Muscle phosphocreatine repletion following single and repeated short sprint efforts


Phosphocreatine (PCr) repletion following either single (1×6 s, n=7) or repeated (5×6 s, departing every 30 s, n=8) maximal short sprint cycling efforts was measured in separate groups of trained subjects. Muscle biopsies (vastus lateralis) were taken pre-exercise before warming up, and then at 10 s, 30 s and 3 min post-exercise. After the 1×6 s sprint PCr concentration was respectively, 55% (10 s; P<0.01), 69% (30 s; P<0.01) and 90% (3 min; NS) of the pre-exercise value (mean±SD) (81.1±7.4 mmol·kg⁻¹ DM), whereas after the 5×6 s sprints, PCr concentration was, respectively, 27% (10 s; P<0.01), 45% (30 s; P<0.01) and 84% (3 min; P<0.01) of the pre-exercise value (77.1±4.9 mmol·kg⁻¹ DM). PCr concentration was correlated with muscle lactate at 30 s (r=-0.82; P<0.05) and 3 min of recovery (r=-0.94; P<0.01) for the 1×6 s sprint, but not for the 5×6 s sprints. The extent of PCr repletion was significantly greater after the 5×6 s sprints than the 1×6 s sprint between both 10 s and 30 s and 3 min, despite lower PCr levels at 10 s, 30 s and 3 min following the 5×6 s sprints. Full repletion of PCr is likely to take longer after repeated sprints than single short sprints because of a greater degree of PCr depletion, such that replenishment must commence from lower PCr levels rather than because of slower rates of repletion.

Many team and individual sports require short sprint efforts to be repeated regularly over the course of a game. Hirvonen et al. (1) have highlighted the importance of the phosphocreatine (PCr) stores to short-term maximal exercise performance. They demonstrated that in a series of maximal sprints (40-100 m) skeletal muscle PCr stores are severely depleted after 5–7 s, and at this point maximal running speed starts to decline, as glycolysis must then provide the bulk of the ATP to complete the sprint. Further, it was found that better sprinters utilized more of their available PCr stores over the first 5–7 s than did sprinters of slightly lesser ability.

When short sprints must be repeated before PCr resynthesis is complete (as is likely, given the unpredictable nature of such games), then glycolytic energy supply becomes increasingly important (2). Indeed, studies of repeated short sprint (≤6 s) exercise protocols have regularly reported blood lactate levels of 12 mmol·l⁻¹ or more (3–5). These levels are very similar to those commonly associated with sustained sprint efforts of 30 s or more. Consequently, repeated short sprint efforts will also result in the accumulation of H⁺ ions and a fall in muscle pH. Both Spriet et al. (6) and Tesch et al. (7) have suggested that these cellular changes are likely to inhibit the rate of PCr resynthesis post-exercise, since the initial fast phase of PCr resynthesis is an oxygen-dependent process, while the subsequent slow phase may be limited by intramuscular pH changes (8). These observations suggest that PCr repletion following repeated short sprints is likely to be slower than after a single short sprint effort. To the best of the authors’ knowledge, there are no research reports that have studied PCr replenishment following either single or repeated maximal short-term (<10 s) sprint exercise.

The first paper to investigate PCr replenishment post-exercise was that of Hultman et al. (9). In a series of experiments where continuous, aerobic workloads lasting several minutes (i.e. not sprint efforts) were used, it was concluded that ‘the resynthesis of PCr after work is complete within a few minutes’. DiPrampero & Margaria (10) later calculated a half-time of 30–40 s for PCr resynthesis based on the
data of (9). Harris et al. (11) subsequently found that there was a fast and slow component in the time-course of PCr recovery. The half-time for the fast component was 21–22 s, and for the slow component more than 170 s. However, a 9-min exhaustive exercise bout (approximately 300 watts) and sustained isometric muscle contraction (40–55 s), rather than short sprints, were the exercise models used in their study. For both models, PCr repletion was not fully complete after 4 min of recovery. The closest information available for sprint exercise comes from the work of several researchers who have examined PCr replenishment after 30 s maximal sprint efforts.

