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Sleep and Performance in Elite Level Athletes

by

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A Doctoral Thesis

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Abstract

There is a widespread belief among elite level athletes and their coaches that adequate sleep is pre-requisite for those seeking to achieve optimum performance. Despite the prevalence of this belief, combined with the common occurrence of sleep complaints among athletes, there has been surprisingly little empirical investigation of sleep in this population; the vast majority of sleep research takes place in 'normal' populations, and employs methods of sleep disturbance that are not relevant to elite level athletes. When athletes have been studied, investigations thus far have failed to measure sleep objectively during the competitive season, and have relied on subjective and retrospective self-report.

The aim of this thesis has been to examine the prevalence of sleep disturbance among elite level athletes, and to investigate the impact that sleep can have on subsequent performance both in training for competition and in competition itself. The impact that training and competing in elite level sport could have on sleep was also investigated, as were a number of other factors related to elite level competition.

A total of 68 elite level athletes, both male and female, from 3 different sports (football, basketball, swimming), volunteered to have their sleep measured by wrist actigraphy for a period of at least 2 weeks. Twenty-seven age-matched sedentary participants were similarly recruited to act as a control group. Thirty-three professional football players, playing in either an England and Wales Premiership or

Championship football club continued to have their sleep measured by wrist actigraphy for a period of eight weeks of the regular competitive season, during which their on-pitch performance was measured by means of the ProZone® player tracking system, and their performance in training was measured by the Catapult X3® GPS system. Both measures are widely used currently to measure performance in professional football, ensuring that performance was measured as it occurred naturally instead of in a contrived setting. Wrist actigraphy was similarly chosen since it allows for long term objective measurement of sleep.

In agreement with anecdotal reports and previous research, evidence of a significant level of sleep disturbance was found among all the types of elite athletes studied. A number of stressors associated with elite competition also demonstrated a significant impact on sleep, particularly to sleep timing following matches, and more generally as a consequence of physical activity during evening matches. Sleep did not have a statistically significant impact on subsequent performance during matches, although, given the narrow margins between success and failure involved in competing at such a high level, the size of the effect in evidence may still have important implications for athletes and coaches. Sleep also demonstrated a significant impact on performance during training.

The evidence of significant sleep disturbance has serious implications for elite level athletes; on its own the level of sleep disturbance has a number of potentially adverse consequences, such as increased risk of infection and illness, compromised metabolism, and sub-optimal recovery from training, potentially serious factors for those training for optimal performance. In addition, the consequences that poor sleep has on training could hamper efforts to prepare properly for elite athletic competition, as well as having a marginal impact on performance itself.

Dedication

I would like to dedicate this thesis to my parents,
Who have never stopped believing in me.

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List of Abbreviations

CPAP	Continuous Positive Airway Pressure
CSA	Central Sleep Apnoea
EEG	Electroencephalogram
GPS	Global Positioning System
HI	High Intensity
nREM	non-Rapid Eye Movement
OSA	Obstructive Sleep Apnoea
PET	Positron Emission Tomography
PFC	Pre-Frontal Cortex
PSD	Partial Sleep Deprivation
REM	Rapid Eye Movement
RPE	Rating of Perceived Exertion
SD	Standard Deviation
SE	Sleep Efficiency
SOL	Sleep Onset Latency
SWS	Slow Wave Sleep
TSD	Total Sleep Deprivation
TST	Total Sleep Time
VO _{2max}	Maximal Oxygen Uptake
WASO	Wakefulness After Sleep Onset

List of Terms

Light intensity exercise	Exercise below an intensity requiring 40% VO_{2max} , such as slow walking.
Medium intensity exercise	Exercise at an intensity requiring ~60% VO_{2max} , such as cycling or brisk walking.
High intensity exercise	Exercise at an intensity requiring ~80% VO_{2max} or higher, such as running. Not to be confused with high intensity activity (below).
High Intensity Activity	Specific speed of movement as defined by the ProZone® player tracking system. Defined as movement at a speed greater than 19.8 km/h.
Injury time	Extra time added to the end of each half of a football match at the discretion of the match referee, to compensate for time spent attending to injured players.

Circadian rhythm	An endogenous biological system which displays a regular oscillation of about 24 hours.
Jet-lag	Desynchrony of the body's circadian rhythms relative to external time cues, due to rapid trans-meridian travel.
Zeitgeber	External time cue which contributes to the entrainment of a circadian rhythm. Translation from German meaning 'time giver.'
Sleep deprivation	A reduction in the time during which sleep is permitted, such that the normal length of sleep is either substantially or completely curtailed.
Sleep fragmentation	Sleep that is characterised by frequent arousals, such as due to a medical disorder like sleep apnoea.

Chapter 1

Literature Review

1.1 - Prelude to Thesis

The notion that obtaining adequate sleep is an important consideration for athletes aiming to achieve optimal performance is often thought to be axiomatic, and is supported by a great deal of anecdotal evidence. A number of athletes competing at the very highest levels of sport such as the Olympic Games have suggested in interviews that they felt they “couldn’t close an eye during the night” and that they were “still tired in the morning” (Erlacher, Ehrlenspiel, Adegbesan & El-Din, 2011). Many athletes and coaches report the belief that sufficient sleep is pre-requisite for achieving their best performance, and experience feelings of anxiety or uneasiness if they do not feel that have had enough sleep before competitions (Atkinson, Buckley, Edwards, Reilly & Waterhouse, 2001; Savis, 1994). While a great deal of research effort has been applied to investigating the impact that nutrition, physiology, biomechanics, equipment and psychology can have on elite athletic endeavour, and while many professional and national Olympic teams will employ dedicated support staff from these disciplines (Reilly, Morris & Whyte, 2009; Thatcher, Thatcher, Portas & Hood, 2009), there has been relatively little application of sleep research to the elite athletic context, despite its apparent importance.

A recent, large scale epidemiological investigation into the sleep complaints of elite level athletes conducted by Erlacher et al. (2011) serves to highlight the widespread nature of the issue, with two thirds of 632 athletes reporting that they have experienced poor sleep before competitions. While most athletes (57%) felt that their disturbed sleep did not have any impact on their subsequent performance, many reported negative effects such as bad mood and increased daytime sleepiness,

with 13% reporting a reduction in their level of performance the subsequent day. The authors also highlighted that few athletes had any effective strategies to help them sleep when they were having difficulty. They also highlight that despite the apparent need for research into sleep in athletes, most existing studies do not include athletic performance as an outcome measure of disturbed sleep, and that there is a need for objective measurement of sleep in this population, due to the oft found discrepancy between objective measures of sleep, such as polysomnography and actigraphy, and subjective reports.

The aim of the current thesis is, therefore, to thoroughly and objectively investigate the sleeping behaviours of professional and elite level athletes, in order to properly establish the level of sleep disturbance in this population. In addition, the current work will seek to explore the impact that sleep may have on elite athletes performance, both during competitive events and during training. This exploration will focus not only on competitive performance, but also on their training and the implications for athletes' general well-being, since the importance of proper training and maintaining a good level of general health are unarguably a vital component in achieving peak performance.

1.2 – Function of Sleep

'Sleep' is not simply a single easily definable state, but is in fact "a complex amalgam of physiologic and behavioural process." (Carskadon & Dement, 2005, p. 13). However, according to the quoted authors it can be (very) broadly defined according to a simple behavioural definition as a 'reversible behavioural state of perceptual disengagement from and unresponsiveness to the environment.' It is also commonly accompanied by features such as postural recumbence, behavioural quiescence, closed eyes and dreaming, although in some unusual cases other behaviours can occur, such as sleepwalking, sleeptalking, tooth grinding and a host of other physical activities. While sleep is commonly discussed as a single entity, and most people will immediately recognise it as the activity that they spend approximately one third of their lives doing, it should not strictly be thought of as one end of a dichotomy with wakefulness, but should instead be considered as part of a continuum of consciousness. It is also important to note that, despite its pervasiveness, answering the simple question 'why we sleep' remains a stubbornly difficult question to answer with any degree of confidence, and has in fact been regarded by some (e.g. Krueger & Obál, 2002) as 'one of the most important unanswered questions in biology.'

Historically, one of the greatest difficulties facing those that seek to investigate sleep in any context, is that there has been (and in many ways continues to be) a great deal of debate regarding the exact function of sleep. Sleep as a behaviour is widely observed throughout the natural world, and even many species of plants display a daily cycle of rhythm, furling their leaves at night and unfurling them during the day (even in the absence of daylight; Dement, 2005). The widespread nature of

sleep highly suggests that it must serve some sort of useful evolutionary function- during sleep, animals are less aware of their surroundings and less able to respond immediately to danger, a situation that one would normally consider as being highly disadvantageous to a creature's survivability, yet sleep remains. However, this key defining feature of sleep (certainly as it applies to non-aquatic mammals) also serves to make investigating sleep as a behaviour most difficult. Sleep is unlike the vast majority of other behaviours in that, while sleeping, organisms display no overt behaviour which could indicate an intent or purpose to their action (Lima & Rattenborg, 2007). Consequently, one of the principle methods used to investigate sleep has been to deprive both humans and animals of sleep, and to examine the consequences on whatever biological or psychological construct that is of interest to the researcher.

Allan Rechtschaffen conducted a large amount of the early research into the function of sleep using the deprivation paradigm to investigate the physiological consequences of extended periods without any sleep in animals. Perhaps one of the most widely known of these studies is the study of total sleep deprivation in rats (Rechtschaffen, Gilliland, Bergmann & Winter, 1983) which aimed to control for the fact that, while human participants can be asked to remain awake voluntarily, animals must be coerced into extended periods of wakefulness, which also tends to place a great deal of stress on the creature. Rechtschaffen et al. employed a design in which one rat was subject to total sleep deprivation, by means of the circular disk that it was placed upon rotating above a water pan whenever the rat fell asleep, which would compel the animal to remain awake in order to avoid getting wet. A yoked control animal was kept in an adjacent cage above a water pan, but would only be compelled to move when the experimental creature fell asleep, and was

therefore able to largely get as much as sleep as it desired. During the course of the study, the experimental animals lost about 92% of their sleep, while the controls only lost about 26%. The consequences of this drastic reduction in sleep were severe. Both the control and experimental animals ate much more food during the course of the procedure, but still lost weight. This effect was, however, far more marked in the experimental animals, and the investigators estimated that the total energy intake of the experimental animals increased by 2.5 times, compared to 1.7 in the control animals, which largely seemed to be to fuel a large rise in metabolic rate. While all of the control animals survived the experience, eventually all of the experimental animals died after (at most) 21 days. The authors also stress that while significant, the weight loss seemed unlikely to be the cause of death: experimental animals weighed about 80% of their starting weight, and they demonstrated that non-sleep deprived rats could survive after losing 70% of their bodyweight. Examinations were carried out on both experimental and control animals and, surprisingly, there were no identifiable differences between the brain, liver, spleen, lungs and stomach in the two animals (the pathologists conducting the examinations were blind to the experimental condition, and were unable to identify which group any specific animal belonged to). While the precise cause of death was not entirely certain, Rechtschaffen et al. suggested that the prolonged sleep deprivation resulted in a decreased ability of the experimental animals to regulate their body heat. During their last days, a marked decrease in the experimental animals' body temperature was noted, which was not replicated in the control animals. The authors suggested (and others have since agreed e.g. Horne, 1988a) that, soon after the onset of sleep deprivation, the animals quickly began to lose body heat, which they tried to compensate for by a voracious increase in food intake, which proved to be inadequate (since they also

lost a significant portion of their initial bodyweight). Initially, the use of existing energy stores, combined with the increased intake, is sufficient to meet the increased metabolic demands apparently placed on the creature. After approximately two weeks there follows a deterioration and heat loss begins to outstrip heat production, at which point body temperature starts to fall, and the animal dies a few days afterwards.

With the results of these early studies, and much similar evidence since then, the function of sleep in small mammals has been suggested to be as an energy conserver (Siegal, 2005), or as Horne (2006) refers to it “the great immobiliser.” (p. 7). Due to their small size, rodents and other small mammals lose a large amount of body heat through their skin, since their surface area is much larger relative to their body size (compared to larger mammals like humans). Consequently, while they are active, small mammals must eat continuously in order to maintain their body heat. Sleep therefore acts to reduce the metabolic demand and offers a rare opportunity for physical rest. In humans and other large animals however, this biological need that every waking moment be spent maintaining a sufficient food intake in order to maintain a stable body temperature does not apply. Due to the larger size of our bodies (and therefore reduced relative surface area through which heat can escape), humans are able to survive up to several days without eating, whilst smaller rodents will survive only a day or so. Because of this, there is no time for rodents to just sit and relax, although it is noteworthy that they could not do so even if there were no need for them to be constantly seeking food, since they do not have a highly developed enough brain. Horne (2006) speculates that the development of the more complex parts of the brains of larger mammals which allow this ability to exist in a

state of 'relaxed wakefulness' could have been partly facilitated by not needing to spend such an inordinate amount of their waking hours looking for and eating food.

This ability for us to relax during wakefulness negates the idea of sleep as an energy conserver or immobiliser. Sleep no longer provides us with significant energy savings compared to being physically relaxed but still awake, yet still sleep remains. The brain restitution hypothesis, originally proposed by Jim Horne (Horne, 1980; Horne, 2006; Horne & Minard, 1985), proposes that the same advancement of the brain (specifically the cortex) that allows humans and other larger mammals to maintain a state of relaxed wakefulness, places such a demand on the brain that it cannot truly disengage from the environment during wakefulness, even when it is seemingly not involved in any active way, and can place an even greater level of 'strain' on the cortex than apparently more thoughtful activities such as reading, since it requires the attention of a larger proportion of the cortex, "watching, listening to, and otherwise sensing something in the wider environment" (Horne, 2006, p. 16) while more directed activities only 'strain' relatively small areas of the cortex. Consequently, the only time our cortex can recover is during sleep, which is suggested as the reason that sleep mostly effects our cortex and cognitive faculties, whilst having little or no significant impact on our physical abilities (which will be discussed in much greater detail later). A restorative function of sleep is also indicated by the fact that the most advanced region of the brain, the pre-frontal cortex (PFC), which is by far the most active part of the brain during wakefulness, also displays the greatest decrease in activity during sleep (Anderson, 2003).

Even so, the question of the function of sleep is further complicated by the fact that, as has been mentioned previously, sleep is not a single homogenous state, and actually consists of a number of distinct stages, which were initially defined and

continue to be investigated by measuring the electrical activity of the cortex (this being the region of the brain that demonstrates the most marked response to sleep) by the use of electrodes placed on the scalp- the electroencephalogram (EEG). The original identification and classification of these various stages of sleep was conducted by Rechtschaffen and Kales (1968), and continues to be the standard criteria used to measure sleep using the EEG.

According to these criteria, sleep can be broadly divided into two distinct states; rapid eye movement (REM) sleep and non-rapid eye movement sleep (nREM). REM sleep is characterised by EEG activation (to a level which is often almost indistinguishable from the electrical activity seen during a waking EEG), lack of muscle tone and bursts of episodic bursts of rapid eye movements under the closed eyelids (Carskadon & Dement, 2005). Although it was not clear just how active the cortex was during REM sleep until the use of the EEG, this distinct state of sleep was first identified as early as 1953 by Aserinsky and Kleitman when they noted the rapid movement of sleepers' eyes, suggesting that sleep was not simply a unitary state of inactivity, but that bursts of activity of some description were occurring at regular intervals. It was also at this time that the connection between REM sleep and dreaming was first made. Aserinsky and Kleitman (1953; 1955) noted that participants roused during REM sleep were far more likely to report that they had been dreaming than those roused during nREM sleep.

In contrast, nREM sleep is characterised by a reduction in electrical output from the cortex relative to waking, and a reduction, but not a total absence, of muscle tone in the voluntary muscles. nREM is conventionally divided into four stages, which draw a rough parallel with depth of sleep on a continuum, with stage 1 sleep being the stage that is closest to wakefulness and has a much lower threshold

for arousal, whilst stage four sleep is marked by a significant reduction in cortical activity, with a concomitantly higher arousal threshold, and arousal from this stage is often accompanied with feelings of grogginess. While these sleep stages are commonly divided into discrete categories, it is generally accepted that they represent a continuous scale of sleep depth rather than a series of distinct non-overlapping stages. For example, K complexes ('negative sharp waves on an EEG, followed immediately by a slower positive component'; Carskadon & Rechtschaffen, 2005), which are one of the defining features of stage two sleep, but may also be present during stage three sleep (Susmakova, 2004). With this in mind, the stages of sleep that have been the subject of most attention in discussions of the specific functions served by various functions of sleep are REM and the combination of stages three and four (stages 3 and 4 are commonly combined and referred to collectively as deep sleep or slow wave sleep (SWS), since they are defined by a significant decrease in the frequency of the electrical activity of the cortex).

REM sleep has historically been particularly linked with memory consolidation, perhaps due in some part to the fact that the brain is unusually active during this phase of sleep, and the frequency with which the content of dreams is reported as having some sort of relevance with a person's waking experience during the preceding day or two. Studies utilizing positron emission tomography (PET) to investigate neural activation during sleep following a procedural learning task in which participants must respond to a sequence of flashing lights which contains an embedded pattern which is gradually learned, have demonstrated that the specific regions of the brain that are most highly activated during the learning of the task, are reactivated during REM sleep after the task (Maquet, Laureys, Peigneux, Fuchs, Petiau, Phillips et al. 2000). However, such reactivation is not unique to REM sleep,

and have also been noted in SWS (Huber, Ghilardi Massimini & Tononi, 2004) and memory consolidation has been demonstrated as being dependent on both stage two sleep and SWS, in addition to REM sleep (Plihal & Born, 1997; Clemens, Fabo & Halasz, 2005; Schabus, Gruber, Parapatics, Sauter, Klösch, Anderer et al. 2004; Walker, Brakefield, Morgan, Hobson & Stickgold, 2002). In contrast, more recent investigations have cast much doubt on the supposed role of REM sleep serving a crucial role in memory consolidation (for a review see Siegal, 2001), and there is compelling evidence to suggest that REM serves a much simpler function.

The first key piece of evidence for this argument is based on the timing and apparent relative 'importance' of different stages of sleep. In healthy young adults, the vast majority of sleep is made up of stage two sleep (45-55% of sleep), SWS accounts for approximately 15-25% of sleep, REM sleep 20-25% of sleep, with the remaining ~5% being stage one sleep (Carskadon & Dement, 2005). This breakdown of the various sleep stages is, however, not spread evenly throughout the typical 7-8 hours of sleep, with SWS predominating during the first third of the night, and REM sleep predominating more during the final third of sleep. A number of authors (e.g. Anderson, 2003; Horne, 2006) have argued that this suggests that there is an immediate need for SWS since it is satisfied as soon as possible. When one compares the sleep architecture of short sleepers (both in habitually short sleepers; Webb & Agnew, 1971; and by experimentally reducing sleep time; Johnson & MacLeod, 1973), while the reduction in total sleep time from 7.5 hours to 4 hours significantly reduces the amount of both REM sleep and stage two sleep, the absolute amount of SWS remains largely unchanged. Further evidence suggesting the specific need for SWS comes from studies investigating the relative levels of 'rebound' following TSD. Horne (1985), found that after a single night's sleep

deprivation, only about 30% of the lost sleep time is recovered. However, only about half the absolute amount of REM sleep is recovered during this recovery sleep, while nearly all of the lost SWS is recovered, further suggesting that SWS is the vital component of sleep. It is also important to note that REM sleep can be significantly suppressed by various drugs, particularly anti-depressant drugs (both tri-cyclic and selective serotonin re-uptake inhibitors; SSRI's) which are taken by millions of patients worldwide, and there appears to be no evidence to suggest a negative impact of this often long term absence of REM sleep (Horne, 2006). While there is a small rebound in REM sleep following the cessation of antidepressant treatment, it only represents a small fraction of the total amount of REM sleep that has been lost.

Another important clue as to the function of REM sleep comes from the changing proportion of time that humans spend in REM sleep throughout the lifespan (and even before birth). While in the uterus, the human foetus experiences REM sleep to a significant degree (as much as 8-10 hours per day), but the predominance of REM sleep as a proportion of overall sleep diminishes drastically during the early years of life, dropping to around five hours per day after the first year of life, and continuing to decline throughout life (albeit the rate of decline slows after adolescence). This observation also stands against the idea of a role for REM sleep in the consolidation of memories, since right at the moment when a new born babies brain is being bombarded by novel stimuli and learning, REM sleep shows a marked decline.

In light of this weight of evidence, it is instead proposed that REM sleep serves as a source of 'pseudo-stimulation' to the developing brain while in the uterus- stimulation that the developing brain would otherwise be deprived in the dark environment. After birth, the environment provides ample stimulation to the brain,

hence REM sleep declines. Horne (2006) argues that REM sleep remains to serve a similar function during adulthood- chiefly as a means keeping the brain stimulated during periods of sleep in such as a way as to prevent the individual from waking, which would serve to fragment and break up the meaningful SWS that is the primary purpose of sleep. Horne argues that rather than thinking of the appearance of REM sleep as the build-up of some kind of 'REM sleep pressure', it actually exists due to the periodic cessation of nREM sleep, which perhaps, cannot be sustained for periods longer than the typical 90-100 minute length of the normal human sleep cycle. Rather than having to wake up every time nREM sleep ceases, Horne proposes that REM sleep serves as a 'fall-back state', allowing sleep to continue uninterrupted.

1.3 – Impact of Sleep Deprivation

As has been commented previously, the function of sleep is most commonly studied by depriving research participants of sleep for a specified period of time, and then assessing the impact that the lack of sleep has on a given domain of functioning or performance. A summary of this research into the consequences of sleep deprivation on the domains that are likely to have a significant impact upon elite level athletes will now be addressed.

1.3.1 – Impact of Sleep Deprivation on Physical Performance

Existing research into the effect that sleep deprivation has tended to employ a 'total sleep deprivation' (TSD) paradigm, using an acute period of extended wakefulness to investigate the deleterious effect it has on simple (usually lab-based) performance measures, such as time to exhaustion at a specific intensity of aerobic exercise or muscular strength. Early studies of this type such as Horne and Pettitt (1984) and Martin (1981) have investigated the impact of 72 hours and 36 hours (respectively) on aerobic performance during a cycling task at 50% of VO_{2max} (Horne & Pettitt, 1984) and during a treadmill running task until exhaustion at 70% of VO_{2max} (Martin, 1981). In both studies it was discovered that there was in fact an overall reduction in physical work rate in both sleep deprivation conditions. There was however, no evidence that this decline in the amount of work that participants did could be accounted for by a decline in the body's capacity to perform that work; physiological responses to exercise such as perspiration, breathing and heart rate were not significantly different following sleep deprivation.

Martin (1981) noted a particularly curious pattern (or lack thereof) in the physical performance of the participants in his study. Concurrent with the overall decrease in time to exhaustion following sleep deprivation, most participants also reported an increased perception of effort on the task following sleep deprivation (the intensity of work was in fact held constant for both trials). Two participants however reported that they perceived the work to be easier following sleep deprivation, while two different participants actually showed an increased performance following sleep deprivation. Martin therefore concluded that since the decline in performance

showed no apparent dependence on physical factors, and the high level of variability in individual participants' performance following sleep deprivation, that the decline in performance was best explained by psychological factors, most importantly motivation.

The importance of proper motivation is further highlighted by Rodgers, Paterson, Cunningham, Noble, Pettigrew, Myles and Taylor (1995), in a study of the impact of 48 hours of continuous sleep deprivation on a variety of physical (and cognitive, which will be addressed shortly) tasks. The aim of the study was particularly aimed towards the military context, so most of the tasks were chosen for being similar to tasks that are common in that situation, such as the number of sandbags carried over a five metre distance during a 30-minute period or the distance walked with a 12 kg rucksack. These military style exercises were performed without any external guidance or encouragement at a pace chosen by the participant. For each of these exercises, the amount of work completed showed a significant decline following sleep deprivation. One task also explicitly required participants to rate the difficulty of the physical work, and to choose for themselves the intensity at which their next bout of exercise would be. Not only did participants again perceive work to be harder following sleep deprivation, when given a chance they also tended to choose an easier level of work. There was one task however where the rate of work was decided for the participants, and they had to adhere to the workload decided for them. This 'forced-pace' exercise failed to demonstrate a significant decline after sleep deprivation. This further adds to the idea that while sleep deprivation does tend to demonstrate a significant deleterious effect on exercise, this is not due to a physiological effect, but is largely due to a decline in the level of participants' motivation. It is also important to note that this pattern has been

replicated in studies employing a partial sleep deprivation (PSD) paradigm rather than TSD. Reilly and Deykin (1983) restricted sleep to only 2.5 hours per day, and found no significant effect on the lung function and capacity to run on a treadmill, even after up to three consecutive days of this significantly reduced sleep.

The lack of an impact of sleep deprivation has also been applied to anaerobic work capacity in addition to aerobic work. Reilly and Deykin (1983) found that one night's partial sleep deprivation (PSD) to 2.5 hours of sleep per day also demonstrated no significant impact on grip strength. In contrast, Reilly and Piercy (1994) found that performance on a more complex and repetitive weightlifting task, requiring the application of proper technique, did decline following PSD, especially after three days of consecutive PSD. This was attributed to the greater complexity of the task compared to a simple grip strength measure, and demonstrated a significant time on task trend, with performance showing a decline as the time on task increased, and participants reported that they experienced difficulty in maintaining their performance on the complex task over time. It could be argued that this is suggestive of the observed performance decrement being due to the psychological decrements associated with sleep deprivation (in this case, the difficulty in maintaining attention on a task while sleepy), rather than being the result of a reduced capacity to perform physical work.

More recent work into the impact of sleep deprivation on anaerobic performance has further highlighted the lack of an impact on physical performance, while suggesting that cognitive factors are responsible for declining performance. Souissi, Sesboüé, Gauthier, Larue & Davenne (2003) employed a TSD paradigm for one night, and again found no adverse physical consequence of sleep deprivation that could account for a drop in performance. Finally, a novel study conducted by

Bambaeichi, Reilly, Cable & Giacomoni (2005) sought to remove cognitive factors entirely, by electrically stimulating the muscles of participants after a single night of PSD consisting of 2.5 hours sleep. Once again no significant impact of this sleep restriction could be demonstrated, which again suggests that the physical capacity to perform work does not appear to suffer following sleep deprivation.

In fact, the existing literature is largely consistent in finding no significant impact of acute sleep deprivation protocols on physical performance, and one is forced to look towards studies involving extreme levels of sleep deprivation before any evidence of performance decrements can be observed. One such study involved the monitoring of players in a charity 5-a-side football match, which aimed to reach 100 hours of continuous play (Reilly & Walsh, 1981). A simple measure of grip strength was measured at regular intervals throughout the match, and demonstrated a deterioration towards the end up the study (which was terminated after 91 hours and 45 minutes), in addition to a general trend towards lower engagement and participation in the match after the second day. While it could be argued that the competitive nature of the activity could act as a source of motivation, in reality the charitable nature of the competition, combined with the reported decrease in engagement with competition on any serious level suggests that this decline was likely to be in line with the previously observed decline in self-paced activity level. This explanation is unlikely to extend to the simplistic measure of grip strength, which we have seen has previously demonstrated a remarkable resistance to shorter periods of sleep restriction.

A similar study reported by Lucas, Anson, Palmer, Hellemans & Cotter (2009), studied the cognitive and physical impact of participation in the 2003 'Southern Traverse Adventure Race' in New Zealand which requires participants to navigate a

411 km course through stages of jogging, trekking, kayaking and mountain biking for approximately 100 hours, during which participants slept for about 90 minutes per day. At the end of the study there was a small but significant overall decrease in performance on a number of physical tasks such as vertical jump height and peak power output. While there is, of course, the rather large confound of the strenuous activity between the baseline and experimental measures, there was never-the-less a large amount of variation in physical performance between participants, with 10 participants actually demonstrating an increase in peak power output after the race, compared to 17 who showed a decrease. This variability again highlights that even extended periods of extreme sleep deprivation do not appear to consistently demonstrate an adverse effect on purely physical measures of performance. Another particularly stark comparison is between the relatively modest impact of extended TSD on physical performance in Reilly and Walsh's (1981) study with the impact that this extended period of wakefulness had on the psychology of participants, which included auditory hallucinations during the second night of continuous waking in two out of ten participants, which extended to both auditory and visual hallucinations in all ten participants by the third night.

The overall conclusion of the existing research seems to demonstrate that while sleep deprivation can have a deleterious effect on performance on physical tasks, this is not due to a reduced capacity to work, but is instead due to psychological factors such as motivation and attention. This presents a significant problem when attempting to apply the findings from these kinds of research studies to the elite athletic context. Compared to a real life athletic performance, in which the participant will have a large personal interest in performing to their very best, lab based measures of simple components of performance of the type reported above

will simply not inspire the same level of motivation and interest in the task. In addition, the level of complexity involved in performing a grip strength or running to exhaustion task pales in comparison to the complex nature of real life athletic competition with all the motivational factors involved. Even studies employing a drill aimed at simulating an aspect of a sport (Cook, Crewther, Kilduff, Drawer & Gaviglio, 2011) do not place a similar level of strain on participants as a “performance”, the outcome of which could have serious consequences for athletes (e.g. financial). It is therefore vital that any attempt to study the relationship between sleep and performance in elite level athletes should employ a performance measure which engenders an equally high level of motivation and interest in the outcome as a real life performance (preferably by measuring athletes’ performance during actual competitions, rather than in contrived laboratory settings).

1.3.2 – Impact of Sleep Deprivation on Cognitive Performance

In comparison to the impact that inadequate sleep has on physical performance, the importance of sleep to cognitive and psychological factors is very well established. As discussed earlier, the restitution of the brain appears to be perhaps the most important function of sleep itself. It is however important to note that the brain cannot be treated as a single entity, but can be divided into numerous different areas and regions, and different areas of the brain contribute to different components of cognitive functioning. Brain imaging studies (e.g. Braun, Baulkin, Wesenten, Carson, Varga, Baldwin et al. 1997) have demonstrated that the area of the brain most active during the day is the pre-frontal cortex (PFC). Given that SWS

in particular is thought to represent a state of recovery for the cortex, it is perhaps not surprising that it is also this area of the brain that shows the greatest decrease in activity during SWS (Maquet, 1999, 2000; Hofle, Paus, Reutens, Fiest, Gotman, Evans et al. 1997). It is also a reasonably logical step to suspect that sleep deprivation will have a disproportionately large effect on aspects of cognitive performance that depend on the PFC (Anderson, 2003).

The PFC is involved in a large number of functions, the exact number of which is still unknown (Anderson, 2003), but seems to largely be responsible for the 'higher cognitive functions' such as the maintenance of wakefulness (Fuster, 1989); decision making (Harrison & Horne, 2000); divergent or flexible thinking (Harrison & Horne, 1999), sustained attention (Kamder, Kaplan, Kezirian & Dement, 2004; May & Hasher, 1998) and planning, maintenance and direction of behaviours (Horne, 1993). While studies investigating the function of various brain regions often come from studying the impact of lesions caused by injury, tumours or surgery, performance decrements in higher cognitive functions are also evident in cases of both acute total sleep deprivation and longer-term partial sleep deprivation. It is particularly crucial to consider the effect that sleep deprivation has on mood and motivation, given that they seem to be at least partly responsible for the detrimental impact that sleep restriction can have on physical performance. It is perhaps not surprising that a person's mood would decline in situations of restricted sleep, and indeed this appears to be the case as has been demonstrated a number of times using the Profile of Mood States questionnaire (POMS; McNair et al., 1971), together with a concurrent drop in motivation (Dinges, Pack, Williams, Gillen, Powell, Ott et al. 1997; Johnson & MacLeod, 1973, Durmer & Dinges, 2005).

As is the case with physical performance, the influence of motivation is as crucial to understanding the impact of sleep deprivation on cognitive performance. The negative impact of prolonged wakefulness on cognitive performance is not a simple matter a linear decrease in performance as wakefulness continues, but it has long been demonstrated that even in cases of 114 hours of continuous wakefulness, sleep deprived individuals are still able to transiently perform cognitive tasks as proficiently as they were able to compared to baseline (Kleitman, 1923; Lee & Kleitman, 1923). Rather than a general decline, under conditions of sleep deprivation cognitive performance tends to demonstrate an 'instability' in performance, where at times the individual is able to resist the effect of the increased sleepiness and perform at or near their best, and at other times the drive for sleep results in a very large reduction in performance. Very often this also takes the form of a 'lapse' in which the individual apparently succumbs to the need for sleep and fails to perform at all (errors of omission), as well as instances in which people respond incorrectly (errors of commission). Doran, van Dongen and Dinges (2001) proposed the 'state instability hypothesis' as an explanation for this variation in performance during sleep deprivation. They suggest wake-state instability occurs when the mechanisms responsible for the initiation of sleep repeatedly interfere with wakefulness, which results in the increasingly variable pattern of performance (depending on compensatory mechanisms; Dorrian, Rogers & Dinges, 2005; Rogers, Dorrian & Dinges, 2003). When properly motivated, it is possible for the sleep-deprived individual to successfully compensate for the effects of prolonged wakefulness for a time (Horne & Pettitt, 1984), ultimately it becomes impossible to prevent intrusions of sleep into wakefulness, to the extent that there have been reports of otherwise

healthy people falling asleep while walking under conditions of sleep deprivation (Nansen, 1999).

One of the problems associated with studying the impact of sleep deprivation on cognitive performance, as noted by the state instability hypothesis, is that the high level of variability in performance during periods of sleep deprivation (which are evident inter-individually due to different people's ability to compensate for sleep deprivation, as well as intra-individually) can mask the impact of sleep deprivation when performance measures are used that are not sufficiently sensitive. As a consequence, Durmer and Dinges (2005) highlight that much of the research that has been conducted has utilised measures that rely on sustained attention and vigilance, since they are PFC domains that appear to most sensitive to sleep loss. The psychomotor vigilance task (PVT; Dinges & Powell, 1985) requires continuous attention in order to respond to a randomly occurring stimulus. There are two main types of errors that occur on this task during prolonged wakefulness. Initially there is a rise in the number of errors of commission, in which participants incorrectly make a response in the absence of the stimulus. Dorian et al. (2005) proposes that these errors represent unsuccessful attempts to compensate for the reduction in performance that participants become aware of when they feel sleepy. As the length of wakefulness increases, an increase in errors of omission are observed, in which participants experience a 'microsleep' intrusion into wakefulness, and fail to respond to the presence of the stimulus at all.

In addition to the impact of sleep deprivation on 'simple' attentional tasks, it can also have an impact upon more complex cognitive tasks, particularly where they require the use of multiple skills in combination. Harrison and Horne (2000), in a review of the literature highlight that while performance on some types of

neurocognitive tasks such as logic-based tasks are relatively robust when sleep deprived, tasks that require multitasking or flexible thinking are affected. For instance when tasks require participants to identify and update existing strategies when presented with new information or to think laterally, a strong effect of sleep deprivation is observed. Durmer and Dinges (2005) suggest that, once again, this can be explained as being a consequence of the inordinate effect that sleep deprivation has on the PFC. In addition to the higher order cognitive functions that have been discussed previously, another of the PFC's primary functions is the 'central executive' which is responsible for 'the ability to plan and co-ordinate wilful action in the face of alternatives...' (Jones & Harrison, 2001), and 'working memory' which is required to hold and manipulate information. Deficits in these two systems have been demonstrated to result in a deleterious effect on tasks in the presence of changing or distracting data (Wimmer, Hoffmann, Bonato & Moffitt, 1992; Horne, 1988b; Blagrove, Alexander & Horne, 1995), remaining focused on relevant cues (Blagrove, Alexander & Horne, 1995; Harrison & Horne, 1999; Blagrove, 1996), thinking flexibly (Harrison & Horne, 1999; May & Kline, 1987), having insight into the reasons for poor performance (Harrison & Horne, 2000; Dinges & Kribbs, 1991), and modifying strategies based on new information (Banderet, Stokes, Francesconi, Kowal & Naitoh, 1981; Harrison & Horne, 1999; Herscovitch, Stuss & Broughton, 1980).

The reason that it is so important to consider the impact that sleep deprivation has on cognitive functions is that, while it may be tempting to think of sports performance as mostly dependent on physical exertion, it is vital not to underestimate the heavy cognitive loads that high level sports performance demands of the athlete (Reilly & Edwards, 2007). Even relatively 'simple' sports such as

running and track cycling still require the mastery of complex physical techniques, in addition to a strong awareness of one's current physiological state and the tactical situation of the race. Track cycling in particular provides a very good example of this. While events such as the team pursuit and sprint require an 'all-out' level of physical exertion, there is still the requirement for athletes to be able to pace themselves adequately and remain an efficient part of the team, riding in very close proximity to others at very high speeds. In the sprint, even a momentary lapse can lead to an accident and the athlete suffering, both in terms of their performance outcomes and in many cases, physical injury. Where more complex large team invasion games such as football, basketball and rugby are concerned, the level of cognitive demand is increased further still, as athletes must be continuously assessing not only their own immediate situation, but also the position and movements of both team mates and opposing players, while trying to achieve their own tactical and performance outcomes. Even the simple act of passing in football requires a great degree of spatial awareness, in addition to an appreciation of threats to both themselves and their intended target from nearby opposing players. Attention, concentration and reaction time are also heavily depended upon, both in striking games (e.g. cricket, baseball) and racquet games (e.g. tennis, badminton). Such sports often require extraordinary reaction times (e.g. a tennis serve hit at 130 mph will take approximately 0.45 seconds to travel the 23.74 metres of a tennis court (International Tennis Federation, 2011), and a 90 mph cricket fast bowl will take approximately 0.5 seconds to travel the 20.12 metres between the stumps (English Cricket Board, 2011). According to Moran (2008) there has been a recent surge in the number of studies investigating the role of cognitive processes in sports performance, in addition to the established research concerning factors like training and nutrition.

Existing research clearly demonstrates the degree to which sleep can influence cognitive performance, but there is a need to examine the implications of current research for the athletic context.

1.3.3 – Sleep and General Health and Well-being

The potential effect that sleep can have upon general health has been the subject of much discussion in the general sleep literature, and any effect that it could have would be of high importance to athletes, whose livelihood depends on maintaining peak physical condition for long periods of time. It is also at this point that the literature takes an unusual departure from the usual sleep-deprivation paradigm, although the reasons for this departure are actually quite informative. While even small amounts of extended wakefulness show such strong effects on cognitive performance, the risk to participants' general health as indicated by these studies is negligible. The best example showing the lack of a negative impact of short-term sleep loss on general health is the widely reported (Horne, 1988a; Gulevich, Dement & Johnson, 1966; Ross, 1965; Johnson, Slye & Dement, 1965) case of Randy Gardner who successfully stayed awake for 11 days (264 hours) continuously in an attempt to beat that world record (which Randy Gardner still holds to this day).

During this attempt, while his cognitive faculties demonstrated the familiar level of decline (including mood changes, speech difficulty, memory impairment and blurred vision), there were no indications that his health was in any danger. During the final twelve hours of the record attempt, a full medical examination was carried

out- blood pressure and pulse were both found to be within normal limits, and his core body temperature showed a slight decline of 1°C compared to norms. The only indications of any adverse health consequences were a slight heart murmur and some congestion of the airways. Blood and urine tests also showed no indications of illness. Following the end of the successful record attempt, recovery was remarkably rapid, considering the length of sleep deprivation and, after three nights of longer than normal sleep, Randy's level of functioning had largely returned to normal, and nocturnal sleep length returned to more usual levels by the fourth night. A battery of neurological tests were carried out 10 days after the attempt (having first been conducted during the final 12 hours), demonstrating that neurological functioning had returned to normal and was generally unremarkable.

Given the lack of any serious negative health consequences of acute sleep deprivation, the focus for research into a relationship between sleep and health has been focused on investigating the consequences of insufficient sleep for long periods of time. Discussions surrounding the idea of 'chronic sleep debt' are hardly unusual. For example a number of large-scale studies have demonstrated that a sizeable minority (15-20%) of otherwise healthy American adults report sleeping less than 6.5 hours per night (Kripke, Garfinkel, Wingard, Klaube & Marler, 2002; National Sleep Foundation, 2002). One of the key difficulties when discussing the idea of chronic sleep debt is that there is as yet no clear consensus on what constitutes the minimum quantity of sleep that is required. One perspective is the notion of 'basal sleep need' which is based on the habitual duration of sleep, which appears to be between seven and eight hours in healthy adults (Dement & Vaughan, 1999; Wehr, Moul, Barbato, Giesen, Seidal, Barker & Bender, 1993; Van Dongen, Maislin, Mullington & Dinges, 2003). In contrast, Horne (1985, 1988a) proposes the core vs

optional sleep hypothesis, based on the fact that sleep architecture is not uniform, with the largest portion of SWS, responsible for “repairing the effects of waking wear and tear on the cerebrum” (Horne, 1988a, p.57) occurring during the first 4-5 hours of sleep (referred to as ‘core sleep’) while the later hours of sleep served to “fill the tedious hours of darkness until sunrise” (p. 57). This hypothesis was supported by evidence suggesting that neurological functions are primarily restored during SWS (Folkard & Akerstedt, 1992; Akerstedt & Folkard, 1997). Other research has (e.g. Wehr, Moul, Barbato, Giesen, Seidel, Barker & Bender, 1993; Van Dongen, Maislin, Mullington & Dinges, 2003), however, presented a difficulty, finding that restriction to 6 hours sleep per night, which the core/optional hypothesis suggests should not demonstrate adverse consequences, produces cognitive performance declines compared to baseline 8 hours sleep per night.

The key determining factor in people’s ability to adapt to chronic reductions in sleep length appears to depend on the abruptness of the curtailment. Experimental studies have demonstrated that when the reduction in sleep length is less severe (as in Horne & Wilkinson, 1985; Johnson & MacLeod, 1973) the resulting consequences were also less severe and more tolerable. In addition, longer-term investigations have suggested that while there may be an initial period of increased sleepiness when sleep is restricted to six or even four hours of sleep, adaptation occurs which prevents further decline in neurocognitive functions or allows them to return to baseline levels (Friedman, Globus, Huntley, Mullaney, Naitoh & Johnson, 1977; Belenky, Wesensten, Thorne, Thomas, Sing, Redmond et al., 2003). A number of physiological findings have also contributed to the idea that long-term sleep restriction could have a negative influence on health. Spiegel, Leproult and Van Cauter (1999) for example, found that, compared to extending daily sleep to 12

hours per day for six days, those restricted to only four hours of sleep per night demonstrated altered levels of the hormone cortisol, as well as a reduced level of glucose tolerance. Spiegel, Leproult, Tasali, Penev and Van Cauter (2003) also found that six days of sleep restricted to four hours led to alterations in levels of leptin which in turn led to alterations in the regulation of hunger and appetite, which the authors suggest could have consequences regarding weight gain.

There is a difficulty however with extending the findings from experimental studies into chronic sleep deprivation since, due to a number of constraints (e.g. financial or ethical), such studies are rarely able to artificially induce a period of sleep restriction that lasts longer than two or three weeks. As a consequence, much of the research that has been conducted in this area has taken an epidemiological approach by investigating the health of groups of people who regularly get less sleep than is normal for the general population, in an attempt to establish if a habitually low level of sleep is associated with poor health. Populations that are regularly studied in this way include those who have been diagnosed with a recognised sleep disorder such as insomnia or sleep apnoea, and shift workers (which can include those on permanent night or evening shifts), in addition to those employed on a 'rotating shift' basis where their hours of work are constantly changing.

Patterns of work in the European Union suggest that approximately 20% of employees work outside normal daytime hours (Frost, Kolstad & Bonde, 2009; 0600-1800) and is suggested as being a risk factor for a number of health issues. Bøggild, Suadicani, Hein & Gyntelberg (1999) provide a review of the many possible causal mechanisms that could be responsible for this, a list which includes factors such as social disruption and behavioural changes as well as the alterations to shift workers' circadian rhythms and reduction in sleep quantity. It is also important to stress that

there are a number of other factors important to health which are related to shift work that may also be exerting a negative influence on health, such as smoking, poor diet and over-consumption of alcohol, in addition to the basic fact that those employed in shift work tend to be of a lower socio-economic status and tend, therefore, to have worse health generally (Frost et al., 2009). Bearing in mind these caveats, there is a large body of evidence that shift work is associated with an increased risk for a number of health issues including; cardiovascular disease, gastrointestinal complaints, cancer, fatigue, myocardial infarction, ischemic stroke, coronary 'events', absenteeism and overall physical and mental health (Merkus, van Drongelen, Holte, Labriola, Lund, van Mechelen & van der Beek, 2012 ; Jansen, van Amelsvoort, Kristensen, van den Brandt & Kant, 2003; van der Hulst, 2003; Harrington, 1994; Knutssen & Bøggild, 2010; Pesch, Harth, Rabsten, Baish, Schiffermann, Pallapies et al., 2010; Vyas, Garg, Iansavichus, Costella, Donnerm Laugsan et al., 2012; Saksvik, Bjorvatn, Hetland, Sandal & Pallesen, 2011).

Another common way of measuring the relationship between sleep and health is to study the health of people who suffer from sleep apnoea, a condition in which there is a periodic lack of sufficient oxygen reaching the lungs during sleep. This can either be caused centrally (Central Sleep Apnoea, CSA), in which normal breathing ceases during sleep, or can be a consequence of a physical obstruction of the airway (Obstructive Sleep Apnoea, OSA). While the experience of those with sleep apnoea is unlikely to be directly applicable to elite level athletes, it does serve as a very useful model for the kind of sleep disturbance that athletes are likely to experience (Davenne, 2009), which manifests as a fragmentation of sleep, characterised by frequent brief arousals at regular intervals during sleep. These micro-arousals are so brief in fact (of the order of a few seconds) that are not usually

remembered by the individual, who are usually referred for medical examination based on the testimony of a bed partner (American Academy of Sleep Medicine, 2006; Kales, Cadieux, Bixler, Soldatos, Vela-Bueno, Misoul & Locke, 1985; Maislin, Pack, Kribbs, Smith, Schwartz, Schwab & Dinges, 1995). In the most severe cases of sleep apnoea, the frequency of arousals can be as often as every minute (60 per hour) and this is associated with significant adverse effects (Stepanski, 2002; Filteness, 2011).

There has been some debate in the literature as to whether the repeated arousals and frequent awakenings during sleep or the episodes of hypoxemia are responsible, since it is quite difficult to separate these effects due to their high level of co-occurrence. Roehrs, Zorick, Wittig, Conway and Roth (1989) however demonstrated through the use of multiple regression that the number and frequency of arousals were significantly associated with the adverse effects noted in those with sleep apnoea, while levels of hypoxemia were not. Colt, Haas, and Rich (1991) also failed to re-produce these negative effects by experimentally inducing hypoxemia in a group of sleep apnoea patients, while experimentally induced micro-arousals did have negative consequences. Perhaps the most convincing evidence comes from studies which have experimentally re-produced the adverse consequences associated with sleep apnoea by fragmenting sleep, usually by means of a loud tone on a fixed schedule (ranging from every minute to every 10 minutes) in order to disrupt sleep without the concomitant hypoxemia that is observed in sleep apnoea (e.g. Bonnet, 1985; Bonnet, 1986; Downey & Bonnet, 1987; Levine, Roehrs, Stepanski, Zorick & Roth, 1987; Magee, Harsh & Badia, 1987; Roehrs, Merlotti, Petrucelli, Stepanski & Roth, 1994).

The functional impact that this sleep fragmentation has on daytime performance compared to sleep deprivation will be discussed at length in section 1.4, however, it is important to note the negative consequences that this type of sleep disturbance can have on health is well documented. For example OSA has been associated with a greater risk of all-cause mortality, diabetes, hypertension, coronary heart disease and stroke, and those with OSA are twice as likely overall to use health care services compared to controls (Ronald, Delaive, Roos, Manfreda, Bahammam & Kryger, 1999). While there is once again the possibility that a spurious third factor is the cause of these effects (which is particularly relevant in OSA, which is most common in the overweight, which is itself a significant health risk). Punjabi & Beamer (2005) suggest that there is compelling evidence to suggest that sleep apnoea could be a plausible causal factor for metabolic dysfunction, which in turn can lead to outcomes such as glucose intolerance (which should be of concern to athletes given the importance of optimal nutrition) and type 2 diabetes. They point to evidence which prospectively links sleep apnoea with glucose metabolism independently of other factors such as body mass index, smoking and physical activity (Al-Delaimy, Manson, Willet, Stampfer & Hu, 2002; Enright, Newman, Wahl, Manolio, Haponik & Boyle, 1996; Grunstein, Stenlof, Hedner & Sjostrom, 1995; Jennum, Schultz-Larsen & Christensen, 1993). Support for a causal relationship between sleep apnoea and glucose intolerance is also provided by studies demonstrating that the successful treatment of sleep apnoea (for instance with CPAP; continuous positive airway pressure which keeps the trachea open with pressurized oxygen) also has a positive effect on participants' glucose metabolism (Brooks, Cistulli, Borkman, Ross, McGhee, Grunstein et al., 1994; Harsch, Schahin, Radespiel-Tröger, Weintz, Jahreiss, Fuchs et al., 2003).

Even where there is not an identifiable sleep disorder or behavioural cause for chronically reduced sleep, a number of large scale epidemiological studies have demonstrated that among those with a self-reported sleep duration of less than seven hours per night, there was an increased overall risk of all-cause mortality and cardiovascular 'events' (such as myocardial infarction or cardiovascular disease; Kripke et al., 2002; Ayas, White, Manson, Stampfer, Speizer, Malhotra & Hu, 2003; Eaker, Pinsky & Castelli, 1992; Newman, Spiekerman, Enright, Lefkowitz, Manolio, Reynolds & Robbins, 2000; Schwartz, Cornoni-Huntley, Cole, Hays, Blazer & Schocken, 1998). Even when one bears in mind the possible spurious effects that could also be influencing the incidence of these negative health outcomes, it does not seem unreasonable to consider the possibility of poor sleep representing a serious concern to athletes, given that even a relatively minor health problem is likely to have grave consequences for an athletes' training and competitive performance.

1.3.4 – Sleep and Immune Function

While it is widely recognised that cognitive performance is the domain which is most dependent upon attaining adequate sleep, there is a growing body of evidence suggesting that poor sleep can also have deleterious effects on immune system function. (Besedovsky, Lange & Born, 2012). As with the vast majority of biological systems, the immune system demonstrates a significant circadian rhythm, but there is also evidence to suggest that sleep itself (once separated from circadian factors) has a significant relationship with the human system. It is important to note that this relationship is 'basically bi-directional' (Besedovsky et al., 2012), meaning

that the functioning of the immune system can exert an influence on sleep in addition to its' being affected by sleep. However, for the purpose of the current discussion, the focus will remain on the ways in which inadequate sleep deprivation can have a (usually deleterious) impact on immune system functioning.

Early interest in the association between sleep and immune functioning possibly arose based on the findings from early sleep research conducted on animals, such as Licklider and Bunch (1946) and a series of studies conducted by Rechtschaffen and colleagues (Rechtschaffen et al., 1983; Everson, Bergmann, Fang, Leitch, Obermeyer, Refetoff et al., 1986; Bergmann, Fang, Kushida, Everson & Rechtschaffen, 1986; Gilliland, Bergmann & Rechtschaffen, 1986) on rats under conditions of total sleep deprivation. During the course of these studies, death was the final outcome for animals subject to total sleep deprivation, occurring after 14 to 21 days. More recent studies have replicated many of these findings (e.g. Koban & Swinson, 2005; Jaiswal & Mallick, 2009; Everson & Toth, 2000) and have suggested that the cause of death could be attributed to 'general health deterioration from generalized infections without exposure to pathogens, which Gomez-Gonzalez, Dominguez-Salazar, Hurtado-Alvarado, Esqueda-Leon, Santana-Miranda, Rojas-Zamorano and Velázquez-Moctezuma (2012) suggest is indicative that sleep has a role to play in the functioning of the immune system.

While it is clearly impractical to attempt to replicate these experiments in humans, there is a growing body of evidence to suggest that sleep also has a role to play in the functioning of the human immune system. Epidemiological and meta-analytic investigations (e.g. Scheer, Hilton, Mantzoros & Shea, 2009; Knutsson, 2003; Cappuccio, D'Elia, Strazzullo & Miller, 2010; Heslop, Smith, Metcalfe, Macleod & Hart, 2002; Ferrie, Shipley, Cappuccio, Brunner, Miller, Kumari & Marmot, 2007)

have suggested that those with disturbed or short sleep are also more likely to exhibit a wide variety of negative health outcomes, such as diabetes, hypertension, cardiovascular disease, obesity and overall mortality. While the high level of co-occurrence between sleep and ill health is highly indicative of an association, the correlational nature of research such as this, not to mention the myriad of confounding factors, mandates the use of experimental research to investigate the possibility of a direct causal relationship.

A number of studies have attempted to measure this relationship by examining participants' immune systems following a period of either total or partial sleep deprivation. For example Shearer, Reuben, Mullington, Price, Lee, Smith et al. (2001) measured the immune system following four days of total sleep deprivation, while Meier-Ewert, Risker, Rifai, Regan, Price, Dinges and Mullington (2004) and Haack, Pollmächer and Mullington (2004) subjected participants to 10 days of partial sleep deprivation, by limiting sleep to only four hours per night. In both of these cases, investigators found evidence to suggest that these acute periods of sleep restriction had an adverse impact on immune system functioning. Faraut, Boudjeltia, Dyzma, Rousseau, David, Stenuit et al. (2011) also suggests that the immune system does not immediately return to pre-sleep restriction levels of functioning once normal sleep duration is resumed, suggesting that even short periods of sleep restriction can have negative consequences for longer periods of time. Evidence also exists suggesting that sleep restriction can have an adverse influence on the levels of circulating white blood cells (Irwin, McClintick, Costlow, Fortner, White & Gillin, 1996; Heiser, Dickhaus, Schreiber, Clement, Hasse, Heenig et al., 2000; Born, Lange, Hansen, Molle & Fehm, 1997; Ruiz, Andersen, Martins, Zager, Lopes & Tufik, 2012).

