2021

Modulators of change-of-direction economy after repeated sprints in elite soccer players

Filippo Dolci

Andrew E. Kilding

Tania Spiteri

Paola Chivers

Ben Piggott

See next page for additional authors

This article was originally published as:
Dolci, F., Kilding, A. E., Spiteri, T., Chivers, P., Piggott, B., Maiorana, A., & Hart, N. H. (2021). Modulators of change-of-direction economy after repeated sprints in elite soccer players. *International Journal of Sports Physiology and Performance, 16* (11), 1649-1655.

Original article available here:
10.1123/ijspp.2020-0740

Authors

Filippo Dolci, Andrew E. Kilding, Tania Spiteri, Paola Chivers, Ben Piggott, Andrew Maiorana, and Nicolas H. Hart

Accepted author manuscript version reprinted, by permission, from *International Journal of Sports Physiology and Performance* (2021), *16*(11): 1649-1655, https://doi.org/10.1123/ijspp.2020-0740.

Modulators of change of direction economy after repeated sprints in elite soccer players.

ABSTRACT

Purpose: To investigate the acute effect of repeat sprint activity (RSA) on change of direction economy (assessed using shuttle running [SRE]) in soccer players and explore neuromuscular and cardiorespiratory characteristics that may modulate this effect. **Methods:** Eleven young elite male soccer players (18.5 ± 1.4 years old) were tested on two different days during a two-week period in their preseason. On day one, lower-body stiffness, power and force were assessed via countermovement jumps, followed by an incremental treadmill test to exhaustion to measure maximal aerobic capacity. On day two, two SRE tests were performed before and after a repeat sprint protocol with heart rate, minute ventilation and blood lactate measured. **Results:** Pooled group analysis indicated no significant changes for SRE following RSA due to variability in individual responses, with a potentiation or impairment effect of up to 4.5% evident across soccer players. SRE responses to RSA were significantly and largely correlated to players' lower-body stiffness (*r*=0.670; *p*=0.024); and moderately (but not significantly) correlated to players' force production (*r*=-0.455; *p*=0.237) and blood lactate after RSA (*r*=0.327; *p*=0.326). **Conclusions**: In summary, SRE response to RSA in elite male soccer players appear to be highly individual. Higher lower-body stiffness appears as a relevant physical contributor to preserve or improve SRE following RSA.

Key Words: movement economy; football; fatigue; potentiation; energy cost.

INTRODUCTION

Soccer is a physically demanding team-sport, requiring players to cover up to 14 km per match, while performing intermittent activities of different modes and intensity, including sprinting, jogging, jumping and technical movements with the ball [1,2]. Video analyses of soccer players illustrates the continuous performance of these activities leads to a progressive decrement in the overall running and match performance toward the end of the game [3,4]. Furthermore, it has also been reported that running performance during matches (i.e. distance covered at high-intensity) can drop acutely, particularly after periods of the game which are played above the average game intensity [5]. For this reason, understanding physiological changes after acute bouts of high-intensity running is important to identify potential causes of acute decrements in running performance and inform the development of specific strength and conditioning programs aimed at preventing reductions in match outputs.

One key physiological determinant of running performance is movement economy [6], which represents the energetic cost (E_C) of movement at submaximal intensities and is the resultant interaction of an athlete's metabolic, physiological, neuromuscular and biomechanical efficiency [6]. The more economical an athlete is, the less energy they require to move [6]. Improved movement economy can benefit soccer players' running performance by lowering the overall relative match physical demand, allowing them to expend less energy to play at given absolute speeds [6]. Supporting this, Hoff, Helgerud [7] estimated that an improvement in movement economy by 5% would increase the distance covered in a match by approximately 1 km. Therefore, it is reasonable to state that reduced (poorer) movement economy over periods of a game would contribute to decrements in running performance, which, together with changes in technical and tactical skills, could impact overall game performance.

Movement economy is 'activity specific', hence a change of direction economy test which assesses movement economy during team-sport crucial activities such as shuttle running (SRE) has recently been developed [8]. This test measures athletes' energetic cost of movement during either continuous 20 m or 10 m shuttle running to enable a more accurate measure of a players' movement efficiency when repeatedly performing key soccer activities such as accelerations, decelerations and changes of direction[8]. This is particularly important given that soccer players perform more than 600 accelerations and decelerations per match, and change activity every 2 to 4 seconds [1].

