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Physical and metabolic demands of training and match-play in the elite football player

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Physical and metabolic demands of training and match-play in the elite football player

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Abstract
In soccer, the players perform intermittent work. Despite the players performing low-intensity activities for more than 70% of the game, heart rate and body temperature measurements suggest that the average oxygen uptake for elite soccer players is around 70% of maximum ($\dot{V}O_{2max}$). This may be partly explained by the 150 – 250 brief intense actions a top-class player performs during a game, which also indicates that the rates of creatine phosphate (CP) utilization and glycolysis are frequently high during a game. Muscle glycogen is probably the most important substrate for energy production, and fatigue towards the end of a game may be related to depletion of glycogen in some muscle fibres. Blood free-fatty acids (FFAs) increase progressively during a game, partly compensating for the progressive lowering of muscle glycogen. Fatigue also occurs temporarily during matches, but it is still unclear what causes the reduced ability to perform maximally. There are major individual differences in the physical demands of players during a game related to physical capacity and tactical role in the team. These differences should be taken into account when planning the training and nutritional strategies of top-class players, who require a significant energy intake during a week.

Keywords: *Match-play activity pattern, substrate utilization, muscle metabolites, fatigue, recovery after matches, training intensity*

Introduction

Since the last FIFA conference on nutrition in soccer in 1994, soccer at the elite level has developed and much research regarding match performance and training has been conducted. It is also clear that science has been incorporated to a greater extent in the planning and execution of training. Earlier scientific studies focused on the overall physiological demands of the game, for example by performing physiological measurements before and after the game or at half-time. As a supplement to such information, some recent studies have examined changes in both performance and physiological responses throughout the game with a special focus on the most demanding activities and periods. New technology has made it possible to study changes in match performance with a high time resolution. Another aspect to have received attention in practical training is information regarding individual differences in the physical demands to which players are exposed in games and training. These differences are not only related to the training status of the players and their playing position, but also to their specific tactical roles. Thus, some top-class clubs have integrated the tactical and physical demands of the players into their fitness training.

This review addresses information on the demands of the game at a top-class level and provides insights into training at the elite level. Thus, it should form the basis for deciding nutritional strategies for these players. The review deals mainly with male players, but at relevant points information about female players is provided.

Match activities

Many time–motion analyses of competitive games have been performed since the first analysis of activities in the 1960s (Bangsbo, 1994; Bangsbo, Nørregaard, & Thorsøe, 1991; Krustrup, Mohr, Ellingsgaard, & Bangsbo, 2005; Mayhew & Wenger,

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1985; Mohr, Krustrup, & Bangsbo, 2003; Reilly & Thomas, 1979; Rienzi, Drust, Reilly, Carter, & Martin, 1998; Van Gool, Van Gerven, & Boutmans, 1988). The typical distance covered by a top-class outfield player during a match is 10 – 13 km, with midfield players covering greater distances than other outfield players. However, most of this distance is covered by walking and low-intensity running, which require a limited energy turnover. In terms of energy production, the high-intensity exercise periods are important. Thus, it is clear that the amount of high-intensity exercise separates top-class players from players of a lower standard. In one study, computerized time–motion analysis demonstrated that international players performed 28% more ($P < 0.05$) high-intensity running (2.43 vs. 1.90 km) and 58% more sprinting (650 vs. 410 m) than professional players of a lower standard (Mohr *et al.*, 2003). It should be emphasized that the recordings of high-intensity running do not include a number of energy-demanding activities such as short accelerations, tackling, and jumping. The number of tackles and jumps depends on the individual playing style and position in the team, and at the highest level has been shown to vary between 3 and 27 and between 1 and 36, respectively (Mohr *et al.*, 2003). Most studies have used video analysis followed by manual computer analysis to examine individual performance during a match. New developments in technology have allowed the study of all 22 players during each one-sixth of a second throughout a match, and the systems are used by many top teams in Europe. There are reasons to believe that in the future such systems will provide significant additional information and will soon find their way into scientific research. For example, using a high time resolution, Bangsbo and Mohr (2005) recently examined fluctuations in high-intensity exercise, running speeds, and recovery time from sprints during several top-class soccer matches. They found that sprinting speed in games reached peak values of around $32\,\mathrm{km \cdot h^{-1}}$ and that sprints over more than 30 m demanded markedly longer recovery than the average sprints (10 – 15 m) during a game.

