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Circadian Variation in Sports Performance

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Summary

Chronobiology is the science concerned with investigations of time-dependent changes in physiological variables. Circadian rhythms refer to variations that recur every 24 hours. Many physiological circadian rhythms at rest are endogenously controlled, and persist when an individual is isolated from environmental fluctuations. Unlike physiological variables, human performance cannot be monitored continuously in order to describe circadian rhythmicity. Experimental studies of the effect of circadian rhythms on performance need to be carefully designed in order to control for serial fatigue effects and to minimise disturbances in sleep. The detection of rhythmicity in performance variables is also highly influenced by the degree of test-retest repeatability of the measuring equipment.

The majority of components of sports performance, e.g. flexibility, muscle strength, short term high power output, vary with time of day in a sinusoidal manner and peak in the early evening close to the daily maximum in body temperature. Psychological tests of short term memory, heart rate–based tests of physical fitness, and prolonged submaximal exercise performance carried out in hot conditions show peak times in the morning. Heart rate–based tests of work capacity appear to peak in the morning because the heart rate responses to exercise are minimal at this time of day. Post-lunch declines are evident with performance variables such as muscle strength, especially if measured frequently enough and sequentially within a 24-hour period to cause fatigue in individuals. More research work is needed to ascertain whether performance in tasks demanding fine motor control varies with time of day.

Metabolic and respiratory rhythms are flattened when exercise becomes strenuous whilst the body temperature rhythm persists during maximal exercise. Higher work-rates are selected spontaneously in the early evening. At present, it is not known whether time of day influences the responses of a set training regimen (one in which the training stimulus does not vary with time of day) for endurance, strength, or the learning of motor skills.

The normal circadian rhythms can be desynchronised following a flight across several time zones or a transfer to nocturnal work shifts. Although athletes show all the symptoms of 'jet lag' (increased fatigue, disturbed sleep and circadian rhythms), more research work is needed to identify the effects of transmeridian travel on the actual performances of elite sports competitors. Such investigations would need to be chronobiological, i.e. monitor performance at several times on several post-flight days, and take into account direction of travel, time of day of competition and the various performance components involved in a particular sport.

Shiftwork interferes with participation in competitive sport, although there may be greater opportunities for shiftworkers to train in the hours of daylight for individual sports such as cycling and swimming. Studies should be conducted to ascertain whether shiftwork–mediated rhythm disturbances affect sports performance.

Individual differences in performance rhythms are small but significant. Circadian rhythms are larger in amplitude in physically fit individuals than sedentary individuals. Athletes over 50 years of age tend to be higher in 'morningness', habitually scheduling relatively more training in the morning and selecting relatively higher work-rates during exercise compared with young athletes. These differences should be recognised by practitioners concerned with organising the habitual regimens of athletes.

1. The Science of Chronobiology

Chronobiology has been defined as the science concerned with investigating and objectively quantifying the mechanisms of biological time structures including the rhythmic manifestations of life.[1] The scientific acceptance of these rhythms was hampered in the middle of the nineteenth century following work carried out by the French physiologist, Claude Bernard. He believed that the body's internal environment (*milieu interieur*) could be considered as constant and resistant to change.[2] In the twentieth century, Bernard's theories of internal constancy were refined and elaborated by Walter Cannon who introduced the term homeostasis.[3]

Homeostasis assumes that physiological functions are controlled around a set-point and that changes in a system are countered by the way of feedback regulation to re-establish constancy or a 'steady state'. Cannon[3] was careful not to consider homeostasis as strict constancy or 'something set and immobile'. Rather, he stressed that physiological functions could vary within limits. It is now recognised that rhythmic variation is the rule rather than the exception in all living things. Biological fluctuations have been shown to be robust, regular and predictable over time.

1.1 Terminology

A biological rhythm has been defined as a sequence of events which in a steady state repeat themselves in time in the same order and same interval.[4] Since many studies have examined differences in human performance between just a few times of day and hence, cannot provide evidence of the presence of a repeating rhythm, the all-encompassing term of 'variations' is adopted in the present review. Any significant fluctuation within the hours of daylight is termed a diurnal variation. Most rhythms can be represented by a sine-wave like the 24-hour body temperature curve shown in figure 1. The time required to complete one cycle is described as the period of a rhythm. Periods of biological rhythms may range from milliseconds to years. Rhythms with a period of 20 to 28 hours are termed circadian (*circa* – about, *dies* – a day).[6] Those rhythms with periods less than 20 hours (e.g. the 90-minute cycle of sleep stages) are termed ultradian. Rhythm periods greater than 28 hours (e.g. the menstrual cycle) are known as infradian. The mean (midway between the highest and lowest values) of a rhythm is termed the 'mesor' (midline estimating statistic of a rhythm). The amplitude of a rhythm is one half the difference between the highest and the lowest point of a fitted cosine curve and should not be confused with the range of a rhythm which is the difference between the maximum and minimum values.[1] The location in time of a rhythm is termed the acrophase, but, strictly, this only refers to sinusoidal oscillations. The term 'peak-time' should be used for non-sinusoidal rhythms. The acrophase can be expressed in angular degrees (1 period = 360°) or absolute units of time e.g. minutes, hours, days, weeks or years.

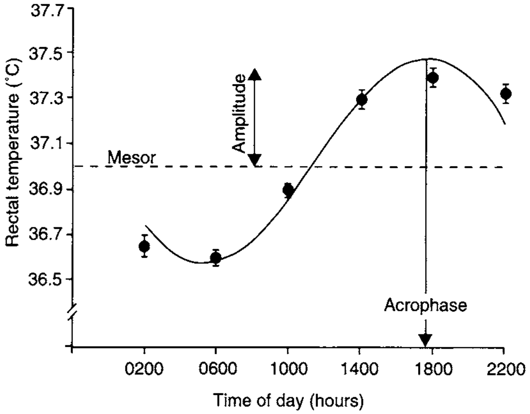

Fig. 1. The circadian rhythm in rectal temperature showing the terminology used to describe a biological rhythm (from Reilly,[5] with permission). *Abbreviation:* Mesor = midline estimating statistic of a rhythm.

1.2 Biorhythm Theory

It is important to distinguish between the scientifically-evaluated biological rhythms and the discredited theory of 'biorhythms' which has recently reappeared in some sports magazines and newspapers in the UK (e.g. *The Guardian,* 14/8/93). Much emphasis has, in the past, been placed on these infradian cycles of emotion, physical well-being and intellectual function. They were proposed by the psychologists Swoboda and Fliess at the turn of this century, who suggested they exist from birth. Most proponents of the theory (e.g. Wolf)[7] cite anecdotal evidence of athletes who have recorded superior performances when at the crest of one of the cycles. Since the three cycles have very different periods, an athlete may be performing on a day close to the crest of at least one of the cycles purely by chance. The periods of biorhythms are not related to any environmental cycle and, when tested using appropriate chronobiological techniques, have been proved to be of no value at all in predicting athletic performance.[8,9] There is also no scientific rationale for relating an athlete's training cycles over a competitive season to his/her biorhythms, e.g. resting on 'caution' days. This should not, however, deter future researchers from scientifically investigating the presence of any infradian rhythms in athletic performance which exist independently from any cycles in training volume.

2. The Basis for Circadian Rhythms

Although biological rhythms are present in a wide range of periods, circadian rhythms have been the most extensively investigated and have the farthest reaching implications for humans. Circadian rhythms in physiological parameters are influenced by rhythmic changes in human behaviour and the environment over a period of 24 hours.[4] For example, human society generally exhibits wakefulness and activity diurnally, when the environmental temperature is higher and when it is light. Fluctuations such as these are termed 'exogenous components' to physiological rhythmicity. Circadian rhythmicity is not fully dependent upon exogenous factors, but has also an 'endogenous component' (colloquially referred to as the biological- or body-clock). Rhythmicity persists if an individual remains awake for several days at a constant level of activity[10] or is placed in 'temporal isolation'. This refers to environmental conditions which do not fluctuate, such as a natural cave[11] or a specially designed isolation chamber.[12] In addition, during nocturnal shift work or transmeridian travel, circadian rhythms do not immediately adjust to a new sleep-wake schedule, but take time to adapt or 'entrain'.[4] The effect of exogenous stimuli (e.g. exercise) upon the parameters of an endogenous rhythm is termed 'masking'.

The most important endogenous self-sustaining pacemaker for circadian rhythmicity is the paired suprachiasmatic nuclei (SCN) located in the anterior hypothalamus, close to the optic chiasm.[13,14] It has been argued that there are other loci of rhythmicity (thus far not conclusively identified), since both total destruction of the SCN does not disrupt *all* circadian rhythms and some circadian rhythms can 'desynchronise' from each other when studied in temporal isolation.[4] Nevertheless, the fact that many circadian rhythms in resting physiological functions exist in the absence of any environmental fluctuations and are obliterated after SCN removal suggests that the dominant pacemaker is able to communicate (neurally and/or neurohumerally) with other hypothalamic centres and endocrine glands.[1] These secondary oscillations, in turn, mediate fluctuations in their respective target tissues resulting in the myriad of resting and performance circadian rhythms in the human.

