

Assessment of Fatigue and Recovery in Sport: Narrative Review

Authors

Thomas Bestwick-Stevenson^{1, 2} , Rebecca Toone³, Emma Neupert⁴, Kimberley Edwards^{1, 2}, Stefan Kluzek^{1, 2}

Affiliations

- 1 School of Medicine, University of Nottingham, Nottingham, United Kingdom of Great Britain and Northern Ireland
- 2 Centre for Sport, Exercise and Osteoarthritis Research Versus Arthritis, University of Nottingham, Nottingham, United Kingdom of Great Britain and Northern Ireland
- 3 Mountain Biking, English Institute of Sport, Manchester, United Kingdom of Great Britain and Northern Ireland
- 4 School of Sport Health and Exercise Science, University of Portsmouth, Portsmouth, United Kingdom of Great Britain and Northern Ireland

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70469 Stuttgart, Germany

Correspondence

Mr. Thomas Bestwick-Stevenson
University of Nottingham
School of Medicine
University of Nottingham
Nottingham
NG7 2RD
United Kingdom of Great Britain and Northern Ireland
Tel.: 0115 8231412
thomas.bestwick-stevenson1@nottingham.ac.uk

ABSTRACT

Fatigue is a phenomenon associated with decreases in both physical and cognitive performances and increases in injury occurrence. Competitive athletes are required to complete demanding training programs with high workloads to elicit the physiological and musculoskeletal adaptations plus skill acquisition necessary for performance. High workloads, especially sudden rapid increases in training loads, are associated with the occurrence of fatigue. At present, there is limited evidence elucidating the underlying mechanisms associating the fatigue generated by higher workloads and with an increase in injury risk. The multidimensional nature and manifestation of fatigue have led to differing definitions and dichotomies of the term. Consequently, a plethora of physiological, biochemical, psychological and performance markers have been proposed to measure fatigue and recovery. Those include self-reported scales, countermovement jump performance, heart rate variability, and saliva and serum biomarker analyses. The purpose of this review is to provide an overview of fatigue and recovery plus methods of assessments.

Introduction

Fatigue is a phenomenon that has been identified as a significant risk factor associated with decreases in physical and cognitive performance [1] and an increase in injury incidence [2, 3]. Acute fatigue associated with physical and mental stress is expected to improve or resolve with appropriate recovery. Risk of injury is often closely associated with lower levels of endurance, fitness and strength, and good structural, biomechanical and mental adaptation to specific tasks and training environment [4, 5]. However, determining a unified definition of fatigue is not a straightforward process [6–12].

The purpose of this paper is to review definitions of fatigue and potential underlying mechanisms linking fatigue with increased injury risk and underperformance. In addition, clinically feasible markers of fatigue, methods developed to measure fatigue will be reviewed and compared.

Definitions of fatigue

Fatigue is often described as a ubiquitous [13], multifactorial [1, 8, 14], and complex phenomenon [8, 15–20], which must be studied from a collective and tissue-specific perspective [10, 11]. However, a common theme between definitions is a decline of the

overall physical or specific cardiorespiratory, neuromuscular, physiological or cognitive function of performing a particular task over time due to acute or chronic exercise and/or mental load [21].

Among various definitions (see ► **Table 1**), fatigue most commonly is defined as a decline in muscular force or power during acute exercise [12, 15, 22–26], exercise-induced decline or impairment of performance [12, 21, 25, 26], or as a decrease in pre-match/baseline physiological and psychological functioning of an athlete secondary to a chronic increase of the physical and mental load [16, 27].

Fatigue definitions in humans are closely related to patterns seen in material fatigue, where structures fail when subjected to a repetitive load and define a type of structural damage even when the material experienced stress range far below the static acute material strength [28]. It is often explained by damage that develops on the microscopic level, which grows until it reaches a critical point when it can no longer sustain the peak load [29]. This is based on the Palgren-Miner linear damage rule used to predict component fatigue based on the summation of the repetitive cycles [30]. This level of fatigue is often described as fatigue damage [29]. It relates to the stress amplitude, but for any detailed analysis, the mean stress must be taken into account [31].

The complexity in defining fatigue in sport is related to multiple domains of recovery and adaptation processes (physical, neuromuscular control and psychological) and their interactions. This is emphasized by fatigue stemming from different or multiple factors, including prolonged physical exertion, persistent mental activity, and sleep deprivation [1]. Based on associations with various stressors, definitions for each potentially causative domain have been created. It is essential to understand that some of the domains are based on observed correlations in studies and can be either causal or non-causal. Often it is assumed that factors have prognostic value based on the potential contribution to the cause of an event (such as an injury or change in performance) through direct or indirect mechanisms [32].

Neuromuscular fatigue has been defined as a reduction in the maximal force a muscle can exert [33], or the inability to sustain exercise at a required power [33, 34]. Physiological fatigue definitions include a weakness from repeated exertion or a decreased response of cells, tissues, or organs following excessive activity, stimulation, or stress [35]. Psychophysiological changes following sustained performance [36] are often linked with a state of an organism's muscles,

viscera, or central nervous system in the absence of sufficient rest. On the tissue level, the fatigue state is often defined as an insufficient restoration of cellular capacity or system-wide energy to maintain the original level of training and/or processing using typical resources [37]. Psychological (or mental) fatigue has been associated with sustained demanding cognitive activities, characterized by an increased feeling of tiredness or exhaustion, an aversion to continuing the ongoing task, plus a reduction in cognitive performance [38–40]. Mental fatigue has been linked with reduced endurance performance on cognitive and physical tasks [41–46] as well as an individual's drive to train [41, 47].

Attempts to define fatigue have resulted so far in the development of fatigue partitions, such as physical-mental [42, 48], central-peripheral [15, 21, 24, 49–51], and acute-chronic [52]. Despite partitioning being important for understanding and managing fatigue, it lacks clarity regarding the broad understanding of fatigue [9, 11]. Furthermore, distinctions between fatigue and other related concepts such as sleepiness [19], effort [53–56], exhaustion [57] and malaise [58] is still limited.

Fatigue and injury risk

Fatigue may impair the joints' kinesthetic and proprioceptive properties [59, 60]. It increases muscle spindle discharge threshold, which interrupts afferent feedback, consequently altering joint awareness [59] affecting static postural control [61, 62], but to a lesser degree, dynamic postural control [62–70]. Effectively, fatigue can be described as an inability of the nervous system to adequately recruit motor units, the basic functional unit of the neuromuscular system associated with force production. As a result, afferent feedback is affecting efferent pathways and muscle. Gribble, Hertel, Denegar, et al. [59] suggested that fatigue and chronic ankle instability create dynamic postural control deficits, which appear to be associated with kinematic changes at the knee and hip.

Muscular fatigue has previously been shown to delay reaction time [71, 72]. With increased reaction time of the gastrocnemius and tibialis anterior muscles associated inversion ankle sprain incidence [73]. Proprioceptive capabilities [74], motor control precision [75], and movement coordination [76] are all affected by muscle fatigue. Unsurprisingly, lower limb extremity kinetics and kinematics have been shown to be affected by fatigue [2].

► **Table 1** Varied definitions of fatigue.

Definition of fatigue	References
A decline in muscular force or power during acute exercise	Taylor, Chapman, Cronin, et al. [12]; Cormack, Newton, McGuigan, et al. [22]; Giannesini, Cozzone and Bendahan [23]; Liederbach, Schanfein and Kremenec [24]; Reilly [25]; Rodrigues, Soares and Tomazini [15]; Waldron and Highton [26]
An exercise-induced decline or impairment of the performance	Taylor, Chapman, Cronin, et al. [12]; Reilly [25]; Waldron and Highton [26]; Knicker, Renshaw, Oldham, et al. [21]
A decrease in pre-match/baseline physiological and psychological functioning of an athlete as a result of the chronic increase of the physiological and mental load	Allen, Lamb and Westerblad [27]; Jones, Griffiths and Mellalieu [16]
Acute impairment of exercise performance that includes both an increase in the perceived effort required to exert the desired force or power output and the eventual inability to produce that force or power output	Liederbach, Schanfein and Kremenec [24]; Davis and Bailey [28]
Accumulated time in competition with insufficient recovery time.	Lewis [29]

Fatigue is considered to be a significant risk factor in injury occurrence [2, 3]. Most injuries occur towards the end of a match or activity when individuals are fatigued [77–81]. For instance, football match injuries incidence increases towards the end of both halves [82], corresponding to 5–10% decrease in distance covered, suggesting evidence of muscular fatigue [83]. Similarly, most amateur rugby league injuries occurred in the second half of matches [77] and are likely to be associated with a fatigue-induced reduction in skill contributing to injuries in these athletes [84].

Joint instability is linked with muscle fatigue associated with muscle dysfunction [66, 85] and strength deficiencies [86–88], affecting postural control and muscles' isokinetic endurance [81, 89]. The strength reduction is related with fewer fibers being recruited [88, 90]. Hypothesis is that muscle fatigue is linked with disturbance in joint position sense, decrease in motoneuron output [81, 91, 92] and/or desensitization of type III and IV muscle afferents [81, 93].

