REVIEW ARTICLE

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Physiological and Metabolic Responses of Repeated-Sprint Activities

Specific to Field-Based Team Sports

Matt Spencer,[1,2] *David Bishop*,[1] *Brian Dawson*[1] and *Carmel Goodman*[1]

1 Team Sport Research Group, School of Human Movement and Exercise Science, The University of Western Australia, Crawley, Western Australia, Australia
2 Department of Physiology, Australian Institute of Sport, Canberra, Australian Capital Territory, Australia

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Abstract

Field-based team sports, such as soccer, rugby and hockey are popular worldwide. There have been many studies that have investigated the physiology of these

sports, especially soccer. However, some fitness components of these field-based team sports are poorly understood. In particular, repeated-sprint ability (RSA) is one area that has received relatively little research attention until recent times. Historically, it has been difficult to investigate the nature of RSA, because of the unpredictability of player movements performed during field-based team sports. However, with improvements in technology, time-motion analysis has allowed researchers to document the detailed movement patterns of team-sport athletes. Studies that have published time-motion analysis during competition, in general, have reported the mean distance and duration of sprints during field-based team sports to be between 10–20m and 2–3 seconds, respectively. Unfortunately, the vast majority of these studies have not reported the specific movement patterns of RSA, which is proposed as an important fitness component of team sports. Furthermore, there have been few studies that have investigated the physiological requirements of one-off, short-duration sprinting and repeated sprints (<10 seconds duration) that is specific to field-based team sports. This review examines the limited data concerning the metabolic changes occurring during this type of exercise, such as energy system contribution, adenosine triphosphate depletion and resynthesis, phosphocreatine degradation and resynthesis, glycolysis and glycogenolysis, and purine nucleotide loss. Assessment of RSA, as a training and research tool, is also discussed.

Sports scientists and coaches alike have suggested that the ability to perform repeated sprints with minimal recovery between sprint bouts, termed repeated-sprint ability (RSA), may be an important aspect of team-sport competition. However, the scientific literature is not abundant with studies investigating the physiology of RSA. In fact, there is surprisingly little research investigating the physiology of either one-off, or repeated, short-duration sprint efforts. Research concerning the fitness component of RSA, using tests that replicate the sprint and recovery durations of field-based team sports, is a relatively new area of investigation with peer-reviewed papers only being published in the past 10 years or so.

While studies documenting the movement patterns of field-based, team-sport competition suggest that the sprint efforts are of short duration (i.e. <4 seconds), the majority of studies investigating the physiology of one-off sprints and repeated-sprint efforts are of considerably longer duration. It is likely that the physiological and metabolic responses of repeated-sprint activities will be influenced by variations in exercise protocols (e.g. exercise mode, sprint duration, number of sprint repetitions, type of recovery, training status). Therefore, if the physiological and metabolic responses of repeated-sprint protocols are to be specific and relevant to field-based team sports, then the sprint and recovery durations should replicate the movement patterns of these sports.

This article attempts to summarise and draw conclusions from the limited studies that have investigated the physiological and metabolic responses of one-off and repeated sprints, with the emphasis on protocols specific to field-based team sports. In addition, an evaluation of the various laboratory and field tests used to assess RSA will be outlined.

1. Movement Patterns in Field-Based Team Sports

Since the early 1970s, many studies have investigated the distance and duration of the common movement patterns performed in field-based team sports, commonly called time-motion analysis. Time-motion analysis is important, as without documented evidence of the durations and distances covered of the various movement patterns (i.e. standing,

walking, jogging, striding and sprinting), it is difficult to quantify the physiological responses and requirements of a particular sport. Although the majority of these studies have been conducted in the sport of soccer,[1-6] other sports have also been investigated such as Australian Rules football,[7-10] field-hockey,[11,12] rugby union[13,14] and Gaelic football.[15] While the aforementioned studies, and others, have furthered our understanding of these particular field-based team sports, they are often difficult to compare because of differences in their methodology.

1.1 Time-Motion Analysis Methodology

The methodological techniques used to obtain time-motion data during team-sport competition have developed since the initial investigations. Time-motion analysis studies conducted in the 1970s commonly used real-time manual recording methodology to document the movement patterns during competition.[4,8] The accuracy and detail of such analysis may be limited as this method relies on the skill and speed of the analysts and does not allow for sections of play to be re-analysed. Other studies have documented the movement patterns via audio recordings.[6,15] However, the majority of studies have used techniques that are based on video recordings and computer software to analyse the data.[1-3,5,9,12] This is the preferred method because of increased accuracy of recording, more comprehensive classification of movement patterns[9] and the ease of re-analysing data. Furthermore, new techniques for obtaining time-motion analysis data have also been developed. One such method consists of a computer-based tracking system that allows the motion activities of players to be monitored on a miniaturised, calibrated version of each competition playing field.[10] The exciting development of new technologies, such as player tracking via global positioning systems, may provide accurate time-motion data in 'real time', which would dramatically reduce the analysis time and errors in comparison to the traditional methods of manually coding players' movements via video playback.

Differences in motion descriptors used also make it difficult to compare studies. The majority of time-motion analysis studies have classified the movement patterns of players into at least five categories: standing, walking, jogging, striding and sprinting, and possibly some skill-related activities (i.e. tackling or ball possession). However, because of the excessive time required to analyse time-motion analysis data, and the difficulties in accurately distinguishing between some movement activities, several studies have combined striding and sprinting into one category usually termed 'high-intensity' movements.[3,9,15,16] While classifying the data in this format provides valuable information, an isolated breakdown of sprint activity (i.e. distance and duration of sprints) is not provided. Therefore, an accurate determination of sprint performance during competition is not possible when sprinting and striding are combined. In order to make meaningful comparisons of the movement patterns between studies, it is recommended that the activities of standing, walking, jogging, striding and sprinting be coded as distinct categories. The breakdown of sub-categories, when required, can be easily totalled. For example, Mohr et al.[2] classified three sub-categories of striding, namely, low-, moderate- and high-speed running.

1.2 Time-Motion Analysis of Sprint Data

Methodological differences and the variety of team sports analysed make it hard to evaluate studies. However, the mean duration of high-intensity movements, for those studies that have combined striding and sprinting into a category, has been reported to be 2.7 seconds in Australian Rules football, with the mean time between high-intensity efforts being approximately 75 seconds.[9] In soccer, the reported mean duration of high-intensity movements is 3.7 to 4.4 seconds[3,5] and the mean distance is 22.4m.[5] The mean time between high-intensity efforts in soccer has been reported to be between 40 and 56 seconds.[3,5] However, in the study of Withers et al.[5] the distance covered sprinting was also reported, allowing an estimate of the approximate number of sprints performed. As expected, when

this calculation is made, the mean time between high-intensity efforts was substantially increased (from 56 to approximately 180 seconds; table I). Nonetheless, in studies that have combined sprinting and striding, the mean duration of high-intensity movements ranges from 2.7 to 4.4 seconds with a recovery duration of approximately 40–70 seconds. However, for motion analysis to be more informative, it is critical that sprinting is included as a separate motion.