Nonetheless, it is unknown how change of direction movement economy is affected by periods of high-intensity activity, such as those that occur during a soccer match and training. This information is crucial to understand whether changes in sport-specific movement economy can contribute to the acute running performance drops constantly observed after intense match-periods [1,4,5]; and in turn guide the selection and development of training strategies to preserve soccer running performance over the duration of a game. For this reason, the aim of this study was to determine acute SRE responses to repeated sprint activities (RSA) in soccer players and identify via correlational analysis which neuromechanical and cardiorespiratory characteristics possibly modulate economy changes after maximal efforts.

METHODS

Subjects

Eleven young outfield elite male soccer players (age: 18.5 ± 1.4 years; height: 179.8 ± 5.6 cm; weight: 68.3 ± 5.3 kg) from a professional Australian soccer club participated in our study. All participants trained five times per week and played one competitive match per week, with a total soccer playing experience of 10.4 ± 2.8 years, and had competed for at least one year at this professional level. Each player (and their parents/caregivers when minors) provided written informed consent. All procedures in this study were approved by the Institutional Human Research Ethics Committees at two Universities (017193F and 19670) and were run in accordance with the Declaration of Helsinki.

Design

This study used a mixed cross-sectional (pre-test post-test) and correlational design, to investigate acute fluctuation of SRE following a period of repeated high-intensity activity and physical factors associated with economy changes. All assessments occurred during the pre-season in an indoor laboratory with a standardised temperature set at 25 ± 3 °C. Participants attended the laboratory on two different days over a two-week period. At their first visit, they performed two countermovement jump (CMJ) trials and were familiarized with the SRE test protocol prior to performing a maximal oxygen uptake (VO_{2max}) test. During their second visit, participants performed the SRE test before and after a standardised repeated sprint activity protocol on the same indoor running surface (Mondo Track, Mondo S.p.A., Italy) (Figure 1). Before each testing session, participants were asked to: 1) avoid engaging in intense physical activity (or training) for the prior 24 hours; 2) avoid eating during the 2 hours preceding each visit; 3) have >7 hours sleep; and 4) refrain from alcohol and caffeine for the prior 24 hours.

**INSERT FIGURE 1 HERE **

Methodology

Anthropometry

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 scale (AE Adams CPWPlus-200; Adam Equipment Inc., CT, USA) at the beginning of the first testing session.

Peak force, peak power and eccentric leg stiffness

Peak force, peak power and eccentric leg stiffness were obtained through CMJ tests after a standardised warm-up. Participants were familiarised with technique, and then performed two jump trials, with a 30-s rest period between each trial. The jumps were performed on in-ground tri-axial force plates sampling at 1000 Hz (Type 9281CA, Kistler, Winterthur, Switzerland) embedded into the floor of the laboratory, and connected to a control unit (Type 5233A, Kistler, Winterthur, Switzerland). Participants were instructed to jump vertically for maximal height whilst keeping their hands on their hips to avoid the aid of arm swing. Data from each jump were recorded using the proprietary software (Bioware v4.0, Kistler, Winterthur, Switzerland), with the jump achieving the highest peak force across the trials, retained for analysis. Variables including, relative peak force ($N \cdot Kg^{-1}$) and relative peak power ($W \cdot Kg^{-1}$) were calculated on a Microsoft Excel (2019, 17.0) spreadsheet according to previous specifications [9]. Additionally, eccentric leg stiffness was obtained by dividing absolute peak force by vertical displacement of centre of mass during CMJ as previously suggested by Secomb, Nimphius, Farley, Lundgren, Tran, Sheppard [10]. This estimation method has been validated and developed following direct measure of stiffness from jump platforms[11]. CMJ tests are valid and reliable measures of force and power of the lower limbs [12]. In our study, these tests were highly reliable (CV ≤ 4.2; ICC ≥ 0.940: relative peak force, relative peak power and eccentric leg stiffness) demonstrating acceptable within- and between-subject reliability.

