagar, Duffield, et al., 2015; Halson, 2014; Nédélec et al., 2015) following competition, may all contribute to a later sleep onset time and increased sleep latency (Shearer et al., 2015). Oda and Shirakawa (2014) reported a significant increase in sleep latency (+14.0 min) following high-intensity exercise prior to sleep compared to no exercise. Significant increases in rectal temperature, skin temperature, and heart rate were observed following the high-exercise condition also. Interestingly, the findings of the current study did not show any significant differences associated with sleep latency between the three nights. However, a large standard deviation was observed for all three nights; G-1, G & G+1 (9 – 54, 6 – 97 & 16 – 60 minutes, respectively), indicating that differences exist within the individual athletes within the sample group. Previous research highlights a high individual response to sleep characteristics in elite athlete settings (Fullagar & Bartlett, 2016; Thornton et al., 2016), which we observed in all of our reported sleep indices as shown in Figure 6. The lack of comparison between the results of the two studies could be associated with the inclusion of elite athletes in the current study in comparison to moderately active participants in Oda and Shirakawa (2014) study. Furthermore, there were noticeable differences in the protocols of the two studies, with athletes in the current study choosing their bedtime as opposed to the requirement of participant's bedtime being set at one-hour post the completion of the high-intensity exercise.

Erlacher et al (2011) reported that out of a sample of 632 athletes, 65.8% reported worse sleep than normal on the night before competition. This data is supported by Juliff et al (2014) reporting 64.0% of athletes experienced sleep disturbances on the night prior to competition. The results of the current study provide further support to the studies of both Erlacher et al (2011) and Juliff et al (2014), as the athletes rated PSQ lowest for G-1 (Part One), and athletes experienced the highest number of WE on G-1 compared to G and G+1 (Part Two). However, we found the night prior to competition (G-1) resulted in the highest sleep duration for both Part One and Two of the study compared to G and G+1 nights, which make it difficult to draw a definitive conclusion between the three studies. A possible

reason for the differing results between the studies could be due to the fact the athletes of the current study compete every week as opposed to some of the athletes surveyed by Juliff et al (2014) and Erlacher et al (2011), whom may only compete at major competitions once per year. The important relationship of sleep prior to competition is evident from previous studies that have an association between poor sleep and poor exercise performance (Souissi, Sesboüé, Gauthier, Larue, & Davenne, 2003), reaction time (Taheri & Arabameri, 2012), running endurance (Oliver, Costa, Laing, Bilzon, & Walsh, 2009), and perceived exertion (Rodgers et al., 1995).

An important finding of the current study was the continued reduction in total sleep time on the night after the game, which is an area that warrants further research. Results from the current study, indicate sleeping patterns may continue to be disrupted, which in turn could compromise the recovery process. The implementation of sleep hygiene education and strategies (Fullagar, Skorski, Duffield, & Meyer, 2016; O'Donnell & Driller, 2017; Van Ryswyk et al., 2017) during and following competition, may be beneficial to see improvements in sleep surrounding evening competition. Only one study, to our knowledge by Fullagar et al (2016) investigated the effect of an acute sleep hygiene strategy following an evening soccer match in 20 male athletes. Results reported that the athletes' total sleep time was significantly greater (1:39 h:min) in the sleep hygiene strategy group when compared to a no sleep hygiene strategy group.

One of the limitations of the current study was the inability to control multiple factors (e.g use of caffeine, nutrition, exposure to melanopically unfriendly light sources), which may have affected the athletes' sleep/wake behavior. The data collection period occurred during in season competition in an elite sport environment; therefore controlling athletes' pre-game routine and behavior was not possible, and would detract from the ecological validity of the results. Another limitation of the current study was the small sample size.

Conclusion

The results of the current study have shown that perceived sleep duration, total time in bed, total sleep time, and sleep onset time are all negatively affected following elite netball matches that take place in the evening. Additionally, the total sleep time on the subsequent night following competition remains significantly reduced. The findings of the current study provide evidence of the sleep patterns of elite female netball athletes and may help coaches and sport scientists better understand the recovery needs and enhance the sleep/wake behavior and patterns prior to and following competition.

CHAPTER FIVE

Sleep and Stress Hormone Responses to Training and Competition in Elite Female Athletes.

O'Donnell, S., Jacobson, G., Bird, S & Driller M. (2018). Sleep and stress hormone responses to training and competition in elite female athletes. *European Journal of Sports Science.* 18(5) 611-618

Link: Findings from Study Two indicate athletes' sleep indices are subjectively and objectively impacted following competition. Given the increase of evening competition in sport, Study Three sought to explain the potential stress response following competition and the subsequent impact on sleep indices.

Abstract

Stress hormone and sleep differences in a competition versus training setting are yet to be evaluated in elite female team-sport athletes. The aim of the current study was to evaluate salivary cortisol and perceptual stress markers during competition and training and to determine the subsequent effects on sleep indices in elite female athletes. Ten elite female netball athletes (mean ± SD; age: 23 ± 6 yrs) had their sleep monitored on three occasions; following one netball competition match (MATCH), one netball match simulation session (TRAIN), and one rest day (CONTROL). Perceived stress (PS) values and salivary cortisol were collected immediately pre (17:15) and post-session (19:30), and at 22:00. Sleep monitoring was performed using wrist actigraphy assessing total time in bed (TTB), total sleep time (TST), efficiency (SE%), latency (SL), sleep onset time (SOT) and wake time (WT). Cortisol levels were significantly higher ($p < 0.01$) immediately post MATCH compared with TRAIN and CONTROL (mean ± SD; 0.700 ± 0.165, 0.178 ± 0.127 and 0.157 ± 0.178 μg/dL, respectively) and at 22:00pm (0.155 ± 0.062, 0.077 ± 0.063, and 0.089 ± 0.083 μg/dL, respectively). There was a significant reduction in TST (-118 ± 112 mins, $p < 0.01$) and SE (-7.7 ± 8.5%, $p < 0.05$) following MATCH vs. TRAIN. Salivary cortisol levels were significantly higher, and sleep quantity and quality were significantly reduced, following competition when compared to training and rest days.

Introduction

Sleep is regarded as an important factor for both optimal performance and recovery in athletes (Forndran, Lastella, Roach, Halson, & Sargent, 2012; Sargent, Halson, et al., 2014; Simpson et al., 2017). However, it has been reported that sleep is often significantly reduced on the nights following training and competition (Fullagar, Skorski, Duffield, Julian, et al., 2016; Sargent & Roach, 2016; Shearer et al., 2015). In one study, looking at a set of 283 elite (individual and team sport) athletes, more than half (52.3%) suffered sleep disturbances following a late training session or competition (Juliff et al., 2015). This reduction in sleep quality and quantity following training and competition is thought to be due to a number of physiological and psychological factors. These may include an increase in core temperature following exercise (Nédélec et al., 2015), an increase in muscle tension and pain following training and competition (Halson, 2014), a disruption from light and noise or increases in psychological stress and 'social' requirements (Fullagar, Duffield, et al., 2015). However, there are few reports showing objective data that either support these perceptions or compares the training and competition environment athletes encounter.

The effects of competition on the sleep patterns of athletes has been reported in a limited number of studies. In 28 male elite rugby union athletes, sleep was monitored following a reference night and following the night of a match (Shearer et al., 2015). The results showed a significant decrease ($p < 0.05$) in h of total sleep time following the match compared to sleep time on the reference night (6:02 ± 1:27 h vs. 7:04 ± 1:01 h, respectively). Another study in 16 elite male football players assessed the effect of a night match on sleep (Fullagar, Skorski, Duffield, Julian, et al., 2016), showing that sleep duration was significantly reduced following a night match compared to both a day match (-2:36 ± 0:45 h, $p < 0.01$) and a day training session (-3:07 ± 0:46 h, $p < 0.01$). A similar finding was also seen in 22 elite male Australian Rules football athletes following night time competition (Sargent & Roach, 2016), where there was a significant reduction ($p < 0.01$) in sleep duration following a night match (5:3 ± 0:6 h) compared to the night following a day match (7:4 ± 1:1 h). Interestingly, very few studies have evaluated sleep patterns or interventions in female athlete

populations (Juliff, Halson, et al., 2017; Leeder et al., 2012; O'Donnell & Driller, 2017), and even less in female team-sport athletes. Leeder at el (2012) reported elite female athletes (n = 43) obtain on average 6:56 h of sleep per night. Whether the similar responses to those seen in the other studies are found in female athletes following competition is yet to be determined.

Another area that has been overlooked in the athlete sleep literature is the psychological stress associated with training and competition. Stress is a characteristic aspect of sports competition, regarded as a psychophysiological process, affecting athletes both cognitively and physiologically (Filaire et al., 2001). Stress is often measured using a combination of perceptual questionnaires and salivary markers such as cortisol, a hormone biomarker widely used to assess athlete stress in a range of sporting environments (Crewther et al., 2013). A study in 12 male judo athletes used cortisol levels to assess psychophysiological stress during competition (Filaire et al., 2001), and reported a significant increase in the hormone ($p < 0.05$) between a rest day when compared to a pre-competition time point for both regional and inter-regional competitions. Cortisol concentrations were also significantly increased at the pre-competition time point in the inter-regional competitions compared to the regional competitions ($p < 0.05$). Similarly, state anxiety, cognitive and somatic anxiety were also significantly higher ($p < 0.05$) in inter-regional competitions compared to regional competitions. Currently, limited investigations on cortisol responses in female athletes exist, with only one study that has evaluated cortisol and perceived stress during a game and training in 20 first division female soccer athletes (Haneishi, Fry, Moore, Schilling, & Fry, 2007). The results showed a significant 250% increase in cortisol levels following the game compared to the training session. However, the study design did not match the training and competition trials for physical intensity, making it difficult to draw conclusions on whether the differences in cortisol levels between trials were related to physiological or psychological factors.

Netball is predominantly a female team-sport that often includes night-matches at the professional level, making elite netball athletes an appropriate cohort for this current study. Furthermore, previous research has shown that quality of sleep may be a problem in elite female netballers (O'Donnell & Driller, 2017). Therefore, the

aim of the current study was to measure different psychophysiological stress markers during a competition day, an intensity-matched training day and a rest day in elite female netball athletes. A secondary aim of the study was to determine the relationship between the psychophysiological stress markers on subsequent sleep indices following the three study days.

Methods

Participants

A total of 10 elite female netball athletes (mean ± SD; age = 23 ± 6 yrs; body mass = 79.8 ± 8.9 kg) volunteered to participate in the current study. Athletes were from the same team and were of international representative standard. The study took place during the in-season competition phase of the netball season, where the team being studied won the National Championship. All participants provided informed written consent before taking part in this study. Ethical approval for the study was obtained through the institution's Human Research Ethics Committee. All participants completed a menstrual history questionnaire, providing information on their menstrual cycles.

Design

The current study took place over a 7-day period, whereby athletes completed one netball competition match (MATCH), one netball training session (TRAIN), and one rest day (CONTROL). The MATCH and TRAIN took place at the same time of day (18:00) and were of the same physical intensity and duration. Individual intensity and duration for MATCH and TRAIN was assessed and matched through the athlete's average heart rate (Polar Electro Oy, Finland), Rate of Perceived Exertion (RPE -Borg's 6-20 scale) (Alexiou & Coutts, 2008; Foster et al., 2001; Gaudino et al., 2015) and the exact on-court playing duration for each individual athlete. The MATCH condition was performed during one of the early rounds of the competition and was played against one of the top teams in front of a capacity crowd. The TRAIN condition was performed as simulated game-play within a team training session, with no crowd in attendance.

Saliva samples were obtained at 3 time points from each athlete for the MATCH, TRAIN and CONTROL trials; immediately PRE (17:15), immediately POST (19:30) and at 22:00. At each time point athletes rated their perceived stress level (PS), using a visual analog scale (VAS) from 0cm ("low stress") to 10cm ("high stress"), adapted from Rumbold et al. (2013) and Oda and Shirakawa (2014). The athletes were instructed to mark a single vertical line at the point on the VAS continuum corresponding to their current stress level. Sleep was monitored on the nights following the MATCH, TRAIN and CONTROL to assess total sleep time (TST), sleep efficiency (SE%) sleep latency (SL), total time in bed (TTB), sleep onset time (SOT) and wake time (WT). To control any dietary variables, athletes recorded their meals and drinks using a smartphone application (MealLogger App, Wellness Foundry, USA) for the MATCH day and were instructed to replicate their diet (nutrition and hydration) for the subsequent TRAIN and CONTROL days. Caffeine was abstained from for each testing day.

Sleep Monitoring

Athletes were required to wear a wrist actigraphy device (Readiband, Fatigue Science, Vancouver, Canada) over the duration of the study period to monitor sleep patterns. The raw activity scores were translated to sleep-wake scores based on computerized scoring algorithms (Sadeh, 2011). The Readiband device has been shown to be reliable in a healthy adult population (Driller et al., 2016) and is commonly used in sporting teams as it is more practical and less intrusive compared to polysomnography (PSG) (Dennis et al., 2016; Shearer et al., 2015). The Readiband device has been validated against the gold standard polysomnography (Dunican et al., 2017). Athletes were instructed to wear the actigraph on their non-dominant wrist (Dennis et al., 2016), continuously for 7 days, with the exception of time spent during on-court training sessions, during competition, or when in contact with water (showering, swimming). Sleep indices were quantified via the Fatigue Science software (16Hz sampling rate: Readiband, Fatigue Science, Vancouver).

Hormone Assesment

At each of the three time points during all three trials, athletes provided a 5-ml saliva sample by passive drool into a sterile plastic tube. Sugar-free gum (Extra, Wrigley's, New Zealand) was used to increase saliva flow (Casto, Rivell, & Edwards, 2017; Crewther, Lowe, Weatherby, Gill, & Keogh, 2009), with saliva samples stored at -20°C until required. On the day of testing, saliva samples were thawed to room temperature and centrifuged at 3000 rpm for 15 minutes to remove mucins. Saliva samples were assayed using a highly sensitive Enzyme Linked Immunosorbent Assay (ELISA) for cortisol (Salimetrics, NSW, Australia), following the manufacturer's instructions. Samples were analyzed in duplicate, using 25 μL of saliva per determination and the ELISA had a lower limit of sensitivity of 0.007 μg/dL. The standard curve ranged from 0.012 μg/dL to 3.0 μg/dL, had an average intra-assay coefficient of variation (CV) of 4.2%, and an average inter-assay coefficient of variation (CV) of 8.5%.

Statistical Analysis

Simple group statistics are shown as mean ± standard deviation unless otherwise stated. A Microsoft Excel spreadsheet was used to estimate the mean effects and 90% confidence intervals (90% CI) of all measured variables between trials (Hopkins, 2006). Magnitudes of the standardized effects were calculated using Cohen's *d* and interpreted using thresholds of 0.2, 0.5 and 0.8 for *small, moderate and large*, respectively (Batterham & Hopkins, 2006). An effect size of <0.2 was considered to be *trivial* and the effect was deemed *unclear* if its 90% confidence interval overlapped the thresholds for *small* positive and negative effects (±0.2) (Batterham & Hopkins, 2006). The distribution of all data was tested with the Shapiro-Wilk normality test. A two-way ANOVA was utilized to examine the effect of conditions on salivary cortisol levels and sleep indices, using a Statistical Package for Social Science (V. 22.0, SPSS Inc., Chicago, IL), with statistical significance set at $p \leq 0.05$.

Results

No significant differences were found between MATCH and TRAIN for mean heart rate (148 ± 8 and 145 ± 10 bpm, *d* = 0.26 ±0.57, *unclear*, respectively), RPE (15 ± 2 and 14 ± 1, respectively), or playing duration (matched exactly).

Sleep Variables

The values for the comparison between the MATCH, TRAIN and CONTROL conditions for sleep variables can be observed in Table 11 and Table 13. There was a significant reduction in TST (-1:58 ± 1:52 h, *d* = -1.41 ±0.77, *large*, p=0.008) and SE (-7.7 ± 8.5%, *d* = -0.79 ±0.50, *moderate*, p=0.018) on the night of the MATCH compared to the TRAIN session (Table 11). A significant increase in SL was observed for the night following the MATCH compared to the CONTROL (50.3 ± 58.5 mins, *d* = 0.89 ±0.69, *large*, p=0.045). Although not statistically significant, there was an increase of 28.5 ± 45.3 mins in SL following the netball MATCH compared to the TRAIN session (67.0 ± 51.9 mins and 38.5 ± 29.3 mins, respectively, *d* = 0.89 ±0.82, *moderate*).

Cortisol

Cortisol levels (Fig. 7; Table 12) were significantly upregulated (354%) POST match when compared to PRE match ($p < 0.001$). There was a significant increase in cortisol concentrations immediately POST MATCH compared to POST TRAIN (293%, p=0.003), which was associated with a *very large* effect (*d* = 3.77 ±0.74) and POST MATCH compared to POST CONTROL (345%, *d* = -3.02 ±0.72, *very large*, $p < 0.001$). A significant increase in cortisol concentration was observed at the 10:00pm time point (*d* = 1.13 ±0.35, *large*, p=0.013) following the MATCH compared to the TRAIN session and a significant increase was observed at 10:00pm between MATCH and CONTROL (*d* = -0.97 ±0.75, *large*, p=0.042).

Perceived Stress

There was a significant increase in perceived stress for the MATCH compared to CONTROL at the PRE time point (Table 12).

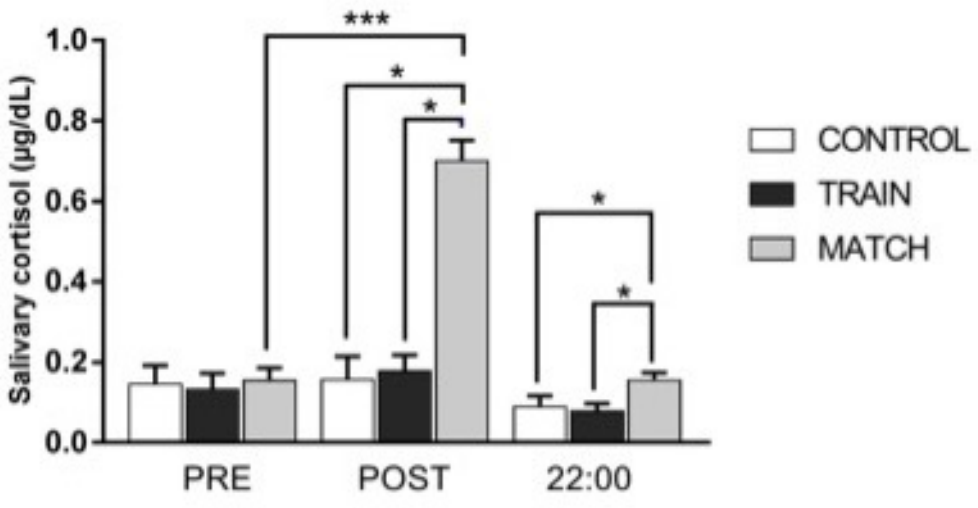

Figure 7 - Salivary cortisol concentrations (µg/dL) pre, post and at 10:00pm for a match (MATCH), training (TRAIN) and rest (CONTROL) day. * indicates a very large effect (Cohen's d) and *** indicates a significant p value <0.001).

