

Assessing Running Economy During Field Running with Changes of Direction: Application to 20 m Shuttle Runs

Martin Buchheit, Bachar Haydar, Karim Hader,
Pierre Ufland, and Said Ahmaidi

Purpose: To examine physiological responses to submaximal field running with changes of direction (COD), and to compare two approaches to assess running economy (RE) with COD, ie, during square-wave (SW) and incremental (INC) exercises. **Methods:** Ten male team-sport athletes performed, in straight-line or over 20 m shuttles, one maximal INC and four submaximal SW (45, 60, 75 and 90% of the velocity associated with maximal pulmonary O₂ uptake [$v\dot{V}O_{2p,max}$]). Pulmonary (VO_{2p}) and gastrocnemius (VO_{2m}) O₂ uptake were computed for all tests. For both running mode, RE was estimated as the O₂ cost per kilogram of bodyweight, per meter of running during all SW and INC. **Results:** Compared with straight-line runs, shuttle runs were associated with higher VO_{2p} (eg, 33 ± 6 vs 37 ± 5 mL O₂·min⁻¹·kg⁻¹ at 60%, $P < .01$) and VO_{2m} (eg, 1.1 ± 0.5 vs 1.3 ± 0.8 mL O₂·min⁻¹·100 g⁻¹ at 60%, $P = .18$, Cohen's $d = 0.32$). With COD, RE was impaired during SW (0.26 ± 0.02 vs 0.24 ± 0.03 mL O₂·kg⁻¹·m⁻¹, $P < .01$) and INC (0.23 ± 0.04 vs 0.16 ± 0.03 mL O₂·kg⁻¹·m⁻¹, $P < .001$). For both SW and INC tests, the changes in RE with COD were related to height (eg, $r = .56$ [90%CL, 0.01;0.85] for SW) and weekly training/competitive volume (eg, $r = -0.58$ [-0.86;-0.04] for SW). For both running modes, RE calculated from INC was better than that from SW (both $P < .001$). **Conclusion:** Although RE is impaired during field running with COD, team-sport players of shorter stature and/or presenting greater training/competitive volumes may present a lower RE deterioration with COD. Present results do not support the use of INC to assess RE in the field, irrespective of running mode.

Keywords: changes of direction, energetic cost of running, accumulated O₂ deficit, near-infrared spectroscopy

Although its importance is no more to prove for middle-distance or long-distance runners,¹ running economy (RE) is also to consider in team sports such as

Martin Buchheit is with the Laboratory of Exercise Physiology and Rehabilitation, EA 3300, Faculty of Sport Sciences, University of Picardie, Jules Verne, Amiens, France, and with the Sport Science Department, Aspire, Academy for Sports Excellence, Doha, Qatar. Bachar Haydar, Karim Hader, Pierre Ufland, and Said Ahmaidi are with the Laboratory of Exercise Physiology and Rehabilitation, EA 3300, Faculty of Sport Sciences, University of Picardie, Jules Verne, Amiens, France.

soccer.^{2,3} Recently, it has been reported that RE, but not maximal pulmonary oxygen uptake ($\text{VO}_{2\text{pmax}}$), discriminated elite soccer players according to their playing level.³ The greater discriminatory power of RE compared with that of $\text{VO}_{2\text{pmax}}$ is suggested to be due to its relations with both central (cardiopulmonary function) and peripheral (metabolic and biomechanical)⁴ factors (ie, $\text{VO}_{2\text{pmax}}$ being mainly related to central factors).⁵

Nevertheless, until now, RE in team-sport players has only been evaluated by means of a “classical” approach,^{3,6,7} which requires players to perform at least one constant-load run on a treadmill. This type of assessment in the laboratory is not practical and does not allow the inclusion of deceleration, acceleration phases and changes of direction (COD), which are intuitively necessary for the assessment of a *team-sport-specific RE*. Changes of direction are known to substantially affect physiological responses to field running^{8,9} and, in turn, the energetic cost of running.^{10,11} To date, compared with straight-line high-intensity intermittent runs, shuttle runs have been shown to elicit higher heart rates (HR), blood lactate ($[\text{La}]_{\text{b}}$) levels and rating of perceived exertion (RPE).⁹ Similarly, the addition of COD during repeated sprints increased cardiorespiratory responses, but did not affect quadriceps deoxygenation levels.⁸ Nevertheless, until now, the impact of COD on the physiological responses to submaximal field running and, in turn, RE, have not been evaluated yet. Simple and time-efficient field-based methods to assess a team-sport-specific RE are still lacking.

The purpose of this study was therefore to examine selected physiological responses to submaximal field running with changes of direction (COD), and to compare two different approaches to assess RE with COD, ie, during square-wave (SW) and incremental (INC) exercises. The second aim of the present study was to determine whether the observed team-sport-specific RE values and the possible differences in RE between the two running modes (ie, with or without COD) could be due to individual attributes (ie, anthropometric measures or weekly training/competitive volume).

Materials and Methods

Subject Recruitment

Ten male intermittent sport athletes (23 ± 4 y, 78.5 ± 5.9 kg, 1.80 ± 0.06 m, $16.1 \pm 3.3\%$ body fat) participated in the study. They were all competing at the regional level in a variety of sports, including futsal ($n = 3$), handball ($n = 3$), volleyball ($n = 1$), rugby ($n = 1$), field hockey ($n = 1$) or tennis ($n = 1$), but none of them was involved in distance running training. Player’s average training/competitive volume over the last 3 mo (2–4 times per week + a weekly competition, 7 ± 3 h·wk⁻¹) was computed during the initial study interview (ie, subjects’ recruitment). Because this variable was later examined as a possible determinant of RE (see below), great attention was paid to ensure that the players accurately reported their weekly training and competitive schedules. In addition, even though the degree of players’ exposure to runs including COD might vary according to the specific running patterns of each sport, we found that all players were consistently performing prolonged (>20 m) runs with COD during at least 60% of their weekly training/competitive time (and more especially during training sessions for tennis and volleyball players).

