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Altered sleep–wake cycles and physical performance in athletes

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Abstract

Sleep–waking cycles are fundamental in human circadian rhythms and their disruption can have consequences for behaviour and performance. Such disturbances occur due to domestic or occupational schedules that do not permit normal sleep quotas, rapid travel across multiple meridians and extreme athletic and recreational endeavours where sleep is restricted or totally deprived. There are methodological issues in quantifying the physiological and performance consequences of alterations in the sleep–wake cycle if the effects on circadian rhythms are to be separated from the fatigue process. Individual requirements for sleep show large variations but chronic reduction in sleep can lead to immuno-suppression. There are still unanswered questions about the sleep needs of athletes, the role of ‘power naps’ and the potential for exercise in improving the quality of sleep.

Keywords: Circadian rhythm; Exercise; Jet-lag; Shift-work

1. Introduction

The sleep–wakefulness cycle is the most discernable of human circadian functions, activity being associated with the hours of daylight and sleep with the hours of darkness. This recurrence on a daily basis is linked with responses of the pineal gland to the environment, its secretion of melatonin being promoted at dusk and inhibited on exposure to morning light. There is a myriad of other biological functions that are knit into a common system of circadian rhythms, cycles in behaviour and in biological functions that recur with a period of about 24 h (*circa diem*).

Many human performance measures follow broadly the typical circadian curve in body temperature, including for example muscle strength, anaerobic power output, joint-flexibility and self-chosen work-rate [1]. Observations from time-trials in swimming [2] and cycling [3] provide indirect support for an endogenous component to these rhythms in exercise performance. There are suggestions that complex skills tend to peak earlier in the day than do gross motor skills, due possibly to an earlier acrophase in the circadian rhythm in alertness compared to that of body temperature [4,5]. This separation of central nervous system arousal from alignment with the body temperature rhythm has been attributed, at least in part, to the circadian rhythm in circulatory catecholamines [6] and to the homeostatic drive for recuperation from fatigue due to time since waking from the previous sleep [7,8]. Indeed, the amount of sleep individuals have acquired in the previous 24 and 48 h has been incorporated into a predictive model for determining fatigue-risk thresholds in normal hours of occupational service [9].

The harmonious co-existence of distinct circadian rhythms cannot be assumed when the normal sleep–wakefulness cycle is disrupted. Such perturbations occur as a result of changes in domestic circumstances that interrupt normal sleep, when anxiety prohibits restful sleep and when operating on nocturnal shift-work. They also apply to travellers on long-haul flights over multiple meridians and to a lesser extent to Muslims fasting during the holy month of Ramadan when eating and drinking are eschewed from sunrise to sunset (see the paper by Reilly and Waterhouse in this special issue). The consequences are usually apparent in mood, alertness and performance [10]. The effects of these disruptions may be more pronounced in athletic activities,

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particularly 'adventure' events where the amount of time allocated for sleep is minimised.

The importance of good quality sleep for sports participants is recognised by practitioners (e.g. [11]). Insights can be gained into the role of sleep by looking at the consequences of disruptions to the sleep–waking cycle and how individuals cope in such conditions. In this review the effects of total sleep deprivation, chronic sleep loss and partial sleep allowances are considered, and results reviewed from both laboratory and field studies. The circumstances inducing jet-lag and nocturnal shift-work are then reviewed along with remedies for counteracting any performance impairments. Sleep disruption in the context of individual differences is discussed prior to setting out guidelines for coping with necessary breaks to normal sleep.

2. Methodological issues

Whilst the study of sleep itself is inherently attractive to researchers due to its fundamental nature, it is beset with methodological problems. Smith and Reilly [12] outlined three features of research protocols required to define the effects of sleep deprivation on athletic performance with the desired level of accuracy. Firstly, the experimental protocol should isolate the homeostatic from the circadian components as these frequently confound each other. Secondly, the protocol should include an externally valid competitive event to reduce motivational confounds and decrease the distortion associated with extrapolation to the real conditions. Thirdly, the research protocol should effectively reduce the many confounding variables affecting sports performance, for example home advantage, climate conditions, changes in fitness and individual circumstances.

Needless to state, all of the above conditions are rarely fulfilled in studies of sleep deprivation. Furthermore, compliance with all of these requirements is impractical in a real-life competitive context. There are also likely to be ethical issues associated with engaging elite performers in an experimental set-up where their performance might be impaired. Finally, the internal validity of research designs is limited since it is not possible to 'blind' the participants or administer an authentic placebo.

The influence of disrupted sleep on the circadian rhythm in exercise performance is also problematic due to the metabolic and physiological sequelae to an exercise trial. Reilly and Bambaeichi [13] highlighted some of the issues confronting researchers when studying circadian rhythms in human performance. Relevant factors included sources of measurement error, selection of physiological and performance measures, use of laboratory or field-based conditions, and the age, gender and health status of the participants. It is evident that the research design must be appropriate to the research question set and dependant variables must be chosen with particular care. In some instances important observations on disturbances to the sleep–wakefulness cycles are made possible as unique research opportunities present themselves, such as in 'extreme adventure' sports. Such measures of entire performance in the field are in contrast with laboratory studies in which individual aspects of performance are recorded more precisely.

There remains the problem of separating the circadian component from the homeostatic drive to sleep. This difficulty arises irrespective of whether sleep is lost in the early morning or is due to a late bedtime. The two processes are compounded in travellers, especially those going westwards on long haul flights. The forced desynchrony procedures of Cajochen et al. [14] may have value in applications to the study of sleep and circadian effects on athletes.

3. Total sleep deprivation

In a study of continuous exercise at moderate intensity, Thomas and Reilly [15] showed that it was possible to maintain activity for at least 100 h non-stop. Energy intake was provided to match the rate of energy expenditure (30.77 MJ day^{-1}) and delivered as a glucose syrup drink. Despite the consistency in muscular power output (which was controlled), the heart rate decreased over the first 2 days of the trial, suggesting a reduction in sympathetic drive. Lung function, indicated by forced vital capacity and forced expiratory volume after 1 s, displayed a deteriorating trend over the 100 h, superimposed on circadian periodicity. There was a significant trend in slowing of visual reaction time with each successive day without sleep. Errors in a signal detection test appeared after the first night of sleep loss, and in mental tasks requiring short-term memory after the second night, although neither task demonstrated a significant circadian rhythm under these conditions. The observations highlighted the erratic nature of performance tasks in these circumstances and the suppression (or masking) of some circadian rhythms in conditions that demand a constant level of muscular power output.

Where participants attempt to achieve entry into the Guinness Book of Records for extreme endurance, activity is usually sustained at a self-chosen intensity. When two teams playing five-a-side football for 91.8 h were monitored, the work-rate demonstrated a significant circadian rhythm each day and a decline from day-to-day [16]. The rhythm in activity was in phase with that of body temperature, and in this instance the heart rate response showed cyclical variation corresponding to the physical activity. Impairment in mental performance was evident after only one night, lapses in attention and delays in reaction time becoming more pronounced than physical measures such as grip strength which proved resistant to fatigue effects induced by lack of sleep.