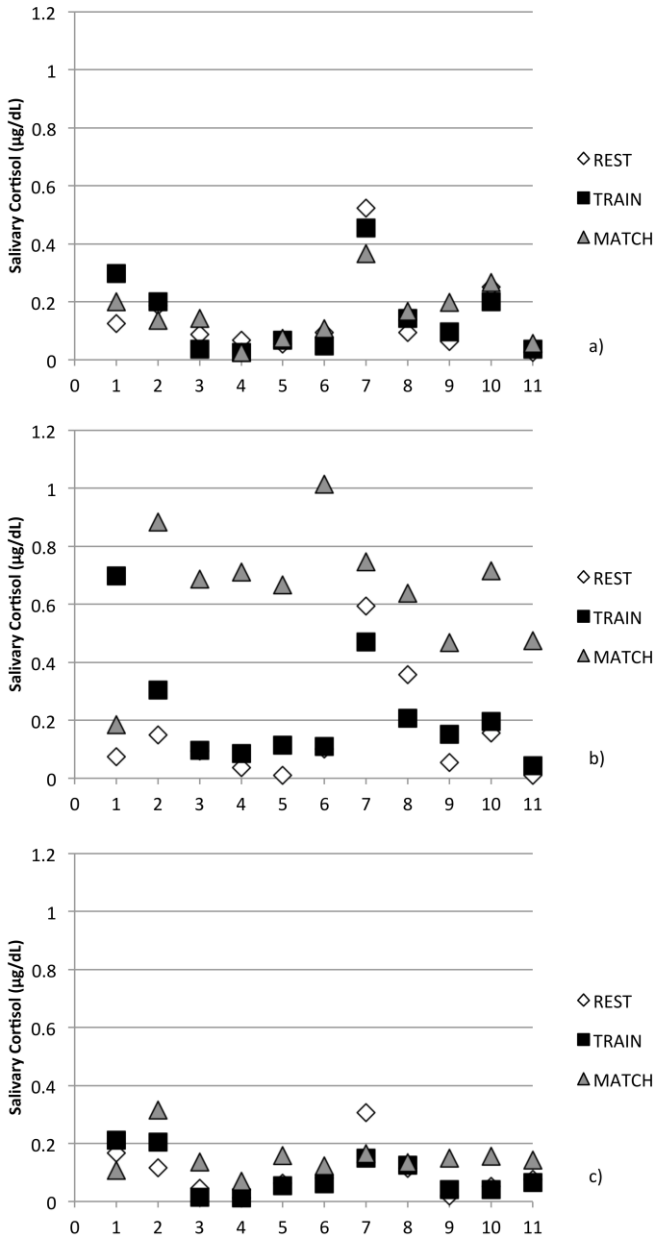

Figure 8 – Individual (n = 10) salivary cortisol response (µg/dL) for a) PRE; b) POST; and c) 22:00pm for a match (MATCH), training (TRAIN) and rest (CONTOL) day.

Table 11 – Values (mean ± SD) for the measured sleep variables in control (CONTROL), training (TRAIN) and match (MATCH) trials.

Sleep Indices	CONTROL	TRAIN	MATCH
Total Sleep Time (h:mm)	8:46 ± 1:03	8:01 ± 1:17^	6:03 ± 1:51#
Sleep Efficiency (%)	85.3 ± 7.2	82.1 ± 8.9^	74.4 ± 10.1#
Sleep Latency (h:mm)	27.5 ± 34.7	38.5 ± 29.3	67.0 ± 51.9#
Total Time in Bed (h:mm)	10:36 ± 2:09	9:56 ± 1:48^	8:22 ± 2:16#
Sleep Onset Time (time of day)	23:39 ± 1:37	23:22 ± 1:26	00:25 ± 1:37
Wake Time (time of day)	07:34 ± 1:06	08:22 ± 1:32^	07:17 ± 0:37#

Significant difference to CONTROL ($p < 0.05$)
^ Significant difference to MATCH ($p < 0.05$)

Table 12 – Values (mean ± SD) for salivary cortisol levels and perceived stress (PS) variables in control (CONTROL), training (TRAIN) and match (MATCH) trials.

	CONTROL	TRAIN	MATCH
Cortisol Pre (µg/dL)	0.145 ± 0.148	0.131 ± 0.132	0.154 ± 0.102
Cortisol Post (µg/dL)	0.157 ± 0.185	0.178 ± 0.127^	0.700 ± 0.165#
Cortisol 22:00 (µg/dL)	0.089 ± 0.084	0.077 ± 0.063#^	0.155 ± 0.062#
PS - PRE (arbitrary units)	2.9 ± 2.5	3.9 ± 2.7	5.2 ± 2.3#
PS – POST (arbitrary units)	2.2 ± 1.8	2.0 ± 1.3	2.3 ± 1.9
PS – 22:00 (arbitrary units)	1.7 ± 1.8	2.1 ± 1.9	3.2 ± 1.7

Significantly different to CONTROL ($p < 0.05$)
^ Significantly different to MATCH ($p < 0.05$)

Table 13 – Data (mean ± SD) for differences between trial conditions for sleep and cortisol levels, including effect sizes (*d*) and 90% confidence limits (90%CL) for comparison between conditions.

	TRAIN - CONTROL (Effect Size)	**CONTROL - MATCH (Effect Size)**	**MATCH - TRAIN (Effect Size)**
Total Sleep Time (h:mm)	-0:45 ± 0:31 0.21 ±0.25 *Small*	2:41 ± 1:50[#] 1.19 ±0.61 *Large*	-1:58 ± 1:52[#] -1.41 ±0.77 *Large*
Sleep Efficiency (%)	3.4 ± 11.9 0.35 ±0.90 *Small*	12.7 ± 13.4[#] 1.15 ±0.89 *Large*	-7.7 ± 8.5[#] -0.79 ±0.50 *Moderate*
Sleep Latency (minutes)	10.8 ± 33.8 -0.34 ±0.71 *Small*	-50.3 ± 58.5[#] -0.89 ±0.69 *Large*	28.5 ± 45.3 0.89 ±0.82 *Moderate*
Total Time in Bed (h:mm)	-0:22 ± 1:56 0.19 ±0.60 *Unclear*	2:04 ± 2:16[#] 0.84 ±0.62 *Large*	-1:39 ± 2:40[#] -0.84 ±0.69 *Large*
Cortisol Pre (µg/dL)	-0.014 ± 0.042 0.09 ±0.17 *Trivial*	0.009 ± 0.079 -0.08 ±0.41 *Unclear*	0.023 ± 0.064 0.16 ±0.26 *Unclear*
Cortisol Post (µg/dL)	0.021 ± 0.096 -0.15 ±0.40 *Unclear*	0.544 ± 0.224[#] -3.02 ±0.72 *Very Large*	0.523 ± 0.178[#] 3.77 ±0.74 *Very Large*
Cortisol 22:00 (µg/dL)	-0.012 ± 0.061 0.17 ±0.51 *Unclear*	0.066 ± 0.088[#] -0.97 ±0.75 *Large*	0.078 ± 0.042[#] 1.13 ±0.35 *Large*

[#] indicates significant difference between conditions ($p < 0.05$).

Discussion

The current study is the first to assess psychophysiological stress markers during competition and training environments and examine their relationship to sleep indices in an elite female athlete population. The main findings from the study were a significant increase in salivary levels of the stress hormone cortisol immediately following a netball match and at 22:00pm, when compared to the same time points following an intensity-matched training session. Reduced sleep quantity and quality following the match compared to the training session were also observed. These findings provide the first evidence that elite female athletes experience higher psychological stress levels following a match and a reduction in both sleep duration and quality.

The results of the current study are consistent with previous investigations that have examined the stress response differences between a competition and training environment (Filaire et al., 2001; Haneishi et al., 2007). The study in female collegiate soccer players (n=20) assessed the response of cortisol and perceived psychological stress during a game and training (Haneishi et al., 2007). Somatic state anxiety and cognitive state anxiety were both significantly greater ($p < 0.05$) pre- and post-game compared with training for all subjects. While we found similar results for increases in cortisol concentrations following a match compared to training, the perceptual stress results differed between the two studies. Although these were not statistically significant, the perceptual stress results from the current study showed trends to higher perceived stress PRE and at 22:00pm following the MATCH (5.2 and 3.2 respectively) compared to TRAIN (3.9 and 2.1, respectively). The inclusion of more in-depth perceived stress measurements, such as the 21-item Self-rating Anxiety Scale (SAS) and the Competitive State Anxiety Inventory-2 (CSAI-2), as used by Haneishi et al. (2007) compared to the VAS scale used in the current study, may have resulted in more sensitive measures to determine perceived stress differences.

Although differing through comparison to a rest day as opposed to a training day, assessment of the psychophysiological stress in judo athletes during competition showed similar results to the current study (Filaire et al., 2001). In the 12 male judo athletes investigated, a significant increase in cortisol concentrations ($p <$

0.05) pre-, post-competition for both a regional and interregional competition compared to a rest day were reported. A possible contributing factor in the difference observed at the POST time point between MATCH and TRAIN in the current study, could be the effect of the crowd. Although speculative, the crowd factor may be similar to the heightened pressure and cortisol response of athletes that play at home compared to away fixtures (Carré, 2006). Previous reports have shown that competition typically creates a psychologically stressful environment, with an anticipatory rise in cortisol concentrations pre-competition (Haneishi et al., 2007; Passelergue, Robert, & Lac, 1999). There are several contributing factors to this, such as playing in front of a large crowd and the pressure of performing that may cause the anticipatory rise in cortisol concentrations pre-competition (Arruda et al., 2016). In contrast to this, in the current study although not significant, athletes rated their PS highest for MATCH (5.2) compared to TRAINING (3.9) at the PRE time point. The saliva sample was taken PRE match when the athletes were in the dressing room before going out to play. Although it is pure speculation at this point, it is possible that if the saliva sample was taken courtside where athletes were exposed to the large crowd, salivary cortisol and perceived stress levels would have been higher.

In regards to sleep, the results of the current study are consistent with and support previous studies that have assessed sleep indices following either competition or training (Eagles et al., 2014; Fullagar, Skorski, Duffield, Julian, et al., 2016; Oda & Shirakawa, 2014; Sargent & Roach, 2016; Shearer et al., 2015). The current study showed the same trends in sleep indices and *large effects* on sleep following an evening match, with sleep duration reduced to 6:03 h (25% reduction), similar to the reduction to 5:30 h (from 7:40 h on the training day; 28% reduction) reported by Sargent and Roach (2016). However, our study differs to theirs as sleep/wake behavior was compared between a competitive match and a training session under the same conditions (time, duration and intensity), whereas their comparisons were made between matches taking place at both day and night. However, the difference in TST found in the current study (-1:58 h less following MATCH compared to TRAIN) are similar with another investigation (H. Fullagar, S. Skorski, R. Duffield, R. Julian, et al., 2016), that reported similar differences between a night match and a day match (~ 2:36 h).

It has been proposed that sleep latency following high intensity exercise late at night is extended, through physiological variables such as increases in core body temperature (Sargent & Roach, 2016), mental stimulation and cognitive fatigue (Fullagar, Duffield, et al., 2015). The physical exertion following late night competition may also cause disruptions to circadian rhythms, in turn causing a phase delay in melatonin production, and delayed sleep onset (Shearer et al., 2015). Another significant finding of the current study was the *moderate to large* reduction in SE following the MATCH compared to both the TRAIN (-7.7%) and CONTROL (-12.7%), which is supportive of the reduction of SE observed following high-intensity exercise prior to bed compared to no exercise in the study by Oda and Shirawaka (2014). The reduction in sleep duration observed in the current study, following the match and training compared to the control day, may be caused by the delay in bedtime due to the timing of the match and training, a point already observed in another study (Fullagar, Skorski, Duffield, Julian, et al., 2016). However, there is little published data on sleep following competition. This is surprising given that periods of sleep loss could potentially compromise the recovery process for those athletes who need to perform to a high standard on a weekly basis (Skein, Duffield, Minett, Snape, & Murphy, 2013). A study by Juliff and collegues (2017) reported significantly longer sleep durations in a six day netball tournament for the top finishing two teams (8:02h) compared to the two bottom ranked teams (7:01h), highlighting the importance of adequate sleep in a competition setting. Therefore, the ability to improve sleep indices following night competition is important, and interventions, such as sleep hygiene education (O'Donnell & Driller, 2017) and relaxation strategies, following a night match may help to improve sleep in athletic populations (Fullagar, Skorski, Duffield, & Meyer, 2016).

A limitation of the current study was that there was only a single testing day for each condition (match, training and control days). Data collected over a season or over multiple games and training sessions would have allowed for a more in-depth knowledge on competition and subsequent sleep indices. A limitation of the current study was the Readiband device accuracy for measuring sleep latency and sleep efficiency, as caution has been recommended when interpreting these

indices (Dunican et al., 2017). A further limitation of the current study was the potential effect of the menstrual cycle phases. Whilst data on menstrual cycles were collected, we were unable to control for these factors, ensuring that testing occurred at the same time of the menstrual cycle for each athlete. Future research should aim to assess any differences in the stress and sleep responses in both match and training environments at different phases of the menstrual cycle.

Conclusion

In summary, the results of the current study indicate that the match environment resulted in *very large* post-match levels of cortisol and reduced sleep quantity and quality when compared to post-training in elite female netball athletes. The findings of this study are novel, in that the physical intensity between match and training scenarios were matched, and suggest that the psychological stress associated with competition may play a large part in the impaired sleep measures. Practitioners should be aware of the extra stress competition elicits, and adequately allow for appropriate recovery in periodised training programs.

CHAPTER SIX

Melatonin and Sleep Responses Following Exercise in Elite Female Athletes

O'Donnell, S., Beaven, C., Jacobson, G., Bird, S & Driller M. Melatonin and sleep responses following exercise in elite female athletes. Under review in *Clocks & Sleep* as a Short Communication

Link: Study Three demonstrated increased cortisol levels following an evening netball match that remained elevated late at night before sleep onset. These elevated cortisol levels were associated with impaired sleep indices following the evening match. Study Four sought to explore a further potential mechanism disturbing sleep indices following evening exercise - melatonin.

Abstract

Purpose: To determine the melatonin concentrations of elite netball athletes following training. Methods: 10 elite female netball athletes (mean ± SD; age = 23 ± 6 yrs) provided saliva samples PRE (17:15h) and POST (22:00h) training (TRAIN), or on a day with no training (CONTROL). Sleep monitoring was performed using wrist actigraphy to assess total time in bed (TTB), total sleep time (TST), sleep efficiency (SE), and sleep latency (SL). Results: Melatonin levels were significantly lower both PRE and POST the TRAIN condition when compared with CONTROL. Conclusion: The scheduling of netball training in the evening is shown to suppress salivary melatonin levels.

Introduction

Athletes experience high training load demands and stress (Lastella, Roach, Halson, & Sargent, 2015; Tuomilehto et al., 2016), with sleep widely regarded as important for performance and recovery (Halson, 2013; Venter, 2012). Athletes often experience poorer sleep quantity in comparison to non-athletes (Driller, Dixon, et al., 2017; Simpson et al., 2017; Swinbourne et al., 2016), and reports have shown that sleep is often impaired on nights following training or competition (Fullagar, Skorski, Duffield, Julian, et al., 2016; O'Donnell, Beaven, et al., 2018b). Several contributing factors may cause sleep disruption, including social/media requirements (Romyn et al., 2015), competition scheduling (H. Fullagar, S. Skorski, R. Duffield, & T. Meyer, 2016), and increases in muscle pain and core temperature following training or competition (Halson, 2014; Oda & Shirakawa, 2014). An additional contributing factor that may impair sleep could be the suppression of melatonin following evening exercise (Monteleone et al., 1990).

Previous research on the effect of melatonin levels following exercise has shown polarized results, with both increases (Buxton, Lee, L'Hermite-Baleriaux, Turek, & Van Cauter, 2003; Carr et al., 1981; Theron, Oosthuizen, & Rautenbach, 1984) and decreases (Buxton et al., 1997; Monteleone et al., 1990) being reported. Carr and colleagues (1981) had reported increased plasma melatonin levels in seven women following serial acute submaximal exercise. Whereas, Monteleone and colleagues (1990), demonstrated reduced melatonin levels in seven male participants following nocturnal physical activity. Melatonin is a hormone that is synchronized from environmental cues, contributing to the initiation of sleep in the circadian system (Escames et al., 2012). Due to the importance of melatonin in the circadian system, its contribution to sleep initiation, and the changes in expression seen after exercise, there is a need for more investigation. In addition, the impact of exercise on biorhythms and sleep is becoming increasing more important to understand with the increase of evening training and competitions occurring for both athletes and non-athletes.

Therefore, the aims of this study were to measure the effects of training on melatonin levels in elite female netball athletes and determine if there was any effect between melatonin levels and subsequent sleep indices.

Methods

Participants

A total of 10 elite female netball athletes (mean ± SD; age = 23 ± 6 yrs; body mass = 79.8 ± 8.9 kg) volunteered to participate in the study. Athletes were from the same team and were of international representative standard. The study took place during the in-season competition phase of the netball season. The athletes were free from any sleep disorders, as assessed through the Pittsburg Sleep Quality Index (PSQI), with a global score of <5 indicating 'good sleepers' (Buysse et al., 1989). All participants provided informed written consent before taking part in this study. Ethical approval for the study was obtained through the institution's Human Research Ethics Committee.

Design

The current study took place over a seven-day period, whereby athletes completed one netball training session (TRAIN), and one rest day (CONTROL). Individual intensity for TRAIN was assessed through the athlete's average heart rate (Polar Electro Oy, Finland) and Rate of Perceived Exertion (RPE – Borg's 6-20 scale) (Borg, 1982). The TRAIN sessions total duration was two hours, taking place at 18:00h and concluding at 20:00h in the evening.

Saliva samples were obtained at two time points from each athlete for the TRAIN and CONTROL days; immediately PRE (17:15h), and at 22:00h. Athletes were instructed to collect the saliva samples in the same room, under the same lighting conditions between the two conditions. Sleep was monitored on the nights following TRAIN and CONTROL to assess total sleep time (TST), sleep efficiency (SE%), sleep latency (SL), and total time in bed (TTB). To control for dietary variables, athletes recorded the meals using a smartphone application (MealLogger App, Wellness Foundry, USA) for the TRAIN day and were instructed to replicate their diet for the subsequent CONTROL day.

Sleep Monitoring

Athletes were required to wear a wrist actigraphy device (Readiband, Fatigue Science, Vancouver, Canada) over the duration of the study period to monitor sleep patterns. The Readiband device has been shown to be reliable in a healthy adult population (Driller et al., 2016; Dunican et al., 2017) and is commonly used in sporting teams as it is more practical and less intrusive compared to polysomnography (Dennis et al., 2016; Dunican et al., 2017). Athletes were instructed to wear the actigraph on the wrist they felt most comfortable (Driller, Tavares, & O'Donnell, 2017) continuously for the monitoring period, with the exception of time spent during on-court training sessions, or when in contact with water (e.g. showering or swimming). The raw activity scores were translated to sleep-wake scores based on computerized scoring algorithms. Sleep indices were quantified via the Fatigue Science software at a sampling rate of 16Hz.

