1.1 What is Fatigue?

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Fatigue is defined as a temporary decline in performance. This can be reversed after a few hours or days of rest. There are many types of fatigue and they can be found on a rather wide spectrum. “On one side of the spectrum we can find acute fatigue: a performance decrement which can be reversed with a few hours of rest.” (Jeukendrup, 2015a, https://bit.ly/2S3Ckuf). Severe fatigue may take longer to recover from (perhaps 24 or 48 hours). When this fatigue gets even more prolonged (several days or weeks of training) and it may take weeks to recover, we refer to this as overreaching.

> Typically, this is a functional form of overreaching because athletes embark on such training blocks to cause extreme fatigue with the end goal to improve their performance. On the other end of the spectrum we have the overtraining syndrome that is very difficult to recover from. It has a large range of symptoms and is not functional but rather pathological. The overtraining syndrome could mean the end of a season or even the career of an athlete. All of these are forms of fatigue and they are clearly on a wide spectrum. (Jeukendrup, 2015a, https://bit.ly/2S3Ckuf).

Understanding fatigue and the consequent exercise limitation is extremely important in sports, with implications for medals, glory, and the sports industry. If we understand the mechanisms of fatigue, we may be able to design strategies to minimise or reduce fatigue. Early investigations on fatigue mechanisms focused on metabolic fuel availability or accumulation of “waste products”. One of the these was lactic acid formation and even today this is widely discussed by coaches and trainers. Lactate has been measured to indicate training zones and training programmes; and it has also been used to determine if an athlete is improving.

> Fatigue during intense exercise was typically portrayed as a consequence of phosphocreatine depletion and lactic acidosis. With evidence that action potential transmission across the neuromuscular junction was not impaired, fatigue was ascribed as largely occurring within the active muscles. Hence, the term “muscle fatigue” is now firmly entrenched

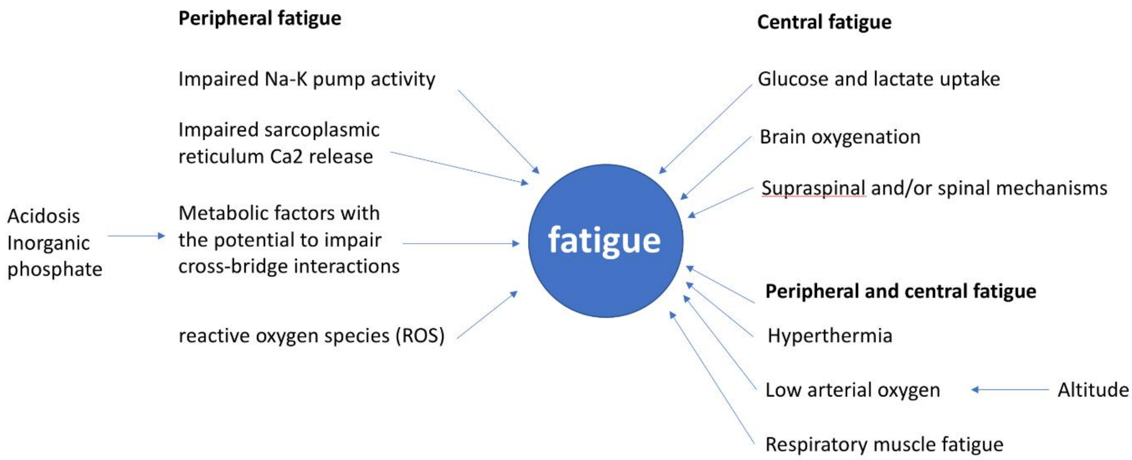
> within the general scientific vocabulary. (McKenna & Hargreaves, 2007, https://bit.ly/2ziUqBm)

It is also clear that muscle fatigue is not the same as fatigue, and fatigue is the most relevant of the

> (...) two for voluntary exercise, since fatigue limiting exercise involves mechanisms within the contracting peripheral or locomotive muscles and encompasses the respiratory muscles, muscle perfusion, other inactive skeletal muscle and organs regulating fuel, metabolite, or ionic homeostasis and, most importantly, within the central nervous system itself. (McKenna and Hargreaves, 2008, p.286).