Studies that have classified sprinting as an individual activity suggest that the mean sprint distance in elite soccer is 10–20m[4,17] or a duration of 2–3 seconds.[1,2,6] The mean sprint duration for field hockey is reported to be 1.8–3.1 seconds,[11,12,20] whereas the mean sprint duration for Australian Rules football is reported to be 2.4 seconds.[7] One valuable statistic that is rarely reported is the mean maximal sprint duration. While the mean sprint duration throughout an elite field-hockey game was 1.8 ± 0.4 seconds, the mean maximal sprint duration was 4.1 ± 2.1 seconds.[12] This variable may be important for designing overload training and assessment protocols. Despite differences in the movement patterns of these field-based team sports and variations in the definition of the term 'sprinting', the reported mean distance and duration of sprinting appears to be quite similar for different sports and is between 10–20m and 2–3 seconds, respectively (table I). However, it is important to consider that athletes will also be required to perform sprints that are greater than the mean.

The number of sprints reported in a game of soccer varies greatly, from 19 to 62.[1,2,4-6,17] This range of sprints performed in a game is within the frequencies reported in studies of field-hockey,[11,12] rugby union[13,14] and Australian Rules football[7,10] (table I). Furthermore, there are considerable variations in the estimated total sprint distance during a game of soccer, which is reported to be between 670–975m,[2,4,5,17] despite the fact that all four of these studies analysed elite soccer players during professional matches. The differences between these studies may be due to considerable changes in the physical conditioning of players during this 20-year period, or variations in the classification of 'sprinting' and 'striding'. Reilly and Thomas[4] defined cruising (striding) and sprinting as mean stride lengths of 1.13m and 1.24m, respectively. Alternatively, Withers et al.[5] reported mean stride lengths of striding and sprinting to be considerably greater, 1.75m and 1.76m, respectively. Furthermore, these stride lengths were individually determined for each subject in the study of Withers et al.,[5] whereas Reilly and Thomas[4] only used one subject to validate their method. Although the reported range in number of sprints and total sprint distance is considerable, some common findings in the motion analysis of sprint activity in team sports are evident when studies have presented mean data. In general, the frequency of sprinting in field-based team sports (i.e. 70–90 minutes in the sports of soccer, field-hockey and rugby) is approximately 20–60 bouts per game, with a total sprint distance of approximately 700–1000m.

In addition to reporting mean data for the time-motion analysis of sprinting, several studies have categorised information into positional roles (table I). Two studies that have categorised positional roles in soccer have reported a trend for forwards to perform more sprints than full-backs.[1,4] In field-hockey, positional differences in the frequency of sprints performed is greater, with strikers and inside-forwards performing approximately twice as many sprints compared with full-back players.[12] The positional differences in rugby union are even greater, with the forwards performing approximately one-third of the number of sprints compared with the backs.[13,14] However, the physical characteristics of rugby union players are quite different to many other field-based team sports, with clear distinctions between the physiological and anthropometrical characteristics of forwards and backs.[21] Therefore, although generalising the time-motion analysis of sprint data provides a good overview of the common traits of this fitness component, individualising the data into specific sports and positional roles is required to further our understanding of this area.

Table I. Time-motion analysis of sprinting during field-based team sports (data are mean values)

Study	Sport	Subjects	Positional role	Method	Sprint duration (sec)	Sprint distance (m)	Sprint frequency	Recovery time between sprints (sec)	Change in motion[a] (sec)
Dawson et al.[7]	Australian Rules	22 E M	All players	Video	2.4	18.6	24	300	6.3
Hahn et al.[8]	Australian Rules	2 T M	All players	Manual		15.5	127[b]		
McKenna et al.[9]	Australian Rules	4 E M	All players	Video	2.7[b]		98[b]	73[b]	
Norton et al.[10]	Australian Rules	53 E M	All players	Computer			21		
Lothian and Farrally[11]	Field hockey	12 T F	All players	Video	3.1		75	56	
Spencer et al.[12]	Field hockey	14 E M	All players	Video	1.8		30	140	5.4
		3 E M	Full-backs	Video	1.5		18	233	5.4
		4 E M	Half-backs	Video	1.6		22	191	5.8
		2 E M	Inside-backs	Video	2.2		39	108	5.3
		5 E M	Strikers	Video	1.9		42	100	5.0
McErlean et al.[15]	Gaelic football	40 T M	All players	Audio	3.9[b]		80[b]	46[b]	
		40 T F	All players	Audio	4.3[b]		62[b]	59[b]	
Docherty et al.[13]	Rugby union	13 T M	Forwards	Video	1.8		10	240	
		14 T M	Backs	Video	2.3		31	77	
Duthie et al.[14]	Rugby union	31 E M	Forwards	Video	2.2		11	436	7.5
		16 E M	Backs	Video	2.9		27	178	7.4
Bangsbo et al.[1]	Soccer	14 E M	All players	Video	2.0		19	284	~7
		4 E M	Defenders	Video	2.0		16	338	
		7 E M	Mid-fielders	Video	2.1		17	318	
		3 E M	Forwards	Video	1.7		24	225	
Barros et al.[17]	Soccer	25 E M	All players	Video		13	55	98	
Drust et al.[18]	Soccer	23 E M	All players	Video					4.0
Mayhew and Wenger[3]	Soccer	3 E M	All players	Video	4.4[b]		519[b]	40[b]	6.1
Mohr et al.[2]	Soccer	18 E M	All players	Video	2.0		39	138	
		24 E M	All players	Video	1.9		26	208	
Reilly and Thomas[4]	Soccer	40 E M	All players	Manual-audio		15.7	62	90	6.4
		11 E M	Mid-fielders	Manual-audio		15.6	68	79	6.0
		8 E M	Full-backs	Manual-audio		15.1	52	104	6.3
		14 E M	Forwards	Manual-audio		16.4	65	83	6.7

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Table I. Contd

Study	Sport	Subjects	Positional role	Method	Sprint duration (sec)	Sprint distance (m)	Sprint frequency	Recovery time between sprints (sec)	Change in motion[a] (sec)
		7 E M	Centre-backs	Manual-audio		14.1	59	92	6.7
Withers et al.[5]	Soccer	20 E M	All players	Video	3.7[b]	22.4[b]	~30 (97[b])	~180 (56[b])	
		5 E M	Full-backs	Video	3.7[b]	24.3[b]	~38 (110[b])	49[b]	
		5 E M	Centre-backs	Video	3.6[b]	20.8[b]	~19 (80[b])	68[b]	
		5 E M	Mid-fielders	Video	3.8[b]	22.6[b]	~29 (110[b])	49[b]	
		5 E M	Forwards	Video	3.5[b]	21.2[b]	~32 (88[b])	61[b]	
Yamanaka et al.[6]	Soccer	10 E M	All players	Audio	3.0		35	154	7.3
		39 T M	All players	Audio	4.5		44	123	5.9
Allen[19]	Touch rugby	12 E M and F	All players	Video		10.1	29		

a Using standard categories of motion (stand, walk, jog, stride and sprint).

b Denotes studies that have combined the motions of sprinting and striding into one category.

audio = analysis via audio play-back, no visual coding; **computer** = analysis via computer tracking; **E** = elite; **F** = females; **M** = males; **manual** = analysis via real-time recording/charting; **manual-audio** = analysis via combination of audio and manual charting; **T** = trained; **video** = analysis via video play-back and usually computer software.

