

Circadian rhythms in exercise performance: Implications for hormonal and muscular adaptation

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Abstract

Almost all physiological and biochemical processes within the human body follow a circadian rhythm (CR). In humans, the suprachiasmatic nucleus regulates sleep-wake cycle and other daily biorhythms in line with solar time. Due to such daily physiological fluctuations, several investigations on neuromuscular performance have reported a distinct CR during exercise. Generally, peak performances have been found to occur in the early evening, at approximately the peak of core body temperature. The increase in core body temperature has been found to increase energy metabolism, improve muscle compliance and facilitate actin-myosin crossbridging. In addition, steroidal hormones such as testosterone (T) and cortisol (C) also display a clear CR. The role of T within the body is to maintain anabolism through the process of protein synthesis. By contrast, C plays a catabolic function and is involved in the response of stress. Due to the anabolic and catabolic nature of both T and C, it has been postulated that a causal relationship may exist between the CR of T and C and muscular performance. This review will therefore discuss the effects of CR on physical performance and its implications for training. Furthermore, this review will examine the impact of muscular performance on CR in hormonal responses and whether could variations in T and C be potentially beneficial for muscular adaptation.

Key words: Diurnal variation, steroidal hormones, neuromuscular adaptation.

Introduction

The concept of circadian rhythms (CR) in human physical performance has been extensively researched (Atkinson and Reilly, 1996; Drust et al., 2005; Redlin and Mrosovsky, 1997; Reilly, 1990). Physical activities involving aerobic fitness, anaerobic fitness, fine and gross motor skills have displayed a clear CR (Bessot et al., 2007; Kline et al., 2007; Reilly et al., 2007). As such, there has been great interest in trying to elucidate the mechanisms responsible for the distinction in exercise performance throughout the day. In humans, the primary circadian pacemaker is the suprachiasmatic nucleus (SCN). The SCN, located within the hypothalamus, receives direct input regarding the solar cycle from the retina (Hastings and Herzog, 2004). With this information provided through the retino-hypothalamic pathway, the SCN co-ordinates daily biological rhythms (ie. hormone secretion, temperature fluctuation, neural activation) in line with the solar time and sleep-wake cycle (Buijs et al., 2003; Waterhouse et al., 2005). These rhythmic oscilla-

tions of biological processes govern many of our habits and actions, and also influence the activities that we perform during the day. Many physiological functions associated with athletic performance have also been shown to follow a specific CR (Winget et al., 1985). Functions such as resting levels of sensorimotor, perceptual, and cognitive performance and several neuromuscular, behavioural, cardiovascular, and metabolic variables have been found to occur in the early evening, in line with peak body temperature rhythm (Cappaert, 1999).

Apart from diurnal variations in physiological systems, the preferential for daytime or nighttime activities is another important psychological factor that must be considered when studying CR in exercise performance. Such a concept has long been recognized with Kleitman (1949) documenting that some people have the consistent preference for daytime activities whilst others have the preference for nighttime activities. The contrasting time preference between individuals (commonly known as 'chronotypes') have been shown to differ in various physiological rhythms such as sleep-wake patterns, biorhythms (ie. core temperature and hormones), sleep inertia, food intake rhythms and maximal oxygen consumption during exercise (Baehr et al., 2000; Hill et al., 1988; Kerkhof, 1985). Due to the wide spectrum of morning-evening preferential, it is believed that this trait reflects the underlying ability or inability in reacting to the various circadian systems (Chelminski et al., 1997). In addition, Youngstedt and O'Connor (1999) also identified seven other variables, that may contribute to the lack of performance in the mornings, which might help to explain the CR in exercise performance; differences in nutritional status from morning to evening; decreased flexibility in the morning; insufficient time to recover from sleep inertia; preferred time of training; differences in the amount of rest between test sessions; individual difference in the physiological response; and differences in motivation and expectancy effect.

