

Physiological responses to shuttle repeated-sprint running

Running title: Shuttle repeated sprints

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ABSTRACT

This study investigated the influence of 180° changes of direction during a repeated-sprint running test on performance, cardiorespiratory variables, muscle deoxygenation and post-exercise blood lactate ([La]_b) levels. Thirteen team sport-players (22±3 yr) performed 6 repeated maximal sprints with (RSS, 6x[2x12.5m]) or without (RS, 6x25m) changes of direction. Best and mean running time, percentage speed decrement (%Dec), pulmonary oxygen uptake ($\dot{V}O_2$), vastus lateralis deoxygenation (Hb_{diff}) and [La]_b were calculated for each condition. Best and mean times for both protocols were largely correlated ($r = 0.63$ and $r = 0.78$, respectively), and were '*almost certainly*' higher for RSS compared to RS (e.g., 5.30±0.17 vs. 4.09±0.17 s for mean time, with the qualitative analysis revealing a 100% chance of RSS time to be greater than RS). In contrast, %Dec was '*possibly*' lower for RSS (2.6±1.2 vs. 3.2±1.3 %, with a 79% chance of a real difference). Compared to RS, $\dot{V}O_2$ (40.4±4.2 vs. 38.9±3.8 mL.min⁻¹.kg⁻¹, with a 90% chance of a real difference) and [La]_b (10.0±1.7 vs. 9.3±2.4 mmol.L⁻¹, with a 70% chance of a real difference) were '*possibly*' higher. Conversely, there was no differences in Hb_{diff} (11.5±3.2 vs. 10.9±3.0 μM, with the comparison rated as '*unclear*'). To conclude, the present results suggest that the ability to repeat sprints can be considered as a general quality. They also suggest that repeated shuttle sprints might be an effective training practice for eliciting a greater systemic physiological load, but perhaps not a greater loading of the vastus lateralis.

Key-Words: repeated-sprint ability; change of direction; near infrared spectroscopy; agility.

INTRODUCTION

Time-motion analysis of team and intermittent sports has revealed that decisive moments in a match are often preceded by short, high-intensity sprints in the range of 10–30 m or 2–4 s [38]. The ability to repeat these high-intensity, short-duration efforts following short recovery periods, has been termed ‘repeated sprint ability’ (RSA), and has been shown to be a good predictor of match-related physical performance in top-level professional soccer players [36]. Thus, RSA is considered an important fitness component for team-sport athletes [24, 38]. As change of direction ability has also been recognized as a strong prerequisite for successful participation in team sports [5], 180° turns have also been introduced in RSA tests (e.g., [12-15, 28, 34]) and during repeated sprint training sessions [4, 11, 12].

To date however, there has been no comparison of RSA tests performed with or without changes of direction, and it is not known whether these tests evaluate different performance qualities. Because their biomechanical and neural determinants are different, previous research has indicated that straight running speed and change of direction ability are distinct physical qualities [5, 37, 43]. However, given the complexity of repeated-sprint determinants [24, 38], it is not evident that results reported for single sprints are applicable to repeated sprints. Several causes of fatigue during multiple sprint work have been suggested, including neuromuscular adjustments [32], a lack of available phosphocreatine (PCr) and accumulation of muscles byproducts (ion H^+ and intracellular Pi) [24, 25]. However, whether changing of direction is likely to affect the respective influences of these factors on fatigue development is not known.

Knowledge about the acute physiological responses to these specific protocols has also important implications for team sport-specific training prescriptions [40], where the improvement of both central (i.e., cardiopulmonary function) and peripheral (e.g., O_2

extraction and utilization, PCr recovery and muscle buffer capacity) determinants of high-intensity intermittent exercise capacity have to be considered [25]. Repeated straight-line sprint running in the field [9] or on a non-motorized treadmill [8] has been shown to elicit a high percentage of maximal $\dot{V} O_2$ and high blood lactate levels (i.e. $> 10 \text{ mmol.L}^{-1}$) [8, 9], while inducing a marked muscle deoxygenation [8], suggestive of an important reliance on peripheral O_2 extraction [19]. However, the acute physiological responses to similar sequences including changes of direction still have not been described. Data obtained during graded aerobic field tests suggest that the introduction of changes of direction increases post-exercise blood lactate concentration, without changes in peak $\dot{V} O_2$ [1]. Since each change of direction requires a braking force followed by a propulsive force, the importance of the force and endurance capabilities of the leg muscles is also likely to be increased as the number of turns increase [5]. Consequently, compared with straight line sprints, if changing of direction during repeated shuttle sprints was effective to increase the aerobic demand of the lower limbs [5], it would be intuitive to observe a greater muscle deoxygenation, with the consequence of an increased fatigue development [8]. However, as running speed (and muscle work) is lower during shuttle runs (because of the acceleration and deceleration phases), lower muscle deoxygenation levels and a reduced percentage of speed decrement [33] could also be expected.