When individuals are deprived of sleep over successive nights, bizarre behavioural episodes, illusions (visual, auditory and olfactory) or hallucinations are often noted. The aetiology of disturbances in cognitive and perceptual processes was examined in another group of footballers playing five-a-side games indoors for 71 h [17]. Blood samples were obtained every 4 h while mood states were monitored at the same time points in the 5-min rest allowed every 50 min. Unprepared-reaction time was sampled by means of a portable devise worn on a harness for administration of a test protocol while play was continued (see Fig. 1). The data suggested that β-phenylethylamine, a naturally occurring brain amine, plays a role in the cycles of unusual behaviour and mood states occurring in these

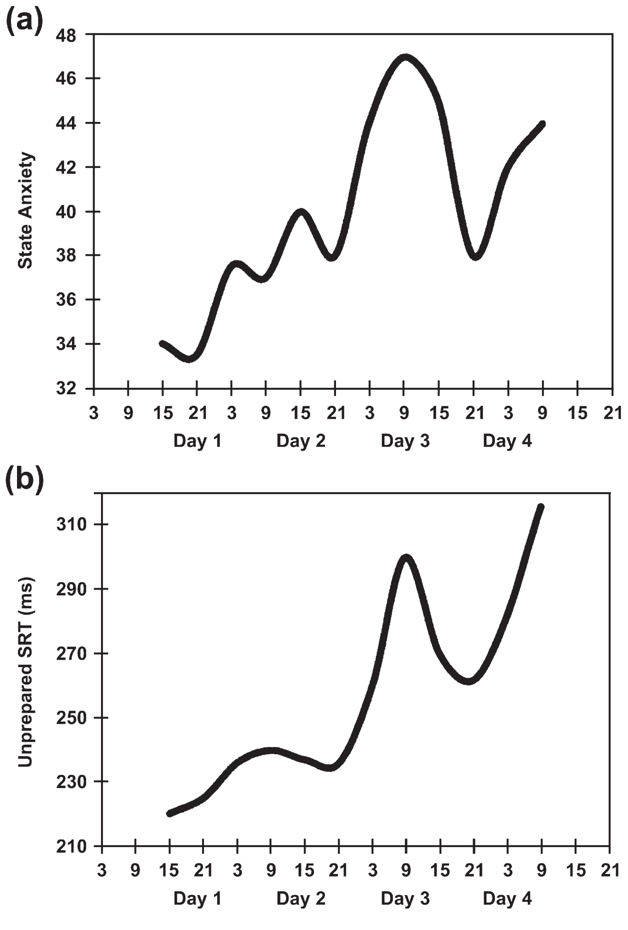


Fig. 1. Changes in anxiety state (a) and unprepared simple reaction time (b) in five-a-side players over 71 h without sleep. The data showed a trend with time of sleep deprivation and a time-of-day effect (data from [17]).

circumstances, since the concentrations of the free amine demonstrated a circadian rhythm superimposed on a progressive day-to-day increase. Despite the occasional episode of erratic behaviour, grip strength remained relatively stable over the 3 days, allowing for the circadian rhythm that existed.

In a study of naval seamen deprived of sleep for over 72 h, How et al. [18] employed a battery of tests related to cognitive and physical performance. The more pronounced declines were observed in cognition, speed and precision while smaller effects were found in routine tests of physical measures. The changes became more evident after 36 h: all performance measures displayed a diurnal rhythm and troughs coincided with the highest ratings for sleepiness.

A similar correlation between subjective states and skills performance was reported when military recruits were monitored whilst being kept awake for three successive nights [19]. An increase in self-rated fatigue coincided with a decline in accuracy of rifle-shooting, both measures exhibiting circadian rhythmicity over the 3 days. The performance curves were in phase with circulating noradrenaline concentrations which rose progressively with a peak each daytime. The increased concentrations of noradrenaline were thought to reflect an increased mental drive necessary to maintain performance in the face of sleep deprivation. Relative changes in noradrenaline and heart rate might be used to characterise heart rate sensitivity to sympathetic nervous stimulation under such circumstances. The observations on the novice soldiers showed how circadian rhythms can persist alongside a progressive trend in fatigue under conditions of complete sleep deprivation. A similar picture is presented for anxiety and unprepared simple reaction time of the subjects playing football indoors for 71 h without any sleep (shown in Fig. 1).

Meta-analyses of relevant studies have confirmed the significant impact of sleep deprivation on psychomotor performance. Koslowsky and Babkoff [20] concluded that the longer the period without sleep, the greater was the effect on performance. Furthermore, decreases in speed were greater than decrements in accuracy. In a second meta-analysis, Pilcher and Huffcutt [21] showed that mood measures were more sensitive than cognitive tasks, which were, in turn, more sensitive than motor tasks during sleep loss. Sports skills frequently incorporate decision-making as well as physical components, errors in either of which are reflected in performance outcomes. Any deterioration in mood is also likely to affect performance where maximum effort and determination are required of the participant.

4. Chronic sleep loss

Observations on chronic sleep loss in realistic conditions have relied mainly on ultra-endurance races, long-distance-sailing and military operations. In these instances some sleep is allowed or taken according to strategies for the competitive event or necessitated by weather conditions.

Smith et al. [22] studied competitors in the Race Across America (RAAM), a solo-bicycle race over 4640 km in the USA, which takes approximately 8 days for elite competitors. Over 3 years the average sleep taken by the winners was 2 h per night. In a comparable Eco-Challenge event completed in 7 days and 2 h, the sleep taken voluntarily by the winning team in 2002 averaged 2.4 h per 24 h. After experiencing extreme physical and cognitive fatigue the previous year, the victorious sleep strategy was to go no more than 30 h without sleep [12]. Whilst participants can complete these competitions over challenging terrain and environmental conditions, the events exact a huge toll on their physical and mental resources.

Chronic sleep disturbances are anticipated by sailors in races across the great oceans and around the world. Bennet [23] studied 19 solo yachtsmen during a transatlantic race that took around 38 days. Most participants awoke at intervals to check weather and direction, one sailor making these checks every 30 min each 24 h. Errors were common among the yachtsmen, and hallucinations were reported by some, illustrating the stress posed by such activities on those who take part in them.

As a strategy to deal with the task associated with sailing single-handed in the Vendee Globe Race over 40 000 km, the British sailor Ellen McArthur used the cluster-napping technique promoted by Stampi et al. [24]. The duration of nighttime sleep varied with weather conditions but it was supported by daytime naps. The strategy entails separating a long sleep into shorter units of 25–40 min each, during which quick checks are conducted on the boat, its navigation equipment and the weather conditions while staying awake, but immediately resuming sleep once these chores are completed. Her average nap lasted 36 min, and total sleep averaged 5.5 h day^{-1} over the 94 days of the 2001 race in which she finished second overall.

Studies have also been conducted on military personnel with a view to charting the effects of an arduous physical regimen whilst on restricted sleep rations. Rognum and co-workers [25] considered that Norwegian soldiers were ineffective at the end of 4 days with only 2 h sleep each night. This conclusion was based on deteriorated performance over a 1-km assault course, a shooting test and a run over 3 km. A diet high in energy intake had not prevented the impairment.

