

Fatigue and Pacing in High-Intensity Intermittent Team Sport: An Update

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Abstract With the advancements in player tracking technology, the topic of fatigue and pacing in team sport has become increasingly popular in recent years. Initially based upon a pre-conceived pacing schema, a central metabolic control system is proposed to guide the movement of players during team sport matches, which can be consciously modified based on afferent signals from the various physiological systems and in response to environmental cues. On the basis of this theory, coupled with the collective findings from motion-analysis research, we sought to define the different pacing strategies employed by team sport players. Whole-match players adopt a ‘slow-positive’ pacing profile (gradual decline in total running intensity), which appears to be global across the different team sports. High-intensity movement also declines in a ‘slow-positive’ manner across most team sport matches. The duration of the exercise bout appears to be important for the selected exercise intensity, with the first introduction to a match as a substitute or interchange player resulting in a ‘one bout, all out’ strategy. In a limited interchange environment, a second introduction to the match results in a ‘second-bout reserve’ strategy; otherwise, the ‘one bout, all out’ strategy is likely to be adopted. These pacing profiles are proposed to reflect the presence of a central regulator that controls the movement intensity of the player to optimize performance, as well as avoiding the harmful failure of any physiological system. The

presence of ‘temporary fatigue’ reflects this process, whereby exercise intensity is consciously modulated from within the framework of a global pacing schema.

Key Points

Pacing in team sport should be considered as the distribution of energy resources that optimize match-running performance, whereas fatigue is a uni-directional construct that relates to the eventual reduction in performance compared with baseline values

The duration of the exercise bout appears to be important for the selected exercise intensity during team sport performance

To optimize running performance in all team sports, whole-match players adopt a ‘slow-positive’ pacing profile, characterised by a gradual decline in total and high-intensity running, whereas part-match players select either ‘all-out’ or ‘reserve’ strategies, depending on their role in the match

Future research should evaluate the factors that facilitate the development of pacing strategies among team sport players

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1 Introduction

The topic of ‘fatigue’ in high-intensity, intermittent team sport has become increasingly popular in recent years, perhaps owing to the advancements in player-tracking

technology, such as global positioning systems (GPS) and multiple camera systems (MCS). Mohr et al. [1] have previously reviewed the topic of fatigue with reference to soccer performance, describing the temporal running patterns of players during matches and proposing a variety of responsible physiological mechanisms. However, their review was limited to soccer and was based upon reports from manual time-motion analysis (TMA) research, which has since been surpassed by newer technologies and requires updating. Furthermore, fresh insights into the mechanisms of acute fatigue have been suggested in the intervening 8-year period, which have advanced the understanding of match-running performance in team sport. These developments have subsequently led to an emergence of research on the related topic of fatigue and 'pacing' in team sport [2–9]. The concept of pacing advances previous notions of acute fatigue during team sport matches and suggests alternative mechanisms for the observed fluctuations in match-running performance. Therefore, to provide a contemporary perspective of fatigue in team sport, an updated review is warranted. With reference to the well researched, professional sports of male soccer, rugby league, rugby union and Australian football (AF), this review will (1) discuss the possible underlying mechanisms responsible for pacing strategies in team sport, and (2) define the different pacing strategies employed by high-intensity, intermittent team sport players during competitive matches.

2 Search Methodology

Both PubMed and SPORTDiscus databases were searched for published literature up to November 2013, using the following keywords in different combinations: 'football', 'soccer', 'rugby league', 'rugby union', 'Australian Football League', 'fatigue', 'pacing', 'global positioning systems', 'time motion analysis', 'movement patterns'. The studies were independently reviewed by each author to remove duplicate samples and exclude papers that did not measure temporal changes in player movement patterns in one of the selected team sports.

3 Defining Fatigue in Team Sport

In the context of team sport, fatigue is indicated by a reduction of maximal force or power that is associated with sustained exercise and is reflected in a decline in performance [10]. In this instance, 'performance' can be identified by the self-regulated movement distance and/or intensity of the player during a match. Reductions in high-intensity ($>13 \text{ km}\cdot\text{h}^{-1}$) running and total distance covered

from baseline values (start of match) have been reported, alongside decreases in neuromuscular force and sprinting performance, before and after soccer matches [11–13]. These findings support the well described decay in total movement distance performance across progressive segments of rugby league [4, 8, 14, 15], rugby union [16, 17] and AF matches [3, 18, 19]. On the basis of such observations, a decline in running performance across the course of a match is thought to broadly identify the physiological impairment of a player, indicative of acute fatigue [1, 2].

This simplified model of fatigue in team sport, which has dominated the literature, predominantly conforms to the so-called 'catastrophe' theory [20, 21], whereby mechanisms (commonly originating at the periphery) are thought to inhibit forceful muscular contraction, thereby reducing physical work capacity [22]. However, inversely, an increase in running performance must reflect either the full, or at least partial, recovery of a player. This phenomenon was noted by Mohr et al. [2], from which the terms 'transient' or 'temporary' fatigue have subsequently emerged [6, 23–27]. These terms refer to a period (typically 5 min) of reduced running intensity, below the mean match intensity, occurring immediately after the most intense period of team sport matches [2]. Thereafter, a total recovery in running intensity may be achieved by soccer players. The selection of a 5-min period appears to account for the random changes in situational variables (i.e. possession, match score) etc. that might prevent the identification of typical match fluctuations if a shorter period were to be used. Whilst more advanced non-linear analyses could be used to identify variations in movement patterns during matches, their application is limited by the typical sample size of match-analysis studies. Whilst a more detailed discussion of fatiguing mechanisms is continued in the following section, it would appear that both progressive declines in match-running intensity between the first and final stages of team sport matches, or temporary reductions in movement, determined via motion-tracking systems, have been widely accepted as a valid indication of fatigue in team sport.