The purpose of this study was therefore to compare sprint performance and the physiologic responses to two commonly used repeated-sprint running tests/training sequences composed of either shuttle or straight-line runs. We hypothesized that repeated sprints performed with and without changes of direction would evaluate different performance abilities and that there would not be large correlations between them. We also expected to observe different physiological responses to the two type of protocols, as reflected by

different levels of either systemic (cardiorespiratory and post-exercise blood lactate responses) and peripheral (muscle deoxygenation) stress.

METHODS

Subjects. We recruited thirteen, well-trained, team-sport players (22 ± 3 y, 75 ± 5 kg, 179 ± 5 cm) for this study. All players were involved (6.4 ± 3.2 h·wk⁻¹) in soccer, handball or basketball and had no history or clinical signs of cardiovascular or pulmonary diseases. The maximal running speed reached at the end of the 30-15 Intermittent Test (30-15_{IFT} [6, 7], V_{IFT}), as well as peak oxygen uptake ($\dot{V} O_{2peak}$) and maximal heart rate (HR_{max}) were 19.6 ± 0.7 km·h⁻¹, 50.2 ± 7.4 mL·min⁻¹·kg⁻¹ and 184 ± 9 b·min⁻¹, respectively. Participants were not currently taking prescribed medications and presented with normal blood pressure levels and electrocardiographic patterns. The study was performed in accordance with the ethical standards of the IJSM [26] and conformed to the recommendations of the Declaration of Helsinki. Participants gave voluntary written consent to participate in the experiment.

Experimental overview. On two distinct occasions (separated by at least 48 h) participants performed, in a randomized order, two sets of six repeated maximal 25-m sprints, departing every 25 s, either with (repeated shuttle sprints, RSS) or without (repeated sprints, RS) 180° shuttle runs. Prior to the study, all subjects were familiarized with both repeated-sprint protocols. For all tests, respiratory gas exchange, heart rate, and hemoglobin variables of the vastus lateralis (near-infrared spectroscopy, NIRS) were recorded. Participants indicated their rating of perceived exertion (RPE, 0-10 Borg's scale) immediately at the end of each test. All tests were performed on an indoor synthetic track where ambient temperature ranged from 18 to 22°C. Subjects were told not to perform exercise on the day prior to a test, and to consume their last (caffeine free) meal at least 3 h before the scheduled test time.

Repeated-sprint ability tests. All tests were preceded by a supervised and standardized warm-up consisting of 5 min of running at 45% of V_{IFT} , 3 min of athletic drills (e.g., skipping, high knee runs), 5 short bursts of progressive accelerations on the track, and 2 maximal 25- (or 2x12.5-) m sprints interspersed by 2 min of passive recovery. Repeated-sprint tests began two min after the last maximal sprint. The best maximal single sprint time was used as the players' reference performance. Subjects performed six repetitions of maximal 25-m sprints, either with (6 x [2 x 12.5 m], RSS) or without (6 x 25m, RS) change of direction, departing every 25 s (Wireless Timing-Radio Controlled, Brower Timing System, Colorado, USA). Even though 180° turns might be considered as extreme compared to the changes of direction commonly observed in team-sports [5], we choose to use shuttle-runs to be consistent with the literature [1]. Between each sprint, subjects performed an active running recovery ($2.0 \text{ m}\cdot\text{s}^{-1}$, [39]). Three seconds prior to the commencement of each sprint, subjects were asked to assume the ready position and await the start signal. During recovery, audio feedback (i.e., time countdown) was given to the subjects so that they maintained the required running speed. Participants were instructed to complete all sprints as fast as possible, and strong verbal encouragement was provided to each subject during all sprints. These tests were adapted from previous sprint running tests [12-15, 28, 34] which have been shown to be reliable (CV = 0.7%, 95% CI [0.5 – 1.2] for total straight-line sprints time [39] or CV = 0.8%, 90% CI [0.6 – 1.0] for mean shuttle-sprints time [28]) and to provide valid estimates of RSA in the field [13, 28]. Three scores were calculated for the RSA tests: the best sprint time ($RS(S)_b$; s), the mean sprint time ($RS(S)_m$; s) and the percent sprint decrement ($RS(S)_{\%Dec}$; %), calculated as follows: $100 - (\text{mean time}/\text{best time} \times 100)$; where the ideal time = $6 \times RS(S)_b$ [8].