In another study, conducted upon 27 soldiers, participants expended 21 MJ day^{-1} over 5 days on a combat course, taking less than 4 h sleep each day. The participants were divided into three equal groups according to energy intake; those on low intake had 7.6 MJ day^{-1}, a medium-intake group had 13.4 MJ day^{-1} whilst the soldiers on high intake were given 17.6 MJ day^{-1} [26]. The participants on the low-energy intake experienced an 8% drop in maximal oxygen uptake ($V_{O_2\ max}$) and a 14% decline in anaerobic power by the end of the course, whereas the other two groups did not show a significant decrease in either of these resources. It seems that a large energy imbalance leads to a deterioration in both aerobic and anaerobic power production when activity is sustained over several days and sleep is reduced. In this study there were not adequate intermediate observations to show transient falls in performance whilst on the combat manoeuvres.

The fall in $V_{O_2\ max}$ with sleep deprivation is not inevitable and no decline in V_{O_2} has been reported at work rates up to 80% $V_{O_2\ max}$ [27]. While maximal oxygen uptake is itself a robust function, a difficulty facing researchers is to get subjects who are deprived of sleep to exercise at progressive work-rates until voluntary exhaustion is reached. Criteria that $V_{O_2\ max}$ is actually attained include a plateau in V_{O_2} before termination, a high blood lactate concentration and a respiratory exchange ratio above 1.10. Some subjects have shown a small decline in $V_{O_2\ max}$ after incurring a sleep debt over two successive nights [28,29] but others [30] have found that maximal aerobic power can be retained, at least after one whole night's sleep loss. Disruptions to normal eating and drinking patterns and to the individual's motivational climate may contribute to a failure to sustain exercise on an incremental test to exhaustion – as is required to satisfy the standard criteria that a maximal physiological state was reached. The neurological basis for such an increased exercise intolerance is uncertain.

Changes in gene expression may help in gaining insights into the consequences of sleep loss on energy processes. Genes expressed during wakefulness to regulate mitochondrial activity and glucose transport are likely to reflect increased energy needs. One gene for the enzyme arylsulfotransferase has shown stronger induction as a function of the length of sleep deprivation. This induction was suggested to reflect a homeostatic response to continuing central noradrenergic activity during loss of sleep [31].

5. Experimental studies in partial sleep deprivation

As the majority of sports entail competition within a single day, the study of partially reduced sleep in the day or days prior to sports contests has more relevance than the study of total sleep deprivation or chronic sleep loss. The experimental regimens have entailed substantially reduced sleep allowances, partly to ensure that all sleep stages are affected and partly also to safeguard against a Type II experimental error. Those studies relevant to sport have included time-trials or components of performance whilst others have employed laboratory-based measures that have more generic applications.

Sinnerton and Reilly [32] focused on swimming performance and on restricted nightly sleep (2.5 h sleep a night). Eight swimmers were tested in a 50-m pool on 4 consecutive days, morning (06:30 h) and evening (17:30 h), under conditions of normal sleep and under partial sleep deprivation. Measurements included grip and back strength, lung function (vital capacity, forced expiratory volume in 1 s), resting heart rate and mood states. Swimming performances over four trials at 50 m and one trial at 400 m were also measured. No decrements were observed with sleep deprivation either in back or grip strength, lung function, or swim times, although these variables demonstrated an effect of time of day. Sleep loss affected mood states, increasing depression, tension, confusion, fatigue and anger, while decreasing vigour significantly. The data were interpreted as supporting Horne's [33] brain restitution theory of sleep, suggesting that the primary need for sleep is located in nerve cells rather than in other biological tissues.

Reilly and Deykin [34] investigated the effects of partial sleep deprivation in a group of trained men (3 nights of sleep loss and a single night of subsequent recovery sleep) on a battery of psychomotor, physical working capacity, and subjective-state tests. A novel feature of the study was the measurement of various performance tasks at the same time as running on a treadmill at 10 km h^{-1} to investigate the effects of exercise as an antidote to sleep loss. The authors concluded that gross motor functions including muscle strength, lung power and endurance running on a treadmill can remain unaffected by 3 nights of severely restricted sleep. Decrements occurred in a range of psychomotor functions, the majority of which were evident after only 1 night of reduced sleep. Exercise had a beneficial effect on arousal after sleep loss, providing an obvious temporary counteraction to falls in mental alertness. All functions monitored were restored to normal after a full night of recovery sleep.

It seems that effects of sleep deprivation apply equally to females as to males. Reilly and Hales [35] restricted the sleep of well-trained females to 2 h per night for 3 nights. Baseline measures were obtained for 4 days as a control. Measurements were made each morning (07:00–09:30 h) and evening (19:00–21:30 h) for oral temperature, lung function, grip strength, anaerobic power output, limb steadiness and speed and subjective sensations at rest and during exercise. Apart from hand steadiness, diurnal variations were observed in all measures in phase with the variation in oral temperature. Gross motor functions were less affected by sleep loss than the tasks requiring fast reactions. A 5-min submaximal exercise bout at 60% $V_{O_2\ \max}$ was effective in reducing the feeling of sleepiness, which was more pronounced in the morning than in the evening. The exercise was rated harder in the morning than in the evening, and the rating was increased with successive days of partial sleep deprivation. It was concluded that the effects of sleep loss may be masked if time of day is not taken into consideration.

While athletes may be able to overcome the adverse effects of sleep loss in single all-out efforts, they may be unable or unwilling to maintain a high level of performance in sustained exercise and in repeated exercise bouts such as those that occur in extended training sessions. Reilly and Piercy [36] focused on weight-lifting tasks, using typical weight-training exercise as maximal lifts and adopting a psychophysical approach toward assessing repeated submaximal efforts. There was no significant effect of sleep loss on performance of maximal biceps curl but a significant effect was noted on maximal bench press, leg press and dead lift. Trend analysis indicated decreased performance in submaximal lifts for all four tasks; the deterioration was significant after the second night of sleep loss. These changes were evident in the perception of effort – whether rated for breathing, muscles or general whole-body feeling – as indicated by the responses to biceps curl (Fig. 2a) and dead lift (Fig. 2b). Results indicate that submaximal lifting tasks are more affected by sleep loss than are maximal efforts, particularly for the first 2 nights of successive sleep restriction. The observations highlighted that the greatest impairments were found the later in the protocol that the lifts were performed, indicating a cumulative fatigue effect due to sleep loss accruing during the training sessions.

The fact that muscle strength may be resistant to the effects of one night's sleep deprivation has been confirmed, whether sleep loss was total [37] or partial [38]. Meney et al. [37] noted that body temperature did not decline as a result of no sleep, and maximal performance in back and leg isometric strength was retained. Bambaeichi et al. [38] conducted measurements at 06:00 and 18:00 h on female subjects using isokinetic dynamometry. Peak torque was about 5% higher in the evening compared to the morning for concentric actions of knee flexors at angular velocities of 1.05 and 3.14 rad s^{-1}. The variations were in phase with changes in rectal temperature but were unaffected by restriction of sleep to 2.5 h overnight. It seems that circadian variations in muscle performance are more robust than are any changes due to sleep deprivation.