There are major individual differences in the physical demands of players, in part related to his position in the team. A number of studies have compared playing positions (Bangsbo, 1994; Bangsbo *et al.*, 1991; Ekblom, 1986; Reilly & Thomas, 1979). In a study of top-class players, Mohr *et al.* (2003) found that the central defenders covered less overall distance and performed less high-intensity running than players in the other positions, which probably is closely linked to the tactical roles of the central defenders and their lower physical capacity (Bangsbo, 1994; Mohr *et al.*, 2003). The full-backs covered a considerable distance at a high-intensity and by sprinting, whereas they performed fewer headers and tackles than players in the other playing positions. The attackers covered a distance at a high intensity equal to the full-backs and midfield players, but sprinted more than the midfield players and defenders. Furthermore, Mohr *et al.* (2003) showed that the attackers had a more marked decline in sprinting distance than the defenders and midfield players. In addition, the performance of the attackers on the Yo-Yo intermittent recovery test was not as good as that of the full-backs and midfield players. Thus, it would appear that the modern top-class attacker needs to be able to perform high-intensity actions repeatedly throughout a game.

The midfield players performed as many tackles and headers as defenders and attackers. They covered a total distance and distance at a high-intensity similar to the full-backs and attackers, but sprinted less. Previous studies have shown that midfield players cover a greater distance during a game than full-backs and attackers (Bangsbo, 1994; Bangsbo *et al.*, 1991; Ekblom, 1986; Reilly & Thomas, 1979). These differences may be explained by the development of the physical demands of full-backs and attackers, since, in contrast to earlier studies (Bangsbo, 1994), Mohr *et al.* (2003) observed that players in all team positions experienced a significant decline in high-intensity running towards the end of the match. This indicates that almost all elite soccer players utilize their physical capacity during a game. Individual differences are not only related to position in the team. Thus, in the study by Mohr *et al.* (2003), within each playing position there was a significant variation in the physical demands depending on the tactical role and the physical capacity of the players. For example, in the same game, one midfield player covered a total distance of 12.3 km, with 3.5 km being covered at a high intensity, while another midfielder covered a total distance of 10.8 km, of which 2.0 km was at a high intensity. The individual differences in playing style and physical performance should be taken into account when planning the training and nutritional strategy.

Aerobic energy production in soccer

Soccer is an intermittent sport in which the aerobic energy system is highly taxed, with mean and peak heart rates of around 85 and 98% of maximal values, respectively (Ali & Farrally, 1991; Bangsbo, 1994; Ekblom, 1986; Krustrup *et al.*, 2005; Reilly & Thomas, 1979). These values can be "converted" to oxygen uptake using the relationship between heart rate and oxygen uptake obtained during treadmill running (Bangsbo, 1994; Esposito *et al.*, 2004;

Krustrup & Bangsbo, 2001). This appears to be a valid method, since in studies in which heart rate and oxygen uptake (by the so-called K_4 apparatus) have been measured during soccer drills, similar heart rates have been observed for a given oxygen uptake as found during treadmill running (Castagna *et al.*, 2005; Esposito *et al.*, 2004). However, it is likely that the heart rates measured during a match lead to an overestimation of the oxygen uptake, since such factors as dehydration, hyperthermia, and mental stress elevate the heart rate without affecting oxygen uptake. Nevertheless, with these factors taken into account, the heart rate measurements during a game seem to suggest that the average oxygen uptake is around 70% $\dot{V}O_{2max}$. This suggestion is supported by measurements of core temperature during a soccer game. Core temperature is another indirect measurement of energy production during exercise, since a linear relationship has been reported between rectal temperature and relative work intensity (Saltin & Hermansen, 1966). During continuous cycling exercise at 70% $\dot{V}O_{2max}$ with an ambient temperature of 20°C, the rectal temperature was 38.7°C. In soccer, the core temperature increases relatively more compared with the average intensity due to the intermittent nature of the game. Hence, it has been observed that at a relative work rate corresponding to 60% of $\dot{V}O_{2max}$, the core temperature was 0.3°C higher during intermittent than continuous exercise (Ekblom *et al.*, 1971). Nevertheless, core temperatures of 39–40°C during a game suggest that the average aerobic loading during a game is around 70% $\dot{V}O_{2max}$ (Ekblom, 1986; Mohr *et al.*, 2004b; Smodlaka, 1978).

More important for performance than the average oxygen uptake during a game, may be the rate of rise in oxygen uptake during the many short intense actions. A player's heart rate during a game is rarely below 65% of maximum, suggesting that blood flow to the exercising leg muscle is continuously higher than at rest, which means that oxygen delivery is high. However, the oxygen kinetics during the changes from low- to high-intensity exercise during the game appear to be limited by local factors and depend, among other things, on the oxidative capacity of the contracting muscles (Bangsbo *et al.*, 2002; Krustrup, Hellsten, & Bangsbo, 2004a). The rate of rise of oxygen uptake can be changed by intense interval training (Krustrup *et al.*, 2004a).