Cardiorespiratory measures. Respiratory gas exchange and heart rate were measured using an automated, portable, breath-by-breath system (K4b², Cosmed, Rome, Italy) during all tests

[31]. Before each test, the O₂ and CO₂ analysis systems were calibrated as recommended by the manufacturer. Data were subsequently filtered and averaged on a 1-s basis for better synchronization with the NIRS data. Minute ventilation (\dot{V}_E), O₂ uptake ($\dot{V}O_2$) and CO₂ production ($\dot{V}CO_2$) data were then averaged for the overall repeated sequence for each subject, so that total analyzed time was 6 x 25 = 150 s (6 x (\approx 4- to 5-s sprint + the following \approx 20-s recovery periods)).

Near-infrared spectroscopy measurements. The portable NIRS apparatus (Portamon, Artinis, Medical System, Zetten, The Netherlands) used in this study is a 2-wavelength continuous wave system, which simultaneously uses the modified Beer–Lambert and spatially resolved spectroscopy methods. The procedure used to collect data was the same as described previously with a similar portable device [10]. Changes in tissue oxyhemoglobin (HbO₂), deoxyhemoglobin (HHb) and total hemoglobin (tHb) were measured using the differences in absorption characteristics of light at 750 and 850 nm. The total saturation index (TSI) and the difference between HbO₂ and HHb ($Hb_{Diff} = (HbO_2 - HHb)/2$) were also calculated. Given the uncertainty of the photon pathlength at rest and during exercise, we used an arbitrary value for the differential pathlength of 3.83; thus values for TSI, HbO₂, HHb, tHb and Hb_{diff} are reported as a change from baseline (30-s averaging before each test) in micromolar units (μ M, HbO₂, HHb, tHb and Hb_{diff}) [20] or percentage (% , TSI). The HHb signal can be regarded as being essentially blood volume insensitive during exercise [18]; thus it was assumed to be a reliable estimator of changes in intramuscular oxygenation status and O₂ extraction in the field of interrogation [18, 20]. Moreover, the use of Hb_{diff} was also considered, since it has been shown to be a relevant alternative to HHb when tHb is not constant; muscle oxygen consumption estimated from Hb_{diff} being more reliable than values estimated from the other NIRS variables [41]. Even though data on the reliability of NIRS-derived indices during

running is still lacking, the technique appears to be sensitive to muscular activity, since small differences in muscular activity (i.e., active compared to passive recovery) during repeated sprint running have been reported to induce significant differences in muscle oxygenation [8]. Moreover, we paid great attention to probe replacement. With the portable device used, firmly attached to the body, there are no moving optical fibers that could cause signal disturbance. NIRS probes were positioned on the vastus lateralis muscle of the leg used when changing direction, approximately 10 cm from the knee joint and along the vertical axis of the thigh. A surgical marker was used to mark the probe placement for accurate repositioning. The probe and the skin were covered with black tape to prevent contamination from ambient light. Skinfold thickness at the site of application of the NIRS probe was determined before the testing sessions using Harpenden skinfold calipers (British Indicators Ltd, UK). The calculated value of skin and subcutaneous tissue thickness was less than half the distance between the source and the detector. During all tests, the NIRS system was connected to a personal computer by Bluetooth for data acquisition (10 Hz), analog-to-digital conversion, and subsequent analysis. Since NIRS measures enable high time-resolution measurements, much more defined than that of pulmonary $\dot{V} O_2$, data were filtered and averaged on 1-s basis. Finally, as for pulmonary gases, data from the entire 150-s repeated sprint sequence were averaged to yield a single value for each subject.

Blood lactate measurement. Three minutes after the end of each repeated-sprint test, a fingertip blood sample (5 μ L) was collected and blood lactate concentration $[La]_b$ was determined (Lactate Pro, Arkray Inc, Japan). The accuracy of the analyzer was checked before each test using standards. The suitability and reproducibility of this analyzer has been previously established throughout the physiological range of 1.0 to 18.0 mmol.L⁻¹ [35].