Norman et al. (12) found there to be little PCr resynthesis after 1 min of recovery following 30 s of sprint cycling. McCartney et al. (13) found that PCr recovered to only 76% of the pre-exercise level after 4 min of recovery following 30 s of maximal cycling; Spriet et al. (6) also found there to be significant, but incomplete, PCr replenishment using the same test protocol. Tesch et al. (7) had subjects perform 30 consecutive maximal knee extensions; after 60 s of recovery PCr stores were approximately 55% of the pre-exercise value. More recently, Bogdanis et al. (14) found that after 30 s of maximal cycling, PCr levels were 64% of the pre-exercise value after 90 s of recovery, but even after 6 min had not fully replenished (85% of the pre-exercise value). In summary, these results suggest that full PCr replenishment following a 30 s maximal sprint effort is not possible within 3 min. While it is likely that PCr utilization will be less in maximal sprint efforts of <10 s than in those of 30 s duration (15), the rate of PCr resynthesis post-exercise may be quite different, as the glycolytic energy contribution to a 30 s sprint will result in a higher concentration of H+ ions and a greater fall in muscle pH which, as mentioned earlier, may inhibit PCr resynthesis.

It is therefore contended that there is a significant gap in the body of knowledge pertaining to PCr replenishment, as no direct measurements of PCr resynthesis following short-term (<10 s) single or repeated sprint efforts have been made, and it is inappropriate to suppose that it will be the same as that found with aerobic exercise, sustained muscle contraction or 30 s sprint efforts. Given the importance of PCr utilization to both single and repeated short sprint performance, and the predominant use of short sprint training by sprinters and team sport players, greater knowledge about PCr recovery after short-sprint exercise would assist in the prescription of more suitable recovery times between training repetitions, which should aid athletic performance. The aim of this project was, therefore, to examine the repletion of PCr following both single (1×6 s) and repeated (5×6 s) short sprint exercise. We hypothesized that PCr repletion would be less complete at the same time-points post-exercise after repeated (5×6 s sprints) compared with a single sprint because of a slower rate of replenishment.

Phosphocreatine repletion after sprinting

Material and methods

Subjects

Seven males, five of whom were state-level volleyballers, and two who were experienced track sprinters, acted as subjects for the single (1×6 s) short sprint condition. Their age and body mass (mean±SD) were, respectively, 26±4 years and 85.9±5.8 kg. Eight different males, comprising six first-grade rugby union players, an experienced beach volleyballer and a touch rugby player, acted as subjects for the repeated (5×6 s) short sprint condition. Their age and body mass (mean±SD) were, respectively, 24±4 years and 88.4±6.7 kg. All subjects gave their informed consent prior to participating, and approval for the study procedures was granted by the Human Rights Committee of The University of Western Australia.

Experimental protocol

Single (1×6 s) sprint. After an earlier familiarization visit, subjects attended the laboratory on the day of testing, having not eaten or consumed caffeinated beverages for the previous 2 h. They were also instructed to avoid intense training on the day prior to the test and not to exercise in the morning before arriving at the laboratory. Before warming up, the subjects lay on an examination couch and had two small incisions made, approximately 10 cm apart and 1 cm long in their right vastus lateralis muscle. One of these was then closed with steristrips while the other was used to procure a resting muscle biopsy sample and then closed. The subjects then performed a warm up, comprising 5 min of submaximal cycling (100 W) and 5 min of static stretching, after which they performed 2–3 practice ‘starts’ on the cycle ergometer before resting for 5 min. After this recovery period the subjects then performed a maximal 1×6 s sprint from a stationary start, remaining seated for the period of the sprint. Strong verbal encouragement was provided to each subject as he performed the sprint. Following the completion of the sprint, further muscle biopsies were taken at 10 s, 30 s and 3 min post-exercise, with the subjects remaining seated on the cycle ergometer for the 10 s and 30 s samples, before transferring to the couch where the final biopsy sample was taken. Toe clips and heel straps were used to secure the feet in the pedals. An air-braked modified racing cycle ergometer (South Australian Sports Institute, Adelaide, Australia) was used for all exercise testing. A gear ratio of 1:7.2 was used on all occasions. The ergometer was integrated with an IBM 486 computer to allow for the collection
Dawson et al.
of data for the calculation of power generated on
each flywheel revolution and work performed during
the sprint (CEDAA data acquisition program; Western
Australian Institute of Sport, Perth, Australia).
Prior to testing, the cycle ergometer was dynamically
calibrated on a mechanical rig (South Australian
Sports Institute) across a range of power outputs
(100–1800 W).