Anaerobic energy production in soccer

That elite soccer players perform 150–250 brief intense actions during a game (Mohr *et al.*, 2003) indicates that the rate of anaerobic energy turnover is high at certain times. Even though not studied directly, the intense exercise during a game leads to a high rate of creatine phosphate breakdown, which to some extent is resynthesized in the following low-intensity exercise periods (Bangsbo, 1994). On the other hand, creatine phosphate may decline (i.e. below 30% of resting values) during parts of a game if a number of intense bouts are performed with only short recovery periods. Analysis of creatine phosphate in muscle biopsies obtained after intense exercise periods during a game have provided values above 70% of those at rest, but this is likely to be due to the delay in obtaining the biopsy (Krustrup *et al.*, 2006).

Mean blood lactate concentrations of 2–10 $\text{mmol} \cdot \text{l}^{-1}$ have been observed during soccer games, with individual values above 12 $\text{mmol} \cdot \text{l}^{-1}$ (Agnevik, 1970; Bangsbo, 1994; Ekblom, 1986; Krustrup *et al.*, 2006). These findings indicate that the rate of muscle lactate production is high during match-play, but muscle lactate has been measured in only a single study. In a friendly game between non-professional teams, it was observed that muscle lactate rose four-fold (to around 15 $\text{mmol} \cdot \text{kg dry weight}^{-1}$) compared with resting values after intense periods in both halves, with the highest value being 35 $\text{mmol} \cdot \text{kg dry weight}^{-1}$ (Krustrup *et al.*, 2006). Such values are less than one-third of the concentrations observed during short-term intermittent exhaustive exercise (Krustrup *et al.*, 2003). An interesting finding in that study was that muscle lactate was not correlated with blood lactate (Figure 1). A scattered relationship with a low correlation coefficient has also been observed between muscle lactate and blood lactate when participants performed repeated intense exercise using the Yo-Yo intermittent recovery test (Krustrup *et al.*, 2003) (Figure 1). This is in contrast to continuous exercise where the blood lactate concentrations are lower but reflect well the muscle lactate concentrations during exercise (Figure 1). These differences between intermittent and continuous exercise are probably due to different turnover rates of muscle lactate and blood lactate during the two types of exercise, with the rate of lactate clearance being significantly higher in muscle than in blood (Bangsbo, Johansen, Graham, & Saltin, 1993). This means that during intermittent exercise in soccer, the blood lactate concentration can be high even though the muscle lactate concentration is relatively low. The relationship between muscle lactate and blood lactate also appears to be influenced by the activities immediately before sampling (Bangsbo *et al.*, 1991; Krustrup & Bangsbo, 2001). Thus, the rather high blood lactate concentration often seen in soccer (Bangsbo, 1994; Ekblom, 1986; Krustrup *et al.*, 2006) may not represent a high lactate production in a single action during the game, but rather an accumulated/balanced response to a number of high-intensity activities. This is important to take into account when interpreting blood lactate concentration as a measure of muscle lactate concentration. Nevertheless, based

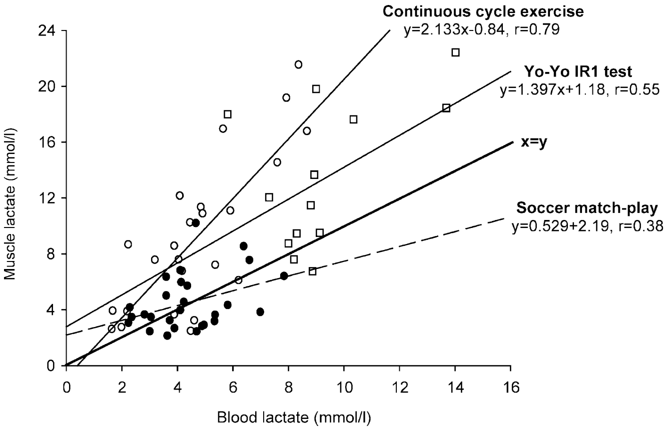

Figure 1. Individual relationships between muscle lactate (expressed in mmol per litre of cell water) and blood lactate during a soccer match (solid circles; data from the present study), at exhaustion in the Yo-Yo intermittent level 1 recovery test (solid squares; data from Krustrup *et al.*, 2003), and after 20 min of continuous cycle exercise at 80% $\dot{V}O_{2max}$ (open circles; data from Krustrup *et al.*, 2004b).

on several studies using short-term maximal exercise performed in the laboratory (Gaitanos *et al.*, 1993; Nevill *et al.*, 1989), and the finding of high blood lactate and moderate muscle lactate concentrations during match-play, it is suggested that the rate of glycolysis is high for short periods of time during a game.