The practical consequences of an impaired immune resulting from restricted sleep have also been studied directly in cases of 'genuine immune response' such as following exposure to vaccinations. Lange, Perras, Fehm, and Born, (2003) for example totally deprived a group from sleeping the night after receiving a vaccine for Hepatitis A. Compared to a control group who slept normally, the sleep-deprived group had half the number of hepatitis antibodies four weeks later. Spiegel, Sheridan and Van Cauter (2002) demonstrated a similar reduction in the strength of the immune response to a vaccine for influenza. Lange, Dimitriv, Bollinger, Diekelmann & Born (2011) even demonstrated that the reduction in immune response was still evident a year after exposure. Even without submitting to experimental sleep restriction, Cohen, Doyle, Alper, Janicki, Deverts & Turner (2009) demonstrated an increased risk of infection among short or disturbed sleepers. Following a two week sleep measurement period, participants were exposed to the common cold virus, with those reporting short or disturbed sleep showing an increased likelihood of being infected.

While it is important to note that the adverse consequences of short or disturbed sleep on the immune system tend to be small, a number of researchers have suggested that poor sleep has an accumulative and long term negative impact on the immune system in humans, which results in an increased susceptibility to infections (Besedovsky et al., 2012; Faraut et al., 2012; Gomez-Gonzalez et al., 2012). The significance of this to athletes is due to the negative impact that contracting such infections can have on their long term training and athletic performance. Since professional athletes depend on being healthy and able to train in order to sustain and improve their athletic performance in order to make a living, if they are exposing themselves to a greater risk of illness or infection due to

inadequate sleep then addressing this is likely to be an important consideration for them.

1.4 – Sleep Deprivation vs Sleep Fragmentation

One of the defining features of a great deal of existing sleep research is the method that is used. Many of the original inquiries into sleep were aimed at addressing the question of the function of sleep. Other behaviours in humans are much easier to investigate because they often have a clearly defined objective, and investigators are simply able to speak to people to find out the reasons they have for whatever it is they are doing. Sleep on the other hand is unusual on account of the fact there are few overt signs of intention during sleep, and other than suggesting that they sleep 'because they feel sleepy', people tend not to have much insight into the reasons for engaging in this behaviour. As a consequence, research has tended to study the consequences associated with not getting enough sleep, on the basis that if a component of functioning is negatively affected following a reduction in sleep then that area has some sort of dependence on attaining adequate sleep, while if an area is unaffected it suggests that it does not depend on how much sleep a person gets. It is on this basic principle that past research has demonstrated that higher cognitive functions are hugely dependent on sleep (since these functions demonstrate considerable decline following reduced sleep), while the capacity to perform physical work does not depend so much on sleep (this capacity remaining largely unchanged following reduced sleep).

In reality, however, it is fairly uncommon for sleep disturbance to be manifested as an acute period of reduced sleep duration, but is more likely to be the result of a shift in the timing of sleep (such as with jet-lag or shift work), or as a persistent discontinuity during sleep itself as is present in a number of sleep disorders such as sleep apnoea and periodic limb movements during sleep (Bonnet & Arand, 2003). The importance of factors such as jet-lag in athletes will be addressed presently; however the impact of such discontinuous sleep, usually referred to as sleep fragmentation (in order to distinguish it from sleep deprivation) is an important factor when considering the impact of sleep disturbance outside a laboratory setting.

A number of experiments have been conducted with the aim of investigating the impact that such continuous sleep fragmentation can have on subsequent performance (e.g. Bonnet, 1985; Bonnet, 1986; Bonnet, 1987; Downey & Bonnet, 1987; Levine et al., 1987; Magee, Harsh & Badia, 1987; Roehrs et al., 1994) using a variety of different protocols for fragmenting sleep, either by varying the frequency of arousals (ranging from 6 per hour to as often as 60 per hour), or by varying the 'arousal criteria.' For example initial studies required that participants signal their arousal by a behavioural task of some description, such as pressing a button or verbally alerting a researcher that they were awake. Later studies have used more subtle criteria for arousal, often not even requiring a conscious signal from participants, but only presenting a stimulus sufficient to alter the electrical output of the brain as measured by EEG. Even when the level of arousal required from participants was at this low level, there was still evidence of a significant deleterious impact on daytime functioning as a consequence of disturbed sleep, provided that the arousals were frequent enough (the required frequency of disturbance has been

suggested by many as being every 10 minutes, since arousal frequencies below 6 per hour have tended not to demonstrate an effect on subsequent functioning, although this has been disputed; Stepanski, 2002).

The sanguine findings from studies such as these to the present discussion are the fact that sleep fragmentation can have as debilitating an effect on subsequent performance as total sleep deprivation. It is also important to note that the functional domains that are most affected by sleep fragmentation (the higher cognitive functions such as vigilance, critical thinking, decision making, sustained attention etc.) are the very same that are adversely affected by sleep deprivation. In addition there has been much discussion as to the mechanism responsible for the adverse consequences on subsequent functioning. Some have argued that changes to the relative amounts of various sleep stages (usually referred to as sleep architecture) is responsible. While the fragmentation procedures described above do not usually result in a marked reduction in total sleep time (approximately one hour at most), there tend to be significant alterations to sleep architecture, with significant reductions in SWS and REM sleep, compensated for by an increase in stage one sleep. It has been argued that the reduction in SWS, as the most restorative portion of sleep as has been discussed previously, is the cause of the observed negative consequences. Other evidence however has cast doubt on this; Stepanski, Lamphere, Roehrs, Zorick and Roth (1987) and Downey and Bonnet (1987) sought to fragment sleep in such a way as to preserve the overall quantity of SWS and retain the relative quantities of each sleep stage during the sleep fragmentation procedure. There appeared to be no difference in the level of subsequent impairment compared to sleep fragmentation procedures which did not preserve sleep architecture, which has led to the suggestion that "fragmented sleep does not have

the same restorative value as uninterrupted sleep” (p. 274, Stepanski, 2002), or the ‘sleep continuity hypothesis’ (Bonnet, 1986). The most important consideration for the current discussion is that fragmented sleep, which has been suggested by some as being the kind of sleep disturbance most likely to be experienced by elite level athletes (for a variety of reasons; Davenne, 2009; Erlacher et al., 2011; Leeder et al., 2012) can have just as a significant negative impact on daytime functioning as sleep deprivation, even when the level of arousal is subtle enough that it goes unreported by the sleeper.

1.5 – Factors Relevant to Sleep in Elite-Level Athletes

1.5.1 – Anxiety and Sleep

Anxiety is one of the most measured constructs in sport psychology (Cox et al., 2003), and it is not unusual for people both in athletic and non-athletic situations to experience ‘pre-performance’ or ‘anticipatory anxiety’ before an event that an individual considers important (Erlacher et al., 2011; Savis, 1994; Langendörfer, Hodapp, Kreutz & Bongard, 2006), and evidence suggests that athletes worry about the effects of inadequate sleep on performance (Leger, Metlaine & Choudat, 2005). Anxiety in athletes is not merely confined to periods of competition however, as they will frequently experience other numerous sources of stress such as coping with injury, competing within their team for selection, concern during periods of poor performance and juggling training with other aspects of life, to name just a few (Davenne, 2009). This is salient because there is a great deal of evidence to suggest

that anxiety also plays a significant role in sleep, and has a great capacity to disturb sleep as Spielman, Yang and Glovinsky (2005) succinctly highlighted, “The buzz of an overactive mind can interfere with falling asleep, and it can interrupt and awaken the sleeper (p. 1404).

The hypothesised relationship between anxiety and sleep most likely arises due to the extraordinarily high levels of co-morbidity between these two complaints; Mellinger, Balter and Uhlenhuth (1985) report that 42% of people reporting sleep disturbance also report elevated levels of anxiety, and Taylor, Lichstein, Durrence, Reidal and Bush (2005) found that those with sleep difficulties are 17 times more likely to have clinically significant anxiety compared to those not reporting sleep difficulties. There is also a high rate of sleep complaints among those with recognised anxiety disorders, such as generalized anxiety disorder (Ohayon, Caulet & Lemoine, 1998; Monti & Monti, 2000), post-traumatic stress disorder (Neylan, Marmar, Metzler, Weiss, Zatzick, Delucchi, Wu & Schoenfeld, 1998; Lamarche & De Koninck, 2007) and panic disorder (Arriaga, Lara, Matos-Oires, Cavaglia & Bastos, 1995; Overbeek, van Diest, Schruers, Kruizinga & Griez, 2005), in as well as among those in a sub-clinical community sample (Ramsawh, Stein, Belik, Jacobi & Sareen, 2009).

There has been much discussion regarding the causal direction of this relationship, since it is entirely plausible that a reduction of or disturbance to sleep could result in an increase in anxiety, just as it is reasonable to imagine that an elevated level of anxiety could interfere with a person sleeping. Indeed there is experimental evidence to support both directions; Kahn-Greene, Killgore, Kamimori, Balkin and Killgore (2007) for instance noted a significant increase in symptoms of anxiety among participants following extended periods of sleep deprivation, while

others have demonstrated that experimentally-induced anxiety has a negative effect on subsequent sleep (Wicklow & Espie, 2000; Gross & Borkovec, 1981). This has led to the suggestion (e.g. Udhe, Cortese & Vedeniapin, 2009) that the relationship between anxiety and sleep is essentially bi-directional, a suggestion which is evident in the cognitive model of insomnia proposed by Harvey (2002).

This model proposes that faulty beliefs about how much sleep is required to function adequately the next day and how much sleep they themselves get lead to individuals with primary insomnia to hold 'negatively toned cognitive activity' during the immediate pre-sleep period. These anxieties about the need for adequate sleep and the perception that they are not achieving this result in distress and physiological arousal, which in turns results in the individual selectively focusing on this arousal, further feeding into the distorted perception that they are not getting enough sleep. This process can continue to run in a cyclical manner, whereby these distorted perceptions further lead to negative cognitions about the need for sleep, while the increasing levels of cognitive and physiological arousal continuously make sleep ever more elusive.

While Harvey's (2002) model was devised in to describe a cognitive mechanism offering an explanation into insomnia, it seems reasonable to suppose that it could be equally applicable to elite athletes experiencing anxiety, such as in the build-up to an important competition or during an important selection period in training, for instance. Harvey's original model proposes that the 'starting point' of the process leading into sleep disturbance arises from an unrealistic belief about how much sleep is required, and it seems likely that athletes could be equally prone to such a belief. We have previously discussed evidence suggesting that the belief that adequate sleep is a requirement for achieving optimal athletic performance (Leger et

al., 2005) and that reports of sleep disturbance are very common among competitive athletes (Erlacher et al., 2011). It also seems perfectly possible that, even if an athlete does not hold unrealistic beliefs about the need for adequate sleep and the consequences of not getting enough sleep, a generalised anxiety (of which there are countless possible causes) could result in a heightened level of cognitive and physiological arousal, which could then result in sleep disturbance. Given the potential ubiquitous and persistent sources of anxiety for elite level athletes, anxiety could be a frequent pressure causing sleep disturbance, most importantly during periods of competition perhaps, but there is certainly good reason to believe that it could be a more persistent factor.

1.5.2 – The Impact of Exercise on Sleep

Exercise is commonly thought to have a generally positive impact on sleep. Vuori, Urponen, Hasan and Partinen (1988) found support for this contention from both large-scale epidemiological surveys and from subjective reports that regular exercise tends to be associated with improved self-reported sleep. Exercise is also encouraged by the American Sleep Disorders Association (Hauri, 1993; Lavie, 1996; Taylor 2001) and the American Academy of Sleep Medicine (2006) as a non-pharmacological intervention to improve sleep. Despite this ‘common-sense’ appeal however, there is a great deal of variability when it comes to empirical evidence.

Meta-analyses (e.g. Youngstedt, O’Connor & Dishman, 1997; Kubitz, Landers, Petruzzello & Han, 1996) find, at best, small effect sizes, and a high degree of

variability of findings which is usually attributed to the heterogeneity of 'exercise.' There are also a wide variety of potentially confounding factors and moderating variables which must be considered. The above meta-analyses found that the duration of exercise and the time of day at which it takes place to be the most important factors contributing to an effect of exercise on sleep. The mechanism responsible is also not clear, and there are a number of other factors that could be contributing to this effect. Exposure to bright light for example, when it is appropriately timed, has demonstrated significant positive effects on sleep (Guilleminault, Clerk, Black, Labanowski, Pelayo & Claman, 1995; Campbell, Dawson & Anderson, 1993), and this is likely to be an important factor when exercise takes place outdoors. It is also possible that the general health benefits associated with regular exercise are responsible for the observed improvements in sleep, rather than as a direct consequence of exercise itself.

One of the great difficulties with this line of research has been as a consequence of the high level of variability between different types of exercise, which has resulted in an overall picture of equivocal findings. A number of authors (e.g. Driver & Taylor, 2000; Youngstedt & Frelove-Charton, 2005; Dunn, Trivedi, Kampert, Clark & Cambiss, 2005; Myllmaki, Kyröläinen, Savolainen, Hokka, Jakonen, Juuti et al., 2011) have arrived at the conclusion that exercise does not have an impact on sleep, whilst a number of others e.g. (Brand, Gerber, Beck, Hatzinger, Pühse & Holsboer-Trachsler, 2010; Sherrill, Kotchou & Quan, 1998; Souissi, Chtourou, Zrane, Cheikh, Dogui, Tabka & Souissi, 2012) have demonstrated an impact of exercise on subsequent sleep. It is also important to consider, that while the majority of experimental findings are regarded as demonstrating an improvement in sleep (usually on account of increased total sleep

time, increased slow-wave sleep and reduced sleep onset latency; Taylor, 2001), Souissi et al. (2012) found that exercise had a negative impact on subsequent sleep, demonstrating the need to consider of the role that moderator variables play in determining how sleep may be affected by exercise, if at all.

There appear to be two key factors which determine the impact that exercise has on sleep, the first being the intensity and duration of exercise, and the second being the time day at which exercise takes place. A number of studies have demonstrated that of exercise be sufficiently intense (at least 50% of VO_{2max}) and last for a considerable length of time (at least 80 minutes) in order to have a measurable impact on subsequent sleep (such as increased SWS and reduced SOL, Horne & Staff, 1983; Trinder, Montgomery & Paxton, 1988; Horne, 1988a), exercise at lower intensities (below 40% VO_{2max}) does not impact upon sleep even when the duration of exercise is prolonged (Paxton, Montgomery, Trinder, Newman & Bowling, 1982). In contrast, where 'extreme' levels of exercise of both very high intensity and duration occur, such as in marathon-length events, Taylor (2001) suggest that sleep is likely to be disrupted by increased levels of movement and awakenings rather than improved. The role of time of day in determining the sort of impact that exercise has upon sleep is consistently shown as being the most important (Taylor, 2001; Youngstedt et al., 1997; Kubitz et al., 1996). The importance of time of day is most frequently hypothesised as being the result of the core body temperature increase associated with exercise; the subsequent thermoregulatory response is suggested to improve sleep (Horne & Staff, 1983; Trinder et al, 1988; Horne & Moore, 1985). The exercise needs to take place close enough to sleep in order for the thermoregulatory response to have an effect, but not so close that it has an alerting effect (Driver & Taylor, 1996). While the suggestion that late night vigorous activity is likely to have a

detrimental impact on sleep (a view supported by the American Academy of Sleep Medicine, 2001), the experimental evidence is still equivocal. For example Myllmaki et al. (2011) found that while late night exercise produced a marked increase in heart rate during the first three hours of sleep, there was not a concomitant disturbance to sleep. In contrast, Souissi et al. (2012) did find evidence of sleep disturbance. Both studies used a maximal aerobic exercise paradigm; the only significant difference appears to be a slight difference in timing. The exercise in the Myllmaki study ended approximately two hours before participants retired to sleep, while exercise ended approximately one hour before bed time in the Souissi study, highlighting the subtle nature of the impact of time of day.

It is also important to note that while the thermoregulatory hypothesis is the most popular explanation, recent evidence has also suggested that exercise can also exert an influence on circadian rhythms, much the same as exposure to bright light (Yamanaka, Hasimoto, Tanahashi, Nishide, Honma, & Honma, 2010), which suggest another plausible mechanism for exercise having an impact on sleep. The human circadian rhythm plays a large part in determining our levels of sleepiness (Horne, 2006), and follows a very distinct pattern throughout a normal day, with the natural 'trough' occurring in the early hours of the morning (at approximately 0400 – 0600 hours) and the peak occurring in the early evening (at approximately 1800 – 2000 hours). It has long been known that, in the absence of external time cues (usually called zeitgebers- literally time-givers in German), the human circadian clock 'free runs' with a length of approximately 24.5 hours per day (Kleitman 1963). In the absence of any zeitgebers the circadian clock naturally tends to extend each day, it is only kept in synchrony with the length of the solar day by these external time cues. Bright light is the strongest of these cues (Czeisler, Buxton & Khalsa, 2005) but its

influence depends strongly on the time of day. Bright light exposure shortly after the natural trough or shortly before the natural peak have a phase advancing effect, in that they bring the time of the evening peak (and morning trough) forward, while exposure after the evening peak have the opposite effect, delaying the trough in the early morning. In practice, exposure to bright light late in the evening tends to make sleep more difficult, while bright light exposure in the morning and early evening is conducive to sleep (as well as a number of other factors such as mood; lack of light exposure during the winter months is the primary cause of seasonal affective disorder; Khalsa, Jewett, Cajochen & Czeisler, 2003; Czeisler, Kronauer, Allan, Duffy, Jewett, Brown & Ronda, 1989; Lam & Levitan, 2000). If exercise has a similar capacity to influence the circadian clock, as is suggested by Yamanaka et al. (2010), it would be expected that regular physical activity during the daylight hours could have a positive impact on sleep, while late night exercise may be expected to have a harmful effect.

Unfortunately, the timing of both training and competitive times of elite level athletic competitions is often dictated by factors other than achieving optimal sleep. Many competitions take place in the evening due to the commercial demands that high-profile sporting events take place during television 'prime time' in order to maximise audiences and revenues. The demands of many sports such as swimming, rowing and running also require athletes to train more than once a day. In order to allow for adequate physiological recovery between training sessions, this often mandates that training sessions take place both early in the morning and again well into the evening. The training involved at such an elite level is also likely to be sufficiently intense and of sufficient duration to have a detrimental impact on

subsequent sleep, all of which suggests that exercise is likely to be exerting a negative influence on sleep in elite level athletes.

1.5.3 – Sleep Hygiene

The term 'sleep hygiene' was first used by Peter Hauri as a description for a set of behaviours aimed at improving sleep in insomniacs (Hauri, 1977). It generally refers to a set of 'rules' of behavioural and environmental factors that are considered to be conducive to good sleep. The original list of rules includes a number of general health practices such as a healthy balanced diet, regular exercise and not over-using substances such as alcohol or caffeine, environmental factors associated with sleep such as the absence of light or noise and a comfortable temperature, and specific sleep related behavioural practices such as consistency in sleeping times from day to day and not engaging in arousing activities in the immediate period preceding sleep. A number of additions have since been made to the original list of suggested practices, including never making a conscious effort to sleep, getting out of bed if one fails to start sleeping within 15 minutes, eliminating the bedroom clock and avoiding the use of hypnotics (Hauri 1992). Engaging in these behaviours is thought to have a negative impact on subsequent and indeed long term sleep (in the case of more persistent factors like erratic sleep scheduling, habitual overuse of alcohol or caffeine or an excessively stimulating bedroom environment).

Although 'inadequate sleep hygiene' has its own diagnostic criteria in both the International Classification of Sleep Disorder (American Academy of Sleep Medicine, 2006) and in the Internal Classification of Diseases (World Health Organisation,

2010), most authors seem to concur that poor sleep hygiene is unlikely to be a cause of primary insomnia in most cases (Morin, 2005; Stepanski & Wyatt, 2003; Yang, Lin, Hsu & Cheng, 2010). It is none-the-less considered to be a factor that can contribute to the continuation of insomnia symptoms, and as such is included as a component in the vast majority of cognitive behavioural therapy based treatments for insomnia (Stepanski & Wyatt, 2003; Edinger, Wohlgemuth, Radtke, Marsh & Quilian, 2001). It is also important to note that while poor sleep hygiene is generally regarded as a contributory rather than a causal factor in insomnia, in sub-clinical and otherwise 'normal' sleepers, knowledge and adherence to recommended sleep hygiene practices has been shown to be positively associated with good sleep (Brown, Buboltz & Soper, 2002; Yang et al., 2010; Gallasch & Gradisar, 2007; Mastin, Bryson & Corwyn, 2006) and experimental evidence has suggested that a failure to follow sleep hygiene recommendations can disturb sleep (Stepanski & Wyatt, 2003; Riedel, 2000).

This is likely to be a relevant consideration in elite level athletes since there are a number of factors that could contribute to athletes transgressing sleep hygiene recommendations, for reasons that are both within and beyond their control. Halson (2008) points out that 'hyperhydration' following training sessions is a reasonably common occurrence among elite level athletes, which will disrupt sleep on account of the need to frequently urinate. A number of other areas of sleep hygiene may find themselves under strain in this population; for example it is recommended that people should not actively 'try' to sleep and that they should try not to worry before sleep. Due to the heightened demands and concurrent level of anxiety, this may not always be possible for elite level athletes. In addition, the scheduling of athletes' sleep will tend to depend on a variety of factors that they are unable to influence,

such as competition times (with major events often taking place well into the evening to satisfy commercial demands) and training times, which are often based on considerations other than achieving optimal sleep such as the need for multiple training sessions per day, mandating training both in the early hours of the morning and again well into the evening in order to allow for adequate physiological recovery between training sessions.

The regularity of sleep scheduling in particular can have a profound impact upon sleep, and was found (alongside alcohol and smoking avoidance) to be one of the most important components of good sleep hygiene. This is likely due to the impact that it can have on the two processes which combine to determine sleep (the two process model; Feinberg, 1974; Borbély, 1982; Horne, 2006), namely the homeostatic sleep drive and the endogenous circadian pacemaker. The effect that erratic sleep scheduling has on homeostatic sleep drive is quite simple to understand, since this increases in a generally linear manner as time awake increases. If for example, an individual sleeps for longer than usual for a 'lie-in' (for example at the weekend, or following a match or particularly strenuous training session), then their drive to sleep at their normally scheduled sleeping time the following night will be reduced, making sleep more difficult. Conversely, attempts to retire to bed earlier than usual, perhaps in anticipation of important events occurring the following day which require additional sleep, are likely to be counter-productive since the reduced homeostatic need makes sleep more difficult. A chaotic sleep schedule due to external demands such as the timing of training and competition can also exert an influence on the circadian pacemaker. Stepanski & Wyatt (2003) suggest that changes to sleep scheduling can alter the times at which a person is exposed to bright light. As has been discussed previously, bright light has been demonstrated as

being the strongest zeitgeber, so altering one's exposure to it by sleeping in a dark room when one is accustomed to being active and outdoors could plausibly have a phase-shifting effect, similar to jet-lag. Strogatz, Kronauer and Czeisler (1987) and Czeisler, Allan, Strogatz, Rhonda, Sanchez, Rios et al. (1986) suggest that sleep initiated earlier than a person is used to are characterised by extended latencies to sleep onset as the circadian pacemaker is still promoting wakefulness. Conversely, sleep initiated later than is customary is characterised by an increase in intrusions of wakefulness as the circadian pacemaker is again promoting wakefulness in line with the established routine. Chaotic or erratic sleep scheduling as a result of competitive or training commitments are therefore a highly likely and plausible source of sleep disturbance in elite level athletes.

1.5.4 – Jet-Lag

'Jet-lag' is a reasonably well known phenomena which describes the adverse consequences associated with rapid trans-meridian travel across multiple time zones. Such adverse consequences include disorientation, light headedness, impatience, lack of energy, general discomfort, mood disturbance and sleep disturbance (Jean-Louis, Kripke & Ancoli-Israel, 2000; Cole, Kripke, Gruen, Mullaney & Gillin, 1992; Reilly & Edwards, 2007), all of which could result in impaired athletic performance (Smith, Efron, Mah & Malhotra, 2013; Richmond, Dawson, Hillman & Eastwood, 2004). Trans-meridian travel is also a fact of life for many elite level athletes, whether it be for specific events such as Olympic Games, or a regular occurrence for

example in professional teams in the USA or Australia where even domestic competitions can involve significant trans-meridian travel.

The mechanism responsible for the negative effects of jet-lag are well understood as resulting from the sudden de-synchrony between the human body's endogenous pacemaker, which follows a relatively stable pattern of variation during the course of the day, and the external environment. Generally speaking the external time cues of a person's environment help to maintain the stability of their circadian rhythms, which actually tend towards a slightly longer period of 24.5-25 hours per day (Kleitman 1963). When these two systems are suddenly jolted out of phase with each other and the external time cues of the individual's new environment are in stark disagreement with their own 'internal' pacemaker, these biological systems start to show signs of sub-optimal functioning. While the sleep-wake cycle is perhaps the most easily identifiable behavioural result of the endogenous pacemaker, most biological systems demonstrate a profound circadian rhythm, including core-body temperature, muscle strength, flexibility, self-chosen work rate and arousal (Atkinson & Reilly, 1996).

In contrast to the lack of evidence regarding the negative consequences on athletic performance as a result of sleep deprivation discussed earlier, athletic performance has been demonstrated as displaying a significant reliance on circadian factors. Reilly and Walsh (1981), for instance, found that during a nearly 100-hour period of continued wakefulness, physiological performance did not decline in a linear fashion as the length of wakefulness increased but instead, continued to fluctuate on a daily basis according to the pattern of core-body temperature, with a peak in performance during the early evening, and the lowest levels of performance observed during the early hours of the morning. In addition, psychological functioning

simultaneously showed evidence of circadian rhythmicity in performance, with a gradual decline as the period of wakefulness continued. A number of studies have confirmed that both cognitive and physical performance shows a marked circadian rhythm, for example in swimming (Baxter & Reilly, 1983; Reilly & Marshall, 1991) and cycling time-trials (Atkinson, Todd, Reilly & Waterhouse, 2005), in anaerobic performance (Reilly, Atkinson, Gregson, Drust, Forsyth, Edwards & Waterhouse, 2006), lactate threshold during exercise (Forsyth & Reilly, 2004) and self-chosen work rate (Coldwells, 1994).

With regards to real world performance, there is a great deal of evidence to suggest that athletic performance of both teams and individuals is impaired following trans-meridian travel (Jehue, Street & Huizenga, 1993; Recht, Lew & Schwartz, 1995; Steenland & Deddens, 1997; Worthen & Wade, 1999), particularly when travel is an eastward direction (in accordance with findings from jet-lag research generally). While the impact of travelling across only one or two time-zones would generally only be expected to be relatively small, findings from the above studies have demonstrated significant reductions in points scored in professional baseball and Aussie rules teams following eastward trans-meridian travel, as well as the finding that eastward travelling American Football teams are simply more likely to lose a game than a westward travelling team, all of which suggests that disruption to athletes' circadian rhythms can and does have significant impact upon both the performance of individual players, and the overall outcome of a competition.

Based on existing research on the role of circadian rhythms in jet-lag, Reilly & Edwards (2007) have compiled a list of recommendations for athletes travelling long distances for competitions. They consider a number of potentially useful interventions, ranging from pharmacological to behavioural. Hypnotics may have

some utility in helping individuals to sleep at times when their circadian pacemaker is trying to keep them awake, although Reilly, Atkinson and Budgett (2001) failed to demonstrate the effectiveness of temazepam in reducing the severity of jet-lag symptoms in British athletes travelling to the USA, and it is also stressed that hypnotics can have adverse side-effects which may be of significant concern to athletes shortly before competition. Some have suggested that the melatonin may have some utility. Melatonin is a natural substance excreted by the pineal gland, and ingestion of melatonin can have both a hypnotic effect (regardless of the time of day at which it is taken) as well as exhibiting a chronobiotic effect if administered at the correct time; ingestion a few hours before the 'trough' in core body temperature produces a phase-advancing effect, while use in the hours following the trough in core body temperature produces a phase-delaying effect. This highlights the importance of timing when it comes to the use of melatonin, so its use should be treated carefully. Research has also suggested that while melatonin can be useful for 'mild' jet-lag, both Edwards, Atkinson, Waterhouse, Reilly, Godfrey and Budgett (2000) and Richmond et al. (2004) failed to demonstrate it has being useful in jet-lag following a time-zone shift of 12 hours (such as the time difference between the UK and Australia). Conversely stimulants may also be useful in preventing sleep at a time that would not be conducive to adaptation to the new time-zone, although once again caution must be exercised. For instance Modafinil has been revealed as a substance of abuse among some sprinters (Reilly, Waterhouse & Edwards, 2005), and caffeine is in fact a 'specified substance' according to the World Anti-Doping Agency (WADA), meaning that the allowable quantities in some sports are subject to restrictions (World Anti-Doping Agency, 2013).

Given the difficulty and potential hazards associated with pharmacological interventions, Reilly & Edwards (2007) also suggest some useful behavioural practices that may reduce the severity of jet-lag symptoms and/or speed up the re-entrainment of athletes' circadian rhythms to the new environment. Atkinson and Speirs (1998) and more recently Yamanaka et al. (2010) suggest that physical activity can have a chronobiotic effect, and if appropriately timed can play a role in speeding up circadian adjustment. Reilly and Edwards (2007) suggest that if training for competition is the primary goal, training times should be arranged so as to occur when the peaks in core body temperature of the individual and the new environment coincide in order to maximise the benefit of each particular training session. Exercise can also be timed in much the same way as exposure to bright light to produce the desired direction of circadian shift; exercise shortly before the peak in core body temperature can effect a phase delay (Yamanka et al. 2010) which may be desirable following westward travel for example. They also suggest that napping during the daytime in the destination time-zone should be discouraged, since it will tend to coincide with the established circadian rhythm in the departure time-zone, rather than the intended rhythm to match up to the new time-zone (Reilly & Edwards 2007).

1.5.5 – Exercise and Immune Function

The impact that physical exercise can have on a person's immune system is an important question, particularly in elite level athletes whose livelihood depends on their ability to sustain intense training and competition for extended periods. Any depression in the immune system could make athletes more susceptible to infections which could result in a significant decline in exercise performance and the ability to sustain heavy training (Roberts, 1986). While there is evidence to suggest moderate levels of exercise are beneficial to general health and the immune system (e.g. Matthews, Ockene, Freedson, Rosal, Merriam & Herbert, 2002), in elite level athletes where training loads are extreme and long-term, the opposite effect has also been suggested; Gleeson (2007) and Nieman (1994) model the relationship as a 'J' shaped curve, where moderate exercise improves immune functioning, while vigorous exercise results in a decline in immune functioning below the level observed in sedentary persons.

A number of studies have observed a transient depression in the functioning of the immune system in the period immediately following prolonged strenuous exercise (Gleeson, 2007; Pedersen & Bruunsgard, 1995; Pyne, 1994; Ronsen, Pedersen, Oritsland, Bahr & Kjeldsen-Kragh, 2001) and this short-term depression has been reported to last from anywhere between 3 hours and 24 hours (Gleeson, 2007), so it seems perfectly plausible that an athlete's immune system may not have recovered fully between multiple sessions taking place on the same day, and perhaps even between days. A number of potential mechanisms have been implicated to explain this observation, such as increased levels of stress hormones

during exercise (Moynihan, Callahan, Kelley & Campbell, 1998), a fall in levels of blood glutamine (Gleeson, 2005), excessive levels of free radicals during exercise (Niess, Dickhuth, Northoff & Fehrenbach, 1999) and even simple causes such as an increased potential for exposure to pathogens as a consequence of the increased depth and rate of breathing (Gleeson, 2007). A number of markers of immune system functioning have shown evidence of depression following acute periods of high intensity exercise (Yamauchi, Shimizu, Kimura, Takemura, Suzuki, Akama et al., 2011), and epidemiological studies have demonstrated that athletes are at a significantly higher risk of developing infections, particularly upper respiratory tract infections, than those who exercise moderately or not at all (Bishop, 2005; Fahlman & Engels, 2005; Nieman, 1994; Nieman, Miller, Henson, Warren, Gusewitch, Johnson et al., 1994) and evidence also demonstrates that athletes are at a greater risk during periods of high intensity training (Yamauchi et al., 2011) and in the weeks immediately following ultra-endurance marathon events (Nieman, Johanssen, Lee & Arabatzis, 1990; Peters, Goetzsche, Grobbelaar & Noakes, 1993).

Due to the serious consequences associated with infection for elite level athletes, the feasibility of countermeasures has also been studied. Fahlman & Engels (2005) suggested that supplementation with Vitamin C and Vitamin E attenuated (but did not eliminate) the depression in immune function among American football players, and both Nehlsen-Cannarella, Fagoaga, Nieman, Henson, Butterworth, Schmitt et al. (1997) and Nieman (1998) suggest that sufficient intakes of carbohydrates can also mitigate somewhat the negative impact on immune functioning. It does not appear that the role that sleep plays in immune system functioning has been widely considered but, given the evidence discussed previously, there is a possibility that sleep could play a contributory role towards a depression in

immune system functioning in elite level athletes. If this were to be the case, interventions aimed at improving sleep could prove to a fruitful avenue of investigation in helping to overcome the increased risk of infection in athletes.

1.5.6 – The Role of Sleep in Learning

The idea that sleep has a role to play in facilitating learning and the formation of memories is not a new one (e.g. Newman & Evans, 1965; Gaarder, 1966), and it has been noted by Stickgold (2005) that the idea can be traced back as far as Roman thinkers in the first century. The importance of learning to elite level athletes is crucial (Moran, 2008). Athletes are required to master complex skills and strategies, and be able to recall and implement them in periods of high stress in the presence of a wide variety of potentially distracting stimuli, and the importance of cognition in elite athletic endeavour is currently receiving a proliferation of interest (Moran, 2008).

Much of the initial interest centred around the role that REM sleep was thought to play in helping to cement the formation of new memories. Evidence from both animal and human studies has demonstrated that the amount of REM in the sleep period following a contrived learning scenario increased (e.g. Zimmerman, Stoyva & Metcalf, 1970), although others have failed to replicate this effect, particularly in humans (Allen, Oswald, Lewis & Tagney, 1972; Zimmerman, Stoyva & Martin, 1978; Horne & McGrath, 1984). The notion that REM sleep plays a distinct role in memory formation has now been comprehensively weakened by a several authors (e.g. Siegal, 2001) who point to a number of flaws. In the case of animal

studies for instance, Gonzalez, Debilly, Valatz and Jouvét (1995) and Rampin, Cespuglio, Chastrette and Jouvét (1991) have suggested that it is the stress that animals experience during experimental learning situations rather than the learning itself which results in an increase in REM sleep, having demonstrated an increase in REM sleep after applying moderate stress in the absence of any learning. In addition, evidence in humans also casts doubt on the idea that REM sleep is crucial for memory formation. Drugs used in the treatment of depression, such as monoamine oxidase inhibitors (MAO's), have demonstrated the ability to completely suppress any REM sleep. Siegal (2001) notes that despite the millions of people who have taken these drugs in sufficient quantities to completely suppress REM sleep, there has not been any evidence to suggest memory impairment as a consequence. Experimental studies such as Diekelmann, Büchel, Born and Rasch (2011) have also demonstrated the non-significance of REM sleep by terminating the sleep of participants following a learning task before the onset of the first period of REM sleep, with no apparent negative impact on learning.

Despite the apparent lack of impact that this specific stage has on learning, the fact that sleep itself plays a role in memory formation appears not be in serious doubt. Several reviews have arrived at the conclusion that sleep plays 'a crucial role' in learning (e.g. Smith, 1995; Walker, 2004). This evidence is based on a large number of experimental studies in which participants are required to learn something, and they are then tested several hours later, with the intervening period either containing sleep or not, with the vast majority of studies finding that performance following a period of sleep is significantly improved compared to an equivalent period of wakefulness (e.g. Walker, Brakefield, Morgan, Hobson & Stickgold, 2002; Diekelmann et al., 2011; Brawn, Fenn, Nusbaum & Margoliash, 2010; Stickgold,

Whidbee, Schirmer, Patel & Hobson, 2000a; Stickgold, James & Hobson, 2000b; Walker et al., 2002; Fischer, Hallschmid, Elsner & Born, 2002; Huber et al., 2004). This apparent improvement in learning during sleep has been replicated for a variety of different types of task, including visual discrimination (Karni, Tanne, Rubenstein, Askenasy & Sagi, 2004) auditory (Atienza, Cantero & Stickgold, 2004) and motor tasks (Robertson, Pascual-Leone & Press, 2004). Kuriyama, Stickgold and Walker (2004) also suggest that complex skills (such as those that might be more relevant to athletes) show a greater positive impact as a consequence of consolidation during sleep than simple tasks, and Stickgold (2005) and Lu and Göder (2012) suggest that shortened sleep, or even sleep fragmented to no greater degree than that indicated by transient EEG arousals is sufficient to impair the normal overnight learning. Taken together, this seems to suggest that a sleep disturbed athlete may find it harder to learn and master the complex skills on which they depend in order to achieve optimal performance.

1.6 – Summary

- The importance of sleep for attaining optimal athletic performance is often assumed by coaches and athletes, however there is a lack of specific evidence to justify this.
- The primary purpose of sleep is for brain restitution.
- Optimal athletic performance requires optimal brain functioning, both in order to facilitate cognitive elements of performance, and physical performance as

influenced by mood and motivation decrements associated with sub-optimal sleep.

- Inadequate sleep also has a number of negative consequences that could have serious implications on athletes such as negative health consequences and the risk of infections jeopardising both their training and competition performance.
- There are numerous potential sources of sleep disturbance among elite level athletes.
- Lab based studies have demonstrated adverse performance consequences following inadequate or disturbed sleep, but to date no research has attempted to study the influence of sleep on performance in a real-life setting outside the laboratory.

1.7 - Aims

The aim of this thesis is to investigate the relationship between sleep and performance in elite level athletes. This work will initially attempt to ascertain the

a) presence and

b) extent of sleep disturbance among athletes.

Current research suggests that evidence of such disturbance is likely to be found, however existing evidence is based only on very small sample sizes (Sargent et al., 2012), on athletes out of the competitive season (Leeder et al., 2012), or based on subjective retrospective reports (Erlacher et al., 2011).

This work then aims to investigate the relationship between sleep and athletic performance in a real-life situation, rather than on elements of performance in a laboratory. Many researchers have commented that the negative impact associated with inadequate sleep can be mitigated or eliminated entirely if participants are sufficiently motivated. Given the obvious differences in terms of motivational climate between research conducted in a lab, compared to a real performance in which the athlete has a highly personal stake, existing lab-based research cannot be assumed to be relevant to athletes. A number of other factors will also be considered, such as comparing athletes' sleep before competitions and their habitual sleep, to examine the role of anticipatory anxiety on sleep in this population, and to investigate differences in sleep before games taking place 'at home' compared to those taking place 'away from home' which mandates sleeping in a hotel before a competition.

Finally, the current work will also aim to ascertain the importance that sleep may have to an athlete's day-to-day training during the competitive season, as well as studying the impact that strenuous training can have on subsequent sleep.

The current work will not attempt to investigate the myriad of potential causes of sleep disturbance among athletes. Given the relatively novel nature of the area of investigation, it seems prudent to first establish that inadequate sleep is associated with significant negative outcomes in the population in question in order to ensure that attempts to understand and rectify inadequate sleep will be fruitful and even necessary.

Chapter 2

Methods

2.1 – Sleep Measurement

The measurement of sleep has presented a cause of methodological difficulty in the field of sleep research, primarily because, during sleep unlike during other activities, organisms display no overt behaviour indicating an intent or purpose behind their actions (Lima & Rattenbourg, 2007). Since research participants are unable to provide any feedback to investigators during sleep, alternative means to measure sleep have been required, the gold-standard measure of which is generally accepted as being the EEG (McCall & McCall, 2012; Ancoli-Israel, 2003; Collop, 2006). This method measures the electrical activity of the brain during periods of sleep by means of a number of electrodes attached directly to the scalp of research participants. While this method provides objective and quantifiable information regarding brain activity during sleep, it is both expensive and laborious; therefore, sleep diaries have historically been used as they allow the collection of large quantities of data and are much cheaper than EEG. There are, however, a number of difficulties associated with using sleep-diaries, primarily that they rely upon the retrospective recall of events. As a result sleep-diaries do not tend to enjoy a great deal agreement with the established gold-standard of EEG (McCall & McCall, 2012; Westermeyer, Sutherland, Freerks, Martin, Thuras, Johnson et al., 2007; Lockley, Skene & Arendt, 1999), and the familiar difficulties associated with questionnaires exist, such as poor compliance, both in terms of actually completing sleep diaries at all, and faithfully completing them each morning immediately after sleep. It is not uncommon, even in clinical settings, for sleep diaries to be completed one week at a time, en masse before they are returned (Ancoli-Israel, Cole, Alessi, Chambers, Moorcroft & Pollak, 2003; Spielman, Yang & Glovinsky, 2005).

In contrast, the use of wrist actigraphy as a cost-effective and objective measure of sleep has become much more widespread in recent years, with the rate of increase in published research using this method increasing at a much faster rate than published studies using EEG (Sadeh, 2011). In contrast to sleep diaries, actigraphy provides an objective and reliable method of measuring sleep, that demonstrates a very high level of agreement with the established gold-standard measure of EEG (McCall & McCall, 2012; Sadeh, 2011; Cole, Kripke, Gruen, Mullaney & Gillin, 1992; Sadeh, Sharkey & Carskadon, 1994; Ancoli-Israel, Cole, Alessi, Chambers, Moorcroft & Pollak, 2003; Jean-Louise, von Gizycki, Zizi, Fookson, Speilman, Nunes et al., 1996) in a wide variety of populations, and is an approved measure of sleep in both healthy and clinical populations according to the American Academy of Sleep Medicine (Morgenthaler, Alessi, Friedman, Owens, Kapur, Boehlecke et al., 2007). In addition to providing an objective, valid and reliable measure of sleep, actigraphy also benefits from being far less invasive than EEG recording (and usually does not exhibit a first-night effect, unlike EEG; Agnew, Webb & Williams, 1966), as well as allowing the collection of data for weeks or even months without needing to be reset by the investigator, while EEG must be reset on a daily basis. Due to the increased convenience and reduced invasiveness of sleep measurement using wrist actigraphy, a number of researchers have specifically recommended actigraphy as an ideal measurement tool in elite level athletes (Leeder, Glaister, Pizzoferro, Dawson & Pedlar, 2012; Leeder, Gardner, Foley, van Someran & Pedlar, 2009; Richmond, Dawson, Hillman, & Eastwood, 2004).

Accordingly, sleep in the current study was measured using wrist actigraphy. While an in-depth discussion with each research participant took place both before and after measurement of their sleep, in order to properly explain to participants how

the actigraphy worked, and also to clarify any points of confusion that arose on the actigraphy, the primary method of determining the timing, length and quality of participants' sleep was based on actigraphy. The specific actiwatch that was used during this thesis was the Actiwatch AW4™ model, produced by CamNTEch (CamNTEch, Cambridge, UK). This device measures movement by means of a piezo-electric accelerometer that records the intensity, duration and amount of movement in all directions. Data are sampled at a rate of 32Hz and the device detects all movement it is subjected to above an acceleration force of 0.05g. The captured data are then logged into 30-second epochs for analysis. These actigraphs also feature an 'event marker' which participants can use to signify specific events taking place during the period of recording, depending on the needs of the individual study. In this case, participants were asked to press the event marker at 'bed time' (defined as the time at which participants are in bed with the intention of sleeping) and again at 'get up time' each morning (defined as the time at which they are consciously awake and are no longer intent on sleeping). Given this information, an automated algorithm (CamNTEch, 2008) then determines, on an epoch-by-epoch basis, when participants were asleep or awake based on the level of activity. This automated algorithm has been demonstrated as having a high level of agreement with EEG methods of distinguishing sleep and wakefulness (e.g. McCall & McCall, 2012), although it cannot provide any data regarding which stage of sleep there wearer is in, unlike an EEG.

Based in this automated algorithm, the proprietary software that accompanies the Actiwatch AW4 provides a number of output parameters of the wearer's sleep, but, for the sake of simplicity, the current work uses only 7 of the more common

sleep parameters that are used in existing sleep research, which provide data regarding the timing, duration and quality of sleep. These are defined as follows:

Timing;

- Bed Time- time (to the nearest minute) at which participants indicate they are in bed with the intention of sleeping, as indicated by pressing the event marker.
- Get Up Time- time (to the nearest minute) at which participants indicate they are no longer in bed with the intention to sleep, as indicated by pressing the event marker.

Duration;

- Total Sleep Time- the total period of time that elapses between the start of sleep and the end of sleep, as defined by the automated algorithm.

Quality;

- Wakefulness After Sleep Onset- the total amount of time spent awake after the start of sleep.
- Sleep Efficiency- the proportion of time spent asleep relative to the total period of time spent in bed (expressed as a percentage).
- Sleep Onset Latency- the period of time which elapses between participant identified bed time, and the onset of sleep identified by the automated algorithm.

- Movements per Hour- the total number of discreet periods of movement detected by the Actiwatch, divided by the total sleep time.

While there a wide variety of actimeters made by different manufacturers, each with their own subtle variations in the above sleep parameters, these are the measurements as they are defined by the manufacturer of the Actiwatch AW4® (CamNTech, Cambridge, UK) used in the present study, and these definitions have been recently validated against EEG (McCall & McCall, 2012).

While it is usually considered desirable for participants to wear the Actiwatch as much as possible, this was simply not practical in the current study. The equipment is both delicate and not entirely waterproof, so in the interests of preserving the equipment it was not thought prudent to ask athletes to wear Actiwatches constantly, largely since this would put the equipment at risk of damage. Also for a number of the athletes there are rules prohibiting the wearing of 'unnecessary' equipment during competition, which precludes the wearing of anything on the wrists. For this reason the vast majority of participants only put their Actiwatches on during the evening and removed them in the morning, so only nocturnal periods of sleep were captured in most cases.

2.2 – Match Based Performance Analysis

One of the major difficulties that exists when attempting to apply the findings from existing sleep research to elite-level athletes arises from the laboratory based nature of much of that research. While experimental designs have proven to be particularly useful in terms of standardising the experience of each participant and in providing control of extraneous variables, they have also tended to feature rather simplistic and narrow measures of performance. This is especially problematic not only because of the importance of the motivational climate in determining how well people can cope with inadequate sleep, but also the fact that lab based performance measures will never be able to approximate the motivational climate that exists in competitive performance. There is the additional problem that the performances required in elite level athletic competition entail a much greater level of complexity than, for instance, running to exhaustion on a treadmill.

As a consequence, the current research has aimed to measure performance in a more meaningful and applicable manner, which will have real significance to research participants and their coaches. Fortunately in professional football, objective and reliable performance measurement is already a widespread practice among teams, and it is these measures of performance that have been used when measuring the performance of participants during competitive matches. The ProZone® (ProZone®, Leeds, England) image-based tracking system is widely used among Premiership and Championship division sides in England and Wales, and indeed throughout Europe. This semi-automated system uses eight cameras placed strategically around football stadia that capture the position of all players on the pitch

at a sampling rate of 10Hz. These series of discrete positional data points are then used to compute the velocity of each individual player during each and every 0.5-second portions of the game using Pythagoras' Theorem. This method of player tracking has been demonstrated as being extremely reliable in determining both the exact position of players at any given moment, as well as their direction and speed of movement (Di Salvo et al., 2009; Di Salvo, Collins, MacNeill & Cardinale, 2006). This data was already being collected by participating teams, and was made available for the current study with the permission of the players and teams involved.

While the ProZone analysis system computes a number of output variables, in keeping with the aim of the current analysis to use measures of performance that are most useful to football players and coaches, only the total amount of distance covered during the match and the distance covered at 'high-intensity' were analysed in terms of the impact that prior sleep had on each of them. Discussions with the sports science support staff at the football clubs of participants revealed that these two measures were the ones that they themselves most widely used when reviewing the match performance of their players. Total distance covered is defined as the total distance covered at any speed, regardless of whether a player was on or off the ball, during the entire match (including 'injury time'). High intensity distance is defined as occurring when a player's average speed for a 0.5-second period is in excess of 19.8 km/h, with the total distance covered being the aggregate distance covered during all 0.5-second epochs above this threshold.

In terms of the importance of these measures, high-intensity distance in particular has been highlighted as being 'a crucial element of football performance' (Mohr, Krstrup & Bangsbo, 2003). Di Salvo, Gregson, Atkinson, Tordoff & Drust (2009) suggest that "high intensity efforts are critical to the outcome of matches as

they relate to activities that are key to the final match result..." (p. 205). It has also been demonstrated as being able to differentiate between levels of play in both female and male football players (Krustrup, Mohr, Ellingsgaard, Bangsbo, 2005; Mohr, Krustrup & Bangsbo, 2003), as well as being sensitive to the physiological changes associated with training (Krustrup & Bangsbo, 2001). Analysis of the levels of high-intensity distance covered by all 20 teams in the English and Welsh Premiership division suggests that high intensity distance covered is related to the overall success of teams during the course of a season (Di Salvo et al., 2009). In addition to the fact that it was considered to be an important factor by coaches, and despite the fact that the total amount of distance covered by players is a rather simplistic measure of performance, Boyd (2011) suggests that it is still an important measure to consider since it has a strong relationship with the total amount of work undertaken by players during competition. An additional consideration is that, while sprinting and high intensity activity tends to occur during crucial moments of matches, they still only account for at most 12% of distance covered during a match, accounting for at most 3% of playing time (Andrzejewski, Chmura, Pluta, Strzelczyk & Kasprzak 2013). Any analysis which omits the total distance covered would therefore confine itself to only measuring a small percentage of the activity that takes place during matches.

2.3 – Training Based Performance Measurement

Similar to the measures used to assess performance during matches, the current investigations have aimed to assess performance during training in a manner which is consistent with measures already widely used by football clubs, and that is as naturalistic as possible, as opposed to using contrived measures of performance as has been used in previous research (e.g. Martin, 1981; Horne & Pettitt, 1974; Bambaiechi et al., 2005). It is fortunate that most professional football clubs already engage in extensive analysis of performance during training, just as they do in matches, so valid and applicable measures of performance were already being collected on all of the football players participating in the current study (a factor which played a part in the decision to proceed with studying football players).

The tracking system that was used to assess training performance data was the Catapult® X3 Athlete Monitoring System (Catapult, London). This system uses a small remote unit that is worn by players during all training sessions, and uses a combination of GPS satellite tracking and a local base station to provide accurate location data for each player, at a sampling rate of 5Hz. These location data are used in a similar manner to the raw data from the ProZone® tracking system to calculate the speed and distance travelled during training sessions. In addition the Catapult system employs a tri-axial accelerometer, sampling at 100Hz, to measure impact forces (such as those occurring when the foot strikes the ground, during sudden changes of direction, or the forces occurring during a tackle). The use of these devices during training has become increasingly popular in field sports such as football (Kelly, Coughlan, Green & Caulfield, 2012; Montgomery, Pyne & Minahan,

2010) and can be used to calculate an overall level of physical exertion that the wearer has given during a specified period of time (PlayerLoad; Boyd, 2011). It is widely used to measure the physical demands in field sports (Montgomery et al., 2010; Boyd, 2011; Young, Hepner & Robbins, 2012), and has been demonstrated as being a reasonably valid measure of force (e.g. Wundersitz, Netto, Aisbett & Gastin, 2013), and has also demonstrated as having a significant relationship with indicators of muscle damage (Young et al., 2012; Wudnersitz et al 2013), suggesting that it is indeed a valid measure of overall exertion. In addition, immediately after each training session players were asked to provide a rating of perceived exertion (RPE) on a scale from 1-10, of how much effort they feel they had applied.

To maintain consistency with the measures used when assessing match performance, and again following discussion as to which measures would be most useful to the sports science support staff at participating clubs, total distance covered during training and high intensity distance covered were again used as measures of physical performance, in addition to the PlayerLoad measurement taken from accelerometer data and the RPE scores provided by players immediately following each training session. Due to the fact that the length of training sessions varies much more considerably than the length of matches, all measures of performance were divided by the length of the training session, with the exception of RPE scores, which were instead divided by the total distance covered, as it seemed like a more important factor in determining how much effort players would exert than would training time. In fact the total amount of distance covered would likely be a better controlling factor, but the other performance measures used directly depend (to varying degrees) on total distance covered anyway, so it would be illogical to control for that factor in these measurement. Where physical activity was to be used as a

predictor (rather than an outcome) for subsequent sleep, the above measures were used in their raw (i.e. not controlled for time or distance) form to assess the total level of physical effort that had been applied in that day's training. In addition, the raw number of accelerations was used as a predictor to assess the level of physical effort. Again this was on the advice of sports science support staff; since harder 'interval' type sessions invariably feature a greater number of accelerations than more 'steady-state' training sessions. While the number of accelerations will contribute towards the player's PlayerLoad value obtained from accelerometer data, the raw number itself is never-the-less used by the sports science support staff as a measure of physical exertion in their players.