Statistical analyses

Statistical analyses were carried out using a Minitab 14.1 Software (Minitab Inc., Paris, France) and data are presented as means and standard deviation (SD). Relative differences (%) in performance are expressed with 90% confidence intervals (90% CI). The distribution of each variable was examined with the Shapiro-Wilk normality test. Homogeneity of variance was verified by a Levene test. Data were assessed for clinical significance using an approach based on the magnitudes of differences [27]. The standardized difference or effect size (ES, 90% CI) of differences in performance, cardiorespiratory, $[La]_b$ and NIRS parameters between the RS and RSS conditions were calculated using the pooled standard deviation [17]. Threshold values for Cohen ES statistics were >0.2-0.5 (small), >0.5-0.8 (moderate) and >0.8 (large). For between-condition comparisons, the chance that the true (unknown) values for RSS were *higher* (i.e., greater than the smallest practically important difference, or the smallest worthwhile [difference] change, SWC [0.2 multiplied by the between-subject standard deviation, based on Cohen's Effect Size principle [17]]), *unclear* or *lower* were calculated. Quantitative chances of *higher* or *lower* values were assessed qualitatively as follows: <1%, *almost certainly not*; 1-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, *possible*; 75-95%, *likely*; 95-99, *very likely*; >99%, *almost certain*. If the chance of having *higher* or *lower* values were both >5%, the true difference was assessed as *unclear* [27]. Linear regressions with Pearson's coefficients were also used to establish the respective relationships between performance and cardiorespiratory parameters for both trials. The following criteria were adopted for interpreting the magnitude of correlation (r (90% CI)) between test measures: < 0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; and 0.9-1.0, almost perfect. If the 90% confidence intervals overlapped small positive and negative values the magnitude was deemed unclear, otherwise that magnitude was deemed to be the observed magnitude [27]. We also postulated that if repeated-sprint

ability is independent of whether or not there are changes of direction and exists as a general quality, rather than a specific quality, individuals would rank similarly despite the different tests (i.e., shuttle vs. straight line). The appropriate statistical test to validate the concept of generality has been suggested to be a correlation coefficient of $r = 0.71$ or greater [16], as this degree of association would suggest a minimum of 50% common variance.

RESULTS

Maximal effort at the start of the repeated sequences. Best sprint time during the RS and RSS tests were $100.1 \pm 1.2\%$ and $99.9 \pm 1.2\%$ of the reference performances undertaken once before the tests, respectively. There was no difference between performances during the test and the reference trials (ES for both tests rated as '*trivial*' and differences, as '*unclear*').

Performance during straight and shuttle repeated-sprint running. Best and mean sprint times, as well as percentages of speed decrement for both protocols are presented in Table 1. Best and mean sprint times were 30.5 ± 4.0 and $29.7 \pm 3.6\%$ slower for RSS than RS, respectively and chances that values for RSS were higher than those for RS were 100% (Figure 1). The percentage speed decrement was lower for RSS compared with RS (standardized difference rated as '*small*' and the chances that the true values for RSS were lower was 79%; Table 1). There was a '*large*' correlation between RS_b and RSS_b ($r = 0.63$ (0.22; 0.85)), while the correlation between RS_m and RSS_m was rated as '*very large*' ($r = 0.78$ (0.48; 0.92), Figure 2). However, the relationship between $RS_{\%Dec}$ and $RSS_{\%Dec}$ was '*unclear*' ($r = -0.24$ (-0.27; 0.64)).

Cardiorespiratory responses and blood lactate concentration during straight and shuttle repeated-sprint running. Mean \dot{V}_E , $\dot{V}O_2$, $\dot{V}CO_2$, post-exercise $[La]_b$ and $\Delta[La]_b$ were

'possibly' higher for RSS compared with RS, with *'small'* standardized differences (Table 2). Conversely, differences in HR and RPE were rated as *'trivial'* and *'almost unlikely'*, thus implying similar HR and RPE responses between the two protocols. Mean differences (90% CI) in $\dot{V}O_2$ and post-exercise $\Delta[La]_b$ values between the two exercise conditions are illustrated in Figure 3. The correlations between $\dot{V}O_2$ ($r = 0.87$ (0.67; 0.95)) and HR ($r = 0.89$ (0.72; 0.96)) measured during the two protocols were *'very large'*. The correlation for $\Delta[La]_b$ during each RSA test was rated as *'large'* ($r = 0.57$ (0.13; 0.82)). However, there was no correlation (*'unclear'*) between RPE reported at the end of each RSA test ($r = 0.31$ (-0.20; 0.69)).