Hormone Assessment

At each of the two time points during the two trials, athletes provided a 5 mL saliva sample by passive drool into a sterile plastic tube, with saliva samples stored at -20°C, until analysed. On the day of testing, saliva samples were thawed to room temperature and centrifuged at 3000 rpm for 15 minutes to precipitate mucins. Saliva samples were assayed using a highly sensitive Enzyme Linked Immunosorbent Assay (ELISA) for melatonin (Salimetrics, NSW, Australia), following the manufacturer's instructions. Samples were analyzed in duplicate, using 100 μL of saliva per determination, with the ELISA having a lower limit of sensitivity of 1.37 pg/mL. The standard curve ranged from 0.78 pg/mL to 50.00 pg/mL, had an average intra-assay coefficient of variation (CV) of 5.7%, and an average inter-assay CV of 7.5%.

Statistical Analysis

Descriptive group statistics are shown as mean ± standard deviation unless otherwise stated. A Microsoft Excel spreadsheet was used to estimate the mean effects and 90% confidence intervals (90% CI) of all measured variables between trials (Hopkins, 2006). Magnitudes of the standardized effects were calculated

using Cohen's *d* and interpreted using thresholds of 0.2, 0.6, 1.2 and 2.0 for *small, moderate, large and very large*, respectively (Hopkins et al., 2009). An effect size of < 0.2 was considered to be *trivial* and the effect was deemed *unclear* if its 90% confidence interval overlapped the thresholds for *small* positive and negative effects (Batterham & Hopkins, 2006). A student's paired *t*-test was used to compare TRAIN and CONTROL conditions for sleep measures, and a two-way analysis of variance (ANOVA) was performed to compare the time points (PRE and 2200h) and the effect of conditions on salivary melatonin levels using a Statistical Package for Social Science (V.22.0, SPSS Inc., Chicago, IL), with significance set at $p \leq 0.05$.

Results

The athletes' mean heart rate during TRAIN was 145 ± 10 bpm with a mean rating of perceived exertion of 14 ± 1.

The values for the comparison between the TRAIN and CONTROL conditions for sleep and melatonin variables can be observed in Table 14. A substantial difference of 8.7 ± 10.4 pg/mL in melatonin was observed immediately PRE TRAIN compared to PRE CONTROL (d = -0.69, $p < 0.05$, Figure 9). There was a significant difference in melatonin levels at the 22:00h time point for TRAIN compared to CONTROL (7.4 ± 7.1 pg/mL, d = -0.74, $p < 0.05$, Figure 9).

There were no statistically significant differences observed between conditions for any of the sleep variables. However, a *small* reduction in TST could be observed following the TRAIN condition to the CONTROL condition (0:21 ± 0.25 h:min, d = 0.21, $p > 0.05$, Table 14).

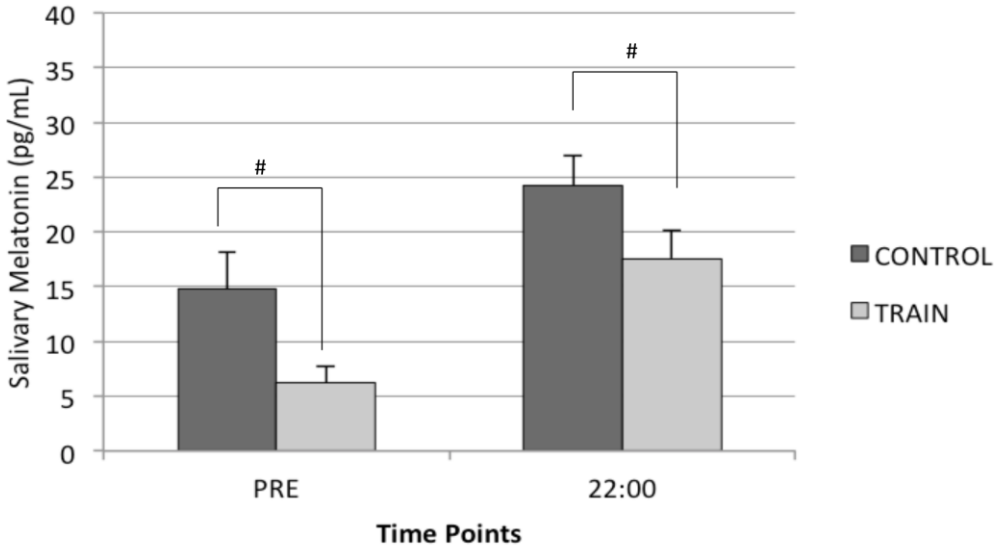

Figure 9 – Salivary melatonin concentrations (pg/mL) PRE and 22:00 for a training (TRAIN) and control (CONTROL) day. # indicates a significant difference between conditions ($p < 0.05$).

Table 14 – Mean ± SD values for salivary melatonin and the measured sleep variables in a training and control environment, including the difference between training and control, P-values and Effect Sizes (±90% confidence intervals).

	Control	**Training**	**Raw Difference (Control - Training)**	**Control - Training Effect Size**
Melatonin (PRE) (pg/mL)	14.8 ± 11.4	6.2 ± 4.8	-8.7 ± 10.4[#]	-0.69 ±0.48 *Moderate*
Melatonin (22:00h) (pg/mL)	24.3 ± 9.2	17.6 ± 8.2	-7.4 ± 7.1[#]	-0.74 ±0.44 *Moderate*
Total Sleep Time (TST) (h:mm)	8:46 ± 1:03	8:01 ± 1:17	-0:45 ± 0:31	-0.21 ±0.25 *Small*
Sleep Efficiency (SE) (%)	82.1 ± 8.9	85.3 ± 7.2	3.4 ± 11.9	0.35 ±0.90 *Small*
Total Time in Bed (TTB) (h:mm)	10:36 ± 2:09	9:56 ± 1:48	-0:22 ± 1:56	-0.19 ±0.60 *Unclear*
Sleep Latency (SL) (min)	27.5 ± 34.7	38.5 ± 29.3	10.8 ± 33.8	0.34 ±0.71 *Small*

[#] Significant difference between conditions ($p < 0.05$)

Discussion

This study presents novel findings on the melatonin response to training and rest days and examines the subsequent sleep indices in an elite female athlete population. The main findings from the study were significantly lower salivary melatonin levels on a training day, both PRE and at 22:00h, when compared to the same time points on a rest day. Whist there was no significant differences for the sleep indices, a general trend towards impaired SL and TST in the TRAIN trial when compared to the control could be observed. These findings provide the first evidence that female athletes express lower levels of melatonin both PRE and POST training, when compared to a rest day, which contribute to the slight trend in impaired sleep that was seen.

The results of the current study are consistent with previous investigations that have examined the suppressed melatonin response following exercise (Buxton et al., 1997; Monteleone et al., 1990). A study in healthy male participants (n=7) assessed the melatonin response following nocturnal physical activity (Monteleone et al., 1990), reporting plasma melatonin levels were significantly suppressed at 23:00 ($p < 0.02$), 1:00 ($p < 0.01$), and at 2:00 ($p < 0.03$) following a 22:40 exercise session compared to the control condition. Similarly, a study in moderately trained males (n=8) assessing the melatonin response following differing intensity and durations of nocturnal exercise (Buxton et al., 1997), reported a phase delay of plasma melatonin secretion following both a three hour low intensity exercise session (63 min) and a one hour high intensity exercise session (-55 minutes) compared to a baseline non-exercising condition. Whilst our study offers support with similarities in suppressed melatonin following exercise, it should be noted there are several differences between the protocols of the studies. Both Buxton et al (1997) and Monteleone et al (1990) measured melatonin in plasma, in comparison to the current study where melatonin was measured through saliva. In addition, the time where exercise was initiated, differs substantially between all three studies; 1:00 (Buxton et al., 1997), 22:40 (Monteleone et al., 1990), and 18:00 in the current study. Lastly, the duration and intensity of the exercise in each study is variable. Each of these, make it very difficult to draw decisive conclusions between the three studies. However, it is

clear, from each study that exercise does have a major impact upon melatonin levels, which in turn will affect human biorhythms and physiological processes related to sleep regulation.

In regards to objective sleep metrics, the results of the current study support previous research that has assessed sleep following evening competition (Fullagar, Skorski, Duffield, Julian, et al., 2016; Juliff, Halson, et al., 2017; Sargent & Roach, 2016; Shearer et al., 2015). Although not statistically significant, a *small* difference was observed following training compared to control for TST (-45 minutes), which was similar to the TST reductions from an evening game observed by Juliff and colleagues (2017) in 42 netball athletes. The physical exertion that occurs from late night training and competition may cause disruptions to circadian rhythms, in turn causing a phase delay in melatonin production, and delayed sleep onset (Shearer et al., 2015). While not statistically significant, a *small* trend was also observed for delayed SL in the current study following training (38.5 minutes) compared to control (27.5 minutes). Interestingly, the athletes SE showed a *small* trend to better sleep following the training compared to the control (3.4%). These findings demonstrate that the impact of exercise (and anticipation of exercise) on the melatonin biorhythm does appear to elicit changes in sleep duration and sleep latency.

Considering the continuous level of training demands athletes' experience, any disruption they face regarding sleep would be disadvantageous. Previous research has highlighted the importance of implementing sleep hygiene education and strategies (Fullagar, Skorski, Duffield, & Meyer, 2016; O'Donnell & Driller, 2017; Van Ryswyk et al., 2017) into athlete's routines, as an aid to maintain or improve sleep indices specifically during and following competition. A strategy that may be beneficial to elite athletes is the implementation of meditation following nocturnal exercise. A study by Tooley et al (2000) investigated the melatonin response in 17 male and female participants following a meditation period. Results reported that the participants' plasma melatonin levels were significantly higher post the meditation period compared to the same time on the control night. Other studies investigating melatonin and health (Cipolla-Neto, Amaral, Afeche, Tan, & Reiter, 2014; Szewczyk-Golec, Woźniak, & Reiter,

2015), has highlighted the implications of suppressed melatonin on general well being. These studies highlight the need to better understand the effects of nocturnal exercise and its interaction with melatonin, especially given the suppression of melatonin levels seen in our studies and their potential effect on sleep quality.

There were a number of limitations with this study, which may have influenced the results. Exposure to artificial light was not controlled, which has been shown to suppress melatonin levels (Anisimov, Vinogradova, Panchenko, Popovich, & Zabezhinski, 2012) and cannot be discounted as having an influence on the results. However, the data was collected in the athlete's own home environment during the control trial, therefore it would have detracted from the ecological validity of the results if this was performed in a laboratory. A further limitation of the current study was the lack of control for the menstrual cycle phases for each individual athlete. This may have influenced melatonin levels by the change in body temperature that occurs across the different phases (Cagnacci, Soldani, Laughlin, & Yen, 1996). Other limitations were the small sample size and the small number of measured time points where saliva was collected, meaning the persistence of the effects of exercise cannot be extrapolated. Regardless of this, a significant impact of exercise on melatonin levels was shown and highlights the need for more research in this area with highly trained athletes.

Conclusion

The results of the current study indicate that the training environment resulted in significantly suppressed melatonin levels with a trend towards impaired sleep indices when compared to a control day in female athletes. Given adequate sleep is crucial for aiding in the psychological and physiological recovery of an athlete, as well as the potential health implications of the disrupted melatonin biorhythms, the findings from this study highlight the importance for future research on the interactions of nocturnal exercise and subsequent melatonin levels.

CHAPTER SEVEN

Sleep-Hygiene Education Improves Sleep Indices in Elite Female Athletes

O'Donnell, S & Driller, M. (2017). Sleep-Hygiene Education Improves Sleep Indices in Elite Female Athletes. *International Journal of Exercise Science.*10(4) 522-530.

Link: Findings from Studies Two to Four indicate disrupted sleep around exercising at night and highlighted other issues related to an athletes sleep. Therefore Study Five sought to assess the intervention of a sleep hygiene education session on enhancing athlete's sleep.

Abstract

The importance of sleep in providing psychophysiological recovery in elite athletes is often overlooked**.** In other populations (eg shift workers and adolescent students), sleep hygiene education may serve to acutely improve sleep indices. However, this is yet to be examined in an elite athlete setting. Therefore, the aim of the current study was to evaluate the effect of a sleep hygiene education session on sleep indices in elite athletes. The study involved 26 elite female netball athletes performing one week of baseline sleep monitoring (PRE), followed by a sleep hygiene education session and a further week of sleep monitoring (POST) in a single group, pre- post design. The sleep hygiene education session focused on providing information on the importance of sleep for athletes and practical tips to improve sleep quality and quantity. Sleep monitoring was performed using wrist actigraphy to assess total sleep time (TST), sleep efficiency (SE%), total time in bed (TTB), sleep latency (SL), wake episodes per night (WE), sleep onset variance (SOV), and wake variance (WV). There was a significant improvement in TST (mean ± SD; 22.3 ± 39.9 minutes, p=0.01) PRE to POST sleep hygiene education session, the difference associated with a *small* effect (ES: 0.39). A significant improvement PRE to POST was found for WV (p=0.03), and for WED (p=0.03). There were no significant differences for SE%, SL, TTB, WE, SOV, SOT, WT. The current study reports that a sleep hygiene education session is effective in improving sleep quantity in elite female athletes in an acute setting.

Introduction

Elite sporting success is underpinned by optimal preparation as well as adequate recovery between training and competition. There is increasing recognition that sleep has a significant role in the performance and recovery of highly-trained athletes (Halson, 2013). According to Halson (2008) and Leeder et al, (2012), sleep quality and quantity is reported to be the single best psychological and physiological recovery strategy available to elite athletes. However, elite athletes often experience inadequate sleep compared with non-athletes (Simpson et al., 2017). Lastella et al (2014) reported that on average, elite athletes obtain 6.8 hours of sleep per night. Furthermore a study by Leeder et al (2012) reported elite female athletes on average obtain 6 hours 56 minutes of sleep. Despite the importance of sleep on athletic performance and recovery, it has been reported that there is limited data on the use of sleep interventions to improve sleep in elite athletes (Eagles, Mclellan, Hing, Carloss, & Lovell, 2014; Juliff et al., 2015; Nédélec et al., 2015).

Recent research has shown that due to a number of factors, elite athletes sleep may actually be inferior when compared to the general population. The increase in core temperature following exercise (Nédélec et al., 2015), increase in muscle tension and pain following training and competition (Halson, 2014), disruption from light and noise and increase in psychological stress (Fullagar, Duffield, et al., 2015) are thought to be contributing factors. More than half (52.3%) of the athletes from a sample of 283 elite (individual and team sport) athletes, reported suffering sleep disturbances following a late training session or competition (Juliff et al., 2015). Furthermore, a study by Eagles et al, (2014) found a significant reduction in sleep quantity in professional rugby union players following game nights compared to non-game nights. The time taken to fall asleep was also significantly longer following a game night compared to a non-game night.

It is thought that sleep hygiene education may help to improve sleep quality and quantity (Stepanski & Wyatt, 2003). Sleep hygiene is described as practicing behaviors that facilitate sleep and avoiding behaviors that interfere with sleep (Halson, 2014; Lacks & Rotert, 1986; Mastin et al., 2006; Stepanski & Wyatt, 2003). Sleep hygiene education includes the provision of advice based on various

aspects of lifestyle and behavior as well as environmental factors that influence sleep such as light, noise and temperature (Kakinuma et al., 2010; Nishinoue et al., 2012; Sousa et al., 2007). The education of sleep and sleep hygiene practices provides athletes with strategies to maximize the amount and quality of the sleep they obtain (Lastella, Roach, Halson, & Sargent, 2015). A study by Kakinuma et al, (2010) evaluated the effect of a sleep hygiene education session in the workforce of an information technology company. Participants (n=391) attended a 50-minute lecture on the role of sleep and the proper sleep environment to promote sleep, followed by a 10-minute question and answer period. The results showed that four weeks following a 1-hour sleep hygiene education session, daytime sleepiness at 14:00 significantly decreased ($p<0.05$). Sousa et al, (2007) investigated the effectiveness of a daily 50 minute sleep hygiene educational program for one week on sleep quality and sleepiness in adolescent students (n=58), with findings showing a significant decrease in sleep latency from 13 to 9 minutes following the sleep hygiene education session ($p<0.01$).

Several other studies have investigated the use of sleep hygiene education programs in a number of different populations with varying levels of success (Chen, Kuo, & Chueh, 2010; Gebhart et al., 2011; Nishinoue et al., 2012), however, to our knowledge, the use of a sleep hygiene education session is yet to be studied in an elite athlete population. Therefore, the aim of the present study was to evaluate the effects of a single sleep hygiene education session on the sleep quality and quantity of female netball athletes over an acute period of time (two weeks) during a pre-season, heavy phase of training.

Methods

Participants

A total of 26 elite female netball athletes (mean ± SD; age = 23 ± 6 y,) volunteered to participate in the current study. Athletes were of international and/or national representative standard (19 and 7, respectively) and the study took place in the pre-season phase of competition. All participants provided informed written consent before taking part in this study. Ethical approval for the study was obtained through the institutions Human Research Ethics Committee.

Protocol

The current study was performed using a single group pre-post design whereby athletes performed one week of baseline sleep monitoring (PRE) followed by a sleep education session and a further week of sleep monitoring (POST). The study took place during the pre-season phase of training, which included approximately 9 training sessions per week spread over 6 days, with a single rest day each week (3 x gym, 4 x on-court sessions, 2 x aerobic conditioning sessions). All training sessions were performed before 15:00 daily and total training volume was approximately 15 hours per week. Both PRE and POST weeks were identical in terms of training schedules and were matched for training intensity and duration by the coaches working with the researchers, to ensure that biological variations and hormonal responses to training were kept similar between weeks. Although not monitored in the current study, athletes were also asked to maintain a normal diet during PRE and to replicate this diet during POST.

Sleep Monitoring

Participants were required to wear a wrist actigraphy device (Fatigue Science, Readiband) as used by Dennis et al, (2016), over a 2-week (14 day) period to monitor sleep patterns. The raw activity scores were translated to sleep-wake scores based on computerized scoring algorithms (Sadeh, 2011). The inter-device reliability of the Readiband actigraph device has been deemed acceptable as described elsewhere (Driller et al., 2016). Actigraphy has been shown to be valid and reliable in normal healthy adult populations (Ancoli-Israel et al., 2003; Sadeh, 2011), and is commonly used in sporting teams as it is more practical and less intrusive compared to polysomnography (PSG) (Dennis et al., 2016). A further benefit of using actigraphy is that participants can monitor their sleep patterns in their own home environment. The five measures obtained from the actigraphy device that were used as sleep indices are described in Table 8 (Driller et al., 2016).

Participants were each allocated an actigraph at the start of the first week (day one - PRE). The participants were instructed to wear the actigraph on their non-dominant wrist (Dennis et al., 2016), for 14 days. Participants were required to

wear the actigraph continuously for the 14-day period, with the exception of time spent during on-court training sessions. Participants were instructed to maintain their usual sleep habits and patterns for this first week of sleep monitoring (day 1 – day 8, PRE), and then to implement the advice given at the sleep education session for the second week of monitoring (day 8 – day 14, POST). At the conclusion of the 14 day period, actigraph devices were collected and the data was retrieved using Fatigue Science software (16Hz sampling rate: Readiband, Fatigue Science, Vancouver). The results from the second week (day 8 – day 14, POST) were used against the first week's results (PRE) to assess the effect of the sleep education session on sleep quality and quantity.