The effects of the androgen testosterone (T) on strength and muscle adaptations to exercise have been well documented (Bhasin et al., 2001; Sinha-Hikim et al., 2002). One of the main functions of T is to maintain anabolism by promoting protein synthesis within the muscular system (Ferrando et al., 1998). Evidence by Kvorning et al. (2006) supported that suppression of endogenous T attenuated strength adaptation in healthy male participants, thus, implying the importance of this hormone in muscular adaptations. Under normal circumstances, the

circadian profile of T is one that displays an early morning maximum before slowly declining as the day progresses (Guignard et al., 1980). By contrast, cortisol (C) is a glucocorticoid that is often used as a marker of both physiological and psychological stress. Prolonged elevation of C has been shown to exhibit an inhibition effect on the neuromuscular system. Tafet et al. (2001) reported a negative correlation between physical performance and prolonged elevated salivary C levels. The circadian profile of C is similar to that of T, which peaks in the morning before slowly declining throughout the day and elevating again within the first few hours of sleep (Guignard, et al., 1980). As both steroidal hormones and exercise performance display such distinct CR and that they have strong implications for exercise adaptation, it may be possible that a relationship exist between both variables despite having an inverse pattern of CR (Hayes et al., 2010).

Therefore, this review aims to outline mechanisms underlying CR in exercise, and the effects it has on exercise performance. In addition, this review will also look at the relationship between the CR of steroidal hormones, T and C, and the CR of exercise performance.

Evidence of CR in exercise performance

There are many underlying factors contributing to a CR in physical performance. These factors can stem from both internal (physiological) and external (environmental) changes that occur throughout the day. Identifying a single cause of performance fluctuation is often difficult because performance fluctuations can be affected by different physiological systems occurring at the same time. Reilly and Waterhouse (2009) identified three major determinants in the contribution towards a CR in sporting performance. The first determinant takes into consideration external (environmental) influences that are usually uncontrollable. These factors include, but not limited to, ambient temperature and physical or psychological arousal from the surrounding environment. The second determinant involves internal (physiological) influences that stem from within the individual (ie. individual's own biological rhythm and their ability to adapt to changes in those rhythms). Lastly, lifestyle (psycho-biological) influences affecting timing preferential in activities, sleeping patterns and the ability to cope with sleep inertia and loss must also be considered.

Controlling for factors affecting physical performance is often difficult, and in some cases, almost impossible to achieve. Environmental factors, either positive or negative in nature, are inevitable in any competition or exercise setting and are often seen as an uncontrollable aspect. Endogenous mechanisms, however, may be manipulated by training and knowledge of the mechanisms of CR may be useful in achieving positive exercise adaptations. As mentioned earlier, CR in exercise performance with morning lows and evening peaks are common findings in many laboratory and field tests (for a summary, refer to Table 1). Traditionally, core body temperature has been used as the primary indicator for CR in biological processes and physical performance. An increase in body

temperature may lead to an increase in carbohydrate utilization over fat as a fuel source, and also, possibly facilitating actin-myosin crossbridge mechanics within the musculoskeletal unit (Starkie et al., 1999). Due to this reason, peak performances have been postulated to occur around the early evenings as it coincides with peak body temperature (Cappaert, 1999). To demonstrate the effects of increased body temperature on exercise performance, a recent study by Taylor et al. (2011) found that by extending the warm-ups in morning test sessions, the attenuation of power and force loss in countermovement jumps may be observed. By adding an additional 20 minutes of active warm-up to a controlled warm-up program, they were able to increase body temperature that was comparable to that in an afternoon session. It was therefore concluded that the increase in body temperature was responsible for the increase in ballistic power output and other jump variables. The results by Taylor and colleagues were also in partial agreement with an earlier study by Atkinson et al. (2005) who examined the influence of warm ups on cycling time trial performances. Results from their study confirmed that warm-up generally improved time trial performance at both times of the day, but mean cycling time was still slower at 0730h than 1730h even after warm-ups. Intra-aural temperature was maintained at a higher temperature throughout the time trials at 1730h, irrespective of whether the cyclists performed a warm-up or not. Their results suggested that superior physical performance was still observed in the afternoon even when subjects performed a vigorous 25-min warm-up in the morning. Another study by Souissi et al. (2007) also confirmed a time-of-day effect on the aerobic contribution during high-intensity exercise. Their study compared peak power, mean power, total work done, and oxygen consumption between a morning and afternoon testing session using a Wingate test. It was found that aerobic contribution was higher in the afternoon session in conjunction with increased body temperature. Furthermore, power loss was greater in the morning than afternoon. From these experiments, it seems clear that a relationship exist between the CR of core body temperature and physical performance capabilities, thus highlighting the importance of active warm-up sessions in the mornings or in colder climates to improve exercise performance.