Participants had no history or clinical signs of cardiovascular or pulmonary diseases. All players were provided with the procedures and risks associated with participation in the study and gave their written informed consent before participation. The study was approved by the local ethic committee and conformed to the declaration of Helsinki.

Experimental Design

Each participant was tested on four occasions, separated by at least 48 h. Participants first performed (session 1 and 2) in a random order, either a straight-line or a 20 m shuttle INC. During sessions 3 and 4, participants performed four 5 min SW runs at different submaximal intensities, with or without COD. Cardiorespiratory variables, medial gastrocnemius oxygenation levels (NIRS), $[La]_b$ and RPE (0–10 on Borg's scale, assessed immediately at the end of each exercise bout) were collected for all tests. Accumulated O_2 deficit (AO_2D) was also calculated for all SW runs as a measure of anaerobic system participation. All tests were performed on an indoor synthetic track where ambient temperature ranged from 18 to 22°C. Height (fixed stadiometer [Holtain Ltd., Crosswell, Crymch, U.K.]), body mass (ADE Electronic Column Scales, Hamburg, Germany) and the sum of four skinfold sites (triceps, subscapular, biceps, supraspinale; Harpenden skinfold caliper [Baty International, Burgess Hill, U.K.]) were measured for each player during the first visit. Players were told not to perform exercise on the day before a test, and to consume their last (caffeine-free) meal at least 3 h before the scheduled test time.

Testing Procedures

Incremental Tests. The incremental field protocol was performed while running either with (20 m shuttles) or without (160 m track) 180° COD. The subjects first ran at 8 km·h⁻¹ for 4 min. The speed was then increased by 0.5 km·h⁻¹ every 30 s until volitional exhaustion.¹² Running pace was governed by a prerecorded beep that sounded at appropriate intervals in order to allow athletes to adjust their running speed as they passed through specific zones of the field.

Submaximal Square-Wave Runs. The four 5 min SW runs were performed either with (20 m shuttles) or without 180° COD (160 m track). Without any warm-up, the athletes performed the SW runs in a stepwise manner at 45, 60, 75 and 90% of the minimal running velocity associated with $VO_{2p,max}$ during the straight-line test (ie, $vVO_{2p,max}$, see below). Running pace was governed as during INC tests. Each run was separated by a 5 (45 to 75%) to 10 min (75 to 90%) passive recovery period. Because no participant was expected to complete the 5 min shuttle run at 90% (corresponding to >100% of shuttle $vVO_{2p,max}$, Table 1), shuttle runs were implemented first; the duration of the corresponding 90% straight-line run was therefore matched with participants stopped at isotime.

Data Collection and Analyses

Cardiorespiratory Measures. Respiratory gas exchange and heart rate (HR) were measured using an automated, portable, breath-by-breath system (K4b², Cosmed, Rome, Italy) during all tests. Before each test, the O_2 and CO_2 analysis systems

were calibrated as recommended by the manufacturer. Cardiorespiratory values were averaged over 10 s periods during INC, and over 5 s periods during SW. Pulmonary $\text{VO}_{2\text{max}}$ was defined as the highest $\text{VO}_{2\text{p}}$ values attained in three consecutive 10 s periods during INC. For each protocol, $v\text{VO}_{2\text{pmax}}$ was defined as the lowest running velocity maintained for at least 1 min that elicited $\text{VO}_{2\text{pmax}}$.¹³ Maximal HR (HR_{max}) was defined as the highest HR value attained in a 10 s period during INC. Gas exchange threshold (GET) was defined as the speed at which there was a nonlinear increase in $V_E/\text{VO}_{2\text{p}}$ without a concomitant nonlinear increase in V_E/VCO_2 .¹⁴

Running Economy During SW. Running economy was calculated for 45, 60 and 75% intensities as end-exercise (last [stationary] 2 min to ensure a steady state had been reached for each running speed) O_2 cost per kilogram of bodyweight, per meter of running for the set running velocities.¹ Allometric scales were not used since there was no correlation between RE and bodyweight in the present study. The difference between RE SW calculated for both running modes was noted as $\Delta\text{RE SW}$.

Running Economy During INC. For INC tests, RE was calculated on the linear part of the $\text{VO}_{2\text{p}}$ /speed relationship (ie, in the speed range from the beginning of the incremental phase to GET; additional values were considered only if the correlation coefficient of the linear regression did not decrease, to provide a conservative estimate of the lowest value for the slope of $\text{VO}_{2\text{p}}$ and speed¹⁵). As proposed by di Prampero et al,¹² for every 30 s step, the $\text{VO}_{2\text{p}}$ was averaged over three time windows (ie, 0–10 s, 10–20 s and 20–30 s). The thus-obtained $\text{VO}_{2\text{p}}$ values were plotted as a function of the corresponding speed. This allowed obtaining three individual relationships between $\text{VO}_{2\text{p}}$ and running speed for each subject. These relationships were then interpolated by least squares linear regressions (with mean values for $r = .92 \pm 0.05$ and 0.94 ± 0.03 for straight-line and shuttle protocols, respectively), the slopes of which yielded three average RE values for each subject. These three slopes were then averaged to yield a single RE value for each subject. The difference between RE INC calculated for both running modes was noted as $\Delta\text{RE INC}$.

Accumulated O_2 Deficit and Percentage of Anaerobic Participation to Each SW Run. To describe the individual $\text{VO}_{2\text{p}}$ /speed relationship, the average $\text{VO}_{2\text{p}}$ measured during last 2 min of the runs at 45, 60 and 75% was used. All $\text{VO}_{2\text{p}}$ /speed relationships were very large, with $r = 1.00 \pm 0.01$ and $r = .99 \pm 0.02$ for straight-line and shuttle protocols, respectively. The AO_2D during the four SW exercise was then calculated as the difference between estimated total O_2 demand (extrapolated from the linear $\text{VO}_{2\text{p}}$ /speed relationship obtained for the respective running mode) and measured total O_2 uptake during each SW.¹⁵ Percentage of anaerobic participation (%Ana) was then calculated for each SW run, as $\text{AO}_2\text{D} \times 100 / \text{estimated total } \text{O}_2 \text{ demand}$.