Sleep Education Session

All participants attended a sleep education session at the conclusion of the first week of sleep monitoring (day 8 - PRE). The sleep education session was provided by a specialist in sleep research and athletic recovery. The education session included a presentation on the importance of sleep for athletes, sleep physiology and sleep hygiene for 50 minutes, followed by a 10-minute question and answer period. The presentation focused on normal human sleep and the role and mechanisms of sleep. Sleep hygiene information was presented to the participants, with instructions given on how to implement correct sleep hygiene practices into their sleep habits and routines. The sleep hygiene education focused on the following 5 practical tips: maintaining a regular bed and wake time, ensuring a quiet, cool and dark bedroom environment, avoidance of caffeine and other stimulants prior to sleep, avoidance of light-emitting technology devices in the hours prior to sleep and implementation of relaxation strategies before bed (e.g progressive muscle relaxation (McCloughan, Hanrahan, Anderson, & Halson, 2014). Participants were encouraged to implement the sleep hygiene advice given to them during the sleep education session into their own sleeping habits and routines for the second week of monitoring. While not measured in the current study, athletes were constantly reminded (daily) to make sure they were implementing the tips during the POST monitoring period, and gave anecdotal feedback that they were adhering to the suggested recommendations.

Statistical Analysis

Simple group statistics are shown as means ± standard deviations unless stated otherwise. A Microsoft Excel spreadsheet was used to estimate the mean effects and 90% confidence intervals (90%CI) of the education session (Hopkins, 2015). Excluding sleep efficiency, data were log-transformed to reduce non-uniformity of error (Hopkins, 2015). Magnitudes of the standardized effects were calculated using Cohen's *d* and interpreted using thresholds of 0.2, 0.6 and 1.2 for *small, moderate and large*, respectively (Batterham & Hopkins, 2006). An effect size of <0.2 was considered to be *trivial* and the effect was deemed *unclear* if its 90% confidence interval overlapped the thresholds for small positive and negative effects (±0.2) (Batterham & Hopkins, 2006). A students paired T-test was used to compare PRE and POST using a Statistical Package for Social Science (V. 22.0, SPSS Inc., Chicago, IL), with statistical significance set at $p \leq 0.05$.

Results

There was a significant increase in TST from PRE to POST following the sleep hygiene education session ($p = 0.008$). The TST from PRE to POST showed an average increase of 22.3 ± 39.9 minutes (Table 15), this difference was associated with a *small* effect size (ES: 0.39). There was a significant decrease in WV ($p = 0.03$) PRE to POST, the difference was associated with a *moderate* effect size (ES: -0.70) and an average decrease of 21.2 ± 34.6 minutes (Table 15). A significant decrease was observed in WED ($p = 0.03$) PRE to POST, the difference was associated with a *small* effect size (ES: -0.57).

SE showed an average increase of 2.6 ± 5.7% resulting in a *small* but not statistically significant difference PRE to POST (ES: 0.26, $p = 0.11$). SL showed an average decrease of 6.7 ± 29.1 minutes PRE to POST. The difference was not statistically significant ($p = 0.29$), however SL was associated with a *small* effect size (ES: -0.27).

Results for TTB ($p = 0.45$), SOV ($p = 0.25$), WE ($p = 0.37$), SOT ($p = 0.28$), and WT ($p = 0.06$) were not significantly different PRE to POST the sleep hygiene education session. The difference PRE to POST was associated with a *trivial*

effect size for TTB (ES: 0.15) and WE (ES: 0.16), and *unclear* effects for SOV, SOT and WT.

Table 15 - Mean ± SD values for the measured sleep variables PRE and POST a sleep hygiene education session, including the absolute PRE to POST change, p-values and Effect Sizes (±90% confidence intervals).

	PRE	POST	Absolute Change (PRE / POST)	P-Value	PRE – POST Effect Size (±90% Confidence Intervals)
Total Sleep Time (mins)	436.0 ± 50.5	458.3 ± 54.8	22.3 ± 39.9	<0.01	0.39 ±0.24 *Small*
Sleep Efficiency (%)	80.6 ± 6.5	82.6 ± 6.7	2.6 ± 5.7	0.11	0.26 ±0.28 *Small*
Total Time in Bed (mins)	545.3 ± 46.7	552.5 ± 44.1	7.2 ± 47.6	0.45	0.15 ±0.34 *Trivial*
Sleep Latency (mins)	28.6 ± 15.6	26.0 ± 15.0	-2.6 ± 12.5	0.29	-0.27 ±0.39 *Small*
Wake Episodes (No. per night)	3.9 ± 2.0	4.1 ± 2.2	0.2 ± 2.1	0.37	0.16 ±0.31 *Trivial*
Sleep Onset Variance (mins)	46.9 ± 23.7	39.9 ± 16.1	-6.7 ± 29.1	0.25	-0.21 ±0.44 *Unclear*
Wake Variance (mins)	72.1 ± 28.7	50.9 ± 21.0	-21.2 ± 34.6	0.03	-0.70 ±0.62 *Moderate*

Wake Episode Duration (WED)	14.1 ± 5.4	11.1 ± 4.0	-3.3 ± 6.6	0.03	-0.57 ±0.57 *Small*
Sleep Onset Time (time of day)	23:13 ± 0:41	23:02 ± 0:46	-11.0 ± 47.9	0.28	-0.18 ±0.43 *Unclear*
Wake Time (time of day)	8:02 ± 0:45	8:31 ± 0:51	29.0 ± 53.9	0.06	0.20 ±0.51 *Unclear*

Discussion

The current study is the first to show that a sleep hygiene education may be used to improve sleep in elite athletes. A single one-hour session of sleep hygiene education resulted in a significant improvement in total sleep time and wake variance, with 22 minute and 21 minute improvements, respectively, from pre to post education in 26 elite female athletes. Whilst there were no significant differences for the other sleep indices, there were some trends towards improvements in total time in bed, sleep efficiency and sleep latency pre to post education. The findings provide evidence that a sleep education session may be useful in improving both sleep quantity and quality of elite athletes in an acute setting of two weeks. Further research is required to establish whether these improvements could translate to improved sleep in a chronic setting.

The results of the current study are consistent with previous studies that have assessed the effect of sleep hygiene education sessions on sleep (Gebhart et al., 2011; Kakinuma et al., 2010; Nishinoue et al., 2012; Sousa et al., 2007). Most of the previous studies, however, have involved participants whom suffer from sleep disturbances or complaints, rather than athletic populations (Chen et al., 2010; Gebhart et al., 2011; Stepanski & Wyatt, 2003). The study by Gebhart et al, (2011) assessed sleep hygiene education effectiveness combined with physical exercise in individuals with sleep disturbances. Participants (n=114) were either assigned to the waiting list group (control) or the intervention group (a 6 week sleep hygiene education and physical exercise intervention). Results showed significant improvements in sleep quality ($p < 0.001$), sleep latency ($p < 0.05$) and sleep duration ($p < 0.01$) in the intervention group from baseline to 6-weeks. While we found similar results for some sleep indices, the current study differs to the Gebhard et al study, through the use of athletes as the participants. Furthermore, in the current study, participants were only exposed to a single one-hour sleep hygiene education session, as opposed to six one-hour sleep hygiene education sessions. It can be assumed that the addition of further education sessions may result in even more significant findings than those found in the current study.

Similar to the current study, Kakinuma et al, (2010) evaluated the effect of a one-hour sleep hygiene education session in healthy participants of an information technology company. The results showed a significant decrease ($p=0.04$) in daytime sleepiness at 14:00, four weeks following the one-hour sleep hygiene education session. The education session focused on the role and mechanisms of sleep and outlined the proper environment to promote sleep. Although not statistically significant, perceived sleep quality appeared to improve as measured through the Pittsburgh Sleep Quality Index (0.67-point decrease). Nishinoue et al, (2012) performed a randomized, controlled trial to evaluate how sleep quality is affected by a sleep hygiene education session combined with one-on-one behavioral therapy. Healthy adult participants ($n=121$) were randomly assigned to either the control group (a group-based sleep hygiene education session) or the intervention group (a sleep hygiene education session combined with 30-minutes of individual behavioral training), with results showing a significant improvement on the global Pittsburgh Sleep Quality Index score in both the intervention ($p<0.01$) and control ($p<0.05$) groups from baseline to three months following the completion of the intervention. The results from the two studies confirm the results found in the current study pertaining to statistical differences in the majority of measured sleep indices.

It has been reported in previous research that on average athletes obtain 6.8 hours of sleep per night (Lastella, Roach, Halson, & Sargent, 2015), with athletes from individual sports obtaining closer to 6.5 hours and team sport athletes obtaining ~7.0 hours per night (Lastella, Roach, Halson, & Sargent, 2015). The results pre and post the sleep hygiene education session in the current study showed the athletes obtained 7.3 hours and 7.6 hours of sleep, respectively, indicating a similar, if not longer total sleep time than that of other team sport athletes. Previous research has reported, disturbances to both sleep quantity and quality has implications for psychological and physical recovery following training sessions (Fullagar, Duffield, et al., 2015). Due to the restorative benefits provided through sleep for athletes, such as hormonal responses and cognitive performances (Davenne, 2009), disruptions in sleep indices may consequently have a negative effect on recovery and performance. A study by Leeder et al, (2012) researched

normative sleeping patterns of elite athletes. The results of their study reported that elite female athletes on average obtained 6 hours 56 minutes of sleep. Sleep latency was 12.7 minutes on average and sleep efficiency was reported as 83.9% (Leeder et al., 2012). Comparable to the current study, our post results were 26 minutes and 82.6% for sleep latency and sleep efficiency, respectively. Although difficult to draw comparisons between the two studies, due to the differences in methods and protocols, the comparison between sleep measures is important due to the limited data on elite athletes. While the TST was similar between studies, the difference in sleep latency appears considerably greater in the current study. A possible reason for this difference was that some training sessions took place in the afternoon during summer in the current study, which could have caused an increase in core temperature in the evening, delaying the onset of sleep.

Limitations of the current study were that the sleep measurements were limited to the use of an objective measure only (actigraphy). The use of sleep logs/diaries and sleep hygiene questionnaires as subjective measures would have provided more detail on the effect of the sleep hygiene education session. While the researchers received anecdotal feedback that the hygiene tips were being practiced, monitoring the adherence to the sleep hygiene advice would have been advantageous in determining what factors may have effected sleep indices. A follow-up of whether these practices had been adhered to in the months following the education session may also provide interesting information. The addition of a control group (no education session) to the experimental design, may have allowed for further comparisons of the sleep-hygiene education. The authors acknowledge that information on the phase of each participant's menstrual cycle may have been appropriate, as this has been shown to have an influence on sleeping patterns (Manber & Bootzin, 1997). More thorough control of diet would be also advantageous in future research. Evaluation of chronic behavioural change including both qualitative and quantitative data following an education session would provide further insight into the efficacy of sleep hygiene education and a worthwhile addition to future research. Future research in the athlete setting may also include performance measures pre and post sleep education to evaluate the effect of sleep indices on athletic performance. Indeed, Mah et al, (2011) has shown that sleep extension over 10-weeks in college basketball athletes lead to

improvements in total sleep time, psychomotor vigilance tasks, daytime sleepiness and mood (Mah et al., 2011).

Conclusion

The current investigation is the first to show that a one-hour sleep hygiene education session has a positive acute effect on improving sleep quantity in elite female athletes. Given adequate sleep is crucial for aiding in the psychological and physiological recovery of an athlete, the findings from this study provide evidence to the importance of educating athletes about sleep and optimal sleep hygiene.

CHAPTER EIGHT

The Influence of Match-Day Napping in Elite Female Netball Athletes

O'Donnell, S., Beaven, C & Driller, M. (2018). The influence of match-day napping in elite female netball athletes. *International Journal of Sports Physiology and Performance.* (In Press).

Link: Findings from Studies Two to Five explored sleep in competition environments and following a sleep hygiene education session in elite athletes. Anecdotally, it is known that athletes use alternate methods to alleviate sleep debt such as napping, however research into this area is currently lacking. Therefore, Study Six sought to examine the role of napping on match days and the effect on subsequent performance and perceptual variables.

Abstract

Purpose: To assess the effect of match-day napping and duration of naps on perceptual and performance indices in elite female netball players over two consecutive netball seasons. Methods: Fourteen elite female netball athletes (mean ± SD; age = 23 ± 6 yr) participated in an observational study over 26 competition matches. On each match day, athletes provided information on their napping habits, perceived energy levels, and then performed 3 countermovement jumps (CMJ) 3h30 prior to the start of the match. One hour following the match, subjective player performance ratings from the players and two members of the coaching staff were obtained. Naps were characterized into 3 conditions for analysis; No Nap (NN), <20 min Nap (SHORT), and ≥20 min Nap (LONG). Results: A significant difference in peak jump velocity was observed between the SHORT and the NN condition in favor of the shorter nap (3.23 ± 0.26 and 3.07 ± 0.36 $m.s^{-1}$, respectively, $d = 0.34$, $p < 0.05$). A *moderate*, significant difference ($d = 0.85$; $p < 0.05$) was observed for the coach rating of performance (out of 10) between the SHORT and the NN condition (7.2 ± 0.8 and 6.4 ± 0.9, respectively) in favor of SHORT. Conclusion: The findings from the study would suggest that a short nap (<20 min) on the day of competition can enhance jump velocity and improve subjective performance in elite netball players, as assessed by coaching staff

Introduction

Elite athletes are exposed to a high level of both physiological and psychological stress leading up to and on the day of competition, and therefore look to utilize a range of different strategies to gain and maintain a competitive edge (Tuomilehto et al., 2016). One strategy that elite athletes use to counteract slept debt and sleepiness in the training and competition environment is a daytime nap (Fushimi & Hayashi, 2008; Lastella, Roach, Halson, & Sargent, 2015; Sargent, Halson, et al., 2014). Napping has been defined as a sleep period less than 50% of an individuals average nocturnal sleep duration (Dinges, Orne, Whitehouse, & Orne, 1987; Thornton et al., 2016; Waterhouse et al., 2007). Although well-documented in the training setting, (Forndran et al., 2012; Sargent, Halson, et al., 2014) at present, there is no research to evaluate the use of a pre match/competition nap on subsequent performance measures and the effect in elite athletes. There are a number of contributing factors that have an effect on both sleep and performance in elite athletes. Some of these factors include travel, match scheduling, media commitments, athlete compliance and a range of other psychological and physiological variables that highlight the difficulty in assessing the relationship between performance and napping. Furthermore, applied research in the elite sport setting can be somewhat difficult, with some coaches being reluctant to add any distractions, especially around competition and important phases of the season.

Previous studies have reported that poor sleep is common in elite athletes (Erlacher, Ehrlenspiel, Adegbesan, & Galal El-Din, 2011; Juliff et al., 2015; Lastella et al., 2014). According to Lastella, Lovell and Sargent (2014), 68% of athletes in their survey experienced poorer than normal sleep on the night prior to competition, resulting in 5 hours and 51 minutes of total sleep time, well below the daily recommendation (Belenky et al., 2003). Furthermore, Juliff, Halson and Peiffer (2015) reported both female athletes and team sport athletes have lower sleep durations (7:36 h:m) than male and individual sport counterparts (7:48 h:m). The reduction in sleep quantity could be proposed as a potential reason for athletes utilizing naps on the day of competition to alleviate the sleep debt and sleepiness from the previous night (Nédélec et al., 2015) and in order to be re-energized and ready to perform. Anecdotal evidence also suggests that when athletes compete at night, naps are often used to attenuate the boredom associated

with waiting for the event. It has been highlighted in previous research, in particular by Davies et al (2010) and Petit et al (2014), that there are two 'ideal' time durations of a nap. The nap duration of less than 20 minutes is considered optimal to avoid slow-wave sleep (deep sleep) (Petit et al., 2014). Alternatively, 90 minutes is also considered optimal as this allows a complete sleep cycle (NREM and REM) to occur, reducing the effects of sleep inertia (Davies et al., 2010). Sleep inertia is a temporary reduction in arousal and performance, which is associated with slow-wave sleep in NREM (Hilditch, Dorrian, & Banks, 2017; Van Dongen et al., 2001). Naps are likely to occur in the mid-afternoon, when there is a dip in the circadian rhythm following lunch, which is a period of time when attention and alertness is reduced (Milner & Cote, 2009).

A study by Waterhouse et al (2007) investigated the effect of a lunchtime nap following partial (4 hour) sleep deprivation on cognitive, motor, and sprint performance in 10 untrained participants. On two separate occasions, participants performed either a 30-minute nap or no nap condition following partial sleep deprivation. The results showed a significant improvement in both the 2-m and 20 m sprint times following the 30-minute nap when compared to no nap. Participant's alertness and visual short-term memory also showed significant improvements in the 30-minute nap condition ($p < 0.01$, & $p = 0.01$, respectively). At present there is limited knowledge on the benefit of napping in a sporting environment. However, Lastella et al (2015) investigated the differences in sleep behaviors across a range of individual and team sport athletes, reporting the nap frequency over a 7-night period for team sport athletes was 11% with a mean duration of 0:59 ± 01:02 h:min, which would suggest it is an area that requires further investigation.

Given many professional athletes compete later at night, the anecdotal reports of napping by athletes on match day is common, however objective measures on the effects of napping on performance are currently lacking. Indeed, the majority of professional level netball matches are played at 19:30 at night as the requirements of television coverage has shifted the scheduling of professional team sport fixtures from the day to the evening, (Fullagar, Duffield, et al., 2015) creating a prolonged match-day period, therefore, promoting the need for napping.

Therefore, the aim of the current study was to assess the effect of pre game napping behaviors on perceived energy levels, neuromuscular performance, and ratings of match performance in elite female athletes over two professional netball seasons.

Methods

Participants

A total of 14 professional female netball athletes (mean ± SD; age = 23 ± 6 yrs) volunteered to participate in the current study. Athletes were of international and/or national representative standard (11 and 3, respectively) and the study took place over two seasons during the Trans-Tasman (Australia/New Zealand) netball competition, which is widely regarded as the top domestic netball competition in the world given the number one and two International Netball Federation rankings of Australia and New Zealand. The status of the athletes involved in this study is reflected in the fact that the team made the semi-finals during both seasons during data collection for this study. All participants provided informed written consent before taking part in this study. Ethical approval for the study was obtained through the institutions Human Research Ethics Committee.

Study Design

The present study incorporates an observational, longitudinal design. All athletes were familiarised with the study protocols prior to the collection of data. The data was obtained over a 26-week collection period of two ANZ championship competitive seasons (13 weeks for each season), which comprised of a total of 26 matches (played once per week). The team being studied won the National Championship in both seasons. Measures were obtained on the day of competition, approximately four hours prior to match commencement, and one-hour following the conclusion of the netball match (Figure 10).

On each match day, six hours prior to the commencement of the match, athletes were required to have two-hours of ‘downtime.’ During this period, athletes were asked to remain in their hotel rooms and were instructed to use this time to relax and prepare for competition using their own pre-match routines. Athletes

individually decided how to use this time (e.g. napping, reading, watching TV). If a nap was taken, athletes were asked to keep track of the estimated duration by the time at which sleep was initiated and the time at which they awoke. At the conclusion of the two-hour downtime period athletes completed a 15-minute walk outside as a team before commencement of their pre-match primer exercises (Table 16) that lasted approximately 15 minutes, followed by jump tests and perceptual measures.

