Muscle Fatigue during Football Match-Play

Clarke, N.D. , Reilly, T. and Drust, B.

REVIEW ARTICLE

Sports Med 2008; 38 (5): 357-367
0112-1642/08/0005-0357/$48.00/0

Muscle Fatigue during Football Match-Play

Thomas Reilly, *Barry Drust* and *Neil Clarke*

Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK

Contents

Abstract

One of the consequences of sustaining exercise for 90 minutes of football match-play is that the capability of muscle to generate force declines. This impairment is reflected in the decline of work-rate towards the late part of the game. Causes of this phenomenon, which is known as fatigue, and some of its consequences are considered in this article. The stores of muscle glycogen may be considerably reduced by the end of the game, especially if there has not been a tapering of the training load. Thermoregulatory strain may also be encountered, resulting in a fall in physical performance, or there may be a reduced central drive from the nervous system. The decline in muscle strength may increase the predisposition to injury in the lower limbs. Central fatigue may also occur with implications for muscle performance. Strategies to offset fatigue include astute use of substitutions, appropriate nutritional preparation and balancing pre-cooling and warm-up procedures. There is also a role for endurance training and for a pacing strategy that optimizes the expenditure of energy during match-play.

In sports where performance must be sustained for a prolonged period, fatigue is represented by the inability to sustain the required work-rate. This decline in physical capability coincident with the onset of fatigue has been defined as a reduced capacity to generate the required level of force.[1] Whilst this phenomenon has been examined extensively in individual sports, such as marathon running and cycling,[2] there has been comparatively little research attention given to the study of fatigue in conditions where work-rate is determined not only by self-chosen exercise intensity, but also by the prevailing demands of competition on the entire team as a unit. Both these considerations apply in field games such as association football (soccer).

In the original narrative reports of Mosso,[3] fatigue was considered to constitute a general physiological breakdown as a prelude to exhaustion. By the middle of the last century, the concept of fatigue was viewed from an interdisciplinary perspective, encompassing perceptual-motor and cognitive phenomena as well as physiological factors.[4] In heavy physical work, fatigue was a consequence of sustained overload on the individual, the severity of work being indicated by energy expenditure, heart rate or core body temperature.[5] As the concepts were applied to high-performance exercise, explanations of fatigue were related to the depletion of energy stores,[6] thermal strain,[7] a failure of excitation-contraction at local muscle level[8] and multiple causes in combination.[9] More recently, central factors have been explored, highlighting the role of the nervous system in the maintenance of muscle performance. It has been proposed that metabolic activity is continuously regulated at rest and during exercise to prevent catastrophic system failure by means of different homeostatic control mechanisms in the brain and peripheral physiological systems.[10] The evidence for the occurrence of fatigue during football match-play is considered in this article. The various mechanisms of fatigue are considered, as are the consequences for a reduced physical capability. Means of preventing or delaying fatigue are proposed.

1. Factors Affecting Work-Rate

Motion analysis has been adopted as a means of recording the work-rate of players during a game.[11] The original method validated by Reilly and Thomas[12] entailed registering the activity of a single individual over the entire game. The activity was broken down according to the intensity of exercise, the distance covered in each discrete bout and superimposed on these events were the types of activity associated with direct involvement in the game. A variation to this approach was the recording of activity on a time-base from video analysis. More recently multi-camera systems synchronized by computer have been adopted by the major European football clubs: data for all players can be determined simultaneously and provided in detailed feedback to the coach or trainer.[13] Whilst these computer-aided systems appear to yield data comparable with the conventional approach, they have not yet been satisfactorily validated for measurement of acceleration and velocity over short distances. This limitation applies to the majority of analytical systems used to support professional soccer teams.

The distance covered per game was found to vary with positional role, the highest distances being covered by midfield players, while those in central defence covered the least distance among those outfield positions. There was a high correlation between maximal aerobic power and total distance covered.[12] This link between aerobic fitness and work-rate was subsequently reported by others,[9] with applications to both junior[14] and female[15] players. The distance covered has also been related to the level of competitive play, the higher distances being covered in the top leagues. This difference is reflected also in the core temperature of players, for example, Ekblom[16] found mean rectal temperatures 0.4°C higher in the top Swedish League compared with values for a lower professional league. Whilst these rises in temperature are likely to be accompanied by sweat losses and a consequent hypohydration, the variability in sweat losses between individuals is likely to preclude a direct link between dehydration and muscle fatigue during match-play.[17]

Irrespective of the level of play and physical fitness of participants, the fall in work-rate in the second half is a consistent finding (see table I). Even as fitness levels improve to enable players to cope better with the demands of the game, these demands

Table I. Comparison of distances covered in the first and second halves of football match-play in several teams[a]

Team	Distance
Belgian players	Covered 444 m more in the first half[22]
English League	Decline in work-rate was inversely related to $\dot{V}O_{2max}$[12]
Danish players	Distance in first half was 5% greater than in second half[23]
Italian Serie A	Distance covered in first half was 160 m greater than in second half[20]
European Cup games	Distance in first half was 50 m (1%) greater than in second half,[24] even not allowing for substitutions

a Results were significant ($p < 0.05$) in all cases.