Muscle biopsies. Samples were taken under local anaes-
thesia (2.5 ml, 1% xylocaine), which was applied to
the skin site prior to each of the two incisions. The percu-
taneous needle biopsy technique (16) with suction ap-
plied manually, was used to obtain the samples. The pre-exercise and 3-min post-exercise samples were
taken from one incision and the 10 s and 30 s post-exer-
cise samples from the other, with the biopsy needle
angled differently on each occasion. These procedures
were used to minimize the number of incisions required
in each subject and to reduce any effects on PCR re-
pletion due to microtrauma caused by the biopsy pro-
cedures. Each sample was immersed in liquid nitrogen
within 2–3 s after it was taken, removed from the
needle, and then stored in liquid nitrogen at −80°C un-
til freeze-dried for analysis. An extract of each muscle
sample was then enzymatically assayed for PCR, ATP,
ADP, creatine (Cr) and lactate (La−) according to the
method of Harris et al. (17). On the resting samples
only, the activity of the enzyme citrate synthase (CS)
was determined in μmol · min−1 · g protein−1 using
the method of Shephard & Garland (18). Muscle homoge-
enate protein concentration was determined using the method of Jansson et al. (20). This variable
was measured as a percent decrement recorded (using the method outlined in (5)) for the work (kJ) and power (W)
scores across the repeated short sprint test were, re-
spectively (mean±SD), 13.7±5.1% and 10.5±5.0%.

Statistics
Muscle metabolites were analysed statistically for
changes across time by a one-way ANOVA with re-
peated measures. A Duncan multiple range post-hoc
test (21) was used to determine the location of sig-
nificant differences. A one-tailed independent t-test
was used to analyse the extent of PCR repletion calcu-
lated between 10 s and 30 s and 30 s and 3 min for
the 1×6 s and 5×6 s test conditions. Pearson product
moment correlation coefficients were also calculated
to examine the relationships between exercise per-
formance, enzyme activity and muscle metabolites. Statistical significance was accepted at the P<0.05
level.

Results
The exercise performance scores for the single and
repeated short sprints are presented in Table 1. The
percentage decrement recorded (using the method
outlined in (5)) for the work (kJ) and power (W)
scores across the repeated short sprint test were, re-
spectively (mean±SD), 13.7±5.1% and 10.5±5.0%.

Muscle enzyme activity
For the single (1×6 s) sprint the resting CS activity
(mean±SD; n=6) was 53.5±9.6 μmol · min−1 · g protein−1 (range 43.0–69.7) and for repeated (5×6 s)
sprints (n=5) 58.9±12.4 μmol · min−1 · g protein−1
(range 41.9–73.3).

<table>
<thead>
<tr>
<th>Study 1: 1×6 s</th>
<th>Work (kJ)</th>
<th>Work (J · kg−1)</th>
<th>Peak power (W)</th>
<th>Peak power (W · kg−1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.3±0.6</td>
<td>83.2±11.3</td>
<td>1406±114</td>
<td>16.1±2.2</td>
</tr>
<tr>
<td>2</td>
<td>7.6±0.4</td>
<td>79.5±8.0</td>
<td>1358±86</td>
<td>15.5±1.6</td>
</tr>
<tr>
<td>3</td>
<td>6.9±0.4</td>
<td>71.9±7.0</td>
<td>1278±77</td>
<td>14.6±1.5</td>
</tr>
<tr>
<td>4</td>
<td>5.7±0.4</td>
<td>64.7±5.8</td>
<td>1167±70</td>
<td>13.3±1.3</td>
</tr>
<tr>
<td>5</td>
<td>5.2±0.4</td>
<td>59.1±5.3</td>
<td>1073±85</td>
<td>12.2±1.1</td>
</tr>
<tr>
<td>Total</td>
<td>31.5±1.9</td>
<td>358.5±34.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Muscle metabolites