Substrate utilization during a soccer match

To provide nutritional strategies for a soccer player it is important to understand the energy demands and to know which substrates are utilized during a game. Muscle glycogen is an important substrate for the soccer player. Saltin (1973) observed that muscle glycogen stores were almost depleted at half-time when the pre-match values were low ($\sim 200\,\text{mmol} \cdot \text{kg}$ dry weight^{-1}). In that study, some players also started the game with normal muscle glycogen concentrations ($\sim 400\,\text{mmol} \cdot \text{kg}$ dry weight^{-1}), with the values still being rather high at half-time but below $50\,\text{mmol} \cdot \text{kg}$ dry weight^{-1} at the end of the game. Others have reported concentrations of $\sim 200\,\text{mmol} \cdot \text{kg}$ dry weight^{-1} after a match (Jacobs, Westlin, Karlsson, Rasmusson & Houghton, 1982; Krustrup *et al.*, 2006; Smaros 1980), indicating that muscle glycogen stores are not always depleted in a soccer game. However, analyses of single muscle fibres after a game have revealed that a significant number of fibres are depleted or partly depleted at the end of a game (Krustrup *et al.*, 2006; see below).

It has been observed that the concentration of free fatty acids (FFA) in the blood increases during a game, most markedly so during the second half (Bangsbo, 1994; Krustrup *et al.*, 2006). The frequent periods of rest and low-intensity exercise in a game allow for a significant blood flow to adipose tissue, which promotes the release of free fatty acids. This effect is also illustrated by the finding of high FFA concentrations at half-time and after the game. A high rate of lipolysis during a game is supported by elevated glycerol concentrations, even though the increases are smaller than during continuous exercise, which probably reflects a high turnover of glycerol (e.g. as a gluconeogenic precursor in the liver; Bangsbo, 1994). Hormonal changes may play a major role in the progressive increase in the concentrations of free fatty acids. The insulin concentrations are lowered and catecholamine concentrations are progressively elevated during a match (Bangsbo, 1994), stimulating a high rate of lipolysis and thus the release of free fatty acids into the blood (Galbo, 1983). The effect is reinforced by lowered lactate concentrations towards the end of a game, leading to less suppression of mobilization of free fatty acids from the adipose tissue (Bangsbo, 1994; Bülow & Madsen, 1981; Galbo, 1983; Krustrup *et al.*, 2006). The changes in free fatty acids during a match may cause a higher uptake and oxidation of such acids by the contracting muscles, especially during the recovery periods in a game (Turcotte, Kiens, & Richter, 1991). In addition, a higher utilization of muscle triglycerides might occur in the second half due to elevated catecholamine concentrations (Galbo, 1992). Both processes may be compensatory mechanisms for the progressive lowering of muscle glycogen and are favourable in maintaining a high blood glucose concentration.

Fatigue during a soccer game

A relevant question when planning training is when fatigue occurs during a soccer game and what the cause of that fatigue is. Several studies have provided evidence that players' ability to perform high-intensity exercise is reduced towards the end of games in both elite and sub-elite soccer (Krustrup *et al.*, 2006; Mohr *et al.*, 2003, 2004; Mohr, Krustrup, & Bangsbo, 2005; Reilly & Thomas, 1979). Thus, it has been demonstrated that the amount of sprinting, high-intensity running, and distance covered are lower in the second half than in the first half of a game (Bangsbo *et al.*, 1991; Bangsbo, 1994; Mohr *et al.*, 2003; Reilly & Thomas, 1979). Furthermore, it has been observed that the amount of high-intensity running is reduced in the final 15 min of a top-class soccer game (Mohr *et al.*, 2003) and that jumping, sprinting, and intermittent exercise performance is lowered after versus before a soccer game (Mohr *et al.*, 2004b, 2005; Rebelo, 1999) (Figure 2). However, the underlying mechanism behind a reduced exercise performance at the end of a soccer game is unclear. One candidate is depletion of glycogen stores, since development of fatigue during prolonged intermittent exercise has been associated with a lack of muscle glycogen. Moreover, it has been demonstrated that elevating muscle glycogen before prolonged intermittent exercise using a carbohydrate diet elevates performance during such exercise (Balsom, Gaitanos, Söderlund, & Ekblom, 1999; Bangsbo, Nørregaard, & Thorsøe, 1992a). Some (Saltin, 1973) but not all (Jacobs *et al.*, 1982; Krustrup *et al.*, 2006; Smaros, 1980) authors have observed that muscle glycogen during a game decreases to values below that required to maintain maximal glycolytic rate ($\sim$200 mmol · kg dry weight^{-1}; Bangsbo *et al.*, 1992b). In a study by Krustrup *et al.* (2006), the muscle glycogen concentration at the end of the game was reduced to 150–350 mmol · kg dry weight^{-1}. Thus, there was still glycogen available. However, histochemical analysis revealed that about half of the individual muscle fibres of both types were almost depleted or depleted of glycogen. This reduction was associated with a decrease in sprint performance immediately after the game. Therefore, it is possible that such a depletion of glycogen in some fibres does not allow for a maximal effort in single and repeated sprints. Nevertheless, it is unclear what the mechanisms are behind the possible causal relationship between muscle glycogen concentration and fatigue during prolonged intermittent exercise.