Maximal oxygen uptake test

The VO_{2max} test was performed on a motorised treadmill with 1% inclination setting. Prior to commencing the test, players were fitted with an automated portable gas analyser (MetaMax 3B, Cortex, Leipzig, Germany) and a heart rate (HR) monitor (H10, Polar, Kempele, Finland) secured around their chest. The portable gas analyser was calibrated at the beginning of each testing day for pressure, gas and volume following procedures indicated by the manufacturer, previously reported to produce good reliability [13]. As per previous research [14] where a VO_{2max} test was performed using a motorised treadmill, participants started running at 10 $km \cdot h^{-1}$ and speed was increased by 2 $km \cdot h^{-1}$ every 3 minutes until they were unable to continue running at the set pace. Oxygen uptake (VO_2) was recorded breath-by-breath and analysed post-test using manufacturer software (Metasoft 3 software, version 3.10, Cortex, Leipzig, Germany).

Change of direction economy test

Change of direction movement economy test consisted of running for 5 minutes over 10 m shuttles in a straight line, with 180 degree changes of direction at each end-point, while wearing a HR monitor (H10, Polar, Kempele, Finland) and calibrated portable gas analyser (MetaMax 3B, Cortex, Leipzig, Germany). The mean speed during the test was 8.4 $km \cdot h^{-1}$, as this is equal to an approximate rate of 14 changes of direction per minute ($COD \cdot min^{-1}$) and suggested to be reliable in soccer players (coefficient of variation = 3.5% to 3.8%) [8]. This speed has been selected because most of the total distance (60-70%) covered during soccer matches is performed at low intensity, including jogging (8kmh) and low speed running (12$km \cdot h^{-1}$)[15]; and COD frequency encompassed the average COD frequency occurring during real games[16]. During the test, speed was set using an audible metronome, producing a beep sound at intervals where the participants were to be on the end-point lines, akin to a ‘Beep Test’. To standardize the pre- and post- SRE tests, participants were instructed to continuously alternate the right and left foot to change direction.

Oxygen uptake, carbon dioxide production (VCO_2), minute ventilation (VE) (litre of air breathed for minute) and respiratory exchange ratio (RER) (ratio between the amount of CO_2 produced in metabolism and oxygen O_2 used) for each SRE test were recorded breath-by-breath and analysed using manufacturer software (Metasoft 3 software, version 3.10, Cortex, Leipzig, Germany). For each variable, mean values over the final minute of each test (4th to 5th minute) were retained for analysis. SRE was expressed relative to body mass values as E_C ($Kcal \cdot kg^{-1} \cdot km^{-1}$) applying previously calculation methods described by Fletcher, Esau, Macintosh [17]. This economy expression method has been suggested to be more valid than expressing economy as oxygen cost during activities at intensities below 85% VO_{2max} (when the absence of non-metabolic CO_2 output makes it possible to assess substrate metabolism from the RER [18]) because it also accounts for substrates use and their relative energetic equivalent for oxygen mole [8]. Verification of steady state VO_2 values was achieved by assessing the change in VO_2 during the final two minutes of each economy test with steady state defined as a change in VO_2 <200$ml \cdot min^{-1}$ [8]. SRE changes (SRE_{CHANGE}) and hyperventilation were both calculated and expressed as percentages, using standard mathematical formula [(post-sprints value – pre-sprints value)·pre-sprints value^{-1}] × 100, “values” used for $\text{SRE}_{\text{CHANGES}}$ included SRE and “values” used for hyperventilation included VE.

Heart Rate

Heart rate was monitored at 5 second intervals during all tests using a HR monitor (H10, Polar, Kempele, Finland), worn on the chest of participants. Mean HR over the last minute of each SRE test was considered as the representative HR.

Repeated Sprint Activity

Repeated sprint activity (RSA) required participants to complete six maximal 40 m shuttle sprints with a 20 second passive recovery period between each sprint. Prior to commencement, the portable gas analyser was removed from participants. During each sprint, participants started from a standing position, 20 cm behind a set of dual-beam electronic timing gates (Smartspeed; Fusion Sport; Brisbane, Australia), then ran 20 m in a straight line, prior to performing a 180° directional change, and running 20 m back through the timing gates as fast as possible. The height of the timing gates was adjusted to be level with each participant’s hip height. Five seconds before starting the next sprint, the participants were asked to re-adopt the starting position and await the countdown. Similar activities have been applied in soccer for repeated sprint ability assessment, considered to be a sport-specific and reliable testing protocol [19]. During all sprints, players received verbal encouragement to perform at their maximum.