The inherent *properties* of the biological clock have been investigated in isolation studies. Aschoff[15] and Wever[12] found in study participants isolated from all external time signals that the period of circadian rhythms deviates slightly but consistently from 24 hours to about 25 hours. Therefore, the endogenous clock will progressively lag behind exogenous fluctuations as time spent in isolation increases up to 12 days. It thus 'free runs'. Endogenous rhythms are synchronised or 'entrained' to the normal 24-hour environment by zeitgebers (German – meaning 'time-givers'), the most important of which are the light-dark cycle and social influences. Light is believed to act as a zeitgeber to the body clock via the transmission of photic information along the retinohypothalamic tract (a neural pathway connecting the retinae with the SCN). Light also entrains and suppresses the production of melatonin by the pineal gland.[16] Melatonin and its precursor serotonin have important roles in sleep regulation, nocturnal secretions being markedly increased. Such chronobiological influences of melatonin have led to the theory that administration of bright light or exogenous melatonin has therapeutic applications in the treatment of such rhythm disturbances as jet lag, shift-work, seasonal affective disorder (SAD), insomnia, blindness and ageing.[16] Melatonin secretion is affected by exercise. Although there are conflicting reports on whether exercise stimulates[17] or inhibits[18] secretion, this influence supports the hypothesis that physical activity is a significant zeitgeber in humans.[19]

3. Human Circadian Rhythms at Rest

3.1 The Body Temperature Rhythm

Body temperature falls to a minimum during sleep at around 0400 hours and begins to rise before wakefulness. This rise usually continues until the acrophase of the rhythm is reached at around 1800 hours.[4] The amplitude of the body temperature rhythm is 0.4 to 0.5°C in young adults (fig. 1). There is considerable evidence that the endogenous component of the temperature rhythm is large: in isolation and constant routine studies, the amplitude of the rhythm is not markedly reduced.[4] The major exogenous influences on body temperature are sleep and exercise. Minors and Waterhouse[4] maintained that the circadian rhythm in deep body (rectal) temperature results mainly from fluctuations in heat loss mechanisms (vasomotor and insensible sweating) rather than heat production (metabolic rate). However, these authors also stressed that it is the set-point of thermoregulation that varies with time of day. Akerstedt[20] reported that the peak noradrenergic activity occurs at about 1200 hours. At this time, the dissipation of heat would be counteracted and deep body temperature rises as a consequence.

3.2 Cardiovascular Rhythms

Heart rate varies with an amplitude of 5 to 15% of the 24-hour mean and an acrophase of around 1500 hours.[5,21] Similar rhythm characteristics are found for stroke volume, cardiac output, blood flow and blood pressure.[21] Circadian rhythms in blood pressure and heart rate are highly influenced by exogenous factors such as sleep, posture, ingestion of food and activity.[22] The influences are such that it has been questioned whether an endogenous component exists at all.[23] Given the multiple exogenous influences on blood pressure, it has been found that fluctuations in blood pressure over 24 hours can be extremely complicated, not necessarily following the classical cosine curve of more endogenous rhythms such as body temperature (fig. 1). Zulch and Hossman[24] reported that blood pressure shows a post-lunch dip followed by a secondary peak in the afternoon. This phenomenon may be especially evident if individuals nap or have a greater than normal post-prandial dip in blood pressure (e.g. aged individuals).[25]

3.3 Rhythms in Ventilation

The two indicators of pulmonary airway resistance (forced expiratory volume and peak expiratory flow) have both been found to vary with time of day falling to minima between 0300 and 0800 hours.[26] Smolensky et al.[27] reported that asthmatic patients exhibit markedly greater amplitudes in airway rhythms depending on the severity of the disease. These findings agree with the observation that symptoms of asthma are exacerbated at night and in the early morning giving rise to the debilitating complaint of 'nocturnal asthma'.[28] For this reason, we advise asthmatic athletes not to perform strenuous training in the early hours of the morning.

3.4 Rhythms in Metabolic Variables

Mejean et al.[29] stated that the blood glucose level at any one time is influenced by 'multiple metabolic phenomena'. This may be the reason why glucose levels appear to be very constant over 24 hours.[4] A few studies (e.g. Swoyer et al.[29]) have detected rhythmicity in this variable, albeit with a very low amplitude. It is more usual to find a small-amplitude ultradian rhythm in blood glucose with peak levels corresponding to the 3 diurnal meals and a fourth increase at the end of sleep.[30] Schlierf[31] found that plasma free fatty acids were higher at night than during the day although this, again, depended greatly on the composition of food ingested.

Minors and Waterhouse[4] reported that oxygen consumption ($\dot{V}O_2$) at rest evidences rhythmicity, dropping to a minimum at around 0400 hours. These authors also maintained that the $\dot{V}O_2$ rhythm is a result and not a cause of the body temperature rhythm. Reilly,[5] however, calculated that the circadian change in core temperature explains only 37% of the range observed in $\dot{V}O_2$. The circadian rhythm in $\dot{V}O_2$ is not attributable to circadian changes in thyroid-stimulating hormone since this variable peaks at the same time as $\dot{V}O_2$ drops to its nadir.[32] Changes in the circulating levels of catecholamines may exert some influence over the rhythm in $\dot{V}O_2$.[4]

3.5 Rhythms in Gastrointestinal Function and Excretion

Circadian rhythms have been documented for gastrointestinal motility patterns, intestinal absorption rates, gastrointestinal enzyme activities and gastric acid secretion.[33] All these parameters have been found to peak diurnally. Goo et al.[34] reported that gastric emptying rates for meals administered at 2000 hours were over 50% slower than emptying rates for the same meal taken at 0800 hours. It is not known whether the gastric emptying of carbohydrate drinks during exercise varies with time of day. Touitou et al.[35] reported that peak levels of urinary electrolytes occur in the afternoon at around 1600 hours (exceptions being urinary chlorides, phosphates and 17-ketosteroids). Circadian changes in urinary pH mirror those of urinary electrolyte level with the most acidic urine (pH = 5.0) reported during sleep, rising to a maximum of 8.0 in the afternoon.[36] Circadian rhythms in urinary pH and excretion of electrolytes should be recognised by drug control centres. Chronopharmacological studies should be performed to ascertain whether an ingested drug would be detected in an athlete's urine at one time of day but not at another.

3.6 Rhythms in Subjective Mood States and Some Hormonal Secretions

Cortisol and growth hormone levels evidence marked peaks several times during sleep.[32] In fact, the growth hormone and cortisol rhythms are strongly influenced by sleep characteristics which are, in turn, affected by habitual levels of physical activity. Plasma levels of adrenaline and noradrenaline peak in the early afternoon, even during successive days of constant routines (i.e. bedrest with no sleep allowed).[4] The documented circadian rhythm in blood volume[37] cannot account for these rhythms in hormone levels since the amplitudes are not similar.

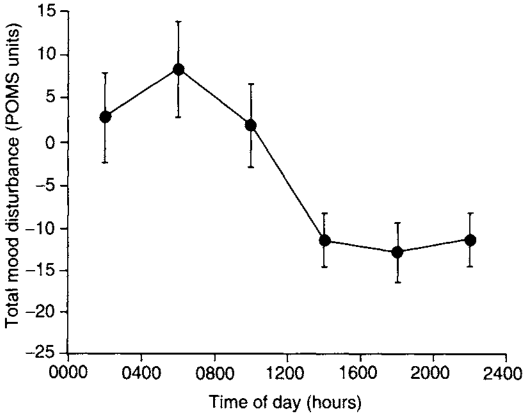

Fig. 2. The circadian rhythm in 'total mood disturbance' – a combination of mood states measured with the Profile of Mood States questionnaire (POMS). Data from 20 individuals aged 18 to 30 years.[42] Higher values indicate worsened mood states.

Circadian variation in catecholamines may mediate fluctuations in arousal. Chronobiological investigations of subjective states of 'arousal' have been usually conducted in conjunction with other experimental variables. For example, some researchers have used simple visual-analogue scales to measure alertness[38] or the inverse of this, fatigue.[39] Other investigators have utilised recognised scales (Stanford Sleepiness Scale)[40] for the measurement of 'sleepiness' or a questionnaire (Profile of Mood states)[41] for assessment of changes in mood (fig. 2).[42,43] All the evidence from these studies suggests that alertness and positive mood states peak in the waking hours (usually evening). Mood and subjective alertness may be important for human performance since they may alter an individual's predisposition for strenuous physical work. Circadian variations in mood states may also affect the 'team cohesion' of a work-group. For example, the ability of individuals to communicate and work together is important for team sports and coaching.

4. Circadian Variations in Sports Performance

4.1 Indirect Evidence

World records in sports events are usually broken by athletes competing in the early evening, the time of day at which body temperature is highest. The mid-eighties series of middle-distance records broken by the British runners; Sebastian Coe, Steve Cram, Steve Ovett and Dave Moorcroft illustrates this, since all were set between 1900 and 2300 hours. Such observations should, of course, be interpreted with caution, since there is a bias for scheduling finals of track and field competitions in the afternoon and world record attempts in the evening due to extraneous influences such as the demands of television. The bias in event scheduling for the early evening can, in some sports be controlled for. In the discipline of competitive cycling known as time trials, the frequency of races is more evenly distributed throughout the daylight hours. The performances of young competitors in 16km races are better when held in the afternoon and evening compared with those scheduled in the morning.[44] When the frequency of trials is standardised at different times of day in simulated competitions, weight-throwers also perform better in the evening than the morning.[45]

The lack of control over environmental influences on performance is the major problem concerning the above evidence from field studies. For instance, environmental temperature may be more favourable to record-breaking performances in the evening, especially in summer. Circadian fluctuations in meteorological conditions such as wind speed and direction may also affect performances in cycling or field sports involving high velocities of projectiles (e.g. discus, javelin, hammer). Nevertheless, tighter control can be exerted over water conditions for swimming. When this is done, the best times for 100 and 400m swims occur, again, in late afternoon/early evening (fig. 3).

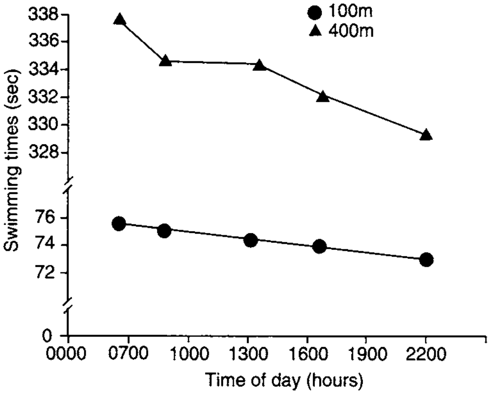

Fig. 3. The effects of time of day on 100m and 400m swimming time trials (from Reilly,[5] with permission).