Chapter 3

Sleep in Elite Level Athletes

3.1 – Introduction

Both anecdotal and more recently research evidence (Savis, 1994; Erlacher et al., 2011; Leeder et al., 2012; Sargent et al., 2012) has laid credence to the notion that sleep disturbance is a common difficulty faced by elite athletes. There are countless potential sources of sleep disturbance among athletes, for example as a consequence of anxiety about an upcoming performance, unusual scheduling of sleep due to competitive timetables, jet-lag and/or sleeping in a novel environment (Davenne, 2009). Even though the impact that the above factors can have on sleep has been reasonably well documented in the mainstream sleep literature (e.g. Dinges et al., 1997; Sagaspe, Sanchez-Ortuno, Charles, Taillard, Valtat, Bioulac & Philip, 2006; Yang et al., 2010; Stepanski & Wyatt, 2003; Arendt, Stone & Skene, 2005), it is not a question, however, that has received much direct attention in sport psychology. While even on its own the lack of data addressing this question would be of concern, it is also important to remember that athletes are an especially heterogeneous group. There are many factors which could feasibly have a differing impact on athletes' sleep based upon the nature of that sport, such as; whether it is a team or individual sport (competitors of individual sports have been reported as experiencing higher levels of anxiety compared to competitors of team sports, which is likely to have an impact upon sleep; Martens, Burton, Vealey, Bump & Smith, 1990); or if it takes place indoors or outdoors (due to the differing levels of exposure to bright light, which is usually thought to be the strongest cue reinforcing circadian rhythms, which play a large role in sleep regulation; Khalsa et al., 2003; Czeisler et al., 1989). In attempting to understand the nature of sleep in elite level athletes it is important to measure sleep during the competitive season (when the above sleep

pressures are most relevant, and where their consequences are most important), and to obtain data from competitors from different sports, which place (potentially) sleep related pressures on competitors in different ways.

Another difficulty in applying the results from mainstream sleep literature to athletes, particularly when one considers the widely cited belief that poor sleep has a negative impact upon performance (Erlacher et al., 2011; Savis, 1994; Leeder et al., 2012; Sargent et al., 2012) arises from the fact that such research has tended to adopt an experimental approach. Using a total or partial sleep-deprivation paradigm, and measuring the impact that an acute period of sleep deprivation has on performance at a task performed immediately afterwards, has problems. Such studies not only restrict sleep in a manner inconsistent with the sleep pressures face by athletes, but also measure performance in an unrealistic manner using simple lab-based measures of components of performance, such as reaction time or exercise-to-exhaustion. Initial research (e.g. Martin, 1981; Horne & Pettitt, 1974; Robert & Hockey, 1997) has highlighted the important role that mood and motivation plays in the relationship between sleep and performance (both physical and cognitive). The motivational climate in any lab-based performance measure will never replicate the climate found in a real performance.

Despite the apparently widespread belief that adequate sleep is a pre-requisite for achieving peak performance (Mah, Mah, Kezirian & Dement, 2011; Reilly & Edwards, 2007; Robson-Ansley, Gleeson & Ansley, 2009; Samuels, 2008), there has been very little research measuring sleep in elite and higher performance athletes. Presently, only three published studies have addressed this question; Erlacher et al. (2011) retrospectively surveyed 632 international, national and university-level German athletes, finding that two-thirds reported experiencing

difficulties sleeping the night before important competitions; Leeder et al. (2012) measured the sleep of a variety of international-level athletes using wrist actigraphy, finding evidence of significant sleep disturbance among athletes compared to controls; and Sargent et al (2012) again used wrist actigraphy to measure sleep of 7 international-level swimmers during an intensive two-week training camp, finding similar evidence of significant sleep disturbance (although the sleep of their athlete sample was not compared directly against a control group). While these studies suggest that athletes are at risk of poor sleep, there are limitations of each. Retrospective recall, particularly recall of sleep which is difficult even under normal circumstances (Morgenthaler et al., 2007; Sadeh, 2011; McCall & McCall, 2012) is fraught with difficulty. Where objective measurement has been used, Leeder et al. 2012 only recorded sleep for four nights (falling short of the seven nights recommended by the American Academy of Sleep Medicine; Morgenthaler et al., 2007), and took place during the off-season, where pressures such as pre-performance anxiety and training schedules are likely to be less severe. Finally Sargent et al. (2012) measured sleep during a period of intense training during a two-week 'training camp.' While doubtless interesting, the sleep patterns observed are also unlikely to be representative of the pressures faced by athletes on a daily basis.

3.2 – Aims

While there is a small but growing body of evidence to suggest that elite-level athletes are prone to poor sleep, current research has suffered from either subjective and unreliable sleep measurement, insufficient duration of sleep measurement, relatively low sample sizes or a lack of evidence based on sleep during the regular competitive season. The current study aims to address these limitations, by measuring sleep objectively during the regular competitive season of elite-level athletes for an extended period of time. Competitors from a number of different sports will be compared against each other as well as against an age-matched group of non-athletic control participants. Both male and female participants will be recruited, so gender will also be included as a factor.

Research Questions

- Is there a significant difference between the sleep characteristics of elite level athletes and controls?
- Do male and female athletes differ in their sleep, compared to male and female controls?
- If such differences do exist, are they stable throughout the night or do they vary according to length of sleep?

3.3 – Method

3.3.1 – Participants

A total of 95 participants were recruited with an age range of 18 to 35 (mean age 23.17 years, standard deviation 4.00 years). No participants reported any evidence of a pre-existing sleep disorder, and none were excessive users of caffeine or alcohol. 27 participants were recruited to act as sedentary controls, defined as self-reported exercise levels below the recommended public health dose of 150 minutes moderate intensity exercise per week (National Health Service, 2013; Centres for Disease Control, 2013). All remaining participants were elite-level athletes from a total of 6 different teams representing 3 different sports. All athletic participants trained on a daily basis, and competed at a national and/or international level. The professional football group contained athletes from 3 different professional football clubs competing in the England and Wales football league (2 Premiership Division teams, 1 Championship Division Team). The university football group and the basketball group were each made up of a single team, while the swimming group was made up of individual athletes recruited from one of British Swimming's National Performance Centres. A summary of all participant groups is available in table 3.1.

<i>Group</i>	<i>n</i>	<i>Age (years)</i>	<i>Gender</i>
Professional Football	33	25.0 (3.7)	Male
University Football	12	20.2 (1.0)	Female
Swimmers	13	20.4 (1.7)	Mixed (7 male, 6 female)
Basketball	10	20.20 (0.6)	Male
Control	27	24.6 (4.6)	Mixed (19 male, 8 female)

Table 3.1. Summary of participants included in the present analysis. Age is presented as mean average (standard deviation).

3.3.2 – Sleep Recording

Participants wore an Actiwatch AW4® activity monitor on their non-dominant wrist for a period of two weeks (33 participants from professional football clubs wore Actiwatches for as long as 60 days continuously as part of other investigations, within this thesis). In these cases, two weeks of sleep data from each individual was randomly selected and the analysis repeated. This made no significant difference to any results, so results presented are from all available data). Participants were asked to wear their activity monitor all day; however practical expediencies relating to the fact that the devices were not waterproof and had to be removed for competition and training (in athletic participants), dictated that the majority of participants did not wear the activity monitor during the middle of the day. Participants were also asked to use the event marker to aid sleep identification and measurement; instructions were for a single button press at ‘bed time’ (explained to participants as being when they were in bed with the intention of sleeping, and to

exclude situations such as reading in bed before trying to sleep), and another single press in the morning to indicate 'get up time' (defined as the point at which participants get out of bed, or are no longer intending to sleep). When bed time and get up time are specified by the participant, the proprietary sleep identification algorithm then identifies the beginning and end of sleep automatically using standardised criteria, as well as the parameters of sleep described in section 2.1. Following the period of sleep measurement, participants were given feedback about their sleep, and any points of confusion that arose in their data were discussed and clarified.

Raw data was analysed using proprietary Actiwatch Sleep Analysis Software 7 (Cambridge Neurotechnology), using the medium sensitivity for wake/sleep identification (CamNTEch, Cambridge, UK). Data were collected in 30-second epochs. Analysis was conducted on the timing (bed time, get up time), length (total sleep time, TST) and quality of sleep (sleep efficiency, SE; sleep onset latency, SOL; wakefulness after sleep onset, WASO; and movement onsets per hour during sleep, movements/hour). The term 'sleep quality' refers to variables which relate to the restfulness and continuity of sleep, based on (e.g.) the contention of Akerstedt, Hume, Minors and Waterhouse (1997) that sleep quality is thought of as being good when it is easy to fall asleep and when sleep is continuous. Details of how these variables are measured using actigraphy are provided in chapter 2.

3.3.3 – Analyses

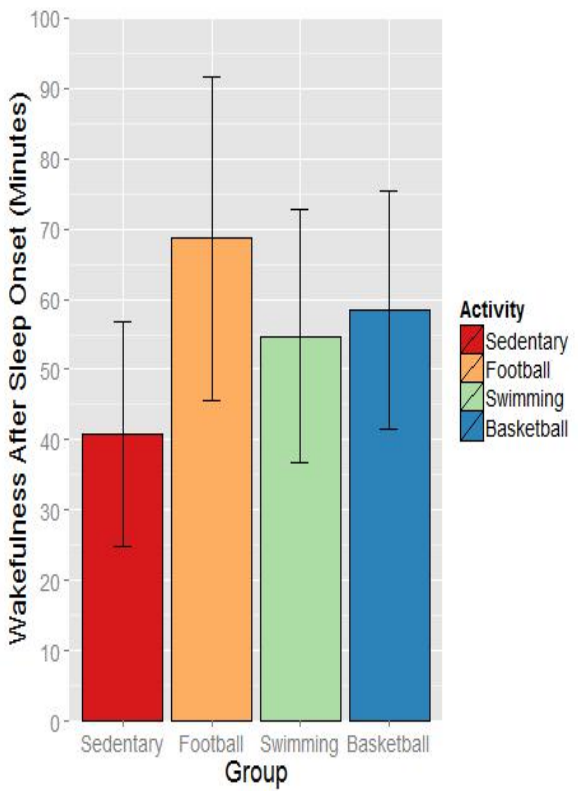
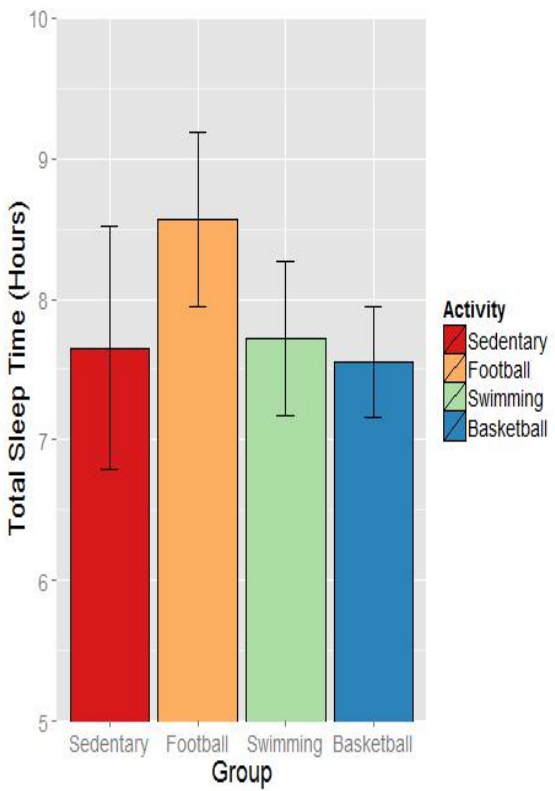
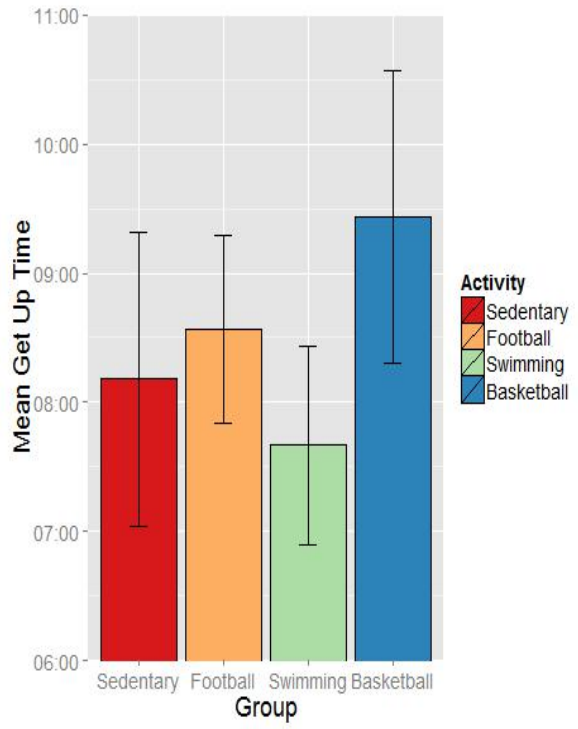
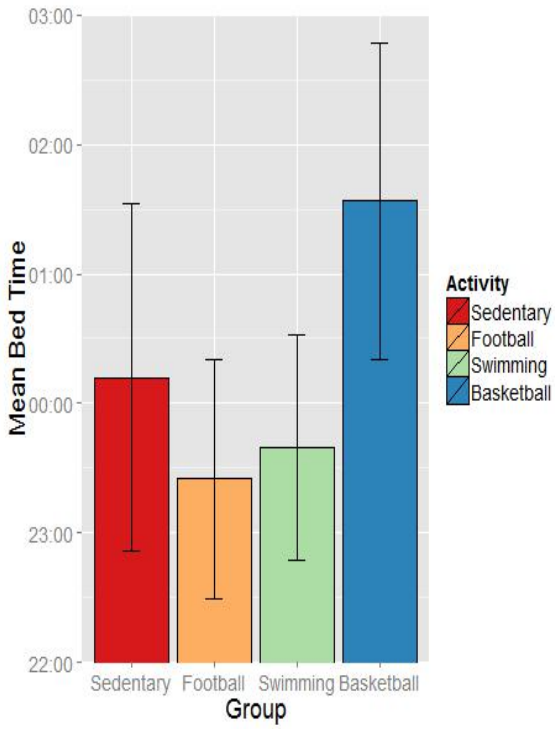
Statistical analysis was conducted using SPSS (Version 20, IBM 2011) and R (Version 2.15, R Core Development Team, 2012). A full list of the specific packages attached to R for the analysis is listed in Appendix A.

Since all the statistical analyses conducted rely on the premise that scores are independent, each individual participants observed values for the measured outcomes were averaged for the analysis period. These averages form the basis of the statistical analysis, therefore each participant contributed only a single score on each measured variable for analysis, to comply with the assumption of independence of measures.

Initial analysis was conducted using MANOVA to examine differences in sleep between individual groups based on activity type (Sedentary, Football, Swimming and Basketball), and due to gender. Follow-up analysis was conducted using univariate ANOVA (in the case of differences between athlete groups) and independent samples t-test (to test for gender differences), with the Bonferroni adjustment applied to control for increased family-wise error, according to Field (2009) and Field, Miles and Field (2012). Significance was set at 5% (two-tailed) in all cases.

3.4 – Results

A comparison of the results are presented in the arrays in figures 3.1 and 3.2 showing the differences in sleeping behaviour based on the activity type of the participants and gender, respectively. Examination of these results would seem to suggest that the type of activity did have a significant impact on sleep (figure 3.1), since, in all cases, there is evidence of significant differences between groups and, in many cases, group averages show a difference greater than one standard deviation from each other. In contrast gender (figure 3.2) did not seem to have a significant impact upon sleep. Results from the omnibus MANOVA confirm this, demonstrating that the main effect of gender did not have a statistically significant effect on the measured sleep parameters ($V = 0.147$, $F_{7,82} = 2.02$, $p > 0.0005$), while the main effect of activity type did ($V = 1.084$, $F_{21,252} = 6.79$, $p < 0.0005$). There was also evidence of a significant interaction effect between gender and activity type. ($V = 0.341$, $F_{14,166} = 2.44$, $p < 0.0005$).



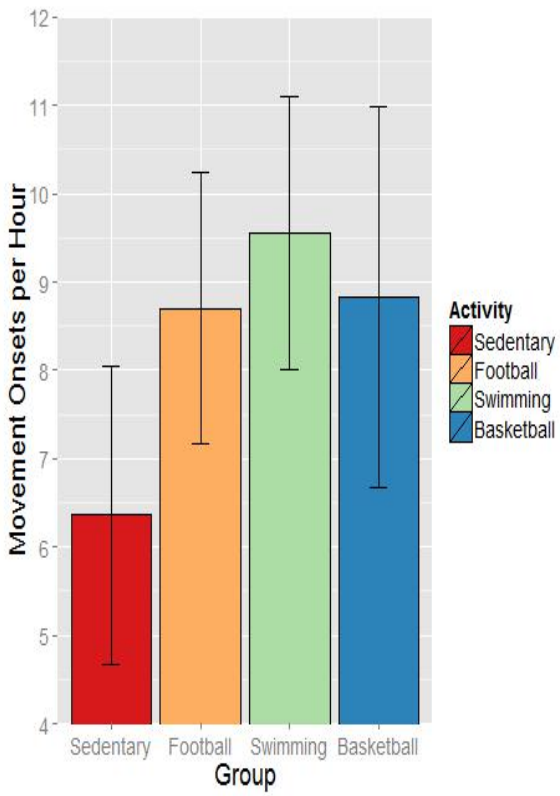
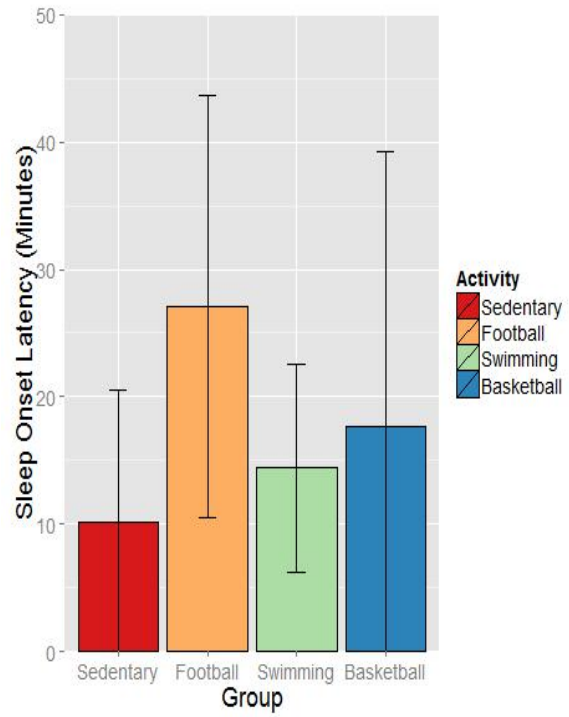
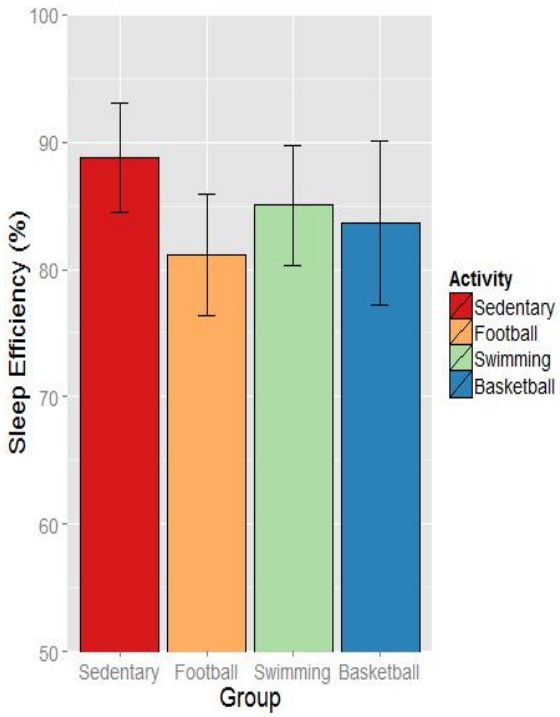
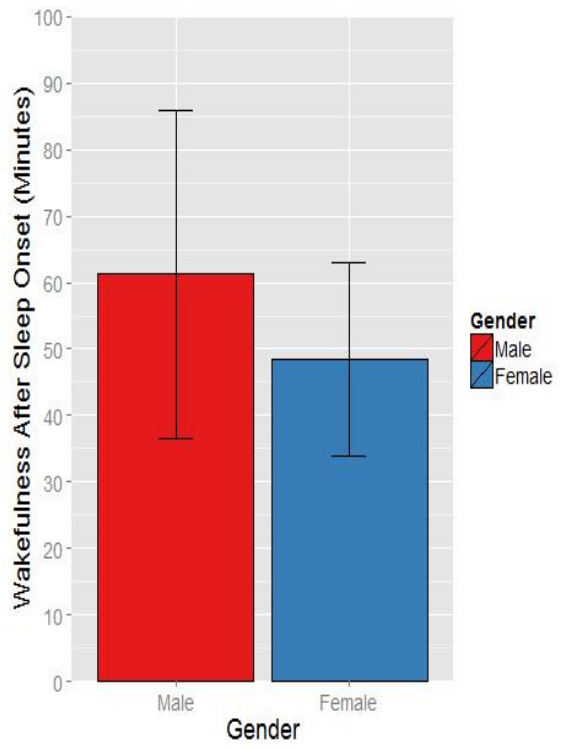
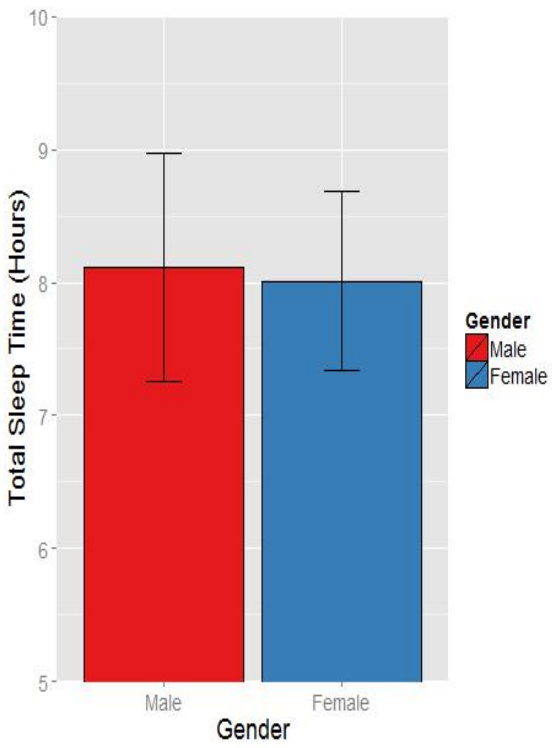
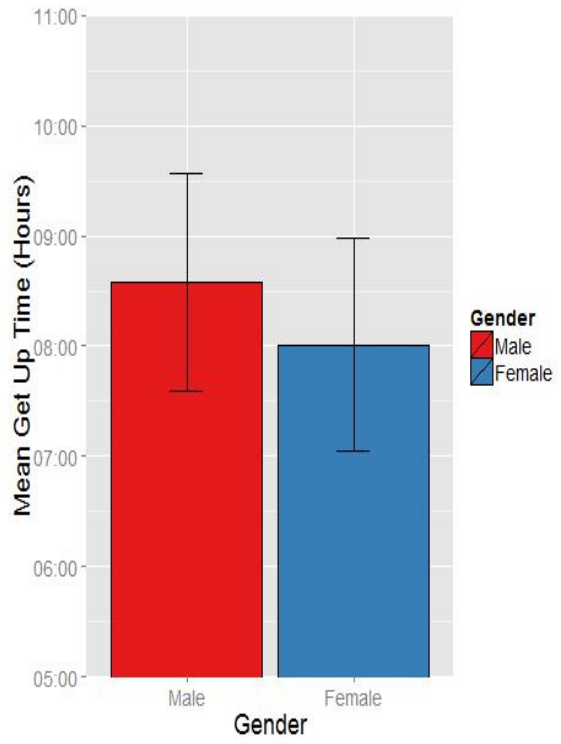
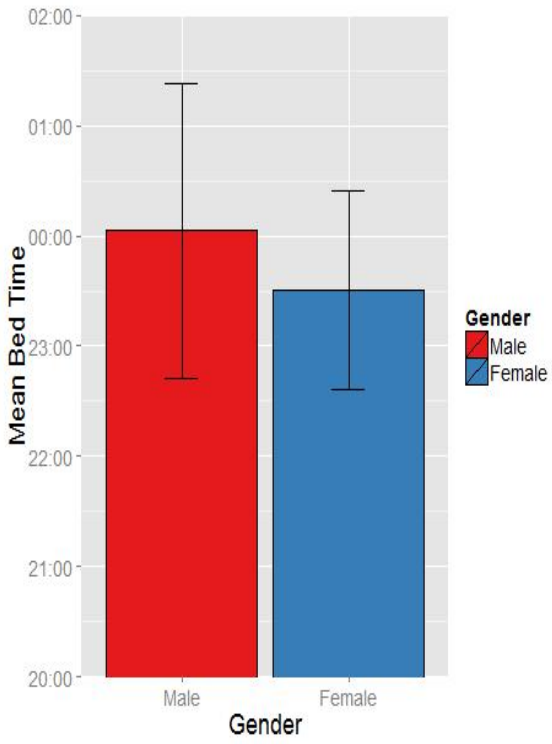


Figure 3.1. Comparison of sleep measures for the main effect of activity type. Bars represent mean averages; error bars show 1 standard deviation of the mean



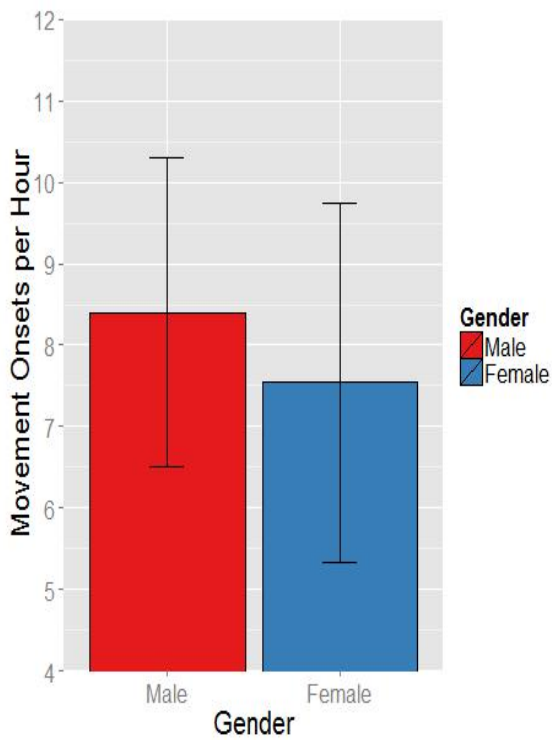
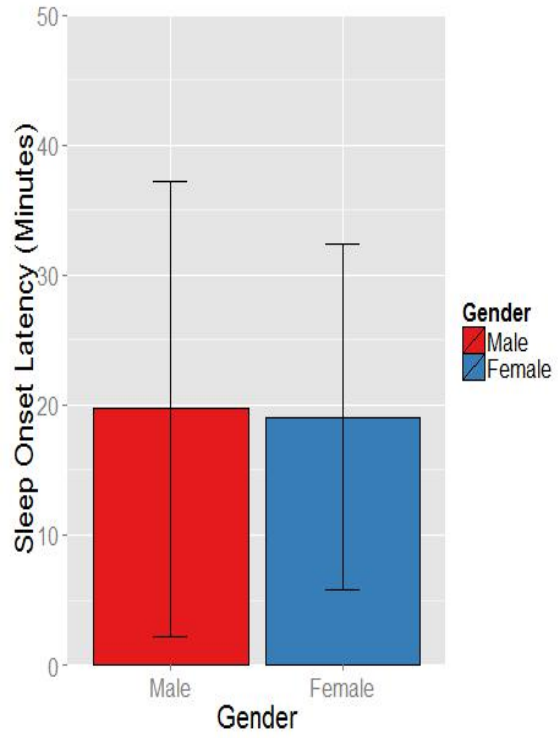
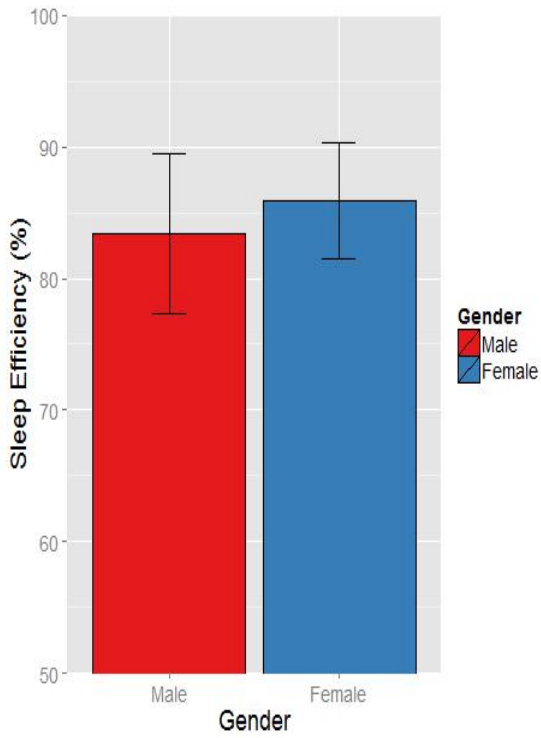


Figure 3.2. Comparison of sleep measures for the main effect of gender. Bars represent mean averages; error bars show 1 standard deviation of the mean.

Follow up analysis conducted for the main effect of exercise type demonstrated a significant effect for all measured sleep parameters, so further post-hoc testing by using Tukey's HSD for pairwise comparisons was conducted to establish precisely where significant differences exist between groups. Groups are compared graphically in figure 3.1, and the results of these pairwise comparisons are detailed in table 3.1 in Appendix B. There are a number of significant differences between the groups. Two distinct groups emerged for the timing of sleep, with basketball players retiring to bed significantly later than all other groups. The remaining groups appear to form a broad continuum, with football players going to bed the earliest (and significantly earlier than the sedentary group), with the swimming group going to bed at a non-significant interval between these two groups. Participants are also split broadly into two groups based in length of sleep, with football players sleeping for approximately one hour longer than all other participants. Pairwise comparisons also demonstrate several significant differences between groups on measures of sleep quality. The control participants as a group exhibited the most restful sleep, taking the shortest time to get to sleep after bed time, less wakefulness after sleep onset, increased sleep efficiency and fewer movements during sleep than all other groups. In particular all athlete groups exhibited a similarly significant excess of movement during sleep compared to sedentary controls. It is not clear if this increased level of movement is a consistent feature of sleep in athletic participants or if it is confined to a specific part of sleep (for example Football players tended to sleep for longer so an increase in movement levels would be expected towards the end of sleep where SWS is less prevalent and lighter stage one and two sleep predominates). Figure 3.3 provides an example Actiwatch output comparing a male football player to a male sedentary control, which demonstrates

the significantly increased level of movement in the football player is a consistent feature during the entire sleep period. Figure 3.4 represents the combination of sleep data for each athlete group in comparison to sedentary controls, which also serves to highlight the apparent consistency of increased movement levels throughout sleep and not limited to any particular period during sleep, suggesting a consistent pattern of increased movement during sleep.

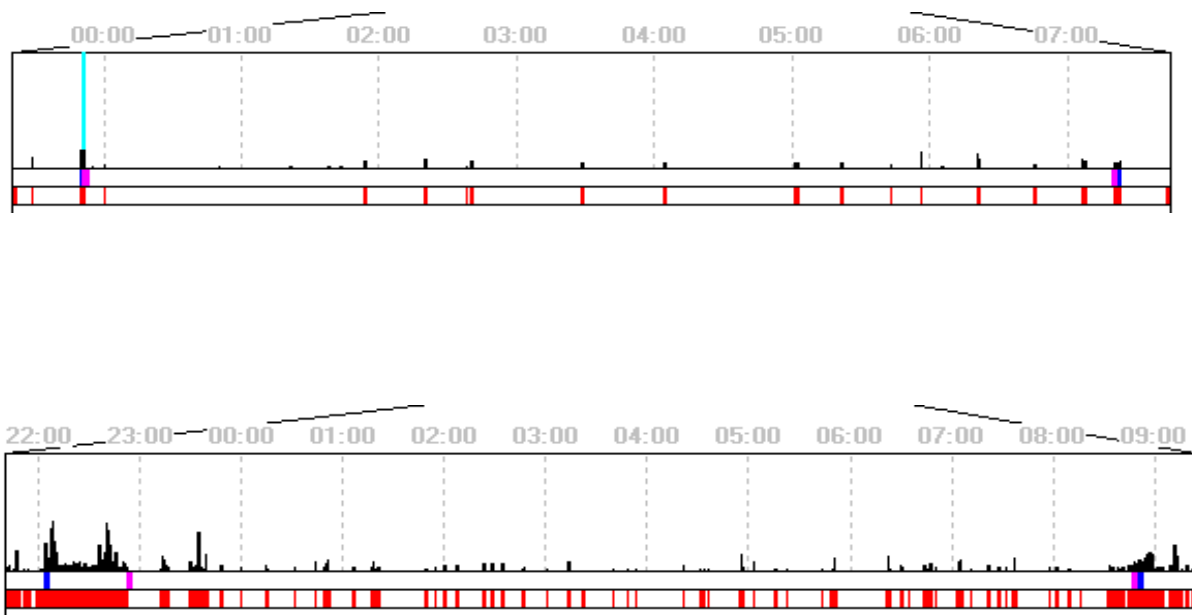


Figure 3.3. Example Actiwatch output comparing a 24 year old male sedentary control (above) to a 24 year old male professional football player. Vertical black lines signify movement, with the height of the bar based on the intensity of movement. The beginning and end of the sleep period is marked by vertical pink lines below the movement trace. Red and white coloured areas correspond to sleep/wake identification (based on comparison to EEG), with red areas corresponding to periods of wakefulness.

Returning to the significant interaction effect from the omnibus MANOVA, post-hoc univariate ANOVA's revealed that there were significant interaction effects between gender and activity type on the timing of sleep (both bed time and get up time). There were no significant interaction effects on the length of sleep or on any measure relating to sleep quality. Excluding basketball players (because there were no female basketball players included in the sample, figures 3.5 and 3.6 demonstrate the source of the interaction effect: while male football players go to bed and get up earlier than their female counterparts, this observation is reversed in swimmers and sedentary controls.

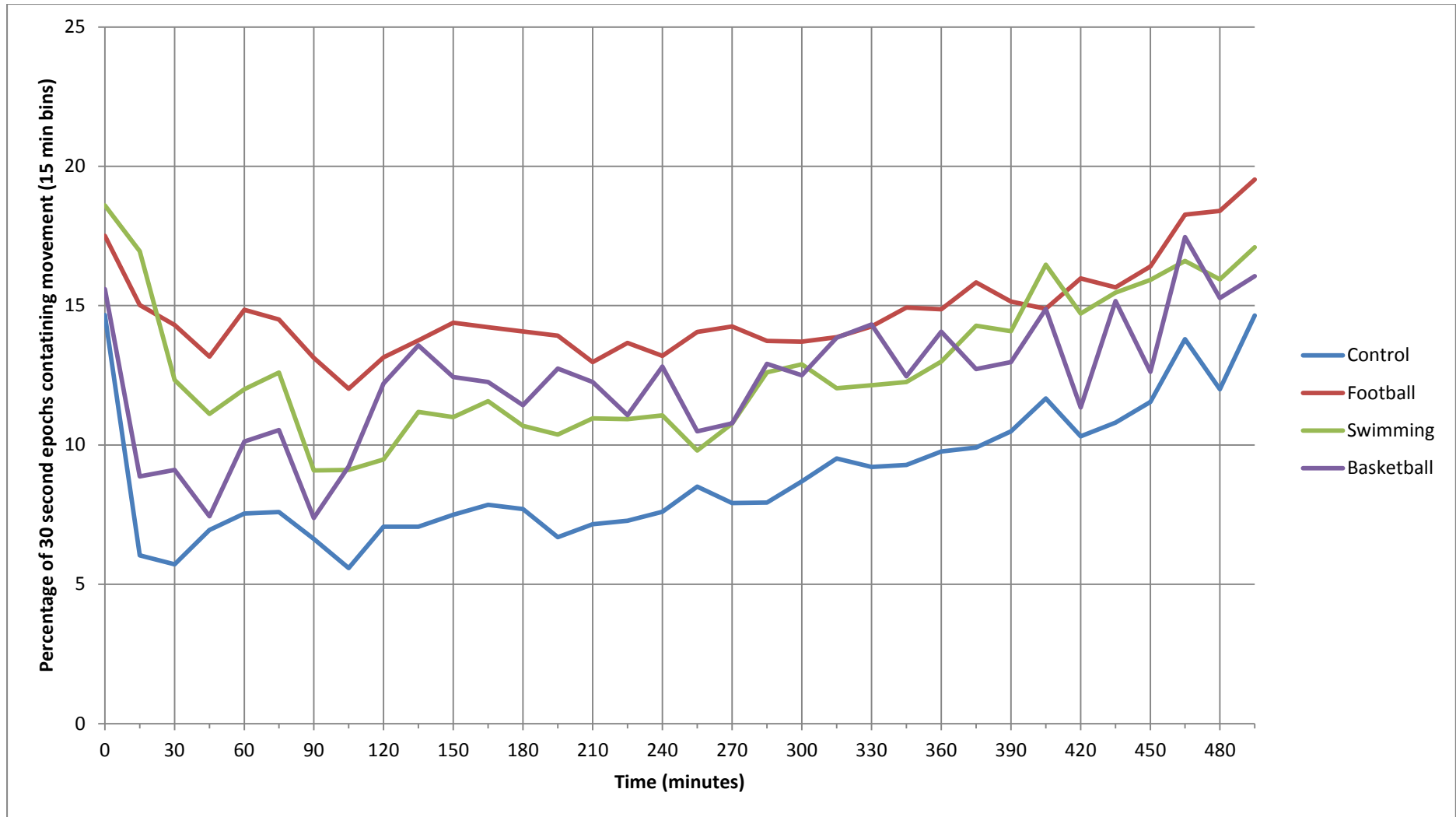


Figure 3.4. Movements level throughout sleep. Measured 30 second epochs are condensed into 15 minute bins, with each point showing the percentage of epochs in each bin containing movement.

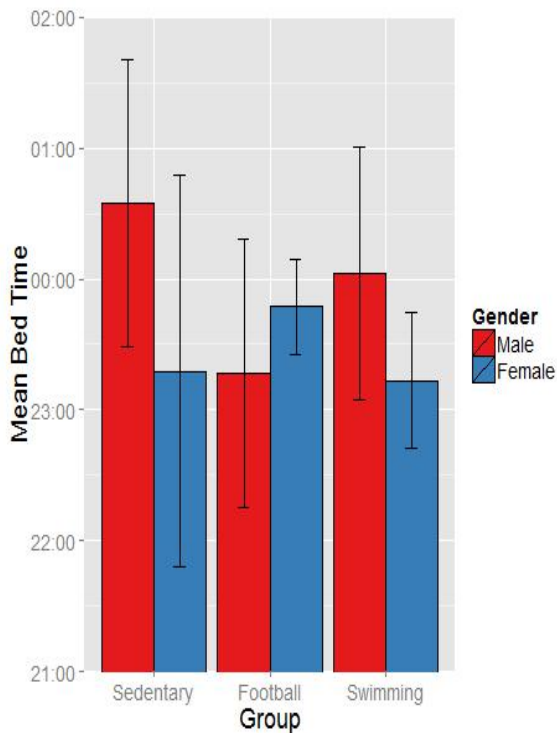


Figure 3.5. The interaction effect between gender and activity type on bed time

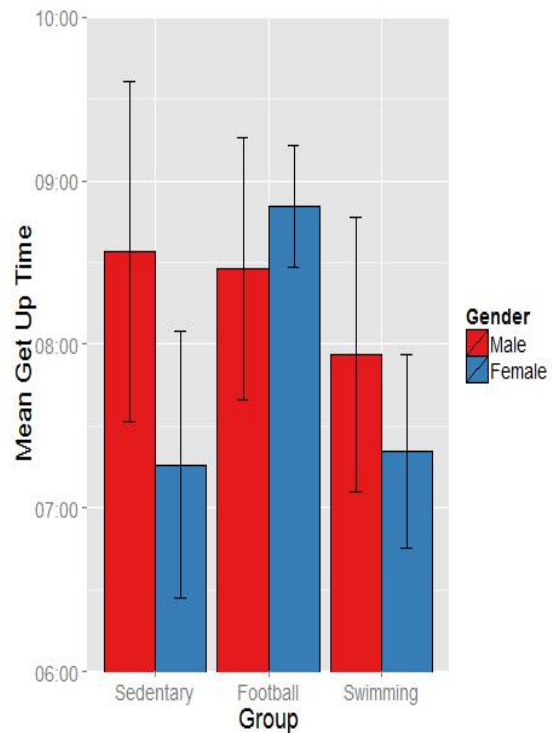


Figure 3.6. The interaction effect between genders and activity type on get up time.

3.5 – Discussion

3.5.1 – Evidence of Sleep Disturbance in Elite Level Athletes

The main findings of this study are to reinforce what has been discovered previously, (Erlacher et al., 2011; Leeder et al., 2012; Sargent et al., 2012) by demonstrating that there are significant differences in sleep between elite level athletes and sedentary control participants. The current study also extends the findings of existing work, representing the largest sample of objectively measured sleep in elite-level athletes, and is also the first to objectively measure the sleep of these participants during the regular competitive season, and not during the off-

season or during a period of higher than usual intensity training. The comparison between several different sports is also informative, as the varying characteristics of each distinct sub-group offers insight and explanation for some of the differences in sleep observed here. The differences in the timing of sleep represent a useful example. Among the data presented here, swimmers of both genders and male footballers retired to bed significantly earlier than other athletic groups. This is likely a direct consequence of the timing of training sessions in these groups, both of which regularly reported to training early in the day, and in the case of swimming often trained a second time in the late afternoon/evening. This disparity between male and female football players is likely a consequence of the fact that the female football players in this sample were based in a university team (and consequently trained in the afternoon or evening), while the professional male footballers would start training early in the morning. In contrast, early training sessions are almost ubiquitous among elite-level swimmers, regardless of whether they are university-based or not. This is a consequence of the demands of swimming being a sport that largely depends upon physical conditioning, which mandates multiple training sessions per day. In order to allow for adequate recovery between sessions, the first training session usually takes place very early in the day. This serves to highlight the heterogeneity between the sleep pressures that athletes face, not just for athletes in different sports, but also between athletes in the same sport but train in different contexts.

3.5.2 – Possible Contributory Factors to Poor Sleep in Athletes

There are a number of factors which could cause or at least contribute towards the disturbance of sleep found in these data, as has been discussed in chapter one of this thesis. There are however a number of further considerations to bear in mind in the light of the data presented here.

Regarding the impact that anxiety can have on sleep in elite-level athletes, for instance, is most often considered in terms of the impact that pre-performance anticipatory anxiety can have on the period of sleep immediately preceding a competition (e.g. Savis, 1994; Davenne, 2009). The results presented here however make it clear that sleep disturbance is consistently in evidence in athletes for a protracted period of time, and does not appear to depend significantly on proximity to a competition. This is particularly demonstrated by the swimmers in the sample, who, unlike the football players and basketball players, had no competitions during the study period. If it is indeed the case that anxiety is one of the contributory factors to poor sleep in athletes, this strongly suggests that it is not limited to specific periods of anxiety, but is a more chronic feature of athletes' sleep. As has been previously noted, anxiety in elite-level athletes is not limited just to periods immediately before competitions, but is also likely to be brought about due to other factors, such as the fact that not only are athletes competing against opposition teams, they are also competing with other members of their own team for inclusion in upcoming competitions. All the football teams in the sample above for instance maintained a 'front bench' team of at least twenty players, but only eleven to fifteen players will play in any given match. Being persistently left out of the match squad will have a

detrimental impact on a player's future career, and so the constant need to impress the management and coaching staff at their team to ensure selection will be a constant source of stress for players.

Another factor which could conceivably be contributing towards poor sleep in athletes stems from the level of physical exercise that is the predominant feature of athletes' day-to-day lives, both in the form of competitions and training. While epidemiological evidence suggests that the widely held belief is that exercise has a positive impact on sleep (Youngstedt & Kline, 2006; Sherrill et al., 1998; Vuori et al., 1988), empirical evidence for this belief is fairly scarce, in addition to depending on studying the impact of recreational levels of exercise on good sleepers (Driver & Taylor, 2000). Neither of these conditions could reasonably be said to apply to elite-level athletes. In contrast, evidence from the study of 'extreme' levels of exercise (marathon type distances and above; Baekland & Lasky, 1966; Shapiro, Bortz, Mitchell, Bartel & Jooste, 1981; Taylor, 2001), suggests that this level of activity tends to have a deleterious impact on subsequent sleep. Another factor to consider when thinking about the impact that exercise can have on sleep is the time of day at which that exercise takes place. Yamanaka et al., (2010) demonstrated that exercise can exert an influence on circadian rhythms even over an acute period. Considering that the timing of competitions is not particularly stable, large changes to the scheduling of sleep could be exerting a continuously deleterious impact on sleep as a consequence. This is particularly true among the professional football players in this sample could vary on a weekly basis between a 'kick-off' time at 1300 hours in the afternoon to 2000 hours in the evening. In combination with matches taking place away from home, this contributes in many cases to a large degree of variability in the sleeping schedules of football players, which is a significant cause for concern from

the perspective of sleep hygiene (Wang, Yang & Tsai, 2005; Hauri, 1977; 1992). The impact that physical activity taking place during training and matches can have on sleep, in addition to the impact that the timing of matches can have on sleep will form a part of the remaining investigations in this thesis.

3.6 – Conclusions

The data presented here have largely backed the conclusion that has been reached by previous studies and anecdotal reports, that sleep disturbance is common among elite athletes. The current work is distinct from existing research by being the first to objectively verify the presence of significant sleep disturbance during the competitive season, rather than during the off-season (Leeder et al., 2012) or during periods of unusually intensive training (Sargant et al., 2012). In terms of sample size this is also the largest study to objectively measure sleep in elite level athletes.

The presence of significant and enduring sleep disturbance among elite level athletes raises a number of questions which will now be addressed during the remainder of this thesis. First and foremost, the impact that sleep can have on performance will be investigated, both during training and during competitive matches in professional football players. In addition the impact that participating in elite-level sport can have on sleep will be examined, including the impact that engaging in regular strenuous activity can have on sleep, as well as other factors such as the organisational stressors associated with competition.

3.7 – Summary

- Elite level athletes demonstrate markedly different sleep to sedentary controls, particularly a significantly lower sleep quality, in agreement with previous research.
- This disturbance is apparently relatively stable during the competitive season, and not confined to pre-competition periods.
- This disturbance is also present throughout the sleep period, and is not confined to any specific portion of sleep.
- There are also specific differences in sleep between groups of athletes (e.g. the timing of sleep in professional athletes compared to student athletes).
- There are a wide variety of factors which may be contributing to sleep disturbance, and existing research suggests that such disturbance would be expected to have a number of negative effects on athletes.

Sleep and Match Performance in Professional Football Players

4.1 - Introduction

While the contention that adequate sleep is an important factor for athletes seeking to achieve maximum performance is a popular one among athletes and their coaches (Erlacher et al., 2011; Savis, 1994), empirical data supporting this notion is difficult to come by, and even more difficult to apply to actual performances of real athletes. All the of the existing research presented thus far has tended to research the impact of acute periods of severe sleep restriction, on laboratory based measures of performance, in 'normal' or otherwise non-elite athletic participants. While it has been acknowledged several times the importance of the role that participants' motivation to perform under conditions of inadequate sleep (Martin, 1981; Souissi et al., 2003; Rodgers et al., 1995; Bambaechi et al., 2005), there has yet to be any research studying athletic performance in a motivationally relevant environment.

This lack of research is likely due in no small part to the practical difficulties associated with the methods most commonly adopted by the sleep research community of total or partial sleep deprivation. It seems highly unlikely that an athlete or coach of an elite athlete would be willing to subject themselves to reduced sleep before an appropriately important competition, in the way that a sleep researcher may wish to subject someone to such an ordeal; because of the suspicion that a decrement in performance would be the result. An alternative method to investigate the relationship between sleep and performance is therefore necessary. A number of recent studies have advocated the use of wrist actimetry as being particularly suitable to the study of sleep in athletes (Erlacher et al., 2011; Leeder et al., 2012;

Sargent et al., 2012) since it allows objective recording of sleep for a protracted period of time, with minimal interference to sleep itself. Such a method would entail measurement of sleep for a period of time sufficient for natural variations in sleep to occur, and simultaneously observing the performance of athletes over the same time period to enable the relationship between sleep and subsequent performance to be investigated and modelled.

An additional benefit of employing such a model is that it would enable a number of further questions to be investigated. Previous literature has highlighted, for example, that a majority of athletes have reported specific problems with sleep before competitions (Erlacher et al., 2011). The collection of objective sleep data for a protracted period would enable a comparison between the sleep that athletes get habitually throughout the season, compared to sleep the night before competitions. Another useful comparison would be to compare sleep before home games to sleep before away games. While sleep the night before a home game may be easier and more routine, since athletes are able to sleep in their own beds near to the place of competition, sleep before away games will often necessitate sleeping in a hotel the night before (which had been demonstrated as having a negative impact on sleep; Davenne, 2009) or travelling long distances on the day of competition, which could place a constraint on an athletes' normal sleeping time. In addition the concept of a 'home-field advantage' is a well-established phenomenon in the Sport Psychology literature, having been observed in a number of sports (Bray & Widmeyer, 2000; Waters & Lovell, 2002; Anderson, Wolfson, Neave & Moss, 2012). A number of contributory factors have been considered, such as crowd behaviour, venue familiarity, referee bias and territoriality. While travel fatigue and routine disruption have been considered as potentially explanatory factors (for away team impairment

rather than home team improvement), it does not appear that the specific role of sleep has been studied itself. Collection of sleep data over a long period will afford such an opportunity.

Finally, just as sleep is thought to be an important factor in influencing subsequent performance, it is also supposed that exercise will exert a reciprocal effect on sleep (Sherrill et al., 1998; Vuori et al., 1988). There is however, a disagreement in the direction of this supposed influence, with some suggesting a positive influence (Brand et al., 2010; Youngstedt & Kline, 2006) and others finding a negative influence (particularly when the exercise is intense and sufficiently close to bed time; e.g. Souissi et al., 2012). Long-term objective sleep data will also enable a comparison to be made between athletes' habitual sleep and their sleep following competitions in order to examine the validity of these suppositions during the competitive season, and without artificially influencing the sleep of the participants involved.

Clearly such a study would also require the use of a valid and reliable measure of performance to compare against the sleep data obtained from participants. The difficulties of performance measurement are perhaps another reason why sleep research has historically taken place in laboratories; the controlled environment allows specific aspects or components of performance (such as reaction time, decision making etc.) to be isolated and studied in a reliable (if not ecologically valid) way. Given the importance of the motivational climate in which a performance takes place, a 'real-life' measure of performance is required.

Fortunately professional football clubs already assess match performance objectively using the Prozone® system, which provides an accurate player-tracking capability during competitive matches. Sports scientists embedded within professional football

teams have been making use of the data this system provides for a number of years to gather objective information regarding the performance of both individual players and teams.

4.2 – Aims

While it seems to be a rather widely held view that adequate restful sleep is at the very least an important factor contributing towards achieving optimal athletic performance, this proposition has been troublesome to examine properly due to a number of methodological and practical difficulties. The current study aims to investigate some of the more commonly asked questions, without experimentally manipulating sleep and by measuring performance as it occurs naturally, rather than in a contrived environment, due to the evidence highlighting the important role that the motivational climate has in determining how people cope with sleepiness. Due to the difficulties associated with trying to manufacture sleep deprivation in the more 'traditional' manner in elite-level athletes, sleep will instead be measured for an extended period of time in order for natural variations in sleep to occur. The impact that these variations have on subsequent performance will then be investigated. A number of comparisons will also be made between how the sleep of athletes in specific situations, namely comparing athletes' habitual sleep to their immediate pre-performance sleep, and their sleep before home competitions compared to before away competitions. Conversely, the potential impact that competing can have on subsequent sleep will also be investigated, by investigating the relationship between

the levels of physical activity during competitions with subsequent sleep, and also comparing sleep after competitions with habitual sleep.

The athletes that will be investigated in the current study will be professional footballers, since there are a number of advantages with this population. Primarily the structure of competition is such that during the competitive season matches take place on a weekly basis, with players' usually playing at least once (and often twice) per week, providing ample opportunity for the collection of performance data from matches. The existence and widespread use of the objective Prozone® match analysis software is another large advantage, since it will enable the collection of validated performance data, which is already used by professional teams, so any results will be immediately understandable and useful to the participants themselves. Finally, the fact that performance measurement is so widespread in this population should mean that participants will be accustomed to being scrutinised in this way, resulting in a minimum level of disruption to their daily routine.

Research Questions

- Is there a relationship between sleep and performance in professional football players?
- Is there any change in sleep before competitions, and does this vary depending on the location and/or time of competition (i.e. home or away, afternoon or evening)?

- Does the strenuous activity involved in elite level competition have a direct impact on subsequent sleep, and does this vary according to location and/or time of competition?

