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Alterations in energy system contribution following upper body sprint interval training

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Abstract

Purpose The primary purpose of this study was to examine the influence of different work-to-rest ratios on relative energy system utilization during short-term upper-body sprint interval training (SIT) protocols.

Methods Forty-two recreationally trained men were randomized into one of three training groups [10 s work bouts with 2 min of rest (10:2, $n = 11$) or 4 min of rest (10:4, $n = 11$), or 30 s work bouts with 4 min of rest (30:4, $n = 10$)] or a control group (CON, $n = 10$). Participants underwent six training sessions over 2 weeks with 4–6 'all-out' sprints. Participants completed an upper body Wingate test (30 s 'all-out' using 0.05 kg kg^{-1} of the participant's body mass) pre- and post-intervention from which oxygen consumption and blood lactate were used to estimate oxidative, glycolytic, and adenosine triphosphate-phosphocreatine (ATP-PCr) energy system provisions. An analysis of covariance was performed on all testing measurements collected at post with the associated pre-values used as covariates.

Results Relative energy contribution ($p = 0.026$) and energy expenditure ($p = 0.019$) of the ATP-PCr energy system were greater in 10:4 (49.9%; 62.1 kJ) compared to CON (43.1%; 47.2 kJ) post training. No significant differences were found between groups in glycolytic or oxidative energy contribution over a 30 s upper body Wingate test.

Conclusion SIT protocols with smaller work-to-rest ratios may enhance ATP-PCr utilization in a 30 s upper body Wingate over a 2-week intervention.

Keywords High-intensity interval training · Wingate test · Upper body training · Performance · Energy expenditure · ATP-PCr

Abbreviations

ATP-PCr	Adenosine triphosphate-phosphocreatine
CON	Control group
EPOC	Excess post-exercise oxygen consumption
MP	Average mean power
PAR-Q+	Physical activity readiness questionnaire
PP	Average peak power
PRR	Perceived readiness rating
SIT	Sprint interval training
TW	Average total work
$V\mathrm{O}_{2peak}$	Peak oxygen uptake
30:4	30 S sprints with 4 min of rest
10:4	10 S sprints with 4 min of rest
10:2	10 S sprints with 2 min of rest

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Introduction

Sprint interval training (SIT) is a form of high-intensity interval training that leads to improvements in aerobic and anaerobic fitness. However, the majority of the existing literature has focused on lower body exercise. This type of lower body high-intensity training has led to alterations in skeletal muscle oxygenation, increased muscle oxidative capacity, and peak oxygen uptake ($V\mathrm{O}_{2peak}$) (Burgomaster et al. 2005; Gillen et al. 2014; Jacobs et al. 2013; Sloth et al. 2013). In addition, SIT has shown to result in enhanced glycolytic enzyme activity and maximum anaerobic power

(Burgomaster et al. 2006; MacDougall et al. 1998). Significant metabolic adaptations and consistent improvements in aerobic and anaerobic fitness from SIT have occurred despite the low-volume training regimens making this a potentially time-efficient strategy for many populations from clinical and sedentary to highly trained athletes (Sloth et al. 2013).

The original SIT protocol involves 4–6 30 s 'all-out' work bouts with 4 min of rest, whereas modified protocols of SIT involve 10–15 s work bouts with 2 or 4 min of rest (Sloth et al. 2013). However, SIT protocols allow for a number of different work-to-rest ratio combinations (Buchheit and Laursen 2013). It has been previously estimated that a single 10 s 'all-out' bout of cycling utilizes aerobic, glycolytic, and ATP-PCr contributions about ~8, ~40 and ~46%, respectively (Girard et al. 2011) while a 30 s 'all-out' bout of cycling utilizes ~19, ~31, and ~50%, respectively (Beneke et al. 2002). Moreover, recovery duration from high-intensity interval exercise has a direct impact on PCr restoration (Forbes et al. 2009), indicating that work-to-rest ratio is an important influential aspect in the training adaptation. In fact, Hazell et al. (2010) has shown that different work-to-rest ratios (i.e. 1:8 vs 1:12 vs 1:24) during lower-body SIT protocols, [original—30 s with 4 min of rest (30:4) and modified—10 s with 2 or 4 min of rest (10:2 and 10:4, respectively)], can cause different adaptations in variables related to aerobic and anaerobic fitness. Specifically, Hazell et al. (2010) observed improvements in 5 km time trial and peak power for all protocols while improvements in VO_{2peak} and mean power were only seen in the 30:4 and 10:4 protocols. Prior studies have attributed SIT adaptations to the initial surge in peak power as opposed to the training volume (i.e. total work completed) (Hazell et al. 2010; Iaia et al. 2015; Lloyd Jones et al. 2017; Zelt et al. 2014). In regard to original and modified protocols matched for work-to-rest ratios, similar SIT adaptations have been seen (Yamagishi and Babraj 2017). Yamagashi and Babraj (2017) utilized a 1:8 work-to-rest ratio over 9 weeks of training and found that both the original and modified (i.e. 15 s with 2 min of rest) protocols similarly improved VO_{2peak} and 10 km time-trial performance during lower body cycling, but only the modified protocol enhanced critical power. Therefore, when work-to-rest ratio is matched, shorter work bouts may induce similar adaptations in performance.