Oxygen Uptake at Similar Relative Exercise Intensities for Both Exercise Modes. Since shuttle SW runs were performed at a higher percentage of (shuttle) $\text{VO}_{2\text{pmax}}$ than straight-line SW runs, expected end-exercise $\text{VO}_{2\text{p}}$ for shuttle runs at 45, 60 and 75% of shuttle $v\text{VO}_{2\text{pmax}}$ were extrapolated from the linear $\text{VO}_{2\text{p}}$ /speed regression obtained previously.

Near-Infrared Spectroscopy Measurements. The portable NIRS apparatus (Portamon, Artinis, Medical System, Zetten, The Netherlands) used to collect data was the same as described previously.¹⁶ Changes in tissue oxyhemoglobin ($[\text{HbO}_2]$)

and deoxyhemoglobin ([HHb]) were measured using the differences in absorption characteristics of light at 775 and 850 nm, with a differential path-length factor of 4. The difference between [HbO₂] and [HHb] was also calculated: [Hb_{Diff}] = [HbO₂] – [HHb]. The use of [Hb_{Diff}] was considered since it has been shown to be a relevant alternative to [HHb] when total hemoglobin ([tHb]) is not constant; muscle oxygen consumption estimated from [Hb_{Diff}] is more reliable than values estimated from the other NIRS variables.¹⁷ Since it is the biarticulate muscles that are the most solicited during acceleration phases and changes of directions,¹⁸ the NIRS probe was positioned on the medial gastrocnemius muscle, used when changing direction (approximately 7 cm from the knee joint and along the vertical axis of the limb). 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. A pneumatic cuff was fixed with elastic adhesive bandage around the thigh (just above the knee) and was used to apply arterial (popliteal cavity) occlusion after each exercise. The cuff was deflated during exercise and adjusted so that the athletes could run without any discomfort. Skinfold thickness at the site of application of the NIRS probe was determined before the testing sessions using Harpenden skinfold calipers. 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.

NIRS VO_{2m} Measurements. Thirty seconds following the end of all SW and INC tests, an arterial occlusion was applied (>280 mmHg) for 10 s. The VO_{2m} was then derived from NIRS by evaluating the rate of decrease in [Hb_{Diff}]: (Δ [Hb_{Diff}]/ Δ time)/2.¹⁹ Concentration changes of Hb_{Diff} were expressed as micromolar per second and converted to milliliters of O₂ per minute per 100 grams (mL O₂·min⁻¹·100 g⁻¹). A value of 1.04 kg·L⁻¹ was used for muscle density.¹⁹

Blood Lactate Measurement. Three minutes after the end of each test, a fingertip blood sample (5 μ L) was collected and [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⁻¹.²⁰

Statistical Analyses

The distribution of each variable was examined with the Shapiro-Wilk normality test. Homogeneity of variance was verified by a Levene test. When data were skewed or heteroscedastic (ie, RE or VO_{2m}), data were transformed by taking the natural logarithm to allow parametric statistical comparisons that assume a normal distribution. For the sake of clarity, however, values presented in the text and figures are nontransformed (ie, back-transformed). Changes in cardiorespiratory, RE, [La]_b and RPE values in the two running conditions were analyzed using a two-factor repeated-measures ANOVA, with one within (“intensity,” ie, 45, 60, 75 and 90%) and one between (“running mode,” ie, straight-line vs shuttle) factor. If a significant interaction was identified, a Bonferroni post hoc test was used to further delineate differences between factors. Differences in cardiovascular parameters, blood

lactate, RPE and RE collected following INC were compared with paired *t* tests (two-tailed). The level of significance was set at $P < .05$. In addition, the magnitude of differences in each variable between both running modes were expressed as standardized mean differences (Cohen's *d*, or effect sizes). Threshold values for Cohen's *d* statistics were >0.2 – 0.5 (small), >0.5 – 0.8 (moderate) and >0.8 (large).²¹ The relationship for between-running conditions differences in VO_{2p} , AO_2D vs running intensity were estimated with a second-order regression model. Pearson's coefficients were also used to establish the respective relationships between RE, ΔRE , anthropometric variables and weekly training/competitive volume. Given the small sample size, the following criteria were adopted for interpreting the magnitude of correlation (*r* [90% CL]) 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% CL overlapped small positive and negative values, the magnitude was deemed unclear; otherwise, that magnitude was deemed to be the observed magnitude.²¹ Finally, within- and between-players coefficients of variation (CV) for RE were calculated as $(\text{SD}/\text{mean}) \times 100$. All statistical analyses were carried out using Minitab 14.1 (Minitab Inc, Paris, France). Data are presented as mean \pm SD unless otherwise stated.

Results

Incremental Exercises

Peak running speed (17.2 ± 1.4 vs 14.8 ± 0.4 $\text{km}\cdot\text{h}^{-1}$, $P < .001$), $\text{vVO}_{2p\text{max}}$ (15.9 ± 1.5 vs 13.4 ± 0.3 $\text{km}\cdot\text{h}^{-1}$, $P < .001$) and speed at GET (12.8 ± 0.9 vs 11.3 ± 0.5 $\text{km}\cdot\text{h}^{-1}$, $P < .001$) were greater for the straight-line compared with the shuttle protocol. There was, however, no difference between protocols in $\text{VO}_{2p\text{max}}$ (56.6 ± 6.4 vs 56.4 ± 6.4 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, $P = .98$, for straight-line vs shuttle runs, respectively), HR_{max} (194 ± 10 vs 194 ± 10 $\text{b}\cdot\text{min}^{-1}$, $P = .91$), $[\text{La}]_b$ (10.5 ± 2.2 vs 10.0 ± 2.7 $\text{mmol}\cdot\text{L}^{-1}$, $P = .44$) and RPE (8 ± 1 vs 8 ± 1 , $P = .12$). VO_{2m} measured at the end of both protocols was also similar (1.4 ± 0.9 vs 1.2 ± 0.7 $\text{mL O}_2\cdot\text{min}^{-1}\cdot 100 \text{ g}^{-1}$, $P = .84$).

