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**REVIEW**

# CIRCADIAN RHYTHMS IN SPORTS PERFORMANCE—AN UPDATE

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We discuss current knowledge on the description, impact, and underlying causes of circadian rhythmicity in sports performance. We argue that there is a wealth of information from both applied and experimental work, which, when considered together, suggests that sports performance is affected by time of day in normal entrained conditions and that the variation has at least some input from endogenous mechanisms. Nevertheless, precise information on the relative importance of endogenous and exogenous factors is lacking. No single study can answer both the applied and basic research questions that are relevant to this topic, but an appropriate mixture of real-world research on rhythm disturbances and tightly controlled experiments involving forced desynchronization protocols is needed. Important issues, which should be considered by any chronobiologist interested in sports and exercise, include how representative the study sample and the selected performance tests are, test-retest reliability, as well as overall design of the experiment.

**Keywords** Athletes, Performance Analogues, Jet Lag, Endogenous and Exogenous Factors, Quasi-Experiments

## INTRODUCTION

Chronobiologists could be considered to have two main preoccupations. First, they are obviously interested in the "hands of the clock"; biological rhythm characteristics (e.g., amplitude or acrophase) are described, and the impact of these characteristics on real world situations (e.g., transmeridian travel) is appraised. Second, chronobiologists are interested in the "mechanisms of the clock"; the origins of a particular biological rhythm are elucidated through various experiments, in which competing exogenous sources of rhythmicity are systematically removed or accounted for.

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The above two preoccupations are obviously not mutually exclusive. The elucidation of the mechanism of a particular biological rhythm may ultimately lead to the development of treatments for rhythm disorders in real-world situations. For example, melatonin is thought to have a role in the control of circadian rhythms and consequently has been hypothesized to reduce symptoms of jet lag in athletes (Atkinson et al., 2003). Conversely, the behavior of a biological rhythm in a real-world situation may offer some insight into the underlying mechanisms of that rhythm. Observations, such as the persistence of circadian rhythms during sleep deprivation or the desynchronization of rhythms during jet lag, support the presence of endogenous control of circadian rhythms (Minors and Waterhouse, 1981). Therefore, it is important to consider the mechanisms and impact of circadian rhythms in tandem.

It is difficult to describe circadian rhythms in variables relevant to sports and exercise, while at the same time provide information on their underlying mechanisms. When an athlete is administered a test of physical performance, there are obvious physiological responses to the exercise involved, which in turn might "mask" any underlying mechanisms. This masking might be acute or long-lasting, depending on the variable measured, and is a particular problem for research on the zeitgeber qualities of exercise (Edwards et al., 2002). Not surprisingly therefore, most researchers (e.g., Atkinson and Reilly, 1996) have, in the past, concentrated on describing the various rhythms and discussing the impact on real sports competitions, rather than elucidating the root causes of circadian rhythmicity in sports performance.

Recently, Youngstedt and O'Connor (1999) criticized research on circadian rhythms in athletic performance. These authors maintained that there is no evidence that circadian rhythmicity in real sports competitions is explained by an endogenous component. They also suggested that the lack of evidence for an endogenous rhythm in physical performance means that sports performance is not affected by either time of day nor circadian rhythm disturbances such as jet lag, when various exogenous factors are taken into account. Interestingly, the assertions made by Youngstedt and O'Connor (1999) did not restrict these authors from the anomalous position of providing advice to travelling athletes on the basis of chronobiological principles (see O'Connor et al., 2004).

Youngstedt and O'Connor's (1999) review should encourage a deeper analysis of the available data and direct the priorities for future research. Nevertheless, we maintain that there is information concerning both the mechanisms and "hands" of circadian rhythms in athletic performance, which was not considered by Youngstedt and O'Connor (1999). We aim, in this review, to: (1) appraise the impact of circadian rhythms in sports performance on real athletes in real sports competitions, and (2) discuss the evidence for and against circadian rhythms in sports performance being mediated endogenously.

## THE IMPACT OF CIRCADIAN RHYTHMS ON SPORTS PERFORMANCE

Notwithstanding any discussions about the relative importance of endogenous and exogenous mechanisms to circadian rhythms in sports performance, it could be argued that if sports performance does vary with time of day in normal everyday conditions, then this has direct impact on the athlete. Performance that occurs outside of the "peak window" over a 24 h period may be potentially less than optimal (Winget et al., 1985) with the within-day variation being greater than that required to differentiate between successful and unsuccessful performers (Hopkins et al., 1999). This impact makes an understanding of the circadian variation in sports performance an important practical consideration for both athletes and coaches in competition (Cappaert, 1999) and might have important implications for both the short- and long-term success of an athlete or team. There is also an impact on athletic training, where the motivational climate of competitive stress is absent, and the training stimulus is highly dependent on the athlete's input of effort.

Important issues at this applied end of the research continuum (Atkinson and Nevill, 2001) are the size of the sample, how representative the research sample is of an athletic population, how well the selected performance tests in the research represent real sports performance, and how well the research design controls for intervening variables, such as learning effects.

### Indirect Evidence for Circadian Variation in Sports Performance

Indirect evidence for the existence of circadian rhythms in sports performance comes from examination of the times of day at which athletes perform best (or worst) in actual sports events. The element, which is maximized in this type of "*ex post facto*" examination, is obviously external validity of sample and performances (Atkinson and Nevill, 2001). Previous evaluations of world record breaking performances in sports events seem to indicate a circadian variation (Atkinson et al., 1999) with world records broken by athletes competing in the early evening, the time of day at which body temperature is highest.

We have stressed in a number of publications (Atkinson and Reilly, 1996; Reilly et al., 2000) that such *ex post facto* research should, of course, be interpreted with caution, since there is a bias for scheduling finals of track and field competitions in the afternoon or evening due to extraneous influences such as the demands of television. The lack of control over environmental influences on performance is also a major problem concerning evidence from field-based studies. For instance, environmental temperature may also be more favorable to record-breaking performances in the evening, especially in the summer (Youngstedt and O'Connor, 1999). 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).