Adequate measurements of players' fatigue and recovery could be a focus of injury prevention strategies in high demanding sports and optimization of the rehabilitation process. In addition, understanding an individual's fatigue levels can facilitate optimal workload (training and match), training adaptation and performance [94].

Markers of fatigue and recovery

Research into markers of fatigue and recovery is a popular area in sports and exercise physiology [95, 96]. Those range from biochemical [97–99], hormonal [97, 100], immunological [101, 102], psychological questionnaires [103], and the assessment of neurological status, including autonomic nervous system balance [97, 104, 105]. The differing markers provide insight for athletes, coaches, and scientists into individual response to these workloads [8]. However, while a limited number of these markers have strong scientific support for their use, and there is currently no single conclusive marker of fatigue [8].

Biochemical markers

Circulating markers in the blood are particularly attractive for assessing training-induced fatigue, offering potentially objective, high accuracy and precision, a clear physiological concept concerning their connection with exercise and fatigue [99, 106], and they have limited interference on training. However, there is currently no recognized single parameter that signifies fatigue and recovery changes during athletic training cycles with a satisfactory reproducibility and sensitivity [100, 106].

Urea, insulin-like growth factor 1 and creatine kinase

Urea and insulin-like growth factor 1 (IGF-1) is suggested for endurance cycling training, and creatine kinase (CK) for high intensity interval training in team sports and strength training as indicators of fatigue [106].

Increased urea and decreased IGF-1 have previously been reported during a fatigued state [107]. Urea, suggesting protein breakdown [97, 100, 106] during prolonged exercise, can also be influenced by dietary protein intake and therefore is not that reliable [108]. IGF-1 has been suggested to show a state of glucose austerity following

the depletion of carbohydrate stores because of endurance training [99, 106]. Both strength and high intensity interval training are characterized by a high proportion of eccentric force production and muscle tension, which leads to muscle fiber damage, and resulting leakage of enzyme CK from the sarcoplasm into the bloodstream [106]. This process has allowed CK to become a classic blood-borne marker of fatigue and strain in relevant disciplines [97, 100, 106]. However, it should be noted that muscle damage is only one aspect of fatigue and other aspects, such as psychological alterations or anabolic-catabolic balance, may play a role in the overall need for recovery [106]. It is also important to state that Hecksteden, Skorski, Schwindling, et al. [106] suggests that blood-borne markers are affected by the metabolic process of the activities causing fatigue, which could help explain why there is a difference in prominent markers for differing activities.

Adenosine

Adenosine concentration increases during exercise and its concentration affects blood flow in skeletal muscles [109], plus has profound tissue-protective effects in situations of ischemia and inflammation [110]. Adenosine inhibits CD8+ T cells by activating adenosine receptors and can cause a significant immunosuppression [111]. It is a promising marker for training adaptations not associated with muscle mass [112]. However there are well recognized difficulties in measuring the adenosine concentration due to the rapid cellular uptake and degradation [113].

Lactate

Blood lactate concentration has also been shown to be sensitive to changes in exercise intensity and duration [8, 114], thus can also be used as a marker of acute fatigue. However, regularly monitoring lactate concentrations during training and competition has limitations, including inter and intra-individual differences in lactate accumulation depending on previous exercise, glycogen content, diet, hydration status, ambient temperature, amount of muscle mass used, plus the time and site of sample procedures [8].

Glutamine

Glutamine is found in various human tissues in high volumes [115, 116], as well as also being the most abundant amino acid in human muscle tissue and plasma [116–118]. Glutamine has also been stated to be the most versatile amino acid [115], this is emphasized by the differing roles glutamine has in a variety of organs and tissues [116]. These roles include maintenance of acid base balance during acidosis, the transfer of nitrogen between organs and detoxification of ammonia, a fuel for gut mucosal cells, a fuel for the immune system cells, a possible direct regulator of protein synthesis and degradation, plus as a nitrogen precursor for the synthesis of nucleotides [115–117]. Plasma glutamine has been suggested as a marker of excessive training loads [108, 115], due to abnormally low plasma glutamine levels being reported in overtrained individuals [108]. However, plasma glutamine levels do not fall after short term high-intensity exercise, but do after an acute bout of prolonged exercise [108], and decreases in plasma glutamine levels can also occur after burns, infections, inflammation, and physical trauma [108, 117, 119]. Diet can affect plasma glutamine levels, with Greenhaff, Gleeson and Maughan [120] reporting concentrations to in-

crease temporarily following the consumption of a meal containing protein, but decrease by about 25% after several days on a low carbohydrate diet. Consequently, to use plasma glutamine as a marker of fatigue, an individual's diet plus the timing of blood sample in relation to the bouts of exercise and food intake must be standardized, it is also important to take other factors, such as infection and tissue injury, must be taken into consideration [108].

Oxidative stress

Markers of oxidative stress have been implicated in acute fatigue [121], with the total anti-oxidative activity being shown to increase following a bout of exercise [122]. Exhaustion levels correlate with isoprostanes and glutathione/oxidized glutathione [123], plus an increased 8-hydroxydeoxyguanosine being reported to continue for two to three days following sleep deprivation [124]. Consequently, biomarkers for oxidative stress and antioxidant activity measured simultaneously are implicated in fatigue conditions in healthy individuals and differentiate from chronic fatigue syndrome [121]. It is important to acknowledge that some oxidative biomarkers cannot be accurately measured *in vivo* due to high reactivity and short biological half-life [121].

Intracellular oxidative stress-related activities can be reduced with low Vitamin D levels, with suboptimal concentrations of serum 25-hydroxy vitamin D failing to suppress oxidative stress conditions and increase intracellular oxidative damage and can lead to apoptosis [125]. Vitamin D supports maintenance of cellular oxidation level and normal mitochondrial functions [125–128]. It has been suggested that vitamin D level can directly affect injury risk, supports recovery, bone health [129], and is essential for optimal muscle function [129–135].

Endocrine biomarkers

Thyroid

Even though energy balance is not used to diagnose chronic fatigue, a negative energy balance can affect endocrine function and influence performance and ability to adapt to training [136].

Thyroid hormones concentration can be influenced by energy balance, thus contributing to fatigue, but this relationship has not been extensively researched [136]. It is known that thyroid hormone concentrations are reduced with increased exercise training due to negative energy imbalance and reduced energy availability [136, 137]. As a result of the reduced availability, physiological processes are downregulated to account for the increased energy expenditure from exercise [136]. Consequently, it is essential for appropriate macronutrient intake to produce positive adaptations to training and to meet the intense energy demands during competition [136]. It can be difficult for athletes completing demanding training schedules to consume the necessary amount of calories to maintain energy balance, and may lead to the physiological processes of fatigue, over training and underperformance [136]. In female athletes, thyroid hormones have been shown to be considerably lower with negative energy balance induced amenorrhoea [138], while amenorrhoeic athletes have a reduced recovery capacity [139] and reduced neuromuscular performance [140]. This can have detrimental effects on athletic performance and recovery due to thyroid hormones regulating metabolism and growth [136]. Thyrotropin (thyroid stimulating hormone) and free triiodothyro-

nine are two examples of this [136, 141] and have been found to be decreased after a prolonged, intense training cycle [136], which is magnified and extended after such a cycle has been reduced [142]. Despite this, Nicoll, Hatfield, Melanson, et al. [136] suggests that thyroid hormones change too slowly to be used as a readily available marker for fatigue. Monitoring of thyroid hormone is thought to have the potential to provide information about the overall training status of individuals, and adaptation [136].

Stress hormone responses

Increases in training loads over several weeks have been associated with repetitive large stress hormone responses, including adrenocorticotrophic hormone, catecholamines, and cortisol. It is thought that downregulation of specific hormone receptors in the target tissues occurs, which decreases the tissues' responsiveness to these hormones [108]. One of the best indicators of fatigue and overtraining is individual mood changes, as training intensifies, with increased negative moods, such as anger, confusion, depression, fatigue, and tension [108, 143]. These changes have been suggested to reflect underlying biochemical and immunological changes, which are communicated to the brain via hormones and cytokines [108]. Consequently, there appears to be various hormonal abnormalities in athletes affected by overtraining syndrome [108, 144].

Cortisol and testosterone ratio

The cortisol/testosterone ratio has been proposed as a marker of training adaptation based on the idea that cortisol is a catabolic hormone while testosterone is an anabolic hormone [108]. So far, several studies included in the review conducted by Eichner [145] did not find a significant change in the ratio in well-trained athletes during progressive increases in training loads [108].

Saliva

The cortisol and testosterone levels in saliva have been shown to provide an accurate measure of fatigue [146, 147]. This is done through previous research showing that levels of hormones taken from saliva, such as cortisol and testosterone, change during and after physical activity, and individual's biochemical response can be determined by examining these alterations [148]. This is shown by cortisol levels increasing by around 2.5 times throughout a rugby match compared to pre-match levels (baseline), and then return back to baseline within four hours [149]. Similarly, cortisol concentrations increased from baseline by ~56 and ~59% at 12 and 36 hours post rugby match, while testosterone concentrations decreased from baseline at the same time points [150].