$\dot{V}O_{2max}$ = maximum oxygen consumption.

themselves are increased as participants raise the pace of the game. Rampinini et al.[18] showed that one top-level Italian professional team covered a greater total distance and a longer distance in high-intensity exercise when playing against the better opponents in the league compared with competing against the poorer sides. Strudwick and Reilly[19] showed that the distance covered by players in the top English League was increased after the Premier League was inaugurated in 1992. The change from first division to Premier League is recognized as a watershed in the professional game, with increased scientific preparation accompanying the increased monetary rewards to elite players. With the adoption of systematic training programmes, there is a suggestion that the fall in work-rate towards the end of a game is less pronounced than it was in previous decades.[20] Aerobic interval training, consisting of 4 × 4-minute bouts at 92–95% of maximal heart rate with 3-minute rest periods in between, performed twice weekly for 4 weeks, was reported to increase maximum oxygen consumption ($\dot{V}O_{2max}$) by 10.8%. This improvement was accompanied by an increase in distance covered in a match by 20%, allowing players to cover greater distances at a higher intensity.[21] The data presented did not indicate whether there was an offset of fatigue and this degree of enhancement of aerobic performance has not been replicated by others.[14] Nevertheless, there is a lack of intervention studies to determine whether training delays the onset of fatigue, reduces the magnitude of the fall in performance when it eventually materializes or affects the phenomenon by means of other interactions.

There is evidence that depletion of muscle glycogen stores in the thigh muscles has led to a pronounced decline in work-rate.[25] Muscle biopsies were obtained from the vastus lateralis of nine players, four of whom had trained hard the day before whilst the remaining five had rested. The players who had rested had more than double the values for muscle glycogen stores of the others before the match. By half-time, those who had trained had low glycogen concentrations in their muscles whilst their team-mates had energy stores still in reserve. When further muscle biopsies were obtained immediately following the game, the four players who had not rested the day beforehand had depleted stores, whilst the others had some glycogen still remaining. Whilst there was no marked difference between the two groups in the first half, the difference for the second half was quite dramatic. The players whose energy stores were depleted, performed fewer sprints and worked less ‘off-the-ball’ than did their colleagues (figure 1).

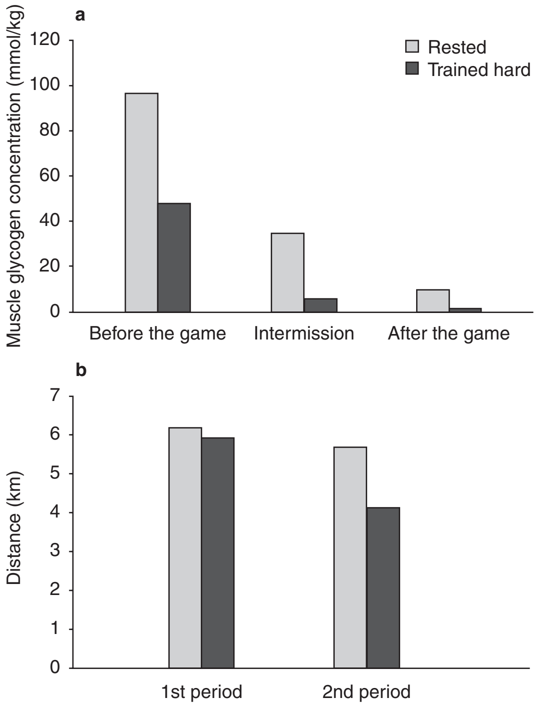

Fig. 1. The depletion of muscle glycogen content during a game is affected by the amount stored before the start and influences work-rate during the second half. Muscle glycogen concentration (mmol/kg wet muscle) is shown for rested and exercised players pre-game, at half-time and post-game (**a**). Graph (**b**) shows distance covered over each half for the two groups.[25]

Some years later, Krustrup et al.[26] focused on muscle and blood metabolites during a soccer game and attempted to relate these changes to sprint performance. They followed 31 Danish fourth division players, monitoring responses over three friendly games and timing 30-m sprints conducted pre-game, at half-time and immediately afterwards. Sprint performance was reduced, both temporarily during the game and immediately after finishing. There was no correlation between the decline in sprint capability and either muscle lactate, muscle pH or total glycogen content. They concluded that low glycogen levels in individual muscle fibres explained the impairment in sprinting at the end of the game and that blood lactate was a poor indication of muscle lactate during match-play.

Fatigue may also be caused by a rise in core body temperature beyond an optimum value, a trend that is accentuated when environmental conditions are hot. Heat stress has been shown to depress performance when the latter is expressed as work-rate per game. Ekblom[16] calculated that the distance covered in high-intensity running during a match amounted to 500 m when the environmental temperature was 30°C compared with 900 m when the temperature was 20°C. It may be that the work-rate is reduced intuitively at the higher ambient temperature in order to avoid a catastrophic dehydration. Mustafa and Mahmoud[27] reported mean body water losses in sweat were 3 L when matches were played in the heat, either in dry heat at 33°C or in high humidity at 26.3°C. These losses of body water exceed the level at which extended performance is likely to be adversely affected[28] and imply that a fatigue effect is likely.