The bias in event-scheduling for the early evening can, in some sports, be controlled. In time trials in competitive cycling the frequency of races is more evenly distributed throughout the daylight hours. The performances of young competitors in 16-km races are better when held in the afternoon and evening compared to those scheduled in the morning (Atkinson, 1994). When the frequency of trials is standardized at different times of the day in simulated competitions, weight-throwers also perform better in the evening than the morning (Conroy and O'Brien, 1974). Tighter control of environmental conditions can be achieved in swimming, where water conditions are held constant throughout the day. Data on swimming performance indicate improved performances for both 100-m and 400-m swims in the afternoon or early evening (Baxter and Reilly, 1983). Similar observations have also been made by others (Rodahl et al., 1976; Arnett, 2002).

### Laboratory Investigations

The lack of full control over extraneous influences on performance is the major problem concerning the evidence outlined above. The need for more conclusive proof of the existence of circadian variation in performance has led to researchers carrying out controlled laboratory-based investigations. These studies are, however, associated with both theoretical and methodological problems.

#### *General Experimental Design*

"Performance," in the context of a sporting action, has a broad meaning (Atkinson, 2002). Successful performance can be dependent on different combinations of fine motor skills, gross motor performance, and cognitive function. Researchers in laboratory-based investigations have tended to isolate separate components of performance and describe the circadian characteristics of each, thereby inferring the ecological validity of the data to the real event. Many of the components measured (e.g., time trials) are directly relevant to sporting events. Variables based on the physiological responses to exercise can be considered to be less relevant to real performance in this respect. While Youngstedt and O'Connor (1999) criticized the representative nature of some variables selected in chronobiological studies into sports performance, they cited the results of a study, which involved the physiological and subjective responses to swimming (rather than swimming times) as evidence against the notion that jet lag hinders sports performance.

It is also essential that the methodological techniques utilized in such laboratory-based studies approximate the required accuracy needed to discriminate between successful and unsuccessful performances within the competitive environment. This difference may be as small as 1% (Hopkins et al., 1999). The detection of such differences requires investigators to display substantial scientific rigor in experimental design and collect data with minimal measurement error. Sample size can also impact on the conclusions derived.

One point worth noting is that, in discussing the impact of measurement error and sample size on circadian rhythm research, too much error in the measurement of performance and/or an insufficient sample size is a type II issue in research. A type II error occurs when a chronobiologist has, after completing an experiment, concluded that circadian rhythmicity is absent for a particular variable when, in reality (in the population), circadian rhythmicity is apparent (Atkinson and Nevill, 1998; Atkinson and Reilly, 1999). Too much measurement error and/or a small sample size means that the "true" circadian rhythm could not be detected. It follows, therefore, that if a circadian rhythm is actually detected in an experiment (in terms of both statistical and practical significance), then this finding cannot be criticized on the basis of too much error or too small a sample size. The issue in this situation is a type I error. The influence of sample size on type I error rates is controlled for naturally in the mathematics underpinning statistical inference. If sample size is low, so are the degrees of freedom in the analysis, making it more difficult for a given test statistic to be deemed statistically significant or a confidence interval to have sufficient precision. A type I error occurs due to biased sampling of participants or incorrect choice of a statistical test, such as employing multiple t-tests on time series data rather than a repeated measures general linear model (Atkinson, 2001).

There are additional problems when a study on circadian rhythms in performance is attempted. For example, it is difficult to administer a large number of consecutive performance tests to humans without eliciting a serial fatigue effect. Consequently, most chronobiological investigations into human performance have employed some sort of transverse design (several subjects studied at a few times of day). Each subject performs the first test session at a different time of day. Conventionally, six or twelve subjects are examined to form what has been termed a "cyclic Latin square" design (Folkard and Monk, 1980). This protocol removes the influence of any learning/fatigue effects that could occur. The optimal design would allow at least *eight* hours between each of the test sessions, so that the measurements are taken over several days. The advantages of this are that subjects could sleep normally between

22:00–06:00 h and 02:00–10:00 h and that the performance variables are examined over two cycles of the circadian rhythm. Alternatively, each of the test sessions could be administered on different days, although the rigorous control procedures would need to be adhered to for 6 days.

Alongside the above general considerations for laboratory investigations, there may be specific issues with each type of performance variable (e.g., cognitive, psychomotor or physical tasks), which are examined.

### *Rhythms in Psychomotor Performance and Motor Skills*

Circadian rhythms are present in several elements of sensory motor, psychomotor, perceptual, and cognitive function (Winget et al., 1985). Simple reaction time (either to auditory or visual stimuli) is fastest in the early evening at the same time as the maximum in body temperature (Reilly et al., 1997). An inverse relationship between the speed and the accuracy with which a simple repetitive test is performed is, however, often observed making accuracy worse in the early evening (Atkinson and Spiers, 1998). Similar tasks, which demand fine motor control (e.g., hand steadiness and the ability to balance), are performed better in the morning, since arousal levels will be lower than the diurnal peak and closer to the optimum level for performance (Colquhoun, 1972). Complex aspects of performance such as mental arithmetic and short-term memory also peak in the early hours of the morning rather than in the evening (Conroy and O'Brien, 1974), though the rhythm is influenced by the load characteristics of the task (Winget et al., 1985).

The accuracy and consistency of both badminton (Edwards et al., 2004) and tennis serves (Atkinson and Spiers, 1998) seem to vary with time of day with higher accuracy observed at 14:00 than 18:00 h (Figure 1). These variations appear to be related more to changes in "fatigue" and "basal arousal" than temperature (Edwards et al., 2004). Circadian rhythms are also observed for soccer-specific performance tests such as chipping, dribbling, and juggling (Reilly et al., 2004a, b).