Square-Waves Exercises

Table 1 shows actual running speeds, running times, HR, $[\text{La}]_b$ and RPE values in responses to the different running bouts. Mean VO_{2p} , VO_{2m} and AO_2D responses, as well as %Ana are presented in Figure 1. While there was a significant intensity \times running mode interaction for VO_{2p} ($P = .01$), HR ($P = .001$), $[\text{La}]_b$ ($P = .001$) and RPE ($P = .001$), there was only a significant intensity effect for VO_{2m} , AO_2D and %Ana (all $P < .01$). The value for VO_{2m} tended, however, to be greater for the COD condition at 60, 75 and 90% (Cohen's *d* rated as small). %Ana also tended to be lower with COD for runs at 45, 60 and 75% (Cohen's *d* rated as small or moderate). Figure 2 illustrates the differences in VO_{2p} and AO_2D responses to COD as a function of exercise intensity. Differences (ie, shuttle – straight-line runs, expressed in %) for VO_{2m} were 7.3 ± 11.8 , 34.7 ± 27.3 , 30.2 ± 18.9 and $186 \pm 162.6\%$ for 45, 60, 75 and 90%, respectively. As illustrated in Figure 3, end-exercise values (last 2 min) at a similar percentage of the $\text{vVO}_{2p\text{max}}$ in the respective running mode were not significantly different for shuttle compared with straight-line runs ($P = .15$).

Table 1 Running speeds and selected parameters during the four square-wave exercises while running in straight line or with changes of directions (shuttles)

Percentage $vVO_{2p,max}$ obtained in the respective running mode	Running time (s)	Total O_{2p} ($mL \cdot kg^{-1}$)	HR ($\%HR_{max}$)	[La] _b ($mmol \cdot L^{-1}$)	RPE
Shuttle					
45	300	128.6 ± 24.6	60 ± 3	2.3 ± 1.0	1 ± 0
60	300	163.2 ± 29.2	72 ± 4 ^a	2.0 ± 0.5	2 ± 1 ^a
75	300	199.5 ± 31.3	84 ± 5 ^{a,b}	3.8 ± 2.6	4 ± 1 ^{a,b}
90	193 ± 64	135.2 ± 49.5	89 ± 3 ^{a,b,c}	6.7 ± 2.3 ^{a,b,c}	6 ± 2 ^{a,b,c}
Straight-line					
51 ± 5	300	133.7 ± 15.8	62 ± 3*	2.2 ± 1.2	1 ± 1
70 ± 6	300	182.7 ± 24.5	76 ± 4 ^{*a}	2.3 ± 1.1	3 ± 1 ^{*a}
90 ± 6	300	232.6 ± 29.0	92 ± 3 ^{*a,b}	5.9 ± 2.2 ^{*a,b}	6 ± 1 ^{*a,b}
108 ± 8	Stopped at 193 ± 64	156.8 ± 32.1	97 ± 2 ^{*a,b,c}	12.2 ± 2.6 ^{*a,b,c}	9 ± 1 ^{*a,b,c}

Note. Actual running speeds during each square-wave run expressed as a percentage of the velocity associated with $VO_{2p,max}$ ($vVO_{2p,max}$) obtained in the respective running mode (i.e., straight-line or shuttle incremental test), total pulmonary oxygen uptake consumed during the 5 min square-wave runs (total O_{2p}), running time, mean heart rate (HR), blood lactate ([L-a]_b) and rating of perceived exertion (RPE). a: significantly different from 45 (or 51)%, $P < .05$; b: significantly different from 60 (or 70)%, $P < .05$; c: significantly different from 75 (or 90)%, $P < .05$. *Significantly between-condition difference, $P < .05$.