4.2 Research Methodology

In order to confirm the above indirect evidence that sports performance varies with time of day, laboratory conditions and pre-test diet and activity of individuals need to be tightly controlled. There are additional problems when a study is attempted. For instance, it is very hard to administer a large number of consecutive performance tests to humans without eliciting a serial fatigue effect.[46] Consequently, most chronobiological investigations into human performance have employed some sort of transverse design (several individuals studied at a few times of day). Reilly and his coworkers in studies examining circadian rhythms in components of physical performance, e.g. Reilly and Down,[47] approached the problem of serial fatigue/learning effects by spacing 6 test sessions 4 hours apart within a 24-hour period. Each individual performs the first test session at a different time of day. Conventionally, 6 or 12 individuals are examined to form what has been termed a 'cyclic Latin square' design.[48] This protocol does allow sufficient time for recovery after each test session and removes any learning/fatigue effects that could occur. However, there is a problem of whether to allow sleep after the test session at 2200 hours, waking participants for the 0200 hours, tests or allowing only about 3 hours of sleep between 0200 and 0600 hours. To alleviate this problem, the above experimental design can be modified so that individuals are examined over a longer time period and at least 8 hours separates each of the 6 test sessions. The advantages of this protocol are that study participants could sleep normally between 2200 hours and 0600 hours and 0200 hours and 1000 hours and that the performance variables are examined over 2 cycles of the circadian rhythm. Alternatively, each of the 6 test sessions could be administered on different days, e.g. Harma et al.,[49] although the rigorous control procedures would need to be adhered to for 6 days.

The most common statistical techniques used in chronobiological studies of human performance are analysis of variance (ANOVA) and cosinor analysis. Although ANOVA models can be employed to identify an effect of time of day on the experimental variable, the rhythm characteristics that were presented in figure 1 cannot be elucidated. For this information, the cosinor techniques that were described by Nelson et al.[50] can be employed. A disadvantage of cosinor analysis is that estimates of rhythm parameters are compromised when the data are nonsinusoidal. Many physiological variables evidence rhythms of shorter periods superimposed on a fundamental period (e.g. post-lunch 'dips' in performance) which would not be detected with conventional cosinor analysis.

4.3 Components Measured Under Controlled Laboratory Conditions

'Performance' is a very broad term and sports events usually comprise a cocktail of task components. In the following sections, an attempt is made to isolate each component of sports performance and describe the circadian characteristics of each.

4.3.1 Psychomotor Performance and Motor Skills

Simple reaction time (either to auditory or visual stimuli) is a major component of performances in sprint events. Reaction time peaks in the early evening at the same time as the maximum in body temperature.[51] As an explanation for this, for every 1°C rise in body temperature, nerve conduction velocity increases by 2.4 m/sec.[52] Often, there is an inverse relation between the speed and the accuracy with which a simple repetitive test is performed.[53] Therefore, accuracy may be worse in the early evening. This illustrates the importance of defining performance since there are many sports which demand accuracy without speed, e.g. golf, darts.

Although the effects of time of day on actual performances in these sports have not been examined, their complex nature probably means that they are performed best at times of day when arousal levels are endogenously low. One task which demands fine motor control, is the ability to balance whilst standing on a 'wobble board'. This task is performed better in the morning, probably because arousal levels would be lower than the diurnal peak and closer to the optimum level for performance.[42] Complex aspects of performance such as mental arithmetic and short term memory also peak in the early hours of the morning rather than the evening.[46] Rhythms in cognitive variables have relevance to sport in that they influence competitive strategies, decisions and the delivery and recall of complex coaching instructions.

Circadian rhythms in psychomotor performance, particularly tasks that entail cognitive operations seem especially prone to a post-lunch 'dip'.[5] This phenomenon describes a transient decline in alertness and performance occurring early in the afternoon. Some aspects of performance deteriorate at this time without a corresponding decrease in body temperature and even if no food is ingested at lunch-time.[52] We advise that this time of day should be avoided when the coach is trying to impart new skills or tactics to a group of athletes.

4.3.2 Joint Flexibility and Stiffness

Joint flexibility (range of movement) shows marked rhythmicity across a wide range of human movements. Gifford[54] noted circadian variation in lumbar flexion and extension, glenohumeral lateral rotation and whole-body forward flexion. Amplitudes of these rhythms can be as high as 20% of the 24-hour mean value (table I). There can be a large inter-individual difference of between 1200 and 2400 hours in the peak-times of flexibility.[54] Wright[55] found that the circadian variation in stiffness (resistance to motion) of the knee joint is similar to that of body temperature with lowest levels of stiffness being recorded in the early evening. However, endogenous mechanisms cannot be fully implicated as the cause of this rhythm since joint stiffness is highly influenced by exogenous factors such as the amount of prior physical activity.[5]

4.3.3 Muscle Strength

Hand grip strength, although moderately correlated with lean body mass and whole-body strength, has its limitations in sport contexts considering the specificity of strength in different sports. Despite this, muscle strength, independent of the muscle group measured or speed of contraction, consistently peaks in the early evening. The relation of the grip strength rhythm to other physiological rhythms (especially body temperature) has promoted its use as a 'marker rhythm' in chronobiology. The rhythm in isometric grip strength peaks between 1400 and 1900 hours with an amplitude of about 6% of the 24 hours' mean.[54,56] The grip strength rhythm is, in part, endogenously controlled since it persists during sleep deprivation[57] and adjusts slowly to changes in sleep-wake regimens.[56] The peak-to-trough variation in grip strength can be 3 times higher than normal in rheumatoid arthritic patients.[58]

When the isometric strength of the knee extensors is measured consecutively during the waking hours of the solar day, 2 diurnal peaks are evident; one at the end of the morning and another in the late afternoon/evening.[59] Performance transiently declines between these times of day. Similarly, there can be a drop in grip strength between 1300 and 1400 hours when the variable is measured every hour for a 24-hour period.[60]

It is difficult to separate a true time of day effect from influences resulting from the experimental protocol. This afternoon decline in performance may be a consequence of a fall in motivation arising from the high number of serial measurements that have been performed. Despite this, when isometric strength measures are recorded under the optimal experimental protocol outlined in section 4, which allows sufficient recovery between test sessions without disturbing sleep,[61] post-lunch declines in performance are still evident (fig. 4A). With respect to the isometric strength of other muscle groups, elbow flexion strength varies with time of day, peaking in the early evening.[62] Back strength is also higher in the evening than the morning. The rhythm has an amplitude of around 6% of the 24-hour mean.[63]

Table I. Circadian characteristics of fitness tests

Fitness test	Acrophase (P decimal hours)[a]	Amplitude (% of 24-h mean)	Reference
Whole-body flexibility	20.21	21.6	42
PWC_{150}	3.83	5.2	43
Standing broad jump	17.75	3.4	47
Leg strength	18.33	9.0	62
Back strength	16.88	10.6	62
Grip strength	20.00	6.0	43

a An acrophase of 17.75 means that the rhythm peaked at 1745h. These acrophases are converted into degrees by the term (–15) in the correction equation.

Abbreviations: P = the acrophase of the 'standard' rhythm; PWC_{150} = physical working capacity at a heart rate of 150 beats/min.

Both concentric (generation of force while the muscle is shortening) and eccentric (generation of force while the muscle is lengthening) strength have been measured at different times of the solar day using isokinetic dynamometry.[63-65] A time of day effect in these variables has been noted with peak values occurring in the early evening, although this is apparent only when measured at slow (between 1.05 and 3.14 rad/sec) angular velocities of movement (fig. 4B). The coefficient of variation of measurements made with computer-controlled dynamometers may be as high as 20% at fast angular velocities of greater than 6 rad/sec.[63] Unless this error is reduced through multiple trials, it probably prevents the detection of any circadian variation. Inadequate test-retest repeatability of measuring equipment is a problem in chronobiological research and may explain why rhythms have not been detected in other performance variables.

4.3.4 Short Term Power Output

Circadian rhythms have been identified in laboratory measures of anaerobic power and conventional tests of short term dynamic activity. Hill and Smith[66] measured anaerobic power and capacity with a modified version of the Wingate test at 0300, 0900, 1500 and 2100 hours. Peak power in the evening was found to be 8% higher than at 0300 hours. Similar results were found for mean power over the 30-second test period. Conversely, Down et al.[67] duplicated measurements at 6 times of the solar day and could not confirm that performance in the Wingate test depends on time of day. Reilly and Down[68] modified a cycle ergometer so that the Wingate test could be applied to arm exercise. Similarly, no significant rhythm was observed in peak or mean power of the arms. The conflicting results between the latter two studies and those of Hill and co-workers may have been due to differences in pre-test protocols. Vigorous warm-up procedures prior to administration of the tests may have 'swamped' any rhythm that may have been present. In addition, the sensitivity of the ergometry used in the Wingate test may have been insufficient to detect such small amplitude rhythms. Recently, more accurate methods of assessing short term high power output on a cycle ergometer have been made available (e.g. Lakomy's flywheel inertia correction equations).[69]

The results of studies that have examined the effects of time of day on fixed-intensity work-rates close to maximal oxygen uptake ($\dot{V}O_{2max}$) seem more conclusive than those that have employed the Wingate test. Hill et al.[70] reported that total work performed in high-intensity constant work-rate exercise on a cycle ergometer was significantly higher in the afternoon compared with the morning. These results agree with the findings of Reilly and Baxter[71] who reported longer work-times and higher peaks of lactate production when set high intensity exercise was performed at 2200 hours compared with 0630 hours.

With respect to other conventional methods of evaluating short term explosive activity, Reilly and Down[48] investigated whether performance in the standing broad jump shows a circadian rhythm. When individual differences in performances were controlled for, significant circadian rhythmicity was found for length of jump with an acrophase of 1745 hours and an amplitude of 3.4% of the 24-hour mean value (table I). Similar rhythm characteristics have been found for vertical jumping performance.[44,72] In view of the fact that jumping records are broken usually by only a few centimetres, time of day should be recognised as a significant factor that influences record breaking attempts or the ability to meet certain performance standards in order to qualify for major championships.