Single (1×6 s) sprint. These results are presented in Table 2 and Fig. 1. After the 1×6 s sprint PCr was, respectively, 55% (10 s post-exercise; P<0.01), 69% (30 s post-exercise; P<0.01) and 90% (3 min post-exercise; NS) of the pre-exercise value. At 10 s post-exercise ATP had fallen by 16% (P<0.01) from the pre-exercise value, remained significantly lower at 30 s post-exercise but had recovered by 3 min post-exercise (NS). There was a sixfold increase in La− after the sprint (10 s post-exercise; P<0.01), although at 3 min post-exercise this had reduced to be three times the pre-exercise level (P<0.01). The extent of PCr repletion was calculated from the differences between the individual PCr values at 10 s and 30 s, and 30 s and 3 min post-exercise, and were, respectively (mean±SD), 10.77±3.45 mmol · kg⁻¹ DM (10 s–30 s) and 16.40±3.94 mmol · kg⁻¹ DM (30 s–3 min). Work and peak power achieved on the single (1×6 s) sprint were not correlated with any pre-exercise metabolite concentration, but were negatively correlated to CS activity (J · kg⁻¹, r=−0.83; P<0.05 and W · kg⁻¹, r=−0.87; P<0.05). The amount of work performed in the sprint was correlated to 10 s post-exercise La− levels (J · kg⁻¹, r=0.77; P<0.05), as well as the change in La− from pre-exercise to 10 s post-exercise (J · kg⁻¹, r=−0.81; P<0.05). At 30 s and 3 min post-exercise PCr concentration was negatively correlated with La− (r=−0.94; P<0.01). At no time-point was PCr concentration correlated with CS activity.

Repeated (5×6 s) sprints. These results are presented in Table 3 and Fig. 1. After the 5×6 s sprints, PCr was, respectively 27% (10 s post-exercise; P<0.01), 45% (30 s post-exercise; P<0.01) and 84% (3 min post-exercise; P<0.01) of the pre-exercise value. At 10 s post-exercise ATP had declined by 34% (P<0.01) from the pre-exercise value and remained significantly lower (P<0.01) at both 30 s and 3 min post-exercise. There was a 14-fold increase in La− after the sprints (10 s post-exercise; P<0.01), and while it declined significantly (P<0.01) from this level at both 30 s and 3 min post-exercise, it still remained well above the pre-exercise value (P<0.01). The extent (mean±SD) of PCr repletion post-exercise was, respectively, 15.73±4.25 mmol · kg⁻¹ DM (10 s–30 s) and 28.50±4.28 mmol · kg⁻¹ DM (30 s–3 min). t-Test analysis showed that these amounts were significantly greater than for the 1×6 s test condition (10 s–30 s: t=2.22, P=0.025; 30 s–3 min: t=5.10, P=0.0002).

Total work and peak power scores on the repeated (5×6 s) sprint test were not related to CS activity (in contrast to the 1×6 s sprint). At 30 s and 3 min post-exercise no significant relationships were found between the metabolites and/or the CS activity, although the change in PCr from 10 s to 30 s post-exercise approached significance when correlated with CS activity (r=0.85; P=0.068); the small sample size (n=5) for CS activity is a limiting factor in assessing these relationships. In contrast to the 1×6 s sprint, PCr levels and the post-exercise changes in this variable did not correlate with La− at either 30 s or 3 min post-exercise.

![Fig. 1. Muscle phosphocreatine repletion following the 1×6 s and 5×6 s exercise conditions.](image-url)
Dawson et al.

Table 3. Mean (±SD) muscle metabolites (mmol·kg⁻¹ DM) measured before and after the 5×6 s sprints

<table>
<thead>
<tr>
<th></th>
<th>Pre-exercise</th>
<th>10 s post-exercise</th>
<th>30 s post-exercise</th>
<th>3 min post-exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP</td>
<td>22.8±2.7</td>
<td>15.1±2.3k,d</td>
<td>16.7±2.1d</td>
<td>19.8±2.6abc</td>
</tr>
<tr>
<td>ADP</td>
<td>3.0±0.1</td>
<td>4.2±0.3k,c,d</td>
<td>3.4±0.2b,c,d</td>
<td>3.1±0.2bc</td>
</tr>
<tr>
<td>TCr</td>
<td>122.3±7.8</td>
<td>123.3±7.2</td>
<td>123.9±8.5</td>
<td>124.3±8.1</td>
</tr>
<tr>
<td>PCr</td>
<td>77.1±4.9</td>
<td>21.1±5.6k,c,d</td>
<td>34.5±5.2k,b,d</td>
<td>64.5±2.3abc,c</td>
</tr>
<tr>
<td>Cr</td>
<td>45.2±4.5</td>
<td>102.2±6.7k,c,d</td>
<td>89.4±8.9k,b,d</td>
<td>59.8±8.6abc,c</td>
</tr>
<tr>
<td>La⁻</td>
<td>7.7±3.2</td>
<td>103.6±17.5k,d</td>
<td>88.0±19.9k,d</td>
<td>62.5±20.4abc,c</td>
</tr>
</tbody>
</table>