Blood Lactate

Blood lactate (BLa) was measured from a lancet-induced fingertip puncture, to provide a 5 µL (microliter) blood sample each collection, analysed with a portable blood lactate analyser (Lactate Pro2 Analyser, Arkray, Kyoto, Japan). Blood lactate was collected three minutes after both SRE tests and RSA and was expressed in mmol·L^{-1} as previously suggested [8].

Statistical Analysis

Reliability for CMJ test was assessed in accordance with Hopkins [20] reliability spreadsheet (available at newstats.org/xrely.xls) to perform pairwise comparison of relative peak force, relative peak power and eccentric leg stiffness scores produced during the two jump trials[21]. automatically. Specifically, using aforementioned spreadsheet, we calculated coefficient of variation (CV) from log transformed data of the two trials and interclass correlation coefficient (ICC) from raw data (as per recommendations[21]) with 95% confidence intervals to indicate direction and magnitude of changes between trials [21]. Variables producing a CV < 10% were considered acceptable for within-subject test reliability as for previous applications in studies assessing performance measures during team-sport-related activities[22]; while ICC values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 were considered as indicative of poor, moderate, good, and excellent between-subjects reliability, respectively[8].

All other data were analysed with SPSS software (Version 25.0; IBM Corp, Chicago, IL, USA) with statistical significance set at $p < 0.05$. Data was described using mean, standard deviation and median and the assumption for normality assessed using Shapiro-Wilk test. Pre-post values of SRE, BLa, RER, VE, VCO_2 and HR were compared using a paired T-Test (or Wilcoxon test for non-parametric values). Cohen’s effect size (*d*) for each variable pre- and post- RSA was calculated. Thresholds for Cohen’s *d* magnitude of effect were defined as >0.2–0.5 (small), >0.5–0.8 (moderate) and > 0.8 (large) [23]. Pearson’s product moment correlation coefficient (*r*) (or Spearman test for non-parametric values) was used to determine relationships between $\text{SRE}_{\text{CHANGE}}$, VO_{2max}, peak BLa, post RSA, hyperventilation (% changes in VE), CMJ relative peak force, CMJ relative peak power, and stiffness. Magnitude of resulting correlation coefficients (with 95% confidence limits) were defined using Hopkins spreadsheet as follows: small (0.1), moderate (0.3), large (0.5), very large (0.7) and extremely large (0.9) [24]. For both the Pearson and Spearman Rho correlation coefficients 95% confidence intervals were calculated using the vassarstats online calculator (available at http://vassarstats.net/rho.html?)

RESULTS

Players' physical and performance characteristics including CMJ peak force and peak power, eccentric leg stiffness, VO_{2max}, and RSA scores are summarised in Table 1. The repeated sprint activity induced progressive increase in fatigue and anaerobic energy use as indicated by a 4.3 ± 2.3 % decrement in sprint time and BLa levels reaching 9.7 ± 3.8mmol$\cdot$L^{-1}

INSERT TABLE 1 HERE

Players intensity during SRE was 71.94 ± 10.82% of their VO_{2max}. SRE (E_C) did not significantly change ($p = 0.731$; $d = 0.10$) from pre-RSA to post-RSA, nor VO_2 ($p = 0.104$; d = 0.13) (Table 2). However, SRE_{CHANGE} indicated high individual variability in responses, with either high improvements or decrements in SRE occurring between participants (Figure 2).

INSERT FIGURE 2 HERE

All other variables during the SRE test (RER, VCO_2, HR, BLa and VE) were changed significantly post-RSA (Table 2). Specifically, changes were large for BLa ($p < 0.001$; $d = 1.24$) and VE ($p < 0.001$; $d = >0.90$); moderate for VCO_2 ($p = 0.005$; $d = 0.54$) and HR ($p = 0.007$; $d = 0.53$); and small for RER ($p <0.001$; $d = 0.18$).