4.3 – Method

4.3.1 – Participants

A total of 26 professional football players currently playing for 2 professional football clubs in the English and Welsh Football league (1 team competing the in the Premiership division; n = 9 players, the other in the Championship division; n = 17 players), were recruited for the study, with an average age of 25.4 years (SD 4.0 years). At the beginning of the study all participants were considered by their club as belonging to the 'first team', and were training on a daily basis and competing on a weekly basis. Participants reported no evidence of pre-existing sleep disorders, and were not excessive users of caffeine or alcohol. Participants were approached through their club, and were told of the study's aims and methods before consenting to participate.

4.3.2 – Sleep Recording

Sleep data were recorded from participants for a period of 2 months during the regular competitive season, using an Actiwatch AW4® (CamNTEch, Cambridge, UK), during which time participants were asked to wear the device continuously, except for bathing, training and competing (to prevent damage to the monitors, and because rules prevent players from wearing any ‘superfluous’ items on their person during competition). This yielded a total of 661 nights of sleep data from all 26 participants, considerably less than the maximum amount of data. This is attributable to mid-season transfers resulting in participants leaving the club, players’ omitting to wear the monitor during periods of injury, and simple forgetfulness. A total of 20 players contributed at least three nights of pre-match sleep data, totalling 81 nights where match data was also available (12.3%; approximately what would be expected for players competing on average, once per week- 14.3%). Participants were instructed to use the event marker of the Actiwatch to indicate ‘bed time’ and ‘get up time’, as described in section 3.3.2.

Sleep data was analysed using the proprietary Actiwatch Sleep Analysis Software 7 (CamNTEch, Cambridge, UK). Data was collected in 30-second epochs, and the medium sensitivity setting was used for sleep/wake identification. Analysis was conducted examining the timing (bed time, get up time), duration (total sleep time; TST), and quality of sleep (sleep efficiency, SE; sleep onset latency, SOL; wakefulness after sleep onset, WASO; and movements per hour during sleep, movements/hour). Details of how these variables are measured using wrist actigraphy are discussed in section 2.1.

4.3.3 – Match Performance

Match performance was measured using the ProZone® image-based player tracking system (ProZone, Leeds, England). An array of 8 video cameras installed in football stadia accurately track all 22 players during the course of a football game, with a measurement frequency of 10Hz. Pythagoras' Theorem is then used on this raw data to calculate the direction and speed of each player during 0.5 second epochs. This tracking system was already being widely used by the sports science staff at the clubs of participants, who were consequently familiar with the output from the system as it was used by them on a daily basis to accurately and objectively measure the performance of players during competitive matches. Discussions with the sports science support staff led to the decision to focus on the total distance covered (since it has a strong relationship with a players total workload; Boyd, 2011), and the amount of distance covered at high intensity, defined as average speed during a 0.5 second epoch above 19.8 km/h (due to the importance of such activity in determining the outcome of matches; Mohr, Krusturup & Bangsbo, 2003; Di Salvo et al., 2009). In order to examine the impact of physical activity on subsequent sleep, the above measures were used as predictors as well as the total playing time and the number of accelerations identified by the ProZone® system. Due to the rules of the English and Welsh Football Association prohibiting the wearing of superfluous items during competition, players are not allowed to wear accelerometers or heart rate measuring devices as they do in training, so these four measures are those commonly used by the support staff to estimate the amount of physical effort applied by players during matches (although it is worth noting that such strict rules are not in

force in a number of European domestic leagues, where the use of wearable tracking technology is permitted).

The collection of these performance measures was already being conducted by the teams of players, and was made available for the present analysis with the permission of the teams and individual players in question.

4.3.4 – Analyses

Statistical analysis was conducted using R (Version 2.15; R Core Development Team, 2012). A list of the attached packages used is available in Appendix A. Comparisons of sleep in different circumstances (e.g. pre-match sleep vs habitual sleep) were analysed initially by repeated measures t-tests, with the Bonferroni adjustment applied (Field, Miles & Field, 2012). While a MANOVA would generally be preferable in situations with multiple outcome measures, this test assumes that multiple measurements on the same individual take place at regular intervals (Field, 2009; Field, Miles & Field, 2012). Each individual's pre-match sleep and non-pre-match sleep must be averaged so that each individual contributes only one measure for pre-match sleep and one for non-pre-match sleep for each outcome measure. This would violate the assumption of equally spaced measurements for a MANOVA analysis. The only alternative to using average scores in this instance would be to trim the data set to only use data from dates that all participants have in common, which would be impractical and not leave sufficient data for a meaningful test. Paired t-tests on each outcome were therefore used, with the Bonferroni

adjustment to control for the inflated familywise error rate associated with multiple comparisons. Significance was set at 5% (two-tailed) in all cases.

To examine the relationship between sleep and subsequent performance, and the relationship between levels of physical activity and subsequent sleep, multilevel modelling was conducted. The seven sleep parameters were each assessed for the extent to which they predict performance, which was itself measured using the 'total metres' and 'high intensity distance' measurements taken by the Prozone® player tracking system, which the sports science support staff at the participating football clubs indicated were the two most important and reliable measurements that were used within the team. Both predictor and outcome variables were standardised by means of a z-transformation according to each individual's average and standard deviation. This standardisation serves a number of purposes. Primarily, it places each individuals' measured scores on the same scale making them directly comparable in a way they would not be if measured using raw scores (e.g. a bed time of 2300 hours might be an early night by one person's standards, and a late night by another's, while a bed time z-score of zero would indicate a bed time consistent with a person's average bed time for all participants). Z-scoring is also serves to 'group-mean centre' the data, which has a number of statistical advantages according to Field, Miles and Field (2012), such as improving the stability of predictors and increasing the independence of estimates which is beneficial when comparing different models. Finally, having scores which centre around zero simplifies the examination of non-linear relationships between predictors and outcomes (where they may occur).

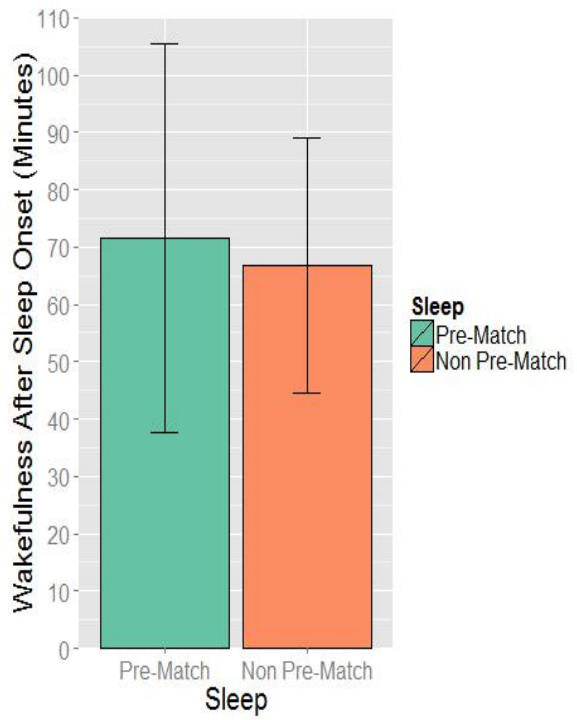
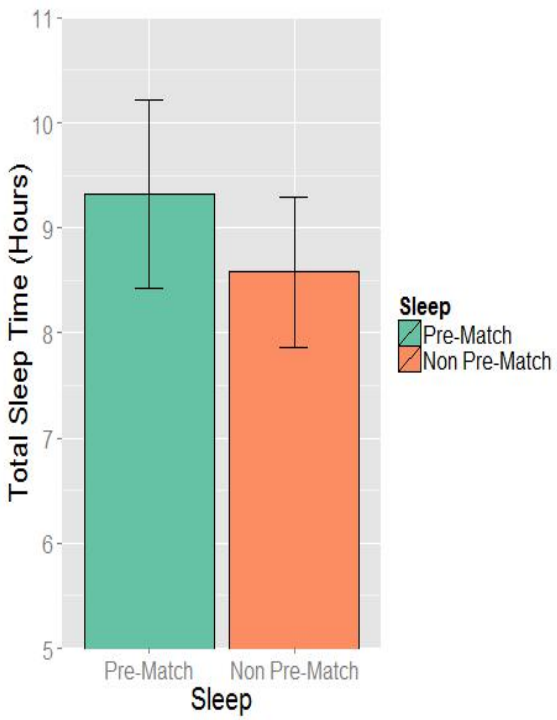
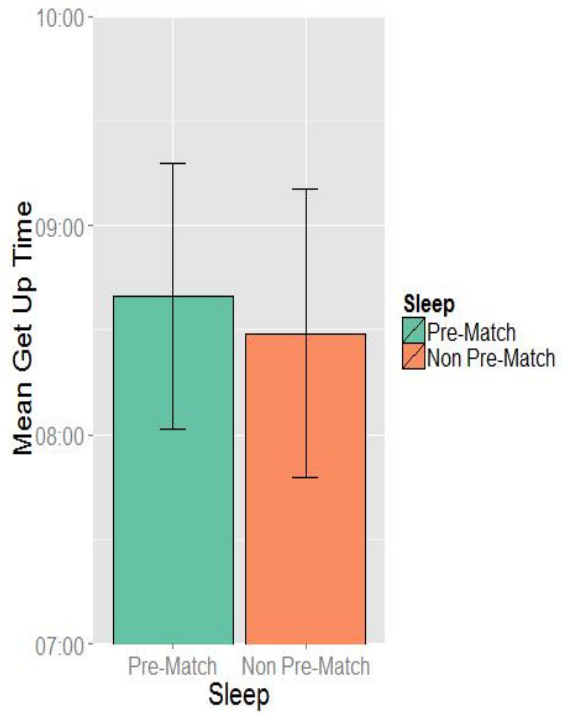
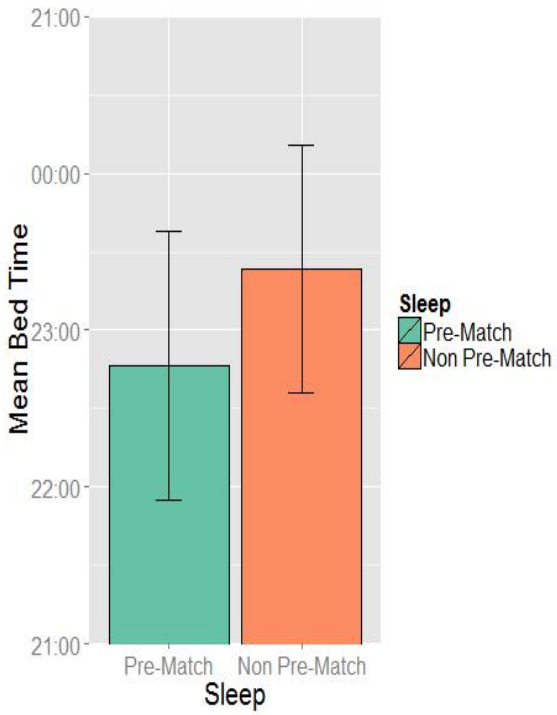
Initial exploration was conducted using the 'all possible subsets' analysis contained within the 'leaps' (Lumley & Miller, 2009), package attached to R, which

computes the model fit using all possible combinations of predictors. Using this to inform a starting point, predictors were then inserted and removed from the model systematically to find the most parsimonious model. Both linear and polynomial non-linear relationships between predictor variables and outcome variables were considered. Model fit was analysed using the 'anova' function in the 'stats' package (R Core Development Team, 2012).

4.4 – Results

4.4.1 – Pre-Match Sleep

Recorded nights of sleep were classified based on whether they immediately preceded a match in which the individual was competing or not. Each individual's measured sleep for each of the seven output parameters was averaged for both 'pre-match sleeps' and 'non-pre-match sleeps'. These data are presented in figure 4.1. Average scores were then analysed by repeated measures t-tests corrected with the Bonferroni adjustment, the results of these tests are summarised in table 4.1 (Appendix C), showing the mean for each sleep parameter for both conditions, and the results of the paired samples t-tests. There was a tendency for players to retire to bed significantly earlier (mean difference 37 minutes, $t_{19} = 3.554$, $p = 0.002$, two-tailed) and sleep for longer (mean difference 44 minutes, $t_{19} = 3.887$, $p = 0.001$, two-tailed) the night before matches, however while all measures of sleep efficiency demonstrated a slight decline the night before matches (increased WASO, SOL, onsets/hour, and reduced SE), these differences were not statistically significant.



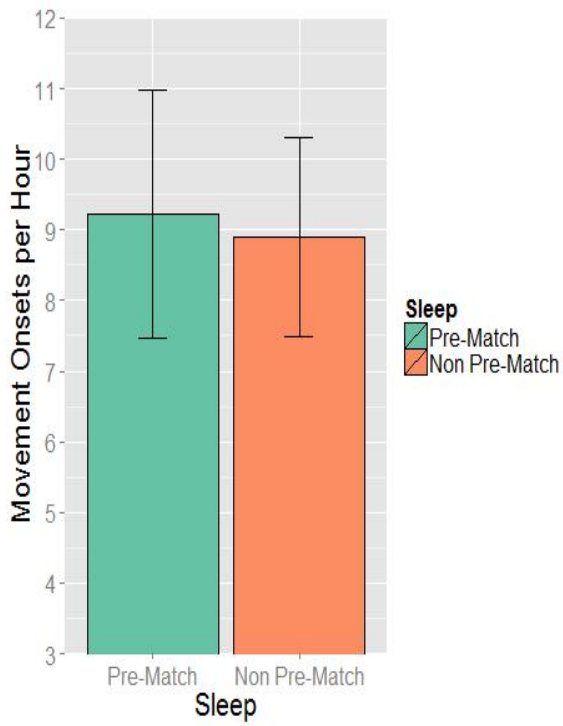
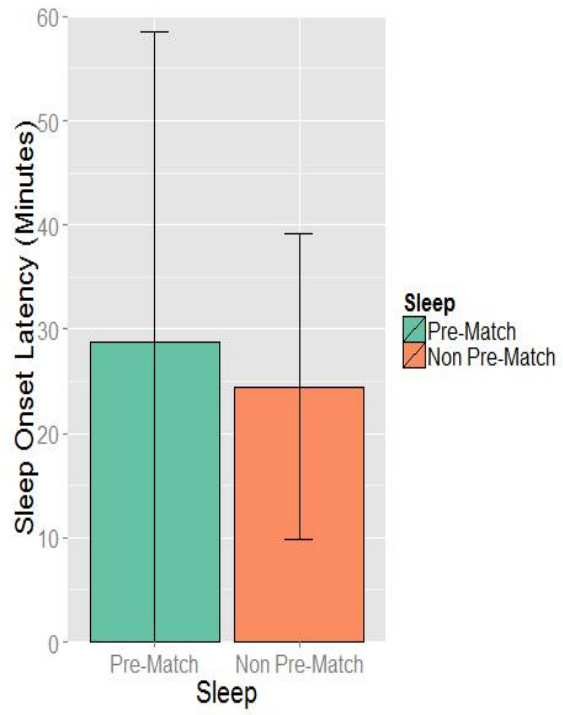
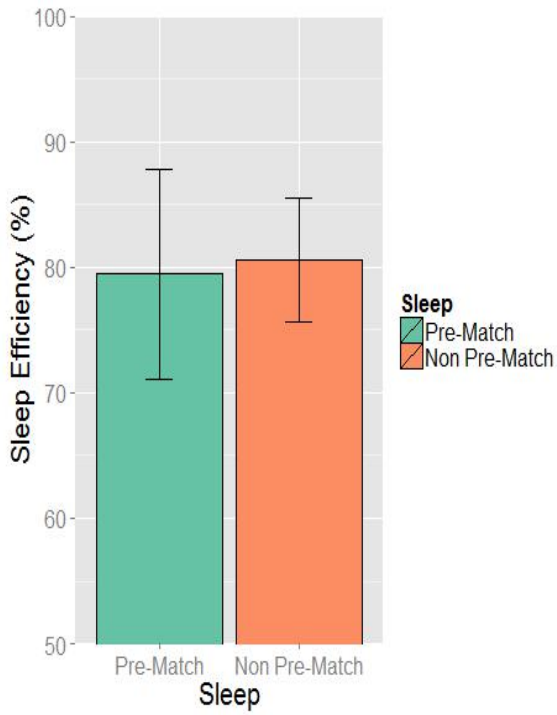
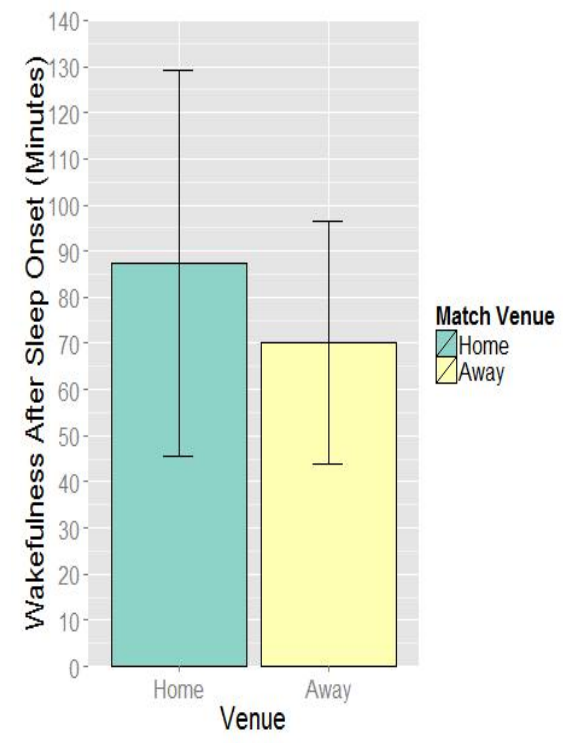
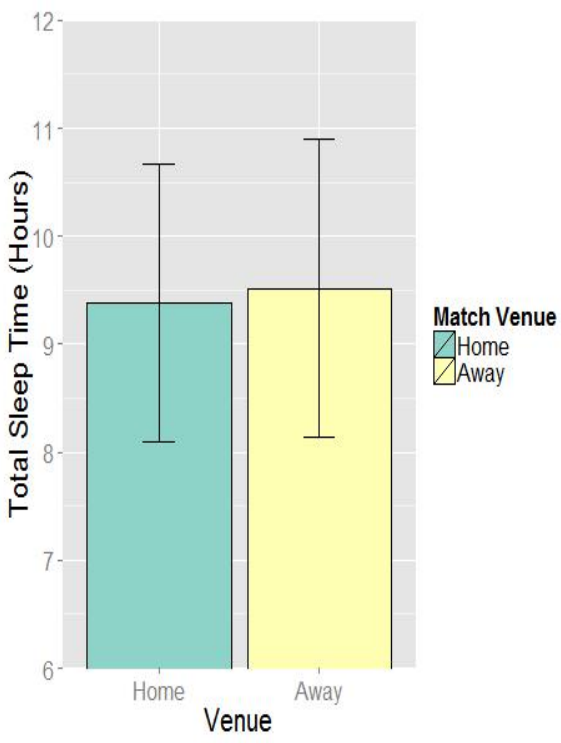
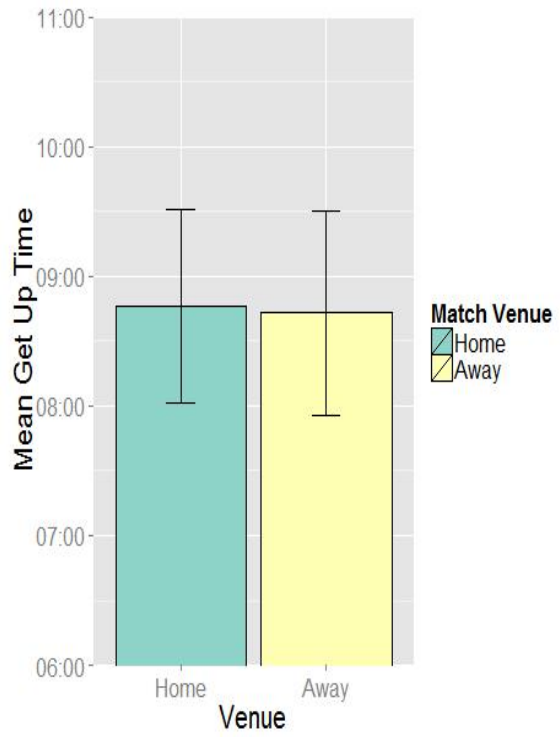
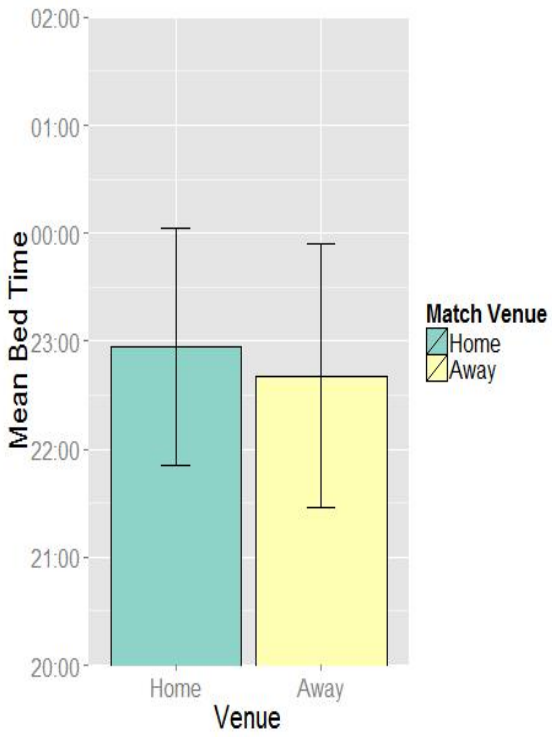


Figure 4.1. Differences in sleep taking place the night before matches compared to sleep not taking place before matches. Bars represent mean averages; error bars represent 1 standard deviation.

4.4.2 – Pre-Home Match Sleep Compared to Pre-Away Match Sleep

Selecting only nights of sleep taking place before matches, data were split into those which occurred the night before a game played at home and those taking place before games played away from home, as shown in figure 4.2, which seem to suggest that there were no significant differences in sleep in these circumstances. This was confirmed by paired samples t-tests, with the Bonferroni adjustment applied, the results of which are summarised in table 4.2 (Appendix C).



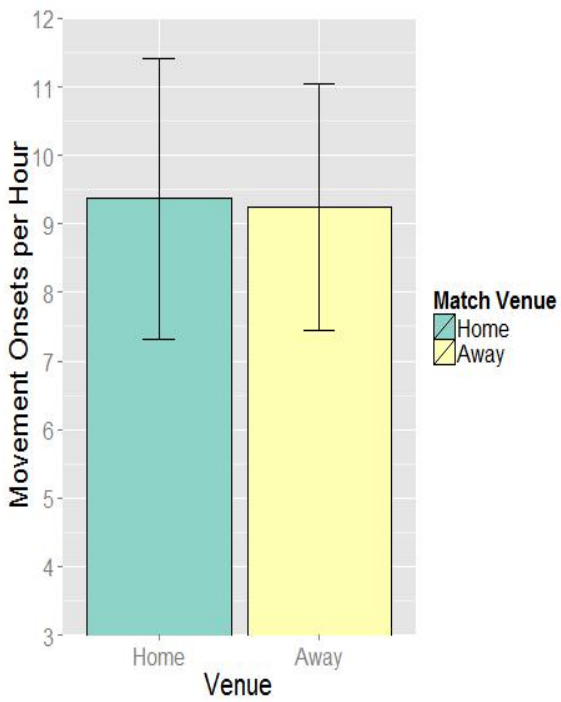
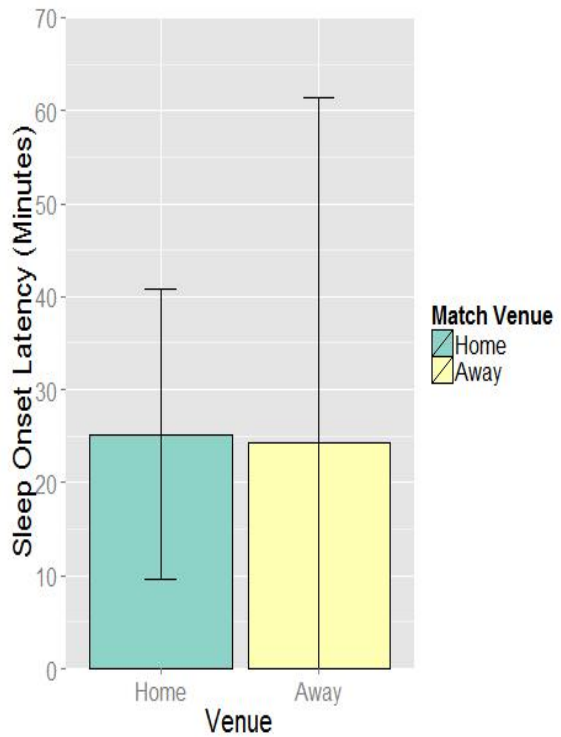
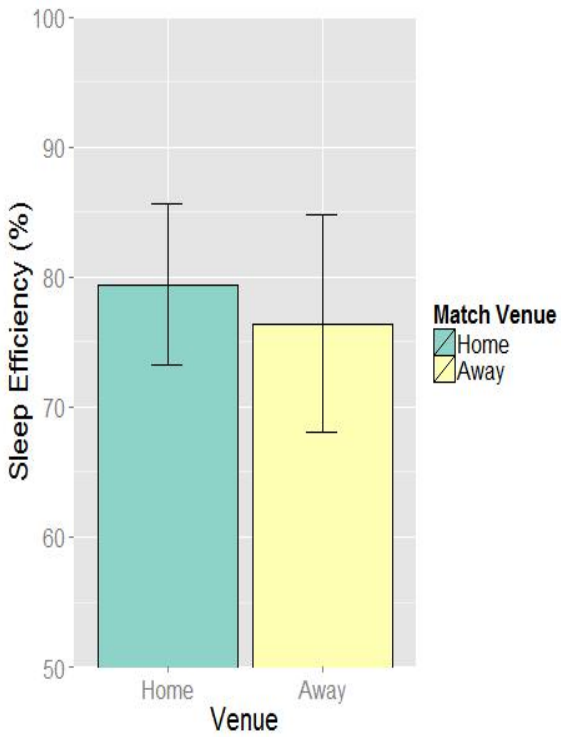
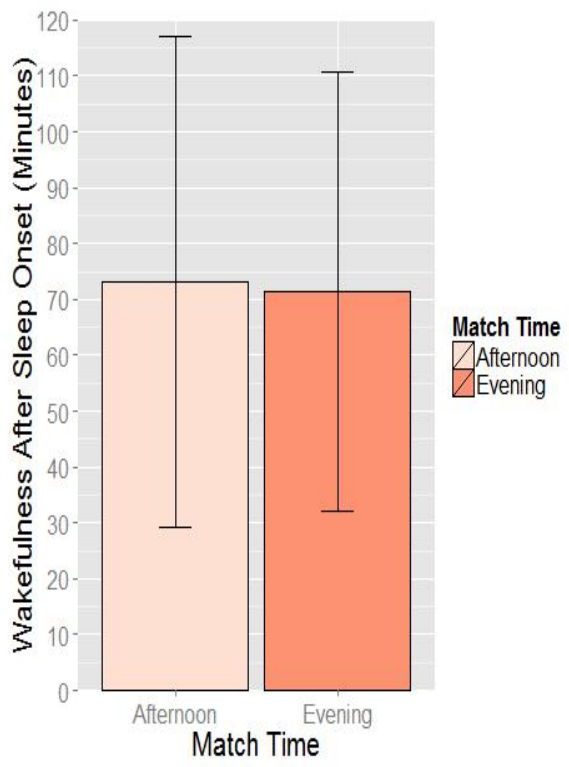
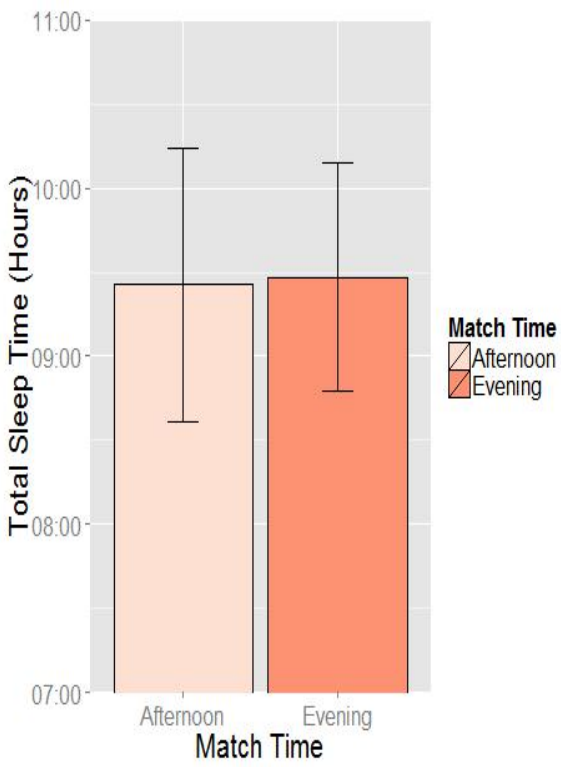
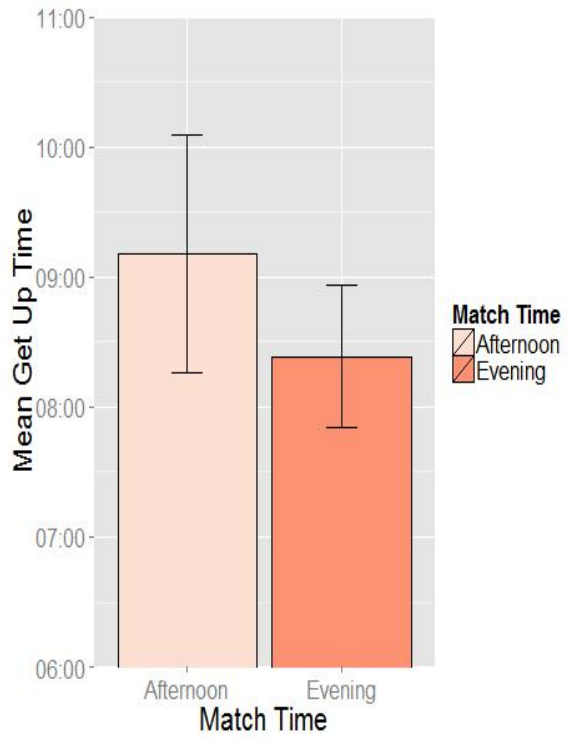
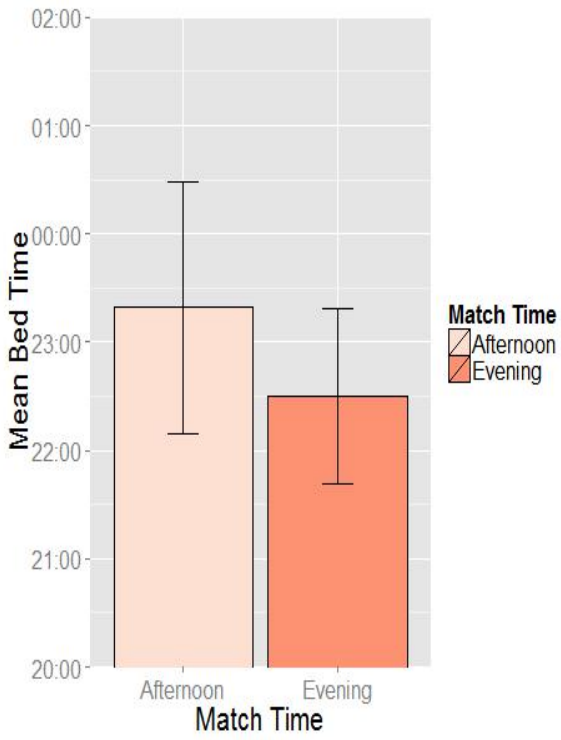


Figure 4.2. Differences in sleep taking place the night before home matches compared to sleep taking place the night before away matches. Bars represent mean averages; error bars represent 1 standard deviation.

4.4.3 – Sleep Before Afternoon Matches Compared to Sleep Before Evening Matches

Again selecting nights of sleep taking place before matches, data was split into those nights before an afternoon match compared to nights before an evening match. Afternoon matches had a 'kick-off' time of between 1300 and 1500 hours, while evening matches had a 'kick-off' time of between 1915 and 2030 hours. These data are presented in figure 4.3. There appears to be no significant differences in the length and quality of sleep in these two situations, although a difference may exist in the timing of sleep. Statistical analysis by paired samples t-test confirms this, with evidence that players' arose significantly earlier before evening matches than before afternoon matches (mean difference 48 minutes, $t_{19} = 2.475$, $p = 0.043$, two-tailed) matched by a trend (albeit a non-significant one, mean difference 49 minutes) for players to retire to bed earlier before evening matches than before afternoon matches. A summary of this analysis is presented in table 4.3 (Appendix C).



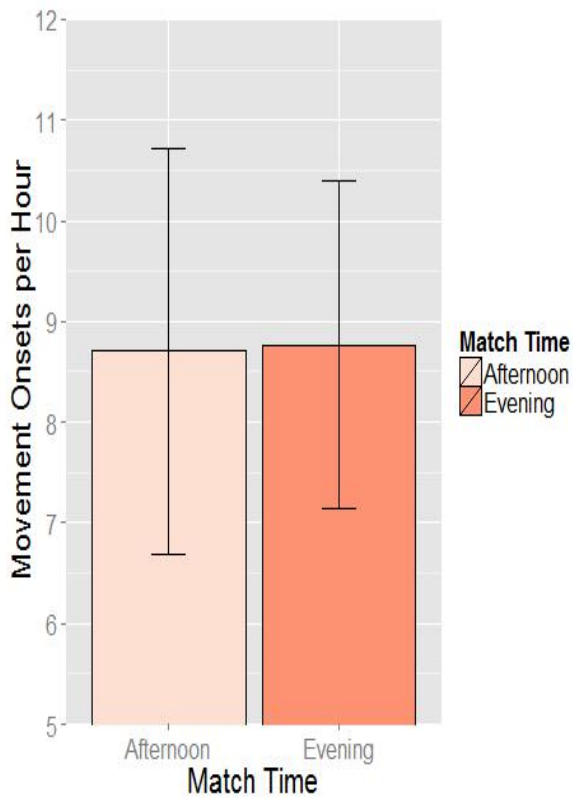
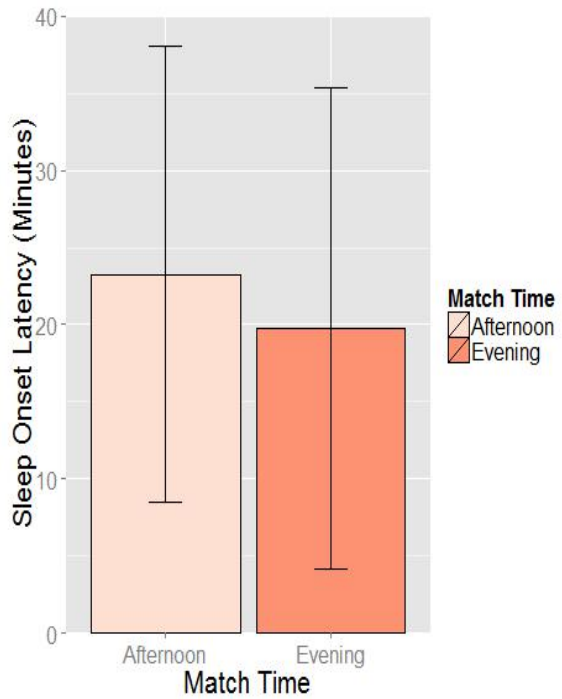
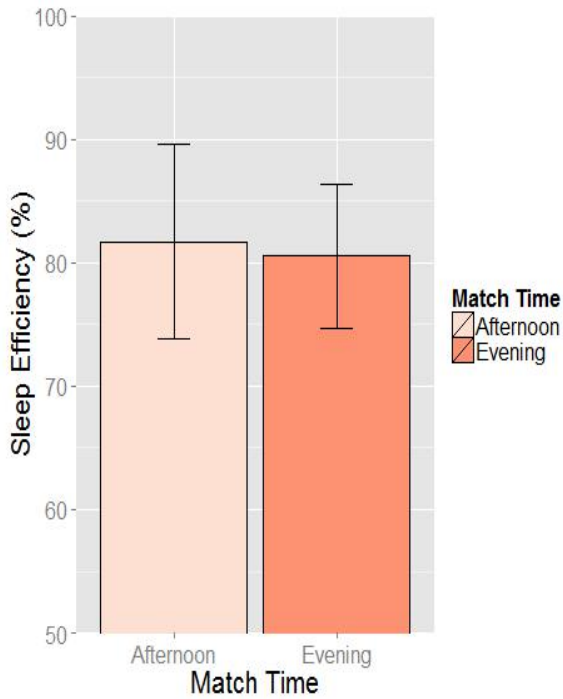


Figure 4.3. Differences in sleep taking place the night before afternoon matches compared to sleep taking place the night before evening matches. Bars represent mean averages' error bars represent 1 standard deviation.

4.4.4 – The Relationship Between Sleep and Subsequent Performance

For each of the outcome variables, each z-scored predictor was entered individually into the multi-level model, once as linear factor and again as a second order (ie parabolic) polynomial. In all cases, attempting to model predictors as having a parabolic rather than a linear relationship with the outcome measures did not significantly enhance the fit of the model, so for the sake of parsimony, a non-linear relationship was discarded in favour of the simpler linear relationship. All of the models presented here take the form of a 2-level multi-level model, where each individual measurement of sleep and subsequent performance constitutes the first level, with each individual's measurements being grouped according to the individual as the second level. The use of a players' on-pitch playing position (ie, goalkeeper, defender, midfielder, striker) and the team to which players belong (since two teams are included in the analysis) were considered as higher level groupings above the second level grouping. Two 3-level (one with playing position, the other with team entered as groupings above the second level) models and single 4-level (with both higher level groupings) were considered, but in all cases these higher level models did not significantly improve model fit, while increasing the level of complexity, and were thus discarded in favour of the more parsimonious 2-level models.

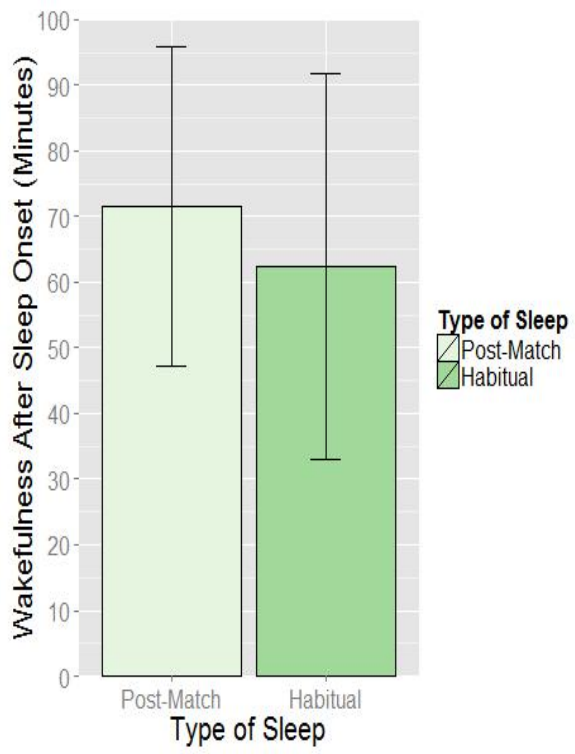
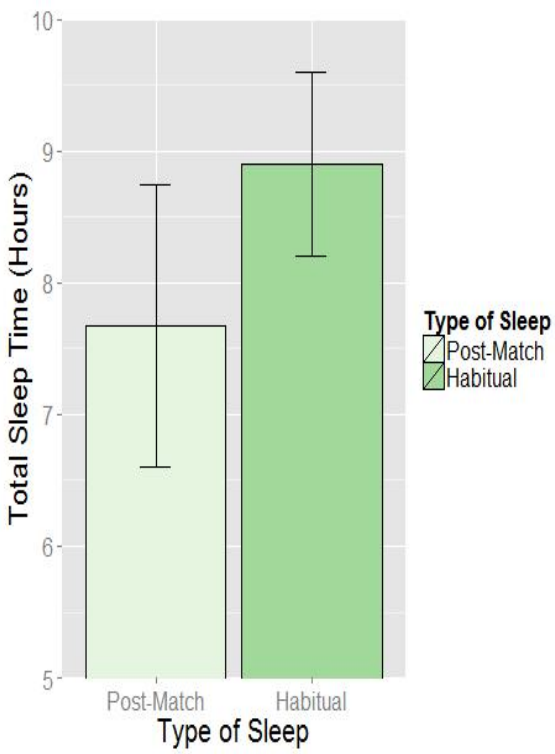
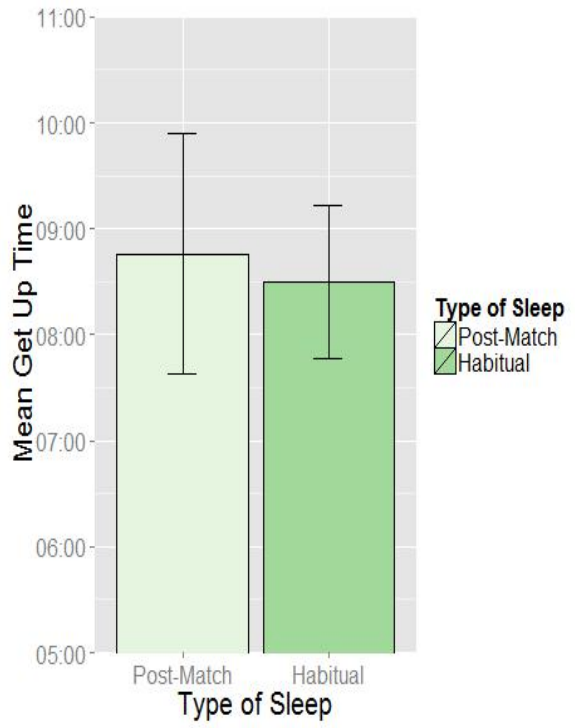
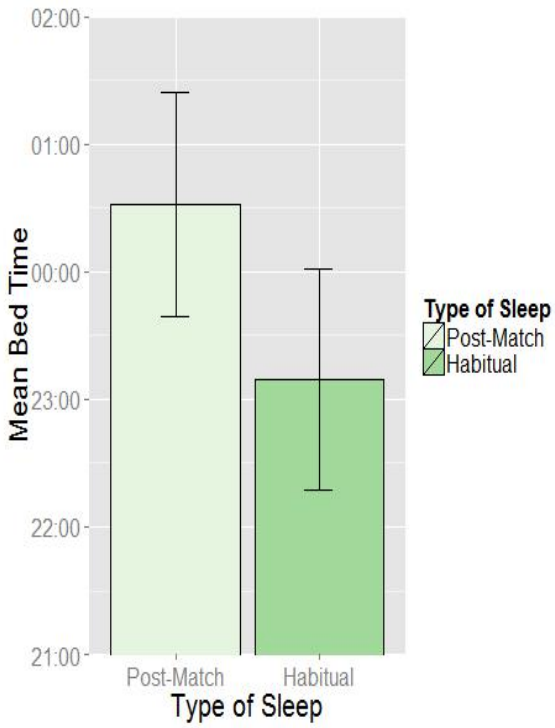
A summary of the results of the 2-level modelling attempting to predict variation in the outcome variables based on each predictor, entered independently of all other predictors, is presented in table 4.4 (Appendix C). While the overall trend seems to be that indicators of good sleep have a beneficial impact on subsequent performance (e.g. a negative relationship between bed time and performance,

positive relationships between sleep quality measures and performance), none of the specified predictors demonstrated a significant relationship with performance. In addition, in the majority of cases (with the exception of the Z-score of total metres covered), the standard error of the regression coefficients crossed zero suggesting there is some uncertainty even as to the direction of the relationship.

Further analysis was conducted to examine the feasibility that models including multiple predictors in combination could provide a more detailed fit to the data. An 'all-possible subsets' analysis was conducted to aid in guiding the direction of this investigation and provide a starting point for more detailed model building, which was then explored manually by adding and removing predictors to investigate the impact upon model fit. While for both outcome measures the fit of the model to the data was improved by the inclusion of multiple predictors, statistical comparison of the model fit using the log-likelihood method (Field, Miles & Field, 2012; Pinheiro & Bates, 2000) demonstrated that the improvement to model fit was not significant. This is most likely a result of collinearity among predictors, so that any attempts to include multiple predictors, while increasing the relative complexity of the model, does not offer a large increase in explanatory power as the inclusion of additional predictors does not further account for variation of the outcomes, as it is essentially the same variation that has (largely) already been accounted for.

4.4.5 – Post-match Sleep

Sleep data was classified as either occurring the night after a match, or as 'habitual' sleep nights, defined as nights of sleep not taking place the night following a match, nor immediately preceding a match. These data are presented in figure 4.5 and appear to demonstrate a later bed time the night following a match, as well as a shorter total period of sleep. Data were analysed by repeated measures t-tests with the Bonferroni correction applied. Results are summarised in table 4.5 (Appendix C). Players went to bed significantly later the night after a match than they otherwise normally would (mean difference 83 minutes, $t_{19} = 6.183$, $p < 0.0005$, two-tailed) and tended to get significantly less sleep after matches than they normally would (mean difference 73 minutes, $t_{19} = 4.509$, $p < 0.0005$, two-tailed), with no significant difference in the time at which players arose from bed the following morning. While all four measures of sleep quality demonstrated a decline the night following matches, these declines were not statistically significant.



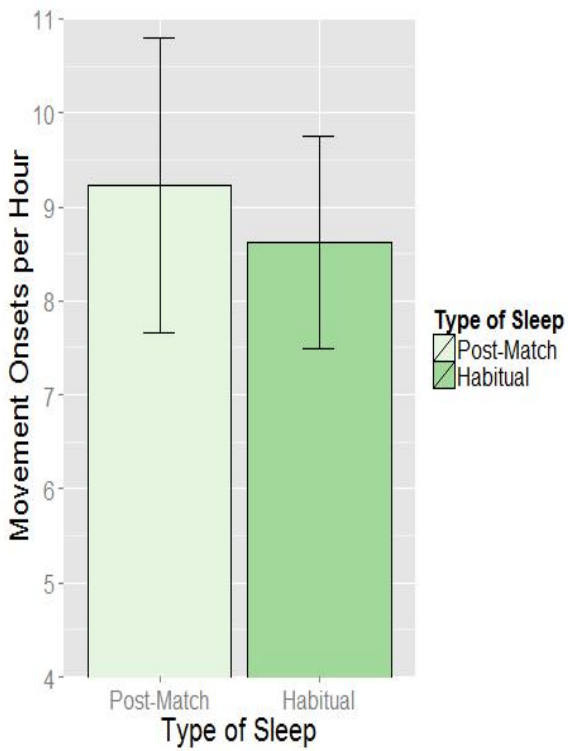
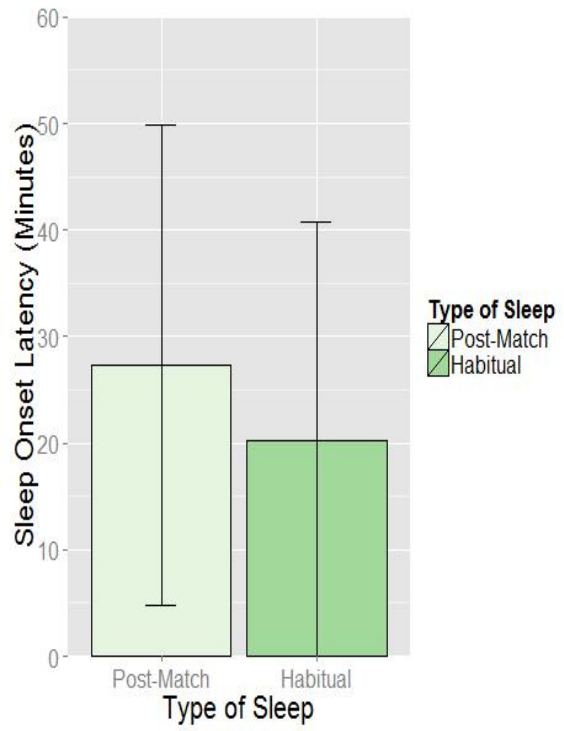
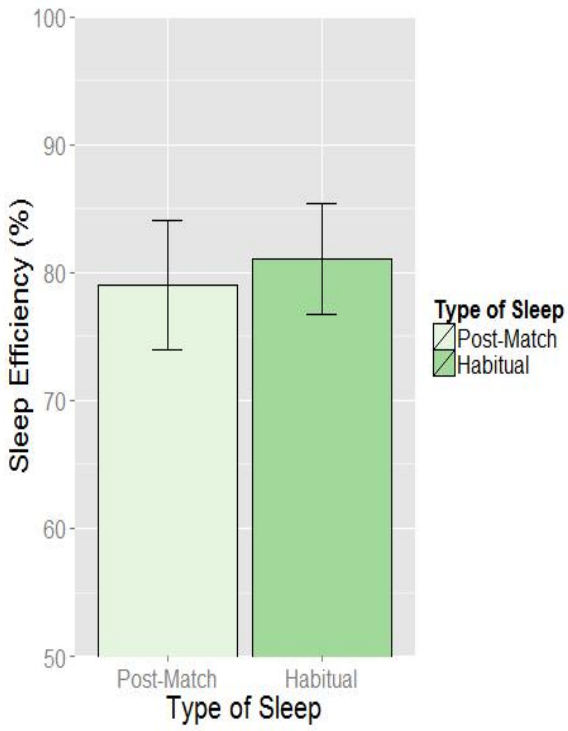
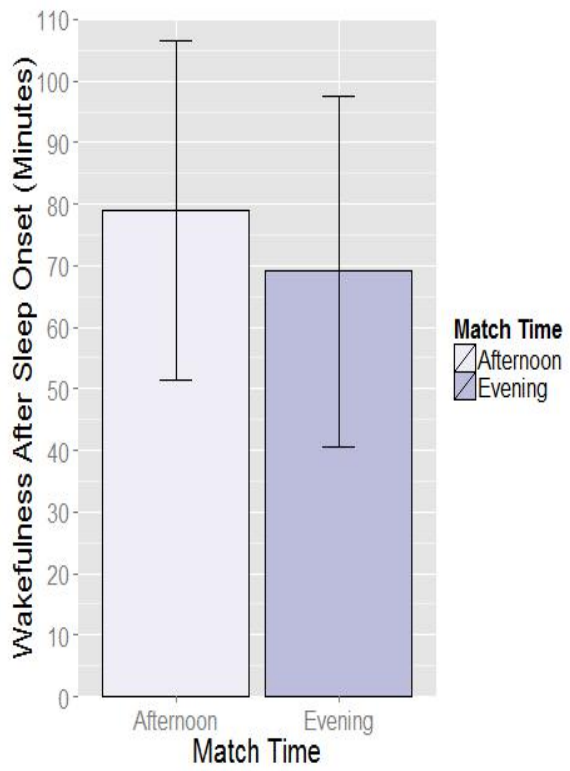
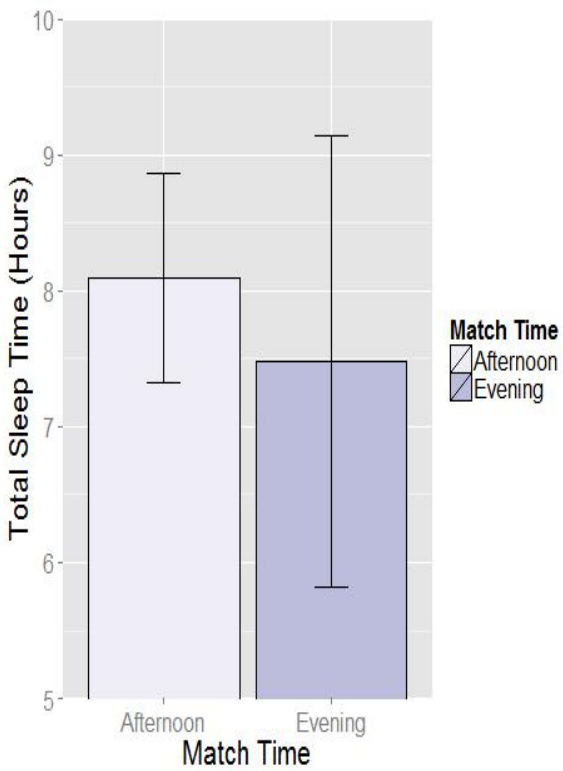
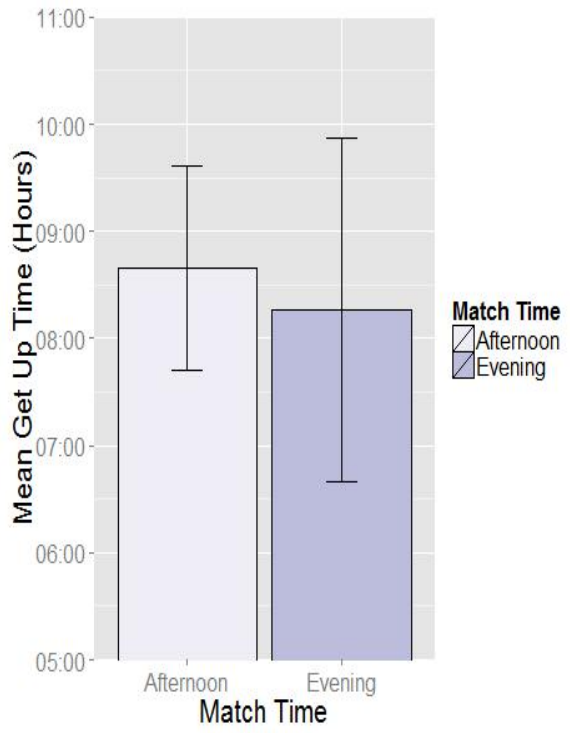
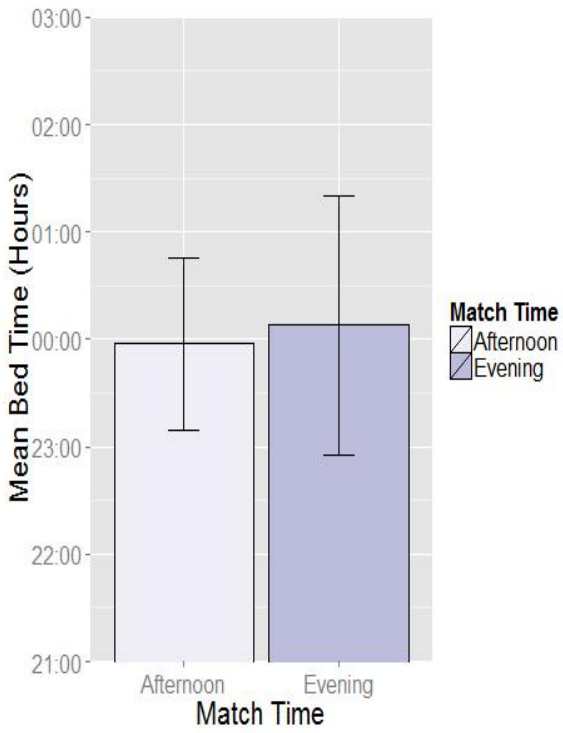


Figure 4.5. Differences in sleep taking place the night after matches compared to normal habitual sleep. Bars represent mean averages; error bars represent 1 standard deviation.