* P<0.01 significantly different from pre-exercise.
† P<0.01 significantly different from 10 s post-exercise.
‡ P<0.01 significantly different from 30 s post-exercise.
§ P<0.01 significantly different from 3 min post-exercise.

Discussion

1×6 s sprint

In response to a 1×6 s sprint, the results show that PCr repletion is approximately 70% complete after 30 s of recovery, and essentially complete after 3 min of recovery, as no significant differences were measured between the pre-exercise and 3 min post-exercise PCr levels. There are no similar experimental data with which to compare these results, as no previous study has investigated the repletion of PCr stores following a single short (<10 s) dynamic sprint. Given the many factors that can affect the rate and degree of PCr repletion, for example free ATP, ADP and Cr (22) plus intracellular pH (11, 23), it does not seem useful to attempt comparisons of the 1×6 s PCr repletion with previous research (eg. 9, 11, 13, 14) as the differences in intensity, duration and mode of exercise would seem sufficient to create a vastly different muscle environment in each case. Muscle metabolism during a 6 s maximal cycling sprint has, however, been investigated previously (15, 24); the values recorded in the present study for the percentage decrease in ATP (16%) and PCr (45%), and increase in muscle La⁻ (sixfold) from resting levels are similar to those reported values.

Performance on the 1×6 s sprint was only found to correlate with CS activity, 10 s post-exercise La⁻ levels and the change in La⁻ from pre-exercise to 10 s post-exercise. The negative correlation between work and power scores and CS activity would seem to reflect the anaerobic power training bias of the subjects and may also indicate a greater proportion of type II muscle fibres, as CS activity would be expected to be higher in athletes with a larger percentage of type I fibres. The CS activity measured here (53.9 μmol·min⁻¹·g protein⁻¹) is less than half that recorded by Green et al. (25) for predominantly endurance trained cyclists (132 μmol·min⁻¹·g protein⁻¹). The correlations between performance measures and La⁻ at 10 s post-exercise are consistent with the energetics of the 6 s sprint, where ATP is resynthesized not only by the rapid degradation of PCr but also via anaerobic glycolysis, therefore resulting in higher levels of La⁻ (1).

Since the repletion of PCr is dependent on oxidative metabolism, faster PCr replenishment may be expected to occur in muscle with elevated aerobic capacity. This has been demonstrated in type I muscle fibres compared to type II muscle fibres (7). The post-exercise PCr values were not related to CS activity at any time-point, in contrast to the findings of Jansson et al. (20) who reported that higher CS activity resulted in greater PCr levels, and lower La⁻ concentrations during recovery from three sets of 30 isokinetic knee extensions. However, after the 1×6 s sprint, PCr was strongly correlated with La⁻ at 30 s and 3 min post-exercise, such that the lower the La⁻ levels, the higher the PCr. An active recovery, which may facilitate a faster removal of La⁻ and H⁺ from the muscle (26), may hasten the repletion of PCr. It should be noted that all subjects in the present studies performed a passive recovery only at the completion of the test; it is possible that further repletion of PCr may have been evident at 30 s and 3 min post-exercise if an active recovery had been used. The lack of relationship between CS activity and the recovery of PCr and removal of La⁻ found here, in contrast to the results of Jansson et al. (20), may be due to differences in exercise mode. The repeated sets of knee extensions performed by the subjects in their study caused a greater disturbance to muscle homeostasis than a single 6 s sprint; ATP and PCr levels declined by 19% and 65% from resting levels in their study, and La⁻ levels rose to 84 mmol·kg⁻¹ DM. The decreases in ATP and PCr levels and increases in La⁻ recorded in the present study are smaller than these values; it may be that CS activity and aerobic metabolism are relatively more important to the recovery of these metabolites at higher degrees of muscle homeostatic disturbance than that caused by a single short sprint.