The fact that components of a certain sports activity might be influenced by time of day in different ways is interesting from a mechanisms perspective. For example, it would be difficult to ascribe differences in the peak circadian times of tennis serve velocity and accuracy to external influences or inadequacies in experimental design, since these observations were made with the same participants in the same conditions. Nevertheless, some performance components (e.g., flexibility) are more difficult to separate in terms of endogenous or exogenous mechanisms.

### *Flexibility*

Gifford (1987) noted circadian variation in lumbar flexion and extension, gleno-humeral lateral rotation, and whole-body forward flexion.

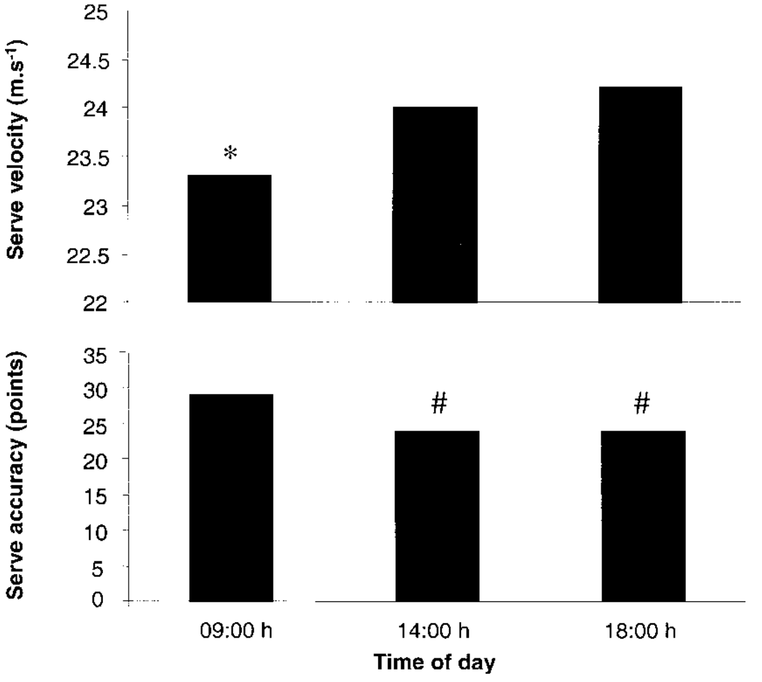


**FIGURE 1** Diurnal variation in tennis serving velocity and accuracy (drawn from data in Atkinson and Spiers, 1998). (*) Significant difference compared to other two times of day. (#) Significant difference from 09:00 h.

Variations are not, however, noted in spinal hyperextension, lateral movement of the spine and ankle plantar, and dorsi-flexion in other investigations (Edwards and Atkinson, 1998). Circadian variation in stiffness (resistance to motion) of the knee joint is similar to that of body temperature with the lowest levels of stiffness being recorded in the early evening (Wright et al., 1969). There can, however, be large interindividual differences of between 12:00 and 24:00 h in the peak-times of flexibility (Gifford, 1987). This variation does not seem to be related to the amount of prior activity as the completion of a 30 min submaximal warm up does not remove within-day differences in whole body flexibility (Edwards and Atkinson, 1998).

### *Strength*

Muscle strength, independent of the muscle group measured or speed of contraction, consistently peaks in the early evening (Reilly et al., 2000). The rhythm in isometric grip strength peaks between 14:00 and 19:00 h with an amplitude of about 6% of the 24 h mean (Reilly et al., 1997). Other muscle groups, e.g., quadriceps (Callard et al., 2000) and adductor pollicis (Martin et al., 1999), exhibit similar rhythm characteristics, though these rhythms are variable and are dependent on the muscle group tested (Gauthier et al., 1996; Strutton et al., 2003) and the mode of muscle contraction (Giacomoni et al., 2004). Elbow flexion strength varies with time of day, peaking in the early evening (Frievalds et al., 1983; Gauthier et al., 1996, 1997). Back strength is also higher in the evening than the morning. The rhythm has an amplitude of around 6% of the 24 h mean (Coldwells et al., 1993). When the isometric strength of the knee extensors is measured consecutively during the waking hours of the solar day, two diurnal peaks are evident; one at the end of the morning and another in the late afternoon/early evening (Reilly, 1990; Reilly et al., 1997). The exact mechanism of these changes in strength are as yet unresolved with both peripheral and central factors, as well as a subharmonic in the circadian rhythm, being implicated (Callard et al., 2000; Martin et al., 1999).

Both concentric and eccentric strength have been measured at different times of the solar day using isokinetic dynamometry (Atkinson et al., 1995; Cabri et al., 1988; Ishee and Titlow, 1986). A time of day effect in these variables has been noted at 1.05, 3.14, 4.19, and 5.24 $rad.s^{-1}$ with peak values occurring in the early evening (Wyse et al., 1994; Gauthier et al., 2001; Souissi et al., 2002). Other researchers suggest that the within-day variation in isokinetic performance variables (e.g., peak torque, average power, maximal work) are only observed at faster velocities (3.14 $rad{\cdot}s^{-1}$) (Deschenes et al., 1998). This may be a result of speed-specific circadian variations in muscle strength that occur as a result of fiber type recruitment patterns. These circadian differences do not, however, extend to the shape of the relationship between torque and angular velocity that remains unchanged throughout the day (Gauthier et al., 2001). The characteristics of the rhythms observed in dynamic strength are similar to those observed for isometric contractions, indicating that the features of the circadian rhythms of the musculoskeletal system can be studied using different types of muscle action (Gauthier et al., 2001). The observed rhythms in strength do not seem to be seen as clearly in females (Phillips, 1994) unless superimposed electrical twitches are applied to the muscle (Bambaeichi et al., 2004). This finding may be related to gender differences in muscle mass affecting the amplitude of the rhythm or to central command playing a greater role in females compared to males.