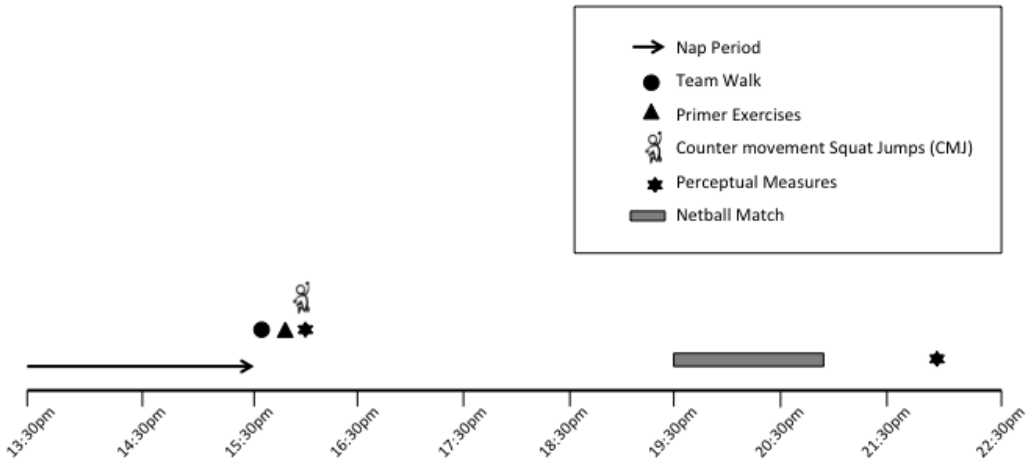

Figure 10 – Study design timeline.

Performance Measures

Thirty minutes following the allocated downtime period (and after the primer exercises), athletes were required to perform countermovement jumps (CMJ) to determine mean velocity, peak velocity and jump height. It has been recommended that a period of 30 minutes following waking from a nap be given prior to commencement of testing, to minimize the effects of sleep inertia (Waterhouse et al., 2007). CMJ were performed using a linear position transducer device (LPT) (GymAware, Kinetic Performance Technology, Canberra, Australia). The LPT was connected to a tablet computer (iPad 3, Apple Inc., USA) and the manufacturers software (GymAware Lite v2.10, GymAware, Kinetic Performance Technology, Canberra, Australia) via a Bluetooth connection. Athletes performed 3 standing CMJ with three seconds rest allowed between each jump. The CMJs were performed from an upright position, making a downward movement to a self-selected depth of their squat and simultaneously

beginning to push off, whilst hands were places upon hips. The reliability of the CMJ protocol in this same population has been reported previously, with coefficient of variations of 6.2% for jump height, 4.7% for peak velocity and 6.7% for mean velocity (O'Donnell, Tavares, McMaster, Chambers, & Driller, 2017).

Perceptual Measures

On completion of the CMJs, athletes provided a rating between 1 and 5 on an energy level scale to rate their current perceived energy level (1=very low, 2=low, 3=average, 4=high and 5=very high). Athletes were also asked if they had taken a nap in the prescribed downtime period, if the athlete answered yes, the duration of the nap was recorded.

One hour following the match, athletes were sent an electronic survey link (Survey Monkey Inc., California, USA) to rate their perceived performance from the match (0=very poor, 5=average, 10=excellent). The same survey was also given to two members of the coaching staff to rate each players performance from the match. The two coaches were blinded to the napping conditions of the athletes.

Table 16 - Outline of Primer Exercises

Warm Up	**Reps**	**Rest (seconds)**
Body Weight Squat	12	60
Body Weight Good Mornings	12	60
Reverse Lunge	10 each side	60
Lateral Lunge	10 each side	60
Press-ups	10	60
Ballistic Preparation	**Reps**	**Rest (seconds)**
Double Leg Squat Drop	5	60
Single Leg Squat Drop	5 each side	60
Double Leg Pogo's	10	60
Double Leg Squat Drop – Tap – Jump	5	60
Single Leg Squat Drop – Tap – Jump	5	60
Banded Counter Movement Jumps	5	60

Statistical Analysis

Nap duration was characterized into 3 conditions; No Nap (NN), <20 min Nap (SHORT), and ≥20 min Nap (LONG). All data is presented as means ± SD unless stated otherwise. Statistical analyses were performed with the Statistical Package for the Social Sciences (V. 22.0, SPSS Inc., Chicago, IL). A one-way analysis of variance (ANOVA) was performed to determine if there was a significant difference on the measured variables of peak velocity, mean velocity, and jump height between nap conditions. Games-Howell post-hoc t-tests were performed to locate differences where main effects were evident, with statistical significance set at $p \leq 0.05$. A Kruskal-Wallis test was conducted to determine if there were differences on the ordinal measured variables of energy level, coach rating and player rating between nap conditions. Pairwise comparisons were performed using Dunn's (1964) procedure. Magnitudes of the standardized effects were calculated using Cohen's *d* and interpreted using thresholds of 0.2, 0.6, 1.2 and 2.0 for *small, moderate, large and very large*, respectively (Hopkins et al., 2009). An effect size of < 0.2 was considered to be *trivial* and the effect was deemed *unclear* if its 90% confidence interval overlapped the thresholds for both small positive and negative effects (Batterham & Hopkins, 2006).

Results

The data set was distributed across the nap conditions as; NN (*n* = 92), SHORT (*n* = 38), and LONG (*n* = 129). The average nap duration of the SHORT and LONG nap conditions were 14.6 and 57.3 minutes, respectively. On average seven athletes napped prior to each game, and the average nap duration was 41.5 minutes. Across the entirety of the study, on at least one occasion, all athletes completed all three conditions.

The values for the comparison of variables between NN, SHORT and LONG can be observed in Tables 17 and 18. As shown in Figure 11, Games-Howell post-hoc analysis revealed a significant difference in peak jump velocity between the SHORT to the NN condition (3.23 ± 0.26 and 3.07 ± 0.36 $m \cdot s^{-1}$, respectively, $p < 0.03$), which was associated with a *small* effect size ($d = 0.34$, Table 18).

Figure 11 shows a significant difference observed in coach rating from the NN to the SHORT condition (6.4 ± 0.9 to 7.2 ± 0.8, $p < 0.01$) in favor of SHORT, which was associated with a *moderate* effect size ($d = 0.85$, Table 18). Pairwise comparisons showed a significant difference in coach rating between LONG and SHORT conditions (6.8 ± 0.8 and 7.2 ± 0.8, respectively, $p < 0.01$), which was associated with a *small* effect size ($d = -0.44$). There were no significant differences ($p > 0.05$) in player rating, energy levels and jump height between any of the nap conditions.

Table 17 - Measured variables over 26 competition days in 14 elite athletes following No Nap, <20 minute Nap and ≥20 minute Nap. Data presented as means ± SD.

Variable	**No Nap (Mean ± SD)**	**<20 min Nap (Mean ± SD)**	**≥20 min Nap (Mean ± SD)**
Energy Levels (0-5 AU)	3.6 ± 0.5	3.5 ± 0.4	3.4 ± 0.5
Peak Jump Velocity ($m.s^{-1}$)	3.07 ± 0.36	3.23 ± 0.26#	3.12 ± 0.29
Mean Jump Velocity ($m.s^{-1}$)	1.70 ± 0.24	1.82 ± 0.20	1.78 ± 0.23%
Jump Height (cm)	38.5 ± 7.4	38.3 ± 7.6	38.2 ± 6.7
Coaches Rating (0-10 AU)	6.4 ± 0.9	7.2 ± 0.8#	6.8 ± 0.8^
Player Rating (0-10 AU)	6.4 ± 0.7	6.6 ± 0.6	6.0 ± 1.1

Significant difference between <20min Nap and No Nap ($p < 0.05$)
% Significant difference between ≥20min Nap and No Nap ($p < 0.05$)
^ Significant difference between <20min Nap and ≥20 min Nap ($p < 0.05$)
AU = arbitrary units

Table 18 - Mean ± SD data for differences between No Nap, <20 minute Nap and ≥20 minute Nap, including effect sizes (*d*) for comparison between conditions.

Variable	**<20 min Nap v ≥20 min Nap Effect Size**	**<20 min Nap v No Nap Effect Size**	**≥20 min Nap v No Nap Effect Size**
Energy Levels (0-5 AU)	-0.10 ± 0.37 ES = -0.22 *Unclear*	-0.11 ± 0.45 ES = -0.22 *Unclear*	-0.22 ± 0.58 ES = -0.47 *Small*
Peak Jump Velocity ($m.s^{-1}$)	-0.06 ± 0.09 ES = -0.20 *Small*	0.11 ± 0.19# ES = 0.34 *Small*	0.04 ± 0.16 ES = 0.13 *Trivial*
Mean Jump Velocity ($m.s^{-1}$)	-0.03 ± 0.10 ES = -0.13 *Trivial*	0.08 ± 0.16 ES = 0.34 *Small*	0.06 ± 0.10# ES = 0.26 *Small*
Jump Height (cm)	0.01 ± 0.04 ES = 0.19 *Trivial*	-0.02 ± 0.04 ES = -0.22 *Small*	0.00 ± 0.03 ES = -0.03 *Trivial*
Coaches Rating (0-10 AU)	-0.44 ± 0.65# ES = -0.49 *Small*	0.76 ± 0.68# ES = 0.85 *Moderate*	0.50 ± 0.97 ES = 0.55 *Small*
Player Rating (0-10 AU)	-0.75 ± 1.36 ES = -0.75 *Moderate*	-0.03 ± 0.73 ES = -0.03 *Unclear*	-0.23 ± 1.24 ES = -0.23 *Unclear*

# Significant difference between conditions ($p < 0.05$)
AU = arbitrary units

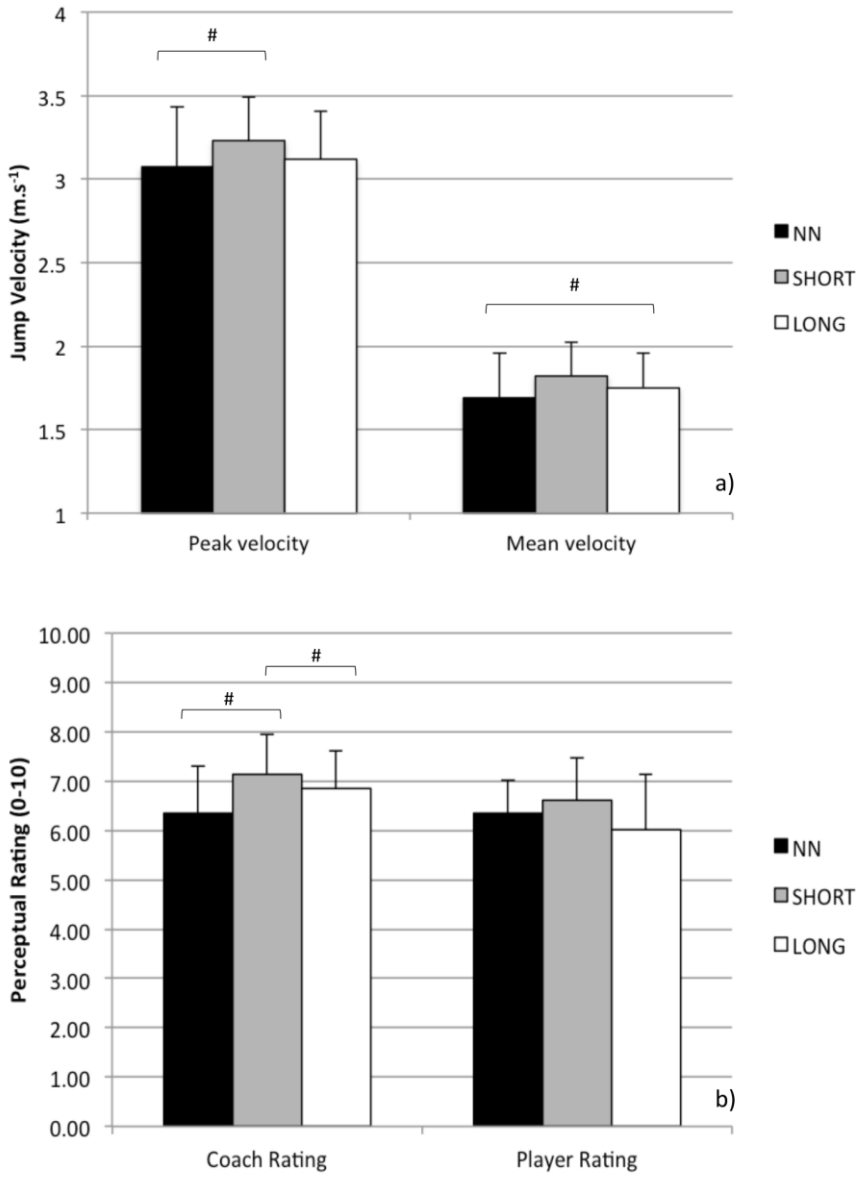

Figure 11 – Mean data from No nap, SHORT and LONG for a) Peak velocity and mean velocity ($m.s^{-1}$) and b) Coach rating and player rating (0-10). # indicates significant difference between conditions ($p < 0.05$).

Discussion

The findings from the current study show that when athletes napped for less than 20-miutes on the day of competition, neuromuscular jump performance and perceived netball performance was observed to be higher in comparison to when athletes did not nap. The current study is the first to assess the effect of a pre-match nap in a competitive setting on energy and performance variables in elite female athletes in a competition setting. The findings provide evidence that varying nap durations may have a positive effect on athletic performance. However, a large standard deviation was observed for all of the results, indicating that multiple outside variables may influence the individual athlete, resulting in the effectiveness of the napping durations being highly individual.

The results from the current study are consistent with the results reported by Waterhouse et al (2007), who showed a significant improvement in the physical performance variables of both 2-m and 20-m sprint times following a similar time period of 30-minute nap compared to a no nap condition. Although the current study differs in the type of physical performance measures used (CMJ v sprint time), we contend that these are both neuromuscular power tests. Therefore, results are comparable between the two studies, with significant improvements found in similar nap duration conditions. In both of the studies the napping period occurred in the mid-afternoon, a time that is associated with a dip in the circadian cycle (Ficca, Axelsson, Mollicone, Muto, & Vitiello, 2010; Milner & Cote, 2009). It has been reported that alertness and attention is often reduced during this period, but no previous research to our knowledge has reported physiological performance effects, which makes it difficult to draw decisive conclusions or compare the two studies to others.

Previous research has reported improvements in mood, subjective sleepiness, alertness, and vigor (Hayashi, Watanabe, & Hori, 1999; Tietzel & Lack, 2001, 2002) following naps of 10 to 20 minutes. Although not directly related, the current study assessed the athletes' energy levels following the allocated nap period. The results of the current study are in contrast to the previous research, with no significant differences found between the three nap conditions; NN, SHORT and LONG. It is postulated that athletes already feel extremely motivated

on game day and it is possible that napping or not napping would not influence their motivation levels to perform, due to a ceiling effect. Therefore, this may be a potential reason for the lack of differences in the energy level results, as energy levels are likely to be related to motivation. A study by Tietzel and Lack (2002) reported a significant improvement in alertness and cognitive performance following a 10-minute nap compared to a no nap condition. Furthermore, Waterhouse et al (2007) reported similar significant improvements in alertness, short-term memory, and accuracy in an 8-choice reaction time test following a 30-minute nap versus no nap condition. Although the current study did not aim to assess cognitive performance following different nap conditions, elite sport requires high levels of mental processing, which may be influenced by differing nap conditions (Fullagar, Duffield, et al., 2015). Therefore, the findings of the two previous studies, warrants future research on cognitive performance and decision making following naps in the professional sport environment.

Previous research (Tietzel & Lack, 2001, 2002) has shown the ideal nap duration to be between 10 to 20 minutes, where the ability to perform upon waking is required. The results from the current study offer support to the previous research on the optimal nap duration, with higher performance jump velocity and coach perceptual measures found in the <20 minute nap condition. Brooks and Lack (2006) have supported the shorter nap duration with their findings indicating shorter nap times can improve performance and alertness, whilst acting as a countermeasure to sleep debt. A point highlighted within previous research, was the possible effect of sleep inertia and the negative effects it may have on performance and functioning post a nap. Sleep inertia has been described as a reduction in the ability to think and impaired performance upon awakening from sleep (Hilditch et al., 2017; Milner & Cote, 2009; Van Dongen et al., 2001). A total period of 30 minutes (15 minute walk and 15 minute primer exercises) before testing began, was implemented in the current study to avoid sleep inertia.

There were several limitations to the present study that require clarification in future research. As this was a field based study, there were multiple variables that were unable to be controlled for, which could have had an impact on performance and the overall results of the study. The athletes were exposed to many different

sleeping environments over the two seasons (hotel rooms and home environments). The athletes were exposed to different pressures to perform that were dependent on the time of the season, team selections, media, win/loss record and general expectations. A study of this magnitude over two competitive seasons in a professional team needed to be minimally invasive on the athletes and coaching staff. Therefore, while there are some factors that could have better controlled, the aim was to produce an ecologically valid piece of research in an applied setting. The use of objective sleep measurements would have provided more in-depth information on the sleep quantity and quality of the naps. The monitoring of sleep on the night prior to competition would have been useful to provide athletes sleeping patterns and potential reasoning for the naps. Furthermore, monitoring sleep on the night of the competition would have allowed for analysis on whether a nap has an effect on subsequent sleep quality and quantity. Given this was an observational study, further intervention studies are also warranted in the athletic population. Such interventions may involve the use of prescribed napping durations on the day of competition in athletes with the aim of determining the optimal duration for performance.

Conclusion

The findings of this study are the first to show the effects of match day napping in an elite athletic environment, suggesting that a SHORT nap on the day of competition is effective in enhancing jump velocity measures and improves subjective performance as assessed by coach player ratings. It has been established in previous research and through the current study, that both physical and cognitive measures are improved following a ~20 minute nap. Moreover, given the importance of optimal performance in competition, the ability to utilize naps may be an effective tool for elite athletes, not just for recovery, but for performance enhancement.

CHAPTER NINE

Summary, Practical Applications, Limitations and Future Research

Thesis Summary

The main aim of the thesis was to investigate the sleep habits of elite female team sport athletes and the relationship between sleep and exercise. Six experimental studies were completed focusing on the mechanisms contributing to the sleep habits and behaviors of elite female athletes. The reliability and validity of a linear position transducer (LPT) device was assessed within a female athlete population in Study One (Chapter Three). Study Two (Chapter Four) involved both subjective and objective sleep monitoring on the night prior to, the night of and the night following competition to quantify the effects on sleep quality and quantity. Building from data obtained in Study Two, Studies Three and Four (Chapters Five and Six) examined mechanisms attributed to poor sleep following evening exercise and competition experienced in elite female athletes. Sleep indices were measured following the implementation of a sleep hygiene education session in Study Five (Chapter Seven). From Study One, the LPT device was used as a performance measure to assess the effect of match-day napping, along with perceptual measures for Study Six (Chapter Eight).

Sleep is regarded as critical to recovery, however there is still a lack of information on elite athletes sleep habits and the numerous factors that can influence both the quantity and quality of sleep (Fullagar, Duffield, et al., 2015; Halson, 2013; Leeder et al., 2012). Sleep loss can negatively impact cognitive (Taheri & Arabameri, 2012), psychomotor (Reyner & Horne, 2013), and athletic performance (Skein et al., 2013). The results within this thesis contribute to and advance the knowledge base of sleep in elite athletes, specifically female athletes.

The results of Study One (Chapter Three) demonstrated the LPT device to be a reliable tool when measuring female athletes' countermovement jump performance. As the LPT device was to be used as a performance tool in Study Three, it was vital that the results were shown to be reliable. Within the current research there is a paucity of reliability and validity studies that use females as the participants; however, it has been assumed the results of current studies using male participants are comparable to female athletes. Therefore, the results from Study Two provide valuable data for future researchers studying female athlete

populations.