4.4.6 – Sleep Following Afternoon Matches Compared to Sleep Following Evening Matches

Data was categorised as either sleep occurring immediately following an afternoon match, or immediately following an evening match. Afternoon and evening matches are defined in the same way as in section 4.3.3, and are presented in figure 4.6, appearing to show no significant differences in sleep following afternoon matches compared to sleep following evening matches. This was confirmed by repeated measures t-tests with the applied Bonferroni correction, the results of which are summarised in table 4.6 (Appendix C).



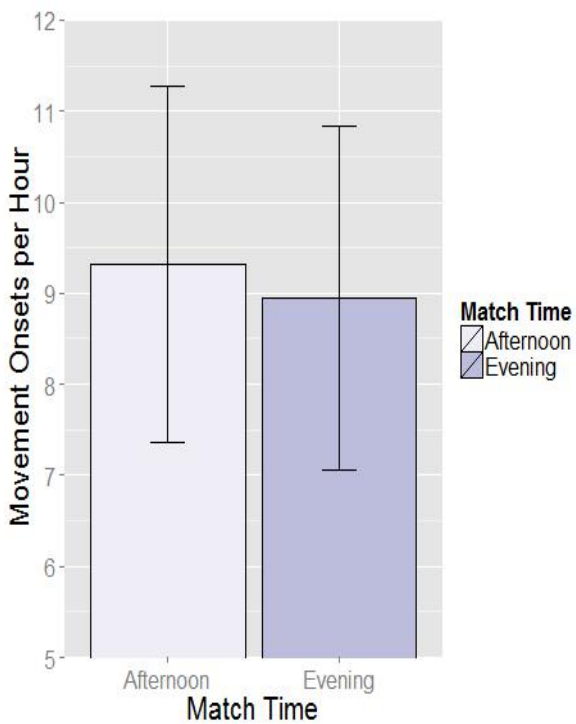
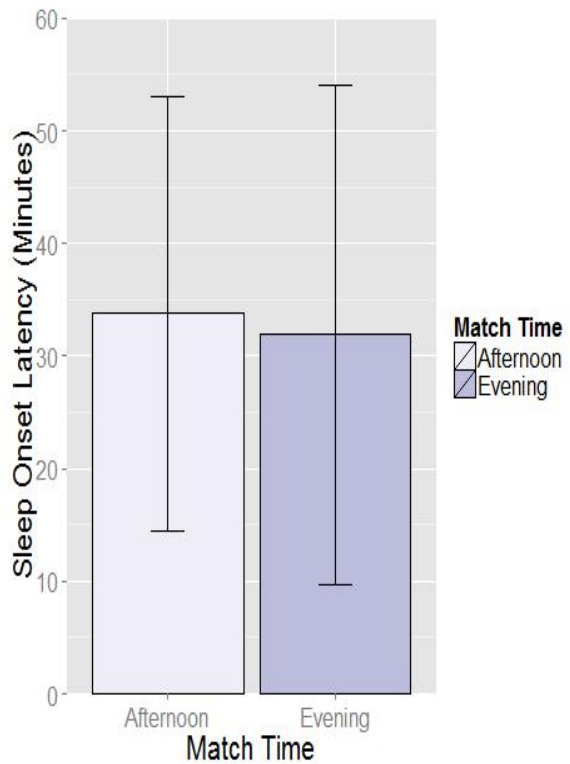
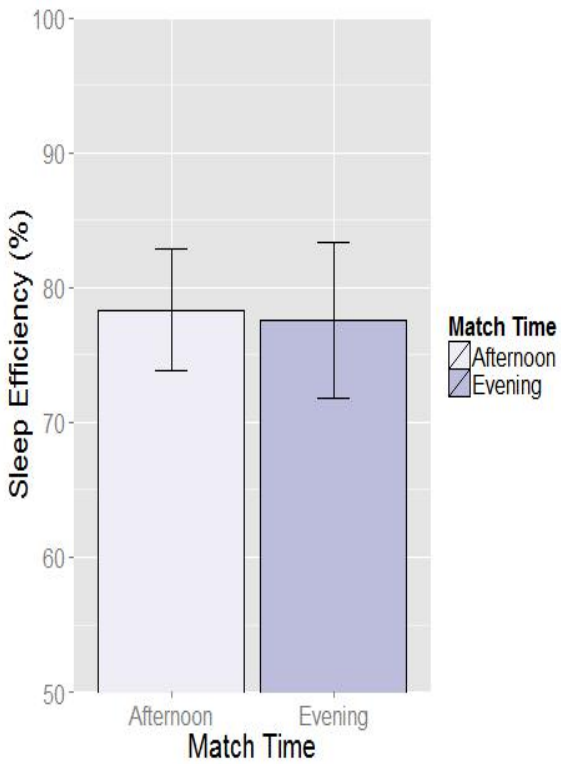


Figure 4.6. Differences in sleep taking place the night after afternoon matches compared to sleep taking place the night after evening matches. Bars represent mean averages; error bars represent 1 standard deviation.

4.4.7 – Relationship Between Physical Activity During Matches and Subsequent Sleep

Data was standardised and used to assess whether the amount of physical work undertaken during a match had an impact on subsequent sleep. Predictors used in this analysis were; time spent on the pitch, total distance covered, distance covered at high intensity speed, and the number of accelerations during the match, as recommended by sports science support staff. As in section 4.3.4, both linear and parabolic relationships were considered and both 3 and 4-level models were considered in addition to the more simplistic 2-level models. Both parabolic modelling and the use of higher level groupings did not add significantly to the explanatory power of the models presented (and in some cases reduced it), and so once again were discarded in favour of the more parsimonious 2-level linear models.

Models were first constructed for all available post-match sleep data, and then a further two times, once with data only from sleep following an afternoon game and again for sleep following an evening game (afternoon and evening games are again defined in the manner as in section 4.3.3) since previous literature has highlighted the importance of time of day on the matter of the impact that exercise has on subsequent sleep. Predictors were first assessed for their individual relationship with the 7 outcome sleep measures, the results of which are presented in table 4.7 (Appendix C). More complex modelling was then attempted, guided by the all-possible subsets analysis in order to determine if a number of predictors entered simultaneously could offer a better fit to the data than the simple single predictor models. Both for the impact that match performance had on subsequent sleep in all

cases, and when data was separated into 'post-afternoon' and 'post-evening matches', while a number of more complex models simultaneously using several predictors did indeed improve the overall fit of the model, this improvement was not statistically significant (as indicated by a statistically non-significant change in the log-likelihood measure of model fit).

4.5 – Discussion

4.5.1 – Pre-Match Sleep

It may come as no surprise given the apparently widespread belief that sleep has a role to play in attaining maximal performance that there was evidence to suggest that football players tend to go to bed earlier than normal the night before a match, and also tend to sleep longer. These increases were not only statistically significant, but are also very likely to be scientifically significant as well; on average players retired to bed 37 minutes earlier and slept for 44 minutes longer the night before a match than they otherwise normally would. Experimental has demonstrated that sleep extension of 90 minutes can have a positive impact on subsequent physical and cognitive performance (Mah et al., 2011), which suggests that sleep extension is beneficial to athletic performance . By contrast the variability in bed time between nights is perhaps more a cause for concern. Consistency in the timing of sleep (sleep scheduling) has been a consistent feature in general sleep hygiene recommendations since its inception (Mastin et al., 2006; Hauri, 1977; 1992), although it is difficult to come across specific recommendations for how much

variation in sleep scheduling is too much and what point it starts having a deleterious effect. It is also difficult to examine the impact that such acute 'night-by-night' variations in sleep scheduling can have on performance, since the expected negative impact relates more to the relationship between a constantly shifting schedule of sleep and a person's circadian rhythms which will manifest over a longer time-scale.

One of the possible impacts that an earlier than usual night of sleep might be expected to have is a negative impact on sleep quality, due to the reduced level of sleep drive one is likely to have. As has been highlighted previously, one of the key processes that determines sleep is the 'simple' linear process of sleep drive (Horne, 2006; 1988a), which broadly suggests that the drive to sleep increases as the length of continued wakefulness increases. If someone goes to bed earlier one night than they have done for previous nights it is reasonable to expect that their level of sleep drive would be reduced, due to the simple fact that they have not been awake as long as usual. This in turn might reasonably be expected to have consequences for the period of sleep that follows.

With regards to sleep quality the night before matches, it could be considered surprising that there were no statistically significant differences between any sleep measure quality the night before matches, compared to the sleep quality of players generally, although it should be noted that there was a trend for sleep quality to be worse before matches. This is in stark contrast to the epidemiological evidence collected by Erlacher et al. (2011) which suggests that we should expect poor sleep the night before matches. It should be noted that in terms of statistical effect size, the current study is, out of necessity, studying sleep as it naturally occurs rather than by directly manipulating it. As a consequence, the size of any differences between the

two conditions is highly likely to be quite small. Despite the sample in the current study being probably the first and certainly the largest attempting to address these questions, it may be that there is simply not enough data to properly examine these differences. There is the possibility of another complication due to the fact that, as was discovered in Chapter 3 of this thesis, the population that is being studied have markedly worse sleep than would be expected from an age-matched control. One of the criticisms often levelled at previous work in the sleep research field is that 'good sleepers' are often recruited for studies, making any sleep improvements difficult to come by due to a 'ceiling effect'; their sleep is already close to being as good as it can be and cannot be improved much further. In studying the current population the reverse problem may have occurred; there may be a 'floor effect', in which players habitual sleep quality (more akin to disordered sleep in extreme cases) is at such a level that any further reduction is difficult to detect.

Besides statistical and measurement difficulties, there is another potential explanation for the disagreement with what might be expected based on what research there is available. While a majority of high performance athletes reported difficulty sleeping the night before competitions, Erlacher et al. (2011) recruited for their study a very wide variety of different athletes from different sports. One of the defining features of the competitive scheduling of professional football in England and Wales is the structure of the season, with matches taking place on a weekly basis during the competitive season (in contrast to many other sports where competitions are relatively infrequent, with extended periods of training between them). One of the consequences of this is that players within a team are constantly competing with each other to earn a place on the team for the next match, and players are exposed to this pressure every single time they train as well as when

they actually compete in matches. If anticipatory anxiety is one of the main driving factors behind the expected sleep difficulty occurring before matches, it may simply be the case that significant levels of anxiety are present more constantly in this population, and there is not in fact a significant increase in levels of anxiety before matches compared to the level of anxiety players experience on a daily basis. If this were to be the case, the lack of a significant decline in sleep quality the night before matches may not be considered so surprising.

4.5.2 - Pre-Home Match Sleep Compared to Pre-Away Match Sleep

The basis for the formation of the idea that sleep in athletes might be expected to be worse (or at least different) the night before an away match compared to sleep the night before a home match arises from existing research highlighting the impact that a number of related behavioural stressors can have on sleep. The two most obvious in this case being the organisational stress and long-distance travel that is much more a feature of away matches than it is home matches, and the need to sleep in a hotel before an away game. Both of these organisational factors have been associated with a negative impact on sleep in the mainstream literature (Davenne, 2009; Reilly & Edwards, 2007).

While the impact that long-distance travel can have on sleep is largely confined to discussions regarding trans-meridian travel and jet-lag, there is also reason to suspect that long distance travel more generally can exhibit deleterious effects on sleep. Such long-distance travel usually involves prolonged periods of

sitting down, often in fairly cramped conditions which could potentially cause discomfort, and has even been associated with factors as serious as ischemia (Crowe, 2004). Long-distance travel may also be expected to impact on the timing and organisation of people's sleep, contrary to sleep hygiene recommendations. This does not appear to have been the case among the professional football players studied here. It may be the case that the factors responsible for the negative impact thought to be associated with long-distance travel are mitigated or eliminated in this population. Evidence from other domains highlights, for example, that athletes in team sports experience lower levels of anxiety than those in individual sports because their travel and organisation is arranged for them by team management, and as such is not a cause of concern for them (Martens et al., 1990). In addition, the earliest kick-off times in domestic competition take place well into the afternoon, so there is by no means a large degree of time pressure, allowing players a long period of time in which to sleep (and which players tend to take advantage of, as was demonstrated in section 4.3.1).

As far as the negative impact that sleeping in a hotel bedroom can have on sleep, this phenomenon is largely ascribed to the 'first-night effect' in which people tend to sleep less well in an unfamiliar environment (Davenne, 2009). Given the importance of the novelty of the sleeping environment in the first night effect, and the fact that as the current population are likely to be more accustomed than most to sleeping in hotels, since they do so on a weekly basis and will likely have done so for the length of their career. It seems plausible that professional football players becoming accustomed to the changes in their sleeping environment associated with sleeping in a hotel, and would therefore not display a marked deterioration in sleep as a consequence. There appears to have been little research directed at

investigating the extent to which people who often sleep in unfamiliar environments could rapidly adjust to a new environment to the extent that it does not significantly alter their sleep.

4.5.3 - Sleep Before Afternoon Matches Compared to Sleep Before Evening Matches

It may be surprising to discover that players got up the morning before an evening match significantly earlier than they did before home matches, matched by a definite trend (although not statistically significant) towards going to bed earlier before evening matches. Since the grouping of nights of sleep data into 'afternoon' and 'evening' includes both home and away matches, it seems unlikely that organisational factors (e.g. travelling to an away game) would be responsible. One plausible possibility is that players could be making time for a daytime nap before evening matches. Conversations with participants highlighted the fact that many players reported that they would often take an extended nap during the day before an evening match. Unfortunately due to the need to remove Actiwatchs for bathing and competitions, most participants did not continue to wear them beyond the nocturnal sleep period, so daytime napping was not measured accurately.

Previous research has highlighted the potential benefits that can occur following a short daytime nap such as increased levels of alertness, and even naps as short as 20 minutes have demonstrated an ability to return one's performance following an acute period of sleep deprivation to baseline 'non-sleep deprived' levels

(e.g. Horne & Reyner, 1996). It may also be worthwhile to consider that the training times of all the professional football players in the present study were invariably in the morning, starting between 0900 and 1000, and not finishing any later than 1400 in the afternoon. Consequently it seems likely that these participants are on a circadian rhythm that places more favour on activity during the morning than in the evening (Horne & Ostberg, 1976; Taillard et al., 1999). Given the late hour that evening matches tend to begin and end, a lunchtime nap or 'siesta' of the type common in some countries may be a prudent way of preparing oneself for optimal performance in the evening when one is accustomed to being physically active in the morning. Of course it is also worth considering the converse; that in most cases young healthy people should not feel that they need to nap during the day if they are getting sufficient nocturnal sleep (Horne, 2006). Given the findings from section 3, this cannot necessarily be taken for granted however. Perhaps if the sleep of professional footballers could be improved to the extent that it was equivalent to the level that would be expected, they would not feel the need to nap during the day in order to feel sufficiently rested and prepared before matches.

4.5.4 - The Relationship Between Sleep and Subsequent Performance

There were no statistically significant relationships between football players' sleep the night before matches and their subsequent performance during the match. This result can be thought of as being rather neatly aligned with the results of existing lab-based studies (e.g. Martin, 1981; Horne & Pettitt, 1974; Bambaiechi et al., 2005), where the capacity to perform physical work was not significantly affected

by sleep deprivation when participants were adequately motivated. It also seems reasonable to imagine that, if research participants in a lab-based setting can be 'adequately motivated' to overcome a level of sleep disturbance far greater than the naturally occurring variations in sleep that are present in the current study, then a real-life performance in which participants have a deep personal interest taking place in front of ~20,000 fans would also provide adequate motivation to perform.

It is however interesting to note the difference in the strength of the relationship between sleep and the two different measures of physical performance. While the results for high-intensity distance covered during matches appears to show little or no dependence on preceding sleep (with most predictors, the margins of one standard error of the regression coefficient cross zero so even the direction of the relationship is not entirely certain). In contrast, the results for total distance covered are far less uncertain, suggesting that that the relationship between sleep and the total distance covered during matches was much more uniform. Once again there are interesting parallels to be made with existing sleep research, specifically the research relating to the differing impact of sleep deprivation on self-paced compared to forced-pace physical activity (Rodgers et al., 1995). If we consider that, as was discussed earlier in chapter 2, high intensity activity is most associated with predicting the outcome of matches (Mohr et al., 2003; Di Salvo, 2009) since it tends to occur when an individual is directly involved in the state of play, this is similar to the 'forced-pace' activity from existing work in that players' activity is forced upon them by competitive circumstances. This type of activity only accounts for a fraction of the total activity players engage in during a match (Andrzejewski et al. 2013), with the rest taking place when a player is perhaps not so directly involved. This is the activity that is accounted for by the total distance covered measurement. Players

should generally not be static in these situations (with the possible exception of the goalkeeper) and should still be tracking the run of play up and down the field, and responding to the movements of opposition players. While such 'off-the-ball' activities are undoubtedly important, since players are not directly involved they may feel that the spotlight is not focused on themselves so much, making this type of activity more akin to the 'self-paced' activity from previous research, this may explain the somewhat greater impact that reduced or disturbed sleep the previous night appears to have.

4.5.5 – Post-match Sleep

The finding that football players tend to go to bed later following a match than they otherwise normally would is perhaps not entirely surprising, especially when one considers that this will include away matches as well as evening matches, which will often finish later than 2200 hours, even before players have travelled home before going to bed. An organisational cause seems to be the most plausible and likely scenario. The more surprising element that appears to be apparent in sleep following matches is that players seem to approximately maintain their normal get up time in the morning, a consequence of which is a significant reduction in their overall sleep time. This is unlikely to be the result of an organisational demand for players to be up at the same time as usual, since in the vast majority of cases players do not train the day following a match.

The results also demonstrated a uniform although statistically non-significant trend for sleep quality to be lower the night following a match. It has been suggested by previous researchers that extreme levels of exercise could exert a negative influence on subsequent sleep as a consequence of the associated elevated levels of muscular soreness and discomfort that is common after such exercise (Youngstedt et al., 1997; Taylor, Rogers & Driver, 1997). It may be plausible that the slight reduction in sleep quality that is evident the night following matches could be responsible for making players being more susceptible to external factors such as light and noise that could in turn result in making them easier to wake in the morning, as a possible explanation for the reduction in sleep time (Youngstedt et al., 1997) - although it could equally be a deliberate choice on the part of the players themselves.

4.5.6 - Sleep Following Afternoon Matches Compared to Sleep Following Evening Matches

Given previous research suggesting that the time of day at which exercise occurs plays a crucial role in determining if that exercise has an impact on subsequent sleep, it is surprising to find that there did not appear to be any significant differences in sleep following afternoon matches compared to sleep following evening matches. There are some important considerations and limitations as to how this difference was addressed in the present research that could be corrected in future.

The first important factor is that a simple afternoon/evening comparison conflates the issue of home matches compared to away matches, and the organisational differences between an evening home match compared to an evening away match are considerable. While it was usual practice for the teams involved to stay in a hotel the night before away matches, they would not normally stay in the hotel again after the match, preferring instead to travel 'home' immediately after the match. Given the national nature of the competition at this level, such travel could often be of the order of 3-5 hours in total, with the consequence that following an evening away match (finishing at approximately 2200 hours), bed time could be delayed until as late as 0300-0400 in the morning, whilst following an evening match played at home could involve less than one hours travel, allowing a bed time of 2300-0000 hours, which would not be much later than normal. Ideally, future research would address this question in a fully factorial manner, separating post-match sleep data into 4 groups (afternoon home match, evening home match, afternoon away match and evening away match). Unfortunately, due to the high level of missing data due to injuries, transfers and player forgetfulness there was not sufficient data in the current study for such an analysis to yield a meaningful result.

An additional caveat to this analysis is due to the findings of previous research that exercise needs to have taken place close enough to bed time in order for the alerting effect of exercise to still be exerting a physiological impact on the sleeper. However, even following an evening match played at home, it is likely that once the match has finished, players have bathed, been debriefed following the match and travelled home, one hour could have easily passed between the end of exercise and sleep. Following an evening match played away from home allows even more time between the cessation of exercise and the onset of the main period

of sleep (as players reportedly often nap on the return journey). It may be the case that, even after matches finishing at ~2200 hours, this is still too long before bed time to have a significantly deleterious impact on sleep.

4.5.7 - Relationship Between Physical Activity During Matches and Subsequent Sleep

While it may appear to be difficult to reconcile with the results presented in 4.3.6, showing that there appears to be no significant difference in sleep following an afternoon match compared to sleep following an evening match, the most startling finding exists when one examines the relationship between how much physical work players undertake during a match and their subsequent sleep, which suggests that a direct relationship is much more likely following an evening match than following an afternoon match. However upon consideration it most likely offers some explanation as to why there was no overall difference between sleep following afternoon matches compared to sleep following evening matches, since a strong relationship between the amount of physical work undertaken during evening matches and subsequent sleep suggests that sleep is only negatively affected when a certain quantity of work has been completed, and, if this amount of work has not been completed, it does not have a significant negative impact on sleep. It seems that the impact that exercise has on subsequent sleep depends just as much on the intensity of the exercise as it does on the timing.

Of course the fact that there is reasonable evidence for a link between the amount of physical work undertaken during evening matches and subsequent sleep calls into question somewhat the suggestion from the previous section and other existing research that, in order for exercise to exert an influence on sleep, it needs to take place sufficiently close to bed time. There has been some debate in previous research (Myllmäki et al., 2011; Dworak, Wiater, Alfer, Stephen, Hollman & Struder, 2008; Souissi et al., 2012) as to what exactly constitutes 'sufficiently close', with some evidence pointing to a time as high as four hours and others suggesting a much closer period of one hour. In the present study, exercise for the most part ceased 1-2 hours before bed time. It may be important to consider that this previous research has tended to focus on the impact that recreational levels of exercise have on sleep, rather than the extreme levels of exercise studied here. In addition, these studies have tended to focus more on sleep quality (particularly SOL) while in this case, excepting a reduction in wakefulness after sleep onset, there is not a convincing relationship between exercise levels and sleep quality, even though there is certainly evidence of a reduction in overall sleep time where levels of physical activity are highest. It may be worth considering the results not in the light of the thermogenic hypothesis on which existing work is based (which posits that the **positive** impact of exercise on sleep is a consequence of the body heating effect of exercise) but instead by considering the influence that exercise can have on circadian factors. In this context, it is not so surprising that exercise (just like light exposure) during the middle portion of the day (i.e. during afternoon matches) exerts no significant impact on sleep, while exercise in the vicinity of the natural circadian peak that occurs during evening matches could have an impact on circadian factors

(in this case a phase delaying effect that is absent from an afternoon match) which could be conspiring to produce an effect on sleep.

4.6 – Conclusions

The aim of this section was to investigate some of the ways in which sleep can affect, and be affected by, participation in elite-level athletic competitions. Reports from athletes have suggested that a majority of them believe that their sleep can be impaired on the night before competitions (Erlacher et al., 2011; Savis, 1994) and that sleep is an important requirement in achieving peak performance. This belief appears to be widespread despite the lack of convincing and objective real-world evidence of either a relationship between sleep and performance outside lab-based performance measures following artificial sleep manipulation, or that sleep is impaired the night before competitions as a result of anticipatory anxiety, organisational stressors or any other factors. Another common notion that has been examined in this section is the impact that exercise may exert on subsequent sleep. Existing literature tends to be based on the idea that exercise has a positive effect on sleep, although some have also suggested that strenuous exercise taking place close to bed time can have an alerting effect, and thus negatively impact upon sleep.

The findings certainly seem to demonstrate that football players seem to value the need for sleep before matches, considering the fact that there is a tendency for them to go to bed significantly earlier and sleep for significantly longer before matches. There does not appear to be any statistically significant reduction in sleep quality on these occasions, although these results do all show a trend in the direction

for a slight reduction in sleep quality. This slight reduction may be a consequence of pre-competitive anticipatory anxiety, or may simply be due to the reduced sleep drive that will likely exist when one tries to go to bed at an earlier time than they are accustomed to (Horne, 2006). The results from the comparison of sleep before home and away competitions seem to suggest that differing organisational factors associated with playing away from home do not appear to exert a significant influence on sleep in this population. This is perhaps not so surprising in a professional team sport, where transport and accommodation arrangements are made for the players by the team management. This may not necessarily be representative of other sports, particularly semi-professional sports in which athletes also work, and so travel and accommodation to and from competitions is likely to be more problematic. The study of a wider variety of elite athletes would be a fruitful area for future research, as the possibility that such factors are responsible could easily be distinguished by studying the similarities and differences between pre-competitive sleep in sports with different characteristics (e.g. team vs individual, professional vs 'amateur', frequent 'seasonal' competition vs infrequent 'training block' sports).

Perhaps the most salient research question that was addressed was the investigation to the impact that sleep can have on subsequent performance during competitions. Although there was no statistically significant evidence to suggest such a relationship, there were trends in that direction, and it is important to consider the distinction between a statistically significant relationship and a relationship that may still be meaningful in the context of elite athletic competition, given that the margins between success and failure are so fine. It is also noteworthy that trends towards an impaired performance following modest declines in sleep occurred, despite the

performance measures in this study being largely physical, circumstances where previous research had demonstrated tended not to be negatively influenced by poor sleep when the performers are adequately motivated (which in the current study it seems reasonable to conclude was the case).

The final broad area of investigation was to examine the ways in which participation in elite athletic competition could exert an influence on sleep. In this regard, there are certainly organisational stressors that appear to exert an influence in shortening sleep after matches, and for sleep to start at a later time. Once again, and contrary to what may be expected based on the majority of the literature, there was also a trend towards a lower quality of sleep following matches. While the vast majority of research effort has been directed towards the potential benefits of exercise towards sleep, this finding appears to support the less pervasive argument that 'extreme' levels of exercise can be detrimental to sleep. The definition of 'extreme' has been thus far been taken to mean events which are 'marathon like' in terms of duration (i.e of the order of at least 2 hours and above; Taylor, 2001; Baekland & Lasky, 1966; Shapiro et al., 1981), the current study perhaps demonstrates that this negative effect could be extended to shorter duration activities which feature periods of high-intensity effort (such as in professional football), compared to the relatively continuous effort level required for long-distance running. One feature of the existing research literature that was broadly supported was the greater ability of exercise to exert an influence on sleep when it occurs later in the day and closer to bed time, a finding which is largely in line with what would be expected based on existing knowledge.

4.7 – Summary

- Professional football players appear to show some appreciation for the importance of sleep before matches, since they consistently go to bed earlier and sleep for longer than normal.
- There appears to be no significant of match venue on pre-competition sleep.
- Sleep does not demonstrate a statistically significant relationship with subsequent performance, in agreement with existing research on the resilience of performance to sleep disturbance when adequately motivated.
- Given the narrow margins that prevail in elite level sport, the impact that sleep can have on subsequent performance may still have practical relevance to athletes.
- Pressures associated with competition demonstrate an ability to influence subsequent sleep, such as the timing of sleep following competition.
- There was no convincing overall pattern for, and influence of, the level of physical activity on subsequent sleep, although the relationship was stronger in evening matches, despite a likely conflation between time of exercise and the venue of matches.

Sleep and Training in Professional Football Players

5.1 – Introduction

In addition to the important role that sleep may have in contributing towards achieving elite athletic performance, it is also important to consider the role that it may have on training for athletic performance. While actual competitive events are certainly the most visible (at least from an external observer's perspective) aspect of elite athletes, there is a vast amount of training that occurs in order to prepare and maintain athletes' levels of fitness and skill that enables them to perform at the very highest levels. This necessitates athletes being able to maintain good health and adequate motivation to continue training for extended periods of time, and maintenance of adequate levels of sleep may help to keep athletes fit and healthy for the duration of the competitive season.

Unfortunately, while competitive events certainly place some very specific sleep pressures on competitors, there are number of factors which one could reasonable expect would also have a negative impact on sleep in the longer term. Factors such as anxiety, for instance, are likely to remain a persistent factor that could have a deleterious impact on athletes throughout the season. In the vast majority of team sports there are (out of necessity in order to cover for periods of injury etc.) many more available players than there are 'spaces' available for them in competition (an entire 'first team' in football will consist of at least 20 players, while matches require no more than 15). Players are therefore in a position of constant competition with their team-mates, battling for selection in upcoming matches. Other pressures could also exert a negative impact on players' sleep, such as periods of injury or familial pressures. While the kind of extreme organisational pressure placed

upon athletes during competition such as travel and accommodation may be less severe during periods of training compared to the period immediately before matches, there is still plenty of scope for them to impair sleep, such as by not permitting the establishment of a consistent schedule of sleep and waking. A number of sports that require multiple training sessions per day generally demand both very early starts in the morning and very late nights, placing yet more pressure on athletes' sleep.

As has been highlighted previously, chronically poor sleep could have a number of potentially deleterious impacts on an athlete, which could in turn go on to have an adverse impact on their ability to train consistently and, indeed, their ability to derive the greatest possible benefit from the training that they perform. Factors such as reduced efficacy of the immune system (Lange et al., 2003; Scheer, Hilton, Mantzoros & Shea, 2009; Knutsson, 2003; Heslop et al., 2002; Ferrie et al., 2007), and reduced glucose tolerance (Spiegel et al., 1999; Spiegel et al., 2003) could inhibit an athlete's ability to train due to periods of illness or reduce capacity to adequately perform during training sessions as a consequence of having insufficient energy. Research has also highlighted that protein synthesis can and does occur during sleep following training (Res, Groen, Pennings, Beelen, Wallis, Gijzen et al., 2012) and, further, that poor sleep can disrupt the biological systems responsible for appetite (Pejovic, Vgontzas, Basta, Tsaoussoglou, Zoumakis, Vgontzas et al., 2010; Spiegel, Tasali, Penev & Van Cauter 2004; Vgontzas, Pejovic, Zoumakis, Lin, Bixler, Basta et al., 2007). Given the almost ubiquitously acknowledged importance of proper nutrition to training for elite level competition, a chronic disturbance to appetite regulation as a result of sub-optimal sleep could have troubling implications for athletic training. Another consideration is the importance of training intensity in

making the very most out of the time available for training. Experimental studies have clearly demonstrated the importance of high-intensity training in maximising the physiological impact of training (e.g. Wang et al., 2012; Laursen & Jenkins, 2002). Suffice to say, training at such intensities requires a not insubstantial degree of motivation to push oneself to the limits of one's physical capacity on a daily basis. While research (including the previous section of the current work) has highlighted that, when adequately motivated, people are capable of overcoming the negative impact that sleep disturbance has on motivation, it remains to be determined if this 'immunity' that seems to present (at least to a degree) in competitive matches can be replicated in training, which is most certainly an entirely different motivational climate. A final note to consider concerns the role that sleep had been demonstrated to play in the consolidation of memories and its role in enhancing skill acquisition taking place after a period of learning (Stickgold, 2005; Siegal, 2001; Walker, 2004). The particular dependence of motor skill learning on post-learning skill acquisition is likely to be especially consequential in the context of elite-athletic endeavour (Moran, 2008). Achieving adequate sleep clearly impacts on a number of areas which are important to athletes training and preparing for competition.

5.2 – Aims

While the question of whether poor sleep negatively impacts upon the performance of elite-level athletes during competitions is one that is often asked, it is arguably even more important to consider the impact that poor sleep could have on athletes during training. Inadequate or impaired sleep could reduce the amount of work that athletes feel they are able to exert during training sessions, and could hamper their recovery post-training, reducing the amount of physiological and skill-based adaptation that can take place following training. The importance of adequate sleep in maintaining optimal functioning of the immune and dietary systems are also a primary concern of athletes preparing for high-level competition.

The present section will investigate if there are fluctuations in the sleep of professional football players during the course of the competitive season, comparing sleep that takes place before training sessions, after training sessions and sleep that neither directly precedes or follows training sessions, in order to assess the ‘stability’ of poor sleep that was evident in section 3 of this thesis. Essentially this will investigate whether the poor sleep (relative to age-matched controls) is a persistent feature in this population during the competitive season, or if it depends more directly on a specific set of circumstances (e.g. is poor sleep more evident following strenuous training sessions?). Additionally the relationship between sleep and subsequent performance during training will be assessed, and the results compared to those contained in section 4. Previous literature suggests that these different performance climates could elicit a different relationship, due to the difference in the motivational climate that will inevitably exist between fully competitive matches and day-to-day training. Finally, the impact that the type of training and subsequent sleep

that takes place in this population will be investigated, in order to determine the role that exercise duration and intensity may play in the poor quality of sleep that has been observed in this population.

Research Questions

- Are there significant differences in the sleep of players the day before and after training, compared to their 'normal' sleep?
- Is there a significant relationship between sleep and subsequent performance during training?
- Does the duration and intensity of training have a direct relationship with subsequent sleep?

5.3 – Method

5.3.1 – Participants

A total of 26 professional football players currently playing for 2 professional football clubs in the English and Welsh Football league (1 team competing in the Premiership division; n = 9 players, the other in the Championship division; n = 17 players) were recruited for the study, with an average age of 25.4 years (SD 4.0 years). At the beginning of the study all participants were considered by their club as belonging to the 'first team', and were training on a daily basis and competing on a weekly basis. Participants reported no evidence of pre-existing sleep disorders, and were not excessive users of caffeine or alcohol. Participants were approached through their club, and were told of the study's aims and methods before consenting to participate.

5.3.2 – Sleep Recording

Sleep data was recorded from participants for a period of 2 months during the regular competitive season, using an Actiwatch AW4® (CamNTEch, Cambridge, UK), during which time participants were asked to wear the device continuously, except for bathing, training and competing (to prevent damage to the monitors). Participants were instructed to use the event marker of the Actiwatches to indicate 'bed time' and 'get up time', as described in section 3.3.2. This yielded a total of 661 nights of sleep data, considerably less than the maximum amount of data. This is attributable to

mid-season transfers resulting in participants leaving the club, players omitting to wear the monitor during periods of injury, and simple forgetfulness. A total of 162 nights of sleep took place immediately prior to training sessions, 136 nights of 'post-training' sleep were available, and 313 nights of sleep data occurred neither immediately before nor immediately after training sessions (or matches).

Sleep data was analysed using the proprietary Actiwatch Sleep Analysis Software 7 (CamNTEch, Cambridge, UK). Data was collected in 30-second epochs, and the medium sensitivity setting was used for sleep/wake identification. Analysis was conducted examining the timing (bed time, get up time), duration (total sleep time; TST), and quality of sleep (sleep efficiency, SE; sleep onset latency, SOL; wakefulness after sleep onset, WASO; and movements per hour during sleep, onsets/hour). Details of how these variables are measured using wrist actigraphy are discussed in chapter 2.

5.3.3 – Measurement of Training Performance

Performance of players during training sessions was measured objectively using the Catapult® X3 Athlete Monitoring System (Catapult, London). A small remote unit is worn by players during training sessions which accurately tracks the two-dimensional location of players using a combination of GPS satellite tracking and a local radio base station (to improve measurement resolution) at a sampling frequency of 5Hz. Raw data is then used to calculate the direction and speed of players during 0.5-second epochs, providing data on the total distance covered during each training session, as well as the distance covered at high intensity, in a

similar manner to the ProZone system used in the previous section. In addition, a tri-axial accelerometer, sampling at 100 Hz, measures the impact forces experienced by players during training and calculates an overall measure of physical exertion that a player has applied (PlayerLoad; Boyd, 2011). Finally, immediately following each training session, players were asked to provide an RPE score on a scale from 1-10 to indicate how much effort they felt they had applied during the session. Due to the fact that training sessions are not uniform in length, measures were divided by the total length of time spent training (for measures where distance covered is a direct contributory factor; total distance covered, high intensity distance covered and PlayerLoad) and by the total distance covered (for player provided RPE scores).

For the analysis of the impact of training on subsequent sleep, the above measures were used in their raw form (i.e. not corrected for training time or distance covered) as measures of how much physical work players had done during the session. In addition to these measures, the total period of time spent training was assessed for the predictive relationship it had with subsequent sleep, as was the total number of acceleration efforts players had produced, for the same reasons as described in the previous section on match performance

Measurement of these performance variables was already being conducted on a day-to-day basis by sports science staff at the participants' clubs, and was regularly used by support staff to measure the performance and physical exertion applied by their players during training. Data were made available for the present analysis with the permission of the players and staff at the clubs in question, yielding a total of 162 training instances that were paired with immediately preceding sleep data, in addition 132 instances of training took place prior to a matched set of sleep data from the subsequent evening.

5.3.4 – Analyses

Statistical analysis was conducted using R (Version 2.15; R Core Development Team, 2012). A list of the attached packages is available in Appendix A. Comparisons of sleep taking place the night before, the night after and 'habitual' sleep that did not occur immediately before or after training sessions were analysed by means of the repeated measures t-test. As in section 4, situations in which multiple outcome measures are being simultaneously tested are generally analysed by means of a MANOVA, however this assumes that multiple measurements of the same individual take place at regular time intervals. Once again each individual's measured sleep under each circumstance was averaged to ensure that each participant contributed only a single score for each situation, in order to satisfy the assumption of the independence of measures. Bonferroni adjustments to correct for inflated family-wise error rates were therefore applied to the repeated measures t-tests in all situations. Significant was set at 5% (two-tailed) in all cases.

Examination of the relationships between sleep and subsequent performance, and between exercise and subsequent sleep, was conducted using multilevel modelling. The seven sleep parameters examined in previous sections were each analysed independently to determine the extent to which they relate to measures of performance, which were measured by the 'total distance' and 'high intensity' distance variables measured using the Catapult tracking system. Since there is naturally much greater variation in the overall length of training sessions compared to the length of competitive matches (which are invariably 90 minutes plus at most 6 minutes, since there is no possibility of extra time in domestic league competitions),

these measures were divided by the total length of time for each training session, in order to account for the fact that a longer training session will almost inevitably entail a greater distance covered, regardless of the amount of effort that is applied. In addition, immediately following each training session players, were asked to rate their level of perceived exertion (Rating of Perceived Exertion; RPE) during the session on a scale from 1-10. Finally, the distance players covered during each session was divided by their reported RPE score, in order to establish if the relationship between the amount of physical work completed and players corresponding RPE score was influenced by sleep. In the case of modelling the impact that training had on subsequent sleep, the seven sleep parameters used earlier were measured as they took place following training sessions and were used as outcome measures. The total time spent training, as well as the total distance and high intensity distance covered were used as predictors, as well as the total number of accelerations that occurred during the training session (since interval type training, characterised by frequent bursts of higher intensity activity are generally more stressful than 'steady-state' training). These were the performance measures most relied upon by the sports science support staff at the clubs in question to determine the intensity of training sessions.

In all cases, both predictor and outcome measures were standardised using a z-transformation, based on each individual's average measurement on each variable throughout the entire measurement period. As in the previous section, this standardisation serves to place all variables on the same measurement scale, and enables the direct comparison between participants, in addition to acting as a method of 'group-mean centring' the data (as detailed in Field, Miles & Field, 2012). Centring of scores around zero also simplifies the examination of non-linear

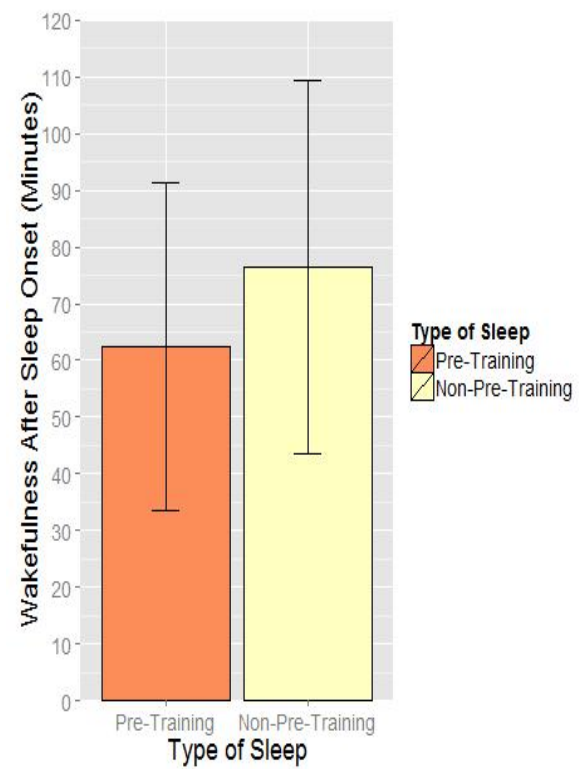
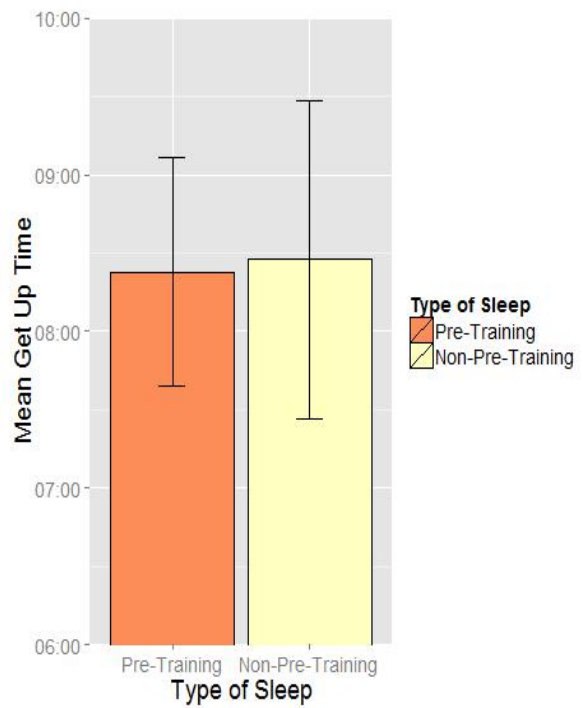
relationships. Initial exploration was conducted using the 'all possible subsets' function contained within the 'leaps' packages (Lumley & Miller, 2009) to establish a useful starting point, and predictors were then systematically added and removed from the overall model to find the most parsimonious model offering the best explanatory fit to the data. Both linear and polynomial non-linear relationships between predictor and outcome measures were considered. Model fit was analysed using the 'anova' command in the 'stats' package (R Core Development Team, 2012).

5.4 – Results

5.4.1 – Variability in Sleep During Periods of Training

Recorded nights of sleep were classified into groups based on whether they took place the night before a training session, the night following a training session, or nights which did not take place either before or after a training session or competitive match. Each player's measured scores on the output criteria were averaged in each category, and both 'pre-training' and 'post-training' averaged scores were compared to the player's averaged 'habitual' sleeping behaviour by means of a repeated measures t-test, corrected for inflated family-wise error rate by applying the Bonferroni adjustment for multiple comparisons. A summary of the results for the difference between pre-training sleep and habitual sleep, and the differences between post-training sleep and habitual sleep, is presented in figures 5.1a and 5.1b respectively (N.B. Some participants did not contribute sufficient 'pre-training' data for a meaningful analysis, while simultaneously providing adequate

'post-training' sleep data, resulting in some participants being excluded from one analysis but not the other. This accounts for the slight difference in habitual average measures). There were no statistically significant differences observed between players' sleep directly before or after training sessions, compared to their habitual sleep during the competitive season. A summary of all these results is available in table 5.1a and table 5.1b in Appendix D.



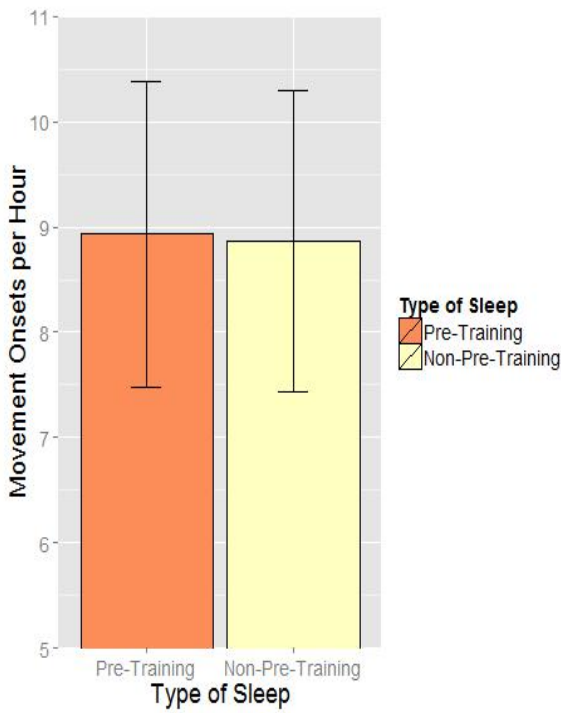
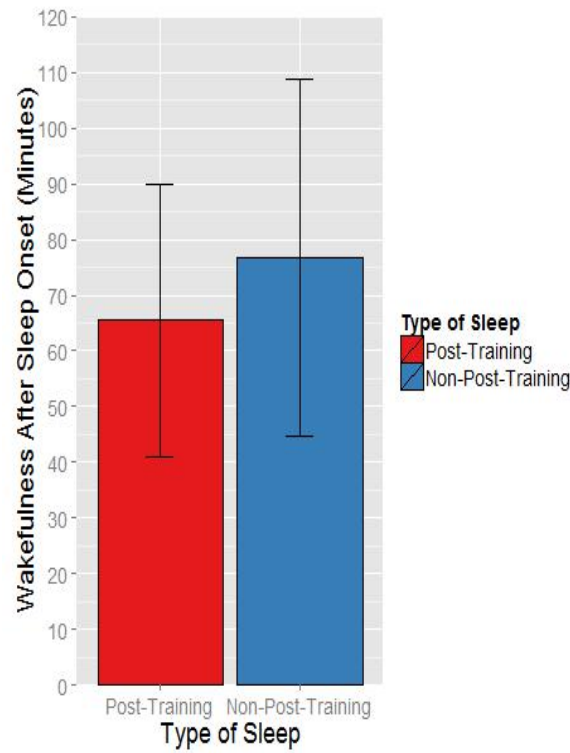
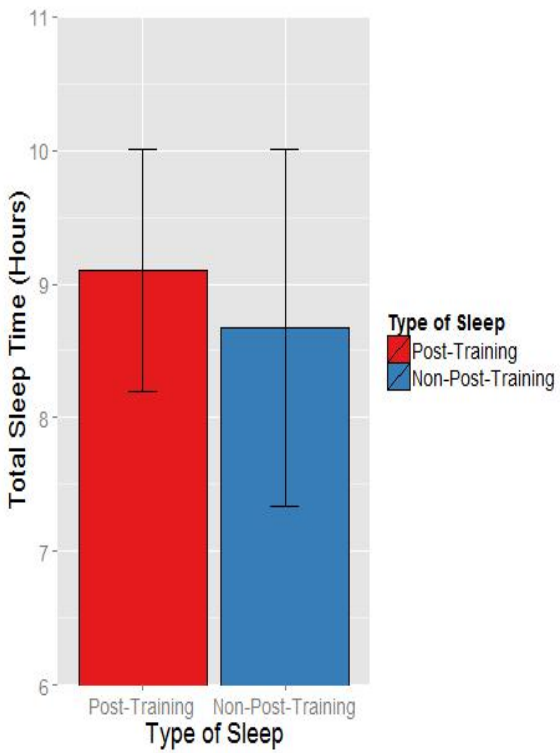
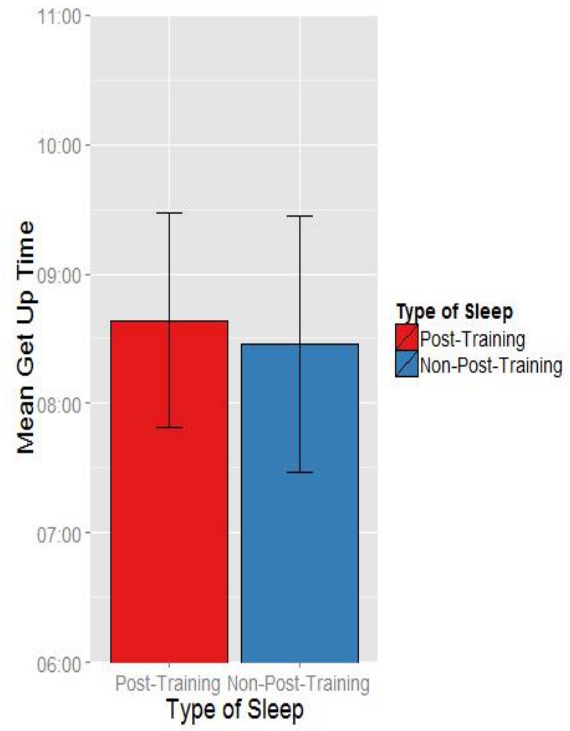
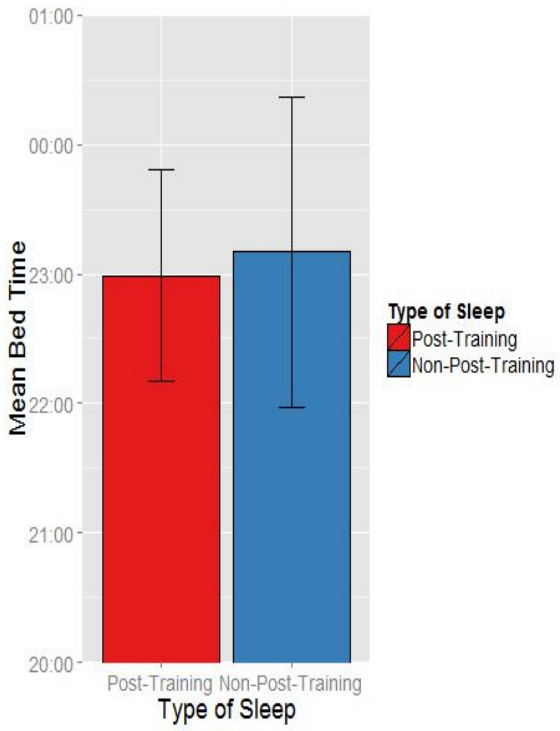


Figure 5.1a. Differences in sleep taking place before training sessions compared to normal 'habitual' sleep. Bars represent mean averages' error bars represent 1 standard deviation.



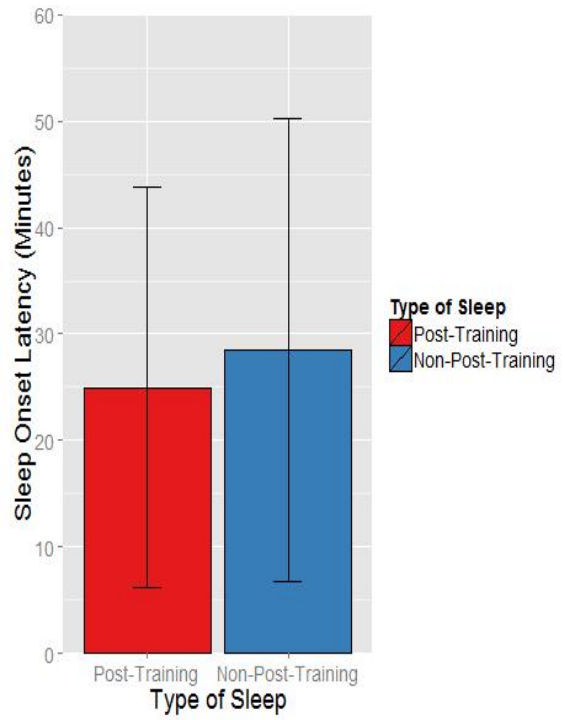
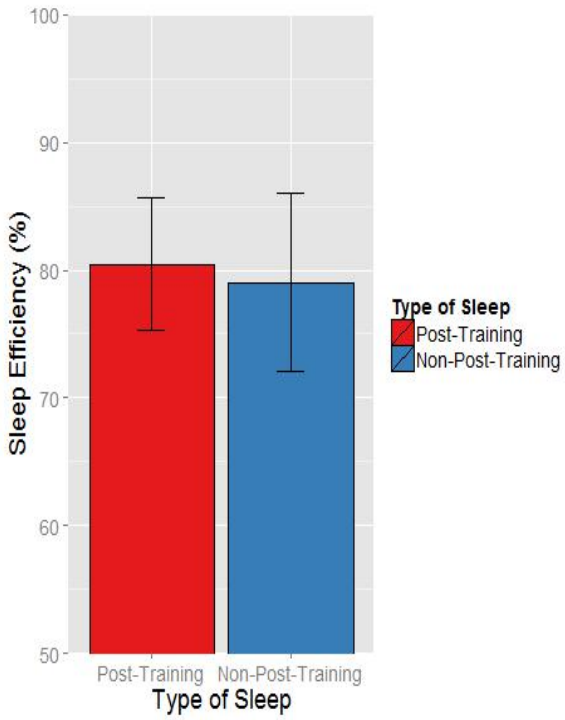


Figure 5.1b. Differences in sleep taking place after training sessions compared to normal 'habitual' sleep. Bars represent mean averages', error bars represent 1 standard deviation.