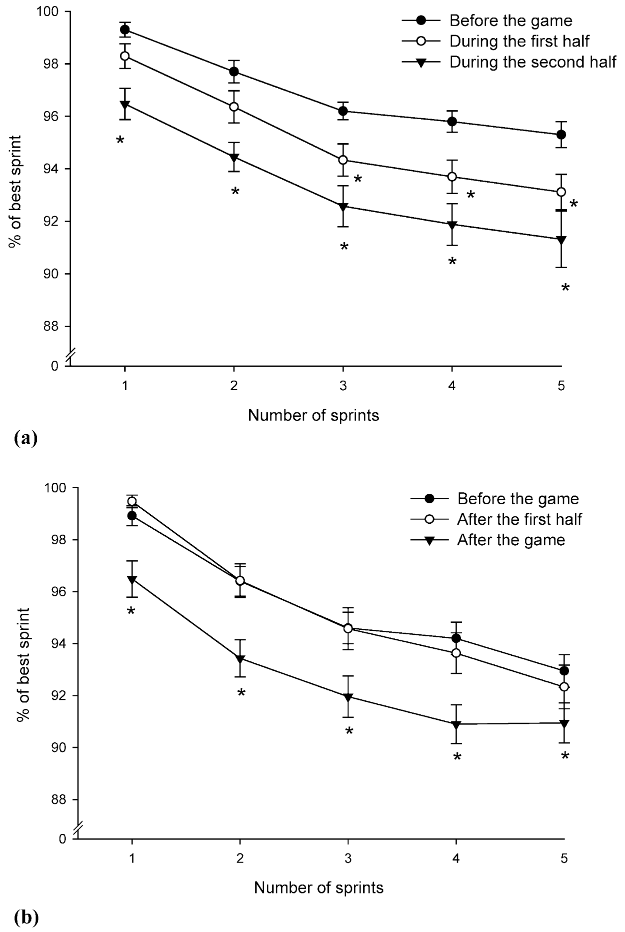

Figure 2. Sprint time (% of the best sprint) of five 30 m sprints separated by a 25 s period of recovery. (a) Before the game (solid circles) and after an intense period in the first (open circles) and second half (solid triangles). (b) Before the game (solid circles) and after the first (open circles) and second (solid triangles) half. Data are means ± standard errors of the mean.

Factors such as dehydration and hyperthermia may also contribute to the development of fatigue in the later stages of a soccer game (Magal *et al.*, 2003; Reilly, 1997). Soccer players have been reported to lose up to 3 litres of fluid during games in temperate thermal environments and as much as 4–5 lires in a hot and humid environment (Bangsbo, 1994; Reilly, 1997), and it has been observed that 5 and 10 m sprint times are slowed by hypohydration amounting to 2.7% of body mass (Magal *et al.*, 2003). However, in the study by Krustrup *et al.* (2006) a significant reduction in sprint performance was observed, although the fluid loss of the players was only about 1% of body mass, and no effect on core or muscle temperature was observed in a study with a similar loss of fluid (Mohr *et al.*, 2004b). Thus, it would appear that fluid loss is not always an important component in the impaired performance seen towards the end of a game.

Temporary fatigue during a soccer match

Recent research using computerized time–motion analysis of top-class professional male soccer players has indicated that players become fatigued during a game (Mohr *et al.*, 2003). Thus, in the 5 min following the most intense period of the match, the amount of high-intensity exercise was reduced to levels below the game average. This phenomenon has also been observed in elite women's soccer (unpublished observations). These findings suggest that performance was reduced after a period of intense exercise, which could have been a result of the natural variation in the intensity in a game due to tactical or psychological factors. However, in another study players performed a repeated sprint test immediately after intense match-play and also at the end of each half (Krustrup *et al.*, 2006). It was shown that after intense periods in the first half, the players' sprint performance was significantly reduced, whereas at the end of the first half the ability to perform repeated sprints had recovered (Figure 2). Together, these results suggest that soccer players experience fatigue temporarily during the game.