Although sprint training has been vastly studied in lower-body exercise, little is known about the acute and chronic responses utilizing upper-body exercise. Upper-body exercise can be an alternative modality for people that are not able to perform lower-body exercise or those that need to improve upper body conditioning. Most studies have shown that the upper body relies on a greater anaerobic requirement than the lower body during 30 s 'all-out' Wingate tests (Harvey et al. 2015; Julio et al. 2019; Zinner et al. 2016), however there is evidence to show that the aerobic contribution

is greater in the upper than lower body (Price et al. 2014). Zinner et al. (2016) noted that the anaerobic predominance in the arms does not appear to limit their ability to increase aerobic fitness in response to SIT. The authors found that 2 weeks of SIT (4–6 30 s 'all-out' sprints) increased aerobic energy production to a greater extent in the arms than the legs represented by higher VO_{2peak} and greater oxygen consumption during a Wingate test along with a lower O_2 deficit, and improved mechanical efficiency (Zinner et al. 2016).

The adaptation of energy system contribution due to different work-to-rest ratios in upper-body exercise is unknown, particularly after short-term SIT. Thus, the purpose of this investigation was to examine the influence of upper-body SIT protocols with varying work-to-rest ratios on relative and absolute energy system utilization during a 30-s upper-body anaerobic task. We hypothesized that the original SIT protocol (i.e. 30 s all-out efforts interspersed by 4 min passive recovery) would lead to a greater utilization of glycolytic energy provisions over the course of a single anaerobic task, whereas modified SIT protocols would lead to a greater ATP-PCr provision.

Methods

Experimental design and methodology

A randomized, repeated measures design was employed to examine the effectiveness of traditional and modified SIT protocols on the trainability of energy system provisions in the upper body. All participants were asked to complete pre- and post-testing Wingate assessments. Following pre-testing, participants were assigned to one of the three training protocols [30 s: 4 min (30:4), 10 s: 4 min (10:4), 10 s: 2 min (10:2)] or control (CON). The training groups then underwent a 2-week training intervention, while the control group was instructed not to significantly alter their current activity level. All participants were asked to maintain their normal caloric intake habits throughout the course of the investigation and to consume the same pre-testing meal prior to each Wingate test. This investigation was a part of a larger study examining the aerobic and anaerobic performance implications following upper body SIT (La Monica et al. 2019).

Participants

Forty-two recreationally active men completed all testing and training sessions and were included in the final analysis. This study was approved by the University of Central Florida's institutional review board and all participants provided written informed consent. Each participant was asked to complete a physical activity readiness questionnaire (PAR-Q+) to identify any exclusion criteria, including the

inability to perform physical exercise and any chronic illness that requires continuous medical care. All participants were not specifically involved in sprint interval training or upper body cycling but were habitually active with a minimum frequency and duration of 2–3 days per week for at least 30 min per day. In an attempt to eliminate residual fatigue, the participants were asked to refrain from any strenuous physical activity for 48 h prior to testing.