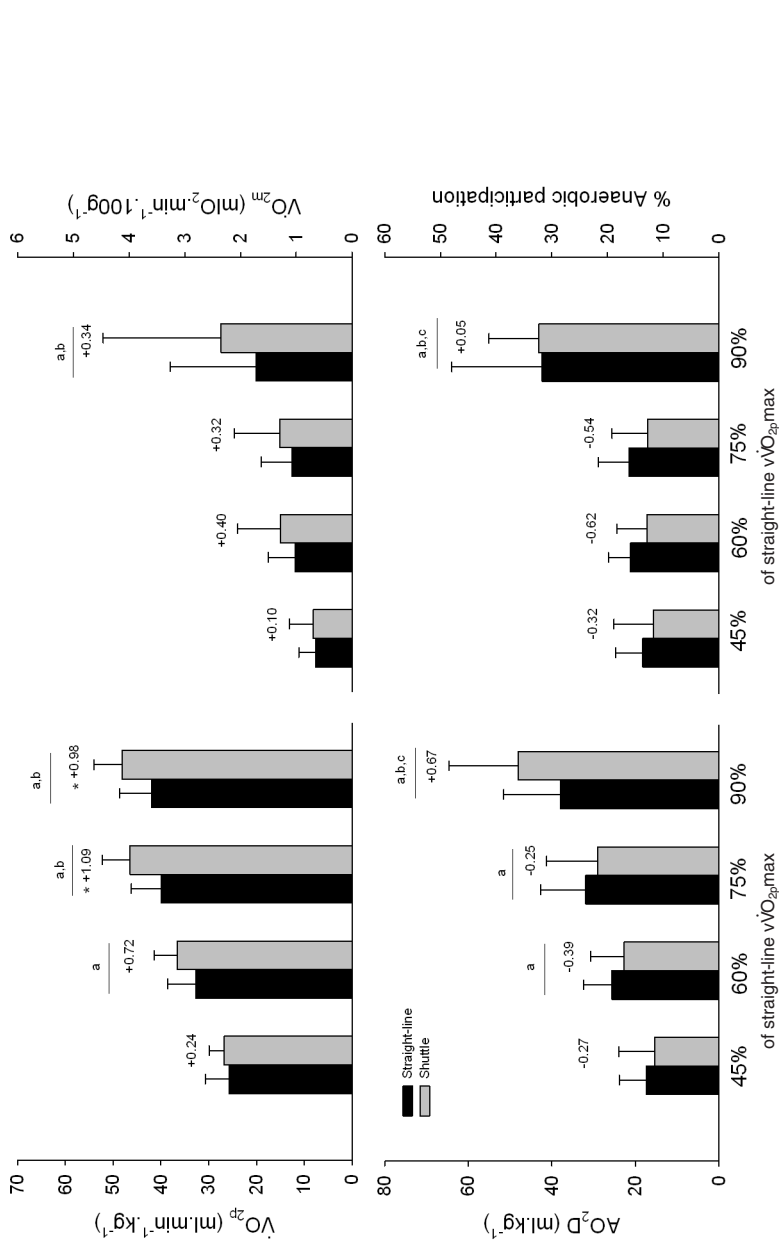


Figure 1 — Pulmonary oxygen uptake (VO_{2p}), medial gastrocnemius oxygen uptake (VO_{2m}), accumulated O_2 deficit (AO_2D) and percentage anaerobic contribution for straight-line and shuttle runs performed at 45, 60, 75 and 90% of the velocity associated with maximal O_2 uptake ($vVO_{2p,max}$) during the straight-line incremental protocol. *Significantly different from straight line. a: significant difference vs 45%, b: vs 60%, c: vs 75%. Numbers provided are standardized differences for shuttle vs straight line (ie, Cohen's d , see methods).

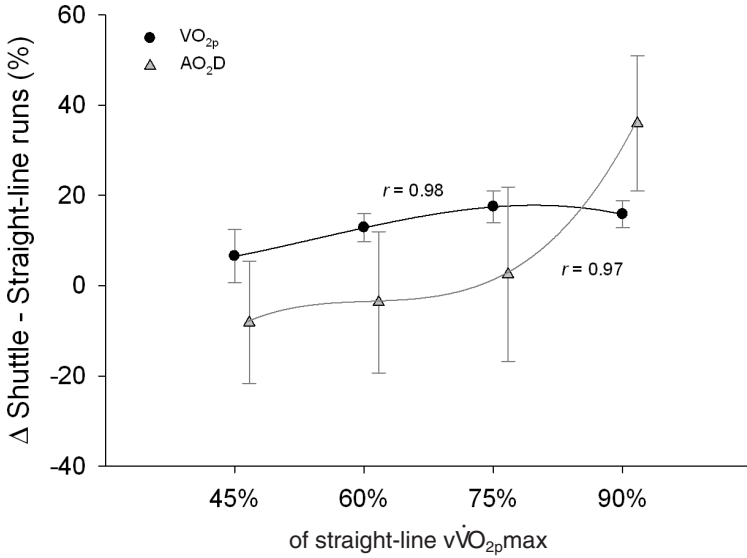


Figure 2 — Difference (\pm SEM) in pulmonary O_2 uptake (VO_{2p}) and accumulated O_2 deficit (AO_{2D}) as a function of exercise intensity, ie, as a percentage of the velocity associated with maximal O_2 uptake ($v\dot{V}O_{2p,max}$) during the straight-line incremental protocol. Muscle O_2 uptake (VO_{2m}) has been excluded for figure clarity (see results section). Lines are best fits for between-running conditions differences in the selected parameters vs running intensity using a second-order regression model.

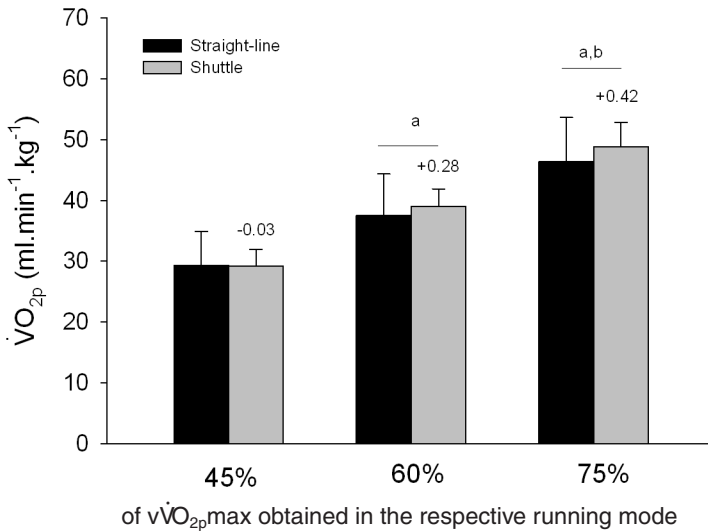


Figure 3 — End exercise (last 2 min) pulmonary oxygen uptake (VO_{2p}) measured for straight-line and estimated for shuttle runs performed a 45, 60 and 75% of the velocity associated with maximal O_2 uptake ($v\dot{V}O_{2p,max}$) during the incremental straight-line and shuttle protocols, respectively. a: significant difference vs 45%, b: vs 60%. Numbers provided are standardized differences for shuttle vs straight line (ie, Cohen's d , see methods).

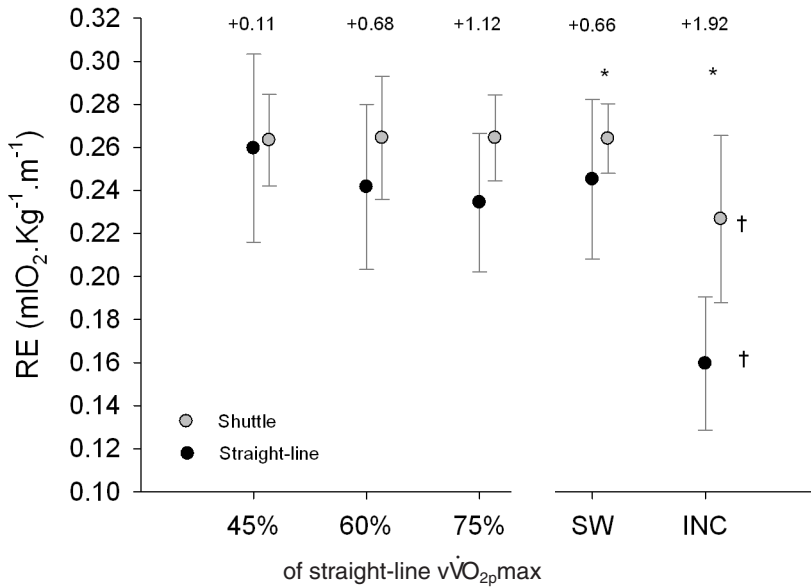


Figure 4 — Running economy (RE) measured during square-wave runs at different intensities relative to the velocity associated with maximal O₂ uptake ($v\dot{V}O_{2pmax}$) during the incremental straight-line test, average RE for the three square-wave runs (SW) and calculated RE during both straight-line or shuttle incremental tests (INC). *Significantly different from straight line. †Significantly different from SW. Numbers provided are standardized differences for shuttle vs straight line (ie, Cohen's *d*, see methods).