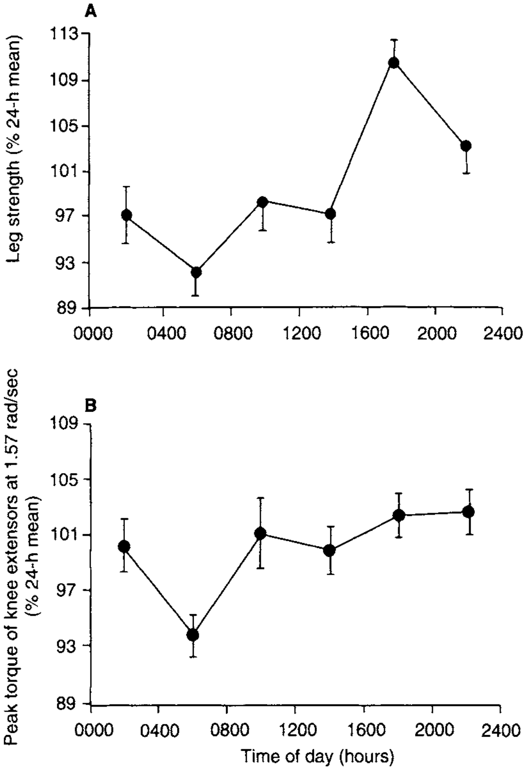

Fig. 4. Circadian rhythms in leg strength. (**A**) Isometric strength of the knee extensors measured with a spring-loaded dynamometer. (**B**) Isokinetic strength of the knee extensors measured with a LIDO dynamometer (Loredan, California) at an angular velocity of 1.57 rad/sec. Data obtained from 20 study participants aged 18 to 30 years).[42]

The evening superiority of swim performances measured in time trials 'in the pool' is likely to be physiological in origin rather than due to circadian changes in water temperature, since mean and peak power output recorded on a swim bench under controlled conditions still vary with time of day.

Amplitudes of these rhythms are 11 to 14% of the 24-hour mean values and the peak-time is about 1800 hours.[73] This circadian variation in swimming performance is greater than the effect of obtaining only 3 hours of sleep for 3 successive nights.[74]

4.4 Physiological Responses

Some circadian rhythms in the physiological responses to exercise are maintained in amplitude, some disappear, whereas others become more marked during exercise. The differing effects of exercise on circadian rhythms could be due to experimental errors such as failure to control prior activity and diet of the study participants. As discussed below, the intensity of exercise and fitness of the individuals involved in the study may also affect the results.

Since fluctuations in body temperature are believed to mediate many circadian rhythms in performance, the characteristics of this rhythm during exercise are important. Reilly and Brooks[75] found that the acrophase and amplitude of the rhythm in rectal temperature remained unchanged during exercise. Rhythms in skin temperature during exercise were generally in phase with their corresponding resting rhythms but depended on the site of measurement. Skin temperature of the exercising limb did not evidence rhythmicity.

Wahlberg and Åstrand[76] exercised 20 men at 0300 hours and 1500 hours at both submaximal and maximal loads. Heart rates during exercise were consistently lower at night, irrespective of work rate, the day-night difference amounting to 3 to 5 beats/min. Cohen and Muehl[77] measured heart rate at rest, during exercise on a rowing ergometer, and in the recovery period of this exercise at 7 times during the solar day. Although cosinor analysis was not used to examine the data, the lowest heart rates were reported to occur between 0400 and 0800 hours. This temporal pattern was evident both during and after exercise.

Cohen[78] repeated the latter study but concentrated on an incremental exercise task. The heart rate responses to maximal exercise just prior to exhaustion did not vary with time of day, suggesting that no rhythm exists in maximal heart rate. However, in many studies of maximal physiological values, it is often unclear as to whether the ceiling of physiological capability was reached during the exercise test. In contrast to the results of Cohen,[78] Reilly et al.[79] found that the rhythm in heart rate persisted during maximal exercise, although with a reduced amplitude compared with the resting rhythm.

The causal nexus of the rhythm in heart rate during exercise is complicated, with possible metabolic, thermogenic and sympathetic influences. Circadian variation in cardiac output during exercise has yet to be identified.[80]

Reilly et al.[79] found that both systolic and diastolic blood pressure measured for 5 mins after a set exercise regimen were unaffected by time of day. As well as outlining the measurement errors associated with conventional sphygmomanometry, these authors suggested that their pre-exercise conditions may have swamped any variations in blood pressure.

Cabri et al.[64] measured blood pressure before and after leg exercise on an isokinetic dynamometer at 6 times of the solar day. Systolic blood pressure did not evidence rhythmicity both pre- and post-exercise. However, diastolic blood pressure (post-exercise) was found to vary with time of day, the rhythm reaching its acrophase between 0000 and 0200 hours. It is not known why the acrophase of this rhythm does not coincide with those of other cardiovascular variables at rest or during exercise.

The results of studies which have examined circadian variations in metabolic responses to submaximal exercise are not as conclusive as those that investigated heart rate responses. Horne and Pettit[81] were unable to detect rhythmicity in the $\dot{V}O_2$ responses to submaximal exercise in untrained individuals. Reilly[82] performed a longitudinal study involving one person in order to control for differing zeitgeber effects between study participants. Circadian rhythmicity was observed in $\dot{V}O_2$ (expressed in ml/kg/min) at a work-rate of 150W, peaking at 1440 hours, but this rhythm could be explained fully in terms of circadian variations in body mass (participants were slightly lighter in the afternoon). Significant rhythmicity in $\dot{V}O_2$ responses to a lighter work-rate than 150W were evident irrespective of changes in body mass. The time required for $\dot{V}O_2$ to reach steady state (expressed as the fifth minute value) was not more than 2 minutes and did not vary with time of day. No circadian variations were found for expired carbon dioxide ($\dot{V}CO_2$) or the respiratory exchange ratio during exercise.

The amplitude of the rhythm in minute ventilation ($\dot{V}E$) is amplified during light or moderate exercise. Reilly and Brooks[83] found that the $\dot{V}E$ response to exercise displayed rhythmicity that was phased similarly to the resting rhythm, but 20 to 40% higher in terms of amplitude. The rhythm in $\dot{V}E$ may explain the reports of mild dyspnoea when exercise is performed in the early morning.

The lack of rhythmicity in metabolic responses to exercise is unequivocal when measured at maximal exercise intensities. In both longitudinal[83] and cross-sectional[84] studies, it has been found that $\dot{V}O_{2max}$ is a stable function, independent of the time of day of measurement. This finding is not surprising since the amplitude of the resting rhythm in $\dot{V}O_2$ if maintained during maximal exercise would be less than 0.5% of $\dot{V}O_{2max}$. Such a small amplitude would be difficult to detect, probably due to the insensitivity of equipment used to measure $\dot{V}O_{2max}$.

Circadian variations in the subjective reactions to exercise may be an alternative explanation for rhythms in maximal exercise performance. Faria and Drummond[84] employed a crossover-treatment and reverse-sequence design to examine the effects of time of day on ratings of perceived exertion (RPE) during graded exercise on a treadmill. The results revealed that there was a dissociation between RPE and heart rate which depended on time of day. The RPE were higher during exercise carried out in the early hours of the morning (0200 to 0400 hours) than in the evening (2000 to 2200 hours). In this study, work-rates were set relative to elicited heart rates of 130, 150 and 170 beats/min. Submaximal heart rate at a set work-rate is lowest at night (see above). Therefore, the higher subjective ratings reported at this time may have been due to higher exercise intensities and not any circadian variation in RPE. Studies that have exercised individuals at levels expressed relative to $\dot{V}O_{2max}$ rather than heart rate have noted a circadian variation in RPE, only during maximal exercise.[71] However, low-intensity exercise when performed many times within a solar day may mediate a transient increase in RPE in the early afternoon.[85]

One response to activity that may be important in injury and rehabilitation contexts is a loss of stature attributed to 'spinal shrinkage'. The rest-activity rhythm present in normal conditions imposes compressive loading on the spine during the day, leading to the extrusion of water through the invertebral disc wall and a consequent loss of disc height. This shrinkage is reversed at night during the recumbency of sleeping. Reilly et al.[86] were the first investigators to characterise fully the circadian rhythm in human stature. Using a stadiometer accurate to 0.01mm, they found that the peak to trough variation of stature was 1.1% of overall stature. Cosinor analysis was found to provide an unsatisfactory fit to the circadian variation, the data being better described by a power function (fig. 5). Peak stature was measured at 0730 hours with the

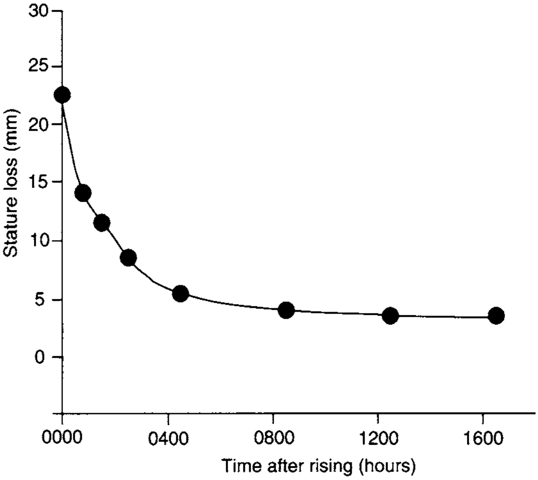

Fig. 5. The loss in stature after waking in the morning. Stature expressed relative to the measurement at midnight (set at 3.5mm).[88]

minimum occurring around midnight. A study by Wilby et al.,[87] which involved female participants, provided results similar to those for men, the mean peak-to-trough variation in stature being 0.92% of overall stature. The shrinkage responses to a 20-minute weight-training session, carried out in the morning and the evening, have also been examined.[87] The results indicated that stature losses were smaller in the evening when body height is in the trough of circadian variation. It was asserted that greater stiffness of intervertebral discs in the evening is likely to increase the risk of injury, although it was also pointed out that higher values of back strength in the evening may serve to compensate for the increase in stiffness.