Study Two (Chapter Four) results showed the athletes sleep was significantly reduced on the night of the game (6:46 h:m) and the night following the game (7:23 h:m) when compared to the night prior to the game. Interestingly, the results for sleep on the night prior to the game provide evidence against previous research and traditionally held hypotheses, with athletes in the current study's total sleep time 8:31 ± 1:02 h:m on average. Furthermore, Study Three (Chapter Five) reported reduced total sleep time (6:03 h:m) and sleep efficiency (74.4%) following an evening game, with *very large* increases in cortisol levels post-match and at 22:00pm.

The data from both Study Two and Three indicate that competition may be associated with poor sleep and it is common for athletes to experience sleep disturbances following evening competition. These findings are consistent with previous research (Fullagar, Skorski, Duffield, Julian, et al., 2016; Juliff, Halson, et al., 2017; Sargent & Roach, 2016; Shearer et al., 2015) reporting impaired sleep indices following evening competition. It has been proposed that a number of physiological and psychological factors contribute to athletes' impaired sleep following evening exercise. These may include increased core temperature following training and competition (Chennaoui et al., 2014; Oda & Shirakawa, 2014), increased psychological stress, 'social' requirements, a disruption from light and noise (Fullagar, Duffield, et al., 2015; Romyn et al., 2015), scheduling of competition (Fullagar, Skorski, Duffield, & Meyer, 2016), and increased muscle pain and tension following training and competition (Halson, 2014). Study Four (Chapter Six) reported reduced levels of melatonin immediately following an evening training session and at 22:00pm compared to a control condition, with trends to impaired subsequent sleep duration. Previous research has also shown exercise to have a major impact on melatonin levels (Buxton et al., 1997; Monteleone et al., 1990), which likely affects human biorhythms and physiological processes related to sleep regulation.

Aligning with previous research, in Study Five (Chapter Seven), athletes' total sleep duration was shown to be between 7.3 hours (baseline), which is comparable to the total sleep duration of ~7 hours on average for team sport athletes in the Lastella et al (2015) study and 6:56 h:m on average for female athletes in the study by Leeder et al (2012). A specific novel finding of Study Five was the significant increase in total sleep time (7.6 h) following a sleep hygiene education session. Although the sleep hygiene education session was only a single acute intervention, the results highlight its importance as a tool to be implemented into a recovery protocol. This work corroborates data from Fullagar and colleagues (2016), who demonstrated a positive effect of an acute sleep hygiene strategy on recovery following a late-night soccer match.

Study Six (Chapter Eight) is the first to the author's knowledge to quantify the effect of match-day napping on performance and perceptual measures, with results indicating when athletes nap duration was <20 minutes, higher neuromuscular jump performance and perceived netball performance were observed, in comparison to when athletes did not nap. It is anecdotally known that athletes nap on the day of competition, with Lastella et al (2015) reported a nap frequency over a 7 night period for team sport athletes was 11% with a mean duration of 0:59 ± 01:02 h:m. There is a prevalence of athletes experiencing sleep disturbances on the night prior to competition with 64.0% (Juliff et al., 2015) and 65.8%, (Erlacher et al., 2011) of athletes reporting poor sleep. The use of a nap has been postulated as a measure to counter the sleep debt experienced from poor sleep (Halson, 2014). Across the two seasons of data collection in Study Six, a total of 182 naps were taken by the fourteen athletes, indicating a high occurrence of athletes choosing to nap on the day of the match with little known on either the positive or negative influence the nap may have to performance. Therefore, the novel data set and findings of Study Six are important to athletes, coaches, and practitioners, as well as providing evidence to fellow researchers and sports scientists.

The studies included within this thesis aimed to provide novel data and further the knowledge of sleep indices in elite female athletes highlighting the effects of competition on sleep indices and hormonal responses (Studies Two, Three and Four), the role of sleep hygiene education (Study Five), and the effect of match-day napping (Study Six). Given the need for elite athletes of team sports to consistently perform on a weekly basis, it is important for athletes themselves, coaches and support staff to understand sleep and the consequences of poor sleep on performance and recovery.

Practical Applications

The following practical applications are based on the outcomes of the six experimental studies within this thesis.

- Sleep hygiene education sessions can be implemented to improve sleep indices in elite athletes. We would suggest that experts working in the sleep area deliver these education sessions.
- Nap durations of under 20 minutes on match days result in higher neuromuscular jump and perceived performance.
- Coaching staff and practitioners working with elite athletes should incorporate adequate recovery time into training schedules to account for the impaired sleep indices experienced following evening competition. This may include scheduling a longer sleep-in following a night of competition.
- Hormonal markers are significantly altered following competition and training, resulting in subsequent disrupted sleep indices. Therefore, practitioners working with elite athletes should be aware of this relationship when planning training periodization programs. Furthermore, an attempt to cause similar levels of stress in training environments should be considered if coaches want to simulate the competition environment.

Limitations

The findings and outcomes presented in the thesis have direct and practical outcomes for understanding sleep in elite athletes. Whilst each experimental study acknowledged its own specific limitations, the overall limitations noted throughout each study are declared below.

Across all studies completed within this thesis, research was conducted in an elite sporting environment, which impacted on the sample size. Every effort was made to control the environment during training and competition (Studies Four, Five and Six); however, there were unavoidable confounding variables that could not be controlled for. For example, media requirements after competition, competition results, team selection and pressure, and time of competition season, may have impacted on athletes sleep. Importantly, the results are reflective of an athletes' real-life training and competition environment and thus have a high degree of ecological validity. In addition, the decision to use an actigraph device as the tool to monitor sleep throughout all studies was made based on the cost, minimal intrusiveness to the athletes and additional ecological validity of results, as opposed to the 'gold standard' of polysomnography. In some of the studies, the design did not include a control group. We acknowledge this as a limitation, however, in the elite team-sport environment it is often difficult to convince coaching staff that only certain members of the team will receive the intervention while others will not. Whilst data on menstrual cycle phases was collected for each athlete throughout the studies, we were unable to control the testing to occur at the same time of the menstrual cycle for each athlete. We acknowledge this as a limitation, as previous research has shown menstrual cycle phases to have an influence on sleeping patterns, in relation to core temperature specifically (Manber & Bootzin, 1997).

Future Directions

From the outcomes and results presented within this thesis, the following key areas for future research are suggested. In future sleep investigations, researchers should assess sleep hygiene strategies with a longitudinal approach, to explore if

acute alterations in an athlete's sleep habits leads to sustainable long-term sleep behaviors. More in-depth research into the effect of relaxation strategies on sleep behavior prior to bed would be of value. Furthermore, future research into the use of different sleep environments and sleep aids (e.g. specific pillows and mattresses) would be worthwhile to see if these sleep aids could generate differences in sleep behavior, and subsequently, performance.

The use of nutritional supplements and their potential to aid in the sleep behaviors of elite athletes is another worthwhile area for future research to investigate. Supplements, such as tart cherry juice are thought to offer aid in sleep indices through the natural source of phytonutrients it contains. Although a small number of studies have examined the effect of sleep extension protocols, further investigation is warranted into this area for elite athletes, given the positive results that have previously been found.

A further area to be investigated is what the actual effect of sleep deprivation and restriction has on sport-specific performance. For example, a comparison of sleep restriction in different sports that require differing amounts of skill (e.g. team sports vs. endurance based sports). Moreover, research investigating how many nights of sleep restriction it takes to inhibit performance would be of interest. Further research is required to better understand the effect of match-day napping at an individual level and the effect that nap duration may have on performance and subsequent sleep indices. Research examining the effect of naps, should include more objective performance measures, whilst ensuring controlled testing conditions.

Finally, a gap in the literature remains for longitudinal sleep monitoring across entire seasons to take place for team sport athletes. The findings from Studies Four and Five in this thesis indicate poor sleep around competition, however it is imperative to establish whether these sleep disturbances may have an effect on performance and player well-being over an entire season, and whether or not this changes due to results and timing of the season. Furthermore, future research should consider sleep monitoring in the nights following competition to decipher how long sleep remains disturbed and therefore the implications of sleep

disruptions for practitioners and coaches managing recovery and training schedules.

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APPENDICES

Appendix A – Co-Authorship Forms for Chapters Three to Eight

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Co-Authorship Form

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Nature of contribution by PhD candidate	Development of study design, data collection and analysis, manuscript preparation and journal submission.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Matthew Driller	Supervision of all stages (study design, data collection and analysis) and critical revision of the manuscript.

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Matthew Driller		**06/02/2018**

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Chapter 4 – The validity and reliability of the GymAware linear position transducer for measuring counter-movement jump performance in female athletes.

O'Donnell, S., Tavares, F., McMaster, D & Driller, M. (2017). The validity and reliability of the GymAware linear position transducer for measuring counter-movement jump performance in female athletes. *Measurement in Physical Education and Exercise Science Journal.* DOI: 10.1080/1091367X.2017.1399892

Nature of contribution by PhD candidate	Development of study design, data collection and analysis, manuscript preparation and journal submission.
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
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Daniel McMaster	Support with data collection and drafting of the manuscript
Samuel Chambers	Support with data collection
Matthew Driller	Supervision of all stages (study design, data collection and analysis) and critical revision of the manuscript

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Name	Signature	Date
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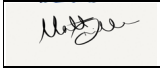
Daniel McMaster		*06/02/2018*
Samuel Chambers		*06/02/2018*
Matthew Driller		*06/02/2018*

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work. Chapter 5 – The influence of match-day napping in elite female netball athletes. O'Donnell, S., Beaven, C & Driller, M. (Under Review). The influence of match-day napping in elite female netball athletes. *International Journal of Sports Physiology and Performance.*

Nature of contribution by PhD candidate	Development of study design, data collection and analysis, manuscript preparation and journal submission.
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Christopher Beaven	Contribution to drafting of the manuscript and critical revision of the manuscript.
Matthew Driller	Supervision of all stages (study design, data collection and analysis) and critical revision of the manuscript.

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Name	Signature	Date
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Nature of contribution by PhD candidate	Development of study design, data collection and analysis, manuscript preparation and journal submission.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Christopher Beaven	Contribution to drafting of the manuscript and critical revision of the manuscript
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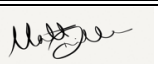
Matthew Driller		**06/02/2018**

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work. Chapter 7 – Sleep and stress hormone responses to training and competition in elite female athletes. O'Donnell, S., Jacobson, G., Bird, S & Driller M. (Under Review). Sleep and stress hormone responses to training and competition in elite female athletes. *European Journal of Sports Sciences.* In Press.

Nature of contribution by PhD candidate	Development of study design, data collection and analysis, manuscript preparation and journal submission.
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Gregory Jacobson	Support to study design, hormonal analysis and contribution to drafting of the manuscript.
Steve Bird	Support to study design and interpretation of data, contribution to drafting of the manuscript.
Matthew Driller	Supervision of all stages (study design, data collection and analysis) and critical revision of the manuscript.

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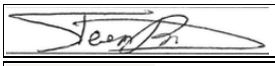
Steve Bird		**6/02/2018**
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Nature of contribution by PhD candidate	Development of study design, data collection and analysis, manuscript preparation and journal submission.
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Christopher Beaven	Contribution to drafting of the manuscript and critical revision of the manuscript.
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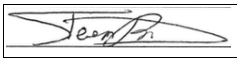
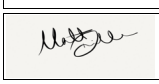
Steve Bird		**6/02/2018**
Matthew Driller		**6/02/2018**

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Appendix B - Inter-device reliability of an automatic-scoring actigraph for measuring sleep in healthy adults.

Driller, M., McQuillan, J & O'Donnell, S. (2016). Inter-device reliability of an automatic-scoring actigraph for measuring sleep in healthy adults. *Sleep Science.* 9(3).

Abstract

Actigraphy has become a common method of measuring sleep due to its non-invasive, cost-effective nature. A new actigraph (Readiband™) that utilises automatic scoring algorithms has been used in the research, but is yet to be evaluated for its inter-device reliability. A total of 77 nights of sleep data from 11 healthy adult participants was collected while participants were concomitantly wearing two Readiband™ actigraphs attached together (ACT1 and ACT2). Sleep indices including total sleep time (TST), sleep latency (SL), sleep efficiency (SE%), wake after sleep onset (WASO), total time in bed (TTB), wake episodes per night (WE), sleep onset variance (SOV) and wake variance (WV) were assessed between the two devices using mean differences, 95% levels of agreement, intraclass correlation coefficients (ICC), typical error of measurement (TEM) and coefficient of variation (CV%) analysis. There were no significant differences between devices for any of the measured sleep variables ($p>0.05$). TST, SE, SL, TTB, SOV and WV all resulted in *very high* ICC's (>0.90), with WASO and WE resulting in *high* ICC's between devices (0.85 and 0.80, respectively). Mean differences of -2.1 and 0.2 mins for TST and SL were associated with a low TEM between devices (9.5 and 3.8 mins, respectively). SE resulted in a 0.3% mean difference between devices. The Readiband™ is a reliable tool for researchers using multiple devices of this brand in sleep studies to assess basic measures of sleep quality and quantity in healthy adult populations.

Introduction

The quantification and measurement of sleep amongst various interventional and population research studies and clinical settings is of increasing importance. Different methods of monitoring sleep have been extensively researched and validated in the literature, with little focus on the inter-device reliability of such tools. Indeed, the precision required to determine changes in sleep patterns amongst different individuals and populations is of critical importance to understanding and interpreting the results of any sleep research studies.

Although considered the gold standard method of sleep measurement, polysomnography (PSG) requires a somewhat intrusive and expensive assessment of sleep indices (van de Water, Holmes, & Hurley, 2011). Moreover, PSG monitoring typically requires attendance at a sleep laboratory with specialist staff, in a foreign environment, which may be inconvenient and unnatural for most individuals. Because of this, attempts have been made to measure sleep using less-invasive methods. Such methods include sleep-logs/questionnaires and wristwatch actigraphy. The use of sleep-logs and questionnaires are common as they are in-expensive and easy to administer. However, these have been shown to have a poor relationship with objective measures of sleep (Lauderdale, Knutson, Yan, Liu, & Rathouz, 2008), therefore questioning their efficacy. Wristwatch actigraphy is a non-intrusive, cost-effective tool used to estimate sleep quantity and quality which has been compared to PSG, showing accuracies of ~90% in some studies for total sleep time and sleep efficiency (Babin, Lee, Halko, Boudreau, & George, 1997; Kushida et al., 2001; Sadeh, 2011) and as such, are widely used in the sleep literature (Sadeh, 2011). Actigraphy involves the use of a device housed in a wristwatch that contains a small accelerometer capable of sensing movement along any one of three axes. The accelerometer samples multiple times per second and with each limb movement, the accelerometer registers this information and stores it in an adjacent memory chip. Once the recording period has finished, the actigraph is downloaded and manually scored for sleep indices by a trained sleep technician (Ancoli-Israel et al., 2003). While the process of manually scoring actigraph data has been described for its inter and intra-scorer reliability, it is difficult to make conclusions on the overall reliability

of actigraphy given the variation of scoring methods, brands of actigraphs and researchers themselves (Sadeh, 2011).

Given the limitations of manually scoring actigraph files, a plethora of new actigraphy devices designed to automatically score sleep have emerged. One such device, the Readiband™ (Fatigue Science, Honolulu, USA), is gaining popularity for its use in sleep research studies (Dennis et al., 2016; Fowler, Duffield, & Vaile, 2015; H. H. Fullagar et al., 2016; Noor, Smith, Smith, & Nissen, 2013). The Readiband™ records data at a sample rate of 16Hz and uses a patented algorithm to automatically score sleep data via download to the companies software. The Readiband™ has been validated against PSG, with levels of accuracy 93% being reported (Russell et al., 2011). However, while the device has been shown to be a valid sleep measurement tool, the inter-device reliability of the Readiband™ is yet to be evaluated. Assessing the inter-device reliability for multiple devices of the same brand and model is important for researchers to have confidence that separate devices are reading in a similar and reliable manner. Indeed, this type of assessment has become commonplace in evaluating the reliability of physical activity trackers (Evenson, Goto, & Furberg, 2015). However, this type of assessment is not yet standard procedure for new actigraphs that measure sleep indices. Therefore, the purpose of the current study was to investigate the inter-device reliability of the Readiband™ by evaluating 77 nights of data from healthy adult participants concomitantly wearing two Readiband™ devices attached together.

Materials and Methods

Participants

A total of 11 healthy adults (4 male/7 female, mean ± SD; age: 33 ± 7 years) volunteered to participate in the current study. All participants provided informed written consent before taking part in the study and were free of any diagnosed sleep disorders. Ethical approval for the study was obtained through the institutions Human Research Ethics Committee.

Methodology

Participants were required to wear two wrist actigraphs (SBV2 Readiband™, Fatigue Science, Honolulu, USA), attached together over a 7-day period to assess inter-device reliability between the two devices (ACT1 and ACT2). The Readiband™ devices have been shown to have good validity (overall accuracy of 93%) when compared to the gold standard of PSG in 50 participants undergoing overnight sleep monitoring at a sleep centre (Russell et al., 2011) and have been accepted as an approved device by the Federal Drug Administration (FDA) based on this validation. The Readiband™ has also been assessed in a mini-validation study against another actigraph (Micro Mini-Motion Loggers, Ambulatory Monitoring Inc., Ardsley, USA) (Dennis et al., 2016) where the two brands of actigraph were attached together for 3 nights in 8 participants, resulting in acceptable levels of agreement for sleep duration and rest duration (r = 0.84 and 0.94, respectively). In the current study, both devices were tightly secured together using electrical tape so that they could not move independently of each other and were worn on the participants' non-dominant wrist before initialization of the two devices to record data in 1-minute epochs (Dennis et al., 2016). This method of determining inter-device reliability of actigraphy monitors has been used previously (Meltzer, Walsh, Traylor, & Westin, 2012). Participants were required to wear the actigraph continuously for the 7-day period, with the exception of time spent in water, bathing or showering. Participants were instructed to maintain their usual sleep habits and general daily activity patterns during the monitoring period. At the conclusion of the recording period, actigraph data were wirelessly downloaded to a study computer using a Nordic 2.4 GHz ANT transceiver, which was then analysed using Fatigue Science software (16Hz sampling rate: Readiband™, Fatigue Science, Vancouver). The raw activity scores were translated to sleep-wake scores based on computerized scoring algorithms. The five measures obtained from the actigraphy device and software that were used as sleep indices are described in Table 5.

Statistical Analysis

Simple group statistics are shown as means ± standard deviations unless stated otherwise. A students paired T-test was used to compare ACT1 and ACT2 using a Statistical Package for Social Science (V. 22.0, SPSS Inc., Chicago, IL), with

statistical significance set at $p \leq 0.05$. Inter-device agreements for ACT1 and ACT2 were examined using intraclass correlation coefficients (ICC) with 95% confidence intervals (95% CI) and interpreted as 0.90–1.00 = *very high* correlation, 0.70–0.89 = *high* correlation, 0.50–0.69 = *moderate* correlation, 0.26–0.49 = *low* correlation and 0.00–0.25 = *little, if any* correlation (Munro, 2005). The mean differences and upper and lower limits of agreement (1.96 standard deviations or 95% of a normally distributed population) between devices were determined in absolute values for TST, SL and SE. Between-device typical error of measurement (TEM) was determined using an excel spreadsheet (Hopkins, 2010) and are presented as a coefficient of variation percentage (CV%) and as absolute values. Similar to Werner et al., (2008), we defined an apriori difference between the 2 devices of ≤ 30 min satisfactory for TST, with a difference < 5% for SE satisfactory.