INSERT TABLE 2 HERE

A significant large correlation between stiffness and SRE_{CHANGE} ($r = 0.67$; $p = 0.024$) only was reported. No significant correlations were detected between SRE_{CHANGE} and CMJ peak force ($r = -0.46$ $p = 0.237$); BLa post RSA (r = 0.33; $p = 0.326$); hyperventilation ($r = 0.43$; $p = 0.188$); CMJ peak power ($r = 0.37$; $p = 0.263$); and SRE_{CHANGE} and VO_{2max} ($r = 0.18$; $p = 0.591$) (Figure 3). Further analysis also indicated that BLa after RSA was significantly and largely correlated with hyperventilation ($r = 0.69$; $p = 0.018$).

INSERT FIGURE 3 HERE

DISCUSSION

This study examined influential factors that impact change of direction economy during shuttle runs (SRE) after repeated bouts of intense sprint activity. Overall, SRE scores of the pooled group did not fluctuate significantly following repeated sprint activities, however, this was due to varied individual responses in SRE_{CHANGE}. Specifically, two-thirds of participants reported impairments (-2% to -4.5%) similar to those observed for endurance runners after exhaustive high-intensity running activities (-3.6% to -4.6%) [25,26].

Among neuromuscular characteristics modulating SRE_{CHANGE} that we measured, eccentric leg stiffness appeared to have the largest impact (a significant and large correlation). Stiffness determines the ability of the musculo-tendinous system to store and return energy when the running stride contacts with the ground [24]; thus players who have higher level of stiffness can transfer force more efficiently, requiring lower muscular work to produce the same given force[27]. This can result in less muscular fatigue to perform a given activity, and preserve key biomechanical aspects such as optimal stride frequencies during sprints for longer [28]. The testing environment should also be considered in the translation of our study's results. Specifically, we assessed SRE over a hard-indoor surface with participants wearing non studded shoes (typically worn in field-grass conditions), which intuitively have a lower shock absorption compared to soccer pitch (grass) and might have favoured stiffness contribution for elastic energy reuse. Regardless it has been suggested that indoor vs grass surface differences are partially counterbalanced by the greater hardness of the sole in a soccer boot compared with the soft sole of the jogging shoes worn for running on hard surface [29], and we encourage further researches to further confer ecological validity to our findings."

In the present study metabolic and cardiorespiratory factors did not significantly correlate to $SRE_{CHANGES}$. However, high anaerobic energy utilisation during sprints (indicated by high BLa after RSA) was moderately and negatively associated with $SRE_{CHANGES}$. A high BLa is indicative of a higher cascade of peripheral physiological disturbances which can impair contractile abilities, hence possibly contributing to increase fatigue and exacerbate energetic cost of muscle contractions [30]. Moreover, a high anaerobic energy use can also contribute to an increased hyperventilation response for lactic acid buffering [31]. In support of this hypothesis, in our study, hyperventilation significantly and largely correlated with BLa after sprints. Hyperventilation mechanisms are characterised by profound respiration, which can impair postural control [32]; and ultimately affect coordination and kinematics aspects of movement, which are other known biomechanical-related determinants of movement economy [6]. This may have further contributed to detrimental changes in SRE observed in our study; but such hypothesis should be confirmed by future studies specifically controlling for kinematic responses after repeated sprints and their relationship with hyperventilation and movement economy.

