Original Investigation

Characterising running economy and change of direction economy between soccer players of different playing positions, levels and sex

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Abstract

Traditional movement economy (ME) measures the energetic cost of in-line running. However, it is debatable whether such a measure is representative of movement efficiency for team sport athletes who are required to run and change direction repeatedly. This study evaluated ME during both in-line running and runs with directional changes and provided a preliminary exploration as to whether these abilities discriminate soccer players according to playing position, level, and sex. Forty-three soccer players were assessed for ME as extrapolated from oxygen uptake during in-line running (RE) and running with changes of directions (using 20 and 10 m shuttle runs [SRE₂₀ and SRE₁₀]) at 8.4 km/h mean speed. ME worsened with change of direction frequency (p < 0.001). Coefficient of determination was high between RE and SRE₂₀ (r² = 0.601) but dropped below 0.5 for RE and SRE₁₀ (r² = 0.280) as change of direction frequency increased. No significant differences were observed between different player positions, however, centre midfielders reported the best ME across any position and running mode, with the largest differences observed in centre backs over SRE₁₀ (41.9 ± 2.7 ml/kg/min [centre midfielders] vs 45 ± 1.8 ml/kg/min [centre backs]; ES = 1.19). No significant differences were observed for SRE₁₀ over any running condition for male players of different playing levels. Female players exhibited better ME than male players with significant differences observed for SRE₁₀ (41.5 ± 2.6 ml/kg/min [females] vs 44 ± 2.6 ml/kg/min [males]; p = 0.013; ES = 0.94). RE does not adequately account for efficiency during activities that involve changes of direction. SRE₁₀ is a stronger discriminator of ME between soccer players of different position and sex.

1. Introduction

Soccer is an intermittent team-sport requiring a complex interaction of technical, tactical and physical qualities to succeed (Gamble, 2006). Among player’s physical qualities, endurance is particularly important to counteract the progressive decrement in the distance and intensity of runs observed during 90-min matches (Dolci, Hart, et al., 2020; Dolci, Kilding, Chivers, Piggott, & Hart, 2020). One critical physical quality affecting endurance performance is movement economy (ME) which represents the energetic expenditure of specific exercises or tasks (Dolci et al., 2018). Specifically, economical players require less energy to execute a given activity, hence are more efficient (and become less fatigued) during the performance of similar game situations (Dolci et al., 2018). For this reason, the quantification of ME values across soccer players in a team environment is considered a relevant and important aspect to identify individual performance characteristics, and evaluate the effectiveness of training programmes aiming to improve endurance performance, which can in-turn influence overall game performance (Dolci et al., 2018).

Studies quantifying ME in soccer have been limited to males and in-line running assessments, and have produced conflicting results regarding the ability of ME to discriminate between playing positions, with two studies reporting a non-significant trend of better ME in midfielders (Nilsson & Cardinale, 2015a; Santos-Silva, Greve, & Pedrinelli, 2017), and one study observing significantly higher ME values for centre midfielders and wide-field players compared to centre backs and strikers (Boone, Deprez, & Bourgois, 2014). The discriminant...
ability of ME also appears to be discordant between playing levels, with one study reporting better ME for first league professional players versus second league professional players; but no further differences between second league professional players and third league semi-professional players (Ziogas et al., 2011). This highlights the potential limitation of ME to satisfactorily distinguish between soccer players of varying positions and playing level, which is perhaps a function of test specificity. For example, the traditional methodology to assess ME in soccer has been adopted from distance running (referred to as running economy [RE]), which requires athletes to run at a constant speed on treadmill (in-line), while breathing throughout a spirometry system capturing metabolic and respiratory values while achieving an oxygen plateau condition (Dolci et al., 2018). However, RE with a straight line running might be unable to account for ME specifically to team-sport tasks (Buchheit, Haydar, Hader, Ufland, & Ahmaid, 2011; Dolci et al., 2018), which require frequent acceleration, deceleration and change of direction (COD) movements (Dolci, Hart, et al., 2020).

Recently, a more specific test which assesses ME during runs with COD (referred to as change of direction economy [CODE]) has been proposed for team-sport athletes to assess economy under sport-specific conditions. Specifically, ME tests involving COD capture more specific information regarding the ability of soccer players’ to perform accelerations, decelerations and directional changes (Buchheit et al., 2011) which are required in games. However, it is not yet known whether RE and CODE describe similar or independent abilities, and if independent, whether CODE can more strongly discriminate between player positions, level or sexes. Accordingly, this study seeks to characterise RE and CODE of soccer players of different playing positions, playing levels and sex; to examine the correlation and coefficient of determination between RE and CODE; and to compare CODE values between positions, levels and sex to assess whether CODE has discriminatory capabilities more sensitive than RE.