1.3 Time-Motion Analysis of Repeated-Sprint Data

While the findings regarding the mean recovery durations between sprints are valuable for estimating the average work-to-rest ratios during competition (table I), they do not provide an insight into the typical movement patterns of RSA, which is acknowledged as an important fitness component of team sports.[22] If a 2- to 3-second sprint is performed every minute or two during a game, as suggested by the literature, it is unlikely that performance will be compromised. It has clearly been shown that when short sprints (approximately 5.5 seconds in duration) are repeated every 120 seconds, there is no decrement in performance, even when 15 sprints are performed in succession.[23] In addition, when the recovery duration is reduced to 90 seconds, a significant decrease in performance time was only evident after the 11th sprint.[23] However, it must be noted that other activities, in addition to sprinting, may lead to fatigue during team-sport competition (i.e. energy expenditure during eccentric contractions, change of direction movements and jogging or striding for extended periods could also contribute to fatigue). Furthermore, because of the unpredictable nature of team sports, short periods of repeated-sprint activity may be required on several occasions throughout a game. While it is likely that this type of movement pattern only contributes a small proportion to the overall motion activity during competition, it may be critical to the result of a game.

There is a paucity of research investigating the nature of repeated-sprint activity during team-sport competition. The first paper, to our knowledge, that has investigated the time-motion analysis of repeated-sprint activity was conducted in elite field-hockey competition.[12] Although the mean recovery time between sprints was approximately 2 minutes during the game analysed (i.e. a mean of 30 ± 12 sprints performed during the 70-minute game), nearly 25% of the recovery periods between sprints were of <21 seconds in duration (figure 1). Furthermore, figure 1 highlights the fact that the most frequent recovery pauses are either of very short duration (i.e. 0–20

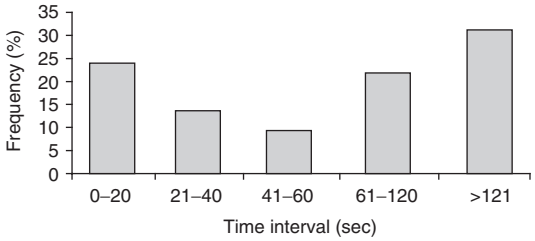

Fig. 1. Frequency distribution of recovery time between sprints during an international field-hockey game (n = 14) [reproduced from Spencer et al.,[12] with permission from Taylor & Francis Group (http://www.tandf.co.uk)].

seconds) or of long duration (i.e. >1 minute), with recovery pauses of 20–60 seconds being infrequent.[12] The definition of a repeated-sprint bout used by Spencer et al.[12] was a minimum of three sprints with a mean recovery duration between sprints of <21 seconds. The authors believed that this might represent a typical period of intense, repeated-sprint activity. Using the aforementioned definition, the mean number of repeated-sprint bouts reported during the field-hockey game was 4 ± 1 and the mean recovery time between sprints was 14.9 ± 5.5 seconds. A maximum of seven sprints was recorded during the repeated-sprint bouts. Furthermore, Spencer et al.[12] reported that approximately 95% of the recovery between sprints, within the repeated-sprint bouts, was active recovery. The majority of this active recovery was of a jogging intensity. Therefore, Spencer et al.[12] suggested that a RSA test, specific to field hockey, may require as many as six to seven sprints with <21 seconds between sprints and involve an active recovery. It is important that this research is replicated with other team sports.

1.4 Summary

Although many studies have investigated the movement patterns of field-based team sports, differences in the methodological techniques used and the classification of motion descriptors make it difficult to compare studies. However, the mean distance and duration of sprints during field-based team sports is quite consistent, being between 10–20m and 2–3 seconds, respectively. Contrary to the aforementioned data concerning sprint distance and duration, there is considerable variation in the frequency of sprints during team-sport games (i.e. 20–60 sprints) and total sprint distance (i.e. approximately 700–1000m). Furthermore, in order to increase our understanding of the RSA of field-based team sports, further research is required to document the time-motion analysis of repeated-sprint activity during team-sport competition. In addition to reporting mean data, such as the average duration or distance of sprinting and recovery motions, future studies should document the specific nature of the repeated-sprint bouts performed.

2. Sprint Metabolism

Section 1 has highlighted the importance of sprinting and repeated sprinting to team-sport performance. An understanding of sprint metabolism is therefore important to comprehend the demands placed on team-sport athletes during competition.

2.1 Energy System Contribution

Several studies have investigated the energy system contribution during maximal sprint exercise of varying duration. Considerable variations in the energy system contributions reported in the literature reflect the different methodological techniques used (i.e. accumulated oxygen deficit and muscle biopsies).[24,25] Medbø et al.[24] measured changes in muscle metabolites and adenosine triphosphate (ATP)-turnover and reported the relative energy system contribution from aerobic processes, anaerobic glycolysis and alactic anaerobic processes (ATP and phosphocreatine [PCr] breakdown) during maximal 30-second sprint cycling to be 38%, 45% and 17%, respectively. These findings support previous studies that have shown the contribution of the aerobic energy system to be 28–40% during a 30-second cycle sprint.[26,27] The aerobic energy system contribution is also considerable during shorter bouts of exercise, and has been reported to be ~30% during sprinting over 12–22 seconds.[24,28] In the 12-second cycle sprint, Medbø et al.[24] measured changes in muscle metabolite and ATP-turnover and calculated the relative contribution of anaerobic glycolysis and alactic anaerobic processes to be 47%

and 22%, respectively. Therefore, during sprint exercise of 10–30 seconds duration, anaerobic glycolysis provided at least twice as much ATP as PCr degradation.

Although the aforementioned findings are very interesting, the sprint durations of field-based team sports are considerably less than 10 seconds. Anaerobic glycolysis has been shown to be substantial during a 6-second cycle sprint, contributing almost as much energy as PCr degradation (44% and 50%, respectively) to the total anaerobic ATP production.[29] Furthermore, anaerobic glycolysis has been reported to be considerable during 2.5 seconds of electrical stimulation at 50Hz, which results in near maximum contraction force.[30] During the first of two periods of electrical stimulation (i.e. 0–1.28 seconds), the total ATP turnover was 11 mmol/kg dry muscle (dm)/sec of which approximately 80% was PCr degradation and anaerobic glycolysis contribution approximately 20%. The second period (i.e. 1.28–2.56 seconds) resulted in a relative contribution of approximately 50% from anaerobic glycolysis. Therefore, these data suggest the PCr degradation and anaerobic glycolysis are activated simultaneously during the commencement of maximal or near maximal exercise. Figure 2 represents the estimated energy system contribution during a 3-second sprint, which is the approximate duration of a sprint in field-based team sports (see section 1). As the ATP production rate during maximal exercise is reported to be as high as 10–15 mmol/kg dm/sec,[30-32] then the estimated total ATP energy release during a 3-second sprint would be approximately 30–45 mmol/kg dm.

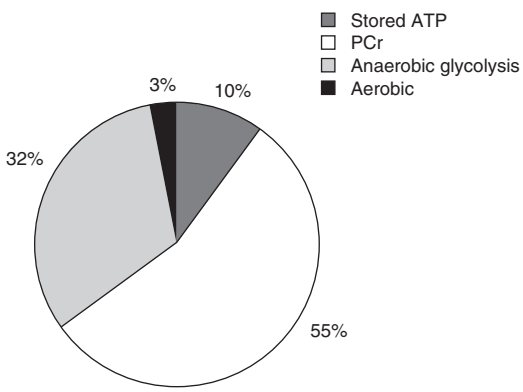

Fig. 2. Estimated energy system contribution of a 3-second sprint.[24,29,30,33,34] **ATP** = adenosine triphosphate; **PCr** = phosphocreatine.