These results should be considered with respect to the study limitations. A significant limitation to this study was the small convenience sample recruited as a proportion of players were at specialist training camps or were required to commit to national training or playing commitments. Although our study involved a sample size higher than other studies reporting acute effects of high intensity activities on economy [25,26], and that reflects the cross-section cohort relative to the number of players competing per team during a match (11 starters), based on our results, our study was underpowered to detect a statistical difference if a difference truly was present. Future studies are required to expand upon and confirm our findings, which will need to consider pooling data across multiple playing groups and sites to better understand the role of SRE in running performance in soccer. Based on our study's data, future studies of correlational analysis between SRE and stiffness, peak force and BLa would require minimal samples of 15, 35, 70 participants respectively (sample size estimation spreadsheet, available at http://sportscience.sportsci.org/). However, appropriately powering studies for pre-post repeated sprints differences in E_C present significant sample size challenges for a similar professional level of participants (sample size estimation n=921; based on difference between two dependent means, two tailed, alpha 0.05, power 0.80; G*Power version 3.1.9.4 2019). Therefore, researchers may need to consider alternate research designs with different player profiles to adequately assess such differences and critically evaluate the translation of those results to sub elite and elite player groups. Biologic or playing maturity in our young participants might not have reached and thus they may not have achieved SRE stability. However, the aim of this study was to evaluate acute (within-day) variation, with recent evidence suggesting that this parameter is stable and does not change significantly in younger soccer players within days[8] or even weeks of training [33]. Further, the variability in SRE results cannot discount that maximal running effort may not have been achieved using the volitional testing protocol as maximal running effort was not explicitly measured, although our reported results for metabolic parameters (BLa) are consistent to those reported for similar maximal efforts in soccer players [34].

PRACTICAL APPLICATIONS

Movement efficiency can be acutely affected by repeated sprints, which are recurrent activities during soccer training and matches. Hence it is important to understand physical aspects that can help to preserve optimal movement efficiency after these high-intensity periods of work.

In this regard, the individual ability to preserve change of direction economy during soccer matches (or training) appears to be partly related to eccentric leg stiffness. Hence training strategies that increase the musculotendinous ability to store and release elastic energy (recently discussed in more details by colleagues[35]) might find relevant application for coaches who wish to preserve soccer players efficiency during games. Additionally, due to the moderate size of correlations with SRE changes, both relative peak force and anaerobic energy use might also modulate SRE responses after sprints. Therefore, the implementation of strength training and metabolic conditioning targeting the peripheral ability of utilizing oxygen available in the muscles, might be a possible beneficial strategy to further mitigate efficiency fluctuation during a game.

CONCLUSIONS

Preserving sport-specific movement economy after high-intensity activities is a challenging aspect to optimise running performance during soccer games. Our study highlights that repeated sprints induce acute and individual-dependent fluctuations in SRE in elite male soccer players; and these fluctuations appear to be largely and positively modulated by higher eccentric leg stiffness; with a possible further contribution of high peak force production ability and low anaerobic energy use during repeated sprints. Future research is required to explore our findings using larger player cohorts; and further assess physical determinants and training strategies for preserving optimal movement economy in soccer (and other team sport athletes) during game-specific activities.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the players for their participation in this research. FD is supported by both a Vice-chancellor’s International Fee Remission Research Scholarship from the University of Notre Dame Australia and supported by a Research Training Program Stipend Scholarship issued by the Australian Government. NHH is supported by a Cancer Council of Western Australia Research Fellowship.

DECLARATIONS OF INTEREST

The authors declare that they have no competing interests.