Although still widely accepted as the primary circadian indicator of physical performance, recent evidence has challenged the traditional views between the relationship of body temperature and exercise performance. Recent studies looking at different time-of-day neuromuscular performance have revealed a distinct CR in physiological variables independent of temperature changes. An example was provided by Martin et al. (1999) who investigated the effect of CR on the neural activation and contractile properties of the human adductor pollicis muscle. Their findings indicated that the force produced during a maximal voluntary contraction (MVC) was higher in the evening than the morning. Since the increase in force of the MVC and electrically induced contractions were similar, it was suggested that the modulation of peripheral contractile mechanisms were responsible for diurnal fluctuations in force. They also proposed that an increase in

Table 1. Effects of circadian rhythm on physical performance.

Attributes	Mode of Experiment	Study	Summary
Aerobic	Swimming	Arnett (2001) ^{c,t} Arnett (2002) ^{a,t} Martin and Thompson (2000) ^{a,t}	These studies have demonstrated an increased physical performance capability and VO _{2max} in the later part of the day. The increase in physical performance was also highly correlated to body temperature, which was also found to be consistently higher later during the day.
	Cycling	Atkinson et al. (2005) ^{a,t} Edwards et al. (2005) ^{a,t} Reilly and Garrett (1998) ^{a,ut}	
Anaerobic/ Strength/Power	Swimming	Kline et al. (2007) ^{a,t} Martin et al. (2007) ^{a,t}	Anaerobic fitness, strength and power have shown to be significantly higher during the day. Although increases in physical performance are correlated to the increase in body temperature, these studies have also shown an increase in neural drive and better coordination between agonist-antagonist contractions. Specific time-of-day training may help improve physical performance at the particular time, however, better performance was still observed later during the day.
	Cycling/Wingate	Bernard et al. (1998) ^{a,ut} Bessot et al. (2007) ^{a,t} Bessot et al. (2006) ^{a,t} Giacomini et al. (2006) ^{a,ut} Hill et al. (1992) ^{a,ut} Moussay et al. (2003) ^{a,t} Reilly and Down (1992) ^{a,ut} Souissi et al. (2002) ^{c,ut} Souissi et al. (2007) ^{a,ut}	
	Resistance/Plyometrics	Bird and Tarpenning (2004) ^{a,t} Häkkinen et al. (1988) ^{a,t} Kraemer et al. (2001) ^{a,t} Pereira et al. (2011) ^{a,ut} Sedliak et al. (2008) ^{a,ut} Sedliak et al. (2008) ^{c,ut} Sedliak et al. (2007) ^{c,ut} Taylor et al. (2011) ^{a,t} Teo et al. (2011) ^{a,t}	
Agility/Coordination	Soccer	Reilly et al. (2007) ^{a,t}	A consistent finding in racquet sport was an increase in serve shot velocity and handgrip on the racquet, however, serve accuracy was not consistent with time-of-day variation. Soccer specific skills were more consistent with time-of-day variation, showing increased ability to dribble and more accurate shots later in the day.
	Racquet Sport	Atkinson and Speirs (1998) ^{a,t} Edwards et al. (2005) ^{a,t}	
Psycho-social	Time-of-day preference	Brown et al. (2008) ^{a,t} Hill et al. (1988) ^{a,ut}	Although studies are limited, the results demonstrate better performance in physical activity during the time of an individual's chronotypological preference (ie. Morning chronotypes perform better in the earlier part of the day).

(a) acute = < 4 weeks protocol, (c) chronic = > 8 weeks protocol; (t) trained subjects = > 12 months training experience, (ut) untrained subjects = < 12 months training experience

force production in the afternoon may be due to enhanced calcium release from the sarcoplasmic reticulum, increased calcium sensitivity of the contractile proteins, and altered myosin ATP_{ase} activity. Another study by Guette et al. (2005) also reported similar findings supporting the evidence that changes at the muscular level may be responsible for diurnal fluctuations in force. Their results demonstrated a significant time-of-day effect on MVC torque of the knee extensors for both dominant and non-dominant legs when, with highest values found at 1800h. They suggested that because the actin-myosin crossbridge process is largely affected by the concentration of inorganic phosphate and that inorganic phosphate presents a CR, the presence of CR in muscular performance could also partly be accounted for by intracellular diurnal variations of inorganic phosphate.