Results

There were no significant differences between devices (ACT1 and ACT2) for any of the measured sleep variables ($p > 0.05$, Table 19). There was a mean difference between devices of -2.1 ± 13.4 minutes over the 77 nights of data for TST. This difference was associated with a *very high* correlation and a low TEM (9.5 mins) and CV (2.3%) between devices (Table 20).

SE resulted in a TEM between devices of 2.4%, which was associated with an ICC of 0.93 – *very high* (Table 16). SL, TTB, SOV and WV also resulted in *very high* correlations between devices and a mean difference of < 1.5 mins (Table 20). Comparison between these devices for these variables also resulted in TEM's of <8.5 mins (Table 20).

The remaining variables; WASO and WE, resulted in *high* correlations between devices, with TEM values of 3.3 mins and 1.2 (wake episodes), respectively (Table 20).

Level of agreement plots showing ±95% limits of agreement between ACT1 and ACT2 for TST, SL and SE are displayed in Figure 12.

Table 19 - Mean ± SD values for both devices (ACT1 and ACT2) for all measured sleep variables and p-values for each comparison.

	ACT1	ACT2	P-Value
Total Sleep Time (mins)	461.6 ± 86.6	459.5 ± 87.9	0.20
Sleep Efficiency (%)	83.0 ± 8.9	83.2 ± 8.9	0.73
Sleep Latency (mins)	21.9 ± 20.0	21.7 ± 19.6	0.79
Total Time in Bed (mins)	564.1 ± 98.7	563.2 ± 99.0	0.55
Wake After Sleep Onset (mins)	11.7 ± 8.0	12.2 ± 8.4	0.32
Wake Episodes (No. per night)	3.5 ± 2.5	3.6 ± 2.6	0.72
Sleep Onset Variance (mins)	-0.8 ± 74.0	-2.3 ± 75.1	0.13
Wake Variance (mins)	-3.1 ± 48.4	-2.6 ± 47.3	0.37
Sleep Onset Time (time of day)	22:47 ± 0:49	22:48 ± 0:49	0.76
Wake Time (time of day)	7:03 ± 0:52	7:02 ± 0:50	0.41

Table 20 - Typical error of measurement (TEM) expressed in raw values and as a coefficient of variation (CV%), mean difference, range of mean difference and intra-class correlation (ICC) for each sleep variable between ACT1 and ACT2.

	TEM (95% CL)	**CV% (95% CL)**	**Mean Difference[#] (±SD)**	**Range of Mean Difference (1.96xSD)**	**ICC (±95%CL)**
Total Sleep Time (mins)	9.5 8.2 – 11.3	2.3 2.0 – 2.8	-2.1 ± 13.4	-28.8 – 24.7	0.99 0.98 – 0.99 *very high*
Sleep Efficiency (%)	2.4 2.0 – 2.9	NA	0.2 ± 3.4	-6.2 – 6.6	0.93 0.89 – 0.96 *very high*
Sleep Latency (mins)	3.8 3.2 – 4.6	32.5 26.9 – 41.1	-0.2 ± 5.4	-10.8 – 10.4	0.97 0.94 – 0.98 *very high*
Total Time in Bed (mins)	8.5 7.3 – 10.3	1.5 1.3 – 1.8	-0.9 ± 12.1	-25.0 – 23.3	0.99 0.99 – 1.00 *very high*
Wake After Sleep Onset (mins)	3.3 2.8 – 3.9	37.8 31.5 – 47.4	0.6 ± 4.6	-8.6 – 9.7	0.85 0.76 – 0.90 *high*
Wake Episodes (No. per night)	1.2 1.0 – 1.4	41.8 34.6 – 52.6	0.1 ± 1.6	-3.2 – 3.3	0.80 0.70 – 0.87 *high*
Sleep Onset Variance (mins)	5.4 4.6 – 6.6	31.8 24.7 – 44.7	-1.5 ± 7.7	-16.8 – 13.9	0.99 0.99 – 1.00 *very high*
Wake Variance (mins)	3.6 3.1 – 4.3	15.0 11.8 – 20.5	0.5 ± 5.1	-21.9 – 25.5	0.99 0.99 – 1.00 *very high*

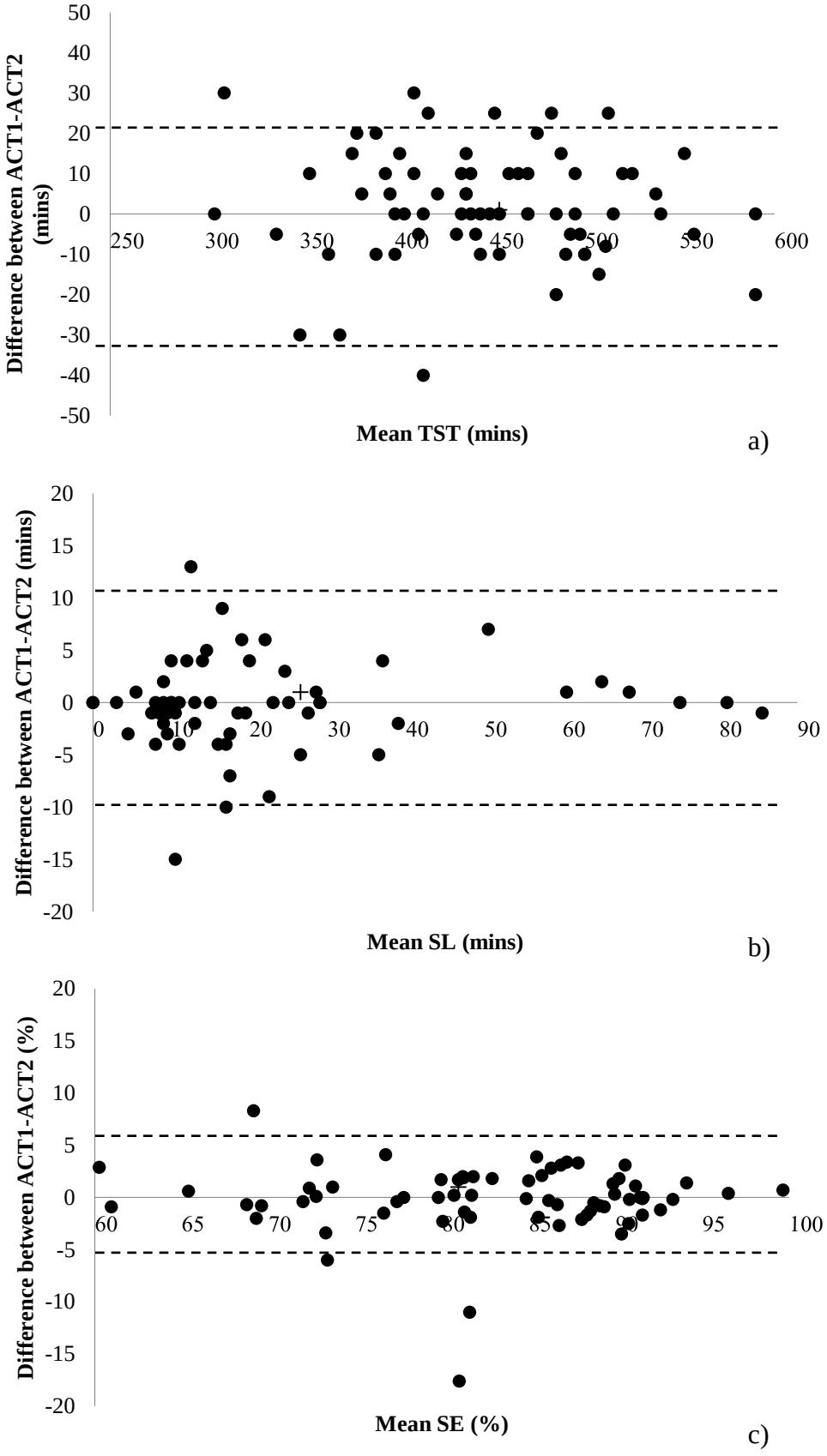

Figure 12 - level of agreement plots showing ±95% limits of agreement between ACT1 and ACT2 for a) total sleep time (TST); b) sleep latency (SL); c) sleep efficiency (SE).

Discussion

The current study was the first to determine the inter-device reliability of a commercially available automatic-scoring actigraph in healthy adult participants by wearing two Readiband™ devices simultaneously. The correlation between devices of the same brand (Readiband™) was *very high* for the most important sleep variables of total sleep time, sleep latency and sleep efficiency, with no significant differences in any of the measured sleep variables between devices. All differences between the two devices in the current study are deemed to be acceptable according to Werner et al., (2008), who stated that a difference between 2 devices of ≤ 30 minutes can be deemed satisfactory for total sleep time, with a difference < 5% for sleep efficiency satisfactory. This suggests that researchers can use multiple devices of the same brand and model within the same study and obtain comparable results. The results in the current study are similar to those described by Dennis et al. [13], who studied the agreement between the Readiband™ and the Micro Mini-Motion Logger actigraphs and reported correlation coefficients of > 0.80 for total sleep time and total time in bed.

A major limitation of actigraphy methods that require manual sleep scoring, is that it introduces human error, as opposed to the automatic scoring device used in the current study. Indeed, proposed limitations of the use of actigraphy in sleep research are the inter-scorer reliability or the potential for intra-scorer bias. The use of a computerized scoring algorithm helps to account for both of these factors. Furthermore, the inter-scorer reliability of sleep data using the 'gold-standard' PSG, for determining sleep-wake has been studied extensively, with agreements between scorers ranging from 65-85% (Penzel, Zhang, & Fietze, 2013; Rosenberg & Van Hout, 2013). In a large comparative study investigating inter-scorer agreement between sleep laboratories, Norman et al. (2000) reported that the level of agreement in sleep indices varies between scorers and between laboratories. Results showed that the level of agreement between laboratories is lower than what can be maintained between scorers within the same laboratory. The authors expressed caution when comparing sleep data scored by experts from separate laboratories (Norman et al., 2000). This would suggest that even PSG for detecting sleep-wake, may have reliability issues as well as lacking ecological validity.

The foreign environment experienced during PSG monitoring in a sleep laboratory may alter the normal sleeping patterns of an individual (Campbell & Neill, 2011). Indeed, differences between at-home and laboratory PSG monitoring have been shown to produce different results (Edinger et al., 1997; Iber et al., 2004). The un-natural laboratory environment, combined with the cost of assessment, accessibility of the laboratory and technicians, makes it difficult to attain for healthy sleepers wanting to monitor their sleep. For this reason, it has been suggested that sleep monitoring at home, in a familiar environment may be the most appropriate for monitoring normal sleep patterns (Iber et al., 2004). Even with at-home PSG monitoring, the comfort of sleeping with multiple electrodes and attachments must be questioned. While PSG monitoring in a laboratory may be important for diagnosing sleep disorders, the basic determination of sleep-wake cycles and sleep efficiency may be adequate for individuals wanting to know more about their sleep hygiene. Therefore, the importance of valid and reliable tools, such as actigraphy, may serve this purpose.

Conclusion

In summary, the results from the current study would suggest that the Readiband™ is a reliable tool for researchers aiming to use multiple devices of the same brand in sleep studies. These findings, along with the previously reported validity of the Readiband™ device, make it an easy to use, practical tool in both the clinical and research setting, without the need for qualified sleep scorers. The automatic scoring make this a novel device that can be used in many different fields to assess basic measures of sleep quality and quantity.

Appendix C - What wrist should you wear your actigraphy device on? Analysis of dominant vs. non-dominant wrist actigraphy for measuring sleep in healthy adults.

Driller, M., Tavares, F & O'Donnell, S. (2017). What wrist should you wear your actigraphy device on? Analysis of dominant vs. non-dominant wrist actigraphy for measuring sleep in healthy adults. *Sleep Science.* 10(3).

Abstract

Objective: Differences in sleep results due to the placement of actigraphy devices (non-dominant vs. dominant wrist) are yet to be determined. Methods: 65 nights of data from 13 adult participants was collected while participants wore two actigraphy devices, one on each wrist. Sleep indices including total sleep time (TST), total time in bed (TTB), sleep efficiency (SE%), sleep latency (SL), wake after sleep onset (WASO), sleep onset time (SOT) and wake time (WT) were assessed between the two devices. Results: There were no significant differences between devices for any of the measured sleep variables ($p > 0.05$). SE%, SL and WASO resulted in *high* correlations between devices (0.89, 0.89 and 0.76, respectively), with all other sleep variables resulting in *very high* correlations (>0.90) between devices. Conclusion: Based on our results, it does not seem critical which wrist the actigraphy device is worn on for measuring key sleep variables.

Introduction

The quantification and measurement of sleep amongst various interventional and population research studies and clinical settings is of increasing importance. Sleep monitoring has also become a substantial consumer industry, with a rising rate of commercial companies producing various wearable sleep monitoring devices (Ko et al., 2015). Although considered the 'gold standard' method of sleep measurement, polysomnography (PSG) requires a somewhat intrusive and expensive assessment of sleep indices. Wrist actigraphy is a non-intrusive, cost-effective tool used to estimate sleep quantity and quality which has been compared to PSG, showing an accuracy of up to 93% in healthy adults for total sleep time and sleep efficiency (Babin et al., 1997; Kushida et al., 2001) and as such is widely used in the sleep literature (Sadeh, 2011).

Actigraphy involves the use of a device housed in a wristwatch that contains a small accelerometer capable of sensing movement along any one of three axes (Sadeh, 2011). The accelerometer is sampled multiple times per second and the actigraph is downloaded and either manually or automatically scored for sleep indices. While actigraphy has become commonplace in both the research and consumer setting, the optimal placement of the actigraph itself is relatively unknown. Traditionally, the majority of research studies recommend that the actigraphy device should be worn on the non-dominant wrist (Sadeh, 2011), however some studies have suggested that it may be more suitable to wear the actigraph on the dominant wrist (Jean-Louis, Mendlowics, Von Gizycki, Zizi, & Nunes, 1999), and others do not specify what wrist it should be worn on (Marino et al., 2013). Furthermore, the new emerging technology over the past decade has seen improved automatic scoring actigraphy devices, reducing the need for sleep technicians. Given the increasing use of actigraphy for monitoring sleep, the new and emerging technology for automatic scoring of devices and the disparate recommendations in the literature, this is an important area that needs further clarification. Therefore, the aim of the current case study was to determine if differences exist between wearing automatic-scoring actigraphy devices on the non-dominant and dominant wrists in healthy adults.

Materials and Methods

Participants

A total of 13 healthy adults (8 male / 5 female, mean SD, age) volunteered to take part in the study. All participants were free of any diagnosed sleep disorders. Ethical approval for the study was obtained through the institutions Human Research Ethics Committee.

Study Design

Participants were required to wear a wrist actigraphy device (Readiband™, Fatigue Science, Vancouver) on each wrist (dominant and non-dominant) over a period of 5 nights. Participants were instructed to maintain their usual sleep habits and general daily activity patterns during the monitoring period, and were instructed to leave the devices on at all times. The Readiband has been validated against PSG, with accuracy levels of 93% being reported (Russell et al., 2011) and research from our laboratory has also shown that the Readiband results in acceptable levels of inter-device reliability (ICC = >0.90) (Driller et al., 2016). At the conclusion of each recording period, actigraphy data were wirelessly downloaded to a computer using a Nordic 2.4 GHz ANT transceiver, which was then analysed using Fatigue Science software (16Hz sampling rate: Readiband™, Fatigue Science, Vancouver). The raw activity scores were translated to sleep-wake scores based on computerized scoring algorithms. Sleep indices including total sleep time (TST), sleep efficiency (SE%), total time in bed (TTB), sleep latency (SL), wake after sleep onset (WASO), sleep onset time (SOT) and wake time (WT) were used for comparison between devices.

Statistical Analysis

Simple group statistics are shown as means ± standard deviations unless stated otherwise. An independent-samples T-test was used to compare dominant and non-dominant wrist measures using the Statistical Package for Social Science (V. 22.0, SPSS Inc., Chicago, IL), with statistical significance set at $p < 0.05$. Inter-device agreements for dominant and non-dominant wrists were examined using Pearson's correlation coefficients (r) with 95% confidence intervals (95% CI) and interpreted as 0.90–1.00 = *very high* correlation, 0.70–0.89 = *high* correlation, 0.50–0.69 = *moderate* correlation, 0.26–0.49 = *low* correlation and 0.00–0.25 =

little, if any correlation (Munro, 2005). Between-device typical error of estimates (TEE) was determined using an excel spreadsheet (Hopkins, 2010) and are presented as a coefficient of variation percentage (CV%) and as absolute values. Similar to Werner et al., (2008), we defined an apriori difference between the 2 devices of ≤ 30 min satisfactory for TST, with a difference < 5% for SE satisfactory.

Results

There were no significant differences between devices for any of the measured sleep variables ($p > 0.05$).

Mean differences of 6 mins and 2 min between non-dominant and dominant wrists for TST and TTB were associated with CV% scores of 4.6 and 3.8%, respectively (Table 21).

TST, TTB, SOT and WT all resulted in *very high* correlations (>0.90), with SE%, SL and WASO resulting in *high* correlations between devices (0.89, 0.89 and 0.76, respectively).

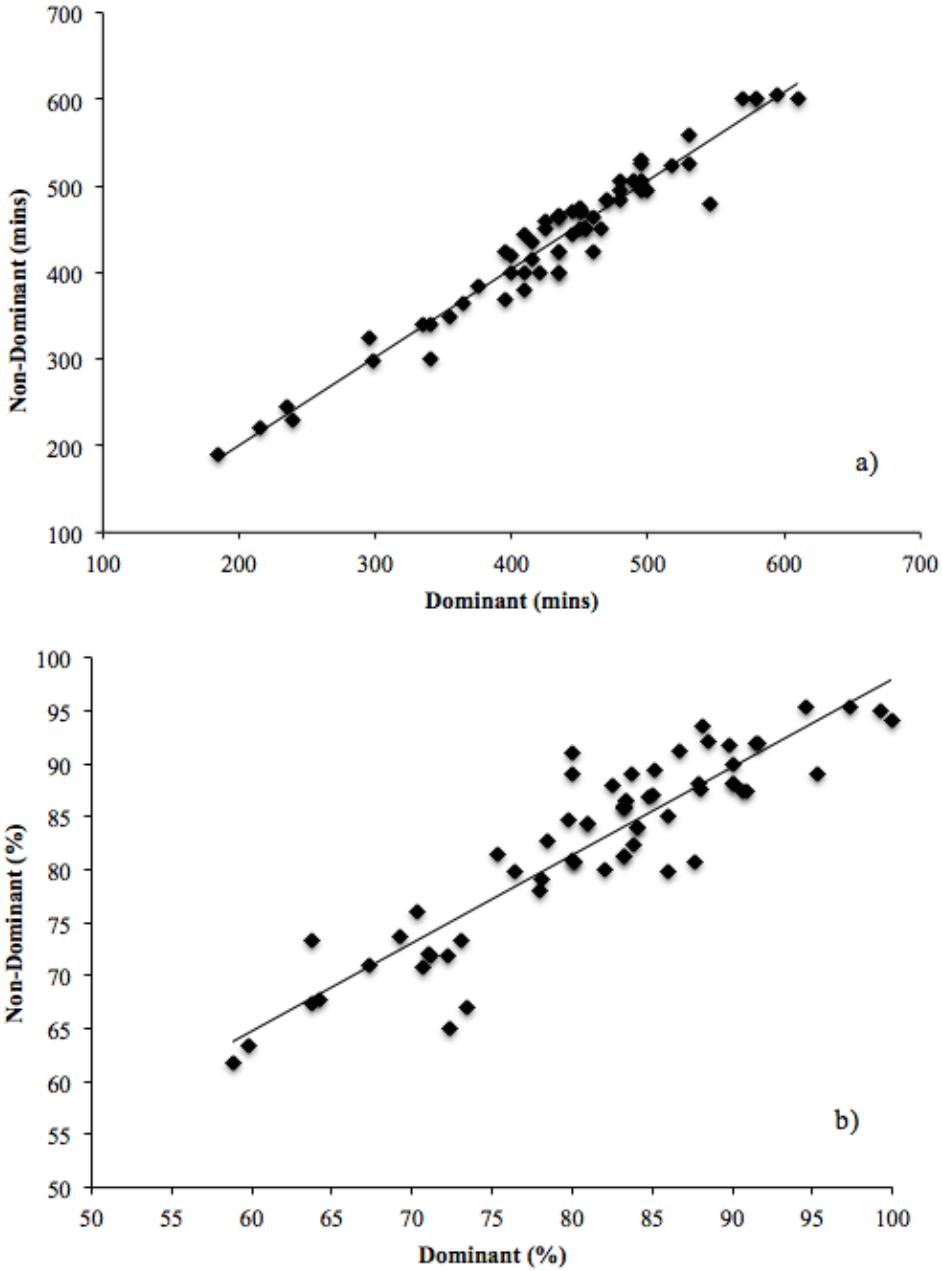

Figure 13 - Correlation plots between non-dominant and dominant wrist actigraphy data for: a) total sleep time (mins), and b) sleep efficiency (%).