4.4.1 Endurance Races and Environmental Temperature

During endurance races in heat, athletes may have to exercise with their body temperatures above the level conducive to optimal performance and close to temperatures normally indicative of heat injury. If endurance exercise is carried out in the afternoon or evening, there might be a greater risk that such body temperatures are attained, since as stated above, the body temperature rhythm is maintained during exercise. Although a set body temperature threshold for heat injury has yet to be confirmed, assuming that a threshold is constant throughout the day, the margin of safety for heat injury can be calculated to be 0.5 to 0.8°C greater in the morning than in the afternoon.

There is evidence from two sources which supports the hypothesis that, in fit individuals, performance in sustained exercise is improved by lower body temperatures. Firstly, pre-cooling body temperature before 1 hour of submaximal exercise by an amount that corresponds to the amplitude of the circadian rhythm causes a significant increase in work-rate.[88] Secondly, there is a significant interaction between self-selected work rate measured every 10 minutes during 80 minutes of submaximal exercise and time of day.[89] In the evening, when body temperature was highest, individuals chose greater work-rates at the beginning of the exercise period in the evening compared with the morning. However, as body temperature rose above optimal levels during the evening exercise, work-rate dropped. In the morning, work-rate gradually increased as body temperature rose towards optimal levels, until, at the end of the exercise period, individuals chose higher work-rates in the morning than in the afternoon (fig. 6). In cold and wet conditions however, athletes running at very low exercise intensities (e.g. charity runners in marathon races) might be at a greater risk of hypothermia in the morning. Their low work-rate might be insufficient to maintain heat balance due to the high loss of heat to the cold environment. In such conditions there is a need for appropriate clothing to safeguard against a dangerous drop in body core temperature.

In the past, it was recognised that environmental temperature is more favourable for athletes in marathon races in the early morning. Consequently in hot and humid places such as Hong Kong, Singapore and Penang, marathons conventionally start at 0500 to 0600 hours. In recent years, various competitive marathons have been scheduled at later times of day to coincide with the demands of television audiences. Such scheduling may be disastrous to athletes if environmental temperature is high. This may apply to the year 2000 Olympic marathon in Sydney if West-European and North American television companies exert their influence over the time of day that the race is held.

4.4.2 Predictive Tests of Physical Fitness

The heart rate responses to submaximal exercise have been employed in predicting maximal aerobic power[90] and physical working capacity.[91] In such tests, heart rates at two or more known submaximal workloads are either entered into tables to predict oxygen consumption at an estimated maximum heart rate, or used to extrapolate a work-rate that elicits a certain heart rate (usually 150 to 170 beats/min). Such tests have been widely adopted for testing large groups of individuals mainly as part of health education programmes, even though they have a large predictive error.[92] Part of this error may be attributable to the time of day at which the test was administered since significant circadian variation has been found for both maximal

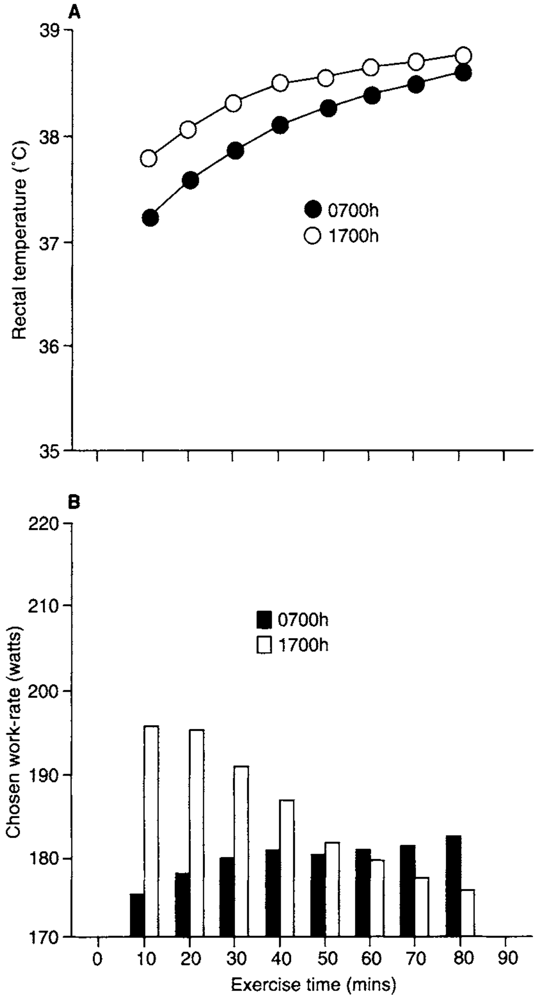

Fig. 6. Effects of time of day on self-chosen work-rate and rectal temperature during 80 mins of exercise on a cycle ergometer.[91] (**A**) Rectal temperature is higher during exercise in the afternoon than in the morning. (**B**) Higher work-rates are initially chosen during afternoon exercise, but these fall towards the end of the exercise period to values below those recorded during morning exercise.

heart rate and heart rate during exercise. This has been confirmed with reported peak-trough variations of predicted $\dot{V}O_{2max}$ ranging from 10 to 25%,[5] a finding which is not replicated in studies that have measured $\dot{V}O_{2max}$ directly (see below). A low heart rate response to exercise results in a high score on these tests. Since the rhythm in heart rate peaks at 1500 to 1600 hours, the acrophase of predictive work capacity may occur almost 180° out of phase with acrophases of body temperature and other performance-related measures (table I).

The equation employed in cosinor analysis for determining circadian functions[50] can be rearranged to calculate, from known circadian characteristics, the 24-hour mean of a fitness test score obtained at any time of the solar day:

$$FT_{corr} = \frac{FT_t}{1 + 0.01A \cdot \cos(15t - 15P)}$$

where t is the time of day at which the fitness test was measured (decimal clock hours), FT_t is the score for the fitness test at time t, A is the amplitude of the 'standard' rhythm (% of 24-hour mean) and P is the acrophase of the 'standard' rhythm (decimal hours).

Circadian data (amplitude, acrophase) from previous studies of the effects of time of day on fitness tests (table I) can be substituted into the above equation to correct the result for time of day. This equation is useful for correcting fitness tests administered to large populations of study participants when it is often not practical to control for time of day. It is stressed, however, that in order for the above equation to be used, the circadian variation must follow a cosinor pattern.

4.5 The Optimum Time of Day for Training

Two issues are relevant here which affect the efficacy of a training programme: (i) the time of day at which athletes are prepared voluntarily to work harder; and (ii) the time of day which elicits the greatest training responses to standardised exercise regimens. With respect to (i), self-chosen work-rate during exercise of less than 40 minutes' duration is higher when that exercise is attempted in the late afternoon/evening (fig. 6).

Atkinson et al.[43] and Coldwells et al.[93] recorded self-chosen work-rate at the start of 30 minutes of exercise on a cycle ergometer and found circadian rhythmicity with an acrophase at 1900 hours and an amplitude of about 7% of the 24-hour mean value. The higher work-rates chosen in the evening were not accompanied by any increases in ratings of perceived exertion. This would be analogous to an athlete adopting greater training loads in the early evening spontaneously without him/ her realising it. The evening preference for higher work rates may not be apparent when prolonged exercise is performed in hot conditions (fig. 6).

Assuming that athletes are exposed to the zeitgebers that are associated with a diurnal existence, it is unlikely that habitual training in the morning over many weeks (carried out by swimmers, for example) would fully reverse the evening-superiority of self-selected training stimuli, although this has never been examined empirically.

Research on the circadian variation in the efficacy of endurance training programmes is equivocal. In one study, the circadian effects of an aerobic training programme in 3 groups of men who exercised in the morning (0900 to 0930), afternoon (1500 to 1530) or evening (2000 to 2030) were examined.[94] Each group performed 30 minutes of cycle ergometer exercise at 60% $\dot{V}O_{2max}$ (therefore the training stimulus was the same irrespective of time of day) for 4 days per week over a 4-week period. The $\dot{V}O_{2max}$ was estimated and adaptive responses of heart rate and blood lactate levels to the training programme were measured. After 4 weeks, the afternoon group showed the greatest increase in estimated $\dot{V}O_{2max}$ max, suggesting that aerobic training is most effective in the afternoon, although all groups were assessed after the training period only in the afternoon. Other research work has found no significant differences in the training responses to morning and evening exercise.[95]

Improvements in muscle strength following training sessions scheduled at 2100 hours have been found to be 20% higher than those following training carried out at 0900 hours,[96] although this is with maximal isometric contractions as the training stimuli (which can themselves vary with time of day) and the responses to training of each group of study participants were examined only at the times of day that they trained at (the group who trained at 2100 hours were examined at that time post-training). Plasma levels of somatotrophin and testosterone have been found to be significantly higher following training in the evening compared with the morning,[97] although, again, maximal muscle contractions, which can be affected by time of day, were used as the training stimuli.

Paradoxically, there is some evidence to suggest that the learning of motor skills is faster when tasks are performed in the early morning; the greatest improvement in the performance of a pursuit rotor task is evident when the task was performed at 0900 hours.[98] Like the studies on strength, it is difficult to separate a true time of day effect on learning/ training (the response) from the ability to perform the task (the stimulus) better at certain times of the day. Further, future investigations should employ sport-specific skills and examine the effect of long term training in the morning on training responses.

Evening exercise may be safer than morning work-bouts. For the reasons stated in section 2, asthmatic athletes should be discouraged from exercising before or soon after breakfast. Caution should also be exerted in the mid afternoon by asthmatic athletes who train in urban areas, since this is usually the peak-time of day for photochemical smog. Willich[99] reported that the risk of acute coronary events is increased 3-fold in the morning compared with other times of day. These authors found a separate effect of physical exertion on cardiac events, the risk being slightly greater in inactive individuals who suddenly perform physical activity. It is not known, to date, whether there is an interaction between these two effects, but it would seem good advice for cardiac patients not to schedule their more intense exercise bouts in the morning.[100] Delayed-onset muscle soreness (DOMS) is a transient condition of musculo-skeletal trauma that can follow vigorous exercise, particularly that involving eccentric muscle contractions. Soreness ratings peak 2 to 3 days after exercise, although any circadian variation within this period has not been researched. The plasma level of creatine kinase increases during DOMS and has been employed as a marker of muscle damage. Lowest ratings of soreness and plasma levels of creatine kinase have been found following exercise performed in the evening.[97] The mechanisms responsible for this finding are unknown.