Findings of increased amounts of cortisol maybe due to cortisol being a primary stress hormone and the post exercise rise is suggested to reflect the metabolic demands placed on the body [150, 151]. It has also been suggested that increased cortisol concentrations may reduce testosterone synthesis [152–154], which could explain the reductions in testosterone concentrations [150]. These findings could also be due to previous studies stating that fatigue may manifest itself as alterations in hormone levels [150, 155] and increased markers of muscle damage, such as increased CK concentration [156, 157].

One benefit of saliva samples, is that they are more stable and sampled easily and repeatedly compared to blood and urine detec-

tion as they can be affected by the kidneys and other factors [1, 20]. Similarly, saliva is simpler and completely non-invasive, unlike blood and urine analysis [20, 22, 158]. Previous research has also stated how human saliva glands are innervated by both the parasympathetic nervous system and activation of the sympathetic nervous system [1, 159, 160], which is important as prolonged physical exertion triggers changes in autonomic nervous system signaled by a simultaneous withdrawal of the parasympathetic nervous system and activation of the sympathetic nervous system [1, 161].

However, despite the benefits of saliva measures it is relatively expensive and time consuming method in applied environments [162]. There is also poor temporal relationships with neuromuscular performance and the multifactorial components of fatigue cannot be assessed in a single biochemical, hormonal, or immunological measure [162]. Consequently the use of biochemical, hormonal, and immunological measures to monitor fatigue should be considered carefully [162].

Immunological markers

Immunological markers indicating fatigue are based on immune system alterations associated with training loads and other stressors [108]. Athletes suffering from overtraining syndrome are often immunosuppressed [108]. Subsequently the use of immunological markers is a logical step of assessing fatigue by assessing an individual's ability to cope with increased training and consequently provide a way of identifying an individual's fatigue status [108]. Similarly, several sections of the immune system function seem to be sensitive to both acute and chronic stress of exercise [108].

A review by Mackinnon [163] states that repeated bouts of intense, prolonged exercise might decrease the number and functional capacity of the circulating leukocytes. Immunosuppression associated with heavy training can also cause a fall in blood concentration of glutamine [108, 164]. Similarly, the circulating number of leukocytes is generally lower in athletes at rest than sedentary individuals [163, 165], which again suggests that exercise can alter the immune function, suggesting a decrease in the immune system function, especially during high workloads [108]. A low blood leukocyte concentration could arise from the hemodilution (expansion of the plasma volume) associated with training or represent changes in leukocyte kinetics, including a decreased release from the bone marrow [108]. The large neutrophilia that comes from a prolonged exercise session could, over periods of heavy training, reduce the bone marrow stores of these crucial cells [108]. Leukocyte cells in the blood have been found to be less mature in athletes than sedentary individuals [166]. Similarly, the phagocytic activity of blood neutrophils has been reported to be significantly lower in well-trained cyclists compared to age, and body mass matched sedentary controls [165]. Mackinnon [167] also found levels of secretory immunoglobulins, such as salivary immunoglobulin A, are lower in well-trained individuals.

Several possible causes of the decreased immune function associated with heavy workloads have been proposed. One of which might simply be the cumulative effects of repeated bouts of intense exercise with the resulting increase of stress hormones, especially glucocorticoids in temporary immunosuppression [108, 168]. It is also possible that there is insufficient time for the immune system to fully recover when exercise is repeated frequently [108]. Addi-

tionally, plasma glutamine levels can alter considerably after exercise, which may become chronically depressed after repeated bouts of prolonged strenuous exercise [117, 164]. Also, through the muscle damage that occurred from repeated bouts of exercise, a decrease of serum concentration can occur, contributing to decreased immunity in athletes, and well-trained individuals have been found to have lower serum concentrations than controls [163].

As a result, it has been suggested that possible markers of fatigue can include blood levels of stress hormones, antibodies, cytokines, and glutamine, plus the ability of leukocytes to respond to the antigens stimulation [108]. It has also been suggested that plasma glutamine/glutamate ratio changes is also a predictor of fatigue in athletes [98, 116].

Cognitive and emotional fatigue measured by psychological questionnaires

Mood changes have been significantly associated with training load and fatigue, consequently, psychological questionnaires are utilized as a method to monitor fatigue [108]. As training increases, athletes tend to develop a dose-related mood disturbance with low scores for vigor and increased scores for negative moods such as anger, confusion, depression, fatigue, and tension [108, 143]. Assessing muscle soreness and fatigue during and after each exercise session has also been suggested [169], which could provide an effective way to monitor the recovery from workloads [108]. Using psychological questionnaires as a marker of fatigue could also be useful as they are a relatively inexpensive and straightforward fatigue marker [8].

Self-reported methods

Typically, these questionnaires gather information on parameters such as muscle soreness, tiredness, sleep health and current stress levels [170]. Self-report questionnaires are widely employed to assess fatigue in sport, of which there is a plethora [12, 171–173]. This is predominantly thought to be due to their low-cost, relative ease of implementation and flexibility, enabling them to be administered across a wide range of individual and team sport settings [174].

Validated self-report questionnaires that are frequently cited in research include the Profile of Mood States (POMS), Total Quality Recovery (TQR), Daily Analysis of Life Demands for Athletes (DALDA), the Recovery Stress Questionnaire for Athletes (REST-Q), the Acute Recovery and Stress Scale (ARSS), and the Rating of Fatigue Scale (ROF) [11, 170, 175–179]. Additionally, Rating of Perceived Exertion (RPE) and session RPE (duration of training session multiplied by RPE) are frequently used to monitor both training load and expected responses to training load [11]. ► **Table 2** shows an overview of the various questionnaires.

There are, therefore, a significant number of questionnaires that can reflect perceptual fatigue. Nonetheless, recent research has demonstrated that even those questionnaires explicitly developed for athletic populations have only adequate measurement properties, with weak content validity and reliability a particular concern [180, 181]. Interestingly, there is widespread evidence that sporting organizations have increasingly chosen to employ their own customized self-report questionnaires over the questionnaires published in the literature [12, 182, 183]. This divergence between research and practice likely stems from the perception that the ex-

► **Table 2** An overview of the differing self-reported methods.

Questionnaire	Overview
Profile of Mood States (POMS)	<ul style="list-style-type: none"> 65-question version addresses six components of mood: tension, depression, anger, vigor, fatigue, and confusion [175, 184, 185]. Widely researched and validated [186]. There is also a short version consisting of 37 questions [187]. Appears to detect fluctuations in mood associated with exercise [188]. Neither the 65-question version or shortened 37-question version appear to be regularly used in competitive sport [174].
Total Quality Recovery (TQR)	<ul style="list-style-type: none"> Split into two sections, perceived and action, which allows for subjective and objective scales, consequently examining qualitative and quantitative aspects [179]. Strong association between athlete well-being and performance [189]. Based around the Borg scale [190], with the aim of matching recovery with perceived exertion [179].
Daily Analysis of Life Demands for Athletes (DALDA)	<ul style="list-style-type: none"> Examines sources and symptoms of stress over 34 questions, with a scale that compares each parameter in respect to normal. Three consecutive days of reporting 'worse than normal' on a specific parameter can indicate a state of stress [173, 191]. Stated to be an effective practical method for monitoring fatigue and recovery [191]. But allowing comparison of a parameter to 'normal,' may prevent fatigue reinforcement, which has been reported as a concern by researchers [192]. Does not attribute a scale to its results. This limits its analysis to individual visual representation rather than group statistical analysis, which can be problematic for those analyzing the questionnaire [180].
Recovery Stress Questionnaire for Athletes (REST-Q Sport)	<ul style="list-style-type: none"> 76 items (plus a warm-up item) on a 0 to 6-point anchored Likert scale, with the shortened version comprising of 36 items. Consists of seven general stress scales, five general recovery scales, three sport-specific stress scales, and four sport-specific recovery scales [105]. Focuses on different elements of sporting and non-sporting stress and recovery, typically covering a time-frame of the preceding three days [105, 181]. Been employed across a range of individual and team sports in several different countries and languages [105, 193–197]. Sub-scales within the questionnaire have demonstrated sensitivity to periods of functional over-reaching [198] and changes in training loads [199, 200] which indicate its potential utility to assess fatigue indirectly through stress and recovery. Requires questionnaires to be completed on regular basis [201].
Acute Recovery and Stress Scale (ARSS)	<ul style="list-style-type: none"> Consists of a list of 32 adjectives, summarized into four recovery and four stress scales representing physical, mental, emotional and overall dimensions [183]. The ARSS and its abridged version, the Short Recovery and Stress Scale (SRSS) enable the balance between stress and recovery to be assessed. Both versions are stated as useful, plus valid and reliable [183]. Appears to be sensitive to perceptual changes of stress and fatigue during intensive training [202].
Rating of Fatigue Scale (ROF)	<ul style="list-style-type: none"> Been argued to provide a valid measure of an individual's fatigue status [11]. Unlike other well established perceived exertion scales [203–207], the ROF scale claims to differentiate between perceptions of fatigue and exertion during exercise, as well as measuring fatigue during recovery [11]. May provide an avenue to track fatigue both during and following training. The use of this scale to date has been limited, The method requires taking measurements during various moments of exercise [11], which would be problematic during sporting performances of various individuals.
Rating of Perceived Exertion (RPE)	<ul style="list-style-type: none"> Well known and commonly used measure [208] is valid and reliable for monitoring athlete's internal training loads [209]. Uses scale from 6 to 20, roughly matched to heart rate [210]. Session RPE suggested detecting accumulated fatigue across multiple days, plus being a surrogate marker of exercise intensity [211].

isting questionnaires lack sports specificity and are too extensive in nature [12]. Customized questionnaires may overcome these problems but potentially raise new issues relating to even weaker validity and reliability [180, 181]. Unless the reliability and validity of custom questionnaires are discerned, conclusions drawn from the data are questionable and should therefore be interpreted with caution [180].