2. Materials and methods

2.1. Participants

Forty-three outfield soccer players (age = 18.5 ± 1.6 years) were recruited from a soccer team competing in the Australian Men’s State League 1st Division (n = 14); a team concurrently competing in the Australian Men’s National Premier League and Youth A-League (n = 13); and a team competing in Australian Women’s Premier Division (n = 16). Player characteristics for each group are described in Table 1. Players competing in the National League and Youth A-League were defined as elite players, owing to their full-time training schedule (up to six times a week) at a professional club; and competing at the highest national competitive level for their age. All other players were defined as sub-elite due to competing within the best three country league-tiers, but training not more than three times a week (plus game) for a non-professional club (Whalan, Lovell, McCunn, & Sampson, 2019). Each participant was provided with an information letter outlining the requirements, benefits, and risks of the research, and provided written informed consent to participate prior to commencing any testing procedures. All procedures in this study were approved by the Human Research Ethics Committees at two Universities (017193F DOLCI and 19670 HART) and were run in accordance with the Declaration of Helsinki (World Medical Association).

2.2. Procedures

A within- and between-subjects experimental design was used to examine ME under three different running conditions (in-line running [RE]; 20 m shuttle running [SRE20]; 10 m shuttle running [SRE10]); across players of different playing positions, playing level, and sex. All assessments occurred during the late pre-season period in an indoor laboratory with a standardised temperature set at 25 ± 3°C. Participants completed a familiarisation session for all ME tests a week prior to their official testing visit at times that suited their schedule, and were asked to comply with the following standardised conditions: (1) avoid alcohol, caffeine, and intense physical activity (or training) for 24 h prior to the test, (2) avoid eating during the two hours preceding the test, and (3) have regular sleep (>7 h) the day before the test. All participants verbally provided confirmation of adhering to pre-testing requirements.

Prior to commencement, participants self-reported their most common playing position during matches over the last 2-year period. Soccer formations are comprised of defensive, midfield and forward lines, thus playing positions were defined as:

- Centre backs: any player in a 3-player defensive line; the three players competing at the centre of a 5-player defensive line; or the two players at the centre of a 4-player defensive line,
- Wide-field players: the two players on the sides of a 4–5-player defensive line (also referred as full-backs); or the two players on the sides of a 4–5-player midfield line, (also referred as external midfielders); or the two players on side of a 3-players forward line (wingers);
During the first 5 min interval, ME was assessed during continuous in-line running (RE) on a motorised treadmill at 1% gradient ramp inclination, to evoke comparable \( V_O_2 \) values to overground running (Jones & Doust, 1996). Thereafter, ME was assessed on an indoor running surface (Mondo Track, Mondo S.p.A., Italy) while performing 5 min shuttle running over 20 metres (SRE20); and 5 min over 10 metres (SRE10). Shuttle run lengths were marked with tape (at 10 and 20 m) to provide players with an axis point to change direction. The mean speed for all intervals was 8.4 km/hr, chosen to be within the range (±1.6 km/hr) of speed used to assess RE with soccer players in prior studies (Dolci et al., 2018), and reflecting jogging to low speed running activities, which are performed to cover 60–70% total match distance (Silva, Magalhães, Ascensão, Seabra, & Rebelo, 2013). While running on the treadmill utilised a pre-set motor speed for RE; for SRE20 and SRE10, speed was set using an audible metronome, producing an audible beep sound every time the participants were to be on the COD line, akin to a beep test. During SRE20 and SRE10, participants were instructed to continuously alternate the right and left foot to change direction to standardise conditions. The performance of this ME testing battery has been recently observed to be a reliable assessment in soccer players, with coefficient of variation ranging from 3.5% to 5.8% (Dolci, Kilding, Spiteri, et al., 2020).

Heart rate (HR) was monitored continuously (5 s intervals) during the testing procedures with the mean HR over the final minute of each 5 min interval considered as representative of the interval demand. Similarly, oxygen consumption (\( V_O_2 \)) and respiratory exchange ratio (RER) for each running mode (RE; SRE20, SRE10) were recorded continuously and averaged during the final minute of each test (4th to 5th minute) to determine ME expressed as oxygen cost (\( O_C; \text{ml/kg/min} \)) and energetic cost (\( E_C; \text{Kcal/kg/km} \)) following calculation methods previously described by Dolci, Kilding, Spiteri, et al. (2020). To assess steady state (defined as an increase in \( V_O_2 <200 \text{ml/min} \) Billat, 2000) the final 2 min period were compared for each test.