Wingate test

Each participant warmed up for 3–5 min at their own pace interspersed with short (2–5 s) maximal sprints with an unloaded weight cradle of 50 W prior to each testing session. The warm up and Wingate test was performed on an upper body cycle ergometer (891E, Monark Upper Body Ergometer, Vansbro, Sweden) using 0.05 kg kg^{-1} of the participant's body mass. Each participant was told to crank as fast as possible from the command of "GO!" and to sprint maximally for the entire 30 s duration on each test. Each participant was seated with the crank arm lined up with the center of the glenohumeral joint and positioned with arms extended, but not fully locked out during cranking. The researchers instructed participants to crank with minimal upper body rotation, feet planted flat on the floor, and a consistent handgrip position. Peak (the highest running average of 1 s generated during the 30 s sprint) and mean (the average power output attained over the entire 30 s sprint) power and total work completed was recorded using the Monark Software (Monark ATS, Vansbro, Sweden) and was previously reported in La Monica et al. (2019).

Determination of energy systems contribution

Estimates of oxidative, glycolytic, and ATP-PCr energy system contribution were generated through oxygen uptake, blood lactate concentration, and the fast component of excess post-exercise oxygen consumption (EPOC), respectively. Oxygen uptake kinetics and blood lactate concentrations were analyzed using GEDAE-LaB software (Bertuzzi et al. 2016). During the Wingate test, oxygen uptake, via breath-by-breath metabolic gas analyzer (Quark CPET, Cosmed, Rome, Italy), was recorded at rest for 5 min prior to the warm-up and the testing trial with the last 30 s used as the baseline reference. The total oxygen consumption during exercise was calculated as the area under the curve (trapezoidal method). The aerobic contribution was calculated as the oxygen uptake during exercise minus the oxygen uptake at baseline. The ATP-PCr contribution was determined by the fast and slow components of EPOC which was analyzed for 5 min using the biexponential and the monoexponential curves to see which best fits the recovery response (see equation below) (Beneke et al. 2002)

$$\dot{V}O_2(t) = Ae^{t/tA} + Be^{t/tB} + \dot{V}O_{20}$$

A is the amplitude of fast component, B is the amplitude of slow component, tA is the fast component time constant, tB is the slow component time constant, VO_{20} is the VO_2 at rest.

However, the difference between the two models was negligible; therefore, the breath-by-breath values were fitted to a monoexponential curve. The fast component of EPOC was utilized in the present study as a representative of ATP-PCr contribution because it has been previously related to ATP-PCr resynthesis (Haseler et al. 1999; Margaria et al. 1933; Roberts and Morton 1978), since oxidative metabolism plays a role in the PCr resynthesis after an intense effort (McMahon and Jenkins 2002). This methodology has been used by other studies with similar protocol (Beneke et al. 2002; Franchini et al. 2016; Julio et al. 2019). Blood samples were obtained from an ear lobe prior to each Wingate test and 3 and 5 min following each test to determine the peak plasma lactate concentration using a lactate analyzer (Lactate Plus, Nova Biomedical, Waltham, MA). The glycolytic contribution was estimated assuming the accumulation of 1 mmol L^{-1} of blood lactate is equivalent to three milliliters of oxygen per kilogram of body mass (di Prampero and Ferretti 1999). The contribution of each energy system was expressed in absolute terms (kJ), assuming the caloric quotient of 20.9 kJ LO_2^{-1} (Gastin 2001), and as a relative percentage of total metabolic work. Lastly, each system was summed to calculate total metabolic work (in kJ).

Exercise training protocol

As previously reported in La Monica et al. (2019), a SIT program consisting of six training sessions (three sessions per week for 2 weeks) was employed, and each session was separated by at least 48 h. Each training session began with a 4-min warm-up at 50 W, and then four 30-s or 10-s all-out repeated sprints using 0.05 kg kg^{-1} (or 5%) body mass loading (Franchini et al. 2016) interspersed by either 2 or 4 min of passive recovery. Training took place on a modified cycle ergometer (894E, Monark Cycle Ergometer, Vansbro, Sweden) that was placed on adjustable scaffolding for arm cranking to achieve the same position and alignment as during the testing procedures (Fig. 1). Participants were instructed to perform all-out sprints trying to reach and maintain the highest power output for every sprint while strong verbal encouragement was given throughout. Training progression increased one repetition every two training sessions, thus four repetitions during the first two training sessions, five repetitions during the middle two training sessions, and six repetitions for the final two training sessions (Hazell et al. 2010). Performance over the course of training was measured as the average peak power (PP), average mean