Recent research confirms that exercise in the heat is associated with reductions in performance.[29] Cheung and Sleivert[30] claimed that hyperthermia may induce fatigue indirectly through high levels of cardiovascular strain impairing blood pressure or through lowered levels of blood flow in critical areas (e.g. brain, splanchnic tissues) or act directly via an effect on the CNS that reduces arousal and/or the ability to activate muscle. A direct effect of high core temperature *per se* on the CNS may be more important than the more traditional cardiovascular model of thermoregulation might suggest, since exhaustion appears to coincide with attainment of a critical internal body temperature around 40°C.[31] Such body temperatures are associated with changes in CNS function including reductions in voluntary activation during isometric actions.[32]

Elevations in the temperature of some body tissues (e.g. muscle) are initially beneficial to performance. Mohr et al.,[33] using a friendly match, demonstrated the benefits of actively increasing the temperature of the muscles during the half-time period. A 7-minute moderate-intensity re-warming (i.e. a second warm-up) period induced by exercise completed at the end of the half-time break resulted in the improved sprint performance when compared with a half-time break in which players did not re-warm. This observation would suggest that such activities are beneficial in preparing players for the high-intensity activities required in the second half of the game. Such activities should, however, be carefully controlled as exercise at too high an intensity may lead to an early depletion of muscle glycogen concentration and an added heat load. These factors may combine to reduce the overall work-rate towards the end of the game.

Mohr et al.[20] implicated physiological phenomena in the aetiology of fatigue occurring transiently within a game. They showed that following a 5-minute peak in exercise intensity, the work-rate decreased in the next 5-minute period. These decreases in work-rate are also probably influenced by the nature of the high-intensity activity as the length of the sprint impacts upon recovery time.[33] This form of fatigue induced by reliance on anaerobic metabolism is temporary, the player recovering when rest pauses are adequate in duration. The duration of the recovery period may, however, vary in relation to the phase of the game. Bangsbo and Mohr[34] examined the recovery duration of elite football players between high-intensity activities during match-play. The recovery duration was approximately 17% shorter in the first than in the second half. Differences were also noted when time intervals were further subdivided into 15-minute blocks with recoveries being extended by 89% in the final 15 minutes when compared with the first 15 minutes of the game.

This transient fatigue may be a consequence of different physiological factors than those associated with the more sustained fatigue observed towards the end of games or more prolonged training sessions. Bangsbo et al.[35] provided a useful list of the possible mechanisms that may explain this phenomenon. These include changes within the CNS, the elevated production of lactate in muscle and its associated impact on the pH of muscle fibres and the status of the muscle's high energy phosphates. None of these factors was considered to be causally related to fatigue, indicating that they may not be the prime determinants of the reduced work-rates observed in football match-play. Changes in the concentrations of potassium in the muscle interstitium seem to provide the best explanation for the transient reduction in force production observed,[9] although more detailed laboratory and field studies may be required before successful interventions that prevent or alleviate the temporary drop in work-rate can be devised.

There is a fall in the muscle force that the leg extensors and flexors can exert as the game progresses. Rahnama et al.[36] used isokinetic dynamometry to record peak torque in the quadriceps and hamstring muscle groups pre-exercise, after 45 minutes and after a second 45 minutes of exercise. The intermittent exercise protocol was designed to elicit the physiological responses corresponding to the exercise intensity of playing a game.[37] Muscle force had decreased by half-time at the three angular velocities of concentric action, a further reduction occurring by the end of 90 minutes of exercise. A similar reduction was observed when the isokinetic movement was performed eccentrically. Alterations in the dynamic control ratio (eccentric knee flexion: concentric knee extension) were observed by the end, denoting a decreased ability to stabilize the knee joint

Gleeson et al.[38] also showed a decreased protection at the knee joint after 90 minutes of repetitive shuttle running compatible with the exercise intensity of match-play. The authors concluded that the exercise caused concomitant impairments in electromechanical delay and in anterior tibio-femoral displacement, that would increase the risk of ligamentous injury.

The work-rate profile may not provide a true reflection of injury risk over the course of 90 minutes of match-play. Rahnama et al.[39] showed that critical incidents entailing an increased risk of major injury tended to peak in the first and last 15-minute periods of a match. The observations of critical incidents in the first 15 minutes were deemed to be a consequence of the warm up, and the need to register a combative impression on opponents. Clearly, an over-intensive start to match-play will have consequences for the metabolic energy remaining as the game nears its end. The peak incidence relating to the final 15-minute section of the game could be due to the combination of increased urgency as the match nears its outcome and the deterioration in muscle performance.

In a separate study, Rahnama et al.[40] monitored electromyographic (EMG) activity in lower-limb muscles during brief runs at 6, 12, 15 and 21 km/hour. These measures were made before starting to exercise at the intensity of soccer match-play, after the 15-minute half-time interval and immediately post-exercise. The amplitude of muscle activity during the run was indicated by the root mean square whose value increased progressively with each running speed. There was an effect of time on the root mean square for rectus femoris, biceps femoris and tibialis anterior to indicate fatigue in these muscles, although activity in gastrocnemius remained unchanged. Such an effect on the EMG activity may reflect the elimination of reflex components from the muscle's responses. These observations provide insights into changes in electrical activity of skeletal muscles induced by exercise of an intensity equivalent to that of match-play; the consequences of these alterations for maximal exercise are unclear, although a reduction in sprint performance has been observed at the end of a game.[41]