5.4.2 – Relationship Between Sleep and Training Performance

For each outcome variable, predictors (having been z-transformed) were entered individually into the multi-level model, once as a linear function and again as a second order polynomial function. In all cases model fit was not significantly enhanced by fitting predictors as a parabolic rather than a linear factor, and so non-linear relationships only were considered further for the sake of parsimony.

A summary of the results for the relationship between each predictor and each outcome measure is presented in table 5.2 (Appendix D). While there appears to be no significant relationship between sleep quality and performance during training sessions, there was a consistent trend towards reduced performance following an unusually late bed time, with evidence for a reduction in terms of distance covered during training sessions (both overall average distance and high intensity distance), as well as a reduction in the effort being applied by players' as measured by the PlayerLoad measure. There was also a significant trend for higher RPE scores (controlled for by distance covered during the training session) following an unusually late bed time. Similarly significant trends were in evidence for duration of sleep, with longer periods of sleep being associated with an increase in the distances covered (both overall and high intensity) as well as PlayerLoad, although there was no association between sleep duration and self-rated RPE scores. More complex multilevel models were constructed which utilized several predictors simultaneously to attempt to model variation in each outcome measure. The starting point was informed by an all possible subsets analysis, after which predictors were entered and removed from the overall model in an iterative fashion manually, to

determine which combination of predictors offered the best overall fit of the model to the data. While these more complex models did indeed tend to improve the overall fit of the model to the data, the increase in model fit was not statistically significant (as determined by the change in the log-likelihood measure of model fit).

5.4.3 – Relationship Between Physical Activity During Training and Subsequent Sleep

For each outcome variable, predictors (having been z-transformed) were entered individually into the multi-level model, once as a linear function and again as a second order polynomial function. In all cases model fit was not significantly enhanced by fitting predictors as a parabolic rather than a linear factor, and so non-linear relationships only were considered further for the sake of parsimony.

A summary of the results for the relationship between each predictor and each outcome measure is presented in table 5.3 (Appendix D). While a number of interesting trends are in evidence, the strongest relationship between physical work and subsequent sleep appears to depend on the amount of ‘high-intensity’ activity that players experience. Increasing the amount of high-intensity distance covered during training sessions were associated with a significantly earlier bed time, as well as a tendency towards a significantly longer period of total sleep. There was also a trend towards higher levels of high-intensity activity being associated with a reduction in sleep quality, as evidenced by the trend towards an increase in wakefulness after sleep onset and sleep onset latency. A number of similar findings

from other predictors were also in evidence, such as increasing levels of total distance covered and increased effort levels as measured by PlayerLoad were also associated with a significant increase in the overall length of the subsequent sleep period. All possible subsets analysis was used to inform the starting point of more complex building employing multiple predictors simultaneously. Predictors were then added and removed manually in an iterative fashion to determine the best set of predictors. While the inclusion of multiple predictors invariably improved the overall fit of the model to the data, this improvement was not statistically significant, as determined by the relatively low amount of improvement of model fit as measured by the log-likelihood statistic.

5.5 – Discussion

5.5.1 – Variability in Sleep During Periods of Training

These results have demonstrated that there appears to be no significant alterations in the sleep of professional football players during the course of a regular competitive season as a function of physical training. The most obvious conclusion seems to be that whatever factors are involved contributing to the unusually poor sleep that was observed in section 3 are reasonably persistent throughout the course of a season, and do not fluctuate enough (at least, not significantly) on a day-to-day basis. Certainly factors such as anxiety could reasonably be thought to be fairly consistent, since, as has been discussed previously, players are in a constant state of intra-team competition with their team-mates, battling for inclusion in the

starting team for upcoming matches. It should also be noted that the organisational stressors against sleep, such as maintaining a consistent schedule, are still present, since matches were taking place throughout the period of analysis. While the current analysis excluded nights of sleep data that took place immediately following a match, the impact of an unusually late night following a match is likely to cause a phase-delay in the individuals' circadian phase, which could continue to exert a negative influence on sleep for several days (as anyone who has experienced forced de-synchrony will testify- one does not tend to recover from jet-lag after a single night's sleep; Horne, 2006; Reilly & Edwards, 2007; Reilly et al., 2005).

Another factor that may be in evidence here, as discussed earlier in section 4, is the idea that a 'floor-effect' may be preventing any further significant degradation of sleep. As was highlighted in chapter 3, the quality of sleep in this population is already significantly worse than would be expected for otherwise healthy adults of the same age, and more closely resembles the sleep of those with diagnosed sleep disorders more than healthy sleep in many cases. Although admittedly a rather bleak assessment, it may simply be the case that their sleep simply cannot (easily) get any worse. Another likely factor to consider once again is that the current study is aiming to uncover a relatively small effect in terms of the impact that training has on sleep, due to the necessity of studying naturally occurring variations in sleep, since experimental manipulation would not be easy to accomplish in the population of interest. It is also certainly the case that the physical training is only one of the factors that could conceivably be exerting an influence on players' sleep. Naturally there are countless others, and it would be simply implausible to attempt to account for every single one of them in the scope of the present study. Assuming that physical training does exert a (small) influence on sleep, it may be the case that the

effect it has is being 'swamped' by any number of these myriad factors. A relatively simple comparison of mean sleep measures may simply not be sensitive enough to identify a small effect when it is drowned out by a number of confounding factors. A direct assessment of the relationship between physical exercise and subsequent sleep would perhaps be more able to 'tease out' these differences, an approach which was carried out using the same data, and the results of which will be discussed presently.

The overriding finding however is that there appears to have been little variation in professional football players' sleep depending on their physical training during the course of the competitive season. This suggests that the factors which contribute towards the poor sleep seen generally in this population are relatively durable and stable during this extended period of time.

5.5.2 – Relationship Between Sleep and Training Performance

In contrast with the findings from section 4, these results demonstrate that the timing and duration of sleep appears to exert a significant influence over the amount of physical work that professional players complete during regular training sessions, in addition to increasing the perception of effort. Considered in the light of existing research which highlights the importance of the prevailing motivational climate (Martin, 1981; Horne & Pettitt, 1974; Bambaiechi et al., 2005) in determining the consequences of inadequate sleep on physical effort, there is a large degree of agreement. In contrast to the data obtained from the inarguably more motivationally

stimulating environment of a competitive match, these results demonstrate that, in the absence of such an immediate and salient source of motivation, the extent to which poor sleep can adversely affect both the perception of physical effort and the actual amount of physical work undertaken is far greater.

The consequences associated with a reduced level of effort being applied during training sessions in concordance with fluctuations in the timing and duration of sleep are likely to be just as serious a concern to athletes and coaches as the possibility that poor sleep could have adverse consequences on match performance. The level of training that is necessary to reach and sustain performance at an elite competitive level requires that athletes 'over-reach.' That is to say, athletes are required to push themselves up to and in fact a little beyond their current physical limits (Hug, Mullis, Vogt, Ventura & Hoppeler, 2003; Coutts, Slattery & Wallace, 2007). An adequate period of recovery is then required, during which time physiological adaptation is allowed to take place and the specific system that was placed under strain becomes stronger. These results suggest that sleep has a significant role to play in determining how much effort athletes are likely to exert during training sessions, which previous research suggests is likely to be a consequence of the increased perception of effort following inadequate sleep, rather than a direct impact on the body's capacity to perform physical work. If sleep is chronically disrupted (as we have seen earlier in section 3), this suggests that throughout the course of the competitive season, professional footballers are frequently not expending as much effort during day-to-day training as they would perhaps be able to if their sleep was improved.

As in all studies, there are a number of important caveats to consider, the first and perhaps most important is the difficulty associated with attributing causation.

While measurements were taken such that sleep immediately before training sessions was modelled against the amount of physical work, and the perception of effort of that physical work that took place following each period of sleep, there are a number of potentially confounding factors that could be contributing towards both. For instance, the sports science staff at one club suggested that, when the team did not have a mid-week fixture, a 'match-replacement' training session was almost ubiquitously scheduled on the Tuesday of that week (the day on which mid-week fixtures generally take place), which featured more match-like exercises and was generally harder than a normal training session. When considered alongside the fact that such unusually strenuous training session tended to be preceded by a rest day, this may offer another explanation for the relationship between sleep and performance the following day, since a rest day may offer players a greater opportunity to plan an adequate period of sleep and go to bed earlier. It should also be pointed out that this potentially spurious effect does not offer a good explanation for the increased perception of effort following poor sleep, when RPE is controlled for by distance covered. One way that future research could attempt to examine this in more detail would be to split training sessions according to how strenuous they are, and examine separately the relationship that prior sleep has on the amount of physical work conducted during training. For example, training could be split into 'match-replacement' training sessions and 'post-match recovery' sessions. The objectives of each type of session are very different, and a different level of physical activity would be expected in each case. It may be possible that the impact that sleep has on training depends on the difficulty of the specific training, and influences one kind of training session more than the other. Of course it may also be the case that the relationship between sleep and training performance is relatively robust.

Unfortunately there was insufficient data available in the present investigation to undertake such a differential analysis. Such a method would likely require collecting sleep and training data from an entire football club for an entire season in order to yield sufficient data for such an analysis.

5.5.3 – Relationship Between Physical Activity During Training and Subsequent Sleep

Predicting the outcome of this data based on the existing literature would be difficult due to the varying hypotheses describing this relationship. Since both of the current prevailing hypotheses about a relationship between exercise and subsequent sleep suggest that activity taking place during the mid-morning to approximately midday should have little impact on subsequent sleep, it might be most expected that there not be a significant relationship between the amount of physical exercise undertaken during training and subsequent sleep in this study. The thermogenic hypothesis (Horne & Staff, 1983; Trinder et al., 1988; Horne & Moore, 1985) would suggest the lack of a relationship, since training sessions would typically end no later than 1300 hours, too far away from bed time for any impact as a consequence of body heating and the subsequently sharper decline in temperature that supposedly accounts for improved sleep. The hypothesis that exercise can exert a circadian effect would also suggest that exercise, like light exposure, taking place during the middle portion of the day would not exert a significant circadian effect (Yamanaka et al., 2010), although training sessions starting at 0900 hours may exert a very slight phase advance due to the early start. There is also uncertainty as to the direction of

any effect that may exist; most existing research suggests that exercise would be expected to make a positive contribution to sleep, but there are instances of 'extreme' levels of exercise having a detrimental impact.

The physical factor that demonstrates the most consistent relationship with subsequent sleep in this case is the amount of distance players cover at high intensity, with increases in the level of high intensity exercise being associated with significantly earlier bed times and significantly longer periods of sleep immediately afterwards. There were also trends for increasing levels of high-intensity distance during training to exert a negative impact on sleep quality, with statistically non-significant trends towards increased wakefulness after sleep onset and a longer latency period before sleep onset. More generally, there was evidence to suggest that more strenuous training sessions, as measured by the total distance covered, the amount of distance covered at high intensity and the level of stress according to the PlayerLoad measurement, tended to be followed by significantly longer periods of sleep.

The fact that increasing levels of physical activity were found to exert a significant impact upon sleep is not entirely surprising, but it would not have been expected for such an effect to be in evidence when the physical activity in this case was taking place during the middle of the day, too far away from bed time for the thermogenic hypothesis to offer a reasonable explanation. The best alternative explanation therefore rests on the notion that exercise exerts an influence over circadian rhythms, suggesting exercise of sufficient intensity taking place during the morning has the capacity to advance the circadian phase of the exerciser, which would explain the association between increasing levels of exercise and earlier bed times, with the exerciser feeling sleepy earlier as a consequence, as well as a

potential explanation for the associated increase in total sleep time, as an expression of the increased drive for sleep. Such a hypothesis has little to offer as an explanation for the trends towards a decrease in sleep quality however. The third explanation arises from the possibility of effects of confounding factors- for example, the possibility that harder training sessions (such as the match replacement sessions) are more likely than others to be followed by a rest day with an absence of training, which would easily account for the increase in sleep time, as players allow themselves a 'lie-in' following such unusually strenuous training sessions.

5.6 – Conclusions

The findings presented here have the potential to have a number of important practical considerations. The finding that the amount of effort that professional football players exert during training sessions displays a significant dependence on their sleep the previous night could be highly interesting to athletes and coaches in particular. Taken in concert with the findings presented in section 3 of this thesis, which highlight the generally poor sleep practices of athletes, there could potentially be a great deal of scope for improvement in the sleep of athletes which, based on these findings, could reasonably be expected to be associated with a concurrent increase in the levels of physical work during training. In addition to the possibility that improvements to sleep could have a beneficial impact upon performance during training, previous research has also suggested that athletes adaptation to training would be likely to exhibit an improvement as a consequence of the beneficial impact that sleep has on protein and carbohydrate metabolism (e.g. Harsch, Schahin,

Radespiel-Tröger, Weintz, Jahreiss, Fuchs et al., 2003; Res et al., 2012). Based on the findings presented here, sleep improvement could prove to be a relatively simple strategy which contributes towards significant enhancements to training.

5.7 – Summary

- There appear to be no systematic differences in sleep taking place before or after training sessions, relative to habitual norms.
- Sleep does display a significant impact upon subsequent performance during training, with increases in the physical activity levels and a reduced perception of effort following earlier and longer periods of sleep.
- Physical activity levels also demonstrated an impact on subsequent sleep, in particular increasing levels of high-intensity activity during training were associated with earlier and longer periods of subsequent sleep, in addition to trends towards a reduction in sleep quality.

Chapter 6

General Discussion

6.1 – Overview of the Investigations Undertaken

This thesis has aimed to examine the sleep of elite-level athletes, and to determine if a relationship exists between sleep and performance in elite athletes during competitions and training. The first study of this thesis demonstrated the extent of sleep disturbance among elite athletes, confirming a common belief among athletes and coaches that difficulty sleeping is a common experience among athletes (Erlacher et al., 2011; Atkinson et al., 2001; Savis, 1994). This study has also extended the knowledge of this phenomena to sleep difficulty among elite athletes during the competitive season, while empirical research to date has been limited to investigations of poor sleep during the off-season (Leeder et al., 2012) and during a particularly intensive period of training (Sargent et al., 2012). This study is also the largest study of objectively measured sleep in elite-level athletes that has been conducted to date. The discovery that sleep disturbance seems to be a rather persistent feature of athletes during an extended period of the season is likely to have serious practical implications; the negative consequences associated with disturbed sleep in the general population are well documented (e.g. Kripke et al., 2002; Merkus et al., 2012; Jansen et al., 2003; Besedovsky et al., 2012) and the knowledge that athletes, whose success depends on gaining every conceivable advantage over their opponents, may be being chronically impaired by sub-optimal sleep, is likely to be an important consideration for athletes and coaches in the future.

The second study aimed to examine a number of questions relating to the possibility of a bi-directional relationship between sleep and elite athletic competition. Concerning the specific question of whether sleep immediately prior to a competition

can exert an influence on sleep, existing research has tended to suggest that, in the absence of adequate motivation, sleep can have an impact on cognitive aspects of performance, as well as an impact on physical measures due to the effect that inadequate or sub-optimal sleep has on mood and motivation. The major difficulty with the extension of this existing research to the current context is that it has artificially manipulated a reduction in overall sleep length, and has measured performance in a way that is not representative of an elite athletic competition. Given the importance of motivation in determining the impact that sleep has on performance, the current study aimed to investigate how variations in sleep were associated with variations in subsequent performances, so that both sleep disturbance and measured performance was entirely natural. In fact, the findings from this investigation demonstrated a remarkable level of consistency with the existing body of research, in that physical measures of performance were generally quite resilient to reductions in sleep, although there was a trend towards a reduction in 'self-paced' activity (also in agreement with existing research; Rodgers et al., 1995). It was also noted however that the margin of difference that is commonly accepted among scientific communities may not be in agreement with the margins that exist in elite athletic spheres, where even small negative impacts on performance are a serious cause for concern, and the margin between success and failure are so narrow. Given this, the impact that sleep could exert on performance may still have serious practical consequences.

The second component of this study was to investigate the ways in which the pressures associated with competing in elite athletic competition can have an impact upon sleep. Once again, while there is an existing body of research investigating the ways in which *exercise* can have on subsequent sleep, such investigations have

tended to recruit conspicuously 'ordinary' research participants, a label which is certainly not attributable to elite-level athletes themselves, as well as the stark contrast in the level of physical exertion that is required of a physical exercise type level of activity compared to the exertion required during elite athletic competition. Perhaps a reflection of the apparent importance that is placed upon attaining adequate sleep, alterations in the sleeping behaviour of professional footballers were in evidence, particularly in terms of players retiring to bed earlier than they normally would and subsequently sleeping longer the night before matches. There was also evidence of alteration to sleep following matches, with players retiring to bed significantly later than their normal time. What was perhaps surprising was that this later bed time did not appear to be dependent on the timing of matches. Where the time of competition was influential, however, was in the direct relationship between the level of physical activity and subsequent sleep. While increasing levels of physical activity during afternoon matches did not display a marked impact on subsequent sleep, physical activity during evening matches did.

The third and final study aimed to investigate the relationship between sleep and performance during training for elite athletic competition. While performance during competitions is likely to be the most salient and visibly important time for athletes to achieve peak performance, the importance of adequate training is a vital component of such attainment. The possibility that sub-optimal sleep could have a deleterious impact on athletes training could be just as important as the impact it has on performance during matches. It is also important to consider once again the role that motivation has on determining how well physical performance will be maintained following poor sleep, and while performance during matches demonstrated a degree of resilience to sub-optimal sleep, the motivational climate that prevails during

training is unlikely to be quite so stimulating. Accordingly, and once again in overall agreement with existing research (Robert & Hockey, 1997), training sessions preceded by earlier and longer periods of sleep demonstrated a greater level of physical work completed by players, in addition to a reduction in the perceived level of effort reported by players, suggesting that improved sleep has a beneficial effect on training.

6.2 – Practical Implications

6.2.1 – Sleep Disturbance in Athletes

Perhaps the most startling and important finding presented within this thesis is the evidence of substantial and apparently pervasive presence of sleep disturbance among elite-level athletes. While this has been hinted at by previous investigations, this is the first that has objectively verified poor sleep in this population throughout the competitive season. In addition, contrary to the suggestion of Erlacher et al. (2011). it also appears that this sleep disturbance is not just limited to period of sleep immediately before competitions, but appears to be a longer-term problem.

6.2.1.1 – Existing Research on Sleep Disturbance

In order to understand what the consequences are likely to be we must turn our attention to the literature examining the impact of sleep fragmentation on daytime functioning. As was highlighted in chapter one, this is distinct from the traditionally studied sleep deprivation in that sleep fragmentation involves continuously provoking sleeping participants into brief periods of arousal during sleep, rather than a simple reduction (or total curtailment) of sleep. The best example of this pattern of sleep fragmentation occurring naturally arises due to sleep apnoea, in which a person ceases to breathe when they fall asleep. The oxygen deficit this causes in very short order results in the person briefly awakening frequently during sleep in order to breathe. These arousal are so brief (less than 10 seconds in most cases) that they are usually not noticed or even remembered by the sleeper the following day, and only 18% to 31% of sleep apnoea patients actually report the choking that interrupts sleep (Kales et al., 1985; Maislin et al., 1995; Coverdale, Read, Woolcock & Schoeffel, 1980) and the diagnosis of sleep apnoea often relies on reports by a bed partner (American Academy of Sleep Medicine, 2006; Guilleminault & Bassiri 2005).

Sleep apnoea is associated with a number of negative consequences on daytime functioning, although there has been some discussion as to whether it is the discontinuity of sleep cause by frequent brief arousals or the hypoxemia during sleep that is the cause of these negative consequences. There have been two lines of research which seek to clarify matters. The first approach is to attempt to separate the effect of frequent arousals during sleep and measures of hypoxemia during sleep. Using multiple regression Roehrs et al. (1989) found that, while the frequency of arousals during sleep significantly predicted subsequent daytime sleepiness in sleep

apnoea patients, hypoxemia did not. Another study (Colt et al., 1991) experimentally induced episodes of hypoxemia in patients with sleep apnoea by exposing them to nitrogen during treatment using continuous positive airway pressure (CPAP), compared to a group only exposed to the usual 100% oxygen CPAP that is often used to treat sleep apnoea. The increased hypoxemia did not lead to any detrimental impact upon subsequent sleepiness the next day, leading to the suggestion that it is indeed the fragmentation of sleep, and not hypoxemia that is responsible for the negative daytime consequences associated with sleep apnoea.

The second approach to determining the role of frequent arousals on subsequent functioning has been to experimentally replicate the sleep fragmentation present during sleep. Michael Bonnet conducted much of the early research in this area, the first study being published in 1985, in which participants slept whilst being monitored by EEG. After participants demonstrated one minute of sleep, they were awoken by a loud tone, at which point they had to confirm that they had been awoken, after which they were allowed to return to sleep for one more minute. It was reported that once participants were used to the method of confirming their arousal, it only took a matter of seconds for participants to indicate that they were awake and return to sleep.

While this procedure only resulted in a reduction to total sleep time of one hour, there was a significant alteration in the sleep architecture of participants, who experienced significant declines in SWS and REM sleep. In terms of how this sleep fragmentation affected participants the following day, scores on the Clyde Mood Scale (Clyde, 1950), Stanford Sleepiness Scale (Hoddes, Zarcone, Smythe, Phillips & Dement, 1973) and performance on a simple reaction time task and a digit symbol substitution task demonstrated a level of decrement which was equivalent to a period

of total sleep deprivation of 40-64 hours. The basic paradigm has been replicated a number of times, using a variety of intervals between arousals (Bonnet, 1986; Levine et al., 1987), from every minute up to every 10 minutes, comparing continuous regular arousals to clustered arousals (Martin, Brander, Deary & Douglas, 1999) and comparing the effects of different arousal criteria on subsequent performance, ranging from requiring a behavioural response from participants such as pressing a button or speaking to a researcher (Bonnet, 1985; 1986; Downey & Bonnet, 1987) to an EEG defined 'arousal' which did not require a behavioural response from participants, but a stimuli was presented such that it disturbed the EEG pattern of the sleeper. This arousal criteria is intended to be a more realistic representation of sleep fragmentation as it appears in sleep apnoeacs and other sleep disorders such as periodic leg movements during sleep.

The findings of such studies have been thoroughly reviewed by Stepanski (2002). The implications which have the greatest relevance to the current discussion are that even arousals only requiring a transient change in the EEG stage of participants lasting as little as three seconds is sufficient to have a detrimental impact on subsequent daytime performance. This is vital because as has been discussed previously the sleep/wake identification used by the Actiwatches in this study have been validated against EEG, suggesting that the level of sleep fragmentation which is evident among the athletes studied here is at a level which is sufficient to have an impact on performance as has been noted in previous studies. The second key factor stemming from experimental sleep fragmentation studies is relationship between the intervals between arousals and subsequent performance. In his review, Stepanski notes that arousals which occur more frequently than once every 10 minutes (or 6 per hour) during sleep cause significant performance

decrements the following day, whereas arousal frequencies lower than 6 per hour have been reported not to increase sleepiness relative to normal uninterrupted sleep. This is especially significant in light of the results presented in chapter 3, which indicate that, while sedentary participants exhibit slightly over 6 movements per hour (while bearing in mind that not **all** movements indicate arousal), all the athletes demonstrated much higher levels of movement per hour, which take them beyond the 6 per hour threshold. All of this suggests that the level of sleep disturbance which is evident here could be having negative consequences in line with those that have been discovered in existing research.

In addition to the concern that the level of sleep disturbance evident amongst the high-performance athletes presented here could be having an adverse effect upon their athletic performances, concern should also be raised regarding the potential long-term consequences of such sleep. While the importance of factors such as proper nutrition and training techniques are almost universally regarded as being self-evident among athletes and their coaches (as is evidenced by the amount of resources dedicated towards the application of these disciplines in professional sports teams), the presence of enduring and pervasive poor sleep among athletes should also be of concern to athletes and coaches hoping to achieve peak performance.

6.2.1.2 – Consequences for General Health

Chronically poor sleep has been associated with a number of negative consequences in addition to decrements in mood and performance that are evident even after relatively modest periods of sleep disturbance. While experimental inquiries into chronic sleep restriction have taken place (e.g Belenky et al., 2003; Herscovitch & Broughton, 1981), the practical difficulties associated with trying to experimentally induce sleep restriction over extended periods has mandated that the majority of insight regarding the longer-term effects of reduced or disturbed sleep has come from studies investigating the prevalence of adverse consequences in populations which already experience such sleep, such as shift workers, sleep apnoeacs and insomniacs.

Particular attention has been paid in these populations to a number of adverse health consequences that are unusually prevalent that seem to be associated with the reduced volume and/or quality of sleep. Rogers and Dinges (2001) note the higher level of medical disorders in shift works, and similar observations have been made in insomniacs (Bonnet & Arand, 2003) and sleep apnoeacs (Punjabi & Beamer, 2005). In addition epidemiological studies have demonstrated that among those who report habitually sleeping less than seven hours per night, there is a small but significant increase in all-cause mortality (Kripke et al., 2002; Ayas et al., 2003). Chronically poor sleep has also been associated with an increased incidence of sick leave from work with a variety of complaints (Merkus et al., 2012). While it seems likely that elite-level athletes should not be concerned with the sort of detrimental effect that fragmented sleep can have on health when

one considers that their overall level of health is vastly superior to the general population, they should perhaps be concerned of the metabolic consequences that can arise as a result of chronically fragmented sleep. Punjabi and Beamer (2005) note that there is credible evidence of a causal relationship between sleep apnoea and an increased resistance to insulin. Given the widely acknowledged importance of nutrition to both elite athletic performance and the crucial role it plays in recovering from and adapting to training, the possibility of long term metabolic dysfunction harming an athletes' ability to get the full gain from training could be a serious concern.

6.2.1.3 – Consequences for Immune Functioning

Another long-term consideration of potential importance is the role that both strenuous training and poor sleep can have on the functioning of the immune system. Even acute periods of sleep deprivation can have long-lasting effects on the functioning of the immune system. Lange et al. (2003) for example found that a single night of sleep deprivation following the administration of a hepatitis vaccination halved the number of antibodies in patients four weeks later, compared to a group who had slept normally. Similar findings have been reported by Spiegel et al. (2002) in response to an influenza vaccine, but disturbed sleep using sleep fragmentation rather than sleep deprivation. In the long term, Faraut et al. (2012) suggest that small amounts of sleep disturbance, built up over a period of time, could have a gradual and cumulative deleterious effect on health. Epidemiological studies of shift workers

add weight to the contention that the immune system is hampered by inadequate sleep (Scheer et al., 2009; Knutsson, 2003; Heslop et al., 2002; Ferrie et al., 2007).

This is of particular concern to the current population because strenuous exercise has also been linked to decrements in the functioning of the immune system (Gleeson, Bishop, Oliveira, McCauley & Tauler, 2011; Gleeson, 2007). This seems likely to be responsible for the reported increase in susceptibility to infections among athletes during periods of heavy training and competition (Fahlman & Engels, 2005; Gleeson et al., 2011; Nieman et al., 1990; Peters & Bateman, 1983), with upper respiratory tract infections being the most commonly reported illness among elite-level athletes (Mackinnon, 2000; Page & Diehl, 2007; Peters & Bateman, 1983), particularly during periods of intense training (Yamaucgi et al., 2011). It does not appear that any of the above quoted studies attempted to properly measure sleep in order to establish if it contributed to the negative immune system outcomes that have been observed in athletes, but it is perhaps a fruitful area for further research to consider since a greater susceptibility to illness over the long term is likely to have adverse consequences on an athlete's training schedule and, if the reasons for this can be better understood, it may be possible to mitigate this susceptibility by improving sleep.

6.2.1.4 – Possible Contributory Factors to Sleep Disturbance in Athletes

It is perhaps surprising that there appears to be such a consistently poor quality of sleep evident among athletes when one considers the ‘common sense’ appeal of the idea that a ‘good tiredness’ (such as from physical activity) leads to a ‘good sleep’ (Davenne, 2009). Such is the appeal of this notion that exercise is endorsed by the American Sleep Disorders Association as being useful to those with disordered sleep, and is often regarded as a non-pharmacological intervention in sleep hygiene discussions (Hauri, 1993; Lavie, 1996). Survey studies have also suggested that the general public seem to regard exercise as having a positive influence on sleep (Youngstedt & Kline, 2006; Sherrill et al. 1998; Vuori et al. 1988). Empirical evidence has however been less than compelling, which Driver and Taylor (2000) in their review of this area attribute to factors such as variation in methodology, a predominance of testing good sleepers (and research that has not recruited good sleepers tend to find a more positive influence of exercise e.g. Youngstedt et al., 1997), and the impetus of such research being to test theories regarding the function of sleep. Most importantly however is the focus on recreational levels of exercise, which are of course not representative of the type of exercise experienced by elite-level athletes.

While light and medium intensities of exercise have been demonstrated by some studies as having an impact on subsequent sleep in the form of an increase in SWS (Bunnell et al., 1983; Horne & Staff, 1983; Trinder et al., 1988), very high levels of exercise such as marathon or ultra-marathon events tend to show the opposite effect (Baekeland & Lasky, 1966; Shapiro et al., 1981, Taylor, 2001). It has been

suggested that the time of day at which exercise takes place is also of critical importance in determining any effect that it is likely to have on subsequent sleep, with the suggestion that high intensity exercise taking place less than 3 hours before sleep tends to have an alerting effect which is responsible for increasing sleep onset latencies and levels of movement during sleep (Driver & Taylor, 1996), although experimental evidence in this regard is also equivocal (e.g. Myllmaki et al., 2011). It is also possible that the time of day of exercise could influence sleep through a circadian mechanism; Yamanaka et al. (2010) and Waterhouse et al. (2002) demonstrated that exercise can exhibit a phase-shifting effect almost as strong as bright light. Given that, it would be expected that exercise taking place after the early evening circadian peak would have a negative impact on sleep due to a phase-delaying effect, exercise during the morning would have a phase-advancing effect, which could increase sleepiness during the evening, while exercise during the middle portion of the day would not have a large effect in any direction.

With the current set of data in mind, it is difficult to imagine that the 'extreme' levels of physical activity are solely responsible for the level of sleep disturbance in evidence. This is particularly evident from the professional footballers included in the sample since their disturbed sleep persists even in the absence of any training on a given day. In addition, their day-to-day training takes place during the morning, between 9 o'clock in the morning and, at the latest, 2 o'clock in the afternoon, which would be expected to have only a minimal impact upon players' circadian pacemaker. Similarly in the swimming sample, training usually takes place very early in the morning and again in the late afternoon/early evening, which would be expected to have a phase-advancing effect, increasing sleepiness towards the end of the day, but they too demonstrated significant sleep disturbance.

One area where circadian factors may have a role to play is as a result of a continuously changing pattern of sleep scheduling, which is again most evident among the professional footballers. As a consequence of the demands of their sport, these athletes often have an unusually late bed time forced upon them, such as following a mid-week match away from home. Since mid-week matches tend not to start until well into the evening, by the time the match has finished and the team travelled home it is not unusual for players to be retiring to bed as late as 3 or 4 o'clock in the morning. Assuming an 8 or 9 hour sleep that night, this will have the effect of altering the players' circadian phase relative to the external environment in just the same way (albeit not as drastically) as trans-meridian travel does in jet-lag (the effects of which upon performance, both 'mainstream' and athletic, have been well documented e.g. Monk, Buysse, Reynolds, Berga, Jarrett, Begley & Kupfer, 1997; Waterhouse, Edwards, Carvalho-Bos, Buckley & Reilly, 2002). Consistency in the timing of sleep is also recognised as an important factor in sleep hygiene discussions, and has been thought of as a factor which contributes to the continuation of poor sleep among those with sleep disorders such as primary insomnia (Wang et al. 2005). Since professional footballers compete on a weekly basis throughout the competitive season, they have a manifestly 'chaotic' schedule of sleep and wake, with sleep times varying on an almost daily basis. Combined with sporadic periods of international travel (for players competing for their national team in addition to their club) this continual variation in circadian synchrony could be a plausible contributory factor to players' persistent poor sleep. There is difficulty however in extending this conjecture, particularly to the swimmers in the current study, since there were no competitions during the study period, and their patterns of sleep and wake scheduling were far more consistent but still demonstrated a similar

level of sleep disturbance. The only significant differences between the swimmers and footballers related to sleep timing and sleep length, which is likely a reflection of the differing demands of their sport, which requires swimmers to arise for training significantly earlier than professional footballers so that a second training session following adequate recovery can take place later in the day.

Another likely contributory factor to poor sleep in athletes is anxiety (Davenne, 2009). It seems likely that athletes will be exposed to heightened levels of anxiety, particularly during times of competition, which perhaps explains why anxiety is one of the most measured constructs in sport psychology (Cox et al., 2003). There are countless potential sources of anxiety for those competing in athletic events, such as fear of failure, negative evaluation from others and not performing at one's best, as well as factors depending upon one's performance such as the financial burden or implications of a negative performance (Scanlan, Sten & Ravizza, 1991; Weiss, Wiese & Klint, 1989; Gould, Horn & Spreeman, 1983). Both the basketball players and football players in the current study were competing on a weekly basis during the study period, and were also part of a larger team between matches during which they will have been competing for selection within that team for inclusion in upcoming matches. While it is understood that anxiety is not necessarily deleterious to athletic performance, the impact that anxiety has depends largely on how it is appraised by the individual (Weinberg & Gould, 2007). The relationship between anxiety and sleep is well understood in the mainstream sleep literature, given the high co-morbidity between anxiety disorders and sleep (Stein & Mellman, 2005), as well as acute sleep complaints before important events (e.g. Langendörfer et al., 2006; Silva, Queiroz, Winckler, Vital, Sousa, Fagundes et al., 2012). A plausible mechanism explaining how competitive anxiety could lead to poor sleep among

athletes exists, based on Harvey's (2002) cognitive model of insomnia. This model is intended to describe how primary insomnia occurs as a result of negatively-toned cognitive activity about the need for adequate sleep and the consequences associated with insufficient during the immediate pre-sleep period, and that this anxiety gives rise to arousal and distress, making sleep more elusive which then feeds back into further negative cognitive activity. It seems eminently plausible however, that an elite level athlete, anxious about an upcoming competition or worried about the security of their place, could experience a similar process leading to disturbed sleep.

6.2.2 – Implications for Athletic Performance

While the results of the analysis into the relationship between sleep and subsequent performance in competitive situations were not statistically significant, these data could still be of considerable interest. At least for total distance covered during matches, the direction of the relationship between sleep and distance covered was in the direction that may be expected, suggesting a positive impact of sleep. Earlier bed times, longer sleep times and greater sleep efficiency were associated with an increase in distance covered on-pitch, while reduced sleep quality (i.e as measured by WASO, SOL and onsets/hour) were associated with decreases in distance covered. In contrast, and in particular for measures of sleep quality, the relationship between sleep and high intensity distance covered was far lower. During a football match, there are inevitably periods of play where a specific individual is more directly involved with the game at some points than at others, for example

when a player is in possession of the ball, or perhaps trying to win possession from an opposition player. In contrast, there will be periods when players are not directly involved in the game, such as defenders when their own team has possession deep in the opposing team's territory. In such a situation the defensive players must remain largely to the rear of their team, in order to be available to cover any sudden change in circumstances. Players not directly involved with a specific passage of play are less likely to have a need to move at 'high-intensity' speed than players who are directly involved, and are perhaps more likely to need to respond quickly to changing circumstances. This draws some useful parallels with lab-based research highlighting the differing effects of sleep deprivation of forced-pace physical work compared to self-chosen pace (Rodgers et al., 1995). In this context, even when players' are 'off the ball' and not directly involved in a particular passage of play, they should not generally be static (the goalkeeper being an obvious exception).

Defending players should still be mobile, tracking the run of play forwards and backwards, as well as lateral movement side-to-side in order to be optimally placed to respond quickly if necessary. It does not seem entirely unreasonable to suggest that this bears some resemblance to the 'self-chosen pace' physical activity work that is used in lab-based studies, in which there is a less immediate motivation to work. Such a possibility may offer an explanation for the greater relationship with poor sleep, just as is in 'classical' sleep-deprivation studies. By comparison, if we accept that high-intensity work tends to take place more when there is an immediate need for the player to do so, this may explain how the increased importance and concurrent motivational immediacy render such movement levels more resistant to previous poor sleep.

Despite the lack of a significant relationship between sleep and performance, it is important to bear in mind the context in which this research takes place, and remember the importance that small differences can have in elite athletic competition (the philosophy of 'aggregation of marginal gains' discussed previously). It is not easy to quantify in football, but for example in sprinting, the difference between the gold medal winning time at the London 2012 Olympic Games (9.63 seconds) and fourth position (9.80 seconds) amounts to only a 1.77%, and the difference to the lowest placed (uninjured) finisher amounts to only 3.6% (London 2012 Organising Committee, 2012). To take an example from the current study, if one takes the results for the relationship between bed time and total metres covered, the results suggest that going to bed 1 standard deviation earlier than normal is associated with an increase in total distance covered of 0.391 standard deviations. Taking the averages of each individual player, this equates to an earlier bed time of 73 minutes being associated with, on average, an increase in distance covered during matches of 820 metres. Given that the average distance covered by all players in all matches studied was 8,435 metres, this equates to an increase of 9.7% following an earlier bed time (a full set of examples can be found in Appendix E). This makes clear the stark contrast between the margins required for statistical significance and the margins that decide the difference between winning and losing in elite sport. Margins as tight as this are common in the world of elite sport, and while the effectiveness of certain strategies or tactics may not be large enough to reach statistical significance, they may never-the-less be an important consideration for players and coaches.

Another important factor to consider with these results is the fact that the best models for the relationship between sleep and subsequent performance were invariably simple linear relationships. Some evidence (e.g. Van Dongen & Dinges,

2003) has suggested that this relationship should be considered as non-linear (which provided the impetus for non-linear modelling of predictors in the current study). While it became apparent that non-linear modelling was not providing sufficient additional explanation of the variance in this case, it should be noted that the increasing level of complexity involved in modelling relationships of this sort generally requires a substantial increase in the quantity of data before such relationships are identifiable. Another important consideration in this regard relies on the fact that the sleep data is unusually constrained due to the circumstances in which the data were gathered. In a lab-based study, the timing or length (or even the quality of sleep, as manipulated in sleep fragmentation studies) can be extensively manipulated, either to produce an increase or decrease in sleep time, or an earlier or later bed time. The present study however resolved to measure sleep as it naturally occurs, since manipulated sleep is an unrealistic likelihood in the vast majority of cases. As was noted earlier, there was a significant trend for athletes to go to bed significantly earlier before matches. This effectively constrains players bed times (expressed as z-scores) to within -1 to 0 (ie 1 standard deviation earlier than normal) of when they would normally go to bed, with very few instances of a positive z-score of sleep time. As such, if the relationship were U shaped, with the centre of the curve approximately around a bed time of 0, the present study only captures one half of the possible data, which on its own would certainly be more likely to resemble a straightforward linear relationship. Since the results of the current study cannot be extrapolated beyond the range of the data present, a future study capturing a wider range of sleep data may very well find that the relationship between sleep and subsequent performance is non-linear.

A final consideration to note is the type of performance measures used in the present study. While the distance players cover during a football match can be affected by factors known to depend heavily on adequate sleep (namely motivation), it is certainly plausible that such factors are responsible for the disparity in the strength of the relationship between sleep and performance as measured by total distance covered and distance covered at high intensity. These measures remain primarily a measure of the amount of physical work completed by players during matches. One of the clearest findings of the work that currently exists is that the capacity to perform physical work is quite robust to decrements in the quantity or quality of sleep. It is cognitive performance that really declines seriously when sleep is inadequate. While how much distance a player covers during a match does depend to an extent on such cognitive factors, a performance measure examining a purely cognitive factor would be more likely to elicit a significant result as a consequence of poor sleep. Future research may wish to consider studying other sports which might allow measures of cognitive performance to be measured more easily in a real-life competitive situation. For future research in professional football players, it would be worthwhile to consider the work currently being undertaken by Peter O'Donoghue and Martin Lames (O'Donoghue, 2012; Lames, 2012), who are using data from the Prozone® tracking system to measure and analyse tactical factors in professional football, such as team cohesion and defensive cover, which may be more sensitive to poor sleep. Unfortunately this type of analysis requires access to the raw Prozone® tracking data, rather than just the summary information provided to football clubs, which was not available for the current investigation.

6.2.3 – Implications for Improved Training

The findings of this thesis which are of perhaps of primary importance to athletes and teams relate to the impact that poor sleep can have on subsequent performance during training, since it suggests that, if sleep could be improved upon, athletes may find that they are able to train harder and receive greater benefits of adaptation to training. Previous research has extended (to 10 hours per night) the amount of sleep that university-level basketball players attained on a daily basis, and observed a significant improvement in these participants on a number of laboratory-style performance measures (Mah et al., 2011). This study extends the implications of this study to performance during real-life training sessions in professional footballers. While the authors cited above point out that in many cases it may be organisationally impractical for athletes to arrange to be asleep for 10 hours per day, this is unlikely to be an insurmountable challenge for professional footballers. During the season these athletes are training only once per day, and their status as professionals means that they are not required to seek outside employment to support themselves, as is often the case in other elite-level sports. If even this relatively straightforward intervention can be effective in improving performance during training sessions, there is great potential that other sleep improvement interventions could prove to be a useful way to improve the effectiveness of training in elite-level athletes. Erratic scheduling of sleep has been demonstrated to be a significant factor in a number of the athletes studied throughout this thesis and, while it has not yet been demonstrated in athletes, education about sleep hygiene routinely features as a component of cognitive-behavioural therapies aimed at improving sleep in both clinical and sub-clinical insomnia (Hauri, 1977; 1992; Stepanski &

Wyatt, 2003). A number of other strategies have also been demonstrated as having a positive influence in sleep, such as body-heating close to bed time in order to exaggerate the circadian drop in core-body temperature, and deep tissue massage to provide relaxation before bed has been suggested as being an effective sleep-improvement intervention (Horne, 2006; Kalichman, 2010; Field, 1998), although once again these strategies have yet to be tested in elite-level athletes. Above all, the findings from section 3 indicate that there is potential for improvement to athletes' sleep, which combined with the findings presented here, also suggest that significant performance gains during training could also be made as a result.

It is also important to note that improvements to sleep would have a number of secondary benefits that are likely to be beneficial to athletes training for elite-level performance. The positive impact that sleep has been found to have on general health and well-being and the functioning of the immune system is likely to have a positive impact on athletes during training. In the light of the evidence presented here it may now be possible for those in the sleep-research community to more confidently suggest that good sleep is an important component for athletes striving to attain maximum performance and, given the raft of potential benefits that could be expected if sleep could be improved, that there could be a considerable desire in sports teams to investigate ways in which sleep could be improved in their athletes (a subject about which there has, thus far, been scant research). Thus, they might more closely monitor the sleep of their athletes as part of the regular monitoring that professional teams already engage in.

An additional implication that may have bearing on improvements that could be made to training is the concept of time-of-day specific training. Recent research conducted by Sedliak, Finni, Peltonen and Häkkinen (2008) has suggested that

adaptation to training relies significantly on circadian processes, and those athletes who train early in the mornings subsequently show greater performance gains when measured in the morning than they do when measured in the evenings, and vice versa. Given that the earliest kick-off times in professional football don't take place until well into the afternoon (approximately 1500 hours), it may be of concern that players universally train in the mornings, which may have the effect of blunting the performance gains that have been made during training when it comes to performance during matches. It may be a fruitful area for future research to consider the role that a mismatch between the time of day of training and performance could have, and could also form the basis of an intervention, by moving the time of training to be more in line to the time at which matches take place. Such an intervention may also prove to have beneficial consequences for players' sleep. Our current understanding of the contribution of circadian factors to sleep regulation highlights the importance of a regular pattern of activity. In addition to having positive consequences in terms of adaptation to training, altering the time of day at which training occurs to be more in line with the time at which competitions take place may also have a stabilising effect on the circadian rhythms of players, reducing the level of day-to-day variability in their sleep and activity schedules. This would be expected to have a positive impact on their sleep generally, which in turn would be expected to result in a number of other associated benefits, both in terms of their training as was demonstrated in the section 5.3.2, and also more generally in terms of improvements to factors such as mood and general health and well-being, as has been highlighted by the existing sleep literature.

6.3 – Methodological Considerations

6.3.1 – Sleep Measurement

Following the suggestion of the few authors that have investigated sleep directly in elite-level athletes, wrist actigraphy was chosen as the principal method of sleep measurement throughout this thesis. While the validity and reliability of this measurement in determining the sleep or wakefulness of participants has consistently been shown to be favourable compared to the established 'gold-standard' measure of EEG (as discussed previously in chapter two of this thesis), there are still a number of limitations associated with this technology. The primary disadvantage of actimetry compared to EEG is the lack of any useful information regarding sleep stages.

While actigraphy presents a number of distinct advantages over EEG in this population (extended measurement period, minimally disruptive, easily transportable), and is certainly preferable to subjective reports, it does not allow for the proper measurement of sleep depth. As was discussed in the first chapter of this thesis, it is clear that not all stages of sleep are equally important, and while excessive movement has been associated with disturbed and fragmented sleep, as well as being an indicator of transition between stages (Carskadon & Dement, 2005), it is not possible to determine if this movement results in a significant reduction in vital SWS, or a reduction in another sleep stage. It is also difficult to establish with any degree of certainty the extent to which the continuity of sleep is being disturbed without using an EEG. There is some existing work which has studied the EEG consequences associated with various types of exercise in non-elite athletes

(Dworak et al., 2008; Myllmaki et al., 2011; Souissi et al., 2012), which suggests that exercise can exert an influence on sleep stages, such as alterations to the quantity of SWS and REM sleep, increasing sleep onset latency, increasing the number of awakenings during the night and increasing the latency to REM sleep. This also depends on the time of day at which exercise takes place, with intense exercise taking place in the evening having a particularly disruptive impact on subsequent sleep (Souissi et al., 2012).

While the use of EEG to measure sleep would clearly have been impractical in the studies presented here, which purposefully sought to measure sleep as it occurs naturally for a protracted period rather than in an artificial setting for a short period, such an investigation would never-the-less be a highly informative exercise. While it may be difficult to recruit elite level athletes to volunteer to have their sleep measured by an EEG the night before competitions due to the level of invasiveness and potential disruption that could result, it would still be an informative exercise to measure the sleep of athletes using an EEG periods of training. Since the sleep disturbance that has been revealed earlier in this thesis appears to be a relatively consistent feature of athletes sleep throughout the season, the use of EEG at any point during the competitive season is likely to yield useful data.

6.3.2 – Performance Measurement

The methods of performance measurement used during this thesis were largely guided by the views and input of the sports science support staff at participating football clubs. This was primarily to ensure that any impact of sleep on these measures of performance would be immediately appreciable to the target audience (which is the same sports science support staff, as well as their athletes and coaches). The limitation of the measures that are widely used in the context of the current study is that they are first and foremost measures of physical, rather than cognitive performance. As was discussed at some length in the first chapter of this thesis, physical performance has consistently demonstrated a remarkable level of resilience under conditions of sleep deprivation, and any decline in physical performance is a 'by-product' of a decline in cognitive performance (specifically mood and motivation). The negative consequences of sleep deprivation on cognitive performance have been consistently demonstrated to be severe, even where sleep restriction is modest. While there has been some measurement of cognitive factors, such as 'self-paced' activity levels contributing towards the total distance covered by players during matches and training, and ratings of perceived exertion provided by players following training sessions, a true measure of in-game cognitive performance would be a much more useful measure. While those deprived of sleep have demonstrated an ability to maintain their performance when adequately motivated, the same cannot be said of cognitive performance (Robert & Hockey, 1997; Horne & Reyner, 1995; Reilly & Walsh, 1981; Durmer & Dinges, 2005).

Any future research undertaken in this area would benefit greatly from measuring cognitive performance as it occurs naturally in elite athletic competition, in

addition to the more physical performance measurements that are presented here. A number of performance analysts (e.g. O'Donoghue, 2012; Lames, 2012) have been making progress using the data from the ProZone system to assess tactical performance of individuals, teams and sub-groups within football teams (e.g. the defensive four). Such tactical performance will depend to a much greater extent on cognitive factors, since the proper implementation of tactics in a complex large team game like football requires the use of skills such as selective and sustained attention, decision making, rapid reaction to stimuli and flexible thinking, all factors which have been previously demonstrated as depending on the PFC that is adversely affected so disproportionately by inadequate sleep. Although such detailed tactical analysis does not appear to be widely used among professional football clubs, where the importance of the 'tacit' knowledge of coaches and players is favoured, such an analysis would arguably be even more useful than the relationship between sleep and (physical) performance that is evident in the current work, and further highlight the importance of sleep to athletes who are striving for peak performance.

6.3.3 – Sample Size

One of the more persistent difficulties that has presented itself during the investigations presented here has been the problem of obtaining an adequate sample size. While a reasonable number of individual football players were recruited and both sleep and performance measures were collected on a daily basis, it may seem that collecting an adequate quantity of data would be a minor concern. The nature of elite-level competition however conspires against this. While the

forgetfulness of participants is perhaps to be expected and interferes with the collection of sleep data (which certainly played a part in the current investigations), a number of other factors also served to reduce the total amount of data collected. For example, shortly after the beginning of the study, one of the participating players was transferred to another club, entirely depriving the analysis of almost all of his data. Periods of injury are also a common feature of elite athletes, which also led to extended periods of time where players were not contributing match or training performance data to complement their sleep data. Players being called up for 'international duty' was another source of completely losing data for players for a two or three week period, in addition to players simply being de-selected from the match squad.

The difficulty due to data loss was compounded by the complexity of the statistical analysis that was conducted in the current investigations. It was clear that a lot of data would be required since the effect-size associated with the impact of natural variations on subsequent performance will naturally be smaller than in a study experimentally reducing sleep more drastically. That is, a larger sample size is necessary to properly investigate the significance of any effect. Further necessitating the need for a large amount of data is that due to the relative novelty of multi-level modelling as an analysis tool, it is very difficult to prospectively determine the required sample size (Field, Miles & Field, 2012). While the sample size in the current investigations met the 'minimum requirements' as suggested by Field, Miles and Field (2012) of having at least 20 'contexts' (in this case context would refer to players, the second level in the model), due to the relatively modest effect size a larger sample size may have been required to properly assess the significance of the findings. There were also difficulties presented in the more straightforward analyses

of difference due to a lack of data. For example the impact that exercise during matches had on sleep was separated into comparing the impact of exercise during home matches compared to away matches, and the impact of exercise during afternoon matches compared to evening matches. A thorough analysis would have called for those levels to have been fully factored (to compare evening home matches to evening away matches and afternoon away matches to evening away matches for instance). These factors were analysed to assess the impact that the timing of matches and the differing organisational stressors that result from away matches can have on subsequent sleep, but a fully factorial analysis could have assessed these factors in combination, but there was not enough data available to conduct such an analysis.

The practical upshot of the combination of a high attrition rate that is prevalent among elite level athletes and the complex nature of the analysis that is required when naturally observing variations in sleep and performance rather than experimentally inducing variation is that a great deal of data will be required, and researchers should expect to lose a lot of data along the way. Any future research conducted in a similar vein to the investigations presented here should seek to recruit an entire team of players to minimise the impact of attrition and ensure that there is sufficient data to properly investigate what are likely to be small effects taking place in a set of complex and varied circumstances.

6.4 – Future Research

There are a number of possible directions that future research into this area could take. One of the primary areas that future research should address is the lack of cognitive measures of performance that are present in this thesis. As discussed previously, the importance of the study of the cognitive consequences of inadequate sleep are especially salient given that most sports include a large cognitive component, and cognitive factors are especially susceptible to poor sleep. This could be accomplished by future work either by a more advanced use of ProZone to assess tactical performance during football matches (O'Donoghue, 2012; Lames, 2012), or by studying different sports which place a much more overt focus on cognitive factors. Sports requiring fine motor control such as archery, shooting and golf are sports with a far greater emphasis on cognitive performance, and may be more amenable to measurement during performance (this is perhaps particularly true of archery and shooting, where the conditions during competition are heavily standardized, which would allow for greater confidence in the reliability of measurement).