One issue with self-reported methods is that changes in perceived fatigue and muscle soreness are also known to outlast reductions in neuromuscular performance and biochemical markers [184]; however, that study was conducted only on rugby players. Similarly, changes in psychological state or mental fatigue are also known to change an individual's sense of effort forcing individuals to down-regulate their exercise capacity [42, 162]. It is supported

by previous studies stating that, despite self-reporting methods being frequently used to assess fatigue, an individual's perception of fatigue is not a robust predictor of the ability to perform [1, 185]. Consequently, it has also been stated that there is a need for objective measures of fatigue [1, 186].

Overall, it is apparent that subjective self-report questionnaires can play an important role in assessing fatigue [187, 188]. However, it is prudent to interpret self-report questionnaires alongside objective measures and reference to an individual's broader training context. It is primarily due to the weak reliability and validity of self-report questionnaires [180], but also because perceptions of fatigue are not always a robust predictor of performance ability [1, 185]. Additionally, poor engagement from those completing self-report questionnaires can reduce questionnaire efficacy, with

social desirability bias potentially confounding responses further [162, 189, 190]. Previous research has also stated how subjective measures are a concern for coaches due to athletes being able to manipulate responses to produce favorable outcomes [162, 189, 190]. Another issue with questionnaires is the possibility of a lack of compliance [162].

Markers of autonomic nervous system alternations

Assessing the autonomic nervous system has also been used as a marker of fatigue. This is due to the suggestion that alterations in the autonomic nervous system status coincides with hormonal changes seen during over training and fatigue [191, 192]. However, differing methods of assessing the autonomic nervous system have been devised.

Heart rate

Monitoring heart rate during exercise is based on the linear relationship between heart rate and oxygen consumption rate during steady-state exercise [8, 193]. However, prescribing and monitoring intensity is based on a percentage of maximum heart rate, but this can be problematic because of daily differences in heart rate, which can be up to 6.5% for submaximal heart rate, and can be affected by factors such as environment, hydration, and medication [8, 194].

Heart rate recovery

Heart rate recovery assesses the rate of decline in heart rate at the end of the exercise, which has been suggested to be a marker of autonomic function and training status in individuals [8, 195]. Exercise is a consequence of increased sympathetic activity, in addition to a reduction in parasympathetic activity [8]. Heart rate recovery is characterized by comparing autonomic nervous system activity, increasing parasympathetic activity and removing sympathetic nervous activity [8, 196]. Various timeframes can be used to calculate heart rate recovery, usually between 30 seconds and 2 minutes, with the difference between heart rate at the end of exercise and 60 seconds post-exercise being the most commonly used timeframe [8, 195].

Heart rate variability

Heart rate variability has been suggested to be a practical non-invasive method for assessing cardiac anomalous nervous system [191, 197]. This is a measurement of the difference between resting and post-exercise heart rate, which has been suggested to show both negative and positive adaptations to training [8, 198]. This in part, might explain why heart rate variability has been suggested by researchers to be used to guide training on a day-to-day basis [191, 199–201]. However, scientific literature has been inconclusive about this marker, with equivocal findings from studies that examined heart rate variability and over training, with findings of increases [202], decreases [203–205], and no difference [197, 206] in cardiac anomalous system activity. Consequently, it is unknown whether a relationship exists between heart rate variability and overtraining, or if the marker can be used to identify the progression of overtraining before complete manifestation [191].

The equivocal findings could be due to the high day-to-day variability in environmental and homeostatic factors plus varying methodological approaches used [8, 198], and exercise the days

before the recordings [191, 207]. These factors, individually or collectively, are likely to explain the discrepancy between studies [191, 197, 206], and thus the lack of sensitivity from heart rate variability measurements to detect fatigue could be due to type 2 errors [191, 208]. To avoid the possible inconsistencies in findings, it has been suggested that both weekly and 7-day rolling averages have validities rather than single-day measurements [8, 191].

Neuromuscular

A decrease in maximal force capabilities of a muscle or muscle group regardless of maintaining a given task or not relates to neuromuscular fatigue [209, 210].

An objective measure of neuromuscular fatigue is the counter-movement jump (CMJ), with the test being shown to be sensitive to match-induced fatigue [65, 150, 155, 184, 211]. The CMJ test is also stated to be a popular test, which is easy to administer and produces minimal amount of additional fatigue [12, 162, 212], all of which allows for repeated assessments of multiple individuals over a short time [212]. It has also been stated that jump procedures reflect the stretch-shortening cycle of lower limb musculature [162, 213]. Previous research has emphasized that athletic performances consist of stretch-shortening cycle movements [212, 214], and stretch-shortening cycle fatigue relates to numerous mechanical, metabolic and/or neural factors [212, 213, 215, 216]. Similarly, it has been stated how reduced neuromuscular function reduced conduction of afferent signals from the fatigue altered state of the muscle will lead to reduced propagation of efferent signals, which affects the ability to create compensatory movement effectively [60, 63]. However, previous research has also found no significant differences in CMJ tests pre and post-football match, when examining peak force, peak power, or rate of force development [217], and elite Australian Rules Football match, when examining mean force and mean power [148]. This could be due to the CMJ test lacking the sensitivity to detect neuromuscular fatigue from a single game [211]. It has also been stated that CMJ tests may overlook a number of fatigue-related neuromuscular changes due to the complex nature of neuromuscular fatigue [21, 212].

Summary of markers of fatigue

The importance of fatigue markers is shown through the aim of assessing fatigue in competitive athletes to individually prescribed training to achieve a balance of maximizing training loads and adaptations while providing adequate recovery for the athlete [106].

Nevertheless, due to difficulties in defining fatigue, it is also challenging to measure and monitor fatigue [6, 7, 12, 218], which is emphasized by no single universally accepted measure of fatigue [1, 8, 12, 21, 219]. Consequently, several markers and/or measures are needed for early fatigue detection [116], with no single marker indicating impending fatigue. Thus, different methods are used. Similarly, Worrell and Perrin [220] have also stated how it is challenging to study the role of muscle fatigue in sustaining injuries.

Conclusion

In conclusion, fatigue is a multifactorial and complex phenomenon. Fatigue has been suggested to be one of the most important injury risk factors. Measuring and monitoring fatigue and recovery can

be difficult, emphasized by no single universally accepted definition or measure of fatigue. Consequently, differing methods are used to monitor them, including self-reported methods, heart rate variability, counter movement jump, and saliva.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