There are likely consequences of muscle fatigue for technical aspects of performance during match-play. One of the skills that has been examined under fatigued conditions is kicking the ball. Lees and Davies[42] used a step-up protocol to induce transient muscle fatigue prior to the assessment of kicking. An impairment in coordination between the upper and lower leg segments led to a faster peak velocity of the foot, but a lower velocity of the ball. The lack of coordination affected the transfer of energy between upper and lower legs, adversely affecting timing and leading to a poor impact position of the foot on the ball in the fatigued state. Apriantono et al.[43] employed repeated loaded extension and flexion motions to induce fatigue when investigating its effect on kinetics and kinematics of instep kicking. In this instance, the reduced ball velocity was associated with lower angular velocities of the toe and the leg before ball contact and a smaller muscle moment during kicking. Impairment in coordination between the limb segments was evident during the final phase of the kicking motion and was attributed to a fatigue effect. It is likely that the disturbances in the interactions between limb segments also affect other skills such as tackling and evading tackles. Coupled with the decreased ability to generate muscle force during the kicking action, the alterations in kinetics before ball impact were thought to increase the susceptibility to injury. This suggestion could be followed up in future research.

2. Countermeasures to Fatigue

2.1 Training

The available evidence would suggest that there is a clear link between the work-rate of players within a game and their physical capacities.[12,14,44,45] Such relationships are also observed for female players[46] and match officials.[47] An individual's physical capabilities are partly predetermined by his or her genetic potential, although the exposure to systematic training is also crucial. This suggestion can be illustrated within a football-specific context by the relationships observed by Mohr et al.[20] between seasonal changes in match-play work-rates and the amount of training completed by elite teams. The work-rate during matches, as indicated by high-intensity running, was highest in the phase of the season when training sessions were more frequent. Fixture congestion resulted in fewer training sessions and a subsequent decline in performance. These observations would suggest that a well structured and appropriate training programme can act as a useful countermeasure to fatigue during games.

Bangsbo et al.[35] stated that the focus of any training intervention, within soccer, should be on developing the capacity to perform intense exercise and on improving the ability to recover between these intense bouts. These improvements would necessitate developments in both the aerobic and anaerobic energy systems. The most efficient way to develop these capabilities may be to perform high-intensity interval type training as this medium may be able to stimulate both aerobic and anaerobic metabolism if the intensity, duration, frequency and recovery periods are sufficient. The delivery of this type of stimulus can be in the form of small-sided games[48] as these, if carefully structured, can elicit heart rates and blood lactate responses of a suitable intensity.[49] Whilst Stolen et al.[50] suggested that these games are of limited use in a conditioning context even if consideration is given to their organization, Impellizzeri et al.[14] found that small-sided games were equally as effective as was aerobic interval training in improving both physiological indices of fitness and match performance. Such discrepancies may be a reflection of a wide range of factors including a ceiling effect inherent in football drills,[50] player motivation and the operationalization of the activity by the coach are also implicated. Further elucidation of the impact of such considerations would require the completion of other applied research projects.

More of a consensus is available in relation to the specific prescription of the training stimulus. Research from Norway[21,50] provides a framework for the prescription of high-intensity intermittent training. Using 4 × 4-minute work periods separated by 3-minute recoveries at an intensity of 90–95% maximal heart rate repeated twice per week for 8 weeks resulted in improvements in both physiological variables ($\dot{V}O_{2max}$, lactate threshold and running economy) and match-play work-rates (increased distance covered, total number of sprints and ball contacts). The duration of the individual training impulses may also be reduced to as low as 30 seconds without too much effect on the training response if the number of repetitions is increased appropriately.[51] Benefits from shorter chronic exposures may also be possible as Stolen et al.[50] demonstrated improvements in aerobic fitness following as little as 13 sessions completed in a 10-day period. These improvements may, however, be dependent on the regular participation of players in matches as this exposure to competition is an important component of the week's energy expenditure.

The completion of specific match activities also necessitates players to have high levels of muscular strength. The inclusion of specific strength training sessions (3 × 5 repetitions × 4 sets at 85% one repetition maximum) for an 8-week period can improve squat and sprint performance and alter the rate of force development.[44] These changes may be beneficial to the performance as they may enable players to improve activities such as kicking, jumping and tackling throughout the game. These adaptations are not affected when aerobic training is completed. McMillan et al.[52] examined the potential impact of aerobic training on muscular performance in professional young football players. Eleven young players completed a 10-week high-intensity aerobic interval training programme. Jump performance, sprint performance and rate of force development were not adversely affected by this additional training, suggesting a relative independence of these parameters. Whilst studies of training effects have demonstrated positive changes on outcome variables, it is not clear whether performance is elevated throughout 90 minutes of sustained exercise and whether there is a positive change in a relevant fatigue index. Additional investigations may further benefit this area and help inform future practice to ensure that the planning of all fitness training is evidence based.

The tapering of training in the days prior to competition helps to avoid reducing muscle glycogen stores before the game. Saltin[25] showed that training hard the day before match-play resulted in a pronounced fall in work-rate in the second half, notably in high-intensity activity off-the-ball. Those players who had rested reaped the physiological benefits of starting with high glycogen depots in their thigh muscles.