REFERENCES

1. Dolci F, Hart NH, Kilding AE, Chivers P, Piggott B, Spiteri T. Physical and Energetic Demand of Soccer: A Brief Review. *Strength Cond J.* 2020; 42(3):70-77.
2. Di Salvo V, Gregson W, Atkinson G, Tordoff P, Drust B. Analysis of high intensity activity in Premier League soccer. *Int J Sports Med.* 2009;30(03):205-212.
3. Sarmento H, Marcelino R, Anguera MT, CampaniÇo J, Matos N, LeitÃo JC. Match analysis in football: a systematic review. *J Sports Sci.* 2014;32(20):1831-1843.
4. Rampinini E, Coutts AJ, Castagna C, Sassi R, Impellizzeri F. Variation in top level soccer match performance. *Int J Sports Med.* 2007;28(12):1018-1024.
5. Fransson D, Krustrup P, Mohr M. Running intensity fluctuations indicate temporary performance decrement in top-class football. *Sci Med Football.* 2017;1(1):10-17.
6. Dolci F, Hart N, Kilding A, Chivers P, Piggott B, Spiteri T. Movement Economy in Soccer: Current Data and Limitations. *Sports.* 2018;6(4):124.
7. Hoff J, Helgerud J. Endurance and strength training for soccer players. *Sports Med.* 2004;34(3):165-180.
8. Dolci F KA, Spiteri T, Chivers P, Piggott B, Maiorana A, Hart NH. Reliability of change of direction economy in soccer players. *Int J Sports Physiol Perform. 20202;1(aop):1-7.*
9. Chavda S, Bromley T, Jarvis P, et al. Force-time characteristics of the countermovement jump: Analyzing the curve in Excel. *Strength Cond J.* 2018;40(2):67-77.
10. Secomb JL, Nimphius S, Farley OR, Lundgren L, Tran TT, Sheppard JM. Lower-body muscle structure and jump performance of stronger and weaker surfing athletes. *Int J Sports Physiol Perform.* 2016;11(5):652-657.
11. Farley CT, Gonzalez O. Leg stiffness and stride frequency in human running. *J Biomec.* 1996;29(2):181-186.
12. Markovic G, Dizdar D, Jukic I, Cardinale M. Reliability and factorial validity of squat and countermovement jump tests. *J Strength Cond Res.* 2004;18(3):551-555.
13. Macfarlane D, Wong P. Validity, reliability and stability of the portable Cortex Metamax 3B gas analysis system. *Eur J Appl Physiol.* 2012;112(7):2539-2547.
14. 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(2):414-419.
15. Silva JR, Magalhães J, Ascensão A, Seabra AF, Rebelo AN. Training status and match activity of professional soccer players throughout a season. *J Strength Cond Res.* 2013;27(1):20-30.
16. Bloomfield J, Polman R, O'Donoghue P. Physical demands of different positions in FA Premier League soccer. *J Sports Sci Med.* 2007;6(1):63.
17. Fletcher JR, Esau SP, Macintosh BR. Economy of running: beyond the measurement of oxygen uptake. *J Appl Physiol (1985).* 2009;107(6):1918-1922.
18. Lacour J-R, Bourdin M. Factors affecting the energy cost of level running at submaximal speed. *Eur J Appl Physiol.* 2015;115(4):651-673.
19. Rampinini E, Bishop D, Marcora S, Bravo DF, Sassi R, Impellizzeri F. Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *Int J Sports Med.* 2007;28(03):228-235.
20. Hopkins WG. Measures of reliability in sports medicine and science. *Sport Med.* 2000;30(1):1-15.
21. Hopkins WG. Spreadsheets for analysis of validity and reliability. *Sportscience.* 2017;21.

22. Sirotic AC, Coutts AJ. The reliability of physiological and performance measures during simulated team-sport running on a non-motorised treadmill. *J Sci Med Sport.* 2008;11(5):500-509.
23. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sport Exerc.* 2009;41(1):3.
24. Barnes KR, Mcguigan MR, Kilding AE. Lower-body determinants of running economy in male and female distance runners. *J Strength Cond Res.* 2014;28(5):1289-1297.
25. Collins MH, Pearsall DJ, Zavorsky GS, Bateni H, Turcotte RA, Montgomery DL. Acute effects of intense interval training on running mechanics. *J Sports Sci.* 2000;18(2):83-90.
26. James DV, Doust JH. Oxygen uptake during moderate intensity running: response following a single bout of interval training. *Eur J Appl Physiol Occup Physiol.* 1998;77(6):551-555.
27. Bojsen-Møller J, Magnusson SP, Rasmussen LR, Kjaer M, Aagaard P. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *J Appl Physiol.* 2005;99(3):986-994.
28. Girard O, Mendez-Villanueva A, Bishop D. Repeated-sprint ability—Part I. *Sports Med.* 2011;41(8):673-694.
29. Sassi A, Stefanescu A, Bosio A, Riggio M, Rampinini E. The cost of running on natural grass and artificial turf surfaces. *J Strength Cond Res.* 2011;25(3):606-611.
30. Mendez-Villanueva A, Hamer P, Bishop D. Fatigue in repeated-sprint exercise is related to muscle power factors and reduced neuromuscular activity. *Eur J Appl Physiol.* 2008;103(4):411-419.
31. Meyer T, Faude O, Scharhag J, Urhausen A, Kindermann W. Is lactic acidosis a cause of exercise induced hyperventilation at the respiratory compensation point? *Br J Sports Med.* 2004;38(5):622-625.
32. Zemková E, Hamar D. Physiological mechanisms of post-exercise balance impairment. *Sports Med.* 2014;44(4):437-448.
33. dolci F. HIIT Shock microcycle improves running performance but not economy in female soccer players *Int J Sports Med.* 2020.
34. Morcillo JA, Jiménez-Reyes P, Cuadrado-Peñafiel V, Lozano E, Ortega-Becerra M, Párraga J. Relationships between repeated sprint ability, mechanical parameters, and blood metabolites in professional soccer players. *J Strength Cond Res.* 2015;29(6):1673-1682.
35. McMahon JJ, Comfort P, Pearson S. Lower limb stiffness: Effect on performance and training considerations. *Strength Cond J.* 2012;34(6):94-101.