### 2.3. Measures

#### 2.3.1. Anthropometry

Each participant’s height was measured to the nearest 0.1 cm using a stadiometer (Model 222, Seca, Hamburg, DE) and weight assessed to the nearest 0.1 kg using a digital weight scale (AE Adams CPWPlus-200; Adam Equipment Inc., CT, USA) at the beginning of the testing session.

#### 2.3.2. Movement economy

Participants performed a 5 min standardised warm-up, including mobility and dynamic stretching exercises, and were then fitted with an automated portable gas analyser (MetaMax 3B, Cortex, Leipzig, Germany) and heart rate monitor (H10, Polar, Kempele, Finland). The portable gas analyser was calibrated at the beginning of every testing day for pressure, gas and volume calibrations in accordance with manufacturer specifications, previously reported to produce good reliability (inter-device technical error of measurement ≤ 1.6%) (Macfarlane & Wong, 2012). Participants commenced the ME testing battery which consisted of 3 × 5 min intervals of running under different conditions interspersed with 3 min passive recovery plus another 4 min of active recovery (walking at a self-selected pace) between each running condition. At the end of each 3 min passive recovery period, blood lactate (BLa) was measured through a lancet-induced fingertip puncture to provide a 5μL (microliter) blood sample, analysed with a portable blood lactate analyser (Lactate Pro2 Analyser, Arkray, Kyoto, Japan).

### Table 1. Players’ characteristics.

| Playing Level | N   | Age (years) Mean ± SD | Height (cm) Mean ± SD | Weight (kg) Mean ± SD | Soccer experience (years) Mean ± SD | Mean Training (sessions per week*) |
|---------------|-----|-----------------------|-----------------------|-----------------------|------------------------------------|-----------------------------------|
| Elite males   | 13  | 18.6 ± 1.2            | 179.4 ± 5.7           | 68.5 ± 4.9            | 10.5 ± 2.6                         | 5                                 |
| Sub-elite males| 14  | 18.1 ± 1.1            | 176.9 ± 9.5           | 68.4 ± 8.6            | 10.4 ± 3.5                         | 3                                 |
| Sub-elite females | 16 | 18.9 ± 2.1            | 164 ± 6.6             | 61.7 ± 6.3            | 10.1 ± 3.5                         | 2                                 |

*Match excluded.

- Centre midfielders: any player in a 3-player midfield line; the three players at the centre of a 5-player midfield line; or the two players at the centre of a 4-player midfield line;
- Strikers: centre forward in a 3-players attacking line or any players in a 2-players attacking line.

Notably, in the wide-field players category, we grouped together sub-categories such as full-backs and external midfielders. This is because players who played full-backs in 4-3-3 or 4-4-2 formations, also reported that they played as external midfielders in the tactical formation such as 3-5-2 or 3-4-3.

### 2.4. Statistical analysis

Statistical analysis was performed using SPSS (IBM SPSS version 25.0; Chicago, IL, USA), with statistical
significance level set at $p < 0.05$. All data were checked for normality using the Shapiro–Wilk test. Linear mixed models (with a pairwise Bonferroni post-comparison) were applied to identify differences in ME (as $O_C$ and $E_C$), $BLa$ and HR across the three different running conditions (RE, SRE$_{20}$ and SRE$_{10}$) as a fixed effect, with participant set as a random intercept using variance component covariance type. The model used a restricted maximum likelihood estimation method. Model residuals were visually inspected, and no major violations were noted. Pearson’s product moment correlation coefficient (or the non-parametric alternative Spearman’s correlation) was then used to determine the relationship between ME during in line running condition (RE), over 20 m shuttle running condition (SRE$_{20}$) and 10 m shuttle running condition (SRE$_{10}$) of all participants. Resulting correlation coefficients with 95% confidence limits were defined as followed: small (0.1), moderate (0.3), large (0.5), very large (0.7) and extremely large (0.9) magnitudes of the correlation coefficient (Barnes, Mcguigan, & Kilding, 2014). Coefficient of determination was calculated as the squared value of Pearson’s product moment correlation coefficient (Thomas & Nelson, 2001). A coefficient of determination lower than 0.50 for physical abilities assessed (RE, SRE$_{10}$ and SRE$_{20}$) were considered to be independent from each other (Thomas & Nelson, 2001).