Fig. 1 Training ergometer

Table 1 Participant characteristics at baseline

	10:2 ($n=11$)	10:4 ($n=11$)	30:4 ($n=10$)	CON ($n=10$)
Age (year)	22.8 ± 3.2	22.4 ± 3.2	23.1 ± 3.2	24.3 ± 3.3
Height (cm)	176.4 ± 6.9	176.2 ± 8.7	172.9 ± 7.1	174.2 ± 4.7
Body mass (kg)	81.2 ± 9.5	83.6 ± 13.3	73.9 ± 12.1	77.6 ± 11.0

Data are mean ± standard deviation (SD) and represent baseline characteristics of the participants training in the 10 s 2 min group (10:2), 10 s 4 min group (10:4), 30 s 4 min group (30:4), or control group (CON). n = sample size

power (MP), and average total work (TW). Additionally, the maintenance of PP was examined over the course of training and calculated as the average PP relative to the participant's PP from their pre-test Wingate (expressed as a percent). An expression of sessional intensity (exercise density) was calculated using the six session training sum of TW divided by the sum of the inter-set recovery. In addition, participants were asked to provide a perceived readiness rating (PRR) within 15 s prior to each sprint. The PRR is a progressive scale from one to five with one stating "Not at all ready to begin" and five stating "Completely ready to begin." All objective and subjective training performance data including the maintenance of PP and exercise density was previously reported in La Monica et al. (2019).

Statistical analysis

In an effort to increase statistical power due to the small sample size, a one-way analysis of covariance was performed on all measurements collected at post-testing to identify differences between groups (10:2 vs. 10:4 vs. 30:4 vs. CON) for energy system utilization (oxidative vs. glycolytic vs. ATP-PCr). The associated pre-testing values of absolute and relative energy system contribution (oxidative, glycolytic, and ATP-PCr) during the Wingate were used as a covariate to account for the influence of initial score variances on training outcomes. In other words, the adjusted pre-test mean standardizes all groups at the same baseline

value to examine differences due to the training intervention. Following a significant F ratio, post hoc Bonferroni pairwise comparisons were used to examine the differences among the groups. With less than 6% of the energy system contribution data missing (Tabachnick and Fidell 2013), multivariate imputation using partial least squares method was performed via JMP Pro 12 (Cary, NC, USA) on energy system contribution to account for the missing breath-by-breath values within the exercise post oxygen consumption measurements. For effect size, the partial eta squared statistic was calculated with an interpretation of 0.01, 0.06, and 0.14 as small, medium, and large effects, respectively. Cohen's d effect size was calculated on all pre- and post-test scores with the interpretation of small (0.2), moderate (0.5), and large (0.8) effects (Cohen 1988). Significance was established at an alpha of $p < 0.05$. All data were reported as mean ± SD. Additionally, post-test measures were reported as mean ± 95% confidence intervals to indicate meaningful changes as compared with covariate adjusted pre-test values. Statistical software (IBM SPSS Statistics for Windows, Version 23.0; Armonk, NY: IBM Corp) was used for all analyses.

Results

Participant's characteristics at baseline are shown in Table 1. As previously reported in La Monica et al. (2019), $V\text{O}_{2\text{peak}}$ significantly increased after the 2-week intervention in 30:4, remained similar in both 10:4 and 10:2, and significantly decreased in CON. In addition, peak and mean power, and total work accomplished during the Wingate test was reportedly not significantly different between groups (30:4 vs. 10:4 vs. 10:2 vs. CON) after the 2-week intervention (La Monica et al. 2019).

Energy system contribution

In regard to relative energy system contribution, significant differences in post-test ATP-PCr were observed between

groups when controlling for pre-test values ($F_{3,37} = 3.393$, $p = 0.028$, $\eta^2 = 0.216$; adjusted pre-test mean = 43.5%). Post hoc analyses showed that the post-test ATP-PCr values in the 10:4 group were greater than CON ($p = 0.026$). No further differences existed between groups (10:2 vs. CON, $p = 0.238$; 30:4 vs. CON, $p = 1.000$; 10:2 vs. 30:4, $p = 1.000$; 10:2 vs. 10:4, $p = 1.000$; 30:4 vs 10:4, $p = 0.405$). No significant differences were observed in post-test oxidative ($F_{3,37} = 1.485$, $p = 0.235$, $\eta^2 = 0.107$; adjusted pre-test mean = 9.9%) or glycolytic ($F_{3,37} = 2.084$, $p = 0.119$, $\eta^2 = 0.145$; adjusted pre-test mean = 46.6%) system utilization between groups (Fig. 2 and Table 2).