An interesting question is what causes fatigue during a game of soccer. Fatigue during match-play is a complex phenomenon with a number of contributing factors. One of these may be cerebral in nature, especially during hot conditions (see Meeusen, Watson, & Dvorak, 2006; Nybo & Secher, 2004). However, it has been shown that for well-motivated individuals the cause of fatigue is muscular in nature (Bigland-Ritchie, Furbush, & Woods, 1986). In the study by Krustrup *et al.* (2006), the decrement in performance during the game was related to muscle lactate. However, the relationship was weak and the changes in muscle lactate were moderate. Furthermore, several studies have shown that accumulation of lactate does not cause fatigue (Bangsbo *et al.*, 1992; Krustrup *et al.*, 2003; Mohr *et al.*, 2004a). Another candidate for muscle fatigue during intense exercise is a low muscle pH (Sahlin, 1992). However, muscle pH is only moderately reduced (to about 6.8) during a game and no relationship with lowered performance has been observed (Krustrup *et al.*, 2006). Thus, it is unlikely that elevated muscle lactate and lowered muscle pH cause fatigue during a soccer game. It may be due to low muscle creatine phosphate concentrations, since performance in intense intermittent exercise has been demonstrated to be elevated after a period of creatine supplementation (Balsom, Seger, Sjödin, & Ekblom, 1995; Greenhaff, Bodin, Söderlund, & Hultman, 1994). After intense periods in a soccer game, muscle creatine phosphate has been observed to be lowered by only 25% (Krustrup *et al.*, 2006). This was due in part to the fast recovery of creatine phosphate and the 15 – 30 s delay in collecting the muscle biopsy in that study. Creatine phosphate may have been significantly lower in individual muscle fibres, since creatine phosphate stores have been reported to be almost completely depleted in individual fibres at the point of fatigue after intense exercise (Søderlund & Hultman, 1991). However, during the Yo-Yo intermittent recovery test where the speed is progressively increased to the point of exhaustion, no changes were observed in muscle creatine phosphate in the final phase of exercise (Krustrup *et al.*, 2003). This fact argues against creatine phosphate having an inhibitory effect on performance during intense intermittent exercise. During the matches studied by Krustrup *et al.* (2006), muscle inosine monophosphate (IMP) concentrations were higher than before the game and elevated blood NH_3 levels also indicate that the adenosine monophosphate (AMP) deaminase reaction was significantly stimulated. On the other hand, the muscle IMP concentrations were considerably lower than observed during exhaustive exercise (Hellsten, Richter, Kiens, & Bangsbo, 1999) and ATP was only moderately reduced. Thus, it is unlikely that fatigue occurred as a result of a low energy status of the contracting muscles. Together, these findings suggest that temporary fatigue in soccer is not causally linked to high muscle lactate, high muscle acidosis, low muscle creatine phosphate, or low muscle ATP.

One has to look for other explanations of the fatigue that occurs after periods of intense exercise in soccer. It has been suggested that the development of fatigue during high-intensity exercise is related to an accumulation of potassium in the muscle interstitium and the concomitant electrical disturbances in the muscle cell (Bangsbo *et al.*, 1996; Sejersted & Sjøgaard, 2000). This hypothesis is supported by the observation of muscle interstitial potassium concentrations of more than $11\,\text{mmol}\cdot\text{l}^{-1}$ during exhaustive exercise (Mohr *et al.*, 2004a; Nielsen *et al.*, 2004; Nordsborg *et al.*, 2003), which according to *in vitro* studies is high enough to depolarize the muscle membrane potential and reduce force development markedly (Cairns & Dulhunty, 1995). In addition, it has been observed that the maximal activity of the Na^+/K^+ pump is reduced with different types of exercise (Fraser *et al.*, 2002), which could lead to greater transient accumulation of potassium during a match. Mean arm venous plasma potassium concentration during a soccer game has been observed to be $5\,\text{mmol}\cdot\text{l}^{-1}$, with individual values above $5.5\,\text{mmol}\cdot\text{l}^{-1}$ (Krustrup *et al.*, 2006), which is only slightly lower than values observed 30 s after exhaustive incremental intermittent exercise (Krustrup *et al.*, 2003). However, these plasma values do not provide a clear picture of the concentrations around the contracting muscle fibres in soccer. Further research is needed to reveal what causes fatigue during soccer matches.

Training of a top-class player

Based on the analysis of the game it is clear that the training of elite players should focus on improving their ability to perform intense exercise and to recover rapidly from periods of high-intensity exercise. This is done by performing aerobic and anaerobic training on a regular basis (Bangsbo, 2005).