Muscle oxygenation during straight and shuttle repeated-sprint running. Figure 4 illustrates changes in Hb_{diff} in one representative subjects during the two protocols. As presented in Table 3, there was no difference between the two protocols for any of the NIRS variables (all standardized differences rated as *'trivial'* and all comparisons considered as *'unclear'*). Mean difference (90% CI) in Hb_{diff} values between the two exercise conditions is illustrated in Figure 3. The respective values for both trials were however all *'largely'* correlated (e.g., $r = 0.68$ for both HHb and Hb_{diff}).

DISCUSSION

In this study, we investigated the effects of 180° turns during repeated-sprint running on sprint times and cardiorespiratory, blood lactate and muscle deoxygenation responses. Consistent with our hypothesis, the correlation coefficient for best sprint times during the two protocols was lower than 0.71 [16]. However, there was a very large correlation between mean sprint times, and fatigue development was lower during the shuttle protocol. We also

observed higher pulmonary oxygen uptake and blood lactate concentration during repeated shuttle sprints, despite no difference in muscle deoxygenation level between trials.

Effect of 180° changes of direction on best and mean sprint times. Since best sprint times during both protocols were similar to the reference maximal sprints undertaken before the tests, the occurrence of pacing strategies was unlikely. As expected, 180° changes of direction induced a 30% increase in best sprint time (Table 1 and Figure 1), which was likely to be related to time lost while decelerating, blocking, and then reaccelerating for the second part of the run [5]. Although the correlation between best sprint time for the two tests was *large*, this correlation ($r = 0.63$) was less than 0.71, which suggests that best sprint time exists as a specific quality, rather than a general quality [16]. That is, best sprint time for the straight-line test does not provide a valid assessment of best shuttle-sprint time (and vice versa) [5, 37, 43]. This suggests that other components (i.e., coordination, balance, flexibility or even the subject's mass [5]) are likely to be important for the performance of sprints with 180° changes of directions. This is consistent with previous findings that indicated no relation between time in a 20-m shuttle run (i.e., 2 x 10 m) and a 30-m (straight line) sprint test [43], and confirms that both tests cannot be used interchangeably. These findings therefore support the use of a specific shuttle-sprint test to assess the ability of team-sport athletes to perform at least single sprint with a change of direction [5, 37, 43]. Regarding mean sprint time, consistent with best sprint time, changing direction also induced a 30% increase in running time (Table 1 and Figure 1). However, on this occasion the correlation coefficient observed between mean repeated-sprint time for the RS and RSS trials was *very large* ($r = 0.78$, Figure 2) and greater than 0.71, suggesting that, in contrast to best (single) sprint time, repeated-sprint ability could be considered more of a general quality [16].

Effect of 180° changes of direction on percentage sprint decrement. The possible higher blood lactate level [1] (used as a proxy of other intramuscular metabolic byproduct accumulation that are more clearly linked to muscular impairment [23]) was expected to be associated with a greater fatigue development (i.e., greater speed decrement score). For example, Gaitanos et al. [21] have previously reported a strong and negative association between post-test blood pH and sprint decrement. In contrast, despite higher blood lactate levels (see below), we observed a lower sprint decrement during the shuttle-sprint in comparison with the straight-line protocol (Table 1 and Figure 1). It is believed that fatigue development during multiple sprint work is inversely related to initial power output (or speed) [33]. Thus, the greater running speed during the straight line protocol would have exacerbated fatigue development compared with the shuttle runs. It is also possible that $[La]_b$ may not best reflect the accumulation of intramuscular metabolites likely to effectively impair muscle function during high-intensity intermittent exercise [30].

Effect of changes in direction on cardiorespiratory and blood lactate responses during repeated-sprint running. This is the first study to investigate cardiorespiratory and blood lactate responses to repeated shuttle-sprint running in the field. Compared with RS, \dot{V}_{E} , $\dot{V}O_2$ and $[La]_b$ were higher during RSS (Table 2 and Figure 3). This partly contrasts with the previous study by Ahmaidi et al. [1] which has reported similar maximal $\dot{V}O_2$ during graded aerobic tests performed with or without changes of direction. Nevertheless, differences in exercise intensity (incremental vs. supramaximal) and type (continuous vs. intermittent) might partly explain these differences. While it would be intuitive to link these findings to disparities in lower limb energetic responses (not directly measured here), the absence of differences in deoxygenation levels (see below) suggests that other mechanisms were responsible for the higher cardiorespiratory and $[La]_b$ values observed. Indeed, increased muscle deoxygenation reflects increased reliance on muscle O_2 extraction [19], and has been