### *Short-Term Performance*

The presence of circadian rhythms in short-term (1 min or less) performance is controversial and may be dependent on the type of exercise performed and the muscle group tested (Bernard et al., 1998). Circadian rhythms have been identified in some laboratory measures of anaerobic power and conventional tests of short-term dynamic activity. Reilly and

Down (1986) observed significant circadian rhythmicity in length of jump, with an acrophase of 17:45 h and an amplitude of 3.4 % of the 24 h mean value, when individual differences in performances were accounted for. Similar rhythm characteristics have also been found for anaerobic power output in a stair run (Reilly and Down, 1992) and vertical jumping performance (Atkinson, 1994; Bernard et al., 1998), but not for sprint times (Bernard et al., 1998).

Short-term performance can also be evaluated using short duration (10–30 sec) maximal ergometer tests. Hill and Smith (1991) measured anaerobic power and capacity with a modified version of the Wingate test at 03:00, 09:00, 15:00, and 21:00 h. Peak and mean power outputs in the evening were found to be higher than at 03:00 h. A circadian rhythm in maximal peak and mean power has also been observed by Souissi et al., (2002, 2003), Melhim (1993), and Deschodt and Arsac (2004). Other studies using similar procedures for both leg and arm ergometry (Down et al., 1985; Reilly and Down, 1986) have not confirmed that performance in the Wingate test depends on time of day. Such differences may be the result of differences in experimental methodologies and the level of sensitivity in the tests employed.

The classical Wingate test was modified by Reilly and Marshall (1991) for performance on a "swim bench." Even though the fourteen competitive swimmers, who volunteered for the study, trained routinely in the early morning, mean and peak power peaked in the evening (18:00 h) with amplitudes of 11 and 14%, respectively.

The results of studies that have examined the effects of time of day on fixed-intensity work-rates close to maximal oxygen uptake ($\dot{V}O_{2\max}$) seem more conclusive than those that have employed supra-maximal exercise such as the Wingate test. Such work-rates would be relevant to athletic events lasting 3–6 min, since this is the typical time an athlete can endure a work-rate equivalent to $\dot{V}O_{2\max}$. Hill et al. (1992) reported that total work performed in high-intensity constant work-rate exercise on a cycle ergometer was significantly higher in the afternoon compared to the morning. These results agree with the findings of Reilly and Baxter (1983) who reported longer work-times (and consequently higher peak lactate production) when set bouts of high intensity exercise was performed at 22:00 h compared to 06:30 h.

### *Physiological Responses to Prolonged Exercise*

Although the physiological responses to exercise are not directly indicative of real athletic performance outcomes, the results of studies on circadian rhythms in these measurements are useful, especially from a mechanisms perspective. The fact that a physiological response to a preset intensity and duration of submaximal exercise varies with time of day is suggestive of some endogenous control of these responses, since factors like motivation to perform maximally are not relevant.

Circadian variation in some cardiovascular parameters such as cardiac output during exercise has yet to be identified (Reilly et al., 2000). Other variables such as blood pressure (Deschenes et al., 1998) and heart rate seem to exhibit circadian rhythmicity (Reilly, 1982; Callard et al., 2001), although there is difficulty in measuring such parameters with the required accuracy under exercise conditions. Cohen and Muehl (1977) measured heart rate at rest, during exercise on a rowing ergometer, and in the recovery period of this exercise at seven times of the solar day with the lowest heart rates occurring between 04:00 and 08:00 h. This temporal pattern was evident both during and after exercise.

The intensity of exercise may be an important determining factor in the observed circadian oscillation (Reilly and Garrett, 1995; Giacomoni et al., 1999). Wahlberg and Åstrand (1973) exercised 20 male subjects at 03:00 and 15:00 h and at both submaximal and maximal exercise loads. Heart rates during exercise were consistently lower at night (3–5 beats $\cdot$ $\mathrm{min}^{-1}$) irrespective of work rate. Other studies using an incremental exercise task have demonstrated the heart rate response just prior to exhaustion, when exercise intensity is maximal, does not vary with time of day (Cohen, 1980). Such discrepancies may be related to a reduction in the range of circadian variability with increasing levels of exercise (Winget et al., 1985) or a failure to detect the circadian rhythm as the ceiling of physiological capability is reached during the exercise test (Atkinson and Reilly, 1996).

The circadian variation in the metabolic response to submaximal exercise is not as conclusive as that of cardiovascular responses, such as heart rate. Horne and Pettit (1984) were unable to detect rhythmicity in the $\dot{V}O_2$ responses to submaximal exercise in untrained athletes. Other investigations (Hill, 1996; Giacomoni et al., 1999) demonstrated rhythms during submaximal exercise that peak from 14:00 to 17:00 h with a range of 13% (Reilly and Brooks, 1982). The time required for $\dot{V}O_{2\max}$ to reach steady state (expressed as the fifth minute value) was not more than 2 min at light exercise intensities and did not vary with time of day (Reilly, 1982). No circadian variations were found for expired carbon dioxide or the time for the respiratory exchange ratio to stabilize during exercise. The amplitude of the rhythm in minute ventilation is amplified during light or moderate exercise. Reilly and Brooks (1982) found that the ventilatory response to exercise displayed rhythmicity that was phased similar to the resting rhythm but 20–40% higher in terms of amplitude. The lack of rhythmicity in metabolic responses to exercise is unequivocal when measured at maximal exercise intensities though Deschenes et al. (1998) have noted a trend for higher values at later points in the day. In both longitudinal (Reilly and Brooks, 1982) and cross-sectional

(Faria and Drummond, 1982; Reilly and Brooks, 1990) studies, it has been found that $\dot{V}O_{2max}$ is a stable function, independent of the time of day of measurement. A critical methodological practice is that subjects not satisfying the criteria that $\dot{V}O_{2max}$ is actually attained (at any time of day) should be recalled to undergo another test.