5×6 s sprints

In response to 5×6 s sprints, departing every 30 s, the results show that PCr repletion is slightly less
than 50% complete after 30 s of recovery, and only approximately 80% complete after 3 min. While other researchers have also studied repeated short sprint exercise (e.g. 3, 27, 28), only Gaitanos et al. (24) have collected pre- and post-exercise muscle metabolite data. However, their experimental protocol incorporated 10×6 s maximal cycling sprints, and they did not measure the repletion of PCr following the end of the exercise test, therefore, no direct comparisons are possible with the present data. The closest comparisons available come from those studies which have measured the repletion of PCr following sustained sprint efforts of 30 s duration; although the 5×6 s sprint protocol used here is different to a continuous sprint, it does produce 30 s of total exercise time and similar post-exercise muscle ATP, PCr and La⁻ values to those measured after 30 s of continuous maximal sprint exercise (13, 14, 15, 29).

McCartney et al. (13) found that PCr levels had recovered to 76% of resting values 4 min after completing a 30 s cycle sprint; similarly, Bogdanis et al. (14) reported that PCr levels were, respectively, 64%, 74% and 86% of resting values after 90 s, 3 min and 6 min of recovery. Further, Bogdanis et al. (29) found PCr to be 74% of resting levels, again after 4 min of recovery from a 30 s cycle sprint. When these results are considered along with the present data, it is clear that full repletion of PCr stores to resting levels takes more than 3 min to be achieved when either a 30 s maximal sprint or several 6 s sprints with only 24 s of recovery separating them are performed. Indeed, the data of Bogdanis et al. (14) suggests that even 6 min of recovery is not sufficient to restore fully the PCr stores after exercise of this nature. However, in each of the aforementioned studies, as well as the present one, a passive recovery was used at the end of the exercise test. As previously mentioned, an active recovery may speed the removal of La⁻ and H⁺ from skeletal muscle (26), which may increase the rate of PCr repletion. Therefore, with an active recovery, PCr resynthesis following repeated short sprints or 30 s sprints may be somewhat quicker than suggested by these results.

The incomplete recovery of the PCr stores observed 3 min after the 5×6 s sprints is not unexpected, given the metabolic state of the muscle at this time-point. While ADP concentration was almost the same as at rest, other factors that can slow PCr repletion were still present. The ATP concentration remained significantly lower than resting levels and La⁻ was still almost nine times greater than the pre-exercise value, indicating that intramuscular pH would have also been decreased. Allsop et al. (30) have reported that intramuscular pH made no significant recovery in the first 10 min of recovery following a 30 s maximal sprint, and was still significantly lower than at rest after 30 min of recovery. Both low ATP concentration and decreased intramuscular pH are thought to slow the recovery of PCr after exercise (6, 8, 22). After 3 min of recovery the initial fast phase of PCr repletion, which is an O₂-dependent process, would be long finished and the subsequent slow phase in progress, which is thought to be limited by the recovery in muscle pH, due to the effect of H⁺ on creatine kinase equilibrium (8).

No significant relationships were found to exist between the variables measured before and after the 5×6 s sprints, in contrast to the 1×6 s sprint. In particular, PCr concentration at 30 s and 3 min post-exercise was not correlated with CS or La⁻, although the amount of PCr recovered from 10 s to 30 s was close to significance when correlated with CS activity. With a larger sample, it is possible that a significant relationship may have been detected. Jansson et al. (20) have reported that the changes in PCr during recovery from three sets of 30 knee extensions were positively correlated with CS activity, demonstrating that the recovery of this metabolite after repeated high intensity exercise efforts is related to the oxidative capacity of the muscle.