In regard to absolute energy system contribution, significant differences in post-test ATP-PCr were observed between groups when controlling for pre-test values ($F_{3,37} = 3.580$, $p = 0.023$, $\eta^2 = 0.225$; adjusted pre-test mean = 50.5 kJ). Post hoc analyses showed that the post-test ATP-PCr values in the 10:4 group were greater than CON ($p = 0.019$). No further differences existed between groups (10:2 vs. CON, $p = 0.404$; 30:4 vs. CON, $p = 1.000$; 10:2 vs. 30:4, $p = 1.000$; 10:2 vs. 10:4, $p = 1.000$; 30:4 vs 10:4, $p = 0.241$).

No significant differences were observed in post-test oxidative ($F_{3,37} = 0.952$, $p = 0.426$, $\eta^2 = 0.072$; adjusted pre-test mean = 11.2 kJ) or glycolytic ($F_{3,37} = 0.141$, $p = 0.935$, $\eta^2 = 0.011$; adjusted pre-test mean = 53.5 kJ) system utilization between groups (Fig. 3 and Table 3). No significant differences were observed in post-test total metabolic work between groups ($F_{3,37} = 1.275$, $p = 0.297$, $\eta^2 = 0.094$; adjusted pre-test mean = 115.3 kJ).

Discussion

This appears to be the first investigation comparing the influence of different work-to-rest ratios during short-term upper body SIT on energy system contribution. Following a 2-week intervention, relative energy contribution, and absolute energy expenditure derived from the ATP-PCr system was greater in the 10:4 group than the CON group with no differences in the 10:2 or 30:4 groups compared to CON. Additionally, the 2-week intervention did not alter glycolytic or oxidative energy contribution between groups. In light of
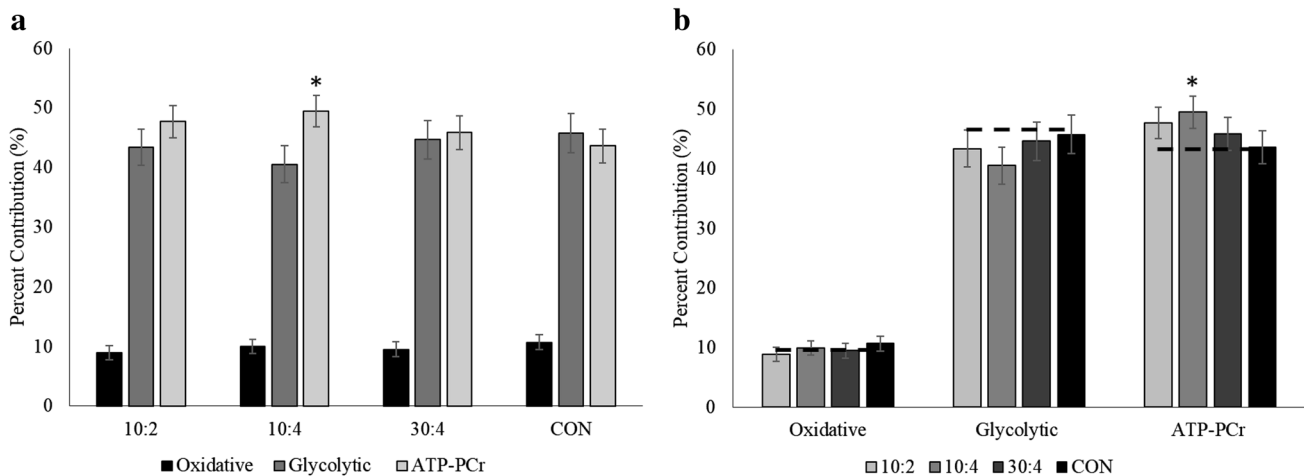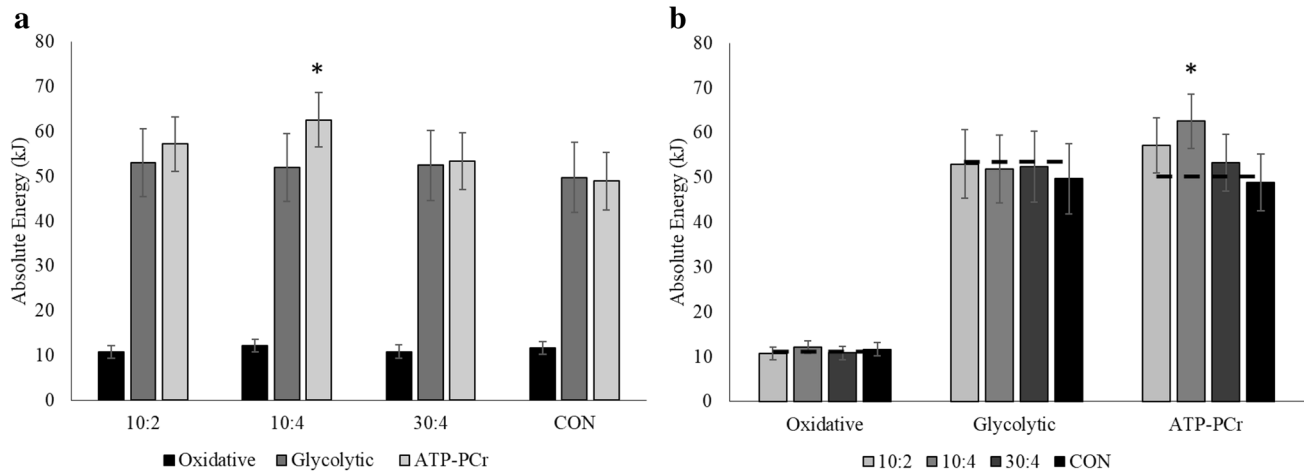
Fig. 2 Relative energy system contribution during the 30 s Wingate test post training. Mean posttest values (±95% confidence interval) adjusted for initial differences in pretest values (dashed line) for 10 s work 2 min rest group (10:2), 10 s work 4 min rest group (10:4), 30 s work 4 min rest group (30:4), and control group (CON): **a** relative contribution between energy systems; **b** relative energy contribution between groups (oxidative; covariate: adjusted pretest mean = 9.9%; glycolytic: covariate: adjusted pretest mean = 46.6%, ATP-PCr; covariate: adjusted pretest mean = 43.5%). *Significantly different from CON ($p < 0.05$)