The lactate threshold, defined as the point at which blood lactate increases exponentially with exercise intensity (Yeh et al., 1983), is commonly used as an indicator of aerobic fitness. It determines the upper limit at which aerobic exercise can be sustained. Forsyth and Reilly (2004) have recently examined the impact of circadian variation on the lactate threshold performed on a rowing ergometer. Reliable methods of evaluating lactated threshold, such as the $D_{max}$ method (Cheng et al., 1992) seem to exhibit circadian variation, which are reflected in changes in physiological parameters such as heart rate and $\dot{V}O_2$. Such findings are invaluable to athletic populations that use such physiological responses to inform training intensities and indicate that lactate threshold tests should be conducted at the same time of day at which the athlete usually trains or competes for accurate prediction of training intensities.

Most of the above research work has concentrated on the physiological responses to exercise in absolute terms rather than in terms of a change in response from the preexercise level. Such an exploration is important again from a mechanisms perspective, since one would be able to separate resting and exercise responses fully. For example, Aldemir et al. (2000) found that the rise, and not just the absolute level, of body temperature during exercise depended on time of day, with a greater rate of change in temperature being observed in the morning.

### *Self-Paced Work*

Cycling activity is frequently used in laboratory conditions to simulate competitive performances. Time trial performance (16.1 km) is improved at 17:30 compared to 07:30 h under laboratory conditions (Atkinson et al., 2005; Figure 2). This may be related to a diurnal variation in pacing strategies with prolonged bouts of cycling that seem to be related to the circadian variation observed in core temperature (Reilly and Garrett, 1995; Figure 3). Such changes in performance may also be accompanied by alterations in an individual's preferred pedal rate and pedal velocity as such variables also vary with the time of day (Moussay et al., 2002, 2003). These changes may reflect alterations in recruitment pattern to benefit coordination and to minimize neuromuscular fatigue as a result of alterations in ankle mobilization rather than changes in muscle torque.

The severity of exercise may be assessed by asking the individual to rate it subjectively on a numerical scale. The subjective reactions to exercise may also be dependent on the time of measurement. Faria and

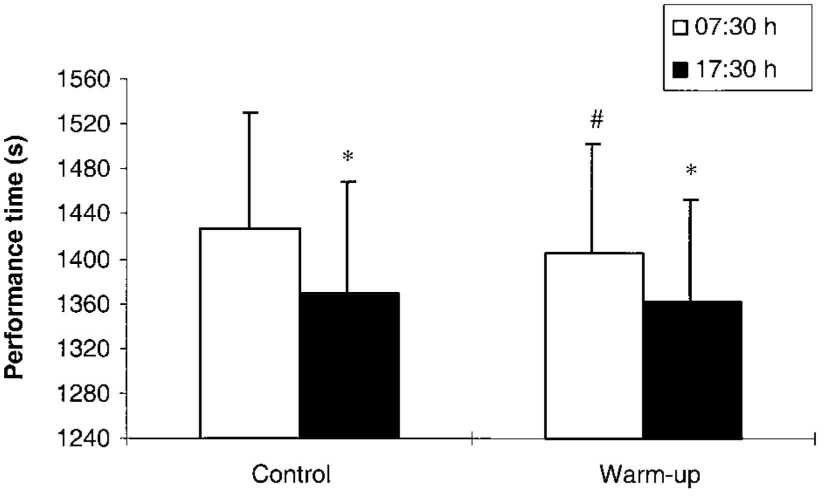


**FIGURE 2** Diurnal variation in 16.1-km time trial performance completed with and without a prolonged pre-exercise warm-up (drawn from data in Atkinson et al., 2005). (*) – times significantly faster in the afternoon compared to the respective morning trail. (#) – time in the morning trial after a warm-up still significantly slower than the afternoon trail performed without a warm-up.

Drummond (1982) 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 was higher during exercise carried out in the early hours of the morning (02:00–04:00 h) than in the evening (20:00–

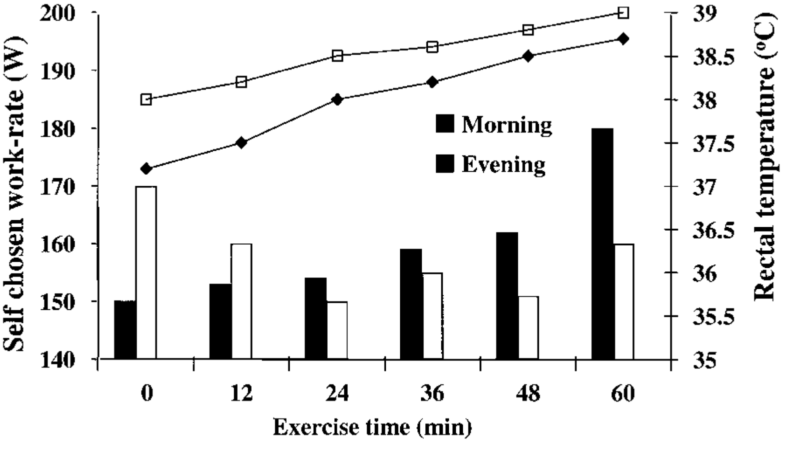


**FIGURE 3** Diurnal variation in self-chosen work rate (bars) and body temperature (line points) during prolonged (60 min) exercise (adapted from Reilly and Garrett, 1995). Open bars – afternoon work-rate, filled bars – morning work-rate, open symbols – afternoon temperature, filled symbols – morning temperature.

22:00 h). Reilly (1990) criticized this study since work rates were set relative to elicited heart rates of 130, 150, and 170 beats · $\min^{-1}$. 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 per se. Studies that have exercised subjects at levels expressed relative to $\dot{V}O_{2\max}$ rather than heart rate have found a circadian variation in RPE at intensities corresponding to lactate threshold (Martin et al., 2001) and maximal exercise (Reilly et al., 2000). However, low-intensity exercise when performed many times within a solar day may mediate a transient increase in RPE in the early afternoon (Reilly et al., 1997).