- [1] Michael DJ, Daugherty S, Santos A et al. Fatigue biomarker index: An objective salivary measure of fatigue level. *Accid Anal Prev* 2012; 45: 68–73
- [2] Santamaria LJ, Webster KE. The effect of fatigue on lower-limb biomechanics during single-limb landings: A systematic review. *J Orthop Sports Phys Ther* 2010; 40: 464–473
- [3] Wilson EL, Madigan ML. Effects of fatigue and gender on peroneal reflexes elicited by sudden ankle inversion. *J Electromyogr Kinesiol* 2007; 17: 160–166
- [4] McIntosh AS. Risk compensation, motivation, injuries, and biomechanics in competitive sport. *Br J Sports Med* 2005; 39: 2–3
- [5] Taimela S, Kujala UM, Osterman K. Intrinsic risk factors and athletic injuries. *Sports Med* 1990; 9: 205–215
- [6] Abbiss CR, Laursen PB. Is part of the mystery surrounding fatigue complicated by context? *J Sci Med Sport* 2007; 10: 277–279
- [7] Enoka R, Duchateau J. Muscle fatigue: What, why and how it influences muscle function. *J Physiol* 2008; 586: 11–23
- [8] Halson SL. Monitoring training load to understand fatigue in athletes. *Sports Med* 2014; 44: 139–147
- [9] Kluger BM, Krupp LB, Enoka RM. Fatigue and fatigability in neurologic illnesses: Proposal for a unified taxonomy. *Neurology* 2013; 80: 409–416
- [10] Marino FE, Gard M, Drinkwater EJ. The limits to exercise performance and the future of fatigue research. *Br J Sports Med* 2011; 45: 65–67
- [11] Micklewright D, Gibson ASC, Gladwell V et al. Development and validity of the rating-of-fatigue scale. *Sports Med* 2017; 47: 2375–2393
- [12] Taylor K, Chapman D, Cronin J et al. Fatigue monitoring in high performance sport: a survey of current trends. *JASC* 2012; 20: 12–23
- [13] Mehta RK, Parasuraman R. Effects of mental fatigue on the development of physical fatigue: a neuroergonomic approach. *Hum Factors* 2014; 56: 645–656
- [14] DeLuca J. Fatigue: its definition, its study, and its future. In: DeLuca J, eds. *Fatigue as a Window to the Brain*. Cambridge, MA: MIT Press; 2005: 319–325
- [15] Rodrigues KA, Soares RJ, Tomazini JE. The influence of fatigue in evertor muscles during lateral ankle sprain. *Foot* 2019; 40: 98–104
- [16] Jones CM, Griffiths PC, Mellalieu SD. Training load and fatigue marker associations with injury and illness: A systematic review of longitudinal studies. *Sports Med* 2017; 47: 943–974
- [17] Chiu LZ, Barnes JL. The fitness-fatigue model revisited: Implications for planning short-and long-term training. *Strength Cond J* 2003; 25: 42–51
- [18] Noakes TDO. Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. *Front Physiol* 2012; 3: 82. doi: 10.3389/fphys.2012.00082
- [19] Shen J, Barbera J, Shapiro CM. Distinguishing sleepiness and fatigue: Focus on definition and measurement. *Sleep Med Rev* 2006; 10: 63–76
- [20] Xu Y, Xiao D, Zhang H et al. A prospective study on peptide mapping of human fatigue saliva markers based on magnetic beads. *Exp Ther Med* 2019; 17: 2995–3002
- [21] Knicker AJ, Renshaw I, Oldham AR et al. Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Med* 2011; 41: 307–328
- [22] Cormack SJ, Newton RU, McGuigan MR et al. Neuromuscular and endocrine responses of elite players during an Australian rules football season. *Int J Sports Physiol Perform* 2008; 3: 439–453
- [23] Giannesini B, Cozzone PJ, Bendahan D. Non-invasive investigations of muscular fatigue: metabolic and electromyographic components. *Biochimie* 2003; 85: 873–883
- [24] Liederbach M, Schanfein L, Kremenic IJ. What is known about the effect of fatigue on injury occurrence among dancers. *J Dance Med Sci* 2013; 17: 101–108
- [25] Reilly T. Physiological aspects of soccer. *Biol Sport* 1994; 11: 3–20
- [26] Waldron M, Highton J. Fatigue and pacing in high-intensity intermittent team sport: An update. *Sports Med* 2014; 44: 1645–1658
- [27] Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: Cellular mechanisms. *Physiol Rev* 2008; 88: 287–332
- [28] Schijve J. *Fatigue of Structures and Materials*. Springer Science & Business Media; 2001
- [29] Ellyin F. *Fatigue Damage, Crack Growth and Life Prediction*. Springer Science & Business Media; 2012
- [30] Zhu S-P, Huang H-Z, Wang Z-L. Fatigue life estimation considering damaging and strengthening of low amplitude loads under different load sequences using fuzzy sets approach. *Int J Damage Mech* 2011; 20: 876–899
- [31] Kwofie S. An exponential stress function for predicting fatigue strength and life due to mean stresses. *Int J Fatigue* 2001; 23: 829–836
- [32] Riley RD, Hayden JA, Steyerberg EW et al. Prognosis Research Strategy (PROGRESS) 2: prognostic factor research. *PLoS Med* 2013; 10: e1001380
- [33] Millet G, Millet G, Lattier G et al. Alteration of neuromuscular function after a prolonged road cycling race. *Int J Sports Med* 2003; 24: 190–194
- [34] Behm DG, Power K, Drinkwater E. Comparison of interpolation and central activation ratios as measures of muscle inactivation. *Muscle Nerve* 2001; 24: 925–934
- [35] Hirshkowitz M. Fatigue, sleepiness, and safety: Definitions, assessment, methodology. *Sleep Med Clin* 2013; 8: 183–189
- [36] Van der Linden D, Frese M, Meijman TF. Mental fatigue and the control of cognitive processes: Effects on perseveration and planning. *Acta Psychol (Amst)* 2003; 113: 45–65
- [37] Phillips RO. A review of definitions of fatigue – And a step towards a whole definition. *Transp Res F: Traffic Psychol Behav* 2015; 29: 48–56
- [38] Pageaux B, Lepers R. The effects of mental fatigue on sport-related performance. *Prog Brain Res* 2018; 240: 291–315
- [39] Boksem MA, Tops M. Mental fatigue: costs and benefits. *Brain Res Rev* 2008; 59: 125–139
- [40] Boksem MA, Meijman TF, Lorist MM. Mental fatigue, motivation and action monitoring. *Biol Psychol* 2006; 72: 123–132
- [41] Schiphof-Godart L, Roelands B, Hettinga FJ. Drive in sports: How mental fatigue affects endurance performance. *Front Psychol* 2018; 9: 1383
- [42] Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J Appl Physiol (1985)* 2009; 106: 857–864

- [43] Dantzer R, Heijnen CJ, Kavelaars A et al. The neuroimmune basis of fatigue. *Trends Neurosci* 2014; 37: 39–46
- [44] MacMahon C, Schücker L, Hagemann N et al. Cognitive fatigue effects on physical performance during running. *J Sport Exerc Psychol* 2014; 36: 375–381
- [45] Emanuel P, Sousa J, Silva M et al. Prior acute mental exertion in exercise and sport. *Clin Pract Epidemiol Ment Health* 2016; 12: 94–107
- [46] McMorris T, Barwood M, Hale BJ et al. Cognitive fatigue effects on physical performance: A systematic review and meta-analysis. *Physiol Behav* 2018; 188: 103–107
- [47] Martin K, Meeusen R, Thompson KG et al. Mental fatigue impairs endurance performance: A physiological explanation. *Sports Med* 2018; 48: 2041–2051
- [48] Lal SK, Craig A. A critical review of the psychophysiology of driver fatigue. *Biol Psychol* 2001; 55: 173–194
- [49] Boyas S, Guével A. Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Ann Phys Rehabil Med* 2011; 54: 88–108
- [50] Davis JM. Central and peripheral factors in fatigue. *J Sports Sci* 1995; 13: 49–53
- [51] Gibson H, Edwards R. Muscular exercise and fatigue. *Sports Med* 1985; 2: 120–132
- [52] Tanaka M, Ishii A, Watanabe Y. Neural mechanisms underlying chronic fatigue. *Rev Neurosci* 2013; 24: 617–628
- [53] Abbiss CR, Peiffer JJ, Meeusen R et al. Role of ratings of perceived exertion during self-paced exercise: what are we actually measuring? *Sports Med* 2015; 45: 1235–1243
- [54] Marcora SM. Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs. *J Appl Physiol* (1985) 2009; 106: 2060–2062
- [55] Smirmaul BdPC. Sense of effort and other unpleasant sensations during exercise: clarifying concepts and mechanisms. *Br J Sports Med* 2012; 46: 308–311
- [56] Swart J, Lindsay TR, Lambert MI et al. Perceptual cues in the regulation of exercise performance—physical sensations of exercise and awareness of effort interact as separate cues. *Br J Sports Med* 2012; 46: 42–48
- [57] Vetter RE, Symonds ML. Correlations between injury, training intensity, and physical and mental exhaustion among college athletes. *J Strength Cond Res* 2010; 24: 587–596
- [58] Van Oosterwijck J, Nijs J, Meeus M et al. Pain inhibition and postexertional malaise in myalgic encephalomyelitis/chronic fatigue syndrome: an experimental study. *J Intern Med* 2010; 268: 265–278
- [59] Gribble PA, Hertel J, Denegar CR et al. The effects of fatigue and chronic ankle instability on dynamic postural control. *J Athl Train* 2004; 39: 321–329
- [60] Rozzi S, Yuktanandana P, Pincivero D et al. Role of fatigue on proprioception and neuromuscular control. In: Lephart S, Fu F, Eds. *Proprioception and Neuromuscular Control in Joint Stability*. Champaign, IL: Human Kinetics; 2000: 375–383
- [61] Takeda K, Mani H, Hasegawa N et al. Adaptation effects in static postural control by providing simultaneous visual feedback of center of pressure and center of gravity. *J Physiol Anthropol* 2017; 36: 31
- [62] Winter DA. *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons; 2009
- [63] Gribble PA, Hertel J. Effect of hip and ankle muscle fatigue on unipedal postural control. *J Electromyogr Kinesiol* 2004; 14: 641–646
- [64] Gribble PA, Hertel J. Effect of lower-extremity muscle fatigue on postural control. *Arch Phys Med Rehab* 2004; 85: 589–592
- [65] Johnston RD, Gabbett TJ, Jenkins DG et al. Influence of physical qualities on post-match fatigue in rugby league players. *J Sci Med Sport* 2015; 18: 209–213
- [66] Lundin TM, Feuerbach JW, Grabiner MD. Effect of plantar flexor and dorsiflexor fatigue on unilateral postural control. *J Appl Biomech* 1993; 9: 191–201
- [67] Miller PK, Bird AM. Localized muscle fatigue and dynamic balance. *Percept Mot Skills* 1976; 42: 135–138
- [68] Nardone A, Tarantola J, Giordano A et al. Fatigue effects on body balance. *Electroencephalogr Clin Neurophysiol* 1997; 105: 309–320
- [69] Ochsendorf DT, Mattacola CG, Arnold BL. Effect of orthotics on postural sway after fatigue of the plantar flexors and dorsiflexors. *J Athl Train* 2000; 35: 26–30
- [70] Sirois-Leclerc G, Remaud A, Bilodeau M. Dynamic postural control and associated attentional demands in contemporary dancers versus non-dancers. *PLoS One* 2017; 12: e0173795
- [71] Hanson C, Klimovitch, Lofthus G. Effects of fatigue and laterality on fractionated reaction time. *J Mot Behav* 1978; 10: 177–184
- [72] Morris AF. Effects of fatiguing isometric and isotonic exercise on resisted and unresisted reaction time components. *Eur J Appl Physiol Occup Physiol* 1977; 37: 1–11
- [73] Willems T, Witvrouw E, Delbaere K et al. Intrinsic risk factors for inversion ankle sprains in females – a prospective study. *Scan J Med Sci Sports* 2005; 15: 336–345
- [74] Sparto PJ, Parnianpour M, Reinsel TE et al. The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *J Ortho Sports Phys Ther* 1997; 25: 3–12
- [75] Parnianpour M, Nordin M, Kahanovitz N et al. The triaxial coupling of torque generation of trunk muscles during isometric exertions and the effect of fatiguing isoinertial movements on the motor output and movement patterns. *Spine* 1988; 13: 982–992
- [76] Skinner H, Wyatt M, Hodgdon J et al. Effect of fatigue on joint position sense of the knee. *J Orthop Res* 1986; 4: 112–118
- [77] Gabbett TJ. Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. *Br J Sports Med* 2000; 34: 98–103
- [78] Jackson ND, Gutierrez GM, Kaminski T. The effect of fatigue and habituation on the stretch reflex of the ankle musculature. *J Electromyogr Kinesiol* 2009; 19: 75–84
- [79] Pinto M, Kuhn JE, Greenfield M et al. Prospective analysis of ice hockey injuries at the Junior A level over the course of one season. *Clin J Sport Med* 1999; 9: 70–74
- [80] Woods C, Hawkins R, Hulse M et al. The Football Association Medical Research Programme: an audit of injuries in professional football: an analysis of ankle sprains. *Br J Sports Med* 2003; 37: 233–238
- [81] Yaggie JA, McGregor SJ. Effects of isokinetic ankle fatigue on the maintenance of balance and postural limits. *Arch Phys Med Rehab* 2002; 83: 224–228
- [82] Ekstrand J, Häggglund M, Waldén M. Injury incidence and injury patterns in professional football: the UEFA injury study. *Br J Sports Med* 2011; 45: 553–558
- [83] Mohr M, Krustup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci* 2003; 21: 519–528
- [84] Gabbett TJ. Incidence of injury in semi-professional rugby league players. *Br J Sports Med* 2003; 37: 36–44
- [85] Tropp H, Odenrick P. Postural control in single-limb stance. *J Orthop Res* 1988; 6: 833–839
- [86] Greig M. The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors. *Am J Sports Med* 2008; 36: 1403–1409
- [87] Small K, McNaughton L, Greig M et al. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *J Sci Med Sport* 2010; 13: 120–125