FIGURES AND TABLES

Figure 1. Testing battery and procedures time course during the official testing session.
RSA = repeat sprint activity.

Figure 2. Percentage changes in shuttle running economy (SRE) expressed as energetic cost (E_C).

Figure 3. Correlations coefficients (r) with 95% Confidence Intervals (CI) between percentage changes in shuttle running economy (SRE) pre- to post- repeated sprints (RSA), stiffness, countermovement jump (CMJ) peak power, blood lactate after repeated sprints and hyperventilation.

Table 1. Participants (n=11) baseline performance characteristics

Performance Measures	**Mean ± SD**
Stiffness (N·m^{-1})	3310.8 ± 776.8
Peak power CMJ (W·kg^{-1})	48.3 ± 6.8
Peak force CMJ (N·kg^{-1})	23.5 ± 1.4
VO_{2max} (ml·kg^{-1}·min^{-1})	63.5 ± 7.7
HR_{max} (beats·min^{-1})	192 ± 11
RSA_{BEST} (seconds)	7.13 ± 0.29
RSA_{MEAN} (seconds)	7.43 ± 0.23
RSA_{DEC} (%)	37.5 ± 0.01
$BLa_{post\text{-}RSA}$ (mmol·L^{-1})	9.7 ± 3.8

VO_{2max} = maximal oxygen uptake; HR_{max} = heart rate maximum; RSA_{BEST} = fastest repeat sprint activity time; RSA_{MEAN} = average repeat sprint activity time; BLa = blood lactate; RSA = repeat sprint activity test; $BLa_{post\text{-}RSA}$ = Blood lactate concentration after RSA; CMJ = countermovement jump.

Table 2. Participants (n=11) physiological variables during shuttle running economy test prior to and following repeated sprint activity (RSA).

Variable	**Pre-RSA**	**Post-RSA**	**Pre-Post Differences**		**% Change**	**Effect size**
	Mean [SD]	**Mean [SD]**	**T-test**	**P value**	**Mean [SD]**	**Cohen's *d***
$VO_{2(L\cdot min^{-1})}$	3.07 [0.35]	3.11 [0.28]	-1.77	0.104	1.6 [3.2]	-0.13
$E_{C\ (kcal\cdot kg^{-1}\cdot km^{-1})}$	1.66 [0.12]	1.67 [0.09]	-0.35	0.731	0.5 [3.3]	-0.10
RER	1.00 [0.36]	0.93 [0.47]	6.34	< 0.001*	6.42 [3.14]	0.18
$VCO_{2\ (L\cdot min^{-1})}$	3.07 [0.38]	2.90 [0.27]	3.54	0.005*	-4.9 [4.6]	0.54
VE $_{(breaths\cdot min^{-1})}$	69.90 [7.09]	75.53 [6.06]	-4.62	< 0.001*	8.4 [6.5]	-0.90
HR $_{(beats\cdot min^{-1})}$	157.1 [18.1]	165.8 [16.1]	-3.39	0.007*	5.8 [5.2]	-0.53
BLa $_{(mmol\cdot L^{-1})}$	1.46 [1.06]	3.91 [2.72]	-2.94[a]	< 0.001*	191.0 [148.4]	-1.24

[a] Wilcoxon Rank test result reported. RER = respiratory exchange ratio; VO_2 = oxygen uptake; E_C = energetic cost; VCO_2 = carbon dioxide production; HR = heart rate; BLa = blood lactate; VE = minute ventilation. * = statistical significance ($p \leq 0.01$).