2.2 Adenosine Triphosphate (ATP) Depletion

Intramuscular ATP stores, in a rested state, are usually reported to be 20–25 mmol/kg dm.[29,31,33,35] Muscle ATP depletion appears to be limited to a maximum of approximately 45% of pre-exercise values during sprint exercise of 30 seconds in duration.[31,36,37] The ATP depletion during maximal exercise of 10–12.5 seconds is reported to be modest, being 14–32% of pre-exercise values.[24,32,38] Furthermore, the ATP depletion during a 6-second cycle sprint is minimal, being 8–16%.[29,31,35] Therefore, it is evident that the decrease in the relative concentration of ATP (mmol/kg dm/sec) during short-duration maximal exercise is small (figure 3a). The maximal ATP turnover rate is approximately 15 mmol/kg dm/sec.[29,33] The fact that many studies have shown that muscle concentration of ATP is largely preserved during maximal exercise, that results in significant depletion of PCr stores,[24,32,38] suggests that PCr is a powerful energy buffer.

2.3 Phosphocreatine (PCr) Degradation

Intramuscular PCr stores, in a resting state, are usually reported to be 75–85 mmol/kg dm[29,31,33,35] with a maximal PCr turnover rate of approximately 7–9 mmol/kg dm/sec.[29,30,33] It has been suggested that the amount of PCr in human muscle provides enough energy for about 5 seconds of maximal sprinting (i.e. maximal run of 50–60m).[40] However, due to the considerable contribution of anaerobic glycolysis and aerobic metabolism to the total ATP supply during short-duration maximal-sprint exercise,[24] PCr stores are usually not completely depleted in this time (figure 3b). It must be noted that a small amount of PCr resynthesis is likely before the muscle biopsies have been taken (i.e. usually <10 seconds). After 30 seconds of maximal exercise, the depletion of PCr stores has been reported to be 60–80% from resting values.[24,31,36,41] Maximal sprint exercise of 10–12.5 seconds results in approx-

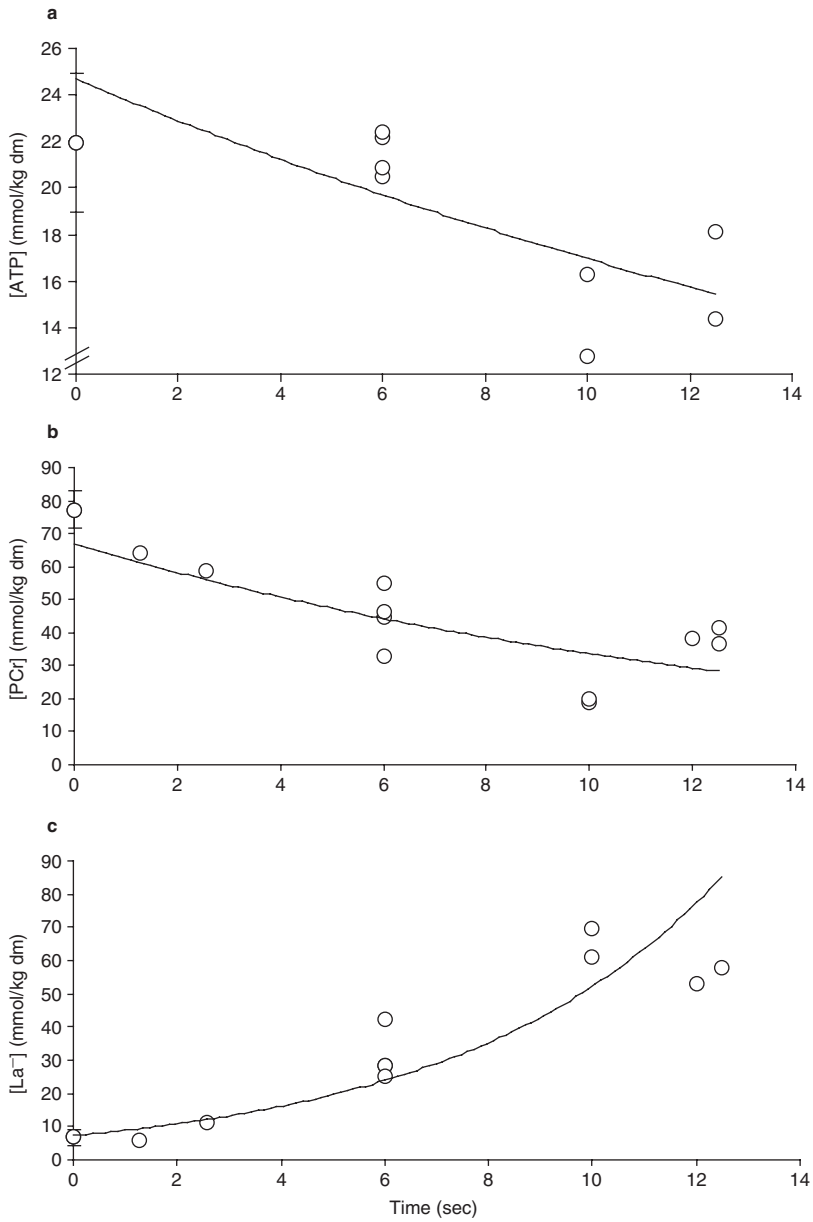

Fig. 3. Relative (**a**) adenosine triphosphate (ATP); (**b**) phosphocreatine (PCr); and (**c**) muscle lactate (La^-) concentrations during maximal sprint exercise.[24,29-33,35,38,39] Resting values have been averaged (±SD) from the aforementioned references. **dm** = dry muscle.

imately 40–70% depletion of PCr stores,[24,32,38,39] whereas PCr depletion is less (i.e. 35–55%) during 6 seconds of sprinting.[29,31,35] Hultman and Sjoholm[30] reported the PCr depletion to be only 26% during 2.5 seconds of electrical stimulation (50Hz). Therefore, sprints commonly associated with field-based team sports (i.e. 2- to 3-seconds duration) are likely to require considerable amounts of energy via anaerobic glycolysis in addition to PCr degradation.

There is evidence to suggest that PCr depletion is not just related to sprint duration, but also to the training status of subjects. Hirvonen et al.[42] demonstrated that PCr depletion was greater in a group of national level 100m track sprinters who possessed a high maximal speed compared with sprinters with a lower maximal speed (10.07 ± 0.13 and 9.75 ± 0.10 m/sec, respectively). The faster sprinters depleted significantly greater amounts of PCr than the slower sprinters, during an 80m sprint (76% and 56%, respectively) and a 100m sprint (71% and 63%, respectively), even though it took the slower sprinters longer. Hirvonen et al.,[42] therefore suggested that sprinting performance is related to the ability to deplete a greater amount of high-energy phosphates and at a faster rate during the initial stages of exercise. Hirvonen et al.[42] speculated that reduced energy supply from high-energy phosphate stores may explain the fatigue which is present after 57 seconds of maximal exercise, as observed by the decrease in running speed from 50 to 80m in their study. Although there is little evidence associating an increase in PCr stores with an increase in one-off, short-duration sprint performance via creatine supplementation,[43] it has been suggested that increasing the rate of PCr utilisation could potentially improve sprint performance.[44] However, an increase in the rate of PCr utilisation has not been shown to occur as a result of 7–8 weeks of sprint training.[31,37] Therefore, it remains speculative as to whether enhanced PCr stores and/or utilisation are due to a response to specific training or to a genetic predisposition.