5. Rhythm Disturbances

Humans often have to overcome rhythm disturbances when shiftwork is adopted or when time-zones are crossed from travelling to different parts of the world. It should be noted that crossing time zones and working shifts are not chronobiologically identical. When multiple time-zones are crossed, a person is normally exposed to all the zeitgebers of the new environment whereas, during shiftwork, any change in the phasing of a person's rhythms has occurred whilst being exposed to some zeitgebers still associated with a diurnal existence (e.g. the light-dark cycle). The consideration of shiftwork is further complicated by the fact that the rhythm disturbances may not be, as in transmeridian travel, isolated events, but can be frequent, occurring every time the shift rotates.

5.1 Shiftwork and Sports Performance

One third of British male manual workers are involved in nocturnal shiftwork.[101] Many shiftworkers wish to, but cannot, perform leisure activities at the same times of day as day workers.[102] For those people participating in team sports or any type of competitive sport, a restriction in leisure-time may become one of the major factors in them leaving shiftwork.[103,104] For people involved in solitary hobbies or those training for (but not competing in) individual sports, this may not be a problem. For example, Atkinson[42] found that 9% of a sample of racing cyclists were shiftworkers. Individual sports other than cycling, which may not be adversely affected by shiftwork, in terms of the opportunity for training are track and field athletics and swimming. Although the opportunity to train for some sports may not be hindered by shiftwork, this training often cannot be scheduled in the early evening which is the time of day associated with the highest self-selected work-rates. The opportunities for the shiftworker to participate in sports competitions are undoubtedly hindered, since these are most often scheduled in the early evening and at weekends. At these times, the shiftworker may be needing recuperative sleep. Even if the shiftworker does manage to arrive at the start of a competition, inappropriately phased rhythms and/or marked sleep deprivation may adversely affect performance. Sport is one of the few leisure activities which may mediate long term favourable changes in physiological functions and/or exacerbate the fatigue of the shiftworker. Physical activity performed at least twice a week is usually included in guidelines for improving shiftwork tolerance.[105] The usefulness of exercise during shiftwork is poorly understood and there is evidence that the majority of shiftworkers do not follow that particular piece of advice.[106] More research is needed regarding not only how leisure interests are affected by shiftwork, but, conversely, how leisure activities, especially those involving exercise, affect tolerance of shiftwork.

5.2 Transmeridian Travel and Sports Performance

The effects of transmeridian travel as a rhythm disturbance on athletic performance have been reviewed previously in this Journal.[107,108] Since most performance components evidence circadian rhythmicity and because circadian rhythms are slow to adapt to time-zone travel, it would be reasonable to hypothesise that athletic performance is affected by transmeridian travel (but not translatitudinal travel). It would also be logical to suggest that performance is *detrimentally* affected by transmeridian travel, given the negative aspects of 'jet lag' (fatigue, sleep disturbances).

O'Connor and Morgan,[108] however, pointed out that there is very little scientific evidence to support these notions. The results of a study by this research group[109] suggested that competitive swimmers who were rapidly translocated in both directions across 4 time zones during a period of heavy training showed *improved* mood and decreased ratings of muscle soreness. Many variables other than time-zone travel may have, however, influenced these findings including the excitement resulting from travelling to a new country, improved mood owing to the athletes returning home and the effects of enforced rest, during the journey, from a vigorous training regime.

A major factor influencing studies of athletic performance is the discrepancy, after a flight, between 'body clock time' and the 'real time' in the new environment. The peak-time of day for most athletic events may still be between 1600 and 2200 hours 'body time', but this may correspond to the morning ('real time') after a long flight to the west. This factor may explain some of the findings in the study by O'Connor et al.[109] since all tests were administered to the athletes at 1300 hours 'real time' on the days before and after the flight (1300 hours after the flight corresponded to 1700 hours pre-flight time which is closer to the peak-time for swimming performance). This factor may also explain the findings of Jehue et al.[110] who reported that the performances of travelling American Football teams depended on how close the game-time corresponded to the usual afternoon peaks in performance. To study, chronobiologically, the influence of time-zone travel on sports performance, athletes should be tested at several times of day for several days after a flight. Alternatively, phase shifts of the sleep-wake cycle could be simulated in the laboratory. Such a study has been performed by Reilly and Maskell[111] who found that performance (e.g. standing broad jump) worsens and takes time to adjust following phase-shifts of the sleep-wake cycle.

6. Individual Differences in Performance Rhythms

The concept of morning and evening types was first considered by scientists in the early part of the twentieth century.[112] Classification of morning types ('larks'), evening types ('owls') and intermediate types (neither larks nor owls) is based on the responses to questions regarding sleep and waking times and the phasing of work and habitual activity. Hill et al.[113] compared the responses to exercise (100W and a work-rate corresponding to $\dot{V}O_{2max}$) on a cycle ergometer between morning and evening types. Diurnal variations in submaximal heart rate, RPE and $\dot{V}O_2$ were not affected by individual chronotype. However, $\dot{V}O_{2max}$ in the evening types group was best in the evening, whereas the $\dot{V}O_{2max}$ of the morning types was not affected by time of day. Burgoon et al.[114] found that maximal exercise performance on a treadmill at 0730 and 1930 hours did not depend on morningness/eveningness scores. Rossi et al.[115] circulated morningness/eveningness questionnaires to golfers who competed at differing times of day and water polo players who performed mostly in the evening. The elite golfers in the experimental sample were reported have higher scores for morningness than the water-polo players. Such individual differences in chronotype should be recognised by coaches when scheduling training sessions. For example, an extreme evening type swimmer may find that attending early morning training sessions is so difficult that he or she quits the sport, even though he/she performs well in the evening competitions.

Women have been found to have higher mean body temperatures over a 24-hour period than men.[116,117] Smaller rhythm amplitudes in body temperature have also been documented for female study participants compared with male participants.[117] Mellette et al.[118] observed that peak temperature occurred later in the solar day and the minimum occurred earlier in women, although it is stressed that these were observations and cosinor analysis was not employed to analyse the data. It is also stressed that from the 3 studies cited above, only one[116] controlled for the phase of the menstrual cycle. Therefore, more work is needed to describe any sex-differences in circadian rhythms, especially those in performance.

Harma et al.[49] and Atkinson et al.[119] reported that the rhythm amplitudes of physically fit individuals were higher than in unfit individuals, when they were studied under standardised laboratory conditions. The greater rhythm amplitude in body temperature for the physically fit study participants was explained by a minimum in the early hours of the morning that was 0.4°C lower than that of the unfit individuals. Mermin and Czeisler[120] found that although exercise during the day increased body temperature, after exercise there was a greater drop in body temperature during sleep relative to what was observed during 'normal' sleep (sleep following no activity during the day). However, the results of the studies by Harma et al.[49] and Atkinson et al.[119] cannot be attributed to this 'post-exercise thermoregulatory overcompensation' since, in their studies, the order of exercise testing was randomised. This implies that the lower nocturnal body temperatures of physically fit individuals may be mediated via endogenous mechanisms (a training effect of habitual physical activity). These exact mechanisms are unknown.

Circadian timing is altered in elderly individuals.[121] This applies to circadian rhythms in body temperature, hormonal secretions, haematological parameters and the urinary excretion of metabolites. Exogenous rhythms such as heart rate and blood pressure are also different in elderly individuals, although probably as a consequence of changes in the sleep-wake cycle and the cardiovascular responses to meals.[25] The most consistent age-related circadian differences are a reduction in the amplitudes or a 'flattening' of the rhythms, as well as a rise, with age, in the inter-individual variability of rhythm acrophases. Rhythm acrophases of elderly individuals often occur earlier than normal in the solar day,[122] in agreement with other observations of earlier wake-times and increased morningness in old age[44] (fig. 7). Veteran cyclists seem to be more morning type individuals, scheduling greater amounts of training before 1400 hours than young adults. This is evident before the older cyclists have retired from work.[44] The performance of veteran cyclists in time trials is also less affected by early morning starts. Laboratory studies have confirmed that, although people aged 50 to 60 years still perform best in the early evening, they also perform relatively well in the morning, age differences in performance being least at this time.[38,89] It is still unclear whether such findings reflect age-related changes in the endogenous clock or exogenous influences such as sleep.

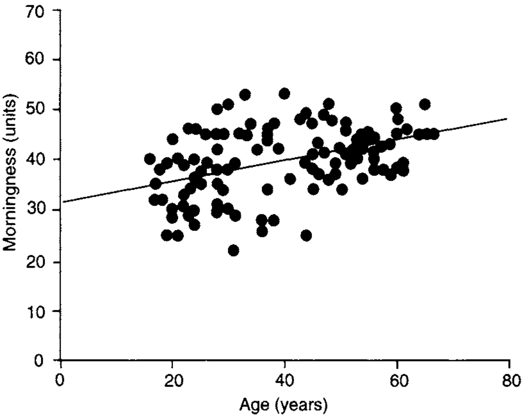

Fig. 7. The relation between age and 'morningness' in 117 competitive cyclists.[42] r = 0.43. p < 0.00001.

7. Conclusions and Future Directions

An attempt has been made in this review to communicate present knowledge of how the time of day influences variables associated with sports performance, as well as to suggest areas for future research.

It is known that many components of performance fluctuate persistently every 24 hours in parallel with the body temperature curve which peaks in the early evening. Research work is needed to ascertain whether the ability to perform tasks demanding complex motor skills varies with time of day.

A limiting factor of prolonged exercise performance in hot conditions is a supra-optimal body temperature. Therefore, we advise that endurance races should be scheduled in the morning when body temperature may be 1°C lower than in the evening and the environmental conditions are more favourable.

Physiological responses to exercise depend on time of day. The heart rate response to a given intensity of exercise is lower in the morning. In fitness tests that employ heart rate as the criterion, scores would be erroneously higher at this time of day.