reported to impair repeated sprint performance [8]. Consistent with present findings, Girard et al. [22] reported that peak $\dot{V} O_2$ was higher during an intermittent racket test compared with an incremental test performed on a treadmill. The authors suggested that the higher $\dot{V} O_2$ observed in the tennis test was due to the involvement of upper-body muscles required for the simulated ball hitting action. Similarly in the present study, it is possible that the higher values for $\dot{V} O_2$ and/or blood lactate accumulation during the shuttle protocol were due to the involvement of additional muscles during the 180° changes of directions, as upper-body (e.g., respiratory, back, abdominal and arms muscles) and bi-articulate leg (e.g., biceps femoris, rectus femorus, hip adductors, ilioasoas) muscles are active during deceleration and acceleration [29]. An alteration of the locomotion-ventilation coupling, as a result of changes in stride patterns and velocity, could have also partially explained the higher ventilatory parameters observed [1]. Finally, the augmented respiratory muscle work (i.e., increased \dot{V}_E) for the shuttle protocol could also have contributed to the higher $\dot{V} O_2$ [42].

Effect of 180° changes in direction on muscle deoxygenation during repeated-sprint running. In the present study, we observed no difference in the changes of NIRS-derived indices between the two protocols (Figure 3). Our results therefore suggest that changing of direction during repeated sprint running is not likely to modify the local O_2 uptake/delivery ratio. As muscle (de)oxygenation levels have been shown to be well related to systemic $\dot{V} O_2$ during (exclusive) leg exercise (e.g., cycling, [2]), the higher pulmonary $\dot{V} O_2$ observed for the shuttle protocol, despite a similar vastus lateralis oxygenation level, provides additional support for the hypothesis that changing direction may have increased the $\dot{V} O_2$ of other lower- or upper-body muscles. Future research should test this hypothesis by examining the recruitment patterns of the vastus lateralis and other lower- and upper-limb muscles during shuttle-sprint running, via electromyography for example.

Limitations of NIRS, such as difficulties with signal quantification, interference by high adipose tissue thickness, and the controversial contribution of myoglobin to the NIRS signal have already been described [3]. However, since our aim was to compare relative differences between two running conditions performed alternatively, these limitations do not affect the interpretation of our results. Moreover, we paid particular attention to HHb and Hb_{diff} signals, which are thought to be essentially blood volume insensitive during exercise (i.e., HHb, [18]) and to provide accurate measures when tHb does not remain constant (i.e., Hb_{diff} [41]). Finally, in accordance with the Fick principle, as $\dot{V} O_2$ is not only related to arterio-venous O₂ difference (inferred here from changes in HHb or Hb_{diff}), but also to O₂ delivery (i.e., cardiac output or muscle blood flow [10]), interferences about muscle metabolism based on NIRS-derived indices alone might be an oversimplification in certain circumstances. Nevertheless, since we observed similar values for indirect indices of either central (HR) or local (tHb) O₂ delivery for both trials, this suggests that our observations concerning differences in vastus lateralis metabolism, based on NIRS-related values, are justified.

In conclusion, despite differences in sprinting times between the shuttle-sprints and the straight-line protocol, mean sprinting time in both tests were largely correlated, suggesting that the ability to repeat sprints could be considered as a general quality. Present results also suggest that changing of direction during short repeated sprint running might be an effective training practice for increasing systemic ‘physiological load’, but perhaps not a greater loading of the vastus lateralis. Future studies examining the training effect of repeated shuttle versus straight-line sprints on team-sport specific performance are warranted.

References

1. *Ahmaidi S, Collomp K, and Prefaut C.* The effect of shuttle test protocol and the resulting lactacidaemia on maximal velocity and maximal oxygen uptake during the shuttle exercise test. *Eur J Appl Physiol* 1992; 65: 475-9.
2. *Belardinelli R, Barstow TJ, Porszasz J, and Wasserman K.* Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. *Eur J Appl Physiol Occup Physiol* 1995; 70: 487-92.
3. *Boushel R and Piantadosi CA.* Near-infrared spectroscopy for monitoring muscle oxygenation. *Acta Physiol Scand* 2000; 168: 615-22.
4. *Bravo DF, Impellizzeri FM, Rampinini E, Castagna C, Bishop D, and Wisloff U.* Sprint vs. Interval Training in Football. *Int J Sports Med* 2008; 29: 668-74.
5. *Brughelli M, Cronin J, Levin G, and Chaouachi A.* Understanding change of direction ability in sport: a review of resistance training studies. *Sports Med* 2008; 38: 1045-63.
6. *Buchheit M.* The 30-15 Intermittent Fitness Test: accuracy for individualizing interval training of young intermittent sport players. *J Strength Cond Res* 2008; 22: 365-374.
7. *Buchheit M, Al Haddad H, Leprêtre PM, Millet G, Newton M, and Ahmaidi S.* Cardiorespiratory and cardiac autonomic responses to 30-15 Intermittent fitness test. *J Strength Cond Res* 2009; 23: 93-100.
8. *Buchheit M, Cormie P, Abbiss CR, Ahmaidi S, Nosaka KK, and Laursen PB.* Muscle deoxygenation during repeated sprint running: Effect of active vs. passive recovery. *Int J Sports Med* 2009; 30: 418-25.
9. *Buchheit M, Laursen PB, and Ahmaidi S.* Parasympathetic reactivation after repeated sprint exercise. *Am J Physiol Heart Circ Physiol* 2007; 293: H133-H41.