4 Mechanisms of Acute Fatigue in Team Sport

Acute fatigue may occur as a result of either, or a combination, of peripheral and central factors. Peripheral fatigue relates to a biochemical change (distal of the central nervous system [CNS]) that limits the muscle's capacity to produce work, whilst central fatigue relates to the reduced central motor 'drive' (CMD) of the CNS (occurring at a spinal or supraspinal level) to recruit available motor units [28–30]. Whilst various mechanisms have been associated with peripheral muscle fatigue, the role of blood lactate

concentration and hydrogen ion (H^+) accumulation has traditionally been cited in the literature [2, 12, 31]. Of course, fatigue is considered to be task dependent, meaning that the mechanism, magnitude and temporal pattern of fatigue relates to the nature of the required task [32, 33]. Therefore, a decline in running performance at the end of a match may not necessarily be caused by the same mechanism that induces transient fatigue over a given 5-min period. As previously recognized by others [1], the potential causes of fatigue during team sport matches are multifaceted and are likely to act in combination to reduce the performance of players. A brief review of these mechanisms is provided in the following sections.

4.1 Sources of Peripheral Fatigue in Team Sport

The traditional assumption that blood lactate accumulation and/or a reduction in pH causes fatigue in team sport has previously been questioned owing to the modest increase in blood lactate during a soccer match [11] compared with intermittent exhaustive exercise [34]. Furthermore, reported blood lactate concentrations sampled during, or after, team sport matches typically average 7–9 $\text{mmol}\cdot\text{l}^{-1}$ and are descriptively similar among rugby league, rugby union and soccer players [11, 31, 35, 36]. Whilst these findings demonstrate that team sport players must tolerate, to some degree, lactate accumulation during team sport matches, blood lactate concentrations do not typically continue to increase across the course of team sport matches [31, 36–38]. Similar trends in lactate concentration have been reported in team sport simulations of rugby league [39], rugby union [40] and soccer [41]. Such findings support the assertion that isolated increases in blood or muscle lactate concentration, and concomitant reductions in pH, are unlikely to explain acute muscle fatigue in humans [11, 42, 43]. Furthermore, while a transient decrease in muscle pH has been reported following the most intense period of a match, this is poorly correlated with decrements in sprint performance [11]. Indeed, supplements such as beta alanine or sodium bicarbonate that are thought to buffer the expected cumulative rise in H^+ , appear to offer only a limited benefit to intermittent team sport or multiple-sprint performance [44–47]. As such, the evidence suggests that other factors contribute to the reduction in running performance among team sport players.

Other peripheral mechanisms, such as the accumulation of inorganic phosphate (P_i), have been associated with reduced muscular force, largely via the inhibition of Ca^{2+} uptake by the sarcoplasmic reticulum or direct interference with cross-bridge cycling [43, 48, 49]. There is evidence that the accumulation of potassium (K^+) in the muscle interstitium coincides with muscle fatigue via a disturbance in action potential propagation over the sarcolemma [42,

50–52] and that both caffeine [53] or nitrate supplementation [54] may attenuate these impairments. Whilst the depletion of phosphocreatine stores might be anticipated to attenuate high-intensity running during team sport matches, soccer players have been shown to perform such activities with low phosphocreatine concentrations in the lower limb musculature [11, 34]. Similarly, blood glucose concentration is also maintained across periods of the match and does not appear to relate to reductions in running performance. Fatigue at the end of team sport matches might also relate to factors such as glycogen depletion [11, 55] and dehydration [56]. Whilst a detailed discussion of environmental conditions (i.e. heat or altitude exposure) is beyond the remit of the current review, the contribution of these factors to contemporary models of fatigue in team sport has become increasingly apparent [4, 57]. Although each of the above factors appears to hold some relationship to fatigue in team sport, it is thought that their direct influence on fatigue is limited by a more complex, integrated control system [58]. It is important to state that substrate availability has a clear role in supporting the running capacity of team sport players, the optimal use of which is optimized by an effective pacing strategy.

4.2 Central Regulation of Movement in Team Sport

It is the contemporary perspective that a complex interaction between the different areas of the brain and both peripheral and central factors, is likely to determine fatigue in sport [20]. Exercise intensity is thought to be determined by a ‘central controller’ that, in response to various physiological signals and environmental cues, regulates exercise intensity to avoid premature fatigue [21, 59–61]. First, athletes are suggested to develop a performance ‘template’ (pacing schema), which sets the expected distribution of energy expenditure for the exercise bout [62–64]. During exercise, threats to homeostasis are signalled via afferent feedback that reaches specific areas of the brain (i.e. dorsal posterior insula) [60]. The perceived magnitude of homeostatic disturbance is then generated by other areas of the brain (i.e. right anterior insula [60]), leading to a feed-forward (efferent) command to reduce CMD, thus altering the pacing strategy [62–64]. Others have reported increased activity of the posterior cingulate gyrus and the precuneus, during ‘hard’ (higher rating of perceived exertion [RPE]) versus ‘easy’ (lower RPE) exercise [65], which are areas of the brain concerned with conscious awareness [66]. These findings demonstrate a collective integration of various physiological signals which, in turn, dictate the conscious control of RPE during exercise [65]. Whilst activity of the specific brain areas has not been reported in relation to team sport performance, Rampinini et al. [13] reported a reduction in the percentage of voluntary muscle activation

and electromyographic (EMG) activity, alongside a decline in sprinting performance, immediately following a soccer match. A decrease in the total distance covered was also observed between the first and second half of the match. These findings are consistent with studies in cycling, whereby a reduction in motor unit recruitment has been identified prior to the onset of peripheral fatigue [67–69]. The theory that a central control system will regulate the running performance of team sport players in an anticipatory manner is logical, given the less predictable nature of team sport matches. However, constructing a pacing schema for team sport performance, and updating this strategy in response to physiological cues, presents a challenge for team sport players.