Running Economy

Figure 4 illustrates RE calculated from the three first SW tests or the INC tests for straight-line and shuttle protocols. We found a running mode ($P = .003$) but no intensity ($P = .24$) effect on RE during SW runs. Compared with the straight-line protocols, RE was impaired with COD for most SW intensities and INC. For both running conditions, the RE calculated from INC was different from that obtained from SW runs (both $P < .001$, Figure 4). During SW runs, within-athletes CVs for RE were 6.1 ± 2.9 and 5.7 ± 4.7 for straight-line and shuttle runs, respectively. Between-athletes CVs were 15.1 and 6.1% for straight-line and shuttle runs, respectively.

Correlations Between RE measured During Both Exercise Modes, Anthropometric Measures and Weekly Training/Competitive Volume

While there was a very large correlation between RE SW straight-line and RE SW shuttle ($r = .72$ [0.28;0.91]), RE INC straight-line and RE INC shuttle were not correlated ($r = .18$ [-0.41;0.67]). Also, there was a correlation neither between RE SW straight-line and RE INC straight-line ($r = -0.22$ [-0.69;0.38]), nor between RE

SW shuttle and RE INC shuttle ($r = -0.01 [-0.56; 0.55]$). Interestingly, Δ RE SW was positively related to height ($r = .56 [0.01; 0.85]$) and negatively to weekly training/competitive volume ($r = -0.58 [-0.86; -0.04]$). Similarly, Δ RE INC tended to be related positively to height ($r = .58 [0.04; 0.86]$) and negatively to weekly training/competitive volume ($r = -0.61 [-0.87; -0.09]$). There was, however, no clear correlation between either RE or Δ RE values and body weight and percentage body fat.

Discussion

The present study is the first to report selected physiological responses, including muscle O_2 uptake, to shuttle runs at various submaximal intensities. This is also the first time that two different field-based approaches to assess a team-sport-specific RE are examined. The four main findings of the present study were as follows. (1) At similar absolute running speeds, 20-m shuttle runs were associated with higher VO_{2p} , VO_{2m} , HR, $[La]_b$ and RPE values (and therefore impaired RE). (2) At similar relative running speeds (ie, as a similar percentage of the vVO_{2pmax} obtained with the respective running mode), estimated VO_{2p} responses were likely similar for both conditions. (3) The RE values calculated from the two incremental field tests differed significantly from these obtained from the square-wave runs. (4) For both square-wave and incremental tests, the differences in RE between the two exercise modes (ie, Δ RE) were largely related to players' height and weekly training/competitive volume.

Physiological Responses to Submaximal Field Running with Changes of Direction

While we acknowledge that the metabolic responses to shuttle runs are likely dependent of the shuttle length (ie, the shorter the distance, the greater the number of COD and probably the greater the metabolic responses), we restricted our examination to 20 m shuttles in the present study, because it is today the most commonly used shuttle running distance in the field. As previously observed for high-intensity intermittent runs⁹ and repeated sprints in the field,⁸ the inclusion of COD during submaximal runs was associated with a greater physiological load, as evidenced by increased cardiorespiratory, muscular O_2 consumption, blood lactate and RPE responses (Figure 1 and Table 1). Despite similar absolute running speed during each square-wave run, the repeated variations in instantaneous running speed (ie, decelerations, stops and [re]accelerations after each COD) were likely responsible for this greater physiological load. In fact, during acceleration and deceleration phases, the energy cost of running is larger than running at constant speed, by an amount that depends on this acceleration/deceleration itself.¹¹ The tendency for the greater VO_{2m} (based on Cohen's *d*, Figure 1) observed during the shuttle runs confirms the expected higher energetic demand of the lower limbs (each COD being thought to increase the energetic demand of the leg muscles as the number of turns increase²²). Present results contrast, however, with the recent study by Buchheit et al.,⁸ who did not report any difference in quadriceps deoxygenation levels between repeated (all-out) sprints performed with or without COD (25 vs 2 × 12.5 m sprints). Differences in exercise intensity and duration, as well as in the methods to approach muscle O_2 demand (absolute HHb_{Diff} levels⁸ vs estimated VO_{2m}

here), might partly explain these discrepancies. In addition, it is also possible that the medial gastrocnemius investigated in the present study was more solicited than the quadriceps,⁸ since it is the biarticulate muscles that are the more active during deceleration and acceleration phases.¹⁸ Finally, the greater magnitude of the changes in VO_{2p} compared with these in VO_{2m} with the addition of COD (based on Cohen's *d* values; Figure 1) might also suggest that the increased VO_{2p} could be also due to the involvement of additional upper-body muscles⁸ during the 20 m shuttle runs.