Table 2 Relative energy system contribution during the 30 s Wingate test before (pre) and after (post) training

	10:2 ($n = 11$)			10:4 ($n = 11$)			30:4 ($n = 10$)			CON ($n = 10$)		
	Pre	Post	d	Pre	Post	d	Pre	Post	d	Pre	Post	d
Oxidative (%)	9.7 ± 3.7	8.9 ± 2.0	−0.27	10.1 ± 2.4	10.0 ± 2.4	−0.04	9.8 ± 3.3	9.5 ± 2.1	−0.11	10.2 ± 3.6	10.8 ± 2.3	0.2
Glycolytic (%)	46.9 ± 6.6	43.5 ± 6.0	−0.54	45.1 ± 6.9	40.1 ± 5.7	−0.79	46.8 ± 6.0	44.7 ± 4.5	−0.4	47.6 ± 5.7	46.1 ± 5.0	−0.28
ATP−PCr (%)	43.4 ± 9.7	47.7 ± 6.2	0.53	44.8 ± 7.9	49.9 ± 5.1	0.77	43.4 ± 6.1	45.8 ± 2.9	0.5	42.3 ± 4.7	43.1 ± 5.3	0.16

Data are mean ± standard deviation (SD) representing raw data measured before and after training in the 10 s 2 min group (10:2), 10 s 4 min group (10:4), 30 s 4 min group (30:4), and control group (CON). n = sample size

Fig. 3 Absolute energy system contribution during the 30 s Wingate test post training. Mean posttest values ($\pm 95\%$ confidence interval) adjusted for initial differences in pretest values (dashed line) for 10 s work 2 min rest group (10:2), 10 s work 4 min rest group (10:4), 30 s work 4 min rest group (30:4), and control group (CON): **a** absolute contribution between energy systems; **b** absolute energy contribution between groups (oxidative; covariate: adjusted pretest mean = 11.2 kJ; glycolytic: covariate: adjusted pretest mean = 53.5 kJ; ATP-PCr; covariate: adjusted pretest mean = 50.5 kJ). *Significantly different from CON ($p < 0.05$)

these results, a previous investigation did not observe any differences in anaerobic performance between groups (La Monica et al. 2019).