In those instances that have been examined, performance has taken different guises. A taxonomy is presented in Table 1 suggestive of how performance in certain types of activity might be affected. Such a classification itself entails broad generalisation, since the effects of sleep loss can be mitigated by the challenging nature of the activity to the individual concerned.

6. Travelling across time-zones

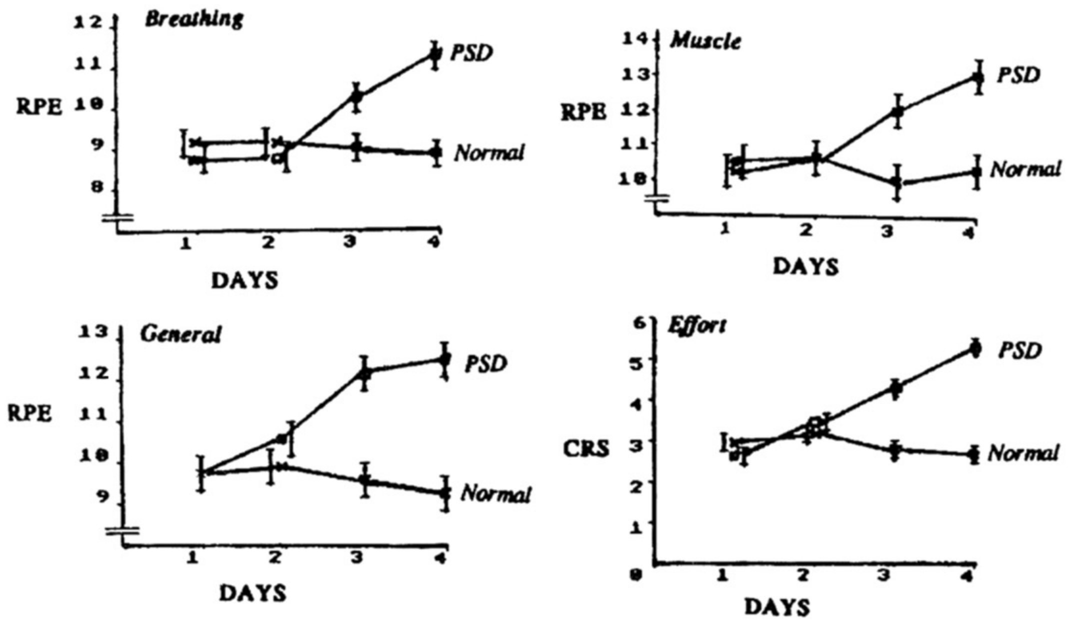
When individuals travel on long-haul flights across multiple meridians, their circadian rhythms are desynchronised. Jet-lag refers to the feelings of disorientation, light-headedness, impatience, lack of energy and general discomfort that follow travelling across time-zones. These feelings are not experienced while travelling directly northwards or southwards within the same time-zone when the passenger simply becomes tired from the journey or stiff after a long stay in a cramped posture. The feelings associated with jet-lag may persist for several days after arrival and can be accompanied by loss of appetite, constipation, difficulty in sleeping and reduced motivation. Although individuals differ in severity of symptoms they experience, many people simply fail to recognise how they themselves are affected, especially in tasks requiring concentration and complex coordination. For instance they may have difficulty in sleeping at the appropriate time but not recognise it as jet-lag. The different components of jet-lag were identified by Waterhouse et al. [39] when they designed the Liverpool Jet-lag Questionnaire. Besides a global sensation of 'jet-lag', symptoms cluster around sleep, fatigue, mental performance and mood, meals and bowel activity.

Following a journey across multiple time zones the body's circadian rhythm at first retains the characteristics of the point of departure. The new environment forces new influences on these cycles, mainly the time of sunrise and onset of darkness, which act as Zeitgebers and adjust the body clock. The body attempts to adjust to this new context but core temperature is relatively slow to do so. It takes about 1 day for each time-zone crossed for body temperature to adapt completely [40]. The individual may not sleep well for a few days but activity and social contact during the day help to adjust the rhythm in arousal. Arousal adapts more quickly than does body temperature to the new time-zone. Until the whole range of biological rhythms adjusts to the new local time, thereby becoming re-sychronized, athletic performance may be below par. A schematic illustration of the adjustment of different key rhythms is shown in Fig. 3. The sleep–wake cycle may be normalised prior to adjustment of body temperature where re-synchronization seems to coincide with disappearance of jet-lag symptoms. Only then does the performance curve return to its normal circadian rhythm (see Fig. 4, Day 7).

The severity of jet-lag is affected by a number of factors besides individual differences. The greater the number of time-zones travelled, the more difficult it is to cope. A 2-h phase shift may have marginal significance but a 3-h shift (e.g. British or Irish sports teams travelling to play European football matches in Russia or teams within the USA travelling coast to coast) will encounter desynchronization to a substantial degree. In such cases the flight times – time of departure and time of arrival – may determine how severe are the symptoms of jet-lag that occur. Training times might be altered to take the direction of travel into account. Such an approach was suggested as a strategy for American football teams travelling across time-zones within the USA and scheduled to play at different times of day [41].

When jet-lag is experienced, symptoms abate after the first 2 or 3 days following arrival, but may still be most marked at particular times of day. There will be a window of time during the day when time of high arousal associated with the time zone departed from and the new local time overlap. This window

(a) Sub-maximal bicep curl



(b) Sub-maximal deadlift

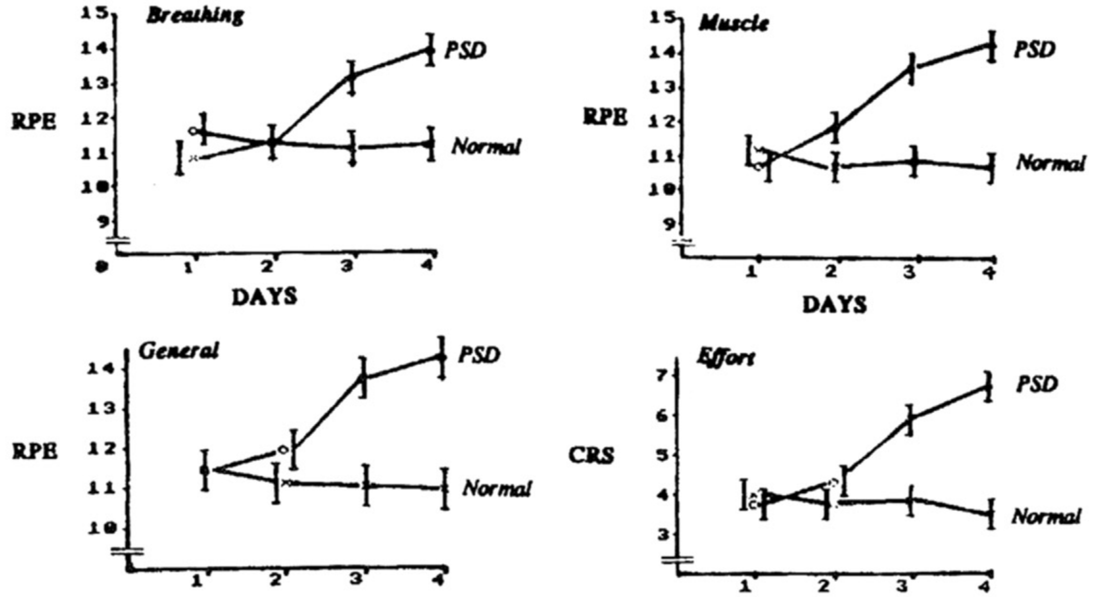


Fig. 2. Perceived exertion (RPE) during sustained biceps curl (a) and deadlift (b), rated for breathing, muscle, and general whole-body feeling. The CRS scale refers to category ratio. Day 1 indicates a baseline day after a normal sleep, and PSD refers to partial sleep deprivation (from [36]).

may be predicted in advance and should be utilised when arranging times for training practices in the first few days at the destination.