Studies should be designed to examine whether exercise performed in the morning is more dangerous for the cardiac patient and asthmatic than at other times of a day. Time of day should also be examined as a factor that mediates the elimination of drugs from an athlete's body. More research work is needed to identify how the rhythm disturbances of shiftwork and transmeridian travel affect the performances of athletes.

There are significant individual differences in the sleep-wake habits of athletes, which are sometimes interpreted as laziness by some coaches. Although an optimal chronotype for sports performance has yet to be identified, a training schedule that is incompatible with an athlete's body clock may be difficult to adhere to.

References

1. Haus E, Touitou Y. Principles of clinical chronobiology. In: Touitou Y, Haus E, editors. Biological rhythms in clinical and laboratory medicine. Berlin: Springer-Verlag, 1992: 6-34
2. Campbell J. Winston Churchill's afternoon nap. London: Aurum Press, 1988
3. Cannon WB. The wisdom of the body. New York: Norton, 1939
4. Minors D, Waterhouse J. Circadian rhythms and the human. London: Wright PSG, 1981
5. Reilly T. Human circadian rhythms and exercise. Crit Rev Biomed Eng 1990; 18: 165-80
6. Halberg F. Physiologic 24-hour periodicity in humans beings and mice, the lighting regimen and daily routine. In: Withrow RB, editor. Photoperiodism and related phenomena in plants and animals. Washington: American Association for the Advancement of Science, 1959: 803-78
7. Wolf W. Rhythmic functions in living systems. Ann NY Acad Sci 1962; 98: 753-1326
8. Reilly T, Young K, Seddon R. Investigation of biorhythms in female athletic performance. Appl Ergon 1983; 14: 215-7
9. Quigley BM. Biorhythms and Australian track and field records. J Sports Med Phys Fitness 1981; 21: 81-9
10. Mills JN, Minors DS, Waterhouse JM. The effects of sleep upon human circadian rhythms. Chronobiologia 1978; 5: 14-27
11. Halberg F, Vallbona C, Dietlin LF. Human circadian circulatory rhythms during weightlessness in extraterrestial flight or bedrest with and without exercise. Space Life Sci 1970; 2: 18-32
12. Wever R. Influence of physical workload on free running circadian rhythms of man. Pflugers Arch 1979; 38: 119-26
13. Green DJ, Gillette R. Circadian rhythm of firing rate recorded from single cells in the rat suprachiasmatic brain slice. Brain Res 1982; 245: 198-200
14. Ralph MR, Foster RG, Davis FC, et al. Transplanted suprachiasmatic nucleus determines circadian period. Science 1990; 247: 975-8
15. Aschoff J. Circadian rhythms in man. Science 1965; 148: 1427-32
16. Arendt J. The pineal. In: Touitou Y, Haus E, editors. Biological rhythms in clinical and laboratory medicine. Berlin: Springer-Verlag, 1992; 348-62
17. Theron JJ, Oosthuizen JMC, Rautenbach MM. Effect of physical exercise on plasma melatonin levels in normal volunteers. S Afr Med J 1984; 66: 838-41
18. Monteleone P, Maj M, Fusco M, et al. Physical exercise at night blunts the nocturnal increase of plasma melatonin levels in healthy humans. Life Sci 1990; 47: 1989-95
19. Piercy J, Lack L. Daily exercise can shift the endogenous circadian rhythm. Sleep Res 1988; 17: 393
20. Akerstedt T. Altered sleep/wake patterns and circadian rhythms. Acta Physiol Scand Suppl 1979; 469: 1-48
21. Smolensky MH, Tatar SE, Bergman SA, et al. Circadian rhythmic aspects of human cardiovascular function: a review by chronobiologic statistical methods. Chronobiologia 1976; 3: 337-71
22. Pickering TG. The influence of daily activity on ambulatory blood pressure. Am Heart J 1988; 116: 1141-5
23. Baumgart P, Walger P, Fuchs G, et al. Twenty-four-hour blood pressure is not dependent on endogenous circadian rhythm. J Hypertens 1989; 7: 331-4
24. Zulch KJ, Hossman V. 24-hour rhythm of human blood pressure. Ger Med Monthly 1967; 12: 513-8
25. Atkinson G, Witte K, Nold G, et al. Effects of age on circadian blood pressure and heart rate rhythms in primary hypertensive patients. Chronobiol Int 1994; 11: 35-44
26. Gaultier C, Reinberg A, Girard F. Circadian rhythms in lung resistance and dynamic lung compliance of healthy children. Effect of two bronchodilators. Respir Physiol 1977; 31: 169-82
27. Smolensky MH, Scott PH, Barnes PJ, et al. The chronopharmacology and chronotherapy of asthma. Annu Rev Chronopharmacol 1986; 2: 229-73
28. Smolensky MH, Alonzo GED. Nocturnal asthma: mechanisms and chronotherapy. In: Touitou Y, Haus E, editors. Biological rhythms in clinical and laboratory medicine. Berlin: Springer-Verlag 1992; 453-69
29. Swoyer J, Haus E, Lakatua D, et al. Chronobiology in the clinical laboratory. In: Haus H, Kabat H, editors. Chronobiology 1982-1983. New York: Karger, 1984; 533-43
30. Mejean L, Kolopp M, Drouin P. Chronobiology, nutrition and diabetes mellitus. In: Touitou Y, Haus E, editors. Biological rhythms in clinical and laboratory medicine. Berlin: Springer-Verlag, 1992; 375-85
31. Schlierf G. Diurnal variations in plasma substrate concentration. Eur J Clin Invest 1978; 8: 59-60
32. Veldhuis JD, Johnson ML, Iranmanesh A, et al. Rhythmic and non-rhythmic modes of anterior pituitary hormone release in man. In: Touitou Y, Haus E, editors. Biological rhythms in clinical and laboratory medicine. Berlin: Springer-Verlag, 1992; 277-91
33. Moore JG. Chronobiology of the gastrointestinal system. In: Touitou Y, Haus E, editors. Biological rhythms in clinical and laboratory medicine. Berlin: Springer-Verlag, 1992; 410-7
34. Goo RH, Moore JG, Greenberg E, et al. Circadian variation in gastric emptying of meals in man. Gastroenterology 1987: 93; 515-8
35. Touitou Y, Touitou C, Bogdan A, et al. Circadian and seasonal variations of electrolytes in ageing humans. Clin Chim Acta 1989; 180: 245-54
36. Robertson WG, Hodgkinson A, Marshall DH. Seasonal variations in the composition of urine from normal subjects: a longitudinal study. Clin Chim Acta 1977; 80: 347-53
37. Wisser H, Breur H. Circadian changes of clinical, chemical and endocrinological parameters. J Clin Chem Clin Biochem 1981; 19: 323-8
38. Atkinson G, Coldwells A, Reilly T, et al. An age-comparison of circadian rhythms in physical performance measures. In: Harris S, Era P, Suominen H, et al., editors. Towards healthy aging – international perspectives. Part 1. Physiological and biomedical aspects. Albany: Center for the Study of Aging, 1994; 205-18