In a typical week for a professional soccer team with one match to play, the players have six training sessions in 5 days (i.e. one day with two sessions), with the day after the match free. If there is a second match in midweek the team often trains once a day on the other days. However, there are marked variations depending on the experience of the coach. Table I presents examples of programmes for an international top-class team during the season.

To obtain information about the loading of the players, heart rate monitoring can be used. It should, however, be emphasized that such measurements do not provide a clear picture about the anaerobic energy production during training. Figure 3 shows an example of the heart rate response for two top-class players during high-intensity aerobic training (drill "Pendulum"; Bangsbo, 2005) consisting of eight 2 min exercise periods separated by 1 min recovery periods. The length of time the heart rate was 80 – 90, 90 – 95, and 95 – 100% of maximum was 8.3, 10.9, and 4.7 min respectively for one player, and 4.8, 11.1, and 5.3 min respectively for the other player. To understand the total demand on a player during a period of training, it is also important to perform measurements in the training sessions that are not specifically aimed at improving the fitness of the players. Table II shows the heart rates of three players during all training sessions over a 2 week preparation period for the World Cup in 2002, with the exception of two strength training sessions. The midfield player had a mean heart rate of 146 and 143 beats · min^{-1} respectively during the training sessions in week 1 and 2, corresponding to 78 and 76% of maximal heart rate, with heart rates of 90 – 95 and 95 – 100% of maximum for 144 and 11.5 min in week 1 and 135 and 8.5 min in week 2 respectively. The estimated mean energy expenditure was 7.6 and 7.5 MJ · day^{-1} in week 1 and 2 respectively. In comparison, the attacker had a lower relative mean heart rate (~70% maximum) and an estimated mean energy expenditure of 5.6 and 6.3 MJ · day^{-1} in week 1 and 2 respectively. Note the marked individual differences in heart rate distribution and energy demand among the players (Table II). Such differences should be taken into account when planning training and nutritional strategies for individual players.

Table I. An in-season weekly programme for a professional soccer team when playing one or two matches a week.

Day	One match a week	Two matches a week
Sunday	Match	Match
Monday	Free	Low-/moderate-intensity aerobic training, 30 min Strength training, 30 min
Tuesday	Warm-up, 15 min Technical/tactical, 30 min High-intensity aerobic training, 23 min Play, 15 min	Warm-up, 15 min Technical/tactical, 30 min High-intensity aerobic training, 10 min Play, 15 min
Wednesday	*Morning* Strength training, 60 min *Afternoon* Warm-up, 15 min Technical/tactical, 30 min Speed endurance training, 20 min	Match
Thursday	Warm-up, 15 min Technical/tactical, 30 min Play, 30 min	Low-/moderate-intensity aerobic training, 40 min Strength training, 30 min
Friday	Warm-up/technical, 25 min Speed training (long), 20 min High-intensity aerobic training, 18 min	Warm-up/technical, 25 min Speed training (long), 10 min High-intensity aerobic training, 20 min
Saturday	Warm-up/technical, 25 min Speed training (short), 20 min Play, 30 min	Warm-up/technical, 25 min Speed training (short), 20 min Play, 30 min
Sunday	Match	Match

Note: For a definition of "training", see Bangsbo (2005).

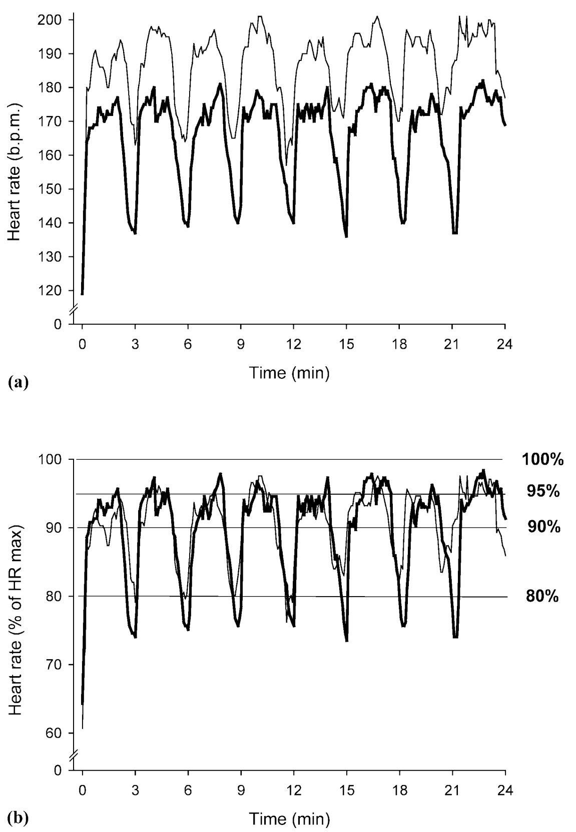

Figure 3. (a) Absolute (beats · min^{-1}) and (b) relative (percent of maximal) heart rate for two players during a high-intensity aerobic exercise drill called "Pendulum". The maximal heart rate of the players was 206 and 185 beats · min^{-1} respectively.