The direction of travel also influences the severity of jet-lag. It is easier to cope with flying in a westward direction compared to flying eastward. In flying westward, the first day is lengthened and the body's rhythms can extend in line with their natural free-running period of about 25 h and thus delay, so reducing the duration of jet-lag. By contrast, travelling from the United Kingdom to Korea (9 h in advance of British Summer Time) and Malaysia (7 h in advance of British Summer Time) required more than 9 and 7 days, respectively, for jet-lag symptoms to disappear in some individuals. In contrast, re-adaptation was more rapid on returning to Britain [42]. However, when time-zone shifts approach near maximal values – the maximum is a 12-h change – there may be little difference between eastward and westward travel and the body clock is likely to adjust as if the latter had occurred [40].

Table 1
A taxonomy of sports and recreational activities affected by sleep loss

Characteristics	Sports	Effects
Low-aerobic, high vigilance	Sailing, road cycling, aiming sports	Errors ↑
Moderate aerobic, high concentration	Field sports, team games, court games	Decision-making ↓
High aerobic, gross skills	Running 3000 m, swimming 400 m	Marginal
Mixed aerobic–anaerobic	Combat sports, swimming, middle distance running	Power ↓
Anaerobic	Sprints, power events	Marginal
Multiple anaerobic efforts	Jumping events, weight-training	Fatigue ↑

Sleeping pills have been used by some travelling sports teams to induce sleep whilst on board. Drugs such as short-acting benzodiazepines are effective in getting people to sleep but they do not guarantee a prolonged period asleep. They have been shown to be ineffective in accelerating adjustment of the body-clock in a group of British Olympic athletes travelling to the USA [43]. Besides, they have not been satisfactorily tested for subsequent residual effects on motor performances such as competitive sports. They may also be counter-productive if administered at the incorrect time. Melatonin can act directly on the body clock as well as being a soporific but the timing of administration is critical. Athletes and support personnel travelling between the United Kingdom and Australia, a journey which can elicit the most severe jet-lag symptoms, were found to derive no benefit [44]. Melatonin administered in the few hours before the trough of body temperature will have a phase-advance effect whereas if administered in the hours after this trough will delay the circadian rhythm [45]. Ingestion of melatonin at other times will have no chronobiotic effect but will still induce drowsiness.

Daytime sleepiness may be overcome by use of pharmacological aids that promote alertness in these conditions and in other circumstances where sleep is lost. Such drugs include modafinil, dextroamphetamine and caffeine [46,47]. Modafinil is used to treat narcolepsy and has been uncovered as a drug of abuse amongst sprinters competing at the World Track and Field Championships [40]. Caffeine can be considered for general use, both fast-acting and slow-release forms of caffeine offering temporary relief of fatigue [48]. Other drugs such as cocaine and nicotine act as CNS stimulants but are addictive and inappropriate for health-related reasons.

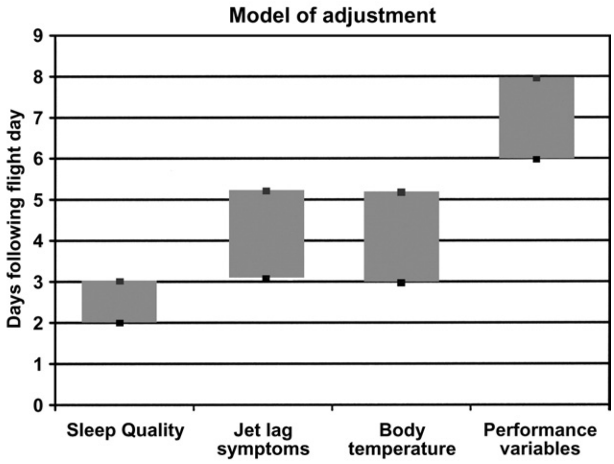


Fig. 3. A schematic illustration of the adjustment of different key rhythms.

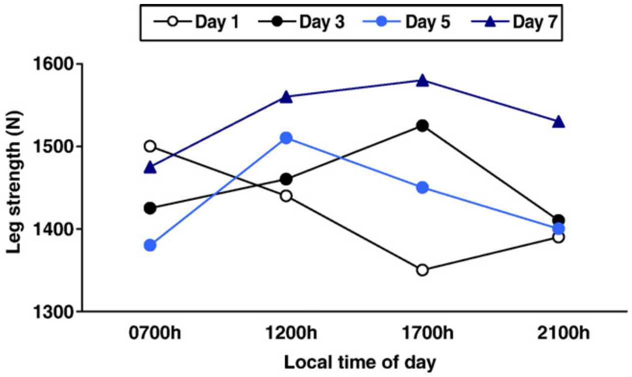


Fig. 4. The diurnal variation in leg strength after travelling between the United Kingdom and Florida, USA (from [50]).

Fitting in as soon as possible with the phase characteristics of the new environment is important. Individuals may already have been informed of the local time for their disembarkation, information that can help in planning the rest of the daily activity. Light inhibits melatonin and natural daylight is the key signal that helps to re-adjust the body clock to the new environment. There may be other environmental factors to consider such as heat, humidity or even altitude. For the first few days after arrival naps should be avoided since a long nap at the time the individual feels drowsy (presumably at the time he/she would have been asleep in the time zone just departed from) anchors the rhythms at their former phases and so delays the adaptations to the new time zone [49].

A phase delay of the circadian rhythm is required after a westward flight and visitors may be encouraged to retire to bed early in the evening. Early onset of sleep will be less likely after an eastward flight. In this case, a light exercise training session on that evening would be helpful in instilling local cues into the rhythms. Exercise does speed up the adaptation to a new time-zone primarily by facilitating adjustment to the appropriate habitual activity in the locality. In contrast, exercise in the morning is not recommended after a long-haul flight to the East since it is normally done outdoors in daylight and collectively these factors could act to delay the body clock rather than promote the phase adjustment required in this circumstance. These practices are based largely on chronobiological principles; methodological difficulties in acquiring supportive evidence from physical performance measures under controlled conditions have forced researchers into an emphasis on subjective measures of jet-lag [50].