During high intensity efforts, the balance between energy stored and expended is limited by PCr storage and resynthesis, respectively (Gastin 2001; Girard et al. 2011). Acutely, lower body 'all-out' cycling can reduce PCr concentrations by ~ 55% after 10 s (Bogdanis et al. 1998) or 55–83% after 30 s (Bogdanis et al. 1996; Parra et al. 2000) along with a drop in pH which is compounded after subsequent sprints and may inhibit glycolytic enzymes (Bogdanis et al. 1996; Cairns 2006; Mendez-Villanueva et al. 2012). A significant amount of passive rest (i.e. 6 min) may resynthesize the majority of PCr (85% of baseline values) and ATP (~ 93% of baseline values) consumed, but H^+ concentration can still be well above baseline values ($144 \pm 32\%$) (Mendez-Villanueva et al. 2012).

PCr resynthesis is complex and dependent initially (i.e. fast component) on oxygen availability with the later stages (i.e. slow component) occurring in response to intramuscular acidosis (McMahon and Jenkins 2002). Therefore, in the present study presumably the 10 s sprint protocols generated a smaller reduction in PCr than the 30 s sprint protocol while the 10:4 protocol also had a greater PCr replenishment than the 10:2 protocol. As a result, the 10:4 group may have had the most optimal work-to-rest ratio to allow for a greater utilization of the ATP-PCr system compared to the other training groups. This may support our main finding that the ATP-PCr contribution was significantly greater in the 10:4 group as compared to the CON group after 2-weeks of training due to its role in energy provision during sprinting as demonstrated by acute studies.

Participants within the 30:4 group had the largest work-to-rest ratio with moderate exercise density (La Monica et al. 2019). Although performance data in upper body sprint interval training is scarce within the literature, Zinner et al. (2016) reported similar average peak power output (507 ± 87 W) and mean power output (356 ± 67 W) compared to our 30:4 group in a comparable population over seven training sessions composed of 4–6 30 s sprints. Based on the performance over the 2-week training period, both 10 s protocols had higher average peak (10:2, 638 ± 147 W vs. 10:4, 611 ± 113 W vs. 30:4, 482 ± 73 W) and mean power (10:2, 495 ± 85 W vs. 10:4, 488 ± 73 W vs. 30:4, 300 ± 38 W) and a greater ability to recover (i.e. perceived readiness rating values) compared to the 30:4 group (La Monica et al. 2019). This would suggest that the quality (peak and mean power) of the sprint was optimized during the 10 s protocols. Further, the 10:4 protocol had the lowest, while the 10:2 protocol had the greatest exercise density, indicating the least and greatest amount of sessional intensity, respectively (La Monica et al. 2019). Therefore, the associated 'lighter' metabolic stress in the 10:4 protocol may have allowed for greater resynthesis of PCr and greater removal of blood lactate during training, thereby prioritizing and increasing ATP-PCr utilization.

In a companion study, La Monica et al. (2019) observed that VO_{2peak} was significantly improved in 30:4, maintained in both 10 s protocols, and significantly decreased in CON. While the current investigation verified an increase in ATP-PCr contribution after 2-weeks in the 10:4 protocol compared to CON, there were no differences in performance related to anaerobic fitness (peak power, mean power or work done) (La Monica et al. 2019). This may suggest that

Table 3 Absolute energy system contributions during the 30 s Wingate test before (pre) and after (post) training