Muscle glycogen concentrations and adaptations to training

A study with the elite players of the Swedish team Malmø FF in the 1970s not only showed that muscle glycogen was lowered after a game, as discussed above, but also that muscle glycogen concentration was only 50% of the pre-match value 2 days after the match (Jacobs *et al.*, 1982). In a recent study, in addition to confirming these earlier findings, we observed that even though the players received a high carbohydrate diet after the game, they only had slightly higher muscle glycogen (Figure 4). Thus, muscle glycogen may be low before a training session 2 days after a game, which is often associated with the players' feelings of tiredness. This has obviously a negative effect on the intensity of the training session. However, one important aspect in relation to the lower muscle glycogen prior to the training should be discussed. Several studies have focused on the effect of nutrition intake and muscle glycogen concentration on the adaptations that occur with training. Pilegaard *et al.* (2002) found that reducing muscle glycogen before exercise elevated the transcriptional activation of some metabolic genes in response to

Table II. Training frequency, duration, heart rate response, and estimated energy expenditure during 2 weeks of training for a defender, a midfield player, and an attacker in the Danish National team in the first part of the preparation period for the 2002 World Cup.

		Number of training sessions (*n*)	Time per session (min)	Total training time (min)	Mean heart rate (beats · min^{-1})	Mean heart rate (% of max)	Heart rate zone*			Energy expenditure per week (MJ)	Energy expenditure per day (MJ)
							80 – 90% max (min)	90 – 95% max (min)	95 – 100% max (min)		
Defender	Week 1	9	83.5	751	143.1	71.9	76.9	31.3	10.1	42.9	6.1
	Week 2	11	82.3	905	142.5	71.6	67.4	53.7	3.9	51.3	7.3
Midfielder	Week 1	10	85.3	853	146.4	77.5	156.3	143.5	11.5	53.4	7.6
	Week 2	11	79.0	869	143.1	75.7	133.7	135.5	8.5	52.6	7.5
Attacker	Week 1	8	85.9	687	129.8	68.3	63.3	52.1	16.2	39.0	5.6
	Week 2	9	80.9	728	136.0	71.6	104.4	60.1	21.9	44.4	6.3

*Expressed as a percentage of maximal heart rate.

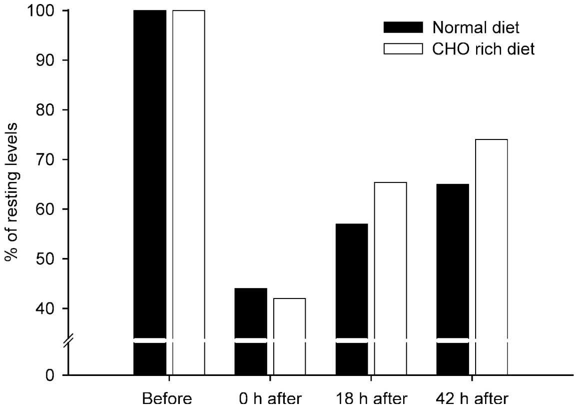

Figure 4. Muscle glycogen concentration (expressed as a percentage of resting values) after a competitive soccer match. Biopsies were obtained from the vastus lateralis muscle 0, 18, and 42 h after a game on two occasions, with a normal diet (solid bars) and a diet high in carbohydrates (open bars).

exercise. Similarly, glucose supplementation has been shown to attenuate the increase in muscle mRNA for several enzymes and transporters, such as PDK-4, UCP-3, and GLUT-4, following exercise (Cluberton, McGee, Murphy, & Hargeaves, 2005; Kuo *et al.*, 1999). However, it is unclear what the effect is at the protein level. A recent study compared training twice a day every second day with one training session a day (Hansen *et al.*, 2005). The increase in citrate synthase was significantly greater in the group that trained twice a day, whereas no differences were observed for the increase in 3-hydroxyacyl-CoA dehydrogenase (HAD). It was proposed that the difference was caused by the group training twice a day performing a number of training sessions (in the afternoon) with lowered muscle glycogen. However, the true differences in citrate synthase were small, and it is unclear whether such an effect also applies to well-trained athletes. Furthermore, the quality of training should also be taken into consideration. The amount of high-intensity work performed during a soccer training session is likely to be higher if the players have high glycogen stores before the training. For a further discussion of these issues, see the article by Hawley, Tipton and Millard-Stafford (2006).

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