Fatigue should not be regarded as a failure of regulation: "the bad guy, but as a highly regulated strategy conserving cellular integrity, function and, indeed, survival." (McKenna & Hargreaves, 2008, p.286).

Figure 1: Overview of Potential Mechanisms of Fatigue



These mechanisms can be divided into mechanisms with a peripheral and central origin.

Source: Prepared by the author based on a number of review papers including (Marqués-Jiménez, Calleja-González, Arratibel, Delextrat, & Terrados, 2017; McKenna & Hargreaves, 2008; Meeusen & Roelands, 2018).

1.1.2 Fatigue is Multifactorial

There are a number of mechanisms that contribute to overall fatigue. Some are of peripheral nature (at the level of the muscle), and others are more central (central nervous system) in nature. It is clear that both play a role in almost all forms of fatigue (see Figure 1).

- Failure of Ca^{2+} release by the sarcoplasmic reticulum is a major causative factor of fatigue in muscle. Insufficient Ca^{2+} release is linked to a reduction in force.
- Ionic homeostasis in the muscle is another potential cause of muscle fatigue. Marked changes in K^{+} and Na^{+} concentrations and impaired Na-K pump activity may also cause fatigue.
- "Numerous metabolic factors have the potential to impair cross-bridge interactions. For example, the role of acidosis has been the subject of debate for many years." (McKenna & Hargreaves, 2007, https://bit.ly/2ziUqBm)
- Several studies suggest an inhibitory effect of increased hydrogen on muscle contraction (velocity) and power production.
- Reactive oxygen species (ROS) may also have an impact on skeletal muscle function. Several studies show that increased ROS production in contracting muscles results in fatigue.
- It has also been suggested that brain metabolism plays a role in fatigue. The uptake of glucose and lactate are increased in the brain with exercise, whilst cerebral oxygenation is decreased. "As a result, the oxygenation of the brain is reduced during exercise and could become a vital factor in 'central fatigue'." (McKenna & Hargreaves, 2007, https://bit.ly/2ziUqBm).
- Central fatigue (fatigue within the central nervous system) may also occur at the level of the spine. Supraspinal and/or spinal mechanisms could be contributing to fatigue during voluntary contractions.
- Hyperthermia worsen fatigue. It is clear that hyperthermia can impair high-intensity exercise performance. There are several reasons why this may happen but one of the reasons is related to the cardiovascular system: there are declines in cardiac output, muscle blood flow, and oxygen uptake in high heat. Furthermore, hyperthermia during prolonged exercise is associated with a reduction of central activation (and thus increased central fatigue). We will discuss the challenges of exercise in high heat in more detail in the course Match Day Preparation and Personalised Nutrition.
- Altitude also affects fatigue. Oxygen availability affects fatigue development and exercise performance. "This occurs via direct effects on both muscular performance and central nervous system motor activation and via inhibitory feedback from those muscles affected by reduced oxygen delivery." (McKenna & Hargreaves, 2007, https://bit.ly/2ziUqBm).
- Respiratory muscle function can also affect fatigue. Studies have shown that in certain exercise conditions, fatigue occurs in respiratory muscles. This in turn can limit arterial oxygenation, with consequent effects on the function of the muscular and nervous system.

In most situations, many of these causes of fatigue contribute to overall fatigue simultaneously. Depending on the conditions, sometimes one mechanism will be more important than the other. It is clear, however, that fatigue is multifactorial and thus, unlikely that one solution will remove overall fatigue.

To illustrate this point, let's have a look at the findings of an older study by Coggan and Coyle (1987), who made cyclists ride to exhaustion on multiple occasions. When cyclists got exhausted and could not maintain the exercise intensity any longer their blood glucose concentration was low. They rested for a little while and received a placebo drink before a second bout of cycling at the same intensity, but the exercise did not last very long before they got exhausted again. When cyclists received a carbohydrate drink, they were able to maintain blood glucose a little higher and they exercised for longer; when glucose was infused directly into the blood at high rates, cyclists were able to exercise even longer. This provided evidence that maintaining high blood glucose was important for performance and that low blood glucose was a cause of fatigue. However, even when the cyclists received glucose, they still fatigued. They fatigued later, but they still fatigued. Thus, there were other mechanisms that also simultaneously contributed to fatigue.