One significant factor that has been consistently overlooked by previous advocates of the ‘peripheral’ model of fatigue is that team sport players self-regulate their running performance during matches in response to dynamically changing environmental stimuli. As such, it should be anticipated that team sport players possess a ‘physiological reserve’, enabling them to perform high-intensity energy expenditure as and when required during matches. Indeed, an increase in high-intensity running would be associated with a transient rise in glycolysis and, in turn, an increase in blood lactate concentration [11, 70]. However, that a lower intensity of running is ‘selected’ by team sport players immediately after, and that performance continues to decline following transient recovery, indicates the presence of a complex system of fatigue. For example, an increased blood lactate concentration beyond the acceptable physiological range, among other biochemical disturbances (i.e. extracellular K^+ and histamine), is suggested to act upon group III and IV nerve afferents that, ultimately, cause an anticipatory down-regulation in running performance [28, 29, 71]. This, in turn, facilitates the removal of lactate from the blood via aerobic metabolism. Likewise, following lactate clearance and sufficient regaining of homeostatic control, the same pathway is used to notify specific areas of the brain (i.e. the insula cortex) that acid–base balance has been re-established to acceptable levels [21, 28, 32]. This process is, perhaps, best demonstrated by the periods of transient fatigue in team sport, whereby reductions in muscle pH during intense match periods are recovered by the end of a match [11]. That significant reductions in match running are consistently noted in the final 15–20 min of team sport matches [2, 8, 15, 18] provides further support for this theory, whereby players appear to scale their energy output in accordance with the length of the bout. That is, team sport players completing whole matches preserve their energy expenditure over the course of the match, such that fatigue is avoided, yet most notable near completion of the bout. This phenomenon has been well described in individual

tasks [72–76] and provides a logical explanation for the pacing profiles observed among whole-match team sport players. In the case of whole-match players, adopting a pacing strategy that optimizes performance is also likely to preserve key energy substrates, such as muscle glycogen, that will facilitate moderate- to high-intensity running during matches.

5 Exertion, Effort and Team Sport Movement Patterns

In conjunction with the reception of afferent physiological signals, other brain areas, such as the right anterior insula, have been postulated to interpret the changes in bodily homeostasis, thus generating a sense of ‘effort’ during performance [77]. The perception of effort can be differentiated from the RPE, which is a general interpretation of the physiological stress induced by exercise and not a reflection of psychological effort per se [78]. It has been postulated that the sense of effort, measured via the Task Effort Awareness (TEA) scale, informs the athlete of when to down-regulate exercise intensity, thus avoiding homeostatic derangement. Swart et al. [78] found that the TEA score consistently reached maximal values during maximal cycling performance, whereas RPE did not. It was suggested that the TEA measures the psychic effort associated with a given level of perceived exertion, thus controlling exercise intensity to avoid catastrophic outcomes.

These findings are extremely relevant to team sport performance, since post-match global RPE (category-ratio scale [CR] 10), recorded among team sport players, very rarely reaches the maximal level (i.e. a score of 10) [8, 79–82]. Furthermore, despite a progressive increase in RPE (Borg 6–20 scale) during team sport simulations, this typically remains sub-maximal throughout the exercise bout [39, 40, 83]. Such findings support the theory that RPE develops as a scalar function of the distance remaining in the exercise bout, ultimately contributing to the control of forceful muscular contraction [62, 73, 74, 76]. Indeed, our laboratory has previously found that RPE at the onset of a time to exhaustion test following simulated team sport activity is inversely related ($r = -0.75$, $P < 0.05$) to the distance covered in the trial (Highton, unpublished observations). Figure 1 shows the incremental, scalar nature of RPE that is commonly observed during simulated soccer matches. Of note is the increase in time-to-exhaustion (~ 2 min) of the carbohydrate-protein (CHO-P) beverage compared with the CHO alone, with a lower RPE at the onset of the time trial.

This phenomenon is in accordance with the utilisation of a so-called ‘hazard score’ (RPE \times fraction of distance remaining) as described by de Koning et al. [63]. The implication of the hazard score and effort sense theories is

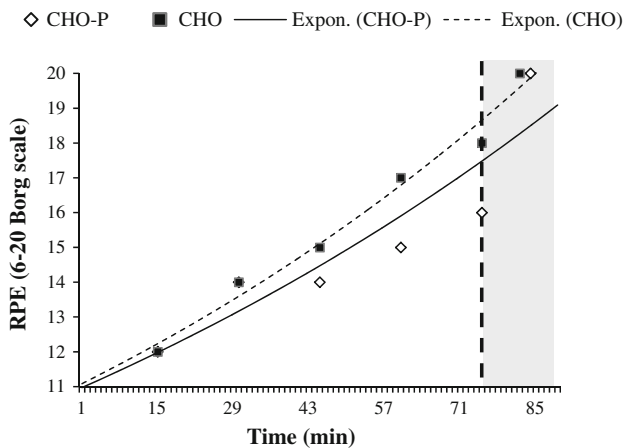


Fig. 1 Rating of perceived exertion (RPE) and time (min) during a soccer simulation protocol. *CHO* carbohydrate feeding during performance, *CHO-P* carbohydrate and protein feeding during performance, *Expon* exponential. The *dashed line* denotes the beginning of the time-to-exhaustion trial

that athletes may alter their exercise intensity during a game based on their perception of exertion and the fraction of time remaining in the exercise bout. That time to exhaustion occurring at the end of a team-sport simulation may be predicted by the RPE at the onset of exercise also supports the previous assertion that conscious regulation of exercise intensity ensures that sufficient energy is reserved to respond to match demands [58]. While there are similarities between team-sport simulation and match performance, it should be clear that we are not suggesting that the fatigue profile is identical between these two different modes of exercise. Rather, during intermittent, multiple-sprint activity, team sport players will adopt a pacing strategy that permits them to optimally complete the bout in a given time frame whilst reserving energy for unanticipated activities. The scalar characteristics of RPE denote that the player is able to compare their current RPE against their expected level of exertion, which ultimately dictates the intensity of the exercise.