Reducing muscle glycogen stores in the days before important games is clearly counter-productive to performance. There may, however, be some occasions when a considered reduction in muscle glycogen concentration can support the training process. The completion of a programmed period of training with low glycogen concentrations can lead to enhanced activation of metabolic genes and increased changes in oxidative enzymes.[53,54] This effect may suggest that fitness training is sometimes better completed in an energy-depleted state, a suggestion that leads to a 'train low, compete high' strategy. Such a recommendation is probably inappropriate for footballers, but may apply in exceptional situations as a consequence of the density of their activity within the competitive season when success in matches is important for the club. It may, however, be useful for short periods of time when the focus is on physiological development as typified by pre-season.

It is also prudent to modify the training programme when the competitive fixture list is congested and there is little time to recover in between matches. Reilly and Ekblom[55] described conditions in training camps and following successive games when immune function and energy balance were negatively affected. Players would be unlikely to sustain activity at the required intensity in such circumstances and a more moderate approach in planning sessions in training camps is advised. Without this cautionary note, players may enter a spiral of underperformance, characterized by a more longer-lasting fatigue.

2.2 Nutrition

Provision of carbohydrates in the build up to a game and on the day of a game has generated a lot of interest since the initial data of Saltin[25] demonstrated the importance of adequate muscle glycogen in the thigh muscles. There is a large volume of literature based on other endurance sports to emphasize the importance of carbohydrate ingestion. The optimal nutritional strategies pre-match[56] and during the game have been reviewed elsewhere.[57] Specifically, it was recommended that players should adapt their carbohydrate intake on a daily basis to ensure adequate fuel for training and recovery purposes. A combination of a high-carbohydrate meal about 3 hours before competing, along with a sports drink was recommended for boosting exercise capacity.

Caffeine has been used in endurance events to stimulate mobilization of fat as a fuel for exercise and spare glycogen stores.[58] It is also a CNS stimulant, which might constitute another benefit. Habitual users may be desensitized to caffeine, which may have no effect on these individuals. Its effect may also be negated if used in combination with carbohydrate loading.[59] There have been suggestions that creatine loading may enhance performance in the repetitive short sprints that recur during a game.

Creatine has proved beneficial in repetitive short sprints on a cycle ergometer.[60] The pattern of sprints in soccer with a short all-out burst every 90 seconds may not be amenable to an ergogenic effect of creatine during competitive matches. When the pattern and intensity of match-play were reproduced in a simulation of the work-rate observed in competitive play utilizing a non-motorized treadmill, the standard creatine loading regimen failed to improve performance in the sprint portion of the protocol (unpublished observation). It may be that adopting a creatine-loading regimen may help in repetitions of so-called 'explosive activity' in training, but is less effective in a competitive context where the addition

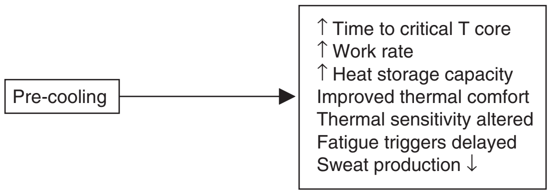

Fig. 2. Ergogenic mechanisms of pre-cooling. **T core** = core temperature; ↓ indicates decrease; ↑ indicates increase.

to bodyweight associated with creatine loading could be counterproductive.[61]

When exercise is conducted in conditions of heat stress, a gradual dehydration accentuates the effects of fatigue. Attention to rehydration at half-time and where feasible during breaks in the game will offset, in part, effects of fatigue.[62] Fluid containing energy and electrolytes can have an additional value[63] over and above pure water.

3. Alternative Strategies to Counteract Fatigue

A strategic use of substitute players during the second half of a game can reduce the effects of fatigue across the team. Mohr et al.[20] showed that the work-rate of substitutes who had been brought on before 75 minutes was superior to that of players lasting the whole game for the final 15 minutes. Whilst substitutions are made mainly for tactical reasons, the identification of players with the most pronounced falls in work-rate for substitution would be prudent.

Pre-cooling the body prior to commencing endurance exercise has been advocated, especially in the heat. The principle is that body temperature will be prevented from rising to a point that adversely affects performance late in the exercise. Drust et al.[64] showed that the benefits of pre-cooling were limited to the first half, being largely lost during the 15-minute interval between the two 45-minute periods. The mechanisms by which pre-cooling yields an ergogenic effect have been described by Reilly et al.[31] and are illustrated in figure 2. They include an increased capacity for storage of metabolic heat, a greater margin before reaching a critical core temperature causing impairment to performance and a likely delay of physiological triggers of fatigue.

In a separate unpublished study, Clarke compared pre-cooling with provision of a sports drink and a combination of the two in exercise corresponding to the intensity of soccer match-play. In this instance, a self-chosen intensity was employed as a psychophysical measure of aerobic capacity and Cunningham and Faulkner's[65] test was used as a measure of anaerobic capacity (figure 3). The superior performances after the combined approach compared with the discrete conditions highlight the importance of a holistic effort to reduce the impact of fatigue.