1×6 s versus 5×6 s sprints

The repeated short sprints caused a much greater disruption to the energy balance in the muscle than did the single 6 s sprint. Tables 2 and 3 show that after the 5×6 s sprints much larger decreases in ATP and PCr, and much greater increases in ADP and La⁻, were evident than measured after the 1×6 s sprint. Collectively, these are important factors in explaining the incomplete repletion of PCr and ATP observed 3 min after completing the 5×6 s sprints, whereas these metabolites were not significantly different from pre-exercise levels 3 min after the 1×6 s sprint. However, it is evident that the incomplete replenishment of PCr shown at 3 min post-exercise after the 5×6 s sprints is not due to a lower rate of repletion since at all time-points post-exercise the calculated extents of PCr re-synthesis were significantly greater for the 5×6 s sprints than for the single 6 s sprint (15.73 vs. 10.77 mmol · kg⁻¹ DM for 10 s–30 s; and 28.50 vs. 16.40 mmol · kg⁻¹ DM for 30 s–3 min). Therefore, despite a greater homeostatic disturbance to the muscle, the absolute amount of PCr repleted was still greater for the 5×6 s sprints. In particular, these results were achieved at a time when muscle La⁻ was much higher, and therefore muscle pH much lower, than in the 1×6 s sprint. Bogdanis et al. (14) have reported a high correlation (r = −0.94) between muscle pH and La⁻ and pyruvate content, and also observed that PCr levels were 74% of the resting value 3 min after completing a 30 s maximal sprint, despite muscle pH being ~6.7. While it is commonly reported that muscle pH is a limiting factor for the slow phase of
Dawson et al.

PCr recovery (7, 8, 11), it would not seem to preclude considerable (although not complete) replenishment of PCr in the first 3 min of recovery from sprint exercise. This time frame includes the fast phase and some part of the slow phase of PCr recovery.

The amount of PCr depleted by the exercise task may be an important factor in determining the extent and rate of PCr repletion post-exercise. With a greater depletion of PCr, as produced by the 5 × 6 s sprints, the replenishment process must begin from a lower starting point. Harris et al. (11) found that the initial velocity of PCr resynthesis after exercise was 2–3 mmol·kg⁻¹·DM·s⁻¹; Bogdanis et al. (14) calculated a similar rate. However, this rate does not last for long in the fast phase of recovery, where the curve is exponential, as shown by the simple rates calculated for the present data; i.e. between 10 s and 30 s (assuming near linear repletion rates over this period and that 20 s elapsed between the freezing of these samples) the average rate of repletion was 0.54 (1 × 6 s) to 0.79 (5 × 6 s) mmol · kg⁻¹ · DM · s⁻¹. The data of Greenhaff et al. (22), who froze their immediate post-exercise muscle sample within 3–5 s, estimate a rate of ~1 mmol · kg⁻¹ · DM · s⁻¹ across the first 20 s of recovery from intense isometric muscle contraction. With the lesser depletion of PCr produced by the single 6 s sprint, the initial rate of PCr repletion may have been lower and/or been maintained for a shorter time than for the 5 × 6 s sprints, hence resulting in a relatively slower rate of repletion. The extent of PCr replenishment calculated here for the 5 × 6 s sprints from 10 s to 3 min (43.4 mmol · kg⁻¹ · DM) is also very similar to that calculated for the data of Bogdanis et al. (14) across the same time frame (42.1 mmol · kg⁻¹ · DM), demonstrating further that the exercise and recovery metabolism for 5 × 6 s sprints departing every 30 s, is very similar to that reported for continuous 30 s sprints.

In conclusion, the present data show that 30 s after a 6 s sprint, PCr stores have recovered to approximately 70% of their resting concentration; therefore, a considerable PCr contribution to ATP resynthesis for a subsequent sprint could occur. However, after 5 × 6 s sprints, with only 24 s of recovery between each effort, PCr stores recover to only 45% of resting levels, and, while not inconsequential, the PCr contribution to ATP resynthesis for further sprints will be reduced, and more ATP must be provided from glycolytic and/or aerobic energy pathways. Sprint performance will decline as the rate of ATP resynthesis will not be as rapid with less PCr available for energy metabolism. After 3 min of recovery, the replenition of PCr stores is essentially complete when a single sprint is performed, but only approximately 80% complete when repeated sprints are done. A recovery period of longer than 3 min is necessary to restore fully the PCr stores after several short sprints (separated by brief recoveries) have been performed. However, the rate of PCr replenishment after repeated short sprints is not slower than after a single short sprint, as has been suggested previously (20). Full replenishment of PCr is likely to take longer after repeated than single short sprints because of a greater level of PCr depletion, such that replenishment must commence from a lower PCr level, rather than because of a slower rate of repletion.

Acknowledgement

The authors gratefully acknowledge the financial assistance provided by the Australian Sports Commission for this project.

References

Phosphocreatine repletion after sprinting