### *How Sound Are the Experiments?*

Youngstedt and O'Connor (1999) argued that circadian variation in performance could be due to variations in dietary habits. Many researchers have measured performance in the morning test session after an overnight fast, but allowed the subjects to eat up to 3 h prior to the afternoon and early evening test sessions. Such differences in dietary controls may mediate circadian changes in glycogen status. Nevertheless, circadian rhythms have been documented for performance components that are not influenced by glycogen status, such as reaction time and anaerobic power (Atkinson and Reilly, 1996). There are also interesting differences in pacing strategy during prolonged exercise, which seem to indicate some independence from dietary status prior to exercise (Reilly and Garret, 1995).

Youngstedt and O'Connor (1999) thought it possible that the circadian variation in some performance measures is due to the fact that the morning test session follows a period of prolonged immobility during sleep. Evidence against this hypothesis includes the fact that there is often a "turnaround" between 22:00 and 02:00 h when performance decreases, even though subjects have been awake for many hours. In addition and as discussed in detail in the next section, performance rhythms are evident in sleep deprivation studies (constant and prolonged level of activity). Finally, recent work from our laboratory indicates that the diurnal changes in cycling time trial performance are evident even after a vigorous warm-up has been undertaken prior to the morning test (Atkinson et al., 2005; Figure 2).

Circadian rhythms in performance could be explained by general differences in the time of day at which individuals schedule their activity and sleep (Youngstedt and O'Connor, 1999). The evidence from research does not agree with this hypothesis. Several researchers (e.g., Boivin et al., 1992) have shown that performance rhythms are only slightly different between extremes of "chronotype" (morning and evening individuals).

The participants involved in the study by Atkinson et al. (2005) were high in morningness, but selected higher power outputs (without any feedback on what these power outputs were) during cycling in the afternoon. This observation does not support the hypothesis forwarded by Youngstedt and O'Connor (1999) that performance rhythms could be prone to "expectancy" influences. In addition, Piercy and Lack (1988) found only a slight difference in the phasing of circadian rhythms following six week periods of athletic training in the morning compared to the same amount of training in the evening.

Youngstedt and O'Connor (1999) postulated that performance is higher in the afternoon because the participants are more rested from a previous day's exercise. However, this factor has been controlled in the research design of many studies in that physical activity prior to the tests has been discouraged and the order of test times has been counterbalanced (one subject's first test session would be in the morning while another subject would be tested first in the evening) (Atkinson et al., 2005).

The results and characteristics of many of the above studies suggest that there is, in part, an endogenous component to human performance. Nevertheless, there are other chronobiological experiments and protocols, which can be performed to quantify fully the relative influence of endogenous and exogenous factors. Chronobiological theory and protocols enable the causes of observed rhythms to be ascertained, though this has rarely been applied to sports performance. A knowledge of these causes would provide a full rationale for giving advice to the athlete.

## A CHRONOBIOLOGICAL PERSPECTIVE ON THE MECHANISMS OF CIRCADIAN RHYTHMS IN SPORTS PERFORMANCE

### Methodological Considerations

There are two methods by which the separation of endogenous and exogenous components can be made experimentally. The first of these requires the direct (exogenous) effects of the environment and sleep-wake cycle to be reduced as much as possible. A protocol to do this is called a "constant routine" (Mills et al., 1978; Czeisler et al., 1985). When this protocol is applied to the circadian rhythm of core temperature (which will be affected by the sleep-activity cycle), it is performed as follows. The subject is required: to stay awake and sedentary (or, preferably, lying down and relaxed) for at least 24 h in an environment of constant temperature, humidity, and lighting; to engage in similar activities throughout, generally reading or listening to music, and to take, identical meals at regularly-spaced intervals. When this protocol is undertaken, it is observed (Figure 4) that the rhythm of core temperature does not disappear, even though its amplitude becomes decreased. Three deductions can be made from this result:

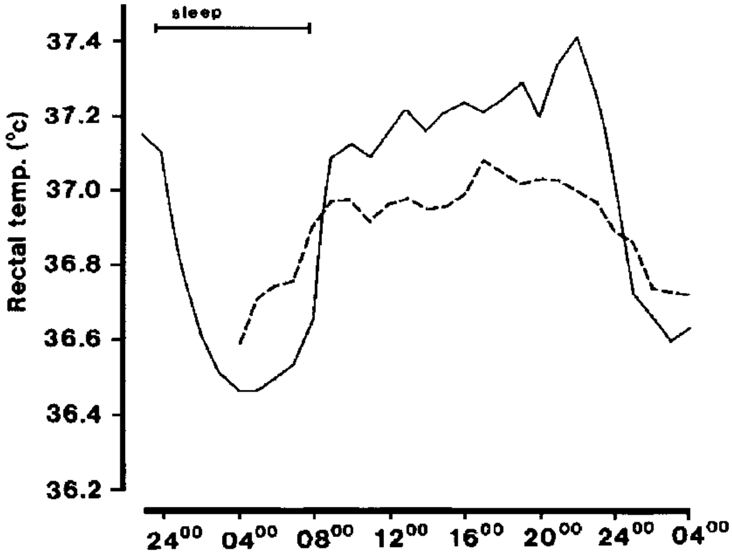


**FIGURE 4** Mean circadian changes in core (rectal) temperature measured hourly in 8 subjects: living normally and sleeping from 24:00 to 08:00 h (solid line); and then woken at 04:00 h and spending the next 24 h on a "constant routine" (dashed line). (Based on Minors and Waterhouse, 1981.)

1. The component of the temperature rhythm that remains must arise from within the body. This is the "endogenous" component and it is attributed to the "body clock."
2. The effect of the environment and the sleep-wake cycle can be inferred from the fact that the two curves differ; this difference is the exogenous component of the original rhythm.
3. In subjects living normally (as is the case in Figure 4), these two components are in phase, both raising core temperature in the daytime and lowering it at night.