By preparing for time-zone transitions and the disturbances they impose on the body's rhythms, the severity of jet-lag symptoms may be reduced. There has been little success in attempting to predict good and poor adaptors to long-haul flights. The fact that an individual feels relatively unaffected on one occasion is no guarantee that the same individual will do so again on the next visit. Regular travellers do benefit from their experiences and develop personal strategies for coping with jet-lag [51,52]. The disturbances in mental performance and cognitive functions have consequences not only for competitors but also for support personnel and medical staff travelling with the team, who too are likely to suffer from jet-lag symptoms. Besides, the long periods of inactivity during the plane journey may lead to the pooling of blood in the legs and in susceptible individuals to a deep-vein thrombosis [53]. Moving around the plane periodically during the journey – about every 2 h – and doing light stretching exercises have been recommended [54].

7. Nocturnal shift-work

Participation in nocturnal shift-work can disrupt human circadian rhythms. The stress provided by shift-work differs from that of traversing multiple meridians in that the environmental signals for biological timekeeping stay constant and the work–rest cycle stays out of phase with the alternations of day and night. This relative permanence means that the body never adapts fully to working at nights.

The difficulty of sleeping during the day is compounded by the distraction of noise and also social factors. Both the amount of sleep taken each day and the quality of sleep as indicated by electroencephalograph recordings are decreased in night-workers sleeping during the day [55]. The extreme difficulty experienced by shift-workers in adjusting to nocturnal shifts forces many to abandon night-work. The unease with the unsocial hours of work and circadian rhythm disturbances has been a concern to the workers' health and well-being [6].

There is a myriad of reports detailing impaired mental and physical performance of shift-workers during the night-time hours. Falls in attention, increases in errors, decreases in vigour and progressive fatigue [56] and impaired performance in perceptual-motor tasks [57] have been associated with failure of circadian rhythms to adapt. In contrast, rhythms adjust relatively quickly to a day-work routine and normal sleep patterns are quickly re-established. Petrilli et al. [58] showed that a tracking task which measured hand-eye co-ordination was sensitive to fatigue-related errors during shift-work and so could be used to determine fitness-for-duty in workplace environments.

Shift-workers are presented with difficulties in organising their domestic, athletic and occupational commitments. Few workers on shift-schedules compete in sport at a high level [59]. Adoption of an optimal shift-system would alleviate adverse effects of night-work and promote a more active lifestyle profile. There is a wealth of evidence that a forward-rotating shift-work programme (morning shift, afternoon shift, and night shift) facilitates adjustment to working at night, although such an option is not always accepted in industrial contexts [60].

8. Lifestyle circumstances

The need for sleep seems to vary between individuals and may range from 5 to 10 h in normal people [33]. Generally, athletes take longer than sedentary individuals for sleep, often supplementing nocturnal sleep with an afternoon nap [6]. Research evidence supports the view that exercise training helps to promote sleep, the intensity of activity being the predominant factor [61]. This effect has led to the recommendation that exercise can be employed as therapy for transient sleeping problems.

The timing of sleep may be influenced by personality type. Extroverts tend to cope more easily with a delayed bedtime than do introverts whose characteristics are more suited to a 'morning-type' behaviour. Whilst chronotypes may be classed according to morning, intermediate or evening types (and about 80% are intermediate types), morning and evening types are rarely associated with significant shifts in the circadian rhythm of their performance capability [62]. There is a shift towards morning-type behaviour with ageing (after 47 years of age) which coincides with a decrease in the amount and quality of nocturnal sleep [59]. In this instance the circadian rhythm in performance becomes slightly phase advanced, and veteran athletes tend to do relatively better in the morning compared to their younger counterparts.

Athletes engaged in strenuous training encounter an under-performance syndrome when the loads experienced are too high to allow recovery to occur. The drop in performance is secondary to signs of overtraining which include untoward endocrine responses, disturbances in metabolic markers and immunological variables. These abnormalities share similarities with those observed after sleep deprivation, including impairment in autonomic, immune, metabolic, hypothalamic and neurochemical function [12]. These associations suggest there is a link between the recuperative processes of sleep and the immune system. In view of the immuno-suppression that occurs for some 4–6 h after strenuous exercise [63], there may be a protective effect of the prolonged sleeps taken by elite athletes. It is thought also that persistent inadequate sleep, or successive nights of shortened or disrupted sleep, causes vulnerability to common colds and upper respiratory tract infections, a suggestion that supports the immunosuppressive effects of sleep loss [64].

The link between sleep loss and immune function has been studied by various authors but consistent conclusions are difficult to draw due to differences between experimental protocols. Nevertheless, there is evidence that natural killer cells are decreased after sleep loss and interleukin (IL-6) levels are increased [10]. Besides, Boyum et al. [65] reported increased infection rates in sleep-deprivation studies involving exercise, along with other factors. Interactions between slow-wave sleep and the immune system have implicated a common role for a number of sleep-related substances (see [6]). The hypothalamus and the raphe system are associated not only with sleep regulation but also with immune function.

In contrast to the sleep profile of athletes, many individuals habitually incur and carry a sleep debt which leads to an increased homeostatic drive to sleep and a likely fall in physical performance. The extent of the sleep debt can be determined by a formal sleep latency test [66]. This phenomenon is likely to explain the beneficial effects of so-called power naps (see [51,52]), and the sensitivity of cognitive function and motivation to time-on-task in sleep-deprivation studies [36].

Table 2
Factors affecting athletic performance after sleep loss (from [12])

- Extreme circadian phase (morning- and evening-types)
- Amount of sleep deprivation
- Decreased motivation
- Decreased physical: cognitive ratio of task
- Increased duration of task
- Increased complexity of task
- Increased degree of exertion
- Decreased fitness level
- Marked interindividual differences
- Low body temperature
- Decreased quantity and quality of sleep
- Energy deficit
- Environmental stress
- Lack of previous experience
- Youth

Ways to improve things

- Pharmacological compounds e.g. caffeine
- Napping

Various pharmacological means have been considered to counter the effects of sleep deprivation on mental fatigue, especially their use in military contexts and in vigilance tasks to maintain both physical and mental performance capability. Such drugs include methylphenidate, pemoline, dextra-amphetamine and modafinil [67]. Most stimulants that have been used in maintaining arousal following sleep loss are banned for use in sport [68], although drugs like caffeine and theophylline are freely imbibed in the course of the normal fluid intake. Both of these methylxanthines have ergogenic properties and have a stimulatory effect on the central nervous system, including an improvement in cognitive performance [69].

An alternative employed by athletes is to exploit the restorative function of short naps, especially if taken at the time of the 'post-lunch dip' in performance that is linked to a propensity towards drowsiness at that time of day. This transient drop in performance typically occurs during the mid-afternoon hours and is attributed to the existence of ultradian biological rhythms that recur within the circadian cycle. The post-lunch dip is accentuated by alcohol and by a high-carbohydrate meal and is more frequently displayed by extreme "morning types". Short naps can produce substantial benefits, as can longer naps for overcoming a sleep debt, providing that time is allowed to overcome sleep inertia – the short-term impairment in wakefulness when woken, particularly from slow-wave sleep [70]. Besides considering sleep inertia, the effects of napping depend on their timing and duration, prior wake time, setting, and individual differences. Those who habitually nap have been reported to derive greater subjective benefit from this practice than did subjects unaccustomed to napping [71]. Even so, both groups are likely to benefit by an improved predisposition to exercise in circumstances where a sleep debt is being repaid.