39. Akerstedt T, Froberg JE. Interindividual differences in circadian patterns of catecholamine excretion, body temperature, performance and subjective arousal. Biol Psychology 1976; 4: 277-92
40. Hoddes E, Zarcone V, Smythe HR, et al. Quantification of sleepiness: a new approach. Psychophysiology 1973; 10: 431-6
41. McNair DM, Lorr M, Droppleman LF. EITS manual for the profile of mood states. San Diego: Educational and Industrial Testing Service, 1971
42. Atkinson G. Effects of age on human circadian rhythms in physiological and performance measures [thesis]. Liverpool: John Moores University, 1994
43. Atkinson G, Coldwells A, Reilly T, et al. Circadian rhythmicity in self-chosen work-rate. In: Gutenbrunner C, Hildebrandt G, Moog R, editors. Chronobiology and chronomedicine. Basic research and applications. Frankfurt am Main: Peter Lang-Verlag, 1993; 478-84
44. Atkinson G, Coldwells A, Reilly T, et al. The influence of age on diurnal variations in competitive cycling performances. J Sports Sci 1994; 12: 127-8
45. Conroy RTWL, O'Brien M. Diurnal variation in athletic performance. J Physiol 1974; 236: 51
46. Monk TH. Chronobiology of mental performance. In: Touitou Y, Haus E, editors. Biological rhythms in clinical and laboratory medicine. Berlin: Springer-Verlag, 1992; 208-13
47. Reilly T, Down A. Circadian variation in the standing broad jump. Percept Mot Skills 1986; 62: 830
48. Folkard S, Monk TH. Circadian rhythms in human memory. Br J Psychol 1980; 71: 295-307
49. Harma MI, Ilmarinen J, Yletyinen I. Circadian variation of physiological functions in physically average and very fit dayworkers. J Human Ergol 1982; 11 Suppl.: 33-46
50. Nelson W, Tong TL, Lee J-K, et al. Methods for cosinor rhythmometry. Chronobiologia 1979; 6: 305-23
51. Kleitman N. Sleep and wakefulness. Chigaco: University of Chicago Press, 1963
52. Winget CM, DeRoshia CW, Holley DC. Circadian rhythms and athletic performance. Med Sci Sports Exerc 1985; 17: 498-516
53. Monk TH, Leng VC. Time of day effects in simple repetitive tasks: some possible mechanisms. Acta Psychol (Amst) 1982; 51: 207-21
54. Gifford LS. Circadian variation in human flexibility and grip strength. Aust J Physiotherapy 1987; 33: 3-9
55. Wright V, Dawson D, Longfield MD. Joint stiffness its characterisation and significance. Biol Med Eng 1969; 4: 8-14
56. Reinberg A, Motohashi Y, Bourdeleau P, et al. Alteration of period and amplitude of circadian rhythms in shift workers. Eur J Appl Physiol 1988; 57: 15-25
57. Reilly T, Walsh T. Physiological, psychological and performance measures during an endurance record for 5-a-side soccer play. Br J Sports Med 1981; 15: 122-8
58. Harkness JA, Richter MB, Panagi GS, et al. Circadian variation in disease activity in rheumatoid athritis. BMJ 1982; 284: 551-5
59. Wit A. Zagadnienia regulacji w procesie rozwoju sily miesnionej na przykladzie zawodnikow uprawiajacych podnoszenie ciezarow [in Polish]. Warsaw: Institute of Sport, 1980
60. Wright V, Dawson D, Longfield MD. Joint stiffness – its characterisation and significance. Biol Med Eng 1969; 4: 8-10
61. Freivalds A, Chaffin DB, Langolf GD. Quantification of human performance rhythms. Am Ind Hyg Assoc J 1983; 44: 643-8
62. Coldwells A, Atkinson G, Reilly T. Sources of variation in back and leg dynamometry. Ergonomics 1993; 37: 79-86
63. Atkinson G, Greeves J, Cable T, et al. Day-to-day and circadian variability of leg strength measured with the LIDO isokinetic dynamometer. J Sports Sci 1995; 13: 18-19
64. Cabri J, Clarys JP, De Witte B, et al. Circadian variation in blood pressure responses to muscular exercise. Ergonomics 1988; 31: 1559-66
65. Ishee JH, Titlow LW. Diurnal variations in physical performance. Percept Mot Skills 1986; 63: 835-8
66. Hill DW, Smith JC. Circadian rhythm in anaerobic power and capacity. Can J Sports Sci 1991; 16: 30-2
67. Down A, Reilly T, Parry-Billings M. Time of day and performance of the Wingate Anaerobic Test. J Sports Sci 1985; 3: 214
68. Reilly T, Down A. Time of day and performance on all-out arm ergometry. In: Reilly T, Watkins J, Borms J, editors. Kinanthropometry III. London: E and FN Spon, 1986; 296-300
69. Lakomy HKA. An ergometer for measuring the power generated during sprinting. J Physiol 1984; 319: 33
70. Hill DW, Borden DO, Darnaby KM, et al. Effect of time of day on aerobic and anaerobic responses to high intensity exercise. Can J Sports Sci 1992; 17: 316-9
71. Reilly T, Baxter C. Influence of time of day on reactions to cycling at a fixed high intensity. Br J Sports Med 1983; 17: 128-30
72. Reilly T, Down A. Investigation of circadian rhythms in anaerobic power and capacity of the legs. J Sports Med Phys Fitness 1992; 33: 343-7
73. Reilly T, Marshall S. Circadian rhythms in power output on a swim bench. J Swim Res 1991; 7: 11-13
74. Sinnerton S, 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 VI. London: E and FN Spon, 1992: 399-405
75. Reilly T, Brooks GA. Exercise and the circadian variation in body temperature measures. Int J Sports Med 1986; 7: 358-62
76. Wahlberg I, Astrand I. Physical work capacity during the day and at night. Work Environ Health 1973; 10: 65-8
77. Cohen CJ, Muehl GE. Human circadian rhythms in resting and exercise pulse rates. Ergonomics 1977; 20: 475-9
78. Cohen CJ. Human circadian rhythms in heart rate response to a maximal exercise stress. Ergonomics 1980; 23: 591-5
79. Reilly T, Robinson G, Minors DS. Some circulatory responses to exercise at different times of day. Med Sci Sports Exerc 1984; 16: 477-82
80. Davies CTM, Sargeant AJ. Circadian variation in physiological responses to exercise on a stationary bicycle ergometer. Br J Ind Med 1975; 32: 110-4
81. Horne JA, Pettit AN. Sleep deprivation and the physiological responses to exercise under steady state conditions in untrained subjects. Sleep 1984; 7: 168-79
82. Reilly T. Circadian variation in ventilatory and metabolic adaptations to submaximal exercise. Br J Sports Med 1982; 16: 115-9
83. Reilly T, Brooks GA. Investigation of circadian rhythms in metabolic responses to exercise. Ergonomics 1982; 25: 1093-7
84. Faria IE, Drummond BJ. Circadian changes in resting heart rate and body temperature, maximal oxygen consumption and perceived exertion. Ergonomics 1982; 25: 381-6
85. Reilly T, Young K. Digit summation, perceived exertion and time of day under submaximal exercise conditions. In: Proceedings of the 20th International Congress of Applied Psychology; 1982 Jul 25-31: Edinburgh. Aston: International Association of Applied Physiology, 1982: 344
86. Reilly T, Tyrrell A, Troup JDG. Circadian variation in human stature, Chronobiol Int 1984; 1: 121-6
87. Wilby J, Linge K, Reilly T, et al. Spinal shrinkage in females: circadian variation and the effects of circuit weight-training. Ergonomics 1987; 30: 47-54

88. Hessemer V, Langusch D, Bruck K, et al. Effects of slightly lowered body temperature on endurance performance in humans. J Appl Physiol 1984; 57: 1731-7
89. Atkinson G, Reilly T. Effects of age and time of day on preferred work-rates during prolonged exercise. Chronobiol Int 1995; 12: 121-9
90. Åstrand P-O, Ryhming I. A nomogram for calculation of aerobic capacity physical fitness from pulse rate during sub-maximal work. J Appl Physiol 1954; 7: 218-21
91. Watson AWS, O'Donovan DJ. The reliability of measurement of PWC 170. Ir J Med Sci 1976; 145: 308
92. Reilly T. Assessment of some aspects of physical fitness. Appl Ergon 1991; 22: 291-4
93. Coldwells A, Atkinson G, Reilly T, et al. Self-chosen work-rate determines day-night differences in work capacity Ergonomics 1993; 36: 313
94. Torii J, Shinkai S, Hino S, et al. Effect of time of day on adaptive response to a 4-week aerobic exercise program. J Sports Med Phys Fitness 992; 32: 348-52
95. Hill DW, Cureton KJ, Collins MA. Circadian specificity in exercise training. Ergonomics 1989; 32: 79-92
96. Hildebrandt G, Gutenbrunner C, Reinhart C, et al. Circadian variation of isometric strength training in man. In: Morgan E, editor. Chronobiology and chronomedicine. Vol. II. Frankfurt: Peter Lang, 1990: 322-9
97. Gutenbrunner C. Circadian variations in physical training. In: Gutenbruner C, Hildebrandt G, Moog R, editors. Chronobiology and chronomedicine. Frankfurt: Peter Lang, 1993: 665-80
98. Hildebrandt G, Strempel H. Chronobiological problems of performance and adaptational capacity. Chronobiologia 1974; 4: 103-5
99. Willich SN, Lewis M, Lowel H, et al. Physical exertion as a trigger of acute myocardial infarction. N Engl J Med 1993; 329: 1684-90
100. Duda M. Should CHD patients avoid morning exercise? Physician Sports Med 1987; 15 (Pt 4): 39-42
101. Young BM. The shift towards shiftwork. New Society 1982; 61: 96-7
102. Hornberger S, Knauth P. Interindividual differences in the subjective valuation of leisure time utility. Ergonomics 1993; 36: 255-64
103. Herbert A. The influence of shift-work on leisure activities. A study with repeated measurement. Ergonomics 1983; 26: 565-74
104. Frese M, Okenek K. Reasons to leave shift-work and psychological and psychosomatic complaints of former shift-workers. J Appl Physiol 1984; 69: 509-14
105. Monk TH, Folkard S. Making shiftwork tolerable. Basingstoke: Taylor and Francis, 1992
106. Wedderburn A, Scholarios D. Guidelines for shift-workers: trials and errors? Ergonomics 1993; 36: 211-8
107. Loat CER, Rhodes EC. Jet-lag and human performance. Sports Med 1989; 8: 226-38
108. O'Connor PJ, Morgan WP. Athletic performance following rapid traversal of multiple time zones. Sports Med 1990; 10: 20-30
109. O'Connor PJ, Morgan WP, Koltyn KF, et al. Air travel across four time zones in college swimmers. J Appl Physiol 1991; 70: 756-63
110. Jehue R, Street D, Huizenga R. Effect of time zone and game time changes on team performance: National Football League. Med Sci Sports Exerc 1993; 25: 127-31
111. Reilly T, Maskell P. Effects of altering the sleep-wake cycle in human circadian rhythms and motor performance. Proceedings of the First IOC Congress on Sport Science Colorado Springs; 1989: 106
112. Horne JA, Ostberg O. Individual differences in human circadian rhythms. Biol Psychol 1977; 5: 179-90
113. Hill DW, Cureton KJ, Collins MA, et al. Diurnal variations in responses to exercise of 'morning types' and 'evening types'. J Sports Med Phys Fitness 1988; 28: 213-9
114. Burgoon PW, Holland GJ, Loy SF, et al. A comparison of morning and evening 'types' during maximum exercise. J Appl Sports Sci Res 1992; 6: 115-9
115. Rossi B, Zani A, Mecacci L. Diurnal individual differences and performance levels in some sports activities. Percept Mot Skills 1983; 57: 27-30
116. Christie MJ, McBreaty E. Deep body temperature: diurnal variation, sex and personality. J Psychosom Res 1977; 21: 207
117. Winget CM, DeRoshia CW, Vernikos-Danellis J, et al. Comparison of circadian rhythms in male and female humans. Waking Sleeping 1977; 1: 359-63
118. Mellette HC, Hutt BK, Askovich SI, et al. Diurnal variations in body temperature. J Appl Physiol 1951; 3: 665-70
119. Atkinson G, Coldwells A, Reilly T, et al. A comparison of circadian rhythms in work performance between physically active and inactive subjects. Ergonomics 1993; 36: 273-81
120. Mermin J, Czeisler C. Comparison of ambulatory temperature recordings at varying levels of physical exertion: average amplitude is unchanged by strenuous exercise. Sleep Res 1987; 16: 253
121. Brock MA. Chronobiology and aging. J Am Geriatr Soc 1991; 39: 74-9
122. Leiberman HR, Wurtman JJ, Teicher MH. Circadian rhythms of activity in healthy young and elderly humans. Neurobiol Aging 1989; 10: 259-65

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