Therefore, that RPE does not typically reach maximal values during team sport performance indicates a sub-maximal physiological exertion, but not necessarily a sub-maximal effort. This is likely to reflect the preservation of energy expenditure, cued from the perceived psychological effort during matches, which acts to restrict the running performance of athletes in order to avoid catastrophic physiological failure [20, 61]. In support of this theory, supplementation of a mixed CHO-P beverage was reported to increase running speed during a self-regulated simulated soccer match, compared with an energy-matched CHO solution, without observing differences in RPE (Fig. 2; [83]). Indeed, both CHO [84] and protein/amino-acid supplementation [85–88] have been suggested to have an

effect on CMD, which in turn might influence the perception of exercise intensity and, perhaps, performance. These findings suggest the presence of a pre-conceived ‘performance template’ [62], whereby the anticipated difficulty of the task/exercise bout is maintained by increasing exercise intensity in the CHO-P conditions above that demonstrated in the CHO trials. In order to establish its role in central fatigue among team sport players, it would be useful for future research to assess the effects of interventions, such as CHO-P, on both RPE and effort perception, particularly in match-like scenarios. Other interventions, such as CHO mouth rinse [89] and caffeine supplementation [90] might also have a similar effect on exertion and effort during team sport matches. There is clear scope for research of this type in team sport performance, given the range of other effortful skill-related tasks (i.e. tackling or dribbling) that are likely to increase the level of perceived psychological stress.

6 Effects of the Environment on Pacing in Team Sport

Peripheral or cardiopulmonary feedback may also be influenced by environmental conditions. For example, the effect of ambient heat and oxygen availability (i.e. hypoxia/altitude) on body temperature or pulmonary ventilation pose immediate threats to bodily homeostasis. Exposure to hot ambient temperatures can increase the rate of catecholamine production [91] reduce cardiac output and, in turn, impair muscle blood flow and oxygenation [92]. Of course, group III and IV nerve afferents are responsive to both biochemical and thermal changes during exercise, the sensitivity of which is exacerbated during ischemic conditions and may cause a central inhibition of the working musculature [29]. The rise in catecholamine production will also enhance glycolysis, thereby increasing the utilization of glucose or glycogen [93] and depleting energy pools for later stages of team sport matches.

A recent analysis of AF players showed that matches played in high (average $>25^{\circ}\text{C}$) ambient temperatures caused a reduction in total distance covered, but not high-intensity activity, compared with matches played in cooler temperatures (average $<17.5^{\circ}\text{C}$) [4]. Core temperatures, measured by an ingestible pill, reached over 40°C in the majority of athletes when exposed to the hot environment, but were below 40°C in cool temperatures. It was suggested that the reduced running distance in hot climates optimized completion of the match and preserved the ability to reach high-intensity thresholds. These findings conform to the theory that match-running performance is centrally regulated on a moment-by-moment basis, prior to catastrophic failure of any physiological system, in accordance with the perceived threat to physiological

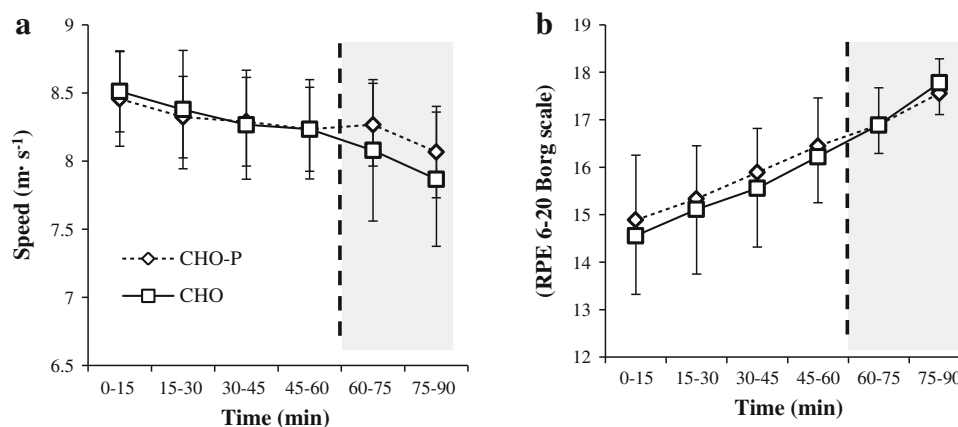


Fig. 2 Changes in (a) average \pm standard deviation running speed and (b) average \pm standard deviation rating of perceived exertion (selected on a 6–20 Borg scale) with carbohydrate and carbohydrate plus protein supplementation during simulated team sport exercise. The shaded area indicates the period in which participants were able to self-regulate their exercise intensity [82]. The rating of perceived

homeostasis [60]. Indeed, the 3 % increase in RPE in the hot matches [4] supports the reciprocal relationship between RPE and exercise intensity. In this instance, the threat of high ambient temperature to thermoregulation was sufficient to reduce the performance advantages of increased movement distance, reflecting an ‘internal negotiation’ of positive (i.e. motivation) and negative (i.e. potential heat exhaustion) influences [20]. In partial agreement with the findings of others, it is likely that afferent feedback conveying a thermoregulatory disturbance to the brain instigated an anticipatory inhibition of heat-generating processes (i.e. forceful muscular contraction) prior to surpassing the ‘critical’ core temperature threshold [94, 95]. However, given that core temperatures in excess of 40 °C were reported by Aughey et al. [4], it would appear that the critical thermoregulatory threshold is not consistent between individuals; this is similar to the proposed individual threshold of peripheral muscle fatigue [28].