2.4 Anaerobic Glycolysis

The early theory that anaerobic glycolysis, during maximal exercise, was only activated when the PCr stores were depleted[45] is clearly not supported by many studies that have reported high muscle lactate concentrations within approximately 10 seconds of exercise (figure 3c). Furthermore, the maximal turnover rate of ATP production via glycolysis is reported to be 5–9 mmol/kg dm/sec.[29,30,32,33] A mean muscle lactate value of approximately 40 mmol/kg dm has even been reported during 6 seconds of maximal sprint cycling.[35] However, the best example of the rapid onset of anaerobic glycolysis during short-duration maximal, or near maximal muscular exercise is provided by Hultman and Sjoholm,[30] who reported a net muscle lactate increase of approximately 4 mmol/kg dm during 1.28 seconds of electrical stimulation (50Hz). It must be noted that lactate production after the stimulation was possible, because of the delay in obtaining and freezing the muscle biopsy samples. Therefore, the literature suggests that anaerobic glycolysis will be activated during 2- to 3-second sprints, which are commonly performed during field-based team sports.

2.5 Summary

Although the majority of research investigating sprint metabolism has studied sprints of long duration (>10 seconds), studies assessing short-duration (<10 seconds) sprinting are more relevant to field-based team-sport performance. It is evident that the anaerobic ATP production during short-duration sprinting is provided by considerable contributions from both PCr degradation and anaerobic glycolysis, confirming the significance of glycolytic activity during this type of exercise. The importance of anaerobic glycolysis is supported by the fact that PCr stores are only partly depleted during short-duration sprinting. The rate of PCr degradation also appears to be related to training status, although this has not been investigated in team-sport athletes.

3. Repeated-Sprint Metabolism

Section 2 outlined the metabolic changes during single effort maximal sprinting. However, as mentioned in section 1, athletes in field-based team sports are required to perform repeated-sprint efforts of maximal or near maximal intensity. Therefore, it is important to gain an understanding of the metabolic effects of repeated-sprint exercise.

3.1 Energy System Contribution

Unlike single effort maximal sprinting, there is very little published research that has studied the relative energy system contribution during repeated-

sprint exercise. Bogdanis et al.[46] investigated the change in muscle metabolism during two, 30-second cycle sprints separated by 4 minutes recovery and reported a reduction in anaerobic energy production of approximately 41% during the second sprint. However, the decline in total work produced was only 18%. This discrepancy in anaerobic energy production and total work was partly explained by the 15% increase in oxygen uptake ($\dot{V}O_2$) during the second sprint.[46] Previous studies, that have used a 30-second, repeated-sprint protocol, have also reported a significant decrease in the rate of glycolysis in subsequent sprints, without a proportional decline in power output.[47,48] A similar metabolic response has been observed during repeated 6-second sprints,[29] a duration which is much more specific to the repeated-sprint activity of field-based team-sport competition.[12] Gaitanos et al.[29] reported that there was no change in muscle lactate during the tenth (and last) sprint, despite the fact that mean power output had only been reduced to 73% of that recorded during the first sprint. It was suggested that a greater contribution from aerobic metabolism partly counteracted the reduction in anaerobic glycogenolysis. Thus, it appears that while the aerobic contribution to a single, short-duration sprint is relatively small, there is an increasing aerobic contribution to repeated sprints.

The energy system contribution during repeated sprints appears to be heavily influenced by the duration of the sprints. Balsom et al.[49] investigated the physiological responses of repeated 15, 30 and 40m sprints (total sprint distance of 600m) with 30 seconds of passive recovery and reported that the post-test $\dot{V}O_2$ was significantly higher after the 30 and 40m sprint trials compared with the 15m trials. In addition to the difference in $\dot{V}O_2$, the significantly lower post-test blood lactate concentration for the 15m sprint trial clearly demonstrates the effect that manipulating the sprint duration has on the contribution of energy systems during repeated-sprint exercise. Furthermore, Balsom et al.[23] established the effect of manipulating the recovery duration in repeated-sprint exercise, by performing 15, 40m maximal sprints with either 30, 60 or 120 seconds of passive recovery. Total 40m sprint times significantly increased in both the 30- and 60-second recovery protocols, after the fifth and eleventh sprint, respectively, whereas there was no significant decrement in performance in the 120-second recovery trial.[23] As expected, $\dot{V}O_2$ measured during the rest periods was elevated in the shorter recovery trials, as was post-test blood lactate concentrations.[23] Therefore, the important variables such as sprint duration, sprint number and recovery duration clearly influence the energy system contribution during short-duration repeated-sprint exercise.

3.2 ATP Depletion and Resynthesis Rate

Similar to the reported changes in one-off sprint performance, muscle ATP depletion is limited to a maximum of approximately 45% of pre-exercise values, during repeated-sprint exercise.[47,50] However, the percentage change in muscle ATP concentration varies greatly, even in studies that have used a similar exercise protocol. For example, both Balsom et al.[51] and Dawson et al.[35] used a protocol of five repetitions of 6-second cycle sprints with 24–30 seconds of recovery between bouts, yet the percentage decrement in muscle ATP was 4% and 24%, respectively. The large difference in the percentage change in muscle ATP concentration is likely to be due to the intensity of exercise performed, as Dawson et al.[35] employed maximal exercise while Balsom et al.[51] employed high-intensity exercise. Furthermore, Dawson et al.[35] reported the ATP concentration to be significantly lower than pre-exercise values after 3 minutes of recovery. It has been suggested that low ATP concentration and reduced intramuscular pH slow the PCr resynthesis rate after intense exercise.[52] This proposal may have important implications for repeated-sprint exercise, which is specific to field-based team-sports, where the recovery time between bouts is minimal (i.e. 20–30 seconds). However, although the rate of PCr resynthesis has been associated with low ATP concentration and reduced intramuscular pH following intense exercise,[52] the initial fast phase of PCr resynthesis is suggested to be dependent on oxygen availability.[53,54]

3.3 PCr Degradation and Resynthesis Rate

Performance of 30-second sprints during repeated-sprint exercise has been associated with the rate of PCr resynthesis.[46,48] Bogdanis et al.[46] reported a high correlation between the percentage of PCr resynthesis and the percentage of power output recovery ($r = 0.84$; $p < 0.05$) during the initial 10 seconds of a second 30-second cycle sprint, with 4 minutes recovery. Bogdanis et al.[46] therefore, suggested that the ability to produce high power outputs is directly related to the resynthesis of PCr. Trump et al.[48] also investigated PCr degradation and resynthesis during 30-second cycling sprints (three sprint bouts separated by 4 minutes of rest). In their study, the resynthesis of PCr was prevented in one leg by occluding blood flow via a pneumatic cuff, during the recovery from sprint two, which resulted in 70% of the reduction in total work during the third sprint being observed in the first 15 seconds. This decrement in performance was explained by the minimal PCr resynthesis by the occluded leg compared with the control leg (3.1 and 47.5 mmol/kg dm, respectively) and possibly by significant differences in hydrogen ion accumulation.[48] However, Trump et al.[48] suggested that the higher hydrogen ion concentration was not the major result of the occluded blood flow condition. The authors argued that both the control and cuffed legs were in an acidotic state (i.e. muscle pH of 6.60 and 6.54, respectively), both conditions had no effect on glycolytic flux during the third sprint (i.e. accumulation of glycolytic intermediates was previously low in the control condition), and the decline of power output was not constant in the cuffed leg (i.e. suggesting a metabolic mechanism to be accountable for the decrement).[48]