One-way analysis of variance (ANOVA) (or Kruskal–Wallis Test for nonparametric variables) was used to compare values for each outcome ME (RE, SRE$_{20}$ and SRE$_{10}$ as both $O_C$ and $E_C$) and the other variables monitored during economy test (HR, RER and $BLa$) across player group differences in (elite male, sub-elite male, sub-elite female). Bonferroni post hoc pairwise comparisons examined differences between level (elite and sub-elite males) and sex (sub-elite males and females). An additional analysis was used to examine player position, with Bonferroni post hoc pairwise comparisons of centre backs, centre midfielders, wide-field players, and strikers. The Hedges’s g effect size (ES) was used to calculate the biased corrected standardised mean difference between ME values of different group categories using an excel spreadsheet available at https://www.cem.org/effect-size-calculator. Threshold values for ES statistics were defined as: >0.2–0.5 (small), >0.5–0.8 (moderate) and >0.8 (large) (Hopkins, Marshall, Batterham, & Hanin, 2009).

3. Results

3.1. Movement economy over different movement economy tests

Mean scores in ME (as $O_C$ and $E_C$), HR and $BLa$ during each running condition are depicted in Figure 1. Linear mixed models (LMM) post hoc comparisons found RE expressed as $O_C$ and $E_C$ was significantly lower than SRE$_{20}$ and SRE$_{10}$ ($p < 0.001$), whereas SRE$_{20}$ was significantly lower than SRE$_{10}$ ($p < 0.001$). For outcome HR, LMM indicated a significantly higher HR for SRE$_{10}$ compared to RE and SRE$_{20}$ ($p < 0.001$); and for SRE$_{20}$ compared to RE ($p < 0.001$). For outcome $BLa$, LMM reported no significant differences across any running mode.

Pearson product movement correlation coefficients indicated a significant large correlation between RE and SRE$_{10}$ expressed as both $O_C$ and $E_C$ ($r = 0.528$, $p < 0.001$ and $r = 0.529$, $p < 0.001$ respectively), and a significant very large correlation between RE and SRE$_{20}$ as $O_C$ and $E_C$ ($r = 0.775$, $p < 0.001$ for both expression approach). Notably, the coefficient of determination indicated that overall, RE can account for SRE$_{20}$, ($r^2 = 0.601$ for both $E_C$ and $O_C$); but not for SRE$_{10}$ ($r^2 = 0.280$ and 0.279 for $E_C$ and $O_C$ respectively).
3.2. Movement economy across players of different positions, level and sex

Descriptive statistics and differences for ME and related secondary cardiorespiratory scores between players of different playing position, competitive level and sex are reported in Table 2; and effect sizes of differences are illustrated in Figure 2.

For each outcome, ANOVA examined player position differences. Post hoc comparisons reported non-significant but large effect size difference between centre mid-fielders and centre backs for both SRE$_{20}$ (ES = 1.10 [OC reported]) and SRE$_{10}$ (ES = 1.19 [OC reported]). In addition, ME demonstrated moderate differences between centre midfielders and wide-field players for each running condition; and between centre midfielder and strikers for SRE$_{10}$, although these were not statistically significant. Moderate differences were also observed for SRE$_{20}$ as OC between defenders and strikers (ES = 0.59) and between defenders and wide midfielders (ES = 0.51), but these also did not reach statistical significance. For all secondary outcome variables (VO$_2$, HR, Bla and RER) there were no significant differences between player position differences with only small or trivial effects. The exception was VO$_2$ which reported moderate to large effects, in particular for SRE$_{10}$ for strikers and defender compared to wide-field players (ES = 0.71 and 0.95 respectively) and centre-midfielders (ES = 0.89 and 1.02 respectively).

ANOVA post hoc between level group differences for elite and sub-elite male players reported no significant and only trivial to small differences for any ME scores. Differences for secondary monitored outcomes variables were all not significant with trivial to small effects reported. The exception was HR during SRE$_{20}$ which was not-significantly but moderately lower for elite players (ES = 0.53). Post hoc comparison between sex for sub-elite females and sub-elite male players reported no significant sex differences, but a moderate effect for RE and SRE$_{20}$ (ES = 0.59 and 0.78 respectively [OC reported]). For SRE$_{10}$, sub-elite female players had significantly better scores than sub-elite male players ($p = 0.013$; ES = 0.94 [OC reported]). Sub-elite females had significantly higher values of Bla, over SRE$_{10}$ ($p = 0.004$; ES = 1.34); higher HR over both SRE$_{20}$ ($p = 0.001$; ES = 0.99) and SRE$_{10}$ ($p = 0.002$; ES = 1.01). Additionally, female players had significantly higher RER over both RE ($p = 0.028$ ES = 0.09) and SRE$_{10}$ ($p < 0.001$ ES = 0.25).