The results from these studies suggest that a variety of mechanisms are involved in the CR of physical per-

formance. These underlying mechanisms usually present their own distinct circadian profile, however, almost all of them seem to show peak in the later parts of the day. It is also because of the fact that CR in sporting performance is affected by multi-factorial mechanisms, that it makes the elucidation of these mechanisms extremely difficult.

Impact of exercise on circadian T and C response

Surprisingly, there is very little evidence in the literature to suggest that exercise, especially strength training, have any influence on the circadian profile of T and C. Several investigations have suggested that time-of-day-specific strength training (TST) can potentially result in modifications to resting hormone levels, however, little is still known about the effects of short-term and long-term training adaptations to the CR of these hormones. A study by Häkkinen et al. (1988) showed that changes in serum T

and C levels due to short-term training might be more indicative of physiological stress response due to TST rather than an actual change in CR. They investigated the daily adaptive responses in both neuromuscular and endocrine systems to a 1-week intensive strength-training period with two training sessions per day in eight elite weight lifters. During the 1-week training period, an increase in total and free serum T levels was found during the afternoon sessions. Total and free serum T concentrations were elevated in both morning and afternoon measures, but after just one day of rest, both markers declined back to pre-training levels. The afternoon sessions also resulted in similar changes in serum C and somatotropin concentrations, but morning C concentrations did not significantly alter throughout the training period. The results from Häkkinen and colleagues were similar to those in a later study by Kraemer et al. (2001). They investigated the effects of heavy resistance training on the waking CR of salivary T and hypothesized that acute bouts of training in the mornings was not sufficient to alter the circadian pattern of salivary T. Salivary samples of ten resistance-trained men were collected pre-, during, post-training and every hour after training to ascertain the circadian pattern of salivary T. Their results concurred with their hypothesis, as there was no significant modification to the circadian pattern of salivary T. The results from these studies suggest that the influences of short-term training protocols were insufficient to alter the circadian profile of T and C. In light of these findings, Sedliak et al. (2007) proposed that a longer training period lasting several weeks was probably needed if any modification in resting hormone levels were to be observed. They found that a 10-week TST program modified resting serum concentrations and CR of T and C as well as improved maximum isometric strength of knee extensors. Results from their study indicated that after ten weeks of TST, overall serum T and C concentrations from 0700h to 2030h declined on both test days; however, the decline in serum T was not significant.

Due to the lack of substantial evidence on the effects of exercise on the circadian profile of T and C, it remains to be seen if exercise can, in fact, exert a strong enough influence to alter the CR of these hormones. From the little evidence that is available, acute exercise and short-term training do not seem to offer the prospect of altering the circadian profiles of T and C to induce any sort of positive strength and muscular adaptations. Long-term TST, however, does seem to offer some promise of influencing hormonal response to a certain extent and improve physical performance capabilities at the particular time of training. More studies are required to investigate the effects of different training stimulus (ie. type of exercise, intensity and work/rest ratio) on the CR of T and C and also to determine if longer (> 10 weeks) TST may induce more permanent changes on T and C.

Impact of circadian T and C response on muscle and strength adaptation

If acute TST were unable to exert any influence to the circadian profile of T and C, can there then be a causal relationship between the CR of T and C with strength and