4. Persistent Fatigue

Football match-play not only places high demands on the body's energy systems but also induces psychological stress on players. When the competitive fixture list is congested, there may be insufficient time in between matches for participants to recover their physiological reserves and their psychological resources. This situation may be ac-

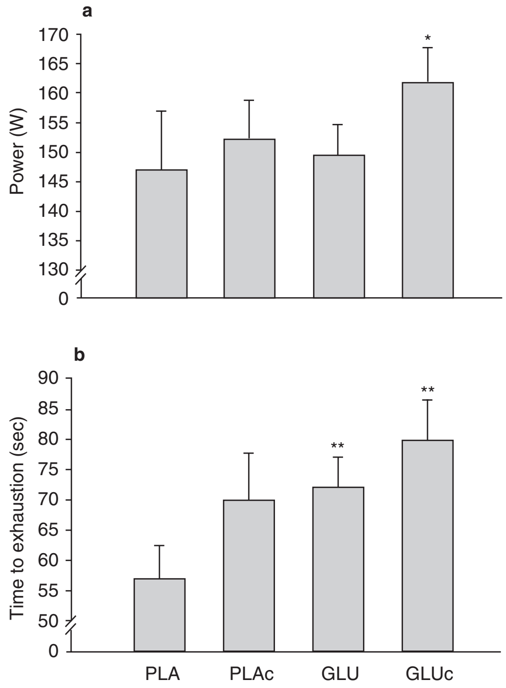

Fig. 3. Performance on a psychophysical test of aerobic capacity (**a**) and on a test of anaerobic capacity (**b**) after 90 minutes of exercise at an intensity corresponding to that of football match-play. **GLU** = sports drink; **GLUc** = sports drink and pre-cooling; **PLA** = placebo; **PLAc** = pre-cooling; * indicates significantly higher than PLA, PLAc and GLU; ** indicates significantly higher than PLA.[66]

centuated by suppression of the immune system for some hours after exercise, leading to an increased risk of incurring upper respiratory tract infections. The end result may be a reduced work-rate during competition, known as underperformance. Players deemed to have underperformed in international tournaments held in mid-summer were found to have played more matches in the later part of their domestic and continental competitions than others judged to have done well.[67] Even so, many footballers exhibit a resilience that allows them to perform competently when successive simulations of match-intensity are completed close together.[68]

Underperformance has been shown to occur during training camps when youth players undergo intensive exercise regimens and when matches are scheduled in rapid succession. Malm et al.[69] demonstrated immunosuppression for 48 hours after playing a game on two successive days. The immunological responses were more marked in players with lower aerobic power, suggesting that endurance fitness may play a protective role in such circumstances. The residual fatigue accrues when recovery is incomplete between matches or when a decrement in capability resulting from successive days of repetitive hard training may carry over into a more persistent underperformance syndrome. A particular concern is with eccentric actions that induce 'delayed-onset muscle soreness', in hamstrings for example, due to abrupt decelerations when running or acting as antagonists to quadriceps activity when kicking. These stretch-shortening cycles cause an impairment in muscle performance, until the muscle adapts to cope according to the 'repeated bouts effect'.[70] This response implies that muscles adapt to training regimens that engage them in stretch-shortening cycles and are impaired less with repeated exposures.

The attention to recovery strategies is an immediate concern of those engaged in sports science support for football players. A combination of approaches is likely to be most effective since players will vary in the extent to which they have been affected. Recovery methods may have specific time-points for their effectiveness, for example, warming down should be soon after the termination of play, energy restoration would have a time-course of 48–72 hours whilst alterations to training loads apply particularly on the day after matches (see table II). Without such strategies, the onset of fatigue is likely to be advanced during the next competitive engagement.

Table II. Factors in the promotion of recovery following muscle fatigue induced by match-play: methods reviewed by Reilly and Ekblom[55]

Active warm-down
Rehydration
Restoration of energy
Deep-water running
Alleviation of muscle soreness
Decrease subsequent training
Attention to lifestyle

5. Conclusions

The evidence that fatigue occurs during a competitive football game is comprehensive. The phenomenon occurs in high-tempo matches as well as in lower leagues, requiring players to pace themselves appropriately in order to last the whole of the game. Whilst the decline in work-rate towards the end of the 90 minutes of intermittent activity can be related to local muscular factors, central factors may also be involved. The reduction in performance capability may also increase the susceptibility to injury. Lack of motivation to maintain high-intensity activity off-the-ball may be influenced by the prevailing score whilst the urgency to avoid defeat or secure a late victory may help in maintaining motivation. Various means are available to help reduce the potentially adverse consequences of fatigue and the efficacy of novel interventions should be explored. In administering any of these available strategies, the appropriate pacing of effort throughout the entire game must be considered.

Acknowledgements

Neil Clarke is funded by a grant from GlaxoSmithKline. The authors have no conflicts of interest that are directly relevant to the content of this review.

References

1. Hawley JA, Reilly T. Fatigue revisited. J Sports Sci 1997; 15: 245-6
2. Reilly T, Secher N, Snell P, editors. Physiology of sports. London: E and FN Spon, 1990
3. Mosso A. Fatigue. London: Swan, 1901