4. Discussion

Running economy (RE) and change of direction economy (CODE, assessed through SRE$_{20}$ and SRE$_{10}$) in soccer players was quantified to understand whether economy of movement over runs with COD had different physical qualities to in-line running. In addition, RE and CODE were characterised across playing positions, level, and sex, and further examined to establish whether these ME assessments had discriminatory capabilities. Our study importantly found that RE and CODE were different, especially when over running modes involving higher COD frequencies (SRE$_{10}$), illustrating that different physical qualities underpin ME assessments. Further, our study demonstrated that SRE$_{10}$ had greater discriminatory ability between players of different position and sex when compared to RE and SRE$_{20}$.

4.1. Movement economy over different movement economy tests.

Shuttle runs evoked higher O$_C$ and E$_C$ than in-line running at the same mean speed, which was especially prevalent as the frequency of COD turns increased (RE vs. SRE$_{20}$ vs. SRE$_{10}$). These findings concur with previous studies using other team-sport athletes who reported higher physical demands for shuttle runs versus in-line running (Buchheit et al., 2011; Stevens et al., 2015) and for shuttle runs with high vs. low COD frequency (every 3 m to once every 9 m) (Hatamoto et al., 2013). The logical reason for this is the greater mechanical work (and in turn cost of muscular contractions) required to decelerate the body, and re-accelerate it the new direction (Minetti, Gaudino, Seminati, & Cazzola, 2012) required in the tests involving shuttle runs, which is not presently captured by commonly used RE assessments. However, the observed increase in O$_C$ and E$_C$ was not followed by a linear increase in Bla, suggesting a lower percentage of anaerobic energy system contribution during submaximal runs with COD. This supports the results from Buchheit and colleagues (Buchheit et al., 2011) who reported a significant increase in anaerobic energy contribution during shuttle runs at only high intensities (90% maximal oxygen consumption [VO$_{2\text{max}}$]). This might be partly due to the higher demand of shuttle runs (compared to in-line running), as (1) eccentric contractions (required to decelerate when approaching COD) (Hader, Mendez-Villanueva, Palazzi, Ahmadi, & Buchheit, 2016) produce less lactic acid than isometric and concentric contractions which are more predominant during continuous in-line running (Douglas, Pearson, Ross, & McGuigan, 2017) and (2) non-locomotor muscle contractions (to stabilise the upper body during COD movements Buchheit et al., 2011) are also likely to produce less lactic acid as they involve no explosive activity. Nonetheless, blood lactate values were lower than standard lactate turning
### Table 2. Descriptive statistics and differences for movement economy values and related secondary variables between players of different playing position, competitive level and sex.