In an exercise protocol that is much more specific to the activity patterns of field-based team sports, Gaitanos et al.[29] investigated the muscle metabolism during ten, 6-second sprints separated by 30 seconds of recovery between sprints. There was a significant decline in peak power output by the fifth sprint and a reduction of 33% by the tenth sprint. In the first sprint, PCr contributed approximately 50% to the total anaerobic ATP production and in the tenth sprint this increased to approximately 80%. However, it must be noted that the absolute contribution from PCr to the total ATP production significantly decreased from sprint one to sprint ten (44.3 ± 4.7 to 25.3 ± 9.7 mmol/kg dm, respectively). The fact that the PCr concentration decreased to 57% of the resting value after sprint one and progressively declined to only 16% after the final sprint is evidence that the vast majority of PCr resynthesis is not complete within short recovery periods (i.e. 30 seconds). In support of this finding, Dawson et al.[35] reported a PCr concentration of 45% of pre-exercise value after 30 seconds of recovery, following a repeated-sprint protocol consisting of five, 6-second cycle sprints separated by 24-seconds of passive rest. Furthermore, after 3 minutes of recovery the resynthesis of PCr was 84% of the pre-exercise value. Therefore, during team-sport repeated-sprint exercise, where typical recovery periods are too brief to fully resynthesis PCr (i.e. 20–30 seconds), there is a decreasing absolute contribution from PCr to the total ATP production.

It has been reported that the greater the PCr degradation, the greater the time that is required for full PCr repletion, as resynthesis must commence from a lower level.[35] However, following substantial PCr depletion, the initial rate of PCr resynthesis increases.[55,56] The resynthesis rate of PCr, following intense exercise, has both a fast and slow component and is best described by a double-exponential.[54,57] The half-time of PCr resynthesis is reported to be between 21–57 seconds.[41,54] Furthermore, following creatine supplementation, a higher rate of PCr resynthesis is evident, which is credited to a reduction in inorganic phosphate accumulation and a higher muscle pH, resulting in a greater mean power output during maximal repeated-sprint exercise.[56] This is an area that warrants further investigation. Another area concerning PCr resynthesis and subsequent performance that requires further investigation is the issue of active recovery between exercise bouts.

As mentioned in section 1, one study has investigated the type of recovery performed during repeated-sprint bouts within international field-hockey

competition and reported that approximately 95% of recovery was of an active nature, with the majority being of a jogging intensity.[12] In a protocol involving repeated high-intensity exercise (15 seconds at 120% of maximum oxygen uptake [$\dot{V}O_{2max}$]) separated by passive or active recovery (15 seconds at 40% of $\dot{V}O_{2max}$), Dupont et al.[58] reported a significantly shorter time to exhaustion with an active recovery. This performance decrement was correlated with a greater decline in oxyhaemoglobin and the authors speculated that active recovery may restrict reoxygenation of myoglobin and PCr resynthesis.[58] In a team sport-specific protocol involving six, 4-second sprints with either 21 seconds of passive or active recovery (32% of $\dot{V}O_{2max}$), a greater power decrement and also a lower final sprint peak power was reported in the active recovery condition.[59] The PCr concentration, percentage of resting level, was non-significantly lower immediately post-test (32.6 ± 10.6 vs $45.3 \pm 18.6\%$; $p = 0.06$) and post-21 seconds of recovery (54.6 ± 9.6 vs $71.7 \pm 14.1\%$; $p = 0.06$) during the active compared with the passive recovery, respectively.[59] Therefore, these preliminary findings suggest that active recovery may hinder PCr resynthesis when undertaken during bouts of repeated-sprint exercise. Further studies are required to confirm these findings during other protocols of repeated-sprint exercise that are specific to the movement patterns of field-based team sports.

3.4 Anaerobic Glycolysis and Glycogenolysis

Repeated-sprint exercise may result in extremely high muscle lactate concentrations, depending on the exercise duration, number of repetitions, recovery duration and the intensity of exercise. For example, McCartney et al.[47] reported a muscle lactate concentration of 150 mmol/kg dm after four, 30-second cycle sprints with 4 minutes of recovery between bouts. Furthermore, two studies using a protocol of two, 30-second cycle sprints separated by 4 minutes of recovery reported post-exercise muscle lactate concentrations to be between 100 and 130 mmol/kg dm.[46,50] However, the relevance of such long-duration, repeated-sprint bouts to field-based team sports is limited. One study, which is more specific to team-sport performance, measured muscle lactate after a single 6-second sprint and after the last sprint of a protocol involving five, 6-second cycle sprints separated by 24 seconds of recovery and reported concentrations of 42.5 and 103.6 mmol/kg dm, respectively.[35] These studies suggest that although extreme muscle lactate concentrations are evident after repeated-sprint bouts of long duration, high concentrations are still apparent following much shorter sprints.

Anaerobic glycolysis is associated with the intracellular accumulation of hydrogen ions, which have been linked as a cause of muscular fatigue.[60] Although repeated sprints result in greater muscle lactate concentrations compared with single sprints, there is a decrease in glycolysis in subsequent sprints. Gaitanos et al.[29] investigated the muscle metabolism during the first and last sprints of a protocol consisting of ten, 6-second cycle sprints with 30 seconds of recovery between sprints. The estimated anaerobic glycogenolytic rate, glycolytic rate and rate of glycogen degradation were significantly greater in the first sprint, compared with the final sprint. The authors reported an 11-fold reduction in glycogenolysis and an 8-fold reduction in glycolysis in the final sprint, despite the fact that the total glycogen degradation was reduced by approximately 37%.[29] Interestingly, during the final sprint, the average power output was still 73% of the first sprint, suggesting that the ATP production was largely derived from PCr degradation and oxidative metabolism.[29] Therefore, it is likely that the contribution of anaerobic glycogenolysis will be reduced during repeated-sprint exercise that simulates field-based team-sport performance.

While considerable reductions in muscle glycogen concentration have been reported during isolated bouts of repeated sprints,[29,46,47] several studies have investigated muscle glycogen degradation during actual soccer games[61-64] or simulated soccer games.[65,66] A game of soccer has been reported to deplete muscle glycogen stores by approximately 85–90%.[61,62] Even after only half a game (i.e. 45 minutes) some players have shown marked depletion. Karlsson[67] reported that the players with the

lowest muscle glycogen concentration at half time covered less distance and had slower average running speeds in the second half compared with the players with the highest muscle glycogen concentration. Similarly, Saltin[64] reported that the players with lower half-time muscle glycogen concentrations covered an average of 1800m less distance in the second half compared with the players with the higher muscle glycogen concentrations. Furthermore, there was a trend for the players with the lower muscle glycogen concentrations before the game, to sprint less and walk more.[64] However, muscle biopsy data obtained during a recent soccer study reported the depletion of muscle glycogen stores to be approximately 53% of pre-exercise value.[63] This level of glycogen depletion is considerably less than the aforementioned studies published 20–30 years ago, which is possibly due to improvements in pre-game nutrition. These data suggest that glycogen loading and resynthesis strategies are important to minimise performance decrements during field-based team-sport performance.