Table 21 - Mean ± SD values for the measured sleep variables between non-dominant and dominant wrist-actigraphy devices. Comparison between devices are reported using mean bias, Pearson correlations (*r*), typical error of estimates (TEE) and coefficient of variation % with 95% confidence intervals.

	Non-Dominant	**Dominant**	**Mean bias**	**Pearson's *r***	**TEE**	**CV%**
Total Sleep Time (mins)	436 ± 72	442 ± 80	6 ± 19	0.97 (0.95 – 0.98)	18 (15 -22)	4.6 (3.8 – 5.7)
Total Time in Bed (mins)	552 ± 85	554 ± 83	2 ± 20	0.97 (0.95 – 0.98)	20 (17 – 25)	3.8 (3.1 – 4.7)
Sleep Efficiency (%)	81 ± 9	82 ± 6	1 ± 4	0.89 (0.81 – 0.94)	4 (3 – 5)	5.3 (4.4 – 6.6)
Sleep Latency (mins)	29 ± 34	28 ± 31	-1 ± 15	0.89 (0.82 – 0.94)	15 (13 – 19)	102.4 (80.2 – 140.7)
Wake After Sleep Onset (mins)	53 ± 38	52 ± 43	-1 ± 28	0.76 (0.61 – 0.86)	25 (21 – 32)	60.5 (47.7 – 82.5)
Sleep Onset Time (time of day)	23:25 ± 1:32	23:24 ± 1:33	-1 ± 11	0.99 (0.99 – 0.99)	12 (11 – 15)	0.8 (0.7 – 1.0)
Wake Time (time of day)	7:30 ± 1:21	7:31 ± 1:21	1 ± 11	1.00 (1.00 – 1.00)	11 (9 – 14)	2.5 (2.1 – 3.1)

Discussion

The main finding in the current study was that there were no significant differences between non-dominant and dominant wrist actigraphy for monitoring sleep in healthy adults. The non-significant differences between devices were associated with *high* to *very high* correlations for all sleep measures and relatively low (~5%) CV's for the key sleep variables of total sleep time, total time in bed and sleep efficiency. The typical error of estimate for total sleep time and total time in bed was ~20 minutes and the mean bias was ~5 minutes, suggesting that there is little difference in what wrist the actigraph is worn on.

The use of wrist-actigraphy for monitoring sleep is becoming increasingly popular in numerous research fields, including athletic (O'Donnell & Driller, 2017), clinical (Briscoe et al., 2014), adolescent (Short, Gradisar, Lack, Wright, & Chatburn, 2013) and pediatric (Conrad, Karlik, Lewandowski Holley, Wilson, & Koh, 2017) populations. However, while traditionally it was suggested that actigraphy devices should be worn on the dominant wrist of participants (Sadeh, Sharkey, & Carskadon, 1994), there is a lack of evidence to show whether or not any differences actually exist. Furthermore, the ever-evolving technology of sleep monitoring via actigraphy has introduced automatic-scoring devices (Driller et al., 2016), further identifying the need to investigate differences in the placement of devices.

As previously suggested (Marino et al., 2013; Zinkhan et al., 2014), care should be taken when interpreting results for WASO and SL when measured via wrist actigraphy, as the accuracy of these measures when compared to PSG is questionable. The current study would support this, as these were the most variable sleep indices between the two devices, with typical error of estimates and CV% of ~25 minutes and ~60% for WASO and ~15 minutes and ~100% for SL, respectively.

Results from the current study would suggest that the placement of the actigraphy device (dominant vs. non-dominant wrist) is not critical for accurate sleep measurement of key sleep measures including total sleep time, total time in bed, sleep onset and wake time. Given this, the authors would recommend that

individuals wearing actigraphy devices, either as general consumers or research participants, should opt to wear their actigraphy device on whatever wrist feels the most comfortable. Indeed, if the device feels uncomfortable, it is more likely to influence adherence to wearing the monitor and overall sleep results.

Appendix D - Assessing a smartphone application to measure countermovement jumps in recreational athletes.

Driller, M., Tavares, F., McMaster, D & O'Donnell, S. (2017). Assessing a smartphone application to measure countermovement jumps in recreational athletes. *International Journal of Sports Science & Coaching*.

Abstract

The use of countermovement jumps as a measure of neuromuscular performance in athletes has become common in the sport setting. Accurate methods of measuring jump parameters are often expensive, difficult to transport and require expert knowledge. A new smartphone application (*My Jump*) claims to be a valid and reliable tool for assessing jump height but is yet to be evaluated by independent researchers. Sixty-one recreational athletes (30 male/31 female, mean ± SD; age: 20 ± 4 y) each performed 3 countermovement jumps (totalling 183 jumps) on a force plate following a standardised warm-up. All jumps were recorded using an iPhone 6s and analysed for jump height (m) and flight time (s) using the *My Jump* application. Jumps were compared between a force plate and *My Jump* for validity with inter-scorer reliability also assessed. Results show that *My Jump* is valid (mean bias = 0.9 cm, r = 0.96) and reliable (typical error of estimate = 1.4 cm) for assessing jump performance in recreational athletes using an iPhone 6s with a 240 Hz high-speed camera. *My Jump* is a cost-effective and easy-to-use alternative for measuring vertical jump performance without the need for specialist equipment or expertise.

Introduction

A commonly used form of neuromuscular ballistic assessment in the sport setting is the vertical jump test. The vertical jump has many derivations that enable information to be gathered about various neuromuscular and performance qualities of an individual athlete (Klavora, 2000).

Many different protocols and devices have been used to assess lower-body power via the vertical jump test (Hopkins et al., 2001). These include the use of yardsticks, contact mats, optical encoders, position transducers, accelerometers, and force plates. Force plates are the most commonly validated measuring devices in the literature and are therefore regarded as the 'gold standard' for measuring jump performance (Buckthorpe, Morris, & Folland, 2012). However, this method can be expensive, not particularly portable and often requires expertise for testing and analysis of the jump data.

The *My Jump* smartphone application uses the recording capability on an iPhone and requires researchers to select the take-off and landing frame on the video of a jump. From these two frame-selections, the *My Jump* application calculates jump height and flight time. *My Jump* has been evaluated previously by the designers of the application (Balsalobre-Fernández, Glaister, & Lockey, 2015; Gallardo-Fuentes et al., 2016), reporting high intra-class correlation coefficients (0.97-0.99), *almost perfect* Pearson correlations (r = 0.97-0.99), small mean differences (0.2cm) and Bland-Altman bias (1.1 cm) between the application and a force plate. However, these results are yet to be confirmed by independent researchers using the latest smartphone technology.

Methods

Participants

30 male and 31 female (mean ± SD; age: 20 ± 4 y; body mass: 76.4 ± 15.2 kg) participants volunteered to take part in the current study. Participants represented a wide range of abilities and training status, from recreational to highly-trained athletes. This was to ensure that the *MyJump* app could be validated across a wide range of jump heights. To be eligible for the study, all participants were required to be free from lower-limb injuries that may have affected their ability to perform

vertical jumps. This study was given ethical approval by the Human Research Ethics Committee at the University of Waikato.

Methodology

The validity of a smartphone app (*My Jump*) to measure counter-movement jump (CMJ) performance was determined by comparing the jump height and flight-time measurements obtained simultaneously with two dual-axis force plates (Dual-Axis Force Platform, PASCO, California, USA) sampled at 200 Hz. Validity was assessed by comparing the *My Jump* app to the 'gold standard' force plate during a single testing session. Following a standardized warm-up including 10 external hip rotations, 10 internal hip rotations, 10 frontal plane leg swings, 10 sagittal plane leg swings, 5 single leg Romanian deadlifts, 10 body weight squats, 10 forward lunges and 3 submaximal jumps at 70, 80 and 90% of perceived maximum effort, each participant performed three maximal CMJs to a self-selected depth on the force plates. Participants kept their hands on their hips for all jumps, with their legs kept straight during the flight phase of the jump. Each jump was separated by 5-seconds. To assess inter-scorer reliability of the *My Jump* application, two members of the research team independently scored 50 jumps of the same video footage using *My Jump*.

Materials

The smartphone app used in the current study calculated the flight time of the CMJ by identifying the take-off and the landing frames of the video, and then transforming it into a jump height using the following equation described in the literature:(Gallardo-Fuentes et al., 2016)

$$h = t^2 \times 1.22625 \quad (1)$$

Where; h = jump height in metres; t = flight time of the jump in seconds. The same equation was also used to calculate jump heights from the force plate data using customized software (WeightRoom, High Performance Sport New Zealand-Goldmine, Auckland, New Zealand). To record the countermovement jump with *My Jump*, a researcher lay prone to the ground with an iPhone 6s (Apple Inc., USA) facing the participant (in the frontal plane), at a distance of 1.5m from the force plate, focusing on the feet of the participant. Once a jump was recorded, the first frame in which both feet were off the ground (take-off phase) and the

subsequently, the first frame in which at least one foot was touching the ground (landing-phase), were selected in *My Jump* in order to calculate jump height and flight time. The iPhone 6s used in the study included a 240 Hz high-speed camera, at a quality of 720p.

Statistical Analysis

All data are presented as means ± SD unless stated otherwise. Statistical significance was set at $p < 0.05$. Comparison of *My Jump* with the 'gold standard' force plate was achieved using a range of previously described methods including paired t-tests, Pearson product-moment correlation analysis, standard linear regression, 95% limits of agreement (LOA), mean bias (%) and typical error of estimate (TEE) (Altman & Bland, 1983; Atkinson & Nevill, 1998; Hopkins, 2015). The magnitude of correlation between *My Jump* and the force plates was assessed using the following thresholds: <0.1, *trivial*; 0.1-0.3, *small*; 0.3-0.5, *moderate*; 0.5-0.7, *large*; 0.7-0.9, *very large*; and 0.9-1.0, *almost perfect*. A Breusch-Pagan test was used to determine heteroskedasticity. Inter-scorer reliability data were analyzed using an Excel spreadsheet for reliability (Hopkins, 2015).

Results

There was *almost perfect* agreement between the *My Jump* and force plate for both jump height ($r = 0.96$) and flight time ($r = 0.96$, Table 22). The mean bias between *My Jump* and the force plate for jump height was 0.9 ± 0.2 cm, which was associated with a TEE of 2.0 cm (Table 22). *My Jump* showed very good inter-scorer reliability (TEE = 1.4 cm, ICC = 0.97, Table 23). The results rejected heteroskedasticity at $p < 0.05$, indicating that there was no heteroskedasticity present across a wide range of jumping abilities.

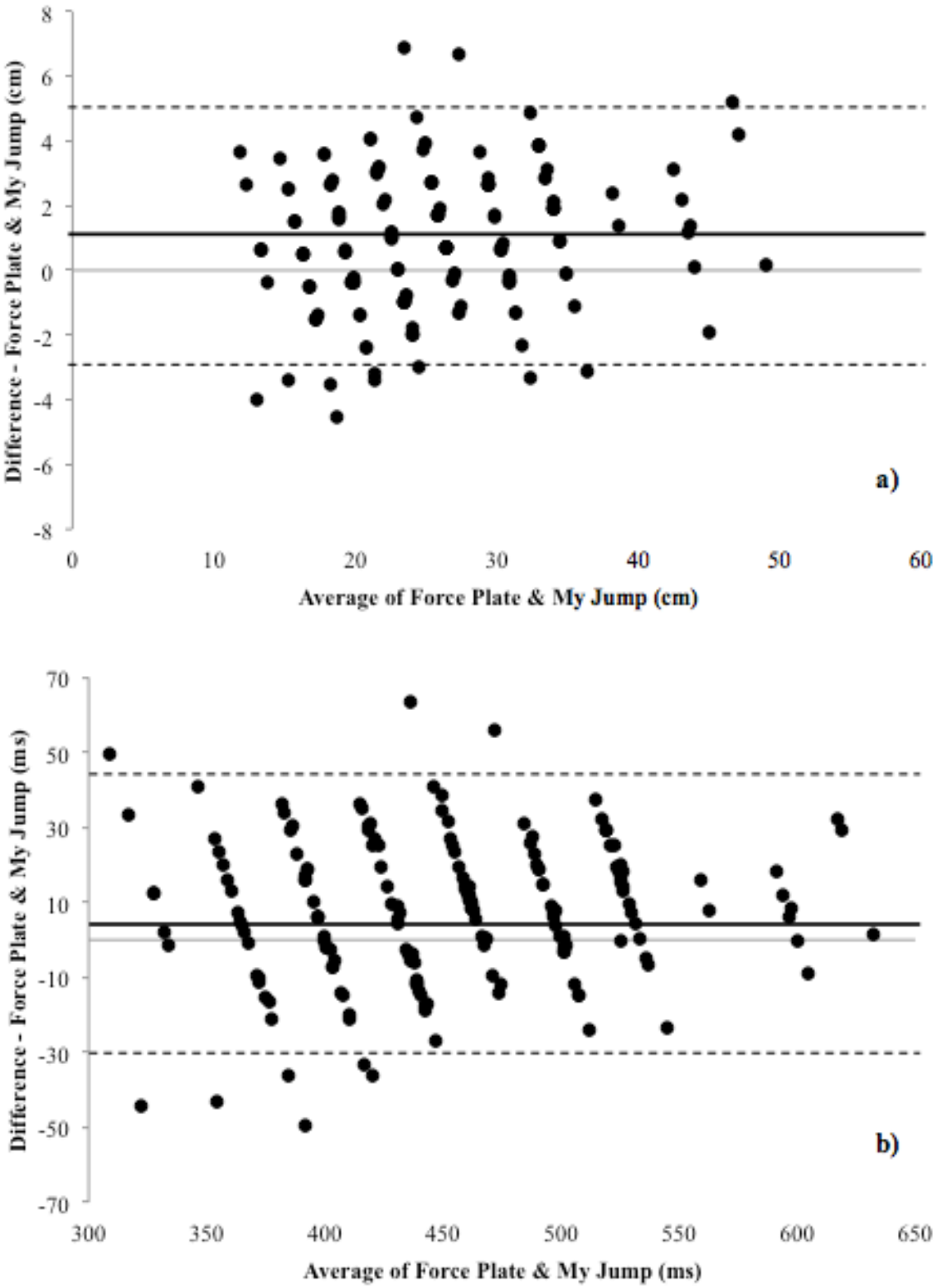

Figure 14 - The level of agreement plots (Bland-Altman) showing 95% limits of agreement (represented as dashed lines) between the force plate and *My Jump* for a) Jump height (cm) and; b) Flight time (ms). Solid black line represents the mean bias between methods.

Table 22 - Comparison of the force plates and *My Jump* app for jump height (cm) and flight time (ms), showing the mean bias, the range of mean difference, typical error of estimate (TEE - raw and %) and the Pearson's-moment correlation (*r*) between the two methods. 2SD = two standard deviations. 90% CI = 90% confidence interval.

	Force plates (Mean ± SD)	*My Jump* (Mean ± SD)	Mean bias raw (Mean ± SD)	Range of mean difference (±2SD)	TEE* (raw) (90% CI)	TEE* (%) (90% CI)	Correlation (*r*)
Jump Height (cm)	25.1 ± 7.5	25.9 ± 7.9	0.9 ± 0.2	-3.2 to 5.0	2.0 (1.8 – 2.2)	9.7 (8.9 – 10.7)	0.96 (0.96 – 0.97)
Flight Time (ms)	448 ± 67	455 ± 69	8 ± 5	-30 to 45	19 (17 – 20)	4.6 (4.3 – 5.1)	0.96 (0.95 – 0.97)

Table 23 - Inter-scorer reliability when using the *My Jump* device to calculate jump height. Means and standard deviations for both scorers are shown alongside absolute typical error of estimate (TEE), coefficient of variation (CV%) and intra-class correlation coefficients (ICC) for the comparison between scorers. Data shown as means ± SD unless stated otherwise. 90% CI = 90% confidence interval.

Scorer 1 Jump Height (cm)	Scorer 2 Jump Height (cm)	TEE (cm) (90% CI)	CV% (90% CI)	ICC (90% CI)
27.5 ± 7.6	26.2 ± 7.5	1.4 (1.2 – 1.7)	5.8 (4.9 – 7.0)	0.97 (0.95 – 0.98)

Discussion

The findings from the current study would suggest that *My Jump* is a valid measurement tool when compared to the 'gold-standard' force plate. This was identified by a low mean bias (0.9 cm) and typical error of estimate (2.0 cm) and an *almost perfect* correlation (r = 0.96) when the two methods were compared (Table 22). This is the first independent study to assess *My Jump* and is in agreement with previous studies from the designers (Balsalobre-Fernández et al., 2015; Gallardo-Fuentes et al., 2016), who descibed similar levels of intra-class correlation coefficients (0.97-0.99), Pearson correlations (r = 0.97-0.99) and mean differences (0.2-1.1 cm) using similar methods to the current study. *My Jump* also resulted in very small differences (TEE = 2.4 cm) in jump height between researchers scoring the same video footage, with no previous experience using the application (Table 23), indicating high levels of inter-scorer reliability. Future researchers and practitioners using the *MyJump* application should ensure that they are using a high speed camera, such as the one used in the current study (240 Hz), as cameras with lower frame-rate and resolution may significantly reduce the accuracy of scoring the jumps. The authors would also suggest that the jumps are performed in adequate lighting conditions and at a maximum distance of 1.5m from the front of the jumper. We conclude that the *My Jump* application is a cost-effective and easy-to-use alternative for measuring vertical jump performance in athletes when using an iPhone 6s.