| Variables                        | Centre back (n = 6) | Wide-field players (n = 11) | Centre midfielders (n = 17) | Strikers (n = 9) | Group differences | Elite males (n = 13) | Sub-elite males (n = 14) | Sub-elite female (n = 16) | Group differences |
|---------------------------------|---------------------|-----------------------------|----------------------------|------------------|-------------------|----------------------|------------------------|---------------------------|-------------------|
|                                 | Mean ± SD           | Mean ± SD                   | Mean ± SD                  | Mean ± SD        |                   | Mean ± SD            | Mean ± SD              | Mean ± SD                 |                   |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           |                   |
| In-line running O C (ml/kg/min) | 34.4 ± 3.0          | 34.9 ± 2.6                  | 33.2 ± 3.2                | 33.5 ± 4.0       | 0.833             | 33.9 ± 2.6           | 35 ± 2.6               | 33 ± 3.0                 | 2.419             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.102             |
| EC (Kcal/kg/km)                 | 1.26 ± 0.11         | 1.28 ± 0.10                 | 1.22 ± 0.08              | 1.23 ± 0.14      | 0.931             | 1.24 ± 0.10          | 1.28 ± 0.09             | 1.21 ± 0.11               | 1.827             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.174             |
| VO2 (L/min)                     | 2.4 ± 0.3           | 2.2 ± 0.2                   | 2.3 ± 0.3                | 2.3 ± 0.4        | 1.440             | 2.3 ± 0.2            | 2.4 ± 0.4              | 2 ± 0.2                  | 8.481             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.001             |
| HR (bpm/min)                    | 149 ± 34.3          | 136.1 ± 48.4                | 134.8 ± 39.9             | 144.2 ± 16.9     | 0.310             | 133.9 ± 13.4         | 143.6 ± 17.6            | 159.5 ± 18.4              | 8.570             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.007             |
| RER                             | 0.94 ± 0.06         | 0.96 ± 0.02                 | 0.95 ± 0.05              | 0.95 ± 0.04      | 0.697             | 0.94 ± 0.04          | 0.93 ± 0.05             | 0.95 ± 0.31               | 7.151             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.028             |
| BLa (mmol/L)                    | 1.6 ± 0.9           | 1.6 ± 0.9                   | 1.6 ± 1                  | 1.8 ± 1.2        | 0.699             | 1.5 ± 1.0            | 1.8 ± 1.1              | 1.6 ± 0.8                | 0.754             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.686             |
| 20 m shuttle running O C (ml/kg/min) | 39.3 ± 3.1         | 37.9 ± 2.3                  | 36.1 ± 2.7               | 36.7 ± 2.5       | 0.634             | 35.7 ± 2.3           | 36.8 ± 2.6             | 38 ± 2.6                  | 4.287             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.117             |
| EC (Kcal/kg/km)                 | 1.45 ± 0.12         | 1.40 ± 0.09                 | 1.33 ± 0.95              | 1.37 ± 0.13      | 2.184             | 1.38 ± 0.11          | 1.41 ± 0.11             | 1.34 ± 0.10               | 2.098             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.136             |
| VO2 (L/min)                     | 2.7 ± 0.4           | 2.4 ± 0.2                   | 2.6 ± 0.04               | 2.7 ± 0.06       | 6.177             | 2.56 ± 0.28          | 2.63 ± 0.41             | 2.23 ± 0.19               | 10.668            |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.005             |
| HR (bpm/min)                    | 159.4 ± 24.6        | 143.4 ± 51.7                | 142.3 ± 42.6             | 153.7 ± 17.4     | 0.308             | 141.6 ± 16.1         | 151.3 ± 19.2            | 170 ± 18.1               | 9.105             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.001             |
| RER                             | 0.97 ± 0.07         | 0.97 ± 0.03                 | 0.97 ± 0.04              | 0.97 ± 0.04      | 1.806             | 0.97 ± 0.03          | 0.95 ± 0.05             | 0.99 ± 0.02               | 5.177             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.075             |
| BLa (mmol/L)                    | 1.8 ± 1.8           | 1.38 ± 0.7                  | 1.3 ± 0.6                | 1.3 ± 0.5        | 0.183             | 1.15 ± 0.40          | 1.70 ± 1.27             | 1.30 ± 0.48               | 1.170             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.557             |
| 10 m shuttle running O C (ml/kg/min) | 45.1 ± 1.8         | 43.8 ± 2.8                  | 41.9 ± 2.7               | 43.8 ± 3.4       | 2.428             | 44.4 ± 3.1           | 44 ± 2.6                | 41.5 ± 2.6               | 4.854             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.013             |
| EC (Kcal/kg/km)                 | 1.66 ± 0.08         | 1.62 ± 0.11                 | 1.55 ± 0.10              | 1.62 ± 0.13      | 2.333             | 1.64 ± 0.12          | 1.62 ± 0.10             | 1.54 ± 0.10               | 3.874             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.029             |
| VO2 (L/min)                     | 3.1 ± 0.3           | 2.8 ± 0.3                   | 2.7 ± 0.4                | 3.1 ± 0.5        | 2.104             | 3.1 ± 0.3            | 3 ± 0.4                 | 2.6 ± 0.2                | 24.175            |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | <0.001            |
| HR (bpm/min)                    | 171.0 ± 20.5        | 154.5 ± 55.6                | 153.7 ± 44.9             | 165.1 ± 18.2     | 0.283             | 155.1 ± 18.3         | 162.3 ± 18.7            | 181 ± 17.7               | 7.357             |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.002             |
| RER                             | 0.99 ± 0.07         | 1.00 ± 0.04                 | 1.00 ± 0.05              | 0.99 ± 0.04      | 0.346             | 1.00 ± 0.03          | 0.96 ± 0.05             | 1.03 ± 0.02               | 16.361            |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | <0.001            |
| BLa (mmol/L)                    | 1.2 ± 0.6           | 1.7 ± 0.9                   | 1.6 ± 0.9                | 1.8 ± 1.1        | 1.963             | 1.4 ± 1.0            | 1.22 ± 0.5              | 2.2 ± 0.9                | 11.301            |
|                                 |                     |                             |                           |                  |                   |                      |                        |                           | 0.004             |