Another key target for future research should be to determine how stable the pattern of poor sleep is among elite athletes. While poor sleep out of season has been objectively confirmed by Leeder et al. (2012), participants were only measured for four days, which is short of the suggested minimum requirement of five to seven days recommended (Rowe, McCrae, Campbell, Horne, Tiegs, Lehman & Cheng, 2008; Sadeh, 2011; Acebo, Sadeh, Seifer, Tzischinsky, Wolfson, Hafer & Carskadon, 1999; Sadeh, 1996) to get a sufficiently detailed picture of sleep. Future research

should also seek to measure the sleep of the same athletes during both the off-season and the in-season in order to establish the differences in sleeping behaviour during these two periods. When one is considering possible causes for the type of sleep disturbance that has been so clearly in evidence in the present investigations, likely factors are pre-competition anticipatory anxiety, strenuous physical activity and the constantly shifting sleep schedules that are associated with late night competition. During the off-season these factors will certainly be mitigated, and for a time many will cease to exist entirely (e.g. competition and the accompanying anxiety). If it transpires that the sleep of athletes continues to show significant signs of disturbance, it could be concluded that these factors are not in fact a primary cause of sleep disturbance. Conversely, in the event that sleep does show an improvement when these factors are removed, it could be concluded that these factors do in fact make a significant contribution towards the poor sleep that is observed, and the possibility of interventions aimed at reducing the impact that such factors have on sleep could then be investigated, with the aim of improving performance. A further consideration would be to establish if there are any differences to the pattern of sleep disturbance during the 'pre-season' period. This period is again distinct and is characterised by a lack of competitive matches (save for the occasional friendly match) and a markedly higher level of training load than exists during the competitive season. This would be a particularly important period for investigation to help determine the extent to which high levels of strenuous activity can impact upon sleep. Taken together a comparative approach examining variations in sleep that may take place as the demands of a specific sport could help to elucidate some of the causes for the sleep disturbance that has been revealed here.

The expansion of research participants to include athletes from a wider variety of sports would also be a highly informative exercise. 'Elite-level athletes' are not a homogenous group, and different sports place different types of stress on people. Sampling from a wider variety of sports would enable a number of potential factors relating to sleep in elite level athletes to be investigated by means of a comparative analysis comparing the various organisational and athletic stressors which are peculiar to individual sports. One especially salient example comes from the scheduling of competition during the season; the present study exclusively studied the performance of professional football players, which features a strongly demarcated competitive season with matches taking place on a weekly basis. Due to the need for adequate recovery following matches, the type of training that dominates for the majority of the season is highly orientated towards maintenance of fitness rather than more taxing training aimed at improving physical fitness. In contrast, sports which are much more dependent on physical conditioning than on tactical factors (e.g. racing sports such as swimming, rowing, distance running) feature extended periods of higher intensity training taking place in 'blocks' in-between periods of competition which occur less frequently. As a consequence of the more physical nature, athletes in these sports are usually required to train multiple times each day, which in turn requires training both early in the morning and late at night, in order to allow for adequate recovery between sessions. In contrast to the competitive and training schedule of the athletes whose performance was studied here, the combination of very early and very late training sessions would place an entirely different set of stressors on such athletes than existed in the current thesis.

Another useful area of interest that could be better addressed by studying the relationship that sleep has with performance in a variety of sports is the impact that circadian factors has on sleep in athletes. In addition to the differing circadian pressures that will be placed on athletes as a consequence of their sport (such as the frequently changing schedules observed in professional football players, or the very early morning training is observed in swimmers), the impact that light exposure can have needs to be considered. Since exposure to bright light is the single strongest factor which influences circadian rhythms (Czeisler et al., 2005; Czeisler 1995; Khalsa et al., 2003), the differences in levels of exposure to light experienced by athletes in sports where training and competition takes place indoors compared to those training and competing outdoors could prove to a useful comparison when considering the role of circadian factors and their contribution to sleep disturbance in athletes.

A final consideration that must be made on the subject of the evidence of sleep disturbance among elite level athletes that has been discussed throughout this thesis is the matter of exactly why athletes seem to exhibit such a markedly lower quality of sleep than age-matched controls. This thesis established in chapter 3 that athletes from 3 different sports all consistently displayed elevated levels of sleep disturbance than would be expected from a group of otherwise normal and healthy individuals. Since the primary purpose of this thesis has been to examine the ways in which sleep can impact upon performance, it has simply not been possible to also conduct a thorough investigation of the precise causes and mechanisms that are responsible for this sleep disturbance. While the fourth and fifth chapters of this thesis did seek to investigate some of the sport-related factors which could be contributing to this phenomena, such as the timing and intensity of physical activity, as well as

organisational stressors brought on by factors such as matches played away from home, there are a myriad of other factors which are also likely to be contributing to sleep disturbance. Having established that changing circumstances arising from competitive demands can exert an influence on sleep, future research should seek to examine some of the other factors differentiating athletes from sedentary controls to try and establish some of the other contributory factors; competitive anxiety in particular could prove to be a fruitful area of research, but other factors that distinguish athletes from non-athletic contemporaries such as dietary, and even caffeine consumption, could all play a role.

Regarding the impact that sleep can have on performance, another key area for future research to consider is the impact that sleep can have on metabolism. While the majority of the existing research into the function of sleep has arrived at the conclusion that the primary purpose of sleep is for restitution of the brain, discounting the impact it may have on the rest of human physiology. While the evidence that brain restitution most certainly is the primary function of sleep, more recent evidence has suggested that metabolism can be negatively affected by inadequate sleep (Harsch, et al., 2003; Res et al., 2012, Al-Delaimy et al., 2002). The possibility that the poor sleep that has been observed here could be exerting a negative influence on athletes' metabolism will have serious implications in terms of performance; the importance of proper nutrition to those seeking to attain peak performance is well founded, and evidence that this aim is being undermined due to inadequate sleep will serve to further highlight the importance of sleep to elite level athletes.

Finally, and perhaps most importantly, future research should aim to investigate the efficacy of sleep-improvement interventions in elite-level athletes, and

determine the extent to which such interventions (should they prove to be effective) can contribute towards improvements in performance. The improvement of performance is without a doubt the single most important consideration for elite athletes and their coaches, since it is upon this that their livelihood rests. It would probably be wise to avoid the use of hypnotics; athletes may be especially averse to the associated side effects and, as Horne (2006) points out, there is the risk that people will become dependent upon them in order to get a proper night's sleep. Discussions with both players and their coaches throughout the course of these investigations does suggest that even slight behavioural modifications could be a fruitful direction in which to aim sleep improvement interventions in this population. While sleep hygiene is rarely indicated as a efficacious treatment on its own for poor sleep in clinical populations, it has not yet been tested in elite-level athletes, who certainly do not follow many of the 'rules' that are present in most sleep-hygiene education programmes. Factors such as inconsistency in the timing of sleep and over-stimulating bedroom environments could be contributing to poor sleep. Another possible intervention could be the mattresses that players themselves sleep on; a strategy which is reportedly followed by the British Cycling Team and the Sky Pro cycling professional team is for individual athletes' bedding to accompany them wherever they go in attempt to ensure a measure of consistency to their sleeping environment. While objective evidence for the effectiveness of this strategy is presently unavailable, it is certainly a strategy worthy of further consideration (particularly in a sport like professional cycling where athletes' sleeping environments changes on a daily basis during races). The efficacy of napping during the daytime before competitions is also worthy of exploration; a number of athletes studied throughout this thesis reported napping during the daytime as part of their

preparation competition. Existing research suggests that even a short nap can have a beneficial impact on performance (e.g. Horne & Reyner, 1996). There are likely to be difficulties with naps longer than 20 minutes, which allow for a full sleep cycle with the accompanying 'grogginess' on waking (Horne, 2006), but they could prove to be a useful strategy where nocturnal sleep is inadequate.

6.5 – Summary

This thesis has offered evidence for the presence of significant sleep disturbance among elite level athletes, supporting the widely reported view of athletes and coaches. This thesis has also been the first to attempt to assess the relationship between sleep and performance as it occurs naturally in elite-level athletes, as opposed to the existing body of literature that has manipulated sleep in an experimental setting and measured the subsequent performance consequences in a manner which is not necessarily representative of performance in elite athletes. The outcomes of this research are directly applicable to athletes. This thesis has also aimed to investigate the contribution that training for, and competing in, elite-level sport can have on sleep. The benefits of this research are primarily to highlight to athletes and coaches that obtaining adequate sleep is a difficulty that many athletes face, and has demonstrated ways in which this difficulty with sleep could be negatively impacting on their performance. It has also highlighted that sleep improvement could turn out to be a fruitful area of interest for performance enhancement in the future; since the evidence suggests that sleep disturbance seems to be a fairly common phenomena among elite-level athletes, there may be a

great deal of room for improvement. It was demonstrated in chapter four that even as simple an intervention as an adjustment to the timing of sleep was associated with an increase in levels of activity during competitive football matches. In addition to the direct performance gains that may result from an improvement to sleep, a number of beneficial secondary effects could result, such as better training, better adaptation to that training and a reduction in the risk of illness which could negatively impact on athletes' preparedness for competition. In terms of the philosophy of 'the aggregation of marginal gains', the potential attached to sleep improvements are clearly worthy of further consideration.

References

- Acebo, C., Sadeh, A., Seifer, R., Tzischinsky, O., Wolfson, A. R., Hafer, A., & Caskadon, M. A. (1999). Estimating sleep patterns with activity monitoring in children and adolescents: How many nights are necessary for reliable measures. *Sleep, 22*, 95-103.
- Agnew, H. W., Webb, W. B., & Williams, R. L. (1966). The first night effect An EEG study of sleep. *Psychophysiology, 2*, 263-266.
- Akerstedt, T. & Folkard, S. (1997). The three-process model of alertness and its extension to performance, sleep latency, and sleep length. *Chronobiology International, 14*, 115-123.
- Akerstedt, T., Hume, K., Minors, D., & Waterhouse, J. (1997). Good sleep- it's timing and physiological characteristics. *Journal of Sleep Research, 6*, 221-229.
- Al-Delaimy, W. K., Manson, J. E., Willet, W. C., Stampfer, M. J., & Hu, F. B. (2002). Snoring as a risk factor for type II Diabetes Mellitus: A prospective study. *American Journal of Epidemiology, 155*, 387-393.
- Allen, S. R., Oswald, I., Lewis, S., & Tagney, J. (1972). The effects of distorted visual input on sleep. *Psychophysiology, 9*, 498-504.

American Academy of Sleep Medicine (2006). *The International Classification of Sleep Disorders* (2nd ed., Pocket Version). Westchester, IL, USA: American Academy of Sleep Medicine.

Ancoli-Israel, S., Cole, R., Alessi, C., Chambers, M., Moorcroft, W., & Pollak, C. P. (2003). The role of actigraphy in the study of sleep and circadian rhythms. *Sleep*, 26, 342-392.

Anderson, C. (2003). The pre-frontal cortex- links between neuropsychological performance and the sleep and wake EEG. Unpublished doctoral dissertation, Loughborough University, Loughborough, UK.

Anderson, M., Wolfson, S., Neave, N., & Moss, M. (2012). Perspectives on the home advantage: A comparison of football players, fans and referees. *Psychology of Sport and Exercise*, 13, 311-316.

Andrzejewski, M., Chmura, J., Pluta, B., Strzelczyk, R., & Kasprzak, A. (2013). Analysis of sprinting activities of professional soccer players. *Journal of Strength and Conditioning Research*, 27, 2134-2140.

Arendt, J., Stone, B., & Skene, D. J. (2005). Sleep disruption in jet lag and other circadian rhythm-related disorders. In M. H. Kryger, T. Roth & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 659-672). Philadelphia, PA, USA: Elsevier Saunders.

Arriaga, F., Lara, E., Matos-Oires, A., Cavaglia, F., & Bastos, L. (1995). Diagnostic relevance of sleep complaints in anxiety and mood disorders. *European Psychiatry*, 10, 386-390.

Aserinsky, E. & Kleitman, N. (1953). Regularly occurring periods of eye motility, and concomitant phenomena, during sleep. *Science*, 118, 273-274.

Aserinsky, E. & Kleitman, N. (1955). Two types of ocular motility occurring during sleep. *Journal of Applied Physiology*, 8, 11-18.

Atienza, M., Cantero, J. L., & Stickgold, R. (2004). Posttraining sleep enhances automaticity in perceptual discrimination. *The Journal of Cognitive Neuroscience*, 16, 53-64.

Atkinson, G. & Reilly, T. (1996). Circadian variations in sports performance. *Sports Medicine*, 21, 292-312.

Atkinson, G. & Speirs, L. (1998). Diurnal variation in tennis service. *Perceptual and Motor Skills*, 86, 1335-1338.

Atkinson, G., Buckley, P., Edwards, B., Reilly, T., & Waterhouse, J. (2001). Are there hangover-effects on physical performance when Melatonin is ingested by athletes before nocturnal sleep? *International Journal of Sports Medicine*, 22, 232-234.

Atkinson, G., Todd, C., Reilly, T., & Waterhouse, J. (2005). Diurnal variation in cycling performance: Influence of warm-up. *Journal of Sports Science*, 23, 321-329.

Ayas, N. T., White, D. P., Manson, J. E., Stampfer, M. J., Speizer, F. E., Malhotra, A., & Hu, F. B. (2003). A prospective study of sleep deprivation and coronary heart disease in women. *Archives of Internal Medicine*, 163, 205-209.

- Baekeland, F. & Lasky, R. (1966). Exercise and sleep patterns in college athletes. *Perceptual and Motor Skills*, 23, 1203-1207.
- Bambaeichi, E., Reilly, T., Cable, N. T., & Giacomoni, M. (2005). The influence of time of day and partial sleep loss on muscle strength in eumenorrhic females. *Ergonomics*, 48, 1499-1511.
- Banderet, L. E., Stokes, J. W., Francesconi, R., Kowal, D. M., & Naitoh, P. (1981). Artillery teams in simulated sustained combat: Performance and other measures. In L. C. Johnson, D. J. Tepas, W.P. Colquhoun, & M. J. Colligna (Eds.), *Biological Rhythms, Sleep and Shiftwork*. New York: Spectrum.
- Baxter, C. & Reilly, T. (1983). Influence of time of day in all-out swimming. *British Journal of Sport Medicine*, 17, 122-127.
- Belenky, G., Wesensten, N. J., Thorne, D. R., Thomas, M. L., Sing, H. C., Redmond, D. P., Russo, M. B., & Balkin, T. J. (2003). Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: A sleep dose-response study. *Journal of Sleep Research*, 12, 1-12.
- Bergmann, B., Fang, V. S., Kushida, C., Everson, C., & Rechtschaffen, A. (1986). Hypothalamic-adrenal variables in paradoxical and total sleep deprivation of rats. *Sleep Research*, 15, 212.
- Besedovsky, L., Lange, T., & Born, J. (2012). Sleep and immune function. *European Journal of Physiology*, 463, 121-137.

- Bishop, N. C. (2005). Exercise and infection risk. In M. Gleeson (Ed.), *Immune Function in Sport and Exercise*, (pp.1-14). Edinburgh, UK: Elsevier.
- Blagrove, M. (1996). The effects of length of sleep deprivation on interrogative suggestibility. *Journal of Experimental Psychology: Applied*, 2, 48-59.
- Blagrove, M., Alexander, C., & Horne, J. A. (1995). The effects of chronic sleep reduction on the performance of cognitive tasks sensitive to sleep deprivation. *Applied Cognitive Psychology*, 9, 21-40.
- Bøggild, H., Suadicani, P., Hein, H. O., & Gyntelberg, F. (1999). Shift work, social class, and ischaemic heart disease in middle aged and elderly men; a 22 year follow-up on the Copenhagen Male Study. *Occupational and Environmental Medicine*, 26, 640-645.
- Bonnet, M. H. & Arand, D. L. (2003). Clinical effects of sleep fragmentation versus sleep deprivation. *Sleep Medicine Reviews*, 7, 297-310.
- Bonnet, M. H. (1985). Effect of sleep disruption on sleep, performance, and mood. *Sleep*, 8, 11-19.
- Bonnet, M. H. (1986). Performance and sleepiness as a function of frequency and placement of sleep disruption. *Psychophysiology*, 23, 263-271.
- Bonnet, M. H. (1987). Sleep restoration as a function of periodic awakening, movement, or electroencephalographic change. *Sleep*, 10, 364-373.
- Borbély, A. A. (1982). A two process model of sleep regulation. *Human Neurobiology*, 1, 195-204.

- Born, J., Lange, T., Hansen, K., Molle, M., & Fehm, H. L. (1997). Effects of sleep and circadian rhythm on human circulating immune cells. *Journal of Immunology*, *158*, 4454-4464.
- Boyd, L. (2011). A new way of using accelerometers in Australian rules football: Assessing external loads. Unpublished doctoral dissertation, Victoria University, Melbourne, Australia.
- Brand, S., Gerber, M., Beck, J., Hatzinger, M., Pühse, U., & Holsboer-Trachsler, E. (2010). High exercise levels are related to favourable sleep patterns in psychological functioning in adolescents: A comparison of athletes and controls. *Journal of Adolescent Health*, *46*, 133-141.
- Braun, A. R., Balkin, T. J., Wesenten, N. J., Carson, R. E., Varga, M., Baldwin, S., Selbie, S., Belenky, G., & Herscovitch, P. (1997). Regional cerebral blood flow throughout the sleep-wake cycle. An H₂(¹⁵O) PET study. *Brain*, *120*, 1173-1197.
- Brawn, T. P., Fenn, K. M., Nusbaum, H. C., & Margoliash, D. (2010). Consolidating the effects of waking and sleep on motor-sequence learning. *The Journal of Neuroscience*, *30*, 12977-12982.
- Bray, S. R. & Widmeyer, W. N. (2000). Athletes perceptions of the home advantage: An investigation of perceived causal factors. *Journal of Sport Behaviour*, *18*, 353-361.
- Brooks, B., Cistulli, P. A., Borkman, M., Ross, G., McGhee, S., Grunstein, R. R., Sullivan, C. E., & Yue, D. K. (1994). Obstructive sleep apnea in obese noninsulin-dependent diabetic patients: Effects of continuous positive

airway pressure treatment on insulin responsiveness. *Journal of Clinical Endocrinology and Metabolism*, 79, 1681-1685.

Brown, F. C., Buboltz, W. C., & Soper, B. (2002). Relationship of sleep hygiene awareness, sleep hygiene practices, and sleep quality in university students. *Behavioural Medicine*, 28, 33-38.

Bunnell, D. E., Bevier, W., & Horvath, S. M. (1983). Nocturnal sleep, cardiovascular function, and adrenal activity following maximal capacity exercise. *Electroencephalography and Clinical Neurophysiology*, 56, 186-189.

Campbell, S. S., Dawson, D., & Anderson, M. W. (1993). Alleviation of sleep maintenance insomnia with timed exposure to bright light. *Journal of the American Geriatric Society*, 41, 829-836.

Cappuccio, F. P., D'Elia, L., Strazzullo, P., & Miller, M. A. (2010). Quantity and quality of sleep and incidence of type 2 diabetes: A systematic review and meta-analysis. *Diabetes Care*, 33, 414-420.

Carskadon, M. A. & Dement, W. C. (2005). Normal human sleep: An overview. In M. H. Kryger, T. Roth, & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (Fourth ed., pp. 13-23). Philadelphia, PA, USA: Elsevier Saunders.

Carskadon, M. A. & Rechtschaffen, A. (2005). Monitoring and staging human sleep. In M. H. Kryger, T. Roth, & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (Fourth ed., pp. 1359-1377). Philadelphia, PA, USA: Elsevier Saunders.

Centers for Disease Control (2013). How much physical activity do adults need?

Retrieved from the World Wide Web, on 15th November 2013, from

<http://www.cdc.gov>

Clemens, Z., Fabo, D., & Halasz, P. (2005). Overnight verbal memory retention correlates with the number of sleep spindles. *Neuroscience*, *132*, 529-535.

Clyde, D. J. (1950). *Construction and Validation of an Emotional Association Test*. Unpublished doctoral dissertation. Pennsylvania State College, Philadelphia, USA.

Cohen, S., Doyle, W. J., Alper, C. M., Janicki, Deverts, D., & Turner, R. B. (2009). Sleep habits and susceptibility to the common cold. *Archives of Internal Medicine*, *169*, 62-67.

Coldwells, A., Atkinson, G., & Reilly, T. (1994). Sources of variation in back and leg dynamometry. *Ergonomics*, *37*, 79-86.

Cole, R. J., Kripke, D. F., Gruen, W., Mullaney, D. J., & Gillin, J. C. (1992). Autonomic sleep/wake identification from wrist activity. *Sleep*, *15*, 461-469.

Collop, N. A. (2006). Polysomnography. In T. L. Lee-Chiong (Ed.), *Sleep: A Comprehensive Handbook* (pp. 973-976). Hoboken, NJ, USA: Wiley.

Colt, H. G., Haas, H., & Rich, G. B. (1991). Hypoxemia vs sleep fragmentation as cause of excessive daytime sleepiness in obstructive sleep apnea. *Chest*, *100*, 1542-1548.

- Colt, H. G., Haas, H., & Rich, G. B. (1991). Hypoxemia vs sleep fragmentation as cause of excessive daytime sleepiness in obstructive sleep apnea. *Chest, 100*, 1542-1548.
- Cook, C. J., Crewther, B. T., Kilduff, L. P., Drawer, S., & Gaviglio, C. M. (2011). Skill execution and sleep deprivation: Effects of acute caffeine or creatine supplementation- a randomized placebo-controlled trial. *Journal of the International Society of Sports Medicine, 8*, 2-9.
- Coutts, A. J., Slattery, K. M., & Wallace, L. K. (2007). Practical tests for monitoring performance, fatigue and recovery in triathletes. *Journal of Science and Medicine in Sport, 10*, 372-381.
- Coverdale, S. G., Read, D. J., Woolcock, A. J., & Schoeffel, R. E. (1980). The importance of suspecting sleep apnoea as a common cause of excessive daytime sleepiness: Further experience from the diagnosis and management of 19 patients. *Australian and New Zealand Journal of Medicine, 10*, 284-288.
- Cox, R. H., Martens, M. P., & Russell, W. D. (2003). Measuring anxiety in athletics: The revised competitive state anxiety inventory-2. *Journal of Sport and Exercise and Psychology, 25*, 519-533.
- Crowe, A. (2004). Case report: stroke following an airline flight. *Canadian Family Physician, 50*, 76-77.
- Czeisler, C. A. (1995). The effect of light on the human circadian pacemaker. In J. M. Waterhouse (Ed.), *Circadian Clocks and their Adjustment* (pp. 254-302). Chichester, UK: Wiley.

- Czeisler, C. A., Allan, J. S., Strogatz, S. H., Ronda, J. M., Sanchez, R., Rios, C. D., Freitag, W. O., Richardson, G. S., & Kronauer, R. E. (1986). Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. *Science*, *233*, 667-671.
- Czeisler, C. A., Buxton, O. M., & Khalsa, S. B. S. (2005). The human circadian timing system and sleep-wake regulation. In M. H. Kryger, T. Roth, & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 375-394). Philadelphia, PA, USA: Elsevier Saunders.
- Czeisler, C. A., Kronauer, R. E., Allan, J. S., Duffy, J. F., Jewett, M. E., Brown, E. N., & Ronda, J. M. (1989). Bright light induction of string (type 0) resetting of the human circadian pacemaker. *Science*, *244*, 1328-1333.
- Davenne, D. (2009). Sleep of athletes- problems and possible solutions. *Biological Rhythm Research*, *40*, 45-52.
- Dement, W. C. (2005). History of sleep physiology and medicine. In M. H. Kryger, T. Roth & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 1-12). Philadelphia, PA, USA: Elsevier Saudners.
- Dement, W. C. & Vaughan, C. (1999). *The Promise of Sleep*. New York: Dell.
- Di Salvo, V., Collins, A., MacNeill, B., & Cardinale, M. (2006). Validation of ProZone®: A new video-based performance analysis system. *International Journal of Performance Analysis in Sport*, *6*, 108-119.
- Di Salvo, V., Gregson, W., Atkinson, G., Tordoff, P., & Drust, B. (2009). Analysis of high intensity activity in Premier League soccer. *International Journal of Sports Medicine*, *30*, 205-212.

- Diekelmann, S., Büchel, C., Born, J., & Rasch, B. (2011). Labile or stable: Opposing consequences for memory when reactivated during waking and sleep. *Nature Neuroscience*, *14*, 381-386.
- Dinges, D. F. & Kribbs, N. B. (1991). Performing while sleepy: Effects of experimentally induced sleepiness. In T. H. Monk (Ed.), *Sleep, Sleepiness and Performance*. Winchester, UK: Wiley.
- Dinges, D. F. & Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behaviour Research Methods, Instruments & Computers*, *17*, 652-655.
- Dinges, D. F., Pack, F., Williams, K., Gillen, K. A., Powell, J. W., Ott, G. E., Aptowicz, C., & Pack, A. I. (1997). Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4-5 hours per night. *Sleep*, *20*, 267-277.
- Dinges, D. F., Rogers, N. L., & Baynard, M. D. (2005). Chronic sleep deprivation. In M. H. Kryger, T. Roth, & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 67-76). Philadelphia, PA, USA: Elsevier Saunders.
- Doran, S. M., van Dongen, H. P. A., & Dinges, D. F. (2001). Sustained attention performance during sleep deprivation: Evidence of state instability. *Archives Italiennes de Biologie*, *139*, 253-267.
- Dorrian, J., Rogers, N. L., & Dinges, D. F. (2005). Psychomotor vigilance performance: A neurocognitive assay sensitive to sleep loss. In C. A. Kushida (Ed.), *Sleep Deprivation*. New York: Marcel Dekker.

- Downey, R. & Bonnet, M. H. (1987). Performance during frequent sleep disruption. *Sleep, 10*, 354-363.
- Driver, H. S. & Taylor, S. R. (1996). Sleep disturbances and exercise. *Sports Medicine, 21*, 1-6.
- Driver, H. S. & Taylor, S. R. (2000). Exercise and sleep. *Sleep Medicine Reviews, 4*, 387-402.
- Dunn, A. L., Trivedi, M. H., Kampert, J. B., Clark, C. G., & Chambliss, H. O. (2005). Exercise treatment for insomnia: Efficacy and dose response. *American Journal of Preventative Medicine, 28*, 1-8.
- Durmer, J. S. & Dinges, D. F. (2005). Neurocognitive consequences of sleep deprivation. *Seminars in Neurology, 25*, 117-129.
- Dworak, M., Wiater, A., Alfer, D., Stephan, E., Hollmann, W., & Struder, H. K. (2008). Increased slow wave sleep and reduced stage 2 sleep in children depending on exercise intensity. *Sleep Medicine, 9*, 266-272.
- Eaker, E. D., Pinsky, J., & Castelli, W. P. (1992). Myocardial infarction and coronary death among women: Psychosocial predictors from a 20-year follow-up of women in the Framingham Study. *American Journal of Epidemiology, 135*, 854-864.
- Edinger, J. F., Wohlgemuth, W. K., Radtke, R. A., Marsh, G. R., & Quilian, R. E. (2001). Cognitive behavioural therapy for treatment of chronic primary insomnia: A randomized controlled trial. *Journal of the American Medical Association, 285*, 1856-1864.

- Edwards, B. J., Atkinson, G., Waterhouse, J., Reilly, T., Godfrey, R., & Budgett, R. (2000). Use of melatonin in recovery from jet-lag following an eastward flight across 10 time zones. *Ergonomics*, *43*, 1501-1513.
- English Cricket Board (2011). Recommended guidelines for the construction, preparation and maintenance of cricket pitches and outfielders at all levels of the game. Retrieved from the World Wide Web, on 18th August 2011, from <http://www.ecb.co.uk>
- Enright, P. L., Newman, A. B., Wahl, P. W., Manolio, T. A., Haponik, E. F., & Boyle, P. J. (1996). Prevalence and correlates of snoring and observed apneas in 5,201 older adults. *Sleep*, *19*, 531-538.
- Erlacher, D., Ehrlenspiel, F., Adegbesan, O. A., & El-Din, H. G. (2011). Sleep habits in German athletes before important competitions or games. *Journal of Sports Sciences*, *29*, 859-866.
- Everson, C. A. & Toth, L. A. (2000). Systematic bacterial invasion induced by sleep deprivation. *American Journal of Physiology, Regulatory Integrative and Comparative Physiology*, *278*, R905-R916.
- Everson, C., Bergmann, B., Fang, V. S., Leitch, C. A., Obermeyer, W., Refetoff, S., Schoeller, D. A., & Rechtschaffen, A. (1986). Physiological and biochemical effects of total sleep deprivation in the rat. *Sleep Research*, *15*, 216.
- Fahlman, M. M. & Engels, H. J. (2005). Mucosal IgA and URTI in American college football players: A year longitudinal study. *Medicine and Science in Sports and Exercise*, *27*, 374-380.

- Faraut, B., Boudjeltia, K. Z., Dyzma, M., Rousseau, A., David, E., Stenuit, P., Franck, T., van Antwerpen, P., Vanhaeverbeek, M., & Kekhofs, M. (2011). Benefits of napping and an extended duration of recovery sleep on alertness and immune cells after acute sleep deprivation. *Brain, Behaviour, and Immunity*, *25*, 16-24.
- Faraut, B., Boudjeltia, K. Z., Vanhamme, L., & Kerkhofs, M. (2012). Immune, inflammatory and cardiovascular consequences of sleep restriction and recovery. *Sleep Medicine Reviews*, *16*, 137-149.
- Feinberg, I. (1974). Changes in sleep cycle patterns with age. *Journal of Psychiatric Research*, *10*, 283-306.
- Ferrie, J. E., Shipley, M. J., Cappuccio, F. P., Brunner, E., Miller, M. A., Kumari, M., & Marmot, M. G. (2007). A prospective study of change in sleep duration: Associations with mortality in the Whitehall II cohort. *Sleep*, *30*, 1659-1666.
- Field, A. (2009). *Discovering Statistics using SPSS* (3rd ed.). London: Sage.
- Field, A., Miles, J., & Field, Z. (2012). *Discovering Statistics using R*. London: Sage.
- Field, T. M. (1998). Massage therapy effects. *American Psychologist*, *53*, 1270-1281.
- Filtness, A. (2011). Obstructive sleep apnoea and daytime driver sleepiness. Unpublished doctoral dissertation, Loughborough University, Loughborough, UK.

- Fischer, S., Hallschmid, M., Elsner, A. L., & Born, J. (2002). Sleep forms memory for finger skills. *Proceedings of the National Academy of Science, USA*, 99, 11987-11991.
- Folkard, S. & Akerstedt, T. (1992). A three-process model of the regulation of alertness-sleepiness. In R. J. Broughton & R. D. Ogilvie (Eds.), *Sleep, Arousal and Performance*. Boston, MA, USA: Birkhauser.
- Forsyth, J. J. & Reilly, T. (2005). Circadian rhythms in blood lactate concentration during incremental ergometer rowing. *European Journal of Applied Physiology*, 92, 69-74.
- Friedmann, J., Globus, G., Huntley, A., Mullaney, D., Naitoh, P., & Johnson, L. (1977). Performance and mood during and after gradual sleep reduction. *Psychophysiology*, 14, 245-250.
- Frost, P., Kolstad, H. A., & Bonde, J. P. (2009). Shift work and the risk of ischemic heart disease- a systematic review of the epidemiological evidence. *Scandinavian Journal of Work and Environmental Health*, 35, 163-179.
- Fuster, J. M. (1989). *The Prefrontal Cortex: Anatomy, physiology, and neuropsychology of the frontal lobe*. New York: Raven Press.
- Gaarder, K. (1966). A conceptual model of sleep. *Archives of General Psychiatry*, 14, 253.
- Gallasch, J. & Gradisar, M. (2007). Relationships between sleep knowledge, sleep practice and sleep quality. *Sleep and Biological Rhythms*, 5, 63-73.

- Gilliland, M. A., Bergmann, B., & Rechtschaffen, A. (1986). High amplitude NREM sleep deprivation in the rat. *Sleep Research, 15*, 218.
- Gleeson, M. (2005). *Immune Function in Sport and Exercise*. Edinburgh, UK: Elsevier.
- Gleeson, M. (2007). Immune function in sport and exercise. *Journal of Applied Physiology, 103*, 693-699.
- Gleeson, M., Bishop, N., Oliveira, M., McCauley, T., & Tauler, P. (2011). Sex differences in immune variables and respiratory infection incidence in an athletic population. *Exercise Immunology Review, 17*, 122-135.
- Gómez-González, B., Dominguez-Salazar, E., Hurtado-Alvarado, G., Esqueda-Leon, E., Santana-Miranda, R., Rojas-Zamorano, J. A., & Velázquez-Moctezuma, J. (2012). Role of sleep in the regulation of the immune system and the pituitary hormones. *Annals of the New York Academy of Sciences, 1261*, 97-106.
- Gonzalez, M. M., Debilly, G., Valatz, J-L., & Jouvet, M. (1995). Sleep increase after immobilization stress: Role of noradrenergic locus coeruleus system in the rat. *Neuroscience Letters, 202*, 5-8.
- Gould, D., Horn, T., & Spreeman, J. (1983). Competitive anxiety in sport: The contribution of achievement goals and perfectionism. *Journal of Sport and Exercise Psychology, 20*, 194-217.
- Gross, R. T. & Borkovec, T. D. (1982). The effects of a cognitive intrusion manipulation on the sleep onset latency of good sleepers. *Behaviour Therapy, 13*, 112-116.

- Grunstein, R. R., Stenlof, K., Hedner, J., Sjoström, L. (1995). Impact of obstructive sleep apnea and sleepiness on metabolic and cardiovascular risk factors in Swedish Obese Subjects (SOS) Study. *International Journal of Obesity and Related Metabolic Disorders*, 19, 410-418.
- Guilleminault, C. & Bassiri, A. (2005). Clinical features and evaluation of obstructive sleep apnea-hypopnea syndrome and upper airway resistance syndrome. In M. H. Kryger, R. Roth, & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 1043-1052). Philadelphia, PA, USA: Elsevier Saunders.
- Guilleminault, C., Clerk, A., Black, J., Labanowski, M., Pelayo, R., & Claman, D. (1995). Nondrug treatment trials in psychologic insomnia. *Annals of Internal Medicine*, 155, 838-844.
- Gulevich, G., Dement, W. C., & Johnson, L. (1966). Psychiatric and EEG observations on a case of prolonged (264 hours) wakefulness. *Archives of General Psychiatry*, 15, 29-35.
- Haack, M., Pollmächer, T., & Mullington, J. M. (2004). Diurnal and sleep-wake dependent variations of soluble TNF- and IL-2 receptors in healthy volunteers. *Brain, Behaviour, and Immunity*, 18, 361-367.
- Halson, S. L. (2008). Nutrition, sleep and recovery. *European Journal of Sport Sciences*, 8(2), 119-126.
- Harrington, J. M. (1994). Shift work and health- a critical review of the literature on working hours. *Annals of the Academy of Medicine, Singapore*, 23, 699-705.

- Harrison, Y. & Horne, J. A. (1999). One night of sleep loss impairs innovative thinking and flexible decision making. *Organizational Behaviour and Human Decision Processes*, 78, 128-145.
- Harrison, Y. & Horne, J. A. (2000). The impact of sleep deprivation on decision making: A review. *Journal of Experimental Psychology: Applied*, 6, 236-249.
- Harsch, I. A., Schahin, S. P., Radespiel-Tröger, M., Weintz, O., Jahreiss, H., Fuchs, F. S., Wiest, G. H., Hahn, E. G., Lohmann, T., Konturek, P. C., & Ficker, J. H. (2003). Continuous positive airway pressure treatment rapidly improves insulin sensitivity in patients with obstructive sleep apnea syndrome. *American Journal of Respiratory and Critical Care Medicine*, 169, 156-162.
- Harvey, A. G. (2002). A cognitive model of insomnia. *Behaviour Research and Therapy*, 40, 869-893.
- Hauri, P. (1977). *Current Concepts: The Sleep Disorders*. Kalamazoo, MH, USA: Upjohn.
- Hauri, P. (1992). Sleep hygiene, relaxation therapy, and cognitive interventions. In P. J. Hauri (Ed.), *Case Studies in Insomnia* (pp.65-84). New York: Plenum.
- Hauri, P. J. (1993). Consulting about insomnia: A method and some preliminary data. *Sleep*, 16, 344-350.
- Heiser, P., Dickhaus, B., Schreiber, W., Clement, H. W., Hasse, C., Hennig, J., Remschmidt, H., Krieg, J. C., Wesemann, W., Opper, C. (2000). White

blood cells and cortisol after sleep deprivation and recovery sleep in humans. *European Archives of Psychiatry and Clinical Neuroscience*, 250, 16-23.

Herscovitch, J. & Broughton, R. (1981). Performance deficits following short-term partial sleep deprivation and subsequent recovery oversleeping. *Canadian Journal of Psychology*, 5, S67-S72.

Herscovitch, J., Studd, D., & Broughton, R. (1980). Changes in cognitive processing following short-term cumulative sleep deprivation and recovery oversleeping. *Journal of Clinical Neuropsychology*, 2, 301-319.

Heslop, P., Smith, G. D., Metcalfe, C., Macleod, J., & Hart, C. (2002). Sleep duration and mortality: The effect of short or long sleep duration on cardiovascular and all-cause mortality in working men and women. *Sleep Medicine*, 3, 305-314.

Hoddes, E., Zarcone, V., Smythe, H., Phillips, R., & Dement, W. C. (1973). Quantification of sleepiness: A new approach. *Psychophysiology*, 10, 431-436.

Hofle, N., Paus, T., Reutens, D., Fiset, P., Gotman, J., Evans, A. C., & Jones, B. E. (1997). Regional cerebral blood flow changes as the function of delta and spindle activity during slow wave sleep in humans. *The Journal of Neuroscience*, 17, 4800-4808.

Horne, J. A. & McGrath, M. J. (1984). The consolidation hypothesis for REM sleep function: Stress and other confounding factors- a review. *Biological Psychology*, 18, 165-184.

- Horne, J. A. & Minard, A. (1985). Sleep and sleepiness following a behaviourally 'active' day. *Ergonomics*, 28, 567-575.
- Horne, J. A. & Moore, V. J. (1985). Sleep EEG effects of exercise with and without additional body cooling. *Electroencephalography and Clinical Neurophysiology*, 60, 33-38.
- Horne, J. A. & Ostberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology*, 4, 97-110.
- Horne, J. A. & Pettitt, A. N. (1984). Sleep deprivation and the physiological response to exercise under steady-state conditions in untrained subjects. *Sleep*, 7, 168-179.
- Horne, J. A. & Reyner, L. A. (1996). Counteracting driver sleepiness: Effects of napping, caffeine, and placebo. *Psychophysiology*, 33, 306-309.
- Horne, J. A. & Staff, L. H. E. (1983). Exercise and sleep: Body-heating effects. *Sleep*, 6, 36-46.
- Horne, J. A. & Wilkinson, S. (1985). Chronic sleep reduction: Daytime vigilance performance and EEG measures of sleepiness, with particular reference to "practice" effects. *Psychophysiology*, 22, 69-78.
- Horne, J. A. (1980). Sleep and body restitution. *Experientia*, 36, 11-13.
- Horne, J. A. (1985). Mammalian sleep function, with special reference to man. In A. Mayes (Ed.), *Sleep Mechanisms and Functions*. London: Van Nostrand.

Horne, J. A. (1988a). *Why We Sleep: The Functions of Sleep in Humans and Other Mammals*. New York: Oxford University Press.

Horne, J. A. (1988b). Sleep deprivation and divergent thinking ability. *Sleep*, *11*, 528-536.

Horne, J. A. (1993). Human sleep, sleep loss and behaviour. Implications for the prefrontal cortex and psychiatric disorder. *British Journal of Psychiatry*, *162*, 413-419.

Horne, J. A. (2006). *Sleepfaring*. New York: Oxford University Press.

Huber, R., Ghilardi, M. F., Massimini, M. F., & Tononi. (2004). Local sleep and learning. *Nature*, *430*, 78-81.

Hug, M., Mullis, P. E., Vogt, M., Ventura, N., & Hoppeler, H. (2003). Training modalities: Over-reaching and over-training in athletes, including a study of the role of hormones. *Best Practice and Research Clinical Endocrinology and Metabolism*, *17*(2), 191-209.

IBM Corp. (2011). IBM SPSS Statistics for Windows, version 20. Armonk, NY, USA: IBM Corp.

International Tennis Federation (2011). Courts- Introduction. Retrieved from the World Wide Web, on 18th August 2011, from <http://www.itftennis.com/technical/equipment>

Irwin, M., McClintick, J., Costlow, C., Fortner, M., White, J., & Gillin, J. C. (1996). Partial sleep deprivation reduces natural killer and cellular immune

- response in humans. *The Federation of American Societies for Experimental Biology Journal*, 10, 643-653.
- Jaiswal, M. K. & Mallick, B. N. (2009). Prazosin modulates rapid eye movements during sleep deprivation-induced changes in body temperature in rats. *Journal of Sleep Research*, 18, 349-356.
- Jansen, N., van Amelsvoort, L. G. P. M., Kristensen, T., van den Brandt, P. A., & Kant, I. (2003). Work schedules and fatigue: A prospective cohort study. *Occupational and Environmental Medicine*, 60 (Suppl. 1), i47-i53.
- Jean-Louis, G., Kripke, D. F., & Ancoli-Israel, S. (2000). Sleep and quality of well-being. *Sleep*, 23, 1115-1121.
- Jean-Louis, G., von Gizycki, H., Zizi, F., Fookson, J., Spielman, A., Nunes, J., Fullilove, R., & Taub, H. (1996). Determination of sleep and wakefulness with the Actigraphic Data Analysis Software (ADAS). *Sleep*, 19, 739-743.
- Jehue, R., Street, D., & Huizenga, R. (1993). Effect of time zone and game time changes in team performance: National Football League. *Medicine and Science in Sports and Exercise*, 25, 127-131.
- Jennum, P., Schultz-Larsen, K., & Christensen, N. (1993). Snoring, sympathetic nervous activity and cardiovascular risk factors in a 70 year old population. *European Journal of Epidemiology*, 9, 477-482.
- Johnson, L. C. & MacLeod, W. L. (1973). Sleep and awake behaviour during gradual sleep reduction. *Perceptual and Motor Skills*, 36, 87-97.

- Johnson, L. C., Slye, E. S., & Dement, W. C. (1965). Electroencephalographic and autonomic activity during and after prolonged sleep deprivation. *Psychosomatic Medicine*, 27, 415-423.
- Jones, K. & Harrison, Y. (2001). Frontal lobe function, sleep loss and fragmented sleep. *Sleep Medicine Review*, 5, 463-475.
- Kahn-Greene, E. T., Killgore, D. B., Kamimori, G. H., Balkin, T. J., & Killgore, W. D. (2007). The effects of sleep deprivation on symptoms of psychopathology in healthy adults. *Sleep Medicine*, 8, 215-221.
- Kales, A., Cadieux, R. J., Bixler, E. O., Soldatos, C. R., Vela-Bueno, A., Misoul, C. A., & Locke, T. W. (1985). Obstructive sleep apnea, I: Onset, clinical course, and characteristics. *Journal of Chronic Diseases*, 38, 419-425.
- Kalichman, L. (2010). Massage therapy for fibromyalgia symptoms. *Rheumatology International*, 30, 1151-1157.
- Kamdar, B. B., Kaplan, K. A., Kezirian, E. J., & Dement, W. C. (2004). The impact of extended sleep on daytime alertness, vigilance, and mood. *Sleep Medicine*, 5, 441-448.
- Karni, A., Tanne, D., Rubenstein, B. S., Askenasy, J. J., & Sagi, D. (1994). Dependence on REM sleep of overnight improvement of a perceptual skill. *Science*, 265, 670-682.
- Kelly, D., Coughlan, G. F., Green, B. S., & Caulfield, B. (2012). Automatic detection of collisions in elite level rugby union using wearable sensing devices. *Sports Engineering*, 15, 81-92.

- Khalsa, S. B., Jewett, M. E., Cajochen, C., & Czeisler, C. A. (2003). A phase response curve to single bright light pulses in human subjects. *Journal of Physiology*, *549*, 945-952.
- Kleitman, N. (1923). The effects of prolonged sleeplessness on man. *American Journal of Physiology*, *66*, 67-92.
- Kleitman, N. (1963). *Sleep and Wakefulness*. Chicago, IL, USA: University of Chicago Press.
- Knutsson, A. & Bøggild, H. (2010). Gastrointestinal disorders among shift workers. *Scandinavian Journal of Work and Environmental Health*, *36*, 85-95.
- Knutsson, A. (2003). Health disorders of shift workers. *Occupational Medicine*, *53*, 103-108.
- Koban, M. & Swinson, K. L. (2005). Chronic REM-sleep deprivation of rats elevates metabolic rate and increases UCP1 gene expression in brown adipose tissue. *American Journal of Physiology, Endocrinology and Metabolism*, *289*, E68-E74.
- Kripke, D. F., Garfinkel, L., Wingard, D. L., Klauber, M. R., & Marler, M. R. (2002). Mortality associated with sleep duration and insomnia. *Archives of General Psychiatry*, *2*, 131-136.
- Krueger, J. M. & Obál, F. (2002). Function of sleep. In T. L. Lee-Chiong, M. J. Sateia, & M. A. Carskadon (Eds.), *Sleep Medicine* (pp. 23-30). Philadelphia, PA, USA: Hanley & Belfus.

- Krustrup, P. & Bangsbo, J. (2001). Physiological demands of top-class soccer refereeing in relation to physical capacity: Effect of intense intermittent exercise training. *Journal of Sports Science*, 19, 881-891.
- Krustrup, P., Mohr, M., Ellingsgaard, H., & Bangsbo, J. (2005). Physical demands during an elite female soccer game: Importance of training status. *Medicine and Science in Sports and Exercise*, 37, 1242-1248.
- Kubitz, K. A., Landers, D. M., Petruzzello, S. J., & Han, M. (1996). The effects of acute and chronic exercise on sleep: A meta-analytic review. *Sports Medicine*, 21, 227-291.
- Kuriyama, K., Stickgold, R., & Walker, M. P. (2004). Sleep dependent learning and motor skill complexity. *Learning and Memory*, 11, 705-713.
- Lam, R. W. & Levitan, R. D. (2000). Pathophysiology of seasonal affective disorder: A review. *Journal of Psychiatry and Neuroscience*, 25, 469-480.
- Lamarche, J. J. & De Koninck, J. (2007). Sleep disturbance in adults with posttraumatic stress disorder: A review. *Journal of Clinical Psychiatry*, 68, 1257-1270.
- Lames, M. (2012). *Computer Science in Sports- an Interdisciplinary Research Area*. Seminar presented at Loughborough University, Loughborough, UK, on 4th May 2012.
- Lange, T., Dimitriv, S., Bollinger, T., Diekelmann, S., & Born, J. (2011). Sleep after vaccination boosts immunological memory. *Journal Immunology*, 187, 283-290.

- Lange, T., Perras, B., Fehm, H. L., & Born, J. (2003). Sleep enhances the human antibody response to hepatitis A vaccination. *Psychosomatic Medicine*, *65*, 831-835.
- Langendörfer, F., Hodapp, V., Kreutz, G., & Bongard, S. (2006). Personality and performance anxiety among professional orchestra musicians. *Journal of Individual Differences*, *27*(3), 162-171.
- Laursen, P. B. & Jenkins, D. G. (2002). The scientific basis for high-intensity interval training. *Sports Medicine*, *32*, 53-73.
- Lavie, P. (1996). *The Enchanted World of Sleep*. New Haven, CN, USA: Yale University Press.
- Lee, M. A. M. & Kleitman, N. (1923). Studies on the physiology of sleep: Attempts to demonstrate functional changes in the nervous system during experimental insomnia. *American Journal of Physiology*, *67*, 141-152.
- Leeder, J. D. C., Gardner, A. S., Foley, S., van Someren, K., & Pedlar, C. R. (2009). The effect of jet lag on parameters of sleep in elite divers quantified by actigraphy. *Medicine and Science in Sport and Exercise*, *41*(5), 57-58.
- Leeder, J., Glaister, M., Pizzoferro, K., Dawson, J., & Pedlar, C. (2012). Sleep duration and quality in elite athletes measured using wristwatch actigraphy. *Journal of Sports Sciences*, *30*, 531-545.
- Leger, D., Metlaine, A., & Choudat, D. (2005). Insomnia and sleep disruption: Relevance for athletic performance. *Clinics in Sports Medicine*, *24*, 269-285.

- Levine, B., Roehrs, T., Stepanski, E., Zorick, F., & Roth, T. (1987). Fragmenting sleep diminishes its recuperative value. *Sleep, 10*, 590-599.
- Licklider, J. C. R. & Bunch, M. E. (1946). Effects of enforced wakefulness upon the growth and the maze-learning performance of white rats. *Journal of Comparative Psychology, 39*, 339 – 350.
- Lima, S. L. & Rattenborg, N. C. (2007). A behavioural shutdown can make sleeping safer: A strategic perspective on function of sleep. *Animal Behaviour, 74*, 189-197.
- Lockley, S. W., Skene, D. J., & Arendt, J. (1999). Comparison between subjective and actigraphic measurement of sleep and sleep rhythms. *Journal of Sleep Research, 8*, 175-184.
- London 2012 Organising Committee. (2012). London 2012: Athletics, 100m Men, Final. Retrieved from the World Wide Web, on 13th November 2013, from <http://www.olympic.org>
- Lu, W. & Göder, R. (2012). Does abnormal non-rapid eye movement sleep impair declarative memory consolidation? Disturbed thalamic functions in sleep and memory processing. *Sleep Medicine Reviews, 16*, 389-394.
- Lucas, S. J. E., Anson, G. J., Palmer, C. D., Hellemans, I. J., & Cotter, J. D. (2009). The impact of 100 hours of exercise and sleep deprivation on cognitive function and physical capacities. *Journal of Sports Sciences, 27*, 719-728.
- Mackinnon, L. T. (2000). Chronic exercise training effects on immune function. *Medicine and Science in Sports and Exercise, 32*, 369-376.

- Magee, J., Harsh, J., & Badia, P. (1987). Effects of experimentally-induced sleep fragmentation on sleep and sleepiness. *Psychophysiology*, *24*, 528-534.
- Mah, C. D., Mah, K. E., Kezirian, E. J., & Dement, W. C. (2011). The effects of sleep extension on the athletic performance of collegiate basketball players. *Sleep*, *34*, 943-950.
- Maislin, G., Pack, A. I., Kribbs, N. B., Smith, P. L., Schwartz, A. R., Schwab, R. J., & Dinges, D. F. (1995). A survey of prediction of apnea. *Sleep*, *18*, 158-166.
- Maquet, P. (1999). Brain mechanism of sleep: Contribution of neuroimaging techniques. *Journal of Psychopharmacology*, *13*, Suppl. 1, S25-S28.
- Maquet, P., Laureys, S., Peigneux, P., Fuchs, S., Petiau, C., Phillips, C., Aerts, J., Del Fiore, G., Degueldre, C., Meulemans, T., Luxen, A., Franck, G., Van Der Linden, M., Smith, C., & Cleeremans, A. (2000). Exercise-dependent changes in cerebral activation during human REM sleep. *Nature Neuroscience*, *3*, 831-836.
- Martens, R., Burton, D., Vealey, R. S., Bump. L., & Smith, D. E. (1990). Development and validation of the Competitive State Anxiety Inventory-2 (CSAI-2). In R. Martens, R. S., Vealey, & D. Burton (Eds.), *Competitive Anxiety in Sport* (pp. 117-213). Champaign, IL, USA: Human Kinetics.
- Martin, B. J. (1981). Effects of sleep deprivation on tolerance to prolonged exercise. *European Journal of Applied Physiology*, *47*, 345-354.

- Martin, S. E., Brander, P. E., Deary, I. J., & Douglas, N. J. (1999). The effect of clustered versus regular sleep fragmentation on daytime function. *Journal of Sleep Research, 8*, 305-311.
- Mastin, D. F., Bryson, J., & Corwyn, R. (2006). Assessing sleep hygiene using the sleep hygiene index. *Journal of Behavioural Medicine, 29*, 223-227.
- Matthews, C. E., Ockene, I. S., Freedson, P. S., Rosal, M. C., Merriam, P. A., & Herbert, J. R. (2002). Moderate to vigorous physical activity and the risk of upper-respiratory tract infection. *Medicine and Science in Sport and Exercise, 34*, 1242-1248.
- May, C. P. & Haser, L. (1998). Synchrony effects in inhibitory control over thought and action. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 363-379.
- May, J. & Kline, P. (1987). Measuring the effects upon cognitive abilities of sleep loss during continuous operations. *British Journal of Psychology, 78*, 443-455.
- McCall, C. & McCall, W. V. (2012). Comparison of actigraphy with polysomnography and sleep logs in depressed insomniacs. *Journal of Sleep Research, 21*, 122-127.
- McNair, D. M., Lorr, M., & Droppleman, F. F. (1971). *Profile of Mood States Manual*. San Diego, CA, USA: Education and Industrial Testing Service.
- Meier-Ewert, H. K., Risker, P. M., Rifai, N., Regan, M. M., Price, N. J., Dinges, D. F., Mullington, J. M. (2004). Effects of sleep loss on C-Reactive protein,

an inflammatory marker of cardiovascular risk. *Journal of the American College of Cardiology*, 43, 678-683.

Mellinger, G. D., Balter, M. B., & Uhlenhuth, E. H. (1985). Insomnia and its treatment: Prevalence and correlates. *Archives of General Psychiatry*, 42, 225-232.

Merkus, L. M., van Drongelen, A., Holte, K. A., Labriola, M., Lund, T., van Mechelen, W., & van der Beek, A. J. (2012). The association between shift work and sick leave: A systematic review. *Occupational and Environmental Medicine*, 69, 701-712.

Mohr, M., Krstrup, P., & Bangsbo, J., (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Science*, 21, 519-528.