Present data show, however, for the first time that the commonly observed increase in anaerobic system participation during the shuttle runs^{8,9} was likely proportional to, or even lower than that of the aerobic system at low intensities ($\leq 75\%$). In fact, the percentage of anaerobic participation tended to be lower for the lowest running speeds (based on Cohen's *d* values; Figure 1 and 2). Therefore, while the introduction of COD at submaximal speeds shifts the overall metabolic cost of running toward higher values (see above and following discussion on RE), COD are more likely to put a (moderately) greater emphasis on the aerobic than on the anaerobic system. We only observed a greater percentage of anaerobic participation for the COD condition at 90% (Figure 1 and 2), which was likely explained by the fact that athletes ran above 100% of their shuttle $v\text{VO}_{2p\text{max}}$; VO_{2p} could not increase further to follow energetic (aerobic) demands. This lower anaerobic contribution with COD is also in line with previous studies that have reported lower blood lactate concentration after sport-specific exercises (ie, small-sided games, including repeated acceleration and deceleration phases and COD) compared with high-intensity running exercises.²³ When considering relative running speeds (ie, at a similar percentage of the $v\text{VO}_{2p\text{max}}$ in the specific running mode), VO_{2p} was not significantly different between the two running conditions (while it tended to be higher for the shuttle compared with the straight-line runs; all Cohen's *d* rated as small, Figure 3). Together with the similar $\text{VO}_{2p\text{max}}$, VO_{2m} , blood lactate and RPE values reached at the end of the two incremental protocols, these results illustrate the idea that submaximal exercise capacity and the associated cardiorespiratory and muscular responses might be tightly adjusted to maximal (possible) exercise capacity (ie, exercise "end point," as $(v)\text{VO}_{2p\text{max}}$ for an incremental tests to exhaustion). In fact, while the linearity of the metabolic cost vs running speed relationship is preserved with the introduction of COD, the rate of aerobic and anaerobic energy production (ie, the slope of their relationships vs running speed) is increased, which likely explains the lower peak running speed reached during the shuttle incremental test. It is, however, worth noting that the reduction in peak running speed (-14%) was higher than the increase in RE ($+8\%$, see below) during the incremental test. This suggests that nonmetabolic factors such as muscle fatigue, muscle structure alteration (because of the eccentric work inherent to deceleration phases) or psychological factors (based on between-condition differences in RPE, which is thought to directly govern exercise tolerance²⁴) might have also played a role in the deterioration of peak running performance during the shuttle incremental test.

Effect of Changes of Direction on Running Economy

Until now, RE has generally been assessed via (repeated) square-wave runs in endurance runners in the field²⁵ or soccer players in the laboratory.^{3,6,7} Present results show for the first time that the present approach with square-wave runs

including accelerations, decelerations and turns is likely appropriate to assess a more *team- or racquet-sport-specific RE* in the field in team-sport athletes. Given the higher gross O_2 cost of exercise during the shuttles SW runs (Figure 1), RE was not surprisingly found to be impaired with COD (Figure 4). As previously reported for treadmill testing,^{1,12,26} we also found RE to be independent of running speed, either for straight-line or shuttle runs (Figure 4). This was first surprising for the shuttle runs, since the absolute number of COD for a given running duration increases with the increase in running speed (ie, a higher RE could have therefore been expected at the higher running speeds). While this remains unclear, it is possible that the sensitivity of RE to COD number is not that high, which may simplify the optimal protocol to use (keeping the number of COD identical throughout the different running speeds requires the shuttle length to be modified). Within-athletes CVs for RE were also low and comparable for both running modes (6.1 ± 2.9 and $5.7 \pm 4.7\%$ for straight-line and shuttle runs, respectively). This is likely explained by the very strong linear relationships between the O_2 cost of exercise and running speed at the three lowest running intensities in both conditions (ie, 45, 60 and 75%, wherein the air resistance is negligible²⁷). Both absolute RE values and between-athletes CVs for the straight-line condition were also within the range of these reported in the literature for nonendurance athletes running on a treadmill.^{6,7}

While applying for the first time in the field di Prampero's¹² method to approach the O_2 cost of exercise from an incremental test, we found that the RE values derived from the incremental tests were systematically better than these calculated via the square-wave tests for both the straight-line and the shuttle protocol (Figure 4). This was first surprising since an impaired, rather than a better, RE could have been expected for the incremental tests. Indeed, compared with constant speed runs (ie, square-wave), the speed changes occurring at the end of each 30-s stage during the incremental field tests are likely responsible for accelerations of the runner's body, which are known to substantially increase the energetic cost of running.¹¹ While these unexpected results remain unclear, it is possible that the somewhat poor RE of our team sport players (ie, ≥ 0.24 mL $O_2 \cdot kg^{-1} \cdot m^{-1}$) was responsible for an exaggerated O_2 cost during the first 4 min period of the incremental tests, which, in turn, lowered the slope of the O_2 vs running speed relationship during the following incremental phase. Taking data derived from the SW runs as the criterion validity measure of RE, present data show therefore that RE calculation from incremental tests might not be valid to assess RE in team-sport players in the field, irrespective of running mode.

Determinants of Running Economy with Changes of Direction

Although the present correlations, given the limited sample size, must be considered with care, these relationships may offer researchers and coaches a starting point toward understanding the determinants of RE with COD, which is likely a key factor of success in team sports.^{2,3} Our present data show that athletes of shorter stature and/or presenting greater training/competitive volumes are likely to present a lower RE deterioration with the addition of COD. While it is not surprising that a shorter stature can help to turn efficiently and then reduce

energy waste, the beneficial impact of weekly training/competitive volume on the changes in RE with COD is in line with previous findings highlighting the trainability of COD abilities.²⁸ It is in fact possible that the athletes presenting the greater training/competitive volume have progressively developed a more economical locomotion during team-sport-specific displacements, which might explain the lower deterioration of their RE with the addition of COD. It should, however, be acknowledged that both the accuracy and the reliability of training/competitive volume assessment, as done in the present study, is unknown and could have affected our results. The fact that the degree of players' exposure to runs including COD, which might vary according to the specificity of each sport, was not precisely determined is another limitation of the present study. The impact of training load (ie, as a combination of both training volume and intensity) on a team-sport-specific RE and on the changes in this RE with COD requires further investigations in a larger number of team-sport players.

Practical Applications

Given the importance of both running economy³ and specific movement patterns in team sports such as soccer, the assessment of a team-sport-specific running economy in the field (ie, including deceleration, changes of direction and acceleration phases) is relevant to provide a precise determination of the specific endurance characteristics of the players. The VO_{2p} data derived from several square-wave submaximal (20 m) shuttle runs, but not from an incremental field test, can help coaches to individualize players' training contents, based on their endurance profile. Even though an improvement in a player's VO_{2pmax} could be achieved through high-intensity interval training sessions,²⁹ a larger volume of low-intensity runs and strength,⁴ team-sport-specific and agility²⁸ training might be required to improve this team-sport-specific running economy.