10. *Buchheit M, Laursen PB, and Ahmaidi S.* Effect of prior exercise on pulmonary O₂ uptake and estimated muscle capillary blood flow kinetics during moderate-intensity field running in men. *J Appl Physiol* 2009; 107: 460-70.
11. *Buchheit M, Mendez-Villanueva A, Delhomel G, Brughelli M, and Ahmaidi S.* Improving repeated sprint ability in young elite soccer players: repeated sprints vs. explosive strength training. *J Strength Cond Res* In press.
12. *Buchheit M, Millet GP, Parisy A, Pourchez S, Laursen PB, and Ahmaidi S.* Supramaximal training and post-exercise parasympathetic reactivation in adolescents. *Med Sci Sports Exerc* 2008; 40: 362-371.
13. *Buchheit M, Spencer M, and Ahmaidi S.* Reliability, usefulness and validity of a repeated sprint and jump ability test. *Int J Sports Physiol Perform* In press.
14. *Castagna C, Abt G, Manzi V, Annino G, Padua E, and D'Ottavio S.* Effect of recovery mode on repeated sprint ability in young basketball players. *J Strength Cond Res* 2008; 22: 923-9.
15. *Castagna C, Manzi V, D'Ottavio S, Annino G, Padua E, and Bishop D.* Relation between maximal aerobic power and the ability to repeat sprints in young basketball players. *J Strength Cond Res* 2007; 21: 1172-6.
16. Clarke D and Clarke H, *Research processes in physical education, recreation and health.* 1970, Engelwood Cliffs, N.J.: Prentice-Hall. pp 370.
17. Cohen J, *Statistical Power Analysis for the Behavioral Sciences.* 1988, Hillsdale: Lawrence Erlbaum. 599.
18. *De Blasi RA, Cope M, Elwell C, Safoue F, and Ferrari M.* Noninvasive measurement of human forearm oxygen consumption by near infrared spectroscopy. *Eur J Appl Physiol Occup Physiol* 1993; 67: 20-5.

19. *DeLorey DS, Kowalchuk JM, and Paterson DH.* Effect of age on O₂ uptake kinetics and the adaptation of muscle deoxygenation at the onset of moderate-intensity cycling exercise. *J Appl Physiol* 2004; 97: 165-72.
20. *DeLorey DS, Kowalchuk JM, and Paterson DH.* Adaptation of pulmonary O₂ uptake kinetics and muscle deoxygenation at the onset of heavy-intensity exercise in young and older adults. *J Appl Physiol* 2005; 98: 1697-704.
21. *Gaitanos GC, Williams C, Boobis LH, and Brooks S.* Human muscle metabolism during intermittent maximal exercise. *J Appl Physiol* 1993; 75: 712-9.
22. *Girard O, Chevalier R, Leveque F, Micallef JP, and Millet GP.* Specific incremental field test for aerobic fitness in tennis. *Br J Sports Med* 2006; 40: 791-6.
23. *Gladden LB.* Lactate metabolism: a new paradigm for the third millennium. *J Physiol* 2004; 558: 5-30.
24. *Glaister M.* Multiple sprint work : physiological responses, mechanisms of fatigue and the influence of aerobic fitness. *Sports Med* 2005; 35: 757-77.
25. *Glaister M.* Multiple-sprint work: methodological, physiological, and experimental issues. *Int J Sports Physiol Perform* 2008; 3: 107-12.
26. *Harriss DJ and Atkinson G.* International Journal of Sports Medicine - ethical standards in sport and exercise science research. *Int J Sports Med* 2009; 30: 701-2.
27. *Hopkins WG, Marshall SW, Batterham AM, and Hanin J.* Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 2009; 41: 3-13.
28. *Impellizzeri FM, Rampinini E, Castagna C, Bishop D, Ferrari Bravo D, Tibaudi A, and Wisloff U.* Validity of a Repeated-Sprint Test for Football. *Int J Sports Med* 2008; 29: 899-905.
29. *Jacobs R, Bobbert MF, and van Ingen Schenau GJ.* Function of mono- and biarticular muscles in running. *Med Sci Sports Exerc* 1993; 25: 1163-73.