Monk, T. H., Buysse, D. J., Reynolds III, C. F., Berga, S. L., Jarrett, D. B., Begley, A. E., & Kupfer, D. J. (1997). Circadian rhythms in human performance and mood under constant conditions. *Journal of Sleep Research*, 6, 9-18.

Montgomery, P. G., Pyne, D. B., & Minahan, C. L. (2010). The physical and physiological demands of basketball training and competition. *International Journal of Sports Physiology and Performance*, 5, 75-86.

Monti, J. M. & Monto, D. (2000). Sleep disturbances in generalized disorder and its treatment. *Sleep Medicine Reviews*, 4, 263-276.

Moran, A. (2008). Cognitive psychology in sport: Progress and prospects. *Psychology of Sport and Exercise*, 10, 420-426.

Morgenthaler, T., Alessi, C., Friedman, L., Owens, J., Kapur, V., Boehlecke, B., Brown, T., Chesson, A., Coleman, J., Lee-Chiong, T., Pancer, J., & Swick, T. J. (2007). Practice parameters for the use of actigraphy in the assessment of sleep and sleep disorders: An update for 2007. *Sleep*, 30, 519-529.

Morin, C. M. (2005). Psychological and behavioural treatments for primary insomnia. In M. H. Kryger, T. Roth & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 726-737). Philadelphia, PA, USA: Elsevier Saunders.

Moynihan, J. A., Callahan, T. A., Kelley, S. P., & Campbell, L. M. (1998). Adrenal hormone modulation of type 1 and type 2 cytokine production by spleen cells: Dexamethasone and dehydroepiandrosterone suppress interleukin-2, interleukin-4, and interferon-gamma production in vitro. *Cellular Immunology*, 184, 58-64.

Myllmaki, T., Kyröläinen, H., Savolainen, K., Hokka, L., Jakonen, R., Juuti, T., Martinmäki, K., Kaartinen, J., Kinnunen, M-L., & Rusko, H. (2011). Effects of vigorous late-night exercise on sleep quality and cardiac autonomic activity. *Journal of Sleep Research*, 20, 146-153.

Nansen, F. (1999). *Farthest North: The Incredible Three-Year Voyage to the Frozen Latitudes for the North*. New York: Random House.

National Health Service (2013). Physical activity guidelines for adults. Retrieved from the World Wide Web, on 15th November 2013, from <http://www.nhs.uk>

National Sleep Foundation (2002). Sleep in America Poll 2002. Washington DC: National Sleep Foundation.

Nehlsen-Cannarella, S. L., Fagoaga, O. R., Nieman, D. C., Henson, D. A., Butterworth, D. E., Schmitt, R. L., Bailey, E. M., Warren, B. J., Utter, A., & Davis, J. M. (1997). Carbohydrate and the cytokine response to 2.5 h of running. *Journal of Applied Physiology*, *82*, 1662-1667.

Newman, A. B., Spiekerman, C. F., Enright, P., Lefkowitz, D., Manolio, T., Reynolds, C. F., & Robbins, J. (2000). Daytime sleepiness predicts mortality and cardiovascular disease in older adults: The Cardiovascular Health Study Research Group. *Journal of the American Geriatric Society*, *48*, 115-123.

Newman, E. A. & Evans, C. R. (1965). Human dream processes as analogous to computer programme clearance. *Nature*, *206*, 534.

Neylan, T. C., Marmar, C. R., Metzler, T. J., Weiss, D. S., Zatzick, D. F., Delucchi, K. L., Wu, R. M., & Schoenfeld, F. B. (1998). Sleep disturbance in the Vietnam generation: Findings from a nationally representative sample of male Vietnam veterans. *American Journal of Psychiatry*, *155*, 929-933.

Nieman, D. C. (1994). Exercise, infection and immunity. *International Journal of Sports Medicine*, *15*, S131-S141.

Nieman, D. C. (1998). Influence of carbohydrate on the immune responses to intensive, prolonged exercise. *Exercise Immunology Review*, *4*, 64-76.

- Nieman, D. C., Johanssen, L. M., Lee, I. W., & Arabatzis, K. (1990). Infectious episodes in runners before and after the Los Angeles Marathon. *The Journal of Sports Medicine and Physical Fitness*, 30, 316-328.
- Nieman, D. C., Miller, A. R., Henson, D. A., Warren, B. J., Gusewitch, G., Johnson, R. L., Davis, J. M., Butterworth, D. E., Herring, J. L., Nehlsen-Cannarella, S. L. (1994). Effect of high- versus moderate-intensity exercise on lymphocyte subpopulations and proliferative response. *International Journal of Sports Medicine*, 15, 199-206.
- Niess, A. M., Dickhuth, H. H., Northoff, H., & Fehrenbach, E. (1999). Free radicals and oxidative stress in exercise-immunological aspects. *Exercise Immunology Review*, 5, 22-56.
- O'Donoghue, P. (2012). *Algorithms Identifying Tactical Variables in (semi-) Automatic Tracking Data in Professional Soccer*. Seminar presented at Loughborough University, Loughborough, UK, on 30th April 2012.
- Ohayon, M. M., Caulet, M., & Lemoine, P. (1998). Comorbidity of mental and insomnia disorders in the general population. *Comprehensive Psychiatry*, 39, 185-197.
- Overbeek, T., van Diest, R., Schruers, K., Kruizinga, F., & Griez, E. (2005). Sleep complaints in panic disorder patients. *Journal of Nervous and Mental Diseases*, 193, 488-493.
- Page, C. L. & Diehl, J. J. (2007). Upper respiratory tract infections in athletes. *Clinics in Sports Medicine*, 26, 345-359.

- Paxton, S. J., Montgomery, I., Trinder, J., Newman, J., & Bowling, A. (1982).
Sleep after exercise of variable intensity in fit and unfit subjects.
Australian Journal of Psychology, 34, 289-296.
- Pedersen, B. K. & Bruunsgaard, H. (1995). How physical exercise influences the
establishment of infections. *Sports Medicine, 19*, 393-400.
- Pejovic, S., Vgontzas, A. N., Basta, M., Tsaoussoglou, M., Zoumakis, E.,
Vgontzas A., Bixler, E. O., & Chrousos, G. P. (2010). Leptin and hunger
levels in young healthy adults after one night of sleep loss. *Journal of
Sleep Research, 19*, 552-558.
- Persch, P. P. A., Middendorp, H. M., Bouhuys, A. L., Beersma, D. G. M., & van
den Hoofdakker, R. H. (1999). Seasonal affective disorder and latitude: A
review of the literature. *Journal of Affective Disorders, 53*, 35-48.
- Pesch, B., Harth, V., Rabsten, S., Baisch, C., Schiffermann, M., Pallapies, D.,
Bonberg, N., Heinze, E., Spickenheuer, A., Justenhoven, C., Brauch, H.,
Hamann, U., Ko, Y., Straif, K., & Brüning, T. (2010). Night work and
breast cancer- results from the German GENICA study. *Scandinavian
Journal of Work and Environmental Health. 26*, 134-141.
- Peters, E. M. & Bateman, E. D. (1983). Ultramarathon running and URTI: An
epidemiological survey. *South African Medical Journal, 64*, 582-584.
- Peters, E. M., Goetzsche, J. M., Grobbelaar, B., & Noakes, T. D. (1993). Vitamin
C supplementation reduces the incidence of post-race symptoms of
upper respiratory tract infection in ultramarathon runners. *American
Journal of Clinical Nutrition, 57*, 170-174.

- Pinheiro, J. C. & Bates, D. M. (2000). *Mixed-Effects Models in S and S-PLUS*.
New York: Springer-Verlag.
- Plihal, W. & Born, J. (1997). Effects of early and late nocturnal sleep on declarative and procedural memory. *Journal of Cognitive Neuroscience*, 9, 534-547.
- Punjabi, N. M. & Beamer, B. A. (2005). Sleep apnea and metabolic dysfunction. In M. H. Kryger, T. Roth, & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 1034-1042). Philadelphia, PA, USA: Elsevier Saunders.
- Pyne, D. B. (1994). Regulation of neutrophil function during exercise. *Sports Medicine*, 17, 245-258.
- Rampin, C., Cespuglio, R., Chastrette, N., & Jouvet, M. (1991). Immobilisation stress induces a paradoxical sleep rebound in rat. *Neuroscience Letters*, 126, 113-118.
- Ramsawh, H. J., Stein, M. B., Belik, S-L., Jacobi, F., & Sareen, J. (2009). Relationship of anxiety disorders, sleep quality, and functional impairment in a community sample. *Journal of Psychiatric Research*, 43, 926-933.
- Recht, L. D., Lew, R. A., & Schwartz, W. J. (1995). Baseball teams beaten by jet lag. *Nature*, 277, 583.
- Rechtschaffen, A. & Kales, A. (1968). *A Manual of Standardised Terminology: Techniques and Scoring System for Stages of Human Subjects*. Los Angeles: UCLA Brain Information Services.

- Rechtschaffen, A., Gilliland, M. A., Bergman, B. M., & Winterer, J. B. (1983). Physiological correlates of prolonged sleep deprivation in rats. *Science*, *221*, 182-184.
- Reilly, T. & Deykin, T. (1983). Effects of partial sleep loss on the subjective states, psychomotor and physical performance tests. *Journal of Human Movement Studies*, *9*, 157-170.
- Reilly, T. & Edwards, B. (2007). Altered sleep-wake cycles and physical performance in athletes. *Physiology and Behaviour*, *90*, 274-284.
- Reilly, T. & Marshall, S. (1991). Circadian rhythms in power output on a swim bench. *Journal of Swimming Research*, *7*, 11-13.
- Reilly, T. & Piercy, M. (1994). The effect of partial sleep deprivation on weight-lifting performance. *Ergonomics*, *37*, 107-115.
- Reilly, T. & Walsh, T. J. (1981). Physiological, psychological and performance measures during an endurance record for 5-a-side soccer play. *British Journal of Sports Medicine*, *15*, 122-128.
- Reilly, T., Atkinson, G., & Budgett, R. (2001). Effect of low-dose Temazepam on physiological variables and performance tests following a Westerly flight across five time zones. *Physiology and Biochemistry*, *22*, 166-174.
- Reilly, T., Atkinson, G., Gregson, W., Drust, B., Forsyth, J., Edwards, B., & Waterhouse, J. (2006). Some chronobiological considerations related to physical exercise. *Clinical Therapeutics*, *157*, 249-264.

- Reilly, T., Morris, T., & Whyte, G. (2009). The specificity of training prescription and psychological assessment: A review. *Journal of Sports Sciences, 27*, 575-589.
- Reilly, T., Waterhouse, J., & Edwards, B. (2005). Jet lag and air travel: Implications for performance. *Clinics in Sports Medicine, 24*, 367-380.
- Res, P. T., Groen, B., Pennings, B., Beelen, M., Wallis, G. A., Gijzen, A. P., Senden, J. M. G., & van Loon, L. J. C. (2012). Protein ingestion before sleep improves postexercise overnight recovery. *Medicine and Science in Sports and Exercise, 44*, 1560-1569.
- Richmond, L., Dawson, B., Hillman, d. R., & Eastwood, P. R. (2004). The effect of interstate travel on sleep patterns of elite Australian Rules footballers. *Journal of Science and Medicine in Sport, 7*, 186-196.
- Riedel, B. W. (2000). Sleep hygiene. In K. L. Lichstein & C. M. Morin (Eds.), *Treatment of Late-life Insomnia* (pp. 125-146). Thousand Oaks, CA, USA: Sage.
- Robert, G. & Hockey, J. (1996). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology, 45*, 73-93.
- Roberts, J. A. (1986). Viral illness and sports performance. *Sports Medicine, 3*, 298-303.
- Robertson, E. M., Pascual-Leone, A., & Press, D. Z. (2004). Awareness modifies the skill-learning benefits of sleep. *Current Biology, 14*, 208-212.

- Robson-Ansley, P. J., Gleeson, M., & Ansley, L. (2009). Fatigue management in the preparation of Olympic athletes. *Journal of Sports Science, 16*, 1-12.
- Rodgers, C. D., Paterson, D. H., Cunningham, D. A., Noble, E. G., Pettigrew, F. P., Myles, W. S., & Taylor, A. W. (1995). Sleep deprivation: Effects on work capacity, self-paced walking, contractile properties and perceived exertion. *Sleep, 18*, 30-38.
- Roehrs, T., Merlotti, L., Petrucelli, N., Stepanski, E., & Roth, T. (1994). Experimental sleep fragmentation. *Sleep, 17*, 438-443.
- Roehrs, T., Zorick, F., Wittig, R., Conway, W., & Roth, T. (1989). Predictors of objective level daytime sleepiness in patients with sleep-related breathing disorders. *Chest, 95*, 1202-1206.
- Roehrs, T., Zorick, F., Wittig, R., Conway, W., & Roth, T. (1989). Predictors of objective level of daytime sleepiness in patients with sleep-related breathing disorders. *Chest, 95*, 1202-1206.
- Rogers, N. L. & Dinges, D. F. (2001). Shiftwork, circadian disruption and consequences. *Journal of Neuroscience, Psychology and Economics, 6*, 58-64.
- Rogers, N. L., Dorrian, J., & Dinges, D. F. (2003). Sleep, waking and neurobehavioral performance. *Frontiers in Bioscience, 8*, S1056-S1067.
- Ronald, J., Delaive, K., Roos, L., Manfreda, J., Bahammam, A., & Kryger, M. H. (1999). Health care utilization in the 10 years prior to diagnosis in obstructive sleep apnea syndrome patients. *Sleep, 22*, 225-229.

- Ronsen, O., Pedersen, B. K., Oritsland, T. R., Bahr, R., & Kjeldsen-Kragh, J. (2001). Leukocyte counts and lymphocyte responsiveness associated with repeated bouts of strenuous endurance exercise. *Journal of Applied Physiology, 91*, 425-434.
- Ross, J. J. (1965). Neurological findings after prolonged sleep deprivation. *Archives of Neurology, 12*, 399-403.
- Rowe, M., McCrae, C., Campbell, J., Horne, C., Tiegs, T., Lehman, B., & Cheng, J. (2008). Actigraphy in older adults: Comparison of means and variability of three different aggregate of measurement. *Behavioural Sleep Medicine, 6*, 127-145.
- Ruiz, F. S., Andersen, M. L., Martins, R. C. S., Zager, A., Lopes, J. D., & Tufik, S. (2012). Immune alterations after selective rapid eye movement or total sleep deprivation in healthy male volunteers. *Innate Immunity, 18*, 44-54.
- Sadeh, A. (1996). Evaluating night waking in sleep-disturbed infants: a methodological study of parental reports and actigraphy. *Sleep, 19*, 757-762.
- Sadeh, A. (2011). The role and validity of actigraphy in sleep medicine: An update. *Sleep Medicine Reviews, 15*, 259-267.
- Sadeh, A., Sharkey, K. M., & Carskadon, M. A. (1994). Activity-based sleep-wake identification: An empirical test of methodological issues. *Sleep, 17*, 201-207.
- Sagaspe, P., Sanchez-Ortuno, M., Charles, A., Taillard, J., Valtat, C., Bioulac, B., & Philip, P. (2006). Effects of sleep deprivation on color-word,

emotional, and specific Stroop interference and on self-reported anxiety. *Brain and Cognition*, 60, 76-87.

Saksvik, I. B., Bjorvatn, B., Hetland, H., Sandal, G. M., & Pallesen, S. (2011). Individual differences in tolerance to shift work- a systematic review. *Sleep Medicine Reviews*, 15, 221-235.

Samuels, C. (2008). Sleep recovery and performance: The new frontier in high performance athletics. *Neurologic Clinics*, 26, 169-180.

Samuels, C. (2008). Sleep recovery and performance: The new frontier in high performance athletics. *Neurologic Clinics*, 26, 169-180.

Sargent, C., Halson, S., & Roach, G. D. (2012). Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. *European Journal of Sport Science*, 12, 1-6.

Savis, F. J. (1994). Sleep and athletic performance: Overview and implications for sport psychology. *The Sport Psychologist*, 8, 111-125.

Scanlan, T. K., Sten, G. L., & Ravizza, K. (1991). An in-depth study of former elite figure skaters: 3. Sources of stress. *Journal of Sports and Exercise Psychology*, 13, 103-120.

Schabus, M., Gruber, G., Parapatics, S., Sauter, C., Klösch, G., Anderer, P., Klimesch, W., Saletu, B., & Zeitlhofer, J. (2004). Sleep spindles and their significance for declarative memory consolidation. *Sleep*, 27, 1479-1485.

- Scheer, F. A., Hilton, M. F., Mantzoros, C. S., & Shea, S. A. (2009). Adverse metabolic and cardiovascular consequences of circadian misalignment. *Proceedings of the National Academy of Science, USA, 106*, 4453-4458.
- Schwartz, S. W., Cornoni-Huntley, J., Cole, S. R., Hays, J. C., Blazer, D. G., & Schocken, D. D. (1998). Are sleep complaints an independent risk factor for myocardial infarction? *Annals of Epidemiology, 8*, 384-392.
- Sedliak, M., Finni, T., Peltonen, J., & Häkkinen. (2008). Effect of time-of-day specific training on maximum strength and EMG activity on the leg extensors in men. *Journal of Sports Science, 26*, 1005-1014.
- Shapiro, C. M., Bortz, R., Mitchell, D., Bartel, P., & Jooste, P. (1981). Slow-wave sleep: A recovery period after exercise. *Science, 214*, 1253-1254.
- Shapiro, C. M., Warren, P. M., Trinder, J., Paxton, S. J., Oswald, I., Flenley, D. C., & Catterall, J. R. (1984). Fitness facilitates sleep. *European Journal of Applied Physiology, 53*, 1-4.
- Shearer, W. T., Reuben, J. M., Mullington, J. M., Price, N. J., Lee, B-N., Smith, E. O., Szuba, M. P., Van Dongen, H. P. A., Dinges, D. F. (2001). Soluble TNF-alpha receptor 1 and IL-6 plasma levels in humans subjected to the sleep deprivation model of spaceflight. *Journal of Allergy and Clinical Immunology, 107*, 165-170.
- Sherrill, D. L., Kotchou, K., & Quan, S. F. (1998). Association of physical activity and human sleep disorders. *Archives of Internal Medicine, 158*, 1894-1898.

- Siegal J. M. (2001). The REM sleep-memory consolidation hypothesis. *Science*, *294*, 1058-1063.
- Silva, A., Queiroz, S. S., Winckler, C., Vital, R., Sousa, R. A., Fagundes, V., Tufik, S., & de Mello, M. T. (2012). Sleep quality evaluation, chronotype, sleepiness and anxiety of Paralympic Brazilian athletes: Beijing 2008 Paralympic Games. *British Journal of Sports Medicine*, *46*, 150-154.
- Smith, C. (1995). Sleep states and memory processes. *Behavioural Brain Research*, *69*, 137-145.
- Smith, R. S., Efron, B., Mah, C. D., & Malhotra, A. (2013). The impact of circadian misalignment on athletic performance in professional football players. *Sleep*, *36*, 1999-2001.
- Souissi, M., Chtourou, H., Zrane, A., Cheikh, R. B., Dogui, M., Tabka, Z., & Souissi, N. (2012). Effect of time-of-day of aerobic maximal exercise on the sleep quality of trained subjects. *Biological Rhythm Research*, *43*, 323-330.
- Souissi, N., Sesboüé, B., Gauthier, A., Larue, J., & Davenne, D. (2003). Effects of one night's sleep deprivation on anaerobic performance the following day. *European Journal of Applied Physiology*, *89*, 359-366.
- Spiegel K., Tasali, E., Penev, P., & Van Cauter, E. (2004). Brief communication: Sleep curtailment in healthy young men is associated with decreased leptin levels, elevated ghrelin levels, and increased hunger and appetite. *Annals of Internal Medicine*, *141*, 846-850.

- Spiegel, K., Leproult, R., & Van Cauter, E. (1999). Impact of sleep debt on metabolic and endocrine function. *Lancet*, *354*, 1435-1439.
- Spiegel, K., Leproult, R., Tasali, E., Penev, P., & Van Cauter, E. (2003). Sleep curtailment results in decreased leptin levels and increased hunger and appetite. *Sleep*, *26*, 174.
- Spiegel, K., Sheridan, J. F., & Van Cauter, E. (2002). Effect of sleep deprivation on the response to immunization. *Journal of the American Medical Association*, *288*, 1471-1472.
- Spielman, A. J., Yang, C-M., & Glovinsky, P. B. (2005). Assessment techniques for insomnia. In M. H. Kryger, T. Roth & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 1403-1416). Philadelphia, PA, USA: Elsevier Saunders.
- Steenland, K. & Deddens, J. A. (1997). Effect of travel and rest on performance of professional basketball players. *Sleep*, *20*, 366-369.
- Stein, M. B. & Mellman, T. A. (2005). Anxiety disorders. In M. H. Kryger, T. Roth, & W. C. Dement (Eds.), *Principles and Practice of Sleep Medicine* (4th ed., pp. 1297-1310). Philadelphia, PA, USA: Elsevier Saunders.
- Stepanski, E., Lamphere, J., Roehrs, T., Zorick, F., & Roth, T. (1987). Experimental sleep fragmentation in normal subjects. *International Journal of Neuroscience*, *33*, 207-214.
- Stepanski, E. J. & Wyatt, J. K. (2003). Use of sleep hygiene in the treatment of insomnia. *Sleep Medicine Reviews*, *7*, 215-225.

- Stepanski, E. J. (2002). The effect of sleep fragmentation on daytime function. *Sleep, 25*, 268-276.
- Stickgold, R. (2005). Sleep-dependent memory consolidation. *Nature, 437*, 1272-1278.
- Stickgold, R., James, L., & Hobson, J. A. (2000b). Visual discrimination learning requires post-training sleep. *Nature Neuroscience, 2*, 1237-1238.
- Stickgold, R., Whidbee, D., Schirmer, B., Patel, V., & Hobson, J. A. (2000a). Visual discrimination task improvement: A multi-step process occurring during sleep. *Journal of Cognitive Neuroscience, 12*, 246-254.
- Strogatz, S. H., Kronauer, R. E., & Czeisler, C. A. (1987). Circadian pacemaker interferes with sleep onset at specific times each day: Role in insomnia. *American Journal of Physiology, 253*, R172-R178.
- Susmakova, K. (2004). Human sleep and sleep EEG. *Measurement Science Review, 4*, 59-74.
- Taillard, J., Philip, P., & Bioulac, B. (1999). Morningness/eveningness and the need for sleep. *Journal of Sleep Research, 8*, 291-295.
- Taylor, D. J., Lichstein, K. L., Durrence, H. H., Reidal, B. W., & Bush, A. J. (2005). Epidemiology of insomnia, depression, and anxiety. *Sleep, 28*, 1457-1464.
- Taylor, E. R., Rogers, G. G., & Driver, H. S. (1997). Effects of training volume on sleep, psychological, and selected physiological profiles of elite female swimmers. *Medicine and Science in Sports and Exercise, 29*, 688-693.

- Taylor, S. R. (2001). The influence of exercise on sleep quality. *The International Sportmed Journal*, 2, 1-10.
- Thatcher, J., Thatcher, R., Portas, M., & Hood, S. (2009). Sport and exercise science. In J. Thatcher, R. Thatcher, M. Day, M. Portas, & S. Hood (Eds.), *Sport and Exercise Science* (pp. 1-5). Exeter, UK: Learning Matters.
- Trinder, J., Montgomery, I., & Paxton, S. J. (1988). The effect of exercise on sleep: The negative view. *Acta Physiologica Scandinavica*, 133, (Suppl. 574) 14-21.
- Udhe, T. W., Cortese, B. M., & Vedeniapin, A. (2009). Anxiety and sleep problems: Emerging concepts and theoretical treatment implications. *Current Psychiatry Reports*, 11, 269-276.
- Van der Hulst, M. (2003). Long work hours and health. *Scandinavian Journal of Work and Environmental Health*, 29, 171-188.
- Van Dongen, H. P. A. & Dinges, D. F. (2003). Investigating the interaction between the homeostatic and circadian processes of sleep-wake regulation for the prediction of waking neurobehavioural performance. *Journal of Sleep Research*, 12, 181-187.
- Van Dongen, H. P., Maislin, G., Mullington, J. M., & Dinges, D. F. (2003). The cumulative cost of additional wakefulness: Dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep*, 26, 117-126.
- Vgontzas, A. N., Pejovic, S., Zoumakis, E., Lin, H. M., Bixler, E. O., Basta, M., Fang, J., Sarrigiannidis, A., & Chrousos, G. P. (2007). Daytime napping

after a night of sleep loss decreases sleepiness, improves performance, and causes beneficial changes in cortisol and interleukin-6 secretion.

American Journal of Physiology, Endocrinology and Metabolism, 292, E253-261.

Vuori, I., Urponen, H., Hasan, J., & Partinen, M. (1988). Epidemiology of exercise effects on sleep. *Acta Physiologica Scandinavia*, 133, (Suppl. 574) 3-7.

Vyas, M. V., Garg, A. X., Iansavichus, A. V., Costella, J., Donner, A., Laugsand, L. E., Janszky, I., Mrkobrada, M., Parraga, G., & Hackam, D. G. (2012). Shift work and vascular events: Systematic review and meta-analysis. *British Medical Journal*, 345, 1136-1147.

Walker, M. P. (2004). A refined model of sleep and the time course of memory formation. *Behavioural and Brain Sciences*, 28, 51-64.

Walker, M. P., Brakefield, T., Morgan, A., Hobson, J. A., & Stickgold, R. (2002). Practice with sleep makes perfect: Sleep dependent motor skill learning. *Neuron*, 35, 205-211.

Wang, L., Zhang, J., Wang, J., He, W., & Huang, H. (2012). Effects of high-intensity training and resumed training on macroelement and microelement of elite basketball athletes. *Biological Trace Element Research*, 149(2), 148-154.

Wang, M-Y., Wang, S-Y., & Tsai, P-S. (2005). Cognitive behavioural therapy for primary insomnia: A systematic review. *Journal of Advanced Nursing*, 50, 553-564.

- Waterhouse, J., Edwards, B., Carvalho-Bos, S., Buckley, P., & Reilly, T. (2002). Circadian rhythms, jet lag, and shift work, with particular reference to athletes. *European Journal of Sport Science*, 2, 1-19.
- Waters, A. & Lovell, G. (2002). An examination of homefield advantage in a professional English soccer team from a psychological standpoint. *Football Studies*, 5, 46-59.
- Webb, W. B. & Agnew, H. W. (1971). Sleep stage characteristics of long and short sleepers. *Science*, 168, 146-147.
- Wehr, T. A., Moul, D. E., Barbato, G., Giesen, H. A., Seidal, J. A., Barker, C., & Bender, C. (1993). Conservation of photoperiod-responsive mechanisms in humans. *American Journal of Physiology*, 265, 846-857.
- Weinberg, R. S. & Gould, D. (2007). *Foundations of Sport and Exercise Psychology* (4th ed.). Champaign, IL, USA: Human Kinetics.
- Weiss, M. R., Wiese, D. M., & Klint, K. A. (1989). Head over heels with success: The relationship between self-efficacy and performance in competitive youth gymnastics. *Journal of Sport and Exercise Psychology*, 11, 444-451.
- Westermeyer, J., Sutherland, R. J., Freerks, M., Martin, K., Thuras, P., Johnson, D., Rossom, R., & Hurwitz, T. (2007). Reliability of sleep logs versus actigraphy in veterans with sleep disturbance and PTSD. *Journal of Anxiety Disorders*, 21, 966-975.

- Wicklow, A. & Espie, C. A. (2000). Intrusive thoughts and their relationship to actigraphic measurement of sleep: Towards a cognitive model of insomnia. *Behaviour and Research Therapy*, 38, 679-394.
- Wimmer, F., Hoffman, R. F., Bonato, R. A., & Moffitt, A. R. (1992). The effects of sleep deprivation on divergent thinking and attention processes. *Journal of Sleep Research*, 1, 223-230.
- World Anti-Doping Agency. (2013). The World Anti-Doping Code: The 2013 Prohibited List, International Standard. Retrieved from the world wide web, on 12th November 2013, from <http://www.wada-ama.org>
- World Health Organization (2010). International classification of diseases and related health problems (10th ed.). Retrieved from the World Wide Web on 16th September 2011, from <http://www.who.int/classifications/icd/en/>
- Worthen, J. N. & Wade, C. E. (1999). Direction of travel and visiting team athletic performance: Support for a circadian dysrhythmia hypothesis. *The Journal of Sport Behaviour*, 22, 279-287.
- Wundersitz, D. W. T., Netto, K. J., Aisbett, B., & Gatin, P. B. (2013). Validity of an upper-body-mounted accelerometer to measure peak vertical and resultant force during running and change-of-direction tasks.
- Yamanaka, Y., Hasimoto, S., Tanahashi, Y., Nishide, S., Honma, S., & Honma, K. (2010). Physical exercise accelerates reentrainment of human sleep-wake cycle but not of plasma melatonin rhythm to the 8-h phase-advanced sleep schedule. *American Journal of Physiology- Regulatory, Integrative and Comparative Physiology*, 298, 681-691.

- Yamauchi, R., Shimizu, K., Kimura, F., Takemura, M., Suzuki, K., Akama, T., Kono, I., & Akimoto, T. (2011). Virus activation and immune function during intense training in rugby football players. *International Journal of Sports Medicine, 32*, 393-398.
- Yang, C-M., Lin, S-C., Hsu, S-C., & Cheng, C-P. (2010). Maladaptive sleep hygiene practices in good sleepers and patients with insomnia. *Journal of Health Psychology, 15*, 147-155.
- Young, W., Hepner, J., & Robbins, D. (2012). Movement demands in Australian rules football as indicators of muscle damage. *Journal of Strength and Conditioning Research, 26*, 492-496.
- Youngstedt, S. D. & Frelove-Charton, J. D. (2005). Exercise and sleep. In G. E. J. Faulkner & A. H. Taylor (Eds.), *Exercise, Health and Mental Health: Emerging Relationships* (pp. 159-189). London: Routledge.
- Youngstedt, S. D. & Kline, C. E. (2006). Epidemiology of exercise and sleep. *Sleep and Biological Rhythms, 4*, 215-221.
- Youngstedt, S. D., O'Connor, P. J., & Dishman, R. K. (1997). The effects of acute exercise on sleep : A quantitative synthesis. *Sleep, 20*, 203-214.
- Zimmerman, J. T., Stoyva, J. M., & Martin, L. (1978). Spatially rearranged vision and REM sleep: A lack of effect. *Biological Psychiatry, 13*, 301-316.
- Zimmerman, J., Stoyva, J., & Metcalf, D. (1970). Distorted visual feedback and augmented REM sleep. *Psychophysiology, 7*, 298.

Appendices

Appendix A	List of R Packages Attached During Analysis
Appendix B	Chapter 3 Results Summary
Appendix C	Chapter 4 Results Summaries
Appendix D	Chapter 5 Results Summaries
Appendix E	Chapter 4 Unstandardized Effects

Appendix A- List of R Packages Attached During Analyses

doBy	Højsgaard, S. & Halekoh, U. (2013). doBy: doBy – Groupwise summary statistics, general linear contrasts, population means (least-squares-means) and other utilities. R package version 4.5-6.
ggplot2	Wickham, H. (2009). <i>ggplot2: Elegant Graphics for Data Analysis</i> . New York: Springer.
graphics	R Core Development Team. (2012). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.
lawstat	Noguchi, K., Hui, W. L., Gel, Y. R., Gastwirth, J. L. & Miao, W. (2009). lawstat: An R package for biostatistics, public policy, and law. R package version 2.3.
leaps	Lumley, T. & Miller, A. (2009). leaps: Regression subset selection. R package version 2.9.
lme4	Bates, D., Maechler, M., & Bolker, B. (2011). lme4: Linear mixed-effects models using S4 classes. R package version 0.999375-42.
lubridate	Grolemund, G. & Wickam, H. (2011). Dates and times made easy with lubridate. <i>Journal of Statistical Software</i> , 40(3) , 1-25).
multilevel	Bliese, P. (2012). multilevel: Multilevel functions. R package

version 2.4.

- nortest Gross, J. & Ligges, U. (2012). nortest: Tests for Normality. R
Package version 1.0-2.
- plyr Wickham, H. (2011). The split-apply-combine strategy for data
analysis. *Journal of Statistical Software*, 40(1), 1-29.
- psych Revelle, W. (2012). psych: Procedures for Personality and
Psychological Research. Northwestern University,
Evanston, USA. R Packages version 1.2.1.
- stats R Core Development Team. (2012). R: A language and
environment for statistical computing. Vienna, Austria: R
Foundation for Statistical Computing.

Appendix B- Chapter 3 Results Summary

	Group 1 - Sedentary	Group 2 - Football	Group 3 - Basketball	Group 4 - Swimming
Sleep Parameter				
Bed Time (time)	00:12 (01:20) ^{2,3}	23:24 (00:55) ^{1,3}	01:33 (01:13) ^{1,2,4}	23:39 (00:52) ³
Get Up (time)	08:10 (01:08) ³	08:34 (00:43) ^{3,4}	09:25 (01:07) ^{1,2,4}	07:39 (00:46) ^{2,3}
TST (hh:mm)	07:39 (00:51) ²	08:34 (00:37) ^{1,3,4}	07:33 (00:23) ²	07:43 (00:32) ²
WASO (minutes)	40 (15) ²	68 (23) ¹	58 (16)	54 (18)
SE (%)	88.79 (4.32) ^{2,3}	81.12 (4.73) ¹	83.63 (6.45) ¹	85.0 (4.72)
SOL (minutes)	10.1 (10.38) ²	27.1 (16.58) ^{1,4}	17.6 (21.65)	14.4 (8.2) ²
Movements / hour	6.37 (1.69) ^{2,3,4}	8.70 (1.54) ¹	8.83 (2.15) ¹	9.55 (1.54) ¹

Table 3.1. Pairwise comparisons between groups based on activity type. Annotations indicate a significant ($p < 0.05$) difference between the named group and the corresponding numbered group (e.g. the sedentary group displayed a significantly different bed time to the football and basketball group, but not the swimming group. The basketball group had a significantly different bed time to all other groups). Measures of central tendency are displayed as mean (standard deviation).

Appendix C- Chapter 4 Results Summaries

	<i>Pre-match</i>	<i>Non-pre-match</i>	<i>t-value</i>	<i>Significance</i>
	<i>Average</i>	<i>Average</i>		<i>(p)</i>
<i>Sleep Parameter</i>				
Bed Time (time)	22:46 (00:51)	23:23 (00:47)	3.554	0.002
Get Up (time)	08:40 (00:38)	08:29 (00:41)	1.155	0.263
TST (hh:mm)	09:19 (00:54)	08:35 (00:43)	3.887	0.001
WASO (minutes)	61 (34)	67 (22)	1.259	0.223
SE (%)	79.5 (8.4)	80.6 (4.9)	0.932	0.363
SOL (minutes)	28.8 (29.8)	24.5 (14.7)	0.829	0.417
Movements / hour	9.2 (1.7)	8.8 (1.4)	1.200	0.245

Table 4.1. Comparison of sleep parameters the night before matches compared to otherwise 'normal' sleep. Measures of central tendency are presented as mean (standard deviation).

	<i>Pre-home-</i>	<i>Pre-away-match</i>	<i>t-value</i>	<i>Significance</i>
	<i>match Average</i>	<i>Average</i>		<i>(p)</i>
<i>Sleep Parameter</i>				
Bed Time (time)	22:57 (01:05)	22:41 (01:13)	0.573	0.578
Get Up (time)	08:46 (00:45)	08:43 (00:47)	0.151	0.883
TST (hh:mm)	09:23 (01:17)	09:31 (01:22)	0.218	0.831
WASO (minutes)	87 (42)	70 (26)	1.251	0.240
SE (%)	79.4 (6.2)	76.4 (8.4)	1.515	0.160
SOL (minutes)	25.2 (15.6)	24.4 (37)	0.088	0.932
Movements / hour	9.37 (2.0)	9.24 (1.80)	0.292	0.776

Table 4.2. Comparison of sleep parameters the night before home matches compared to sleep the night before away matches. Measures of central tendency are presented as mean (standard deviation).

	<i>Pre-afternoon match Average</i>	<i>Pre-evening match Average</i>	<i>t-value</i>	<i>Significance (p)</i>
Sleep Parameter				
Bed Time (time)	23:19 (01:10)	22:30 (00:49)	1.976	0.089
Get Up (time)	09:11 (00:55)	08:23 (00:33)	2.475	0.0425
TST (hh:mm)	09:25 (00:49)	09:28 (00:41)	0.068	0.948
WASO (minutes)	73 (44)	61 (39)	0.091	0.930
SE (%)	81.7 (7.9)	80.6 (5.8)	1.437	0.194
SOL (minutes)	23.3 (14.8)	19.8 (15.6)	0.538	0.608
Movements / hour	8.71 (2.02)	8.77 (1.62)	1.116	0.301

Table 4.3. Comparison of sleep parameters the night before afternoon matches compared to sleep the night before evening matches. Measures of central tendency are presented as mean (standard deviation).

	<i>Total Metres (Z)</i>			<i>High Intensity Metres (Z)</i>		
	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>
	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>
<i>Predictors</i>						
Bed Time	-0.391	0.268	0.157	-0.331	0.232	0.167
Get Up Time	0.337	0.246	0.182	0.291	0.254	0.264
TST	0.211	0.201	0.303	0.165	0.175	0.356
WASO	-0.220	0.183	0.239	-0.052	0.171	0.765
SE	0.308	0.203	0.140	0.042	0.191	0.826
SOL	-0.232	0.214	0.287	0.055	0.183	0.764
Onsets/hour	-0.168	0.211	0.434	0.079	0.176	0.656

Table 4.4. Regression coefficients, standard error and significance of the relationship between z-scored sleep parameters and subsequent z-scored performance measures during competitive matches. Interpretation is similar to a 'standard' linear regression in that regression coefficients presented here represent direction and magnitude of the impact that a unit change in each predictor has on the outcome variable. e.g. a higher (i.e. later) bed time of 1 standard deviation is associated with an average decrease in total metres covered in a match of 0.391 standard deviations.

	<i>Post-match</i>	<i>Habitual</i>	<i>t-value</i>	<i>Significance</i>
	<i>Average</i>	<i>Average</i>		<i>(p)</i>
<i>Sleep Parameter</i>				
Bed Time (time)	00:33 (00:56)	23:10 (00:52)	6.183	<0.0005
Get Up (time)	08:46 (01:10)	08:30 (00:43)	0.977	0.345
TST (hh:mm)	07:40 (01:04)	08:53 (00:42)	4.529	<0.0005
WASO (hh:mm)	01:11 (00:24)	01:02 (00:29)	1.356	0.197
SE (%)	79.1 (5.1)	81.1 (4.3)	1.454	0.168
SOL (minutes)	27.3 (22.5)	20.2 (20.5)	1.769	0.099
Movements / hour	9.23 (1.57)	8.62 (1.13)	1.505	0.153

Table 4.5. Comparison of sleep parameters the night following matches compared to normal 'habitual' sleep. Measures of central tendency are presented as mean (standard deviation).

	<i>Post-afternoon</i>	<i>Post-evening</i>	<i>t-value</i>	<i>Significance</i>
	<i>Match Average</i>	<i>Match Average</i>		<i>(p)</i>
<i>Sleep Parameter</i>				
Bed Time (time)	23:57 (00:48)	00:08 (01:12)	0.105	0.696
Get Up (time)	08:39 (00:57)	08:16 (01:36)	1.357	0.212
TST (hh:mm)	08:05 (00:46)	07:29 (01:40)	1.280	0.236
WASO (hh:mm)	01:19 (00:28)	01:09 (00:28)	0.823	0.435
SE (%)	78.3 (4.5)	77.6 (5.8)	0.288	0.781
SOL (minutes)	33.8 (19.3)	31.9 (22.2)	0.170	0.870
Movements / hour	9.32 (1.95)	8.95 (1.89)	0.669	0.522

Table 4.6. Comparison of sleep parameters the night following afternoon matches compared to sleep following evening matches. Measures of central tendency are presented as mean (standard deviation).

	<i>Bed Time</i>			<i>Get Up Time</i>			<i>Total Sleep Time</i>		
	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>
	<i>Coefficient</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient</i>	<i>Error (β)</i>	<i>(p)</i>
	<i>(β)</i>			<i>(β)</i>			<i>(β)</i>		
Predictors									
<i>Playing Time</i>									
<i>All Post Match</i>	0.223	0.163	0.185	-0.106	0.199	0.599	-0.316	0.201	0.133
<i>Post Afternoon Match</i>	0.292	0.175	0.140	0.534	0.209	0.038	0.013	0.161	0.939
<i>Post Evening Match</i>	0.118	0.292	0.700	-0.587	0.232	0.045	-0.570	0.229	0.047
<i>Total Metres Covered</i>									
<i>All Post Match</i>	0.257	0.149	0.102	-0.077	0.156	0.629	-0.317	0.138	0.033
<i>Post Afternoon Match</i>	0.058	0.227	0.805	0.576	0.340	0.134	0.129	0.166	0.463
<i>Post Evening Match</i>	0.336	0.321	0.344	-0.425	0.200	0.087	-0.515	0.256	0.100
<i>High Intensity Metres</i>									
<i>All Post Match</i>	0.008	0.207	0.970	-0.170	0.177	0.351	-0.432	0.160	0.014
<i>Post Afternoon Match</i>	-0.119	0.222	0.607	0.164	0.185	0.406	0.119	0.185	0.541
<i>Post Evening Match</i>	0.619	0.387	0.171	-0.628	0.232	0.043	-0.809	0.214	0.013
<i>Number of Accelerations</i>									
<i>All Post Match</i>	-1.222	0.369	0.748	-0.283	0.188	0.149	-0.438	0.227	0.083
<i>Post Afternoon Match</i>	-4.012	2.922	0.303	-1.140	1.737	0.579	-0.316	0.539	0.617
<i>Post Evening Match</i>	-0.231	0.576	0.708	-0.557	0.356	0.193	-0.512	0.216	0.077

	<i>Wakefulness After Sleep Onset</i>			<i>Sleep Efficiency</i>		
	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>
	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>
Predictors						
<i>Playing Time</i>						
<i>All Post Match</i>	-0.220	0.143	0.139	0.066	0.159	0.624
<i>Post Afternoon Match</i>	-0.015	0.212	0.945	-0.058	0.246	0.821
<i>Post Evening Match</i>	-0.401	0.190	0.079	0.191	0.254	0.480
<i>Total Metres Covered</i>						
<i>All Post Match</i>	-0.137	0.130	0.304	-0.086	0.155	0.584
<i>Post Afternoon Match</i>	0.355	0.267	0.225	-0.179	0.264	0.520
<i>Post Evening Match</i>	-0.446	0.183	0.059	0.173	0.288	0.575
<i>High Intensity Metres</i>						
<i>All Post Match</i>	-0.032	0.158	0.843	-0.190	0.182	0.312
<i>Post Afternoon Match</i>	0.398	0.273	0.188	-0.672	0.356	0.101
<i>Post Evening Match</i>	-0.275	0.233	0.291	-0.028	0.243	0.914
<i>Number of Accelerations</i>						
<i>All Post Match</i>	0.169	0.265	0.539	-0.634	0.558	0.282
<i>Post Afternoon Match</i>	0.752	0.542	0.230	-1.631	0.481	0.077
<i>Post Evening Match</i>	-0.261	0.319	0.460	0.190	0.444	0.690

<i>Predictors</i>	<i>Sleep Onset Latency</i>			<i>Movements / hour</i>		
	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>
	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>
<i>Playing Time</i>						
<i>All Post Match</i>	0.156	0.171	0.374	0.092	0.198	0.647
<i>Post Afternoon Match</i>	0.270	0.222	0.264	-0.211	0.416	0.627
<i>Post Evening Match</i>	0.108	0.254	0.686	0.192	0.254	0.479
<i>Total Metres Covered</i>						
<i>All Post Match</i>	0.218	0.176	0.232	0.090	0.194	0.648
<i>Post Afternoon Match</i>	0.353	0.347	0.196	-0.186	0.388	0.648
<i>Post Evening Match</i>	0.008	0.313	0.980	-0.071	0.215	0.754
<i>High Intensity Metres</i>						
<i>All Post Match</i>	0.112	0.202	0.586	0.290	0.221	0.205
<i>Post Afternoon Match</i>	0.428	0.267	0.153	-0.502	0.542	0.385
<i>Post Evening Match</i>	-0.185	0.288	0.549	0.055	0.272	0.849
<i>Number of Accelerations</i>						
<i>All Post Match</i>	0.428	0.415	0.327	0.263	0.408	0.534
<i>Post Afternoon Match</i>	1.321	0.579	0.150	0.348	0.978	0.756
<i>Post Evening Match</i>	-0.260	0.839	0.654	0.140	0.317	0.682

Table 4.7. Beta coefficients, standard error and significance of the relationship between individually z-scored measures of physical work performed during matches and subsequent sleep. Interpretation is similar to a standard linear regression; coefficients represent the impact of a unit change in the predictor on the outcome (e.g. an increase in playing time of 1 standard deviation relative to a players normal playing time results in an increase in bed time of 0.223 standard deviations).

Appendix D- Chapter 5 Results Summaries

	<i>Pre-training</i>	<i>Habitual</i>	<i>t-value</i>	<i>Significance</i>
	<i>Average</i>	<i>Average</i>		<i>(p)</i>
<i>Sleep Parameter</i>				
Bed Time (time)	23:10 (00:52)	23:19 (01:04)	0.575	0.573
Get Up (time)	08:23 (00:44)	08:28 (01:01)	0.435	0.669
TST (hh:mm)	08:43 (00:50)	08:35 (01:19)	0.593	0.561
WASO (hh:mm)	62 (29)	76 (33)	1.292	0.214
SE (%)	80.9 (5.7)	79.2 (7.1)	1.222	0.239
SOL (minutes)	21.1 (18.7)	25.7 (18.6)	1.200	0.247
Movements / hour	8.9 (1.5)	8.9 (1.4)	0.218	0.830

Table 5.1a. Comparison of sleep parameters the night before training sessions compared to habitual sleep. Measures of central tendency are presented as mean (standard deviation).

	<i>Post-training</i>	<i>Habitual</i>	<i>t-value</i>	<i>Significance</i>
	<i>Average</i>	<i>Average</i>		<i>(p)</i>
<i>Sleep Parameter</i>				
Bed Time (time)	23:00 (00:49)	23:10 (01:12)	0.842	0.411
Get Up (time)	08:38 (00:50)	08:27 (00:59)	1.228	0.235
TST (hh:mm)	09:06 (00:54)	08:40 (01:20)	1.913	0.072
WASO (hh:mm)	65 (25)	77 (32)	1.279	0.217
SE (%)	80.5 (5.2)	79.0 (6.9)	1.045	0.310
SOL (minutes)	25.0 (18.8)	28.5 (21.8)	0.774	0.449
Movements / hour	9.1 (1.1)	8.8 (1.4)	0.726	0.477

Table 5.1b. Comparison of sleep parameters the night following training sessions compared to habitual sleep. Measures of central tendency are presented as mean (standard deviation).

	<i>Total Metres/minute</i>			<i>High-Intensity Distance/minute</i>		
	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>
	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>
<i>Predictors</i>						
<i>Bed Time</i>	-0.217	0.097	0.030	-0.180	0.078	0.026
<i>Get Up Time</i>	0.050	0.143	0.728	0.065	0.095	0.501
<i>TST</i>	0.355	0.112	0.003	0.218	0.096	0.027
<i>WASO</i>	0.117	0.092	0.207	0.104	0.073	0.162
<i>SE</i>	0.022	0.081	0.784	-0.061	0.063	0.333
<i>SOL</i>	0.126	0.104	0.232	0.125	0.074	0.099
<i>Onsets/hour</i>	0.074	0.082	0.370	0.071	0.073	0.338

<i>Predictors</i>	<i>PlayerLoad/minute</i>			<i>RPE/metre</i>		
	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>
	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>
<i>Bed Time</i>	-0.316	0.133	0.024	0.380	0.179	0.042
<i>Get Up Time</i>	0.064	0.135	0.640	0.092	0.156	0.560
<i>TST</i>	0.398	0.145	0.010	-0.327	0.204	0.119
<i>WASO</i>	0.151	0.113	0.190	-0.327	0.180	0.079
<i>SE</i>	-0.053	0.101	0.606	0.207	0.164	0.217
<i>SOL</i>	0.233	0.120	0.061	0.358	0.213	0.103
<i>Movements/hour</i>	0.074	0.082	0.127	0.103	0.127	0.103

Table 5.2. Beta coefficients, standard error and significance of the relationship between z-scored sleep parameters and subsequent z-scored performance measures during training sessions. Interpretation of regression coefficients is similar to interpretation of 'standard' regression, in that coefficients represent the direction and magnitude of the impact that a unit change in a predictor has on an outcome variable e.g. a later bed time by 1 standard deviation reduces the total distance covered per minute by (on average) 0.217 standard deviations.

	<i>Bed Time</i>			<i>Get Up Time</i>			<i>Total Sleep Time</i>		
	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>
	<i>Coefficient</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient</i>	<i>Error (β)</i>	<i>(p)</i>
	<i>(β)</i>			<i>(β)</i>			<i>(β)</i>		
<i>Predictors</i>									
<i>Training Time</i>	-0.118	0.119	0.328	0.051	0.129	0.694	0.137	0.096	0.159
<i>Total Distance</i>	-0.168	0.213	0.433	0.156	0.219	0.480	0.342	0.144	0.022
<i>High Intensity</i>	-0.526	0.233	0.028	0.173	0.245	0.483	0.516	0.185	0.007
<i>Distance</i>									
<i>Number of</i>	0.142	0.136	0.303	0.152	0.105	0.155	-0.071	0.106	0.505
<i>Accelerations</i>									
<i>RPE</i>	0.035	0.118	0.771	0.328	0.131	0.018	0.151	0.103	0.151
<i>Player Load</i>	-0.368	0.208	0.087	0.354	0.261	0.185	0.505	0.180	0.009

	Wakefulness After Sleep Onset			Sleep Efficiency		
	Regression	Standard	Significance	Regression	Standard	Significance
	Coefficient (β)	Error (β)	(p)	Coefficient (β)	Error (β)	(p)
Predictors						
Training Time	-0.187	0.125	0.141	0.296	0.148	0.050
Total Distance	0.070	0.189	0.714	0.343	0.213	0.114
High Intensity Distance	0.427	0.254	0.100	-0.154	0.303	0.612
Number of Accelerations	-0.144	0.159	0.368	0.112	0.176	0.526
RPE	-0.205	0.146	0.168	0.282	0.167	0.102
Player Load	0.084	0.262	0.750	0.157	0.315	0.622

	<i>Sleep Onset Latency</i>			<i>Movements/hour</i>		
	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>	<i>Regression</i>	<i>Standard</i>	<i>Significance</i>
	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>	<i>Coefficient (β)</i>	<i>Error (β)</i>	<i>(p)</i>
<i>Predictors</i>						
<i>Training Time</i>	0.120	0.127	0.350	-0.095	0.151	0.532
<i>Total Distance</i>	0.148	0.212	0.489	0.072	0.215	0.737
<i>High Intensity</i>	0.402	0.241	0.101	0.419	0.305	0.175
<i>Distance</i>						
<i>Number of</i>	0.043	0.139	0.760	-0.071	0.172	0.682
<i>Accelerations</i>						
<i>RPE</i>	0.352	0.128	0.001	-0.113	0.206	0.588
<i>Player Load</i>	0.384	0.243	0.124	0.143	0.340	0.678

Table 5.3. Beta coefficients, standard error and significance of the relationship between z-scored measures of physical activity during training and subsequent z-scored sleep parameters.

Appendix E- Chapter 4 Unstandardized Effects

	Standardised Effect Size (β)	Predictor		Outcome		Percentage Change*
		<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	
Total Distance						
<i>Bed Time (hh:mm)</i>	-0.391	23:17	01:13	8435	2098	-9.73%
<i>Get Up Time (hh:mm)</i>	0.337	08:31	01:00	8435	2098	8.38%
<i>TST (hh:mm)</i>	0.211	08:42	01:18	8435	2098	5.25%
<i>WASO (minutes)</i>	-0.220	01:08	00:35	8435	2098	-5.47%
<i>SE (%)</i>	0.308	80.4	6.5	8435	2098	7.66%
<i>SOL (minutes)</i>	-0.232	25.1	21.8	8435	2098	-5.77%
<i>Movements/hour</i>	-0.168	8.95	1.39	8435	2098	-4.18%

	Standardised Effect Size (β)	Predictor		Outcome		Percentage Change*
		<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	
HI Distance						
<i>Bed Time (hh:mm)</i>	-0.331	23.17	01:13	950	362	-12.61%
<i>Get Up Time (hh:mm)</i>	0.291	08:31	01:00	950	362	11.09%
<i>TST (hh:mm)</i>	0.165	08:42	01:18	950	362	6.29%
<i>WASO (minutes)</i>	-0.052	01:08	00:35	950	362	-1.98%
<i>SE (%)</i>	0.042	80.4	6.5	950	362	1.60%
<i>SOL (minutes)</i>	0.055	25.1	21.8	950	362	2.10%
<i>Movements/hour</i>	0.079	8.95	1.39	950	362	3.01%

Table 6.1. Data for unstandardized effect sizes for the impact of sleep on subsequent match performance, showing the impact on the outcome variables that is associated with a change of a single standard deviation of each predictor, and the magnitude of change expressed as a percentage

*Percentage change associated with an increase in the predictor of one standard deviation.