Notes: c= non parametric values, Welch F statistic reported; b missing heart rate data from 1 participant; d missing heart rate data from 2 participants. Bonferroni Pairwise Comparisons: ▲ no significant differences following Bonferroni Pairwise Comparison; ▲ significant difference between elite males and sub-elite females, ▲ significant difference between sub-elite males and sub-elite females. RE = running economy; SRE20 = 20 m shuttle running economy; SRE10 = 10 m shuttle running economy; O C = oxygen cost; E C = energetic cost; VO2 = oxygen uptake; RER = respiratory exchange ratio; HR = heart rate, BLa = blood lactate.
point values (4 mmo/L) (Ziogas et al., 2011), which indicates that running intervals were performed at intensities below the lactate threshold. Hence, whether aerobic and anaerobic energy contribution to running activity with and without COD increases linearly at exercise intensities above the lactate threshold requires further investigations.

To the best of the authors’ knowledge, this is the first study to examine the ability of RE to account for movement efficiency over shuttle runs (CODE), which are more specific to soccer, as they involve key movements patterns such as acceleration, deceleration and COD (Buchheit et al., 2011). Previous studies, specifically involving soccer players, report a low coefficient of determination between in-line sprint (20 m) and COD sprints ($r^2 = 0.109–0.209$) (Buttifant, Graham, & Cross, 2001; Little & Williams, 2005), indicating that the ability to quickly perform maximal sprints relative to COD are disparate physical qualities. Our study extends on these findings by demonstrating that the efficiency of movement during activities involving COD is also a disparate physical quality to in-line running, but only when the frequency of COD is high (i.e. SRE$_{10}$ but not SRE$_{20}$). This is in agreement with Sheppard and Young’s (Sheppard & Young, 2006) suggestion that there is a lower transfer from in-line activities to COD activities as the COD frequency increases. Importantly, the frequency of COD during SRE$_{10}$ (rather than during SRE$_{20}$) more closely replicates the mean of changes in locomotor patterns occurring during a soccer match (every ~3 s) (Dolci, Hart, et al., 2020) which further supports the inadequacy of using RE to account for team-sport specific efficiency and movement economy in sports such as soccer.

Efficiency of movement is determined by a complex interaction of cardiopulmonary and neuromechanical factors (Dolci et al., 2018). The inability of RE to account for SRE$_{10}$ is likely due to significant alterations in cardiopulmonary and neuromechanical contributions to specific running modes (Dolci et al., 2018). In particular, a high lower-body stiffness has been previously reported as a major contributor of RE because it allows for greater elastic energy reutilisation during continuous running and, in turn, helps to reduce the energetic cost of required muscle contraction (Barnes et al., 2014). However, elastic energy reutilisation is greatly reduced during runs with COD, because of the prevalence of concentric muscle activity to continuously re-accelerate the body when changing direction (Zamparo et al., 2016). This suggests that other neuromuscular qualities, such as muscular power, might be a more important determinant of CODE to compensate lower elastic energy utilisation and contribute to the increased metabolic cost. Kinematic aspects may also play a role as they have been reported to greatly affect efficiency of movement, and vary depending on the specific running mode (Dolci et al., 2018). Specifically, during the performance of maximal activities, it has been observed that kinematics aspects leading to faster in-line acceleration (i.e. decreased stride length, increased forward lean and knee lift in the initial step) differ from most relevant kinematics aspects for faster COD sprints (increased stride frequency) (Hewit, Cronin, & Hume, 2013). Hence, whether these kinematics factors allow also for more efficiency during submaximal runs with COD is worthy of future investigations.

### 4.2. Movement economy across players of different positions, level, and sex

Movement economy between playing positions displayed no significant differences in our study, however, this was limited by a relatively small sample size for this analysis. Although, effect sizes indicated a trend...
for midfielders having better ME than all other positions, which was especially observed for SRE\textsubscript{10} and when compared to centre backs (36.11 ± 2.7 vs. 39.3 ± 3.1 mmol\textsubscript{O2}/kg/min). To our knowledge, no other studies have compared scores of ME during shuttle run tests across different playing positions; however, during in-line running, midfielders have been previously reported to exhibit significant (Boone et al., 2014) or non-significant but moderate to large effects for better ME compared to centre backs (Nilsson & Cardinale, 2015\text{a}; Santos-Silva et al., 2017). The volume of running has been suggested to be a crucial factor for improving ME in athletes (Barnes & Kilding, 2015), and centre midfielders might develop better ME because of their greater running distances during matches (and likely training) than other position (Sarmento et al., 2014). Additionally, evidence suggests that centre midfielders perform significantly more accelerations and decelerations than centre backs during a match (164 ± 7 vs. 129 ± 6 respectively [match mean reported]) (Dalen, Jørgen, Gertjan, Havard, & Ulrik, 2016). According to training specificity principles, this might further contribute to the development of efficiency over the performance of runs with directional changes, as these incorporate continuous acceleration and deceleration phases. Further research is warranted to investigate this relationship and other factors which might justify the trend for better SRE\textsubscript{10} values in centre midfielders.