30. *Krustrup P, Mohr M, Steensberg A, Bencke J, Kjaer M, and Bangsbo J.* Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med Sci Sports Exerc* 2006; 38: 1165-74.
31. *McLaughlin JE, King GA, Howley ET, Bassett DR, Jr., and Ainsworth BE.* Validation of the COSMED K4 b2 portable metabolic system. *Int J Sports Med* 2001; 22: 280-4.
32. *Mendez-Villanueva A, Hamer P, and Bishop D.* Fatigue responses during repeated sprints matched for initial mechanical output. *Med Sci Sports Exerc* 2007; 39: 2219-25.
33. *Mendez-Villanueva A, Hamer P, and Bishop D.* Fatigue in repeated-sprint exercise is related to muscle power factors and reduced neuromuscular activity. *Eur J Appl Physiol* 2008; 103: 411-9.
34. *Nakamura FY, Soares-Caldeira LF, Laursen PB, Polito MD, Leme LC, and Buchheit M.* Cardiac Autonomic Responses to Repeated Shuttle Sprints. *Int J Sports Med* 2009.
35. *Pyne DB, Boston T, Martin DT, and Logan A.* Evaluation of the Lactate Pro blood lactate analyser. *Eur J Appl Physiol* 2000; 82: 112-6.
36. *Rampinini E, Bishop D, Marcora SM, Ferrari Bravo D, Sassi R, and Impellizzeri FM.* Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *Int J Sports Med* 2007; 28: 228-35.
37. *Sheppard JM and Young WB.* Agility literature review: classifications, training and testing. *J Sports Sci* 2006; 24: 919-32.
38. *Spencer M, Bishop D, Dawson B, and Goodman C.* Physiological and metabolic responses of repeated-sprint activities: specific to field-based team sports. *Sports Med* 2005; 35: 1025-44.
39. *Spencer M, Fitzsimons M, Dawson B, Bishop D, and Goodman C.* Reliability of a repeated-sprint test for field-hockey. *J Sci Med Sport* 2006; 9: 181-4.

40. *Stone NM and Kilding AE.* Aerobic conditioning for team sport athletes. *Sports Med* 2009; 39: 615-42.
41. *van Beekvelt MC, van Engelen BG, Wevers RA, and Colier WN.* In vivo quantitative near-infrared spectroscopy in skeletal muscle during incremental isometric handgrip exercise. *Clin Physiol Funct Imaging* 2002; 22: 210-7.
42. *Wetter TJ, Harms CA, Nelson WB, Pegelow DF, and Dempsey JA.* Influence of respiratory muscle work on VO₂ and leg blood flow during submaximal exercise. *J Appl Physiol* 1999; 87: 643-51.
43. *Wisloff U, Castagna C, Helgerud J, Jones R, and Hoff J.* Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br J Sports Med* 2004; 38: 285-8.

Figures legends

Figure 1. Mean (\pm SD) differences in best and mean sprint times, and percentage speed decrement (%Dec) measured for repeated-sprint running without (RS) and with (RSS) shuttle runs (bars indicate uncertainty in the true mean changes with 90% confidence intervals) (n = 13). Trivial areas were calculated from the smallest worthwhile change (see methods)

Figure 2. Relationship between best (upper panel) and mean (lower panel) sprint times recorded during the repeated straight line-sprint (RS) and repeated shuttle-sprint (RSS) ability tests. Dashed line represents 95% confidence interval.

Figure 3. Mean (\pm SD) differences in pulmonary oxygen uptake ($\dot{V}O_2$), vastus lateralis deoxygenation level (Hb_{diff}) and blood lactate accumulation ($\Delta[La]_b$) measured for repeated-sprint running without (RS) and with (RSS) shuttle runs (bars indicate uncertainty in the true mean changes with 90% confidence intervals) (n = 13). Trivial areas were calculated from the smallest worthwhile change (see methods).

Figure 4. Changes in Hb_{diff} in one representative subjects during the straight-line (RS) and shuttle (RSS) protocols. Values are reported as a change from baseline (30-s averaging before each test) in micromolar units (μM), using a differential pathlength factor of 3.83.