- [88] Rahnema N, Reilly T, Lees A et al. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *J Sports Sci* 2003; 21: 933–942
- [89] Ekdahl C. Postural control, muscle function and psychological factors in rheumatoid arthritis: Are there any relations? *Scand J Rheumatol* 1992; 21: 297–301
- [90] Bangsbo J. The physiology of soccer – with special reference to intense intermittent exercise. *Acta Physiol Scand Suppl* 1994; 619: 1–155
- [91] Kernell D, Monster A. Motoneurone properties and motor fatigue. *Experimental Brain Research. Exp Brain Res* 1982; 46: 197–204
- [92] Macefield G, Hagbarth K-E, Gorman R et al. Decline in spindle support to alpha-motoneurons during sustained voluntary contractions. *J Physiol* 1991; 440: 497–512
- [93] Green H. Neuromuscular aspects of fatigue. *Can J Sports Sci* 1987; 12: 7s–19s
- [94] Borresen J, Lambert MI. Autonomic control of heart rate during and after exercise. *Sports Med* 2008; 38: 633–646
- [95] Bellenger CR, Fuller JT, Thomson RL et al. Monitoring athletic training status through autonomic heart rate regulation: a systematic review and meta-analysis. *Sports Med* 2016; 46: 1461–1486
- [96] Buchheit M, Simpson M, Al Haddad H et al. Monitoring changes in physical performance with heart rate measures in young soccer players. *Eur J Appl Physiol* 2012; 112: 711–723
- [97] Meeusen R, Duclos M, Foster C et al. European College of Sport Science; American College of Sports Medicine. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Med Sci Sports Exerc* 2013; 45: 186–205
- [98] Smith DJ, Norris SR. Changes in glutamine and glutamate concentrations for tracking training tolerance. *Med Sci Sports Exerc* 2000; 32: 684–689
- [99] Steinacker JM, Lormes W, Reissnecker S et al. New aspects of the hormone and cytokine response to training. *Eur J Appl Physiol* 2004; 91: 382–391
- [100] Urhausen A, Gabriel H, Kindermann W. Blood hormones as markers of training stress and overtraining. *Sports Med* 1995; 20: 251–276
- [101] Gabriel H, Urhausen A, Valet G et al. Overtraining and immune system: a prospective longitudinal study in endurance athletes. *Med Sci Sports Exerc* 1998; 30: 1151–1157
- [102] Meyer T, Faude O, Urhausen A et al. Different effects of two regeneration regimens on immunological parameters in cyclists. *Med Sci Sports Exerc* 2004; 36: 1743–1749
- [103] Kellmann M. Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring. *Scand J Med Sci Sports* 2010; 20: 95–102
- [104] Kaikkonen P, Rusko H, Martinmäki K. Post-exercise heart rate variability of endurance athletes after different high-intensity exercise interventions. *Scand J Med Sci Sports* 2008; 18: 511–519
- [105] Buchheit M. Monitoring training status with HR measures: do all roads lead to Rome? *Front Physiol* 2014; 5: 73
- [106] Hecksteden A, Skorski S, Schwindling S et al. Blood-borne markers of fatigue in competitive athletes – results from simulated training camps. *PLoS One* 2016; 11: e0148810
- [107] Faria EW, Parker DL, Faria IE. The Science of Cycling. *Sports Med* 2005; 35: 285–312
- [108] Gleeson M. Biochemical and immunological markers of over-training. *J Sports Sci Med* 2002; 1: 31–41
- [109] Ballard HJ. ATP and adenosine in the regulation of skeletal muscle blood flow during exercise. *Acta Physiol Sin* 2014; 66: 67–78
- [110] Vizi É, Huszár É, Csoma Z et al. Plasma adenosine concentration increases during exercise: a possible contributing factor in exercise-induced bronchoconstriction in asthma. *J Allergy Clin Immunol* 2002; 109: 446–448
- [111] Koyas A, Tucer S, Kayhan M et al. Interleukin-7 protects CD8+ T cells from adenosine-mediated immunosuppression. *Sci Signal* 2021; 14: eabb1269
- [112] Włodarczyk M, Kusy K, Slominska E et al. Changes in blood concentration of adenosine triphosphate metabolism biomarkers during incremental exercise in highly trained athletes of different sport specializations. *J Strength Cond Res* 2019; 33: 1192–1200
- [113] Ramakers B, Pickkers P, Deussen A et al. Measurement of the endogenous adenosine concentration in humans in vivo: Methodological considerations. *Curr Drug Metab* 2008; 9: 679–685
- [114] Beneke R, Leithäuser RM, Ochentel O. Blood lactate diagnostics in exercise testing and training. *Int J Sports Physiol Perform* 2011; 6: 8–24
- [115] Rowbottom DG, Keast D, Morton AR. The emerging role of glutamine as an indicator of exercise stress and overtraining. *Sports Med* 1996; 21: 80–97
- [116] Halson SL, Lancaster GI, Jeukendrup AE et al. Immunological responses to overreaching in cyclists. *Med Sci Sports Exerc* 2003; 35: 854–861
- [117] Walsh NP, Blannin AK, Robson PJ et al. Glutamine, exercise and immune function. *Sports Med* 1998; 26: 177–191
- [118] Castell L, Newsholme E. The relation between glutamine and the immunodepression observed in exercise. *Amino Acids* 2001; 20: 49–61
- [119] Mackinnon LT, Hooper SL. Plasma glutamine and upper respiratory tract infection during intensified training in swimmers. *Med Sci Sports Exerc* 1996; 28: 285–290
- [120] Greenhaff P, Gleeson M, Maughan R. The influence of an alteration in diet composition on plasma and muscle glutamine levels in man. *Clin Sci* 1988; 74: 20
- [121] Fukuda S, Nojima J, Motoki Y et al. A potential biomarker for fatigue: Oxidative stress and anti-oxidative activity. *Biol Psychol* 2016; 118: 88–93
- [122] Wadley AJ, van Zanten JJV, Paine NJ et al. Underlying inflammation has no impact on the oxidative stress response to acute mental stress. *Brain Behav Immun* 2014; 40: 182–190
- [123] Margonis K, Fatouros IG, Jamurtas AZ et al. Oxidative stress biomarkers responses to physical overtraining: implications for diagnosis. *Free Radic Biol Med* 2007; 43: 901–910
- [124] Ikegami K, Ogyu S, Arakomo Y et al. Urinary 8-hydroxydeoxyguanosine levels and psychological reactions after sleep deprivation. *J UOEH* 2010; 32: 1–10
- [125] Wimalawansa SJ. Vitamin D deficiency: effects on oxidative stress, epigenetics, gene regulation, and aging. *Biology (Basel)* 2019; 8: 30
- [126] Ryan ZC, Craig TA, Folmes CD et al. 1 α , 25-Dihydroxyvitamin D3 regulates mitochondrial oxygen consumption and dynamics in human skeletal muscle cells. *J Biol Chem* 2016; 291: 1514–1528
- [127] Bouillon R, Verstuyf A. Vitamin D, mitochondria, and muscle. *J Clin Endocrinol Metab* 2013; 98: 961–963
- [128] Sarsour EH, Kumar MG, Chaudhuri L et al. Redox control of the cell cycle in health and disease. *Antioxid Redox Signal* 2009; 11: 2985–3011
- [129] Shuler FD, Wingate MK, Moore GH et al. Sports health benefits of vitamin D. *Sports Health* 2012; 4: 496–501
- [130] Bartoszewska M, Kamboj M, Patel DR. Vitamin D, muscle function, and exercise performance. *Pediatr Clin* 2010; 57: 849–861
- [131] Ceglia L. Vitamin D and its role in skeletal muscle. *Curr Opin Clin Nutr Metab Care* 2009; 12: 628–633