In this study, no significant difference was found for ME between elite and sub-elite males, regardless of the running mode. This was somewhat unexpected as sub-elite players trained less than their elite counterparts, with training a critically potent stimulus to develop movement economy (Barnes & Kilding, 2015). These results also contrast with previous studies that have indicated in-line ME is significantly better for professional players than semi-professional players with similar VO\textsubscript{2max} (Ziogas et al., 2011). However, it is common for endurance athletes (Maldonado, Mujika, & Padilla, 2002), and even soccer players (Nilsson & Cardinale, 2015\text{b}), to have a counterbalanced physiological profile (i.e. better VO\textsubscript{2max} coupled with a worse ME, or vice versa). This might be the case in our study since elite players exhibited a lower HR over any running condition, which during submaximal constant work, is a good predictor of higher aerobic capacity (Åstrand & Ryhming, 1954). Hence, we cannot exclude that elite players in our study had a significantly higher VO\textsubscript{2max} and were thus still utilising a lower percentage of their maximum available energy to move. Future studies should evaluate whether expressing movement efficiency as %VO\textsubscript{2max} can produce different outcomes when comparing players of different levels.

When comparing players of the same level but different sex, female players exhibited a trend towards superior RE and SRE\textsubscript{30}, and significantly superior SRE\textsubscript{10}, for oxygen cost and energy cost measures. These findings concur with most ME related studies on endurance runners that female athletes are more economical than males at absolute running speeds (Barnes et al., 2014; Davies & Thompson, 1979; Hopkins & Powers, 1982; Maughan & Leiper, 1983). For instance, the most recent of these studies indicated that compared to well-trained male runners, female runners utilised lower oxygen during in-line running at any speed between 12 and 18 km/h, although their effect size difference was smaller than for shuttle running in our study (0.40 vs 0.94) (Barnes et al., 2014). Female athletes have a greater proportion of type-I muscle fibres than males, which is associated with higher muscle vasodilatory capacity, capillarisation and fatigue-resistance, and in turn can increase aerobic efficiency especially during more muscular-fatiguing exercise conditions (such as runs with directional changes) (Tiller et al., 2021). Nonetheless, another possible explanation for the lower oxygen utilisation could be partly due to female players relying more on anaerobic energy contribution than their male counterparts (not accounted for in traditional ME calculations), as indicated by the significantly higher BLa in our study, particularly during SRE\textsubscript{10}. Indeed, the production of 1 mmol/L of lactate has been suggested to have an energetic equivalent of approximately 3mmol\textsubscript{O2}/kg (Scott, 2006) and might partly explain the larger sex differences observed over this specific running condition. However, similar to ME values between sub-elite and elite male players, we could not assess ME as %VO\textsubscript{2max}. We cannot exclude that female players appeared more economical only in absolute terms but were still utilising a higher percentage of their maximal energy to move as higher HR and the largely higher RER over any running condition (which is also highly associated with a lower VO\textsubscript{2max} (Ramos-Jiménez et al., 2008). This should be further investigated in future studies.

5. Conclusions
RE and CODE (assessed over shuttle runs) are two independent abilities; and CODE rather than RE is a stronger discriminant ability between players of different playing position and sex. In particular, over SRE\textsubscript{10} (higher numbers of directional changes and most similar to soccer), centre midfielders and centre backs appear the most, and least, efficient players’ respectively, whereas female players had significantly better scores than males over SRE\textsubscript{10}. However, no differences between
male players of different level were evident, regardless of running mode. These findings highlight the inadequacy of traditional running economy assessments as a sport-specific measure of movement efficiency in soccer; and can be used to help provide benchmark scores to evaluate soccer players movement economy under more specific running conditions (RE and CODE). Research using larger sample sizes is encouraged to strengthen our findings. Future research should also seek to extend the evaluation of ME over changes of direction using different angles and speed.

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Disclosure statement
No potential conflict of interest was reported by the author(s).

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