	10:2 (n=11)			10:4 (n=11)			30:4 (n=10)			CON (n=10)		
	Pre	Post	d	Pre	Post	d	Pre	Post	d	Pre	Post	d
Oxidative (kJ)	11.6±2.9	11.0±2.5	−0.22	11.1±2.3	12.2±2.5	0.46	10.8±3.0	10.6±2.0	−0.08	11.3±4.1	11.7±3.3	0.11
Glycolytic (kJ)	57.2±8.6	55.4±19.3	−0.12	50.3±11.1	49.8±12.1	−0.04	52.5±9.5	51.7±12.9	−0.07	54.1±14.6	50.1±10.0	−0.32
ATP-PCr (kJ)	54.8±17.6	59.8±14.9	0.31	49.8±11.1	62.1±14.1	0.97	49.2±11.7	52.6±10.5	0.31	47.8±12.8	47.2±11.1	−0.05

Data are mean±standard deviation (SD) representing raw data measured before and after training in the 10 s 2 min group (10:2), 10 s 4 min group (10:4), 30 s 4 min group (30:4), and control group (CON). n=sample size

ATP-PCr contribution precedes improvements in anaerobic performance and may need a longer training intervention to express enhanced anaerobic characteristics. Alternatively, the 10:4 group may have seen an increase in anaerobic performance if a 10 s all-out sprint test was applied rather than the 30 s Wingate test since it relies on a higher ATP-PCr contribution. Recently, De Poli et al. (2019) reported similar findings after creatine supplementation where there was an increase in the proportion of ATP-PCr in the absence of performance improvement during a time limit test at $115\% \dot{V}O_{2max}$ while using the same method to quantify energy system contribution (EPOC and lactate) as the current investigation. Thus, we hypothesize that the similarities in physical performance despite differences in ATP-PCr contribution may be related to adjustments in other fatigue parameters over the course of a training session, such as decreased motor neuron activity (Mendez-Villanueva et al. 2012), or lowered calcium release (Allen et al. 2008). Mendez-Villanueva et al. (2012) observed a persistent decrease in electromyography amplitude along with changes in power output over fatiguing maximal contractions leading to a reduction in total work. A reduction in action potential amplitude, an accumulation of inorganic phosphate due to the breakdown of PCr, and mechanical stress may disrupt T-tubule-sarcoplasmic reticulum interaction, thereby lowering calcium release and extending recovery (Allen et al. 2008).

Therefore, based upon performance and intensity metrics, the 10:4 protocol appeared to be ideal for developing energy yield from the ATP-PCr system while maintaining maximal aerobic fitness. Since the Wingate test, which was utilized as a standardized method to quantify energy system contribution in this study, has a high glycolytic demand (Beneke et al. 2002; Franchini et al. 2016; Julio et al. 2019), we can hypothesize that shorter work bouts (< 10 s 'all-out') or a greater resistance during training than currently utilized may be needed to elicit improvements in performance (peak and mean power and total work) since shorter protocols have higher ATP-PCr contribution (Gaitanos et al. 1993; Gastin 2001). Perhaps longer-term training interventions with larger work-to-rest ratios (i.e. 1:30, 1:36, 1:42, etc.) are needed to elicit alterations in glycolytic and oxidative energy system utilization.

As discussed in a review by McMahon and Jenkins (2002) the factors affecting the rate of phosphocreatine resynthesis are not simple, with both fast and slow components influenced by muscle pH and adenosine diphosphate concentrations. While large variations exist between methodologies, bias may be minimized in the present study through use of the same measurement technique pre- and post-training, and the evaluation of differences at post being analyzed relative to a standard baseline. Measurement of PCr stores in future studies would be useful to elucidate if this protocol

yielded an increase in initial PCr concentrations or if the capacity to replenish PCr was improved after the 2-week training program.

Conclusions

This investigation offers a novel examination of the energy system contributions of the upper body with short-term original and modified SIT and is the first study to indicate that a smaller work-to-rest ratio SIT protocol may enhance ATP-PCr utilization during an anaerobic exercise bout without changes in anaerobic performance. High-intensity intermittent exercise involving the upper body musculature may benefit individuals participating in activities, such as judo, rock, climbing, rugby league, and wrestling (García-Pallarés et al. 2011; Garrett and Kirkendall 2000; Horswill et al. 1992; Koukoubis et al. 1995; Lovell et al. 2013). Thus, the work-to-rest ratio elicited in the 10:4 protocol may be applied to athletes that need to improve energy generated by the ATP-PCr system while maintaining maximal aerobic fitness. The training protocols implemented in this study may also suggest a minimal dose response for alterations in energy system contribution.

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Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest to report.

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