3.5 Purine Nucleotide Loss

Repeated-sprint activities that simulate the movement patterns of field-based team sports may also result in a reduction of the total purine nucleotide pool, as this type of exercise requires a high skeletal muscle ATP turnover. Brief bouts of high-intensity exercise decrease muscle ATP content, which is closely matched by an increase in inosine monophosphate (IMP) and ammonia.[68] Further degradation of IMP to inosine and then in turn to hypoxanthine may result.[69] The hypoxanthine produced may diffuse from the muscle and accumulate in the plasma.[70] This may represent a loss of purine nucleotides from the muscle, as the hypoxanthine cannot diffuse back into the muscle. The extent of purine nucleotide loss depends on the nature of the repeated-sprint exercise protocol, specifically the number of sprints performed,[71] the sprint duration,[49] the exercise intensity[72] and the recovery duration between sprints.[23]

Adenine nucleotide degradation occurs as PCr concentration decreases and the rate of ATP hydrolysis exceeds the rate of ATP rephosphorylation. The fact that PCr resynthesis is reported to improve with training,[73] may indicate that trained athletes with a greater RSA may limit the loss of purine nucleotides and the subsequent accumulation of plasma hypoxanthine. Repeated-sprint training has been shown to decrease muscle inosine production rate and plasma hypoxanthine concentration in untrained subjects after a 30-second cycle sprint.[37] Team sport-specific repeated-sprint training has also been reported to reduce the change in plasma hypoxanthine concentration following an exercise protocol involving five, 6-second cycle sprints separated by 24 seconds of passive recovery in elite field-hockey players.[74] However, no significant correlation was reported between changes in plasma hypoxanthine concentration and decline in peak power ($r = -0.32$) or total work produced ($r = 0.12$) in the same group of hockey players performing the same repeated-sprint protocol.[75]

3.6 Summary

It is evident that the relative contribution of anaerobic glycogenolysis is reduced during the performance of subsequent sprints, which is partially explained by an increase in aerobic metabolism. Furthermore, the sprint duration may significantly alter the relative energy system contribution during repeated-sprint exercise. The degradation and resynthesis rate of PCr is related to the performance decrement during subsequent sprints. In addition, the greater the PCr degradation, the greater the time required for complete repletion. A loss of purine nucleotides from the muscle may also occur during repeated-sprint exercise. However, this loss of purine nucleotides may be reduced with specific training.

4. Tests of Repeated-Sprint Ability

The assessment of various physiological and performance parameters during tests of RSA has increased over recent years. Researchers suggest that this information will enhance the understanding of this fitness component for many team sports. Many different exercise protocols have been used to inves-

Table II. Tests of repeated-sprint ability

Study	Exercise mode	Sprint distance (m)	Sprint duration (sec)	No. of reps	Recovery duration (sec)	Recovery mode
Aziz et al.[77]	Run-track	40	~5.5	8	30	Stretching
Balsom et al.[49]	Run-track	15	~2.6	40	30	Passive
	Run-track	30	~4.5	20	30	Passive
	Run-track	40	~6	15	30	Passive
Balsom et al.[80]	Cycle		6	10	30	Passive
Balsom et al.[87]	Cycle		6	10	30	NR
Balsom et al.[88]	Run-treadmill		6	15	24	Passive
Balsom et al.[51]	Cycle		6	5	30	Passive
Bishop et al.[89]	Cycle		6	5	24	Self-selected
Dawson et al.[35]	Cycle		6	5	24	Slow cycle
Dawson et al.[78]	Run-track	40	~5.5	6	24	Walk
Fitzsimons et al.[82]	Run-track	40	~5.8	6	24	Walk
	Cycle		6	6	24	Self-selected
Gaitanos et al.[90]	Run-nm treadmill		6	10	30	Passive
Gaitanos et al.[29]	Cycle		6	10	30	Passive
Hamilton et al.[83]	Run-nm treadmill		6	10	30	Passive
Hautier et al.[79]	Cycle		5	15	25	Passive
Holmyard et al.[84]	Run-nm treadmill		6	10	30	NR
	Run-nm treadmill		6	10	60	NR
Mujika et al.[76]	Run-track	15	~2.3	6	24	NR
Signorile et al.[86]	Cycle		6	8	30	Cycle-60W
Stathis et al.[71]	Cycle		10	4	50	Passive
	Cycle		10	8	50	Passive
Wadley and Le Rossignol[91]	Run-track	20	~3	12	~17	NR
Wragg et al.[92]	Run-track	34.2	~7.5	7	25	Jog

NR = not reported; **reps** = repetitions; **run-track** = over-ground running; **run-treadmill** = running on motorised treadmill; **run-nm treadmill** = running on non-motorised treadmill.

tigate RSA. Differences in exercise mode, sprint duration, number of sprint repetitions, type of recovery, and training status of subjects make it difficult to evaluate and compare between studies. In addition, the large differences between some exercise protocols and the repeated-sprint activity patterns of team sports may question the validity and sport-specific relevance of many of these protocols.

4.1 Sprint Duration

The sprint duration in tests of RSA in the published literature vary from approximately 2.5[49,76] to 10 seconds.[71] The majority of studies, however, have used repeated 5-[77-79] or 6-second[29,35,80-86] sprint protocols (table II). These studies have justified the use of 6-second sprints by suggesting that this may represent the duration of repeated sprints performed in field-based team sports. Although there has been little research investigating the nature of repeated-sprint activity during team-sport competition,[12] time-motion analysis data from sports such as soccer, field hockey and rugby suggest that the mean duration of sprints are commonly shorter than 6 seconds (i.e. mean duration of 2–3 seconds)[1,2,12,14] [see section 1]. However, while the reported mean sprint duration is approximately 2 seconds, the average maximal sprint duration is approximately 4 seconds in elite field-hockey competition.[12] Therefore, a repeated-sprint protocol comprised of sprints that are shorter than the commonly used 6 seconds, may provide a more valid assessment of team-sport repeated-sprint activity.

4.2 Number of Sprint Repetitions

The number of sprint repetitions used in the aforementioned studies range from 2 to 40. The range in the number of sprint repetitions is still considerable (i.e. from 5 to 15) even when the sample of studies is limited to those that selected 5- to 6-second sprint durations (table II). Although a change in performance may be easier to identify when many (i.e. 10–15) sprint repetitions are performed, the relevance to the repeated-sprint activity of team sports may be diminished. Time-motion analysis data from elite field-hockey competition suggest that a maximum of 4–7 repetitions are performed during repeated-sprint exercise bouts.[12] Therefore, using these preliminary data, a protocol involving approximately 6–7 sprints may best represent an intense bout of repeated-sprint activity specific to field-based team sports. Further studies are required to confirm these findings with other field-based team sports during competition. Once these data are obtained, this may allow for a generalisation of RSA tests.