It is beyond the scope of this book to discuss all mechanisms of fatigue in great detail. For such purpose, a number of excellent review papers can be consulted (Kirkendal, 1990; Marqués-Jiménez et al., 2017; McKenna & Hargreaves, 2008; Meeusen & Roelands, 2018.)

1.1.3 Fatigue in Team Sports

It is clear that fatigue is a complex phenomenon with many different causes that contribute to the actual fatigue experienced by a player. In general, we can distinguish two main types of fatigue during a game. First, there is the acute fatigue after an intense bout of running. With repeated sprints and insufficient recovery, sprints get slower. If enough recovery time is allowed, sprint performance is recovered and the fatigue is, thus, of a transient nature. Then, there is the longer term fatigue that develops over the course of a game. This fatigue occurs at all levels of play. Even the very best footballers display some fatigue during a match.

The figure below (Figure 2) is shows a study from Krustrup et al., (2006) where players were asked to perform five 30-metre sprints (about 4 seconds) with 30-second recovery. They did this during the first half, during the second half, and at the end of the game. First, it can be seen that 30 seconds is not enough to completely recover between sprints and that performance declines over the course of 5 sprints. It is also clear that there is an accumulated effect of repeated sprints on performance ability: Performance declines in the second half and even more at the end of the game. In practical terms, this means that at the end of a match a player covers 30 metres at an approximate 8% slower pace than at the start of the match. This is about 2 metres that a player 'concedes' as a result of fatigue when compared to the first half. "So if by the end of the game a defender is fatigued, but the striker is not, then the striker has a 2m advantage and that is more than enough to allow him away from the tackle, onto goal and perhaps, a match-winning moment."

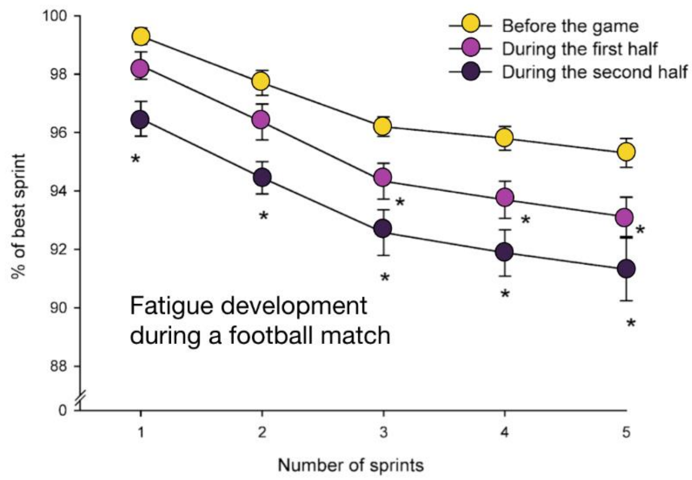
Running performance has been analysed frequently as an important aspect of football performance. "It is a common finding that the number of sprints, the total amount of high-intensity running and distance covered are lower in the second half than in the first half of a game" (Bangsbo, 2014, https://bit.ly/2QeSH9V)

This was probably first reported by Reilly and Thomas (1979) but confirmed later by many others (Bangsbo, 1994; Bangsbo, Norregaard, & Thorso, 1991; Carling & Dupont, 2011; Mohr, Krustrup, & Bangsbo, 2003). The findings have been confirmed in both elite and sub-elite football players (Carling & Dupont, 2011; Krustrup et al., 2006; Mohr et al., 2003). A study reported that distance covered by players was 18 % lower in the second half than in the first half of a game regardless of playing position (Bradley, Di Mascio, Peart, Olsen, & Sheldon, 2010). Another study showed that the distance covered performing high-intensity activities can be 20% lower in the last 15 minutes than in the first 15 minutes of the match, regardless of playing position (Sparks, Coetzee, & Gabbett, 2017).

> Furthermore, the total distance covered at different intensities in the first half can significantly influence the distances covered in the second half and can have a significant impact on the recovery immediately following the most intense 5-min periods of the second half. (Bradley et al. , 2010 https://bit.ly/2OXzq8d)

Other studies have demonstrated that explosive activities such as jumping, sprinting, and intermittent exercise performance are significantly lower after a game compared to the performance before a game (Krustrup et al., 2006)

Figure 2: Repeated Sprint Performance Before the Game, During the First Half and After the Second Half



Source: adapted from Krustrup et al., 2006.