The second method for separating the exogenous and endogenous components of a circadian rhythm is "forced desynchronization" (Kleitman and Kleitman, 1953; Boivin et al., 1992). This approach is based on the observation that the body clock is not able to adjust to an imposed lifestyle whose period differs substantially from 24 h—that is, is outside the range of entrainment. Therefore, if subjects live on "days" of 27 h in length (with 9 h of sleep and 18 h of activity each "day"), their exogenous component is equal to this period; however, the endogenous component of the circadian rhythm cannot follow this imposition but rather retains a period close to 24 h—its intrinsic period, or *tau*. With this protocol, 8 × 27 h "days" approximately equal 9 × *tau*, and this length of time is called a "beat cycle." One result of this protocol is that the endogenous component of the rhythm moves continually out of phase with the sleep-wake cycle and then back into phase. If a variable (for example, core temperature) is measured regularly throughout a beat cycle, then it can be averaged in one of two ways. First, if the results are averaged using *tau* as the reference time, then any phase of this average rhythm is mixed with all phases of the imposed (27 h) sleep-wake cycle. That is, provided that the activity during the sleep-wake cycle is similar day-by-day, any effects due to it will be averaged out, and the rhythm observed will represent the endogenous component of the measured rhythm. Second, if the temperatures are averaged using 27 h as the reference time, then any phase of this average rhythm is mixed with all phases of the endogenous (period = *tau*) cycle. That is, any effects due to the body clock will be averaged out, and the rhythm observed will represent the exogenous component of the measured rhythm.

### Application of Chronobiological Principles to Athletic Performance

It is clear from the above that the demonstration of circadian rhythmicity in physical performance when subjects are living normally does not enable the relative importance of the exogenous and endogenous components of the rhythm to be completely determined. Direct investigations of the endogenous and exogenous components of physical activity require measurements to be made during constant routines or forced desynchronization protocols. However, no such studies seem to have been performed. The main reason for this with regard to the constant routine protocol is that performing the tests would exert a direct effect upon variables, such as core temperature, so negating the aim of the protocol. (It will be recalled that this protocol requires the subjects to be resting throughout.) Such a criticism is less cogent when applied to the forced desynchronization protocol, however, and there would seem to be value in perfoming such studies.

Even so, there is one study (Reilly and Walsh, 1981) in which the heart rate and percentage of time active was measured indoors in four soccer players during a sponsored exhibition, in which self-chosen activity was continuous for about 86 h. During this time, the environment and activity regimen were fairly constant, the players being required to be active for 55 min each hour. Therefore, the study can be regarded as one using a modified version of a constant routine. The results showed a trend in both variables to decrease with time but, superimposed upon this, there were transient falls in heart rate and activity in the middle of each nighttime, and transient peaks in the middle of each daytime. In another study (Davenne and Lagarde, 1995), elite cyclists cycled for 24 h at a constant rate (estimated to be 45% of their maximal capacity as measured in the daytime) in a gymnasium that was maintained at a constant temperature. Subjects were allowed to stop for massages, and it was observed that the frequency and length of these increased between 02:00–08:00 h. These studies suggest, respectively, that self-paced activity is less in the middle of the night than in the middle of the day and that, if the amount of activity is constant, then it is harder to sustain in the middle of the night. While the results cannot be attributed to the environment (which remained constant), the extent to which the rhythms observed reflect changes in the ability to exercise and/or the motivation to do so remains unclear, but the results indicate that some endogenous component is present.

The results also illustrate a general parallelism between rhythms of physical performance and core temperature. (Core temperature was measured in the study of Davenne and Lagarde, 1995, and can reasonably be assumed to have been normally phased in the study of Reilly and Walsh, 1981.) This parallelism has been found in many studies that have been performed under normal conditions, and a causal link between the two has often been assumed, since activities of the muscles and nerves, the cardiovascular and respiratory systems, and metabolism are all promoted by a rise of temperature. However, such an interpretation does lead to the paradoxical suggestion that, since the resting temperature is lowest in the middle of the night, the *greatest* amount of exercise could be performed at this time, since core temperature could rise by a greater amount then than during the middle of the day (assuming that the body temperature at which heat stress causes fatigue is constant). Indeed, the fact that core temperature starts lower in the earlier part of the daytime accounts for the observation that self-chosen work rate can be better sustained at this time in exercise exceeding 60 min in duration, when core temperature is rising from a lower starting point (Atkinson and Reilly, 1996).

Instead of considering that the circadian rhythms of sports performance are wholly exogenous in origin, an alternative interpretation would be to consider that the complex changes required for exercise have both exogenous and endogenous components, and that the endogenous component is a reflection of the body clock. This implies that the circadian response to exercise is similar in origin to the rhythm of core temperature, and this could account for the general parallelism between the two rhythms. There is a considerable amount of evidence that the circadian rhythm of core temperature results from changes in the "set-point" of heat loss mechanisms (summarized in Aldemir et al., 2000; Waterhouse et al., 2004), and that these can be considered to be reflections of the activity of the body clock. It seems likely that similar differences with time of day might exist in the central and peripheral components of the response to exercise. Since the constituents of athletic performance—metabolism, the cardiovascular and respiratory systems, muscle strength, and the control of movement by the central nervous system—have all been shown to have some endogenous component, even though this might be rather small on some cases, it is illogical to consider that athletic perfomance might possess no such component.

## Jet Lag: Impact and Mechanisms

Whatever the detailed nature of the origin of the circadian rhythmicity of physical performance, unless it contains no endogenous component whatsoever, problems in sports performance would be predicted to arise in the days immediately after a time-zone transition due to the slow adjustment of the body clock to a change in local time (Waterhouse et al., 1997). As a result, the normal synchrony between the endogenous and exogenous components of circadian rhythms (see Figure 4) will be lost until adjustment of the body clock to the new time zone has taken place. The lack of adjustment of the body clock will mean that activity will be performed at times that are no longer near to the temperature maximum; for example, after a flight to Eastern Australia (10 time zones to the east of the UK), activity at 15:00 h by local time will initially coincide with the temperature minimum. Also, the inappropriately timed body clock will mean that sleep will be more difficult and fractionated than normal; for example, after the flight to Eastern Australia, sleep will initially be attempted at about 14:00–22:00 h by "body time."