Some of the factors influencing physical performance after sleep loss are listed in Table 2 [12]. Individual circumstances might include periods of negative energy balance such as when undergoing weight-control dietary regimens or religious daytime fasts such as practised by Muslims during their holy month.

9. Overview

The sleep–wakefulness cycle is a fundamental feature of human survival and its disruption is common in contemporary society. Physiological and behavioural responses to sleep deprivation have been investigated with a view to identifying more clearly the biological necessity of sleep. Technologies used in clinical investigations, such as polysomnography and electroencephalography, have shed insights into the nature of sleep disorders and appropriate therapies. In contrast, studies of physical performance have relied on monitoring responses to exercise in laboratory and field settings. These respective approaches have been combined in addressing the interactions between exercise and sleep, and have led to the prescription of exercise as therapy for difficulties in sleeping [72]. In a clinical context, exercise is potentially a healthy, safe and socially acceptable alternative to expensive therapeutic treatment for insomnia. A complementary development has been the attempt to promote regular good quality sleep in the lifestyle of athletes, and the use of restorative naps in the daytime for those training twice a day [11]. The specific sleep characteristics that support such practices are yet to be clarified.

It seems that the behavioural and biological effects of sleep loss are fairly well defined and cannot be ignored by athletic practitioners. The consequences of sleep loss for human error leading to industrial and aviation accidents are recognised in the ergonomics community. In contrast, the impact of such errors in sports activities with physical contact between participants is rarely considered in the sports injuries literature. There are many instances in practice of individuals overcoming sleep disruptions and circadian rhythm disturbances to achieve excellence in competitive outcomes. Identifying the mechanisms by which they can do so provides a real challenge to researchers for the future.

References

[1] Atkinson G, Reilly T. Circadian variation in sports performance. Sports Med 1996;21:292–312.
[2] Baxter C, Reilly T. Influence of time of day in all-out swimming. Br J Sports Med 1983;17:122–7.
[3] Atkinson G, Todd C, Reilly T, Waterhouse J. Diurnal variation in cycling performance: influence of warm-up. J Sports Sci 2005;23:321–9.
[4] Atkinson G, Speirs L. Diurnal variation in tennis service. Percept Mot Skills 1998;86:1335–8.
[5] Reilly T, Farrelly K, Edwards B, Waterhouse J. Effects of time of day on the performance of soccer-specific motor skills. In: Reilly T, Cabri J, Araujo D, editors. Science and football: V. London: Routledge; 2005. p. 268–70.
[6] Reilly T, Atkinson G, Waterhouse J. Biological rhythms and exercise. Oxford: Oxford University Press; 1997.
[7] Carrier J, Monk TH. Circadian rhythms of performance: new trends. Chronobiol Int 2000;17:719–32.
[8] Van Dongen HPA, Dinges DF. Sleep, circadian rhythms and psychomotor vigilance. Clin Sports Med 2005;24:237–49.
[9] Dawson D, McCulloch K. Managing fatigue: it's about sleep. Sleep Med Rev 2005;5:365–80.
[10] Bonnet MH. Acute sleep deprivation. In: Kryger MH, Roth T, Dement WC, editors. Principles and practices of sleep medicine. 4th ed. New York: Elsevier; 2006. p. 51–66.
[11] Reilly T. Science of training – soccer: a scientific approach to developing strength, speed and endurance. London: Routledge; 2006.

[12] Smith RS, Reilly T. Athletic performance. In: Kushida C, editor. Sleep deprivation: clinical issues. pharmacology and sleep loss effects. New York: Marcel Dekker; 2005. p. 313–34.

[13] Reilly T, Bambaeichi E. Methodological issues in studies of rhythms in human performance. Biol Rhythm Res 2003;34:321–6.

[14] Cajochen C, Wyatt JK, Czeisler CA, Dijk DJ. Separation of circadian and wake duration-dependent modulation of EEG activation during wakefulness. Neuroscience 2002;114:1047–60.

[15] Thomas V, Reilly T. Circulatory, psychological and performance variables during 100 hours of continuous exercise under conditions of controlled energy intake and work output. J Hum Mov Stud 1975;1:149–55.

[16] Reilly T, Walsh TJ. Physiological, psychological and performance measures during an endurance record for 5-a-side soccer play. Br J Sports Med 1981;15:122–8.

[17] Reilly T, George A. Urinary phenylethamine levels during three days of indoor soccer play. J Sports Sci 1983;1:70.

[18] How JM, Foo SC, Low E, Wong TM, Vijayan A, Siew MG, et al. Effect of sleep deprivation on performance of Naval seamen: I. Total sleep deprivation on performance. Ann Acad Med 1994;23:669–75.

[19] Froberg JC, Karlsson CG, Levi L, Lidberg L. Circadian rhythms of catecholamine excretion, shooting range performance and self-ratings of fatigue during sleep deprivation. Biol Psychol 1975;2:175–88.

[20] Koslowsky M, Babkoff H. Meta-analysis of the relationship between total sleep deprivation and performance. Chronobiol Int 1992;9:132–6.

[21] Pilcher JJ, Huffcutt AI. Effects of sleep deprivation on performance a meta-analysis. Sleep 1996;19:318–26.

[22] Smith RS, Walsh J, Dement WC. Sleep deprivation and the race across America. Sleep 1998;22:303.

[23] Bennet G. Medical and psychological problems in the 1972 singlehanded transatlantic yacht race. Lancet 1973;2:747–54.

[24] Stampi C, Broughton R, Mullington J, Rivers M, Campos J. Ulrashort sleep strategies during sustained operations: the recuperative value of 80-, 50- and 20-min naps. In: Costa G, Cesana G, Kogi K, Wedderburn A, editors. Shiftwork: health, sleep and performance. Frankfurt: Peter Lang; 1990.

[25] Rognum TO, Vartdal F, Rodahl K, Opstad PK, Knudsen-Baas O, Kindt E, et al. Physical and mental performance of soldiers on high- and low-diets during prolonged heavy exercise combined with sleep deprivation. Ergonomics 1986;29:859–67.

[26] Guezennec CY, Sabatin P, Legrand H, Bigard AX. Physical performance and metabolic changes induced by combined prolonged exercise and different energy intake in humans. Eur J Appl Physiol 1994;68:525–30.

[27] Horne JA, Pettit AN. Sleep deprivation and the physiological response to exercise under steady state conditions in untrained subjects. Sleep 1984;7:168–79.

[28] Plyley MJ, Shephard RJ, Davis GM, Goode RC. Sleep deprivation and cardiorespiratory function – influence of intermittent submaximal exercise. Eur J Appl Physiol 1987;56:338–44.

[29] Chen HI. Effects of 30-h sleep loss on cardiorespiratory functions at rest and in exercise. Med Sci Sports Exerc 1991;23:193–8.

[30] Martin BJ, Gaddis GM. Exercise after sleep deprivation. Med Sci Sports Exerc 1981;13:220–3.