Conclusion

Present results confirm that compared with straight-line runs, runs including COD (ie, 20 m shuttle runs) are associated with greater overall energetic demands, and, in turn, an impaired RE. Present findings also show that the assessment of a *team- or racquet-sport-specific RE* (including accelerations, decelerations and turns) appears to be possible with the use of several square-wave submaximal (20 m) shuttle runs, but they do not support the use of incremental field tests to assess running economy in the field in nonendurance athletes. Present results restricted to 20 m shuttle runs should, however, be considered with caution before being generalized to other shuttle lengths and/or COD angles. Future work is also needed to investigate the cost of running/displacements through more sport-specific movement patterns.³⁰

Acknowledgments

The authors declare no conflict of interest. The authors thank Pierre-Marie Leprêtre for his help in data collection, Hani Al Haddad and Alberto Mendez-Villanueva for suggestions during the preparation of the manuscript, and the subjects for their enthusiastic participation.

References

1. di Prampero PE, Atchou G, Bruckner JC, Moia C. The energetics of endurance running. *Eur J Appl Physiol Occup Physiol*. 1986;55:259–266.
2. Iaia FM, Rampinini E, Bangsbo J. High-intensity training in football. *Int J Sports Physiol Perform*. 2009;4:291–306.
3. Ziogas GG, Patras KN, Stergiou N, Georgoulis AD. Velocity at lactate threshold and running economy must also be considered along with maximal oxygen uptake when testing elite soccer players during preseason. *J Strength Cond Res*. 2011;25:414–419.
4. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med*. 2004;34:465–485.
5. Coyle EF. Integration of the physiological factors determining endurance performance ability. *Exerc Sport Sci Rev*. 1995;23:25–63.
6. Helgerud J, Engen LC, Wisloff U, Hoff J. Aerobic endurance training improves soccer performance. *Med Sci Sports Exerc*. 2001;33:1925–1931.
7. Impellizzeri FM, Marcora SM, Castagna C, et al. Physiological and performance effects of generic versus specific aerobic training in soccer players. *Int J Sports Med*. 2006;27:483–492.
8. Buchheit M, Bishop D, Haydar B, Nakamura FY, Ahmaidi S. Physiological responses to shuttle repeated-sprint running. *Int J Sports Med*. 2010;31:402–409.
9. Dellal A, Keller D, Carling C, Chaouachi A, Wong DP, Chamari K. Physiologic effects of directional changes in intermittent exercise in soccer players. *J Strength Cond Res*. 2010;24:3219–3226.
10. Osgnach C, Poser S, Bernardini R, Rinaldo R, di Prampero PE. Energy cost and metabolic power in elite soccer: a new match analysis approach. *Med Sci Sports Exerc*. 2010;42:170–178.
11. di Prampero PE, Fusi S, Sepulcri L, Morin JB, Belli A, Antonutto G. Sprint running: a new energetic approach. *J Exp Biol*. 2005;208:2809–2816.
12. di Prampero PE, Salvadego D, Fusi S, Grassi B. A simple method for assessing the energy cost of running during incremental tests. *J Appl Physiol*. 2009;107:1068–1075.
13. Billat LV, Koralsztein JP. Significance of the velocity at VO₂max and time to exhaustion at this velocity. *Sports Med*. 1996;22:90–108.
14. Wasserman K, Whipp BJ, Koyl SN, Beaver WL. Anaerobic threshold and respiratory gas exchange during exercise. *J Appl Physiol*. 1973;35:236–243.
15. Bosquet L, Duchene A, Delhors PR, Dupont G, Carter H. A comparison of methods to determine maximal accumulated oxygen deficit in running. *J Sports Sci*. 2008;26:663–670.
16. Buchheit M, Laursen PB, 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;107:460–470.
17. van Beekvelt MC, van Engelen BG, Wevers RA, Colier WN. In vivo quantitative near-infrared spectroscopy in skeletal muscle during incremental isometric handgrip exercise. *Clin Physiol Funct Imaging*. 2002;22:210–217.
18. Jacobs R, Bobbert MF, van Ingen Schenau GJ. Function of mono- and biarticular muscles in running. *Med Sci Sports Exerc*. 1993;25:1163–1173.
19. Van Beekvelt MC, Colier WN, Wevers RA, Van Engelen BG. Performance of near-infrared spectroscopy in measuring local O₂ consumption and blood flow in skeletal muscle. *J Appl Physiol*. 2001;90:511–519.
20. Pyne DB, Boston T, Martin DT, Logan A. Evaluation of the Lactate Pro blood lactate analyser. *Eur J Appl Physiol*. 2000;82:112–116.
21. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41:3–13.

22. Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport: a review of resistance training studies. *Sports Med.* 2008;38:1045–1063.
23. Buchheit M, Lepretre PM, Behaegel AL, Millet GP, Cuvelier G, Ahmaidi S. Cardio-respiratory responses during running and sport-specific exercises in handball players. *J Sci Med Sport.* 2009;12:399–405.
24. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J Appl Physiol.* 2009;106:857–864.
25. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol.* 1999;86:1527–1533.
26. Helgerud J, Storen O, Hoff J. Are there differences in running economy at different velocities for well-trained distance runners? *Eur J Appl Physiol.* 2010;108:1099–1105.
27. Pugh LG. The influence of wind resistance in running and walking and the mechanical efficiency of work against horizontal or vertical forces. *J Physiol.* 1971;213:255–276.
28. Young WB, McDowell MH, Scarlett BJ. Specificity of sprint and agility training methods. *J Strength Cond Res.* 2001;15:315–319.
29. Helgerud J, Hoydal K, Wang E, et al. Aerobic high-intensity intervals improve VO₂max more than moderate training. *Med Sci Sports Exerc.* 2007;39:665–671.
30. Hoff J, Wisloff U, Engen LC, Kemi OJ, Helgerud J. Soccer specific aerobic endurance training. *Br J Sports Med.* 2002;36:218–221.