- [132] Ceglia L. Vitamin D and skeletal muscle tissue and function. *Mol Aspects Med* 2008; 29: 407–414
- [133] Dirks-Naylor AJ, Lennon-Edwards S. The effects of vitamin D on skeletal muscle function and cellular signaling. *J Steroid Biochem Mol Biol* 2011; 125: 159–168
- [134] Hamilton B. Vitamin D and human skeletal muscle. *Scand J Med Sci Sports* 2010; 20: 182–190
- [135] Holick MF. The vitamin D deficiency pandemic and consequences for nonskeletal health: mechanisms of action. *Mol Aspects Med* 2008; 29: 361–368
- [136] Nicoll JX, Hatfield DL, Melanson KJ et al. Thyroid hormones and commonly cited symptoms of overtraining in collegiate female endurance runners. *Eur J Appl Physiol* 2018; 118: 65–73
- [137] Loucks AB, Heath EM. Induction of low-T3 syndrome in exercising women occurs at a threshold of energy availability. *Am J Physiol* 1994; 266: R817–R823
- [138] Loucks AB, Callister R. Induction and prevention of low-T3 syndrome in exercising women. *Am J Physiol* 1993; 264: R924–R930
- [139] Harber VJ, Petersen SR, Chilibeck PD. Thyroid hormone concentrations and muscle metabolism in amenorrheic and eumenorrheic athletes. *Can J Appl Physiol* 1998; 23: 293–306
- [140] Tornberg ÅB, Melin A, Koivula FM et al. Reduced neuromuscular performance in amenorrheic elite endurance athletes. *Med Sci Sports Exerc* 2017; 49: 2478–2485
- [141] Cioffi F, Senese R, Lanni A et al. Thyroid hormones and mitochondria: with a brief look at derivatives and analogues. *Mol Cell Endocrinol* 2013; 379: 51–61
- [142] Baylor L, Hackney A. Resting thyroid and leptin hormone changes in women following intense, prolonged exercise training. *Eur J Appl Physiol* 2003; 88: 480–484
- [143] Morgan WP, Costill DL, Flynn MG et al. Mood disturbance following increased training in swimmers. *Med Sci Sports Exerc* 1988; 21: 107–114
- [144] Lehmann M, Foster C, Dickhuth H-H et al. Autonomic imbalance hypothesis and overtraining syndrome. *Med Sci Sports Exerc* 1998; 30: 1140–1145
- [145] Eichner ER. Overtraining: consequences and prevention. *J Sports Sci* 1995; 13: 41–48
- [146] Hagen J, Gott N, Miller DR. Reliability of saliva hormone tests. *J Am Pharm Assoc* 2003; 43: 724–726
- [147] Vining RF, McGinley RA, Symons RG. Hormones in saliva: mode of entry and consequent implications for clinical interpretation. *Clin Chem* 1983; 29: 1752–1756
- [148] Cormack SJ, Newton RU, McGuigan MR. Neuromuscular and endocrine responses of elite players to an Australian rules football match. *Int J Sports Physiol Perform* 2008; 3: 359–374
- [149] Elloumi M, Maso F, Michaux O et al. Behaviour of saliva cortisol [C], testosterone [T] and the T/C ratio during a rugby match and during the post-competition recovery days. *Eur J Appl Physiol* 2003; 90: 23–28
- [150] West DJ, Finn CV, Cunningham DJ et al. Neuromuscular function, hormonal, and mood responses to a professional rugby union match. *J Strength Cond Res* 2014; 28: 194–200
- [151] Kraemer WJ, Ratamess NA. Hormonal responses and adaptations to resistance exercise and training. *Sports Med* 2005; 35: 339–361
- [152] Crewther BT, Cook C, Cardinale M et al. Two emerging concepts for elite athletes. *Sports Med* 2011; 41: 103–123
- [153] Daly W, Seegers C, Rubin D et al. Relationship between stress hormones and testosterone with prolonged endurance exercise. *Eur J Appl Physiol* 2005; 93: 375–380
- [154] Doerr P, Pirke KM. Cortisol-induced suppression of plasma testosterone in normal adult males. *J Clin Endocrinol Metab* 1976; 43: 622–629
- [155] Roe G, Till K, Darrall-Jones J et al. Changes in markers of fatigue following a competitive match in elite academy rugby union players. *SA J Sports Med* 2016; 28: 2–5
- [156] Cunniffe B, Hore AJ, Whitcombe DM et al. Time course of changes in immunoendocrine markers following an international rugby game. *Eur J Appl Physiol* 2010; 108: 113–122
- [157] Jones MR, West DJ, Harrington BJ et al. Match play performance characteristics that predict post-match creatine kinase responses in professional rugby union players. *BMC Sports Sci Med Rehabil* 2014; 6: 38
- [158] McLean BD, Coutts AJ, Kelly V et al. Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *Int J Sports Physiol Perform* 2010; 5: 367–383
- [159] Garrett J. The proper role of nerves in salivary secretion: a review. *J Dent Res* 1987; 66: 387–397
- [160] Proctor GB, Carpenter GH. Regulation of salivary gland function by autonomic nerves. *Auton Neurosci* 2007; 133: 3–18
- [161] Klein LC, Corwin EJ. Seeing the unexpected: how sex differences in stress responses may provide a new perspective on the manifestation of psychiatric disorders. *Curr Psychiatry Rep* 2002; 4: 441–448
- [162] Twist C, Highton J. Monitoring fatigue and recovery in rugby league players. *Int J Sports Physiol Perform* 2013; 8: 467–474
- [163] Mackinnon LT. *Exercise and Immunology*. Champaign, IL: Human Kinetics; 1998
- [164] Parry-Billings M, Budgett R, Koutedakis Y et al. Plasma amino acid concentrations in the overtraining syndrome: possible effects on the immune system. *Med Sci Sports Exerc* 1992; 24: 1353–1358
- [165] Blannin AK, Chatwin LJ, Cave R et al. Effects of submaximal cycling and long-term endurance training on neutrophil phagocytic activity in middle aged men. *Br J Sports Med* 1996; 30: 125–129
- [166] Keen P, McCarthy D, Passfield L et al. Leucocyte and erythrocyte counts during a multi-stage cycling race ('the Milk Race'). *Br J Sports Med* 1995; 29: 61–65
- [167] Mackinnon LT. Exercise, immunoglobulin and antibody. *Exerc Immunol Rev* 1996; 2: 1–35
- [168] Khansari DN, Murgu AJ, Faith RE. Effects of stress on the immune system. *Immunol Today* 1990; 11: 170–175
- [169] Noakes T. *Lores of Running*. 2nd ed. Cape Town: Oxford University Press; 1992
- [170] Rushall BS. A tool for measuring stress tolerance in elite athletes. *J Appl Sport Psychol* 1990; 2: 51–66
- [171] Buchheit M. Sensitivity of monthly heart rate and psychometric measures for monitoring physical performance in highly trained young handball players. *Int J Sports Med* 2015; 36: 351–356
- [172] Raglin J, Morgan W. Development of a scale for use in monitoring training-induced distress in athletes. *Int J Sports Med* 1994; 15: 84–88
- [173] Thorpe RT, Atkinson G, Drust B et al. Monitoring fatigue status in elite team-sport athletes: implications for practice. *Int J Sports Physiol Perform* 2017; 12: 27–34
- [174] Coutts AJ, Cormack S. Monitoring the training response. In: Joyce D, Lewindon D, Eds. *High-performance Training for Sports*. Champaign, IL: Human Kinetics Publishers; 2014: 71–84
- [175] Kenttä G, Hassmén P. Overtraining and recovery. A conceptual model. *Sports Med* 1998; 26: 1–16
- [176] Nässi A, Ferrauti A, Meyer T et al. Psychological tools used for monitoring training responses of athletes. *Perform Enhanc Health* 2017; 5: 125–133