4. Bartlett FC. Fatigue following highly skilled work. Proc R Soc B 1943; 131: 247-54
5. Christensen EH. Physiological valuation of work in the Nykroppa Iron Works. In: Floyd WF, Welford WT, editors. Symposium on fatigue. London: H.K. Lewis, 1953
6. Hermansen L, Hultman E, Saltin B. Muscle glycogen during prolonged severe exercise. Acta Physiol Scand 1967; 71: 129-39
7. Nielsen B. Heat stress and acclimation. Ergonomics 1994; 37: 49-58
8. Green HJ. Mechanisms of muscle fatigue in intense exercise. J Sports Sci 1997; 15: 247-56
9. Bangsbo J. The physiology of soccer: with special reference to intense intermittent exercise. Acta Physiol Scand 1994; 151: Suppl. 619: 1-155
10. St Clair Gibson A, Goedecke JH, Harley YX, et al. Metabolic setpoint control mechanisms in different physiological systems at rest and during exercise. J Theor Biol 2005; 236: 60-7
11. Reilly T. Motion analysis and physiological demands. In: Reilly T, Williams AM, editors. Science and soccer. London: Routledge, 2003: 59-72
12. Reilly T, Thomas V. A motion analysis of work-rate in different positional roles in professional football match-play. J Hum Move Stud 1976; 2: 87-97
13. Carling C, Williams AM, Reilly T. Handbook of soccer match analysis. London: Routledge, 2005
14. Impellizzeri FM, Marcora SM, Castagna C, et al. Physiological and performance effects of generic versus specific aerobic training in soccer players. Int J Sports Med 2006; 27: 483-92
15. Krustrup P, Mohr M, Ellinsgaard H, et al. Physical demands during an elite female soccer game. Med Sci Sports Exerc 2005; 37: 1242-8
16. Ekblom B. Applied physiology of soccer. Sports Med 1986; 3: 50-60
17. Shirrefts SM, Sawka MN, Stone M. Water and electrolyte needs for football training and match-play. J Sports Sci 2006; 24: 679-707
18. Rampinini E, Bishop D, Marcora SM, et al. Validity of simple field tests as indicators of match related physical performance in top level professional soccer players. Int J Sports Med 2007; 28: 228-35
19. Strudwick T, Reilly T. Work-rate profiles of elite premier league football players. Insight FA Coach Assoc J 2001; 42 (2): 28-9
20. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to the development of fatigue. J Sports Sci 2003; 21: 519-28
21. Helgerud, J, Engen LC, Wisloff U, et al. Aerobic endurance training improves soccer performance. Med Sci Sports Exerc 2001; 33: 1925-31
22. Van Gool D, Van Gerven D, Boutmans J. The physiological load imposed on players during real match-play. In: Reilly T, Lees A, Davids K, et al., editors. Science and football. London: E and FN Spon, 1988: 51-9
23. Bangsbo J, Norregaard L, Thorso F. Activity profile of competition soccer. Can J Sports Sci 1991; 16: 110-6
24. Di Salvo V, Baron R, Cardinale M. Time motion analysis of elite footballers in European cup competitions. Communication to VIth World Congress on Science and Football; 2007 Jan 15-20; Antalya
25. Saltin B. Metabolic fundamentals in exercise. Med Sci Sports 1973; 5: 137-46
26. Krustrup P, Mohr M, Steensberg A, et al. Muscle and blood metabolites during a soccer game: implications for sprint performance. Med Sci Sports Exerc 2006; 38: 1165-74
27. Mustafa KY, Mahmoud NE. Evaporative water loss in African soccer players. J Sports Med Phys Fitness 1979; 19: 181-3
28. Barr SI. Effects of dehydration on exercise performance. Can J Appl Physiol 1999; 24: 164-72
29. Drust B, Rasmussen P, Mohr M, et al. Elevations in core and muscle temperature impairs repeated sprint performance. Acta Physiol Scand 2005; 183: 181-90
30. Cheung SS, Sleivert GG. Multiple triggers for hyperthermic fatigue and exhaustion. Exerc Sport Sci Rev 2004; 32: 100-6
31. Reilly T, Drust B, Gregson W. Thermoregulation in elite athletes. Curr Opin Clin Nutr Metab Care 2006; 9: 666-71
32. Nybo L, Secher NH. Cerebral perturbations provoked by prolonged exercise. Prog Neurobiol 2004; 72: 223-61
33. Mohr M, Krustrup P, Nybo L, et al. Muscle temperature and sprint performance during soccer matches: beneficial effect of re-warm-up at half time. Scan J Med Sci Sports 2004; 14: 156-62
34. Bangsbo J, Mohr M. Variations in running speeds and recovery time after a sprint during top class soccer matches. Med Sci Sports Exerc 2005; 37: S87
35. Bangsbo J, Mohr M, Krustrup P. Physical and metabolic demands of training and match-play in the elite football player. J Sports Sci 2006; 24: 665-74
36. Rahnama N, Reilly T, Lees A, et al. Muscle fatigue induced by exercise simulating the work-rate of soccer. J Sports Sci 2003; 21: 933-43
37. Drust B, Reilly T, Cable NT. Physiological responses to laboratory-based soccer-specific intermittent and continuous exercise. J Sports Sci 2000; 18: 885-92
38. Gleeson NP, Reilly T, Mercer TH, et al. The influence of acute endurance activity on leg neuromuscular and musculoskeletal performance. Med Sci Sports Exerc 1998; 30: 596-608
39. Rahnama N, Reilly T, Lees A. Injury risk of playing actions during competitive soccer. Br J Sports Med 2002; 36: 354-9
40. Rahnama N, Lees A, Reilly T. Electromyography of selected lower-limb muscles fatigued by exercise at the intensity of soccer-match play. J Electromyogr Kinesiol 2006; 16: 257-63
41. Reilly T, Rigby M. Effect of an active warm-down following competitive soccer. In: Spinks W, Reilly T, Murphy A, editors. Science and football IV. London: E and FN Spon, 2002: 226-9
42. Lees A, Davies T. The effects of fatigue on soccer kick biomechanics. J Sports Sci 1988; 6: 156-7
43. Apriantono T, Nunome H, Ikegami Y, et al. The effect of muscle fatigue on instep kicking kinetics and kinematics in association football. J Sports Sci 2006; 24: 951-60
44. Hoff J, Helgerud J. Endurance and strength training for soccer players. Sports Med 2004; 24: 165-80
45. Rampinini E, Coutts AJ, Castagna C, et al. Variation in top level match performance. Int J Sports Med 2007; 28: 1018-24
46. Krustrup P, Mohr M, Ellingsgaard H, et al. Physical demands during an elite female soccer game: importance of training status. Med Sci Sports Exerc 2005 Jul; 37: 1242-8
47. Krustrup P, Mohr M, Bangsbo J. Activity profile and physiological demands of top-class soccer assistant refereeing in relation to training status. J Sports Sci 2002; 20: 861-71
48. Reilly T. An ergonomics model of the soccer training process. J Sports Sci 2005; 23: 561-72
49. Sassi R, Reilly T, Impellizeri F. A comparison of small-sided games and interval training in elite professional soccer players. In: Reilly T, Cabri J, Araujo D, editors. Science and football V. London: E and FN Spon, 2005: 341-3
50. Stolen T, Chamari K, Castagna C, et al. Physiology of soccer: an update. Sports Med 2005; 25: 501-36
51. Krustrup P, Bangsbo J. Physiological demands of top-class soccer refereeing in relation to physical capacity: effect of intense intermittent exercise training. J Sports Sci 2001 Nov; 19 (11): 881-91