One of the most obvious effects of these disruptions is that subjects suffer from "jet lag". This is characterized by an assortment of symptoms including fatigue (and yet inability to sleep at the new night time), headache, irritability, losses of concentration and motivation, and gastrointestinal disorders including indigestion, loss of appetite, and bowel irregularities (Waterhouse et al., 1997). The exact interpretation to be placed on "jet lag" depends on the individuals and details of their journey (Waterhouse et al., 2002) and also on the time of day when it is measured (Waterhouse et al., 2003). Thus, in the early morning and late evening, estimates of jet lag correlate most with aspects of the recent and forthcoming sleep, respectively; in the middle of the day, by contrast, the higher correlations are with the perceived falls in motivation and the ability to concentrate.

Even though many aspects of physical performance appear to be little affected by sleep loss, for mood, motivation, and mental performance, sleep loss is more deleterious (Folkard, 1990; Meney et al., 1998; Waterhouse et al., 2001). While the excitement of a competition might override these effects, when the routine of training prior to an event is concerned, the combination of effects of sleep loss and jet lag is likely to be a negative influence. Trainers, coaches, and the individuals themselves must be aware of this, and expect training to be more arduous and less rewarding in the days immediately after a time-zone transition.

Field studies of performance after a time-zone transition have sometimes been unconvincing with regard to showing a deterioration in performance (Youngstedt and O'Connor, 1999). This might reflect the fact that the design of the study and the difficulty of making accurate measurements in such circumstances, the exogenous component of the rhythms (which will have adjusted to the time zone) are very marked, or that any circadian effects are overridden by the excitement of the moment. The difficulty of introducing a control condition (e.g., a flight of a similar duration but one which does not cross any time zones) into jet lag studies means that the design of these studies is at best quasi-experimental (Atkinson and Nevill, 2001). Single assessments at a particular time of day before and after the flight (O'Connor et al., 1991) can be misleading due the fact that the timing of the circadian rhythm will be different at the destination compared to at home. A test performed at 18:00 h at the new destination could be at a different time in terms of the body clock. Multiple measurements of performance at the destination (e.g., Reilly et al., 2001; Figure 5) are therefore essential and would offer greater insight into the relative endogenous nature of the rhythms.

The fact is that elite athletes do suffer from jet lag (Edwards et al., 2000; Waterhouse et al., 2000; Lemmer et al., 2002) and there are reports of

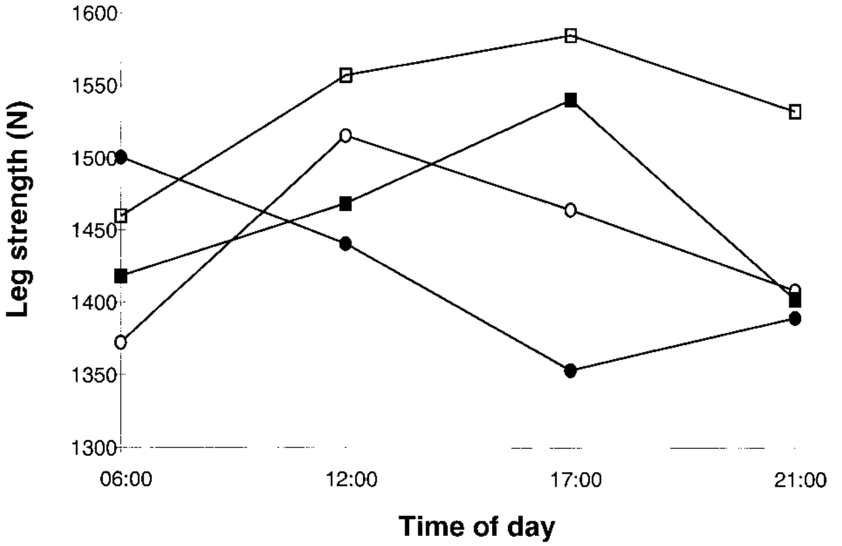


**FIGURE 5** A quasi-experiment (Reilly et al., 2001) into the effects of transmeridian travel on a performance variable (leg extension strength). Measurements were obtained four times a day on four post-flight days. The diurnal profiles suggest gradual adjustment of the circadian rhythm to the new time zone (5 hours difference). Open bars – afternoon work-rate, filled bars – morning work-rate, open symbols – afternoon temperature, filled symbols – morning temperature.

how to promote adjustment of athletes to time-zone transitions (Cardinali et al., 2002; O'Connor et al., 2004). Promoting adjustment hardly seems appropriate unless there exists at least the possibility that performance will be impaired! In some cases, there is field evidence that performance is impaired and that the circadian rhythms are phased more appropriately for the time zone just left (Reilly et al., 2001; Figure 5). In summary, therefore, while more and better field studies are required, chronobiological considerations and the limited evidence available indicate that physical performance is likely to be impaired immediately after a time-zone transition, particularly if it entails routine training rather than a competitive event.

## CONCLUSION

We have discussed circadian rhythms in sports performance from both an applied and basic research perspective. From an applied perspective, the main considerations that influence whether time of day does affect sports performance are external validity of the research sample and how close the selected performance tests mimic real sports competitions. From a basic perspective, the validity of the study conclusions depends on how well exogenous factors have been controlled or discounted in the experiment.

The optimal time for performance will be dependent on the type of activities required in the sport and their relative importance to the overall performance (Reilly et al., 2000) as the component circadian rhythms may peak at different times (Winget et al., 1985). Analysis of the different rhythms in performance would suggest that the performance of skill-based sports and those requiring complex competitive strategies, decisions and the delivery, and recall of coaching instructions is best completed in the morning. Sports that require substantial physical efforts should be completed later in the day. The timing of sports that require both elements is less clear. It should, however, be noted that these suggestions may represent an oversimplification of the situation.

There is a wealth of information from both applied and experimental work, which, when considered together, suggests at least some input of endogenous mechanisms to circadian variations in sports performance.

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