- [177] McNair DM, Lorr M, Droppleman LF. *Manual Profile of Mood States*. San Diego, CA: Educational and Industrial Testing Service; 1971
- [178] Kölling S, Schaffran P, Bibbey A et al. Validation of the acute recovery and stress scale (ARSS) and the short recovery and stress scale (srss) in three english-speaking regions. *J Sports Sci* 2020; 38: 130–139
- [179] Kellmann M, Kallus KW. *Recovery-Stress Questionnaire for Athletes: User manual*. Human Kinetics 2001
- [180] Jeffries AC, Wallace L, Coutts AJ et al. Athlete-reported outcome measures for monitoring training responses: A systematic review of risk of bias and measurement property quality according to the COSMIN guidelines. *Int J Sports Physiol Perform* 2020; 15: 1203–1215
- [181] Duignan C, Doherty C, Caulfield B et al. Single-item self-report measures of team-sport athlete wellbeing and their relationship with training load: a systematic review. *J Athl Train* 2020; 55: 944–953
- [182] Gallo TF, Cormack SJ, Gabbett TJ et al. Self-reported wellness profiles of professional Australian football players during the competition phase of the season. *J Strength Cond Res* 2017; 31: 495–502
- [183] Gastin PB, Meyer D, Robinson D. Perceptions of wellness to monitor adaptive responses to training and competition in elite Australian football. *J Strength Cond Res* 2013; 27: 2518–2526
- [184] Twist C, Waldron M, Highton J et al. Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *J Sports Sci* 2012; 30: 359–367
- [185] Van Dongen H. Comparison of mathematical model predictions to experimental data of fatigue and performance. *Aviat Space Environ Med* 2004; 75: 15–36
- [186] Caldwell JA, Mallis MM, Caldwell JL et al. Fatigue countermeasures in aviation. *Aviat Space Environ Med* 2009; 80: 29–59
- [187] Coyne JO, Haff GG, Coutts AJ et al. The current state of subjective training load monitoring—a practical perspective and call to action. *Sports Med Open* 2018; 4: 58
- [188] Saw AE, Main LC, Gastin PB. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *Br J Sports Med* 2016; 50: 281–291
- [189] Meeusen R, Duclos M, Gleeson M et al. Prevention, diagnosis and treatment of the overtraining syndrome: ECSS position statement ‘task force’. *Eur J Sport Sci* 2006; 6: 1–14
- [190] Ndlec M, McCall A, Carling C et al. Recovery in Soccer: Part I—post-match fatigue and time course of recovery. *Sports Med* 2012; 42: 997–1015
- [191] Plews DJ, Laursen PB, Kilding AE et al. Heart rate variability in elite triathletes, is variation in variability the key to effective training? A case comparison. *Eur J Appl Physiol* 2012; 112: 3729–3741
- [192] Kuipers H. *Training and Overtraining*. Philadelphia, PA, USA: Lippincott Williams & Wilkins; 1998
- [193] Hopkins WG. Quantification of training in competitive sports. *Sports Med* 1991; 12: 161–183
- [194] Bagger M, Petersen P, Pedersen P. Biological variation in variables associated with exercise training. *Int J Sports Med* 2003; 24: 433–440
- [195] Daanen HA, Lamberts RP, Kallen VL et al. A systematic review on heart-rate recovery to monitor changes in training status in athletes. *Int J Sports Physiol Perform* 2012; 7: 251–260
- [196] Shetler K, Marcus R, Froelicher VF et al. Heart rate recovery: validation and methodologic issues. *J Am Coll Cardiol* 2001; 38: 1980–1987
- [197] Uusitalo A, Uusitalo A, Rusko H. Exhaustive endurance training for 6–9 weeks did not induce changes in intrinsic heart rate and cardiac autonomic modulation in female athletes. *Int J Sports Med* 1998; 19: 532–540
- [198] Plews DJ, Laursen PB, Stanley J et al. Training adaptation and heart rate variability in elite endurance athletes: opening the door to effective monitoring. *Sports Med* 2013; 43: 773–781
- [199] Hautala AJ, Kiviniemi AM, Tulppo MP. Individual responses to aerobic exercise: the role of the autonomic nervous system. *Neurosci Biobehav Rev* 2009; 33: 107–115
- [200] Kiviniemi AM, Hautala AJ, Kinnunen H et al. Endurance training guided individually by daily heart rate variability measurements. *Eur J Appl Physiol* 2007; 101: 743–751
- [201] Kiviniemi AM, Hautala AJ, Kinnunen H et al. Daily exercise prescription on the basis of HR variability among men and women. *Med Sci Sports Exerc* 2010; 42: 1355–1363
- [202] Hedelin R, Wiklund U, Bjerle P et al. Cardiac autonomic imbalance in an overtrained athlete. *Med Sci Sports Exerc* 2000; 32: 1531–1533
- [203] Hynynen E, Uusitalo A, Konttinen N et al. Cardiac autonomic responses to standing up and cognitive task in overtrained athletes. *Int J Sports Med* 2008; 29: 552–558
- [204] Uusitalo A, Uusitalo A, Rusko H. Heart rate and blood pressure variability during heavy training and overtraining in the female athlete. *Int J Sports Med* 2000; 21: 45–53
- [205] Hynynen E, Uusitalo A, Konttinen N et al. Heart rate variability during night sleep and after awakening in overtrained athletes. *Med Sci Sports Exerc* 2006; 38: 313–317
- [206] Hedelin R, Kenttä G, Wiklund U et al. Short-term overtraining: effects on performance, circulatory responses, and heart rate variability. *Med Sci Sports Exerc* 2000; 32: 1480–1484
- [207] Buchheit M, Laursen PB, Al Haddad H et al. Exercise-induced plasma volume expansion and post-exercise parasympathetic reactivation. *Eur J Appl Physiol* 2009; 105: 471–481
- [208] Al Haddad H, Laursen P, Chollet D et al. Reliability of resting and postexercise heart rate measures. *Int J Sports Med* 2011; 32: 598–605
- [209] Kennedy R, Drake D. The effect of acute fatigue on countermovement jump performance in rugby union players during preseason. *J Sports Med Phys Fitness* 2017; 57: 1261–1266
- [210] Bigland-Ritchie B, Woods J. Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle Nerve* 1984; 7: 691–699
- [211] McLellan CP, Lovell DI, Gass GC. Markers of postmatch fatigue in professional rugby league players. *J Strength Cond Res* 2011; 25: 1030–1039
- [212] Gathercole R, Sporer B, Stellingwerff T et al. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *Int J Sports Physiol Perform* 2015; 10: 84–92
- [213] Komi PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech* 2000; 33: 1197–1206
- [214] Kallerud H, Gleeson N. Effects of stretching on performances involving stretch-shortening cycles. *Sports Med* 2013; 43: 733–750
- [215] Avela J, Kyrolainen H, Komi PV et al. Reduced reflex sensitivity persists several days after long-lasting stretch-shortening cycle exercise. *J Appl Physiol* (1985) 1999; 86: 1292–1300
- [216] Nicol C, Avela J, Komi PV. The stretch-shortening cycle. *Sports Med* 2006; 36: 977–999
- [217] Thorlund JB, Aagaard P, Madsen K. Rapid muscle force capacity changes after soccer match play. *Int J Sports Med* 2009; 30: 273–278
- [218] Edwards T, Spiteri T, Piggott B et al. Monitoring and managing fatigue in basketball. *Sports (Basel)* 2018; 6: 19
- [219] Bishop PA, Jones E, Woods AK. Recovery from training: a brief review: brief review. *Strength Cond Res* 2008; 22: 1015–1024
- [220] Worrell TW, Perrin DH. Hamstring muscle injury: the influence of strength, flexibility, warm-up, and fatigue. *J Orthop Sports Phys Ther* 1992; 16: 12–18