The findings of Aughey et al. [4] are consistent with previous reports that sub-maximal team sport running intensity is reduced when performed in hot ambient temperatures [96, 97]. Furthermore, these findings are in agreement with the reported reductions in sub-maximal running, but not sprint performance, induced by hot ambient temperatures in multiple-sprint performance [98]. Collectively, these findings suggest that core temperature contributes to the anticipatory reduction in CMD, inhibiting sub-maximal movement in order to maintain sprinting performance. In order to confirm the generalizability of this theory, it would be useful for future research to consider the effects of hypoxia/altitude exposure on match-running performance. Whilst the deleterious effects of reduced

exertion is suggested to reflect both the physical sensations of exercise and the psychological/psychic effort required to perform the task [78]. CHO carbohydrate feeding during performance, CHO-P carbohydrate and protein feeding during performance, RPE rating of perceived exertion

muscle oxygenation on CMD and subsequent repeated-sprint performance is well established [99–102], there has been no investigation of adult team sport performance in hypoxic environments.

7 Pacing in Team Sport

In specific reference to dehydration, Edwards and Noakes [58] were the first to articulate the relationship between team sport performance and a complex central control system. It was suggested that team sport players regulate their efforts during matches based on macro-, meso- and micro-pacing strategies. The macro-pacing strategy is determined before the match and represents the pacing ‘schema’ of the athlete, which can be modulated between-halves (i.e. meso) or on a continual basis (i.e. micro) by the player. The meso- and micro-regulation of performance is suggested to be dependent upon the degree of homeostatic disturbance, such as poor fluid balance (i.e. dehydration). This is proposed to alter the running performance of the player via afferent feedback to the brain centres and, in turn, efferent commands back to the working musculature. The theory posited by Edwards and Noakes [58] enhances the understanding of the well publicised phenomenon of ‘transient fatigue’, which is likely to reflect the fine (micro) adjustments in movement intensity selected by players in response to situational match variables. Whilst some form of ‘fatigue’ is likely to occur during these periods, it is perhaps more appropriate to relate this phenomenon to a more complex behavioural model that avoids such an outcome. The consistent balancing act, whereby brief periods of ‘peak’ intensity are consistently followed by a

significant brief period of reduced intensity, below the match average, might demonstrate a complex planned strategy on behalf of the player, rather than a chance occurrence. Whilst there are various reasons (i.e. tactical) outside of a player's control that could be responsible for fluctuations in movement intensity, the gross movement patterns of team sport players are often quite predictable. That is, micro adjustments ultimately lead to 'macro' outcomes that are commonly observed in the majority of team sports (see following sections).

The proposal that players are able to determine (consciously or otherwise) and modulate their output of energy dependent on the nature of the competition provides a logical explanation for the varied patterns of running performance observed during team sport matches. Pacing has previously been erroneously considered to represent the conservation of energy expenditure during competition [3]. However, whilst a player might down-regulate energy output in order to preserve energy for later match periods, this represents only one type of pacing strategy. For a player to optimally perform their required tasks, it may be more appropriate to utilise their energy resources during earlier periods of a match. For example, players who are substituted/interchanged are provided with a shorter period in which to exert their influence on the match and are less likely to have been depleted of energy substrates or experiencing homeostatic disturbance. An a priori knowledge of their role as a 'partial-match' player is likely to alter their macro-pacing strategy, which would require an extremely different approach to training and match preparation. The model of Edwards and Noakes [58] provides concise guidelines for the interpretation of match-running performance among team sport players; however, the lack of available match performance data at that time limited the application of this model to real match performances. The following sections address this across selected team sports and provide definitions for the different pacing strategies that are employed during matches.

8 Describing Pacing Profiles in Team Sport

A variety of different pacing strategies have been described for individual sports, such as cycling [103–108]. Among individual sports, selecting the correct pacing strategy enables the completion of a known distance in the shortest possible time (i.e. closed-loop tasks) [103]. The selected pacing strategy is strongly influenced by the duration of the exercise bout, with short (≤ 4 -min) time-trial performance optimized with a so-called 'positive' strategy (faster start, slower finish [104]), middle-distance (≥ 4 -min) races producing 'even-paced' strategies, and negative pacing profiles (slower start, faster finish) characterizing longer

duration races [103]. When the split times of athletes have been tracked with greater resolution, so-called 'hyperbolic' pacing profiles have been identified during middle- to long-distance races [103]. Such profiles are characterized by fast starts, followed by slower middle portions, and are concluded by an 'end spurt'. Each of the aforementioned pacing styles is adopted with the aim of optimizing performance whilst also preserving (to different degrees) the homeostatic regulation of the various physiological systems within tolerable ranges [62]. For example, in the instance of an all-out pacing strategy, the athlete will complete the bout faster by starting quickly but only if the distance is short enough to permit such a severe threat to homeostasis without causing catastrophic outcomes. Conversely, adopting a more conservative negative strategy also considers the ratio of homeostatic threat (cost) to performance (benefit), which must be weighted differently in order to achieve the appropriate outcome. The evidence presented hereafter demonstrates that the movement of team sport players during competition, while more complex, should not be considered differently. That is, there are various pacing profiles that characterize match-running performance among team sport players that appear to be dependent on the structure of the sport (i.e. rules or tactics) and, most importantly, the duration of the exercise bout.

Whilst it is acknowledged that various factors, such as opposition quality, score line and playing venue are all likely to influence match-running performance [109], the consistent gross temporal patterns of total and high-intensity movement observed in team sport performance should not be overlooked, since this may be the difference between higher or lower playing standards in team sport [2, 7, 110–112]. Indeed, with increased resolution, the variability in match-running performance may demonstrate non-linear dynamic properties, similar to the self-organizing behaviour that emerges during both cycling time trials [113] or from dyadic pairings in team sport [114]. Consistent with the proposal of Edward and Noakes [58], dynamically changing patterns reflect the micro-pacing strategy of the player, which ultimately form the meso- and macro-profiles across the match. This might be anticipated for most sporting activities, reflecting the regulation of energy expenditure by an intrinsic biological control process [113]. Indeed, there is previous evidence of micro-variability (within-lap), despite even-paced strategies (between-laps), during mountain biking races [115]. That predictable gross movement patterns are ultimately observed during team sport matches, regardless of the seemingly random changes in factors such as score-line or possession, demonstrates the robust nature of macro-pacing strategies. It is not our contention that movement patterns are unaffected by situational match variables that occur outside of the player's command but, rather, we suggest

that these factors are incorporated into the pacing schema of a player such to optimize the overall distribution of their energy expenditure across the course of a match. Accordingly, the focus of the following descriptions is to describe the generalized patterns of running performance that occur in selected team sport. Given the aforementioned importance of higher-intensity exercise to elite playing standards in team sport [2, 7, 110–112], it is relevant to understand the ways in which running intensity might be optimized during matches.

9 Soccer Pacing Profiles: ‘Slow Positive’ and ‘One Bout All Out’

Among the studies assessing changes in match-running performance in professional soccer players, a typical decline of approximately 20 % in total distance covered has been reported between the first and last 15 min of a match [2, 6, 23, 24, 116, 117]. In the majority of, but not all, instances [118], this value is reduced to approximately 10 % when total distance covered between the first and second halves are compared [13, 26, 119, 120]. The distance covered at high intensity may also be up to 15–45 % lower in the final 15 min than in the first four 15-min periods among elite, professional players [2, 6, 23, 117, 120–122].

To the best of the authors’ knowledge, there has been no investigation of pacing strategy among substitute players. However, it has been shown that substitutes entering the field of play in the final 15–25 min of a match complete more high-intensity running than whole-match players [2, 6, 123]. Indeed, there is a positive relationship between higher-intensity (i.e. $\text{m}\cdot\text{min}^{-1}$) running and the proximity of the substitution to the end of the match [6]. Such findings are consistent with the suggestion that ‘fatigue’ occurs at the end of a match among whole-match players and that match-running intensity is scaled in proportion to the remaining match duration. That is, shorter match periods result in greater match intensities, whilst longer match durations result in lower match intensities. Moreover, unlike in other team sports, soccer players do not specialize as either ‘whole-match’ or ‘partial-match’ players, and are not typically conditioned with this in mind. Therefore, it is the length of the bout, alone, that encourages a substitute to approach a soccer match at a higher intensity than they would if they had started the match. An observation (Waldron, unpublished observation) (Fig. 3) of an elite under-16 soccer player being brought on (substituted) for 14 min at the end of a competitive match demonstrates the commonly adopted all-out nature of performance in this scenario.

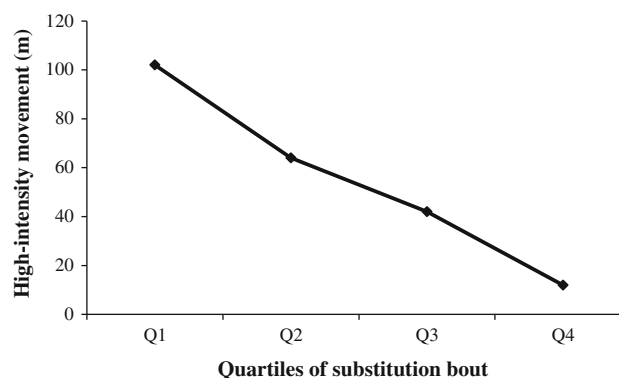


Fig. 3 High-intensity running distance, measured using a 5 Hz global positioning system, across quartiles of a 14-min period in an elite under-16 youth soccer player (Waldron, unpublished observation). *Q* quartiles of the entire bout

Collectively, it would appear that ‘whole-match’ soccer players adopt pacing profiles that, according to previous descriptions, are best described as ‘positive’ in nature [103]. However, a parabolic shape is not apparent, nor is an end spurt commonly reported in the final periods of a match. While there is some suggestion that positional role and opposition might influence the running strategy [6], the general pattern of performance is unequivocal. Therefore, it is suggested that whole-match performance in soccer is described as a ‘slow-positive’ pacing profile. A ‘slow-positive’ strategy means that the intensity of running will progressively decline across the match, which is likely to be interrupted by two adjacent periods of the highest and lowest intensity. This strategy is suggested to reflect the macro-pacing schema of the player, permitting optimal completion of the bout, whilst also reserving the capacity for transient periods of high-energy activity. Such activity will require a micro-adjustment of the pacing strategy, often followed by a period of lower intensity activity. Nevertheless, the ‘slow-positive’ decay in total running distance will continue to develop in accordance with the overall schema of the player, ensuring that the match is completed in an optimal manner, with only limited changes to bodily homeostasis. While there is limited information on substitute players, the reported findings indicate that a higher intensity is maintained for a shorter period, conforming to a ‘one bout, all out’ strategy. This strategy is likely to predominate among substitute soccer players, given that their introduction to the match typically occurs late in the second half, with no further opportunity to be interchanged. This leaves soccer players with a short period of time with which to influence the outcome of the match, at a time when full-match players are pre-fatigued or having to adopt a different pacing strategy. It should be noted that the definition of an ‘all-out’ pacing strategy in

team sport may differ from its traditional meaning in individual sports, since the degree of reserve physiological capacity is unknown. However, such instances are the closest equivalent in a team sport environment.

10 Rugby League: ‘Slow-Positive’, ‘One-Bout, All-Out’ and ‘Two-Bout Reserve’

The movement profiles of professional rugby league players are now well established. Given the nature of contact sports such as rugby league, players generally cover less distance than sports such as soccer (mean 6–8 vs. 10–14 km [7, 14, 39]). Across a whole match (~80 min), rugby league players also demonstrate a ‘slow-positive’ pattern of fatigue, which is remarkably similar to that of soccer players. The decay in running performance is also of a similar magnitude to that in soccer, with players typically reducing their high-intensity running distance by approximately 20–30 % between the first and final quartiles of the match [8, 15]. This value is reduced to approximately 10 % between halves of the match [7, 110, 124]. Interestingly, there is typically no change in tackle frequency over the course of a match [15], which might reflect the structured format of rugby league, including a six-tackle turnover, 10-m retreat and the offside law. Such rules constrain the movement of the players, and dictate the frequency of tackling and ball-carrying actions that occur. While the maintenance of tackle frequency across the match does not adequately describe the magnitude of collisions, such findings might indicate a sacrifice of running performance to maintain tackling performance. As such, rugby league players must adopt a macro-pacing template that optimizes their performance from within the constraints of the various control variables.

The interchange rule, permitting up to 10–12 replacements (depending on the country of competition and year) during any stage of a match represents another specificity of rugby league. Waldron et al. [8] showed that interchanged players (typically forwards), paced their first exercise bout (first half ~20 min) differently from their second (second ~20 min) during Super League matches. The interchanged players adopted a ‘one bout, all out’ strategy in their first-half bout, beginning the first quartile of this match period at intensities higher than whole-match players. This was followed by a stepwise decline in both total and high-intensity movement per minute between every playing quartile of the first bout. After a period of recovery (i.e. removal from the field), the players adopted an intensity lower than the average of whole-match players, which, thereafter, led to an end spurt in the final quartile of bout two. This phenomenon can be referred to as a ‘two-bout reserve’ strategy. Each of these strategies is outlined

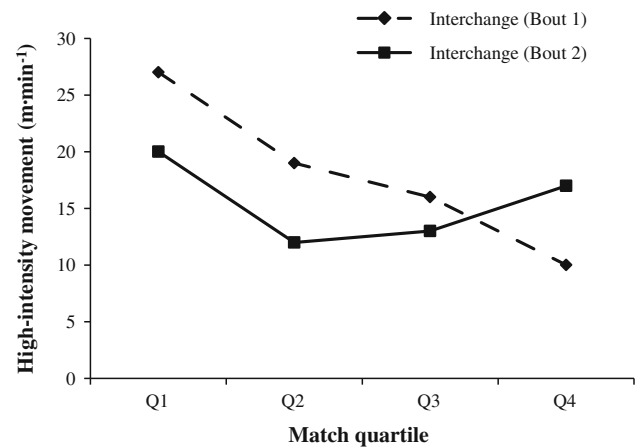


Fig. 4 High-intensity running profile ($\text{m}\cdot\text{min}^{-1}$), measured using a 5 Hz global positioning system, across quartiles of an elite rugby league match (Waldron, unpublished observation). Q quartiles of each bout

in Fig. 4, which provides a real-life example (Waldron, unpublished observation) of an elite interchange rugby league player, performing two bouts of approximately 20-min duration.

Black and Gabbett [5] reported similar pacing strategies among Australian rugby league players, performing a higher total distance than whole-match players in the first bout, followed by a reduction in intensity, culminating in an end spurt in the second interchange bout (i.e. second-bout reserve). Whilst the same findings were not reported for high-intensity running, the $18 \text{ km}\cdot\text{h}^{-1}$ speed classification used by Black and Gabbett [5] is likely to have disregarded the running captured in the lower ($14 \text{ km}\cdot\text{h}^{-1}$) category employed by Waldron et al. [5]. Given that rugby league players may be interchanged on multiple occasions (typically twice), their first interchange bout is performed in the knowledge that they can be removed from the field if excessive fatigue ensues. This appears to affect the pacing model of rugby league players, resulting in an aggressive running strategy in the first bout. As the number of available interchanges is reduced throughout the game, there is less certainty that they can be removed from the field if the same scenario occurs in the second bout. The result is a more tentative approach to match performance, reflected by a reservation of running distance and an end-spurt.

11 Australian Football (AF): ‘Slow Positive’ and ‘One Bout, All Out’

AF players cover the largest distances out of all team sport players (mean ~12.3 km), equating to distance covered of $124 \text{ m}\cdot\text{min}^{-1}$ [19]. Across whole AF matches, an approximate 10 % decline in total running performance can be

observed between the first and second halves or the first and final quartiles [3, 19, 125, 126], which is slightly larger (20 %) for high-intensity movement [3, 126]. It has also been suggested that low-intensity movement is reduced across a match in order to preserve high-intensity running [4, 127]. Therefore, whilst the decrement in high-intensity performance is not always found in AF matches, players appear to scale their energy output in relation to the length of the bout, remaining aware of the importance of high-intensity movement.

The overall change in movement distance during AF matches conforms to the aforementioned ‘slow-positive’ pacing strategy, thus denoting a global finding among all of the football codes. AF is the only selected team sport in the current review that has an unlimited interchange rule, permitting players from the interchange bench (three, plus one substitute) to continuously replace others from the field. This rule appears to have a substantial effect on the aforementioned high-intensity movement patterns of all players, with significant relationships (r 0.52; P = 0.01) between the number of interchanges and the amount of high-speed running performed, particularly in the final quarters of the match [128]. The unlimited interchange rule also provides players with the assurance that they can be replaced if signs of fatigue are demonstrated, which is likely to influence the pacing strategy, regardless of the bout number. However, although these findings suggest that the introduction of interchange players might influence the running intensity of others, an overall decline in the running performance of whole-match players was still reported [128]. In further support of this notion, a report conducted on behalf of the Australian football league (AFL) [129] demonstrated that players who are interchanged more frequently perform more high-intensity efforts and, more importantly, markedly reduce their average match speed as a function of playing duration. Indeed, there was a typical curvilinear reduction of ~ 2 km·h⁻¹ in the average speed of players after 3 min of match play [129]. Therefore, given the increase in intensity that ensues when interchange players are introduced to the match, and that they can be replaced at any point in time, a ‘one-bout, all-out’ pacing strategy exists among these players. In this instance, AF players appear to treat each bout similarly, adopting high-intensity running from the outset of their interchange bout. The interchange rule will be capped at 120 during the 2014 season [130], which might have an influence on the pacing strategy that is adopted.

12 Rugby Union: ‘Slow Positive’ and ‘Flat’

While there have been numerous investigations of match-running performance in rugby union [31, 131–134], to the authors’ knowledge, only two studies have addressed the

change in movement across progressive segments of matches [16, 135]. In accordance with the global findings among other team sport, Roberts et al. [16] reported an approximate 10 % decline in total running distance across matches, suggesting a slow-positive pacing strategy. However, there was no change in high-intensity running across the match, which is in contrast with the findings among other team sports of a similar duration (~ 80 min). Lacombe et al. [135] also reported no change in work-to-rest ratios between halves of international rugby union matches. Whilst there was some indication that the magnitude of accelerations decreased between halves among some of the players, this was not consistently reported. Therefore, the higher-intensity movement profiles of elite rugby union players are typically ‘flat’ across matches. It is likely that the continual performance of so-called ‘static-exertions’ (i.e. non-running energy expenditure), such as tackling, rucking and mauling, is responsible for this finding. As such, high-intensity performance might be of relatively less importance to rugby union match play than to other sports [2, 7, 103, 105]. These suggestions are supported by the comparatively lower running distance performed by rugby union players during matches, equating to an average of 60–80 m·min⁻¹ [132].

The above findings describe some of the control variables present in the rugby union match play, which must be managed by players in order to optimise their contribution to a match. Given the close proximity of players, particularly forwards, to the defensive line in rugby union, and the high frequency of rucking activity [37, 136], the ability of players to reach higher-intensity zones is limited. It is likely that the different pacing strategies employed by rugby union players have not yet been revealed in current research and may require more detailed analyses of static exertions. For example, recent techniques have been developed to measure force generated during scrums in rugby union matches [137]. Given the energy cost associated with whole-body resisted movements [138, 139], it is likely that the ability of players to generate force during scrums will alter across a match. Indeed, Roberts et al. [16] reported a reduction in high-intensity efforts following the final five scrums compared with the first five during a rugby union match. Typically, it is forwards, rather than backs, who are substituted during rugby union matches, which might also result in a different pacing strategy; however, this is yet to be systematically investigated in rugby union.

13 Conclusion

Pacing strategies are important to understand in team sport since they reveal how players best manage their

energy resources during matches. Knowing how players distribute their energy reserves and manage ‘fatigue’ during matches will help researchers to develop effective intervention strategies. However, further research is required to understand what factors might influence the pacing strategies of elite team sport players. Nutritional interventions, training history and experience are all factors that could potentially alter the pacing strategy of a team sport player. Pacing and fatigue are considered as inherently related factors, each of which occur during team sport performance. Pacing in team sport should be considered as the distribution of energy resources that optimize match-running performance to suit the requirements of a given scenario; whereas fatigue is a uni-directional construct that relates to the eventual reduction in performance compared with baseline values. Of course, the type of pacing strategy adopted will dictate both the timing and the degree of observed fatigue.

The macro-strategy of whole-match players is described as ‘slow-positive’ pacing, which appears to be global across the different team sports. Among the team sports selected for this review, high-intensity movement, which is typically associated with higher standards of performance, declines in a ‘slow-positive’ manner across the match. However, this is not the case in rugby union, whereby ‘flat’ profiles are associated with high-intensity performance. Other factors might better reflect the pacing strategy of rugby union players, such as static exertions performed across the match. Based on the available evidence, the first introduction to a match as a substitute or interchange player results in a ‘one-bout, all-out’ strategy. In a limited interchange environment, a second introduction to the match results in a ‘second-bout reserve’ strategy; otherwise, the ‘one-bout, all-out’ strategy is likely to be adopted. These pacing profiles are proposed to reflect the presence of a central regulator that controls the movement intensity of the player to optimize performance, as well as avoiding the harmful failure of any physiological system. The presence of ‘temporary fatigue’ among different sports reflects this process, whereby exercise intensity is consciously modulated from within the framework of a global pacing schema. Future research is required to establish the ways in which pacing templates are developed and the extent to which pacing can be optimized in team sport performance. For example, factors such as age, experience and cognitive development [140, 141] have been suggested to influence the pacing strategy of individual athletes and could feasibly influence team sport players in the same way.

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