52. McMillan K, Helgerud J, MacDonald R, et al. Physiological adaptations to soccer-specific endurance training in professional youth soccer players. Br J Sports Med 2005; 39: 273-7
53. Hildebrandt AL, Pilegaard H, Neufer PD. Differential transcriptional activation of select metabolic genes in responses to variations in exercise intensity and duration. Am J Physiol Endocrinol Metab 2003; 285: 1021-7
54. Hansen AK, Fischer CP, Plomgaard P, et al. Skeletal muscle adaptation: training twice every second day vs. training once daily. J Appl Physiol 2005; 98: 93-9
55. Reilly T, Ekblom B. The use of recovery methods post-exercise. J Sports Sci 2005; 23: 619-27
56. Clark K. Nutritional guidance and soccer players for training and competition. J Sports Sci 1994; 12: 543-50
57. Williams C, Serratosa L. Nutrition on match day. J Sports Sci 2006; 24: 687-97
58. Graham T. The possible actions of methylxanthines on various tissues. In: Reilly T, Orme M, editors. Clinical pharmacology of sport and exercise. Amsterdam: Excerpta Medica, 1997: 257-70
59. Jacobson TL, Febbraio MA, Arkinstall MJ, et al. Effect of caffeine co-ingested with carbohydrate or fat on metabolism and performance in endurance-trained men. Exp Physiol 2001; 86: 137-44
60. Casey A, Constantin-Teodosiu D, Howell S, et al. Creatine ingestion favorably affects performance and muscle metabolism during maximal exercise in humans. Am J Physiol 1996; 271: E31-7
61. Hespel P, Maughan RJ, Greenhaff PL. Dietary supplements for football. J Sports Sci 2006; 24: 749-61
62. Clarke ND, Drust B, MacLaren DPM. Strategies for hydration and energy provision during soccer-specific exercise. Int J Sport Nutr Exerc Metab 2005; 15: 625-40
63. Burke LM, Loucks AB, Broad N. Energy and carbohydrate for training and recovery. J Sports Sci 2006; 24: 675-85
64. Drust B, Cable NT, Reilly T. Investigation of the effects of pre-cooling on the physiological responses to soccer-specific intermittent exercise. Eur J Appl Physiol 2000; 81: 11-7
65. Cunningham DA, Faulkner JA. The effect of training on aerobic and anaerobic metabolism during a short exhaustive run. Med Sci Sports Exerc 1969; 1: 65-9
66. Clarke ND. Strategies for optimal hydration and energy provision for soccer-specific exercise [dissertation]. Liverpool: Liverpool John Moores University, 2006
67. Ekstrand J, Walden M, Hagglund M. A congested football calendar and the well being of players: correlation between match exposure of European footballers before the World Cup 2002 and their injuries and performances during that World Cup. Br J Sports Med 2004; 38: 493-7
68. Sari-Sarraf V, Reilly T, Doran DA, et al. The effect of single and repeated bouts of soccer-specific exercise on salivary IgA. Arch Oral Biol 2007; 52: 526-32
69. Malm C, Ekblom O, Ekblom B. Immune system alteration in response to two consecutive soccer games. Acta Physiol Scand 2004; 180: 143-55
70. Cleak MJ, Eston RG. Delayed onset muscle soreness: mechanisms and management. J Sports Sci 1992; 10: 325-41

Correspondence: Prof. *Thomas Reilly*, Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Henry Cotton Campus, 15-21 Webster Street, Liverpool, L3 2ET, UK.
E-mail: t.p.reilly@ljmu.ac.uk