[31] Cirelli C. Functional genomic of sleep and circadian rhythm, invited review: how sleep deprivation affects gene expression in the brain – a review of recent findings. J Appl Physiol 2002;92:394–400.

[32] Sinnerton SA, Reilly T. Effects of sleep loss and time of day in swimmers. In: MacLaren D, Reilly T, Lees A, editors. Biomechanics and medicine in swimming: swimming science V. London: E. and F.N. Spon; 1992. p. 399–405.

[33] Horne JA. Why we sleep. Oxford: Oxford University Press; 1988.

[34] Reilly T, Deykin T. Effects of partial sleep loss on subjective states, psychomotor and physical performance tests. J Hum Mov Stud 1983;9:157–70.

[35] Reilly T, Hales A. Effects of partial sleep deprivation on performance measures in females. In: McGraw ED, editor. Contemporary ergonomics. London: Taylor and Francis; 1988. p. 509–13.

[36] Reilly T, Piercy M. The effect of partial sleep deprivation on weight-lifting performance. Ergonomics 1994;37:107–15.

[37] Meney I, Waterhouse J, Atkinson G, Reilly T, Davenne D. The effect of one night's sleep deprivation in temperature, mood and physical performance in subjects with different amounts of habitual activity. Chronobiol Int 1998;15:349–63.

[38] Bambaeichi E, Reilly T, Cable NT, Giacomoni M. The influence of time of day and partial sleep loss on muscle strength in eumenorrheic females. Ergonomics 2005;48:1499–511.

[39] Waterhouse J, Edwards B, Nevill A, Atkinson G, Reilly T, Davies P, et al. Do subjective symptoms predict our perception of jet lag. Ergonomics 2000;43:1514–27.

[40] Reilly T, Waterhouse J, Edwards B. Jet lag and air travel: implications for performance. Clin Sports Med 2005;24:367–80.

[41] Jehue R, Street D, Huizenga R. Effect of time zone and game time on team performance: National Football League. Med Sci Sports Exerc 1993;25:127–31.

[42] Reilly T. Environmental stress. In: Reilly T, Williams AM, editors. Science and soccer. 2nd ed. London: Routledge; 2003. p. 165–84.

[43] Reilly T, Atkinson G, Budgett R. Effect of low-dose temazepam on physiological variables and performance tests following a westerly flight across five time zones. Int J Sports Med 2001;22:166–74.

[44] Edwards BJ, Atkinson G, Waterhouse J, Reilly T, Godfrey R, Budgett R. Use of melatonin in recovery from jet-lag following an eastward flight across 10 time zones. Ergonomics 2000;43:1501–13.

[45] Drust B, Waterhouse J, Atkinson G, Edwards B, Reilly T. Circadian rhythms in sports performance – an update. Chronobiol Int 2005;22:21–44.

[46] Schwartz J. Pharmacologic management of daytime sleepiness. J Clin Psychiatry 2004;65(Suppl 16):46–9.

[47] Caldwell JA, Caldwell JL. Fatigue in military aviation: an overview of military-approved pharmacologic countermeasures. Aviat Space Environ Med 2005;76(Suppl 5):C39–51.

[48] Beaumont M, Batejat D, Pierard C, Van Beers P, Denis J, Coste O, et al. Caffeine or melatonin effects on sleep and sleepiness after rapid eastward transmeridian travel. J Appl Physiol 2004;96:50–8.

[49] Minors DS, Waterhouse J. Anchor sleep as a synchroniser of rhythms on abnormal routines. Int J Chronobiol 1981;7:165–88.

[50] Waterhouse J, Reilly T, Atkinson G. Jet-lag. The Lancet 1997;350:1611–6.

[51] Waterhouse J, Edwards B, Nevill A, Carvalho S, Atkinson G, Buckley P, et al. Identifying some determinants of 'jet-lag' and its symptoms: a study of athletes and other travellers. Br J Sports Med 2002;36:54–60.

[52] Waterhouse JM, Minors DS, Waterhouse ME, Reilly T, Atkinson G. Keeping in time with your body clock. Oxford: Oxford University Press; 2002.

[53] House of Lords Select Committee on Science and Technology. Air travel and health. London: The Stationery Office; 2000.

[54] Reilly T, Waterhouse J. Sport, exercise and environmental physiology. Edinburgh: Elsevier; 2005.

[55] Akerstedt T. Searching for the countermeasure of night-shift sleepiness. Sleep 2006;29:19–20.

[56] Bohle P, Tilley A. Predicting mood change on night shift. Ergonomics 1993;36:125–34.

[57] Monk TH, Folkard S. Making shiftwork tolerable. Basingstoke: Taylor and Francis; 1992.

[58] Petrilli RM, Jay SM, Dawson D, Lamond N. The impact of sustained wakefulness and time of day on OSPAT performance. Ind Health 2005;43:86–92.

[59] Reilly T, Waterhouse J, Atkinson G. Ageing, rhythms of physical performance, and adjustment to changes in the sleep–activity cycle. Occup Environ Med 1997;54:812–6.

[60] Fisher FM, de Moreno C, de Fernandez L, Berwerth A, dos Santos AM, Bruni Ade C. Day- and shiftworkers' leisure time. Ergonomics 1993;36:43–9.

[61] Reilly T. Exercise and sleep: an overview. In: Watkins J, Reilly T, Burwitz L, editors. Sports science. London: E and F.N. Spon; 1986. p. 414–9.

[62] Reilly T, Marshall S. Circadian rhythms in power output on a swim bench. J Swim Res 1991;72:11–3.

[63] Reilly T, Ekblom B. The use of recovery methods post-exercise. J Sports Sci 2005;23:619–27.

[64] Moldofsky H. Central nervous system and peripheral immune functions and the sleep–wake system. J Psychiatry Neurosci 1994;19:368–74.

[65] Boyum A, Wiik P, Gustavsson E, Veiby OP, Reseland J, Haugen AH, et al. The effect of strenuous exercise, calorie deficiency and sleep deprivation

on white blood cells, plasma immunoglobulins and cytokines. Scand J Immunol 1996;43:228–35.

[66] Dement WC. Sleep extension: getting as much extra sleep as possible. Clin Sports Med 2005;24:251–68.

[67] Caldwell JA, Caldwell JL. In: Kushida CA, editor. Sleep deprivation: clinical issues, pharmacology and sleep loss effects. New York: Marcel Dekker; 2005. p. 387–446.

[68] Mottram DR. Drugs in sport. 4th ed. London: Routledgem; 2005.

[69] Graham TE. The possible actions of methylxanthines on various tissues. In: Reilly T, Orme M, editors. The clinical pharmacology of sport and exercise. Amsterdam: Elsevier; 1997. p. 257–70.

[70] Brooks A, Lack L. Naps. In: Kushida CA, editor. Sleep deprivation: clinical issues, pharmacology and sleep loss effects. New York: Marcel Dekker; 2005. p. 457–74.

[71] Evans FJ, Cook MR, Cohen HD, Orne EC, Orne MT. Appetitive and replacement naps: EEG and behavior. Science 1977;197:687–8.

[72] Youngstedt S. Effects of exercise on sleep. Clin Sports Med 2005;24:355–65.