The examples above show fatigue gradually developing over 2 times 45 minutes.

Players may also experience temporary fatigue during a game: fatigue that develops within seconds or minutes that disappears during moments of relative rest (walking, jogging). Male elite football players have on a number of occasions been shown to engage in reduced high-intensity exercise, below game average, in the five-minute period following the most intense period of the match. (Di Mascio & Bradley, 2013; Mohr *et al.*, 2003).

"These reductions in performance after a period of intense exercise could result from the natural variation in game intensity due to tactical or psychological factors." (Bangsbo, 2014, https://bit.ly/2zUr3Vi).

A third type of fatigue that players may experience is the fatigue they begin the training or match with. This is a more chronic fatigue that may have accumulated over days or weeks of hard training and match play with insufficient recovery (this type of fatigue is usually a form of overreaching).

We can distinguish 3 types of fatigue during training or match play:

1. Chronic fatigue that may exist at the start of training or a match, as a "leftover" from previous days or weeks.
2. Gradual fatigue developing over the course of exercise duration (for example 2 x 45 min match).
3. Temporary fatigue as a result of shorter duration higher intensity bouts that require seconds or minutes to recover from.

1.1.4 Mental Fatigue

Football players are required to remain alert for long periods during matches, they need to process tactical instructions and adhere to tactical strategies from the coach. They also need to make decisions in fractions of seconds and constantly adjust to changes in the opposition and their team mates. Especially in matches, players have to make many quick and accurate decisions and this often happens under tremendous pressure from fans, coach, other players, and of course the media. All decisions players make will be judged. Players are also constantly receiving and processing information in a highly dynamic environment. In addition, players have to cope with the mental stress resulting from the expectations of coaches, supporters, sponsors and media. All these factors combined with home stress (family, wife, girlfriend, and other daily life factors) can add up to a significant "mental load" that can result in mental fatigue. This in turn can negatively affect (physical) performance.

Until recently, relatively little had been known about the effects of mental fatigue on football performance. However, recent studies have shown that mental fatigue can affect many aspects of football performance, including football-specific running. "Several studies have shown that mental fatigue can have a negative impact on cognitive function and skilled performance in settings such as driving" (Smith, Coutts, et al., 2016).

Other studies have demonstrated that mental fatigue has limited influence on maximal voluntary activation and strength, explosive power, and anaerobic work capacity, but endurance performance is impaired. In a study, mental fatigue was induced by giving players hard cognitive tasks under pressure before measuring performance:

> Players completed two football performance tests in a randomized, counterbalanced order. This test was preceded by 30 min of the mentally challenging and fatiguing task or 30 min of reading magazines (control treatment). The players reported to be more fatigued after the mentally challenging task. Thus, mental fatigue was induced. This mental fatigue significantly reduced running distance in an intermittent running test (yo-yo test). Mental fatigue also impaired shot speed and accuracy. . (Smith, Coutts, et al. 2016, https://bit.ly/2TBn5df)

“Another study suggested that mental fatigue impairs accuracy and speed of soccer-specific decision-making.”(Smith, Coutts, et al. 2016, https://bit.ly/2TBn5df)

One might argue that the methods used were not football specific and this is clearly true. However, the studies did demonstrate that mental fatigue should be considered when preparing footballers for competition. “Indeed, since both mental and physical fatigue have been reported to negatively affect physical and technical performance and increase the risks of injury, managing fatigue is now a major part of scientists’ work in football.” (Smith, Coutts, et al. 2016, https://bit.ly/2TBn5df)

There is a need to better understand the best ways to approach the issue of mental fatigue. When players get physically fatigued, the training programme is adapted… However, what if the players are mentally fatigued? Should training be adapted? Should players under high levels of mental fatigue prepare differently for matches? These questions are important, especially during periods of congested match fixtures or leading in to important matches and championships.

There are many components to fatigue in soccer – studies have found, for example, that a footballer often leaves the field with near maximal glycogen depletion (this will be discussed in more detail in other sections). In other words, just as a marathon runner is liable to “hit-the-wall”, or a cyclist is liable to “bonking”, if a footballer fails to replace energy, her or she may be ‘running on empty’ by the end of a match. (Sportsscientists, 2010, https://bit.ly/2K9is66).