muscle adaptation? Studies that have tried to look at the relationship between diurnal fluctuations of T and C on neuromuscular adaptations have, by far, shown contrasting results. Sale et al. (2008) provided evidence of the negative effects of increased C on neuromuscular functioning in the mornings. They compared the efficacy of the neuromuscular system in the morning and evening by stimulation of the primary motor cortex using transcranial magnetic stimulation. They found that motor-evoked potentials, ascertained by electromyographic recordings, were lower in the morning and attributed the cause to increased C levels. To confirm their findings, they administered oral hydrocortisone to subjects and administered the same protocol in the afternoon. Similar decrements in motor-evoked potential were found after the administration of oral hydrocortisone. Although their findings did demonstrate a decrease in neuromuscular efficacy after orally administering hydrocortisone, it is also highly possible that neurotransmitters (ie. GABA, dopamine and serotonin) involved in the up-regulation of inhibitory networks within the CNS may have also influenced lower motor-evoked potentials in the mornings as they also present a CR (Monti and Jantos, 2008; Murillo-Rodriguez et al., 2009). Another study by Bird and Tarpinning (2004) demonstrated that the CR of hormonal profiles may play a part in creating an environment more favorable for anabolism, therefore optimizing strength and muscle adaptations associated with resistance exercise. They showed that by performing heavy-resistance exercises in the evenings, C and T/C ratio profiles was positively altered. Pre-exercise C concentrations were also lower in the evening, thus increasing T/C ratio suggesting a reduced catabolic environment beneficial for training adaptations. However, due to the fact that the experiment only tested subjects across two separate days, whether the changes in T/C ratio would be permanent or transient, remains unknown at this point. Furthermore, the subjects used in the study were individuals who have at least twelve months of prior weight-lifting experience. It is likely that the positive alteration in hormonal profile observed was inevitably influenced by the subject's training status and training time preference as opposed to an untrained person (Lusa Cadore et al., 2009).

By contrast, a recent study by Teo et al. (2011) found that acute diurnal variations of T and C did not display a strong relationship with the CR of force and power output. Utilizing twenty subjects with at least twelve months of resistance training experience, four time-of-day sessions (0800h, 1200h, 1600h and 2000h) were scheduled across four different days for the measure of dynamic and isometric force and power. Before each testing session and on the other three time points, salivary samples were collected for the analysis of T and C. Although both hormonal responses (T and C) and physical performance displayed a circadian pattern, no correlation was found between the two variables. This was further supported by West et al. (2010) who provided evidence of no such relationship between strength increases and changes to endogenous anabolic hormones (growth hormones, IGF-1 and T). They divided participants into two separate groups; one group performed isolated arm curls to maintain basal hormonal concentrations, and another group

performed the identical arm exercise followed by an immediate high-volume leg resistance exercise to elicit large increases in endogenous hormones. After 15 weeks, increases in muscle cross-sectional area, type I and type II muscle fibres were similar between both groups. They concluded that increased endogenous hormones were not responsible for strength and hypertrophic adaptations.

Seemingly, the notion that diurnal fluctuations of hormonal profiles can influence daily changes in neuromuscular performance remains doubtful. Daily differences between peak and nadirs of anabolic and catabolic hormones are naturally small and are unlikely to exert any significant effect on the neuromuscular system. Any observable neuromuscular change by endogenous anabolic hormones to may therefore have to be influenced by long-term training protocols which is more likely to result in an overall elevation of anabolic hormones throughout the day (Ahtiainen et al., 2003). In light of the contrasting evidence provided, it is suggested that the interpretation of diurnal fluctuation hormonal profiles associated with exercise performance must be done with caution, as there is only limited evidence at this point in time. It remains to be seen if indeed an association can be made linking the CR of T and C with strength and muscular adaptations.

Conclusion

The current review has presented evidence that biological and psychological rhythms exert a major effect on physical performance. Although enhanced performance is most frequently seen in the early evenings, taking into consideration an individual's chronotype and using specific time-of-day training seems to be an effective method in improving physical performance at a particular point of time. The use of active warm-ups, especially in the mornings or cold environments, should also be performed so as to increase body temperature prior to any competitions or training. With regards to the relationship between CR of hormones and physical performance, it remains to be seen if a causal relationship may be established. The interpretation of data associated with modification of circadian hormonal profiles must be done with caution, as those changes may only be transient in nature and can be influenced by an individual's level of training experience.

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Key points

- A distinct CR can be observed in physical performance.
- CR of exercise performance is highly associated with CR in core body temperature
- Both T and C display a clear CR, however, the current evidence does not show a clear relationship with neuromuscular adaptations.
- TST is able to induce changes in physical performance variables at the particular time point, but not for the circadian profile of T and C.

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