It is quite clear from the literature that the duration and number of repeated sprints has a substantial impact on the change in performance parameters measured throughout the exercise protocol. Balsom et al.[49] clearly demonstrated this point by conducting three repeated-sprint exercise protocols that differed in sprint duration and number of repetitions, but were identical in total sprint distance and recovery duration. Balsom et al.[49] showed that 40, 15m sprints (approximately 2.6 seconds) could be repeated every 30 seconds without any detrimental effects on performance. However, repeated 30m and 40m sprint times (approximately 4.5 and 6 seconds, respectively) significantly increased, with 40m sprint time significantly longer after the third repetition. Therefore, careful consideration should be made when selecting the duration and number of sprints for a test of RSA. As mentioned in section 3, variations in the duration and number of sprints may significantly alter the relative energy system contribution and metabolic demand of the exercise.

4.3 Recovery Duration

The recovery duration may also have a considerable effect on changes in sprint performance during repeated-sprint exercise protocols. Mean power output during 6-second sprints on a non-motorised treadmill can be maintained for ten repetitions when separated by 60 seconds of recovery. However, when the recovery duration is reduced to 30 seconds, only five repetitions can be performed before mean power output is significantly decreased.[84] Similarly, when 15, 40m over-ground sprints (approximately 5.5 seconds) are completed with 30 seconds of passive recovery between each sprint, a performance decrement of approximately 10% is observed.[23] However, when the recovery period is increased to 60 or 120 seconds, the decline in performance is markedly reduced (approximately 3% and 2%, respectively).[23] Holmyard et al.[84] speculated that a reduced recovery time may be due to an incomplete resynthesis of PCr and also greater muscle acidosis. Therefore, if performance on a repeated-sprint test is to be related to team sport-specific RSA, the recovery duration between sprints should reflect that of the sport (i.e. reflect the recovery duration within repeated-sprint bouts and not just averaged over the entire game).

4.4 Type of Recovery

Although the majority of studies that have investigated RSA have used passive rest as the recovery mode (table II), sub-maximal active recovery appears to be beneficial in reducing the decline in repeated-sprint performance.[86,93] Signorile et al.[86] investigated the effect of passive versus active recovery (cycling at 60W) on performance during eight, 6-second cycle sprints. The authors reported significantly greater mean peak power and total work during the 30-second active recovery trial. Ahmaidi et al.[93] also reported that active recovery (5 minutes at a workload corresponding to 32% of $\dot{V}O_{2max}$) increased power outputs at high braking forces during repeated bouts of 6-second cycle sprints. Although Signorile et al.[86] did not collect any biochemical data, they did speculate that the active recovery may have hastened the removal of

lactate from the active muscles and increased its utilisation as a fuel source by neighbouring muscle fibres. Thus, it is possible that low-intensity active recovery, as brief as 30 seconds in duration, may decrease muscle acidosis when performed during repeated-sprint exercise. This is likely to be important as RSA has been negatively associated with changes in blood and muscle pH.[81,94] Furthermore, the vast majority of recovery within repeated-sprint bouts, during elite field-hockey competition, is of an active nature.[12] Therefore, team-sport athletes may be inadvertently minimising muscle acidosis during competition.

4.5 Mode of Exercise

The mode of exercise used to test RSA may also have an influence on performance. Studies investigating RSA have used cycle ergometers, motorised or non-motorised treadmills, or over-ground running as the mode of exercise (table II). Fitzsimons et al.[82] recommend that the exercise mode used should be sport specific as they only reported moderate correlations ($r = 0.62–0.68$; $n = 15$; $p < 0.02$) between decline in sprint performance (percentage decrement in peak power vs run time) and absolute RSA scores (total work vs total run time) when assessing the degree of association between RSA tests performed on a cycle ergometer or during over-ground running. It has even been suggested that the type of cycle ergometer used may influence performance during high-intensity exercise.[79] For example, fatigue during isokinetic cycle exercise is represented by a decrease in force when pedalling frequency is constant.[95] However, fatigue on a friction-loaded cycle ergometer is represented by a decrease in maximal velocity when the friction force is constant.[96] Therefore, it is suggested that the mode of exercise should be specific to the sport (i.e. over-ground running for field-based team sports).

4.6 Training Status

Training status is also likely to influence performance on tests of RSA. Bishop and Spencer[97] showed that elite team-sport athletes obtain significantly greater initial peak power and total work during five repeated 6-second cycle sprints compared with a group of well trained endurance athletes that were matched for $\dot{V}O_{2max}$. However, the decline in peak power throughout the five sprints was significantly greater in the group of team-sport athletes. In contrast, Hamilton et al.[83] reported no difference in decline of peak power throughout a series of ten, 6-second sprints on a non-motorised treadmill, between groups of moderately trained team-sport and endurance-trained subjects. However, a significantly greater decline in mean power output was found in the team-sport group. It must be noted that the endurance-trained group of Hamilton et al.[83] had a significantly greater $\dot{V}O_{2max}$ than the team-sport group. It is important to acknowledge that although team-sport athletes will usually produce a greater peak power, this will be associated with a greater power decrement when compared with endurance athletes. Furthermore, data on duplicate trials of RSA suggest that total work or total sprint time are considerably more reliable than power decrement or sprint time decrement.[82] Therefore, the training status of subjects should be taken into account when interpreting changes in performance during tests of RSA.

4.7 Summary

While RSA has been the subject of many research studies in recent years, changes in performance appears to be heavily reliant on the make-up of the exercise protocols used. It is evident that each of the variables of exercise mode, sprint duration, number of sprint repetitions, recovery duration and type of recovery can significantly affect performance. Furthermore, RSA may also be influenced by the training status of the subjects. Therefore, if tests of RSA are to be relevant to performance in field-based team sports, the test variables need to be specific to the movement patterns. Further research is required to investigate the nature of repeated-sprint activity during field-based team-sport competition.

5. Conclusions

Studies of RSA, specific to field-based team-sport activity, have only appeared in the scientific

literature over the past decade or so. Although various time-motion analysis studies have documented the mean sprint distance and duration to be between 10–20m and 2–3 seconds, respectively, there are a scarcity of data regarding the movement patterns of repeated-sprint activity. Further research is required to document the repeated-sprint activity during field-based team-sport competition, which would further our understanding of this specific fitness component. There are surprisingly little published data regarding the physiological and metabolic requirements of one-off, short-duration sprinting and repeated sprinting (<10 seconds duration), that is relevant to field-based, team-sport performance. During one-off, short-duration sprinting, considerable contributions from both PCr degradation and anaerobic glycolysis provide the vast majority of the total ATP production, resulting in only partly depleted PCr stores. During repeated sprinting, the relative contribution of anaerobic glycogenolysis is reduced when subsequent sprints are performed, which is partially explained by an increase in aerobic metabolism. Furthermore, the degradation and resynthesis rate of PCr is related to the performance decrement and a loss of muscle purine nucleotides may also occur during subsequent sprints. The relative energy system contribution during repeated-sprint exercise may be significantly altered by the exercise protocol (i.e. exercise mode, sprint duration, number of sprint repetitions, recovery duration, type of recovery and training status). Therefore, tests of RSA should be specific to the movement patterns documented during competition, in order to be relevant to performance in field-based team sports.

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Correspondence and offprints: *Matt Spencer*, Western Australian Institute of Sport, PO Box 139, Claremont, WA 6010, Australia.
